NASA Contractor Report 177578

Technology Needs for High-Speed Rotorcraft

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Prepared for
Ames Research Center
CONTRACT NAS2-13070
April 1991

National Aeronautics and
Space Administration

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SECTION I

INITIAL TECHNOLOGY ASSESSMENT AND CONCEPT DEFINITION

SUMMARY

This study consists of three main tasks: Initial Technology Assessment and Concept Definition, Technology Evaluation for Selected Concepts, and the Enabling Technology Plan. The overall goal of the study is to identify the technology requirements of high-speed rotorcraft (≥ 350 KTAS) which maintain helicopter-like hover efficiencies. To achieve the study goal, sizing the concept represents a secondary priority. Of more importance, is the ability to perform technology sensitivity studies for selected concepts.

During the first task, five concepts were evaluated based on specified measures of effectiveness. These concepts included the Tilt Wing, Tilt Rotor, Rotor/Wing, Folding Tilt Rotor and Trail Rotor. The latter was evaluated in two configurations: a turbofan convertible engine version and a propfan version. The results of the evaluation demonstrated that the concepts employing integrated lift or propulsion systems, such as the Tilt Wing, Tilt Rotor and Rotor/Wing, exceeded the effectiveness of the other concepts employing dual systems, such as the folding rotor concepts. The extra weight and drag of the folding rotor systems significantly contributed to their poor performance.

An initial technology assessment demonstrated the dramatic impact of IHPTET goals on all the concepts, leading to the preliminary conclusion that improvement in propulsion is perhaps the single most important technology across all concepts. The propulsive efficiency of the prop/rotor concepts requires some means to reduce tip speed in cruise if they are to achieve 450 KTAS. The required tip speed reduction is about 50% from hover. Improvements in rotor aerodynamics are aimed toward cruise efficiency, over hover power requirements for these vehicles. Another important result indicates that the drive systems for these high-speed vehicles contribute immensely to their empty weight. Since cruise typically sizes the vehicles, the maximum power requirements occur in this regime while tip speed requirements decrease by nearly 50%. The increased torque in this flight mode severely impacts the drive system weight. This tends to make prop/rotor vehicles sensitive to anything which increases cruise power due to the cascading effect throughout the system.

The Rotor/Wing benefits from possessing an integrated lift system and by not possessing a drive system (it is reaction driven). Its "Achilles Heel" is the inefficiency of power transmission (only about 50%) and the requirement to use less than optimum efficiency, low by-pass ratio turbofan engines. The combination of poor fuel economy and less than desired wing loading increases the fuel requirements and the gross weight of the vehicle. However, the empty weight remains low indicating the probability of reduced maintenance and acquisition costs. Like the other concepts, its lack of development assures risk, but for the purposes of the study, since identification of needed technology is the goal, risk is down played.

Concepts selected for the second task included the Tilt Wing, in the military transport mission, and the Rotor/Wing, in the ground attack role. Extensive sizing and performance were accomplished on these concepts during this task, results of which may be found in the Appendix. Closer focus on the conversion of Tilt Wing demonstrated a clear relationship between wing loading, disk loading **and** high-lift devices used on the wing. An effort to increase conversion wing loading of the Rotor/Wing resulted in the ability to convert in a more benign manner, while reducing the disk loading of the vehicle. Sensitivity studies confirmed technology impacts of Task 1. Again, propulsion technology leads in improvement potential. Another area for improvement in Tilt Wing technology occurs due to an increase in conversion wing loading. This concept's characteristic large wing may be reduced by increasing its stall angle, by

increasing its $C_{L_{max}}$, by increasing drag, or a combination of all. Reducing the wing size, while maintaining nominal conversion characteristics, significantly reduces cruise drag and weight. One means to achieve high lift is the application of circulation control.

The results of Task 3 highlight time lines and suggest institutions, such as industry, government and universities best suited to specific technology development. The development of technology begins with analytical methodology development and proceeds through testing/validation and subsystem flight demonstration. Finally, the technologies for each concept are rated according to risk and payoff and prioritized. Critical technologies are identified as hose that without development would prohibit flight in one of the flight regimes.

Recommended high-payoff areas for investigation include:

Tilt Wing-

- Feasibility study of a high-lift wing
- Feasibility study of prop/rotor RPM reduction schemes
- Preliminary design/test of a 450 knot prop/rotor

Rotor/Wing-

- Assess dynamics of stopping a two-bladed rotor/wing
- Configuration wind tunnel testing
- Assess concept feasibility and vehicle dynamics during conversion using a radio controlled model

Continuing the IHPTET Program.

The authors would like to acknowledge the significant contribution to the final report made by many individuals. They are: Andrew Elliott, John Fish, Robert Fitzpatrick, Don Kunz, Derek LeThanh, Lawson Robinson, and Brian Smith. Their time and effort is greatly appreciated.

INTRODUCTION

Development of an air vehicle capable of helicopter efficiency and jet-transport-like cruise speeds depends on the synergistic combination of advanced technologies into a configuration adapted to a specified mission. The U. S. Patent Office issued patents for high-speed rotorcraft as early as the late 1920's[1]. Several concepts flew as technology or feasibility demonstrators, with varying degrees of success, in the late 1950's and early 1960's. Recently, the XV-15, and the V-22 tilt-rotor aircraft represent the most practical attempts at the goal of hover and high-speed flight, but they cannot achieve the high-speed cruise desired for this study. The increased speed range dictates the need to examine different concepts and technologies, to include those which have previously been proposed.

INITIAL CONCEPT SELECTION

The selection process for Task 1 concepts included a brainstorming session attended by a ten member, multi-disciplinary team. This team submitted sixteen concepts (Figure 1), some with multiple configurations for consideration. These concepts included, from left to right:

Tilt Wing
Tilt Rotor
Trail-Rotor Convertiplane
Folding Tilt Rotor
Aft Rotor/Wing
Tail Sitter Rotor/Wing
Variable Geometry Rotor/Wing
Stopped Rotor/Wing
Rotor-in-Wing
Composite Aircraft
Pancake Engine Aircraft
Rotating Airfoil
Rotating Wing
VTOL Wing Lifter
Tube Fan
Actuator Disk

Prior to evaluation, the proposer explained the concept to the group to ensure understanding of the concept. This led to further discussions and in some cases, modifications of proposed concepts. At this point, only comments regarding understanding of the concepts were allowed, to ensure free flow of ideas.

Each concept received an evaluation of good (3), fair (2), or poor (1) rating in nine areas. This evaluation did not include formal analysis due to time limitations, but drew on the expertise within the group to conceptually evaluate the concepts. The nine areas for evaluation included:

Propulsion
Stability and Control
Structures
Conversion
Hover Efficiency (Disk Loading < 50)
High-Speed Potential (Cruise 350-500 Kts)
Design Complexity
Multimission Capability
CTOL/VTOL Capability

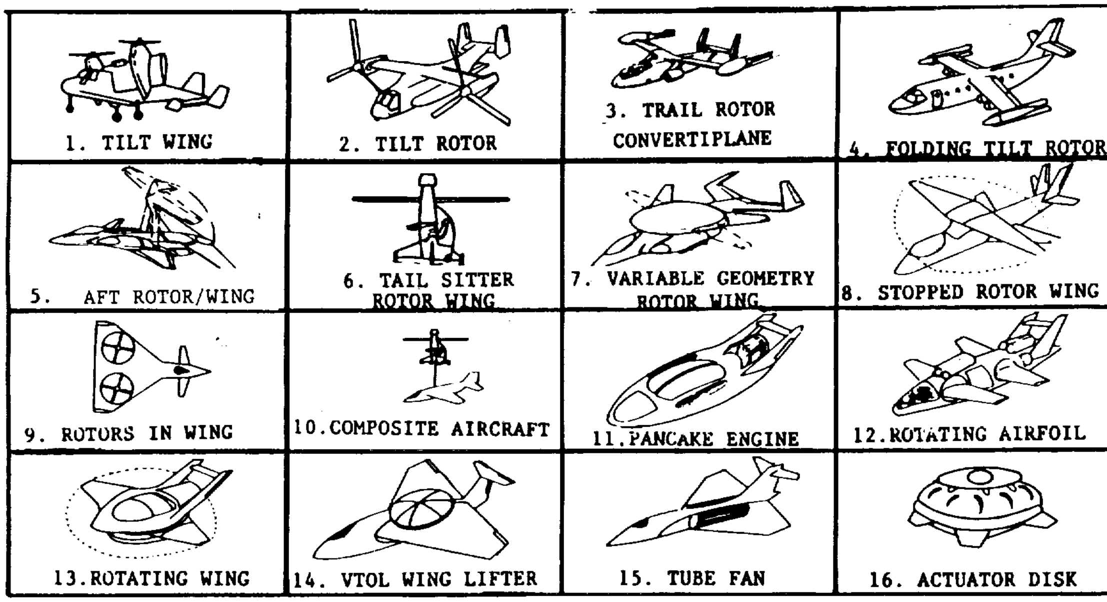


FIGURE 1-1. SIXTEEN CONFIGURATIONS PROPOSED BY TEN PERSON MULTI-DISCIPLINARY GROUP

Initial Concept Description

The matrix, in Figure 1-2, depicts the results of the concept evaluation. Some comments on each configuration follows:

Tilt Wing- Limited descent capability in conversion. High-speed limitation is based on prop/rotor for propulsion. Hover efficiency is determined by prop/rotor diameter.

Tilt Rotor- High-seed cruise potential is limited by rotor efficiency in cruise.

Trail-Rotor Convertiplane/Folding Tilt Rotor- Conversion may pose technological problems. Folding rotors require a more complex hub.

Aft Rotor/Wing- Stability and control during conversion poses major problems due to large C.G. shift and center of lift as the wing moves aft to the fixed wing configuration. Also, maintaining lg flight could be difficult. The large hinge structure and seals required for the reaction drive system leads to concerns about the structure and complexity of the system.

Tail-Sitter Rotor/Wing- Conversion received a poor rating due to experiences with this type of VTOL aircraft during the '60s. It lacks a CTOL capability and multimission flexibility.

Stopped Rotor/Wing- Conversion dynamics were considered somewhat risky based on work accomplished in the mid '60s.

Rotor-in-Wing- This concept suffered due to the incompatibility of low disk loading rotors and desired high wing loading for cruise. It presents a difficult structural problem as well. Wings would typically be thick, which would hurt the high-speed cruise capability.

CONCEPT / CATEGORY	TILT WING 1	TILT ROTOR 2	TRC/ FTR 3	AFT R/W 5	T-SIT R/W 6	STOP R/W 8	ROTOR-IN-WING 9
PROPULSION	3	3	3	3	3	3	3
STRUCTURES	3	3	3	2	3	2	1
DESIGN COMPLEXITY	3	3	1	1	2	2	2
STABILITY & CONTROL	2	3	3	2	3	3	3
CONVERSION	3	3	2	2	1	2	3
HOVER EFFICIENCY	2	3	3	3	3	3	2
HIGH-SPEED POTENTIAL	2	2	3	3	3	3	1
CTOL/VTOL CAP	3	3	3	3	1	3	3
MULTIMISSION CAP	3	3	3	3	2	3	3
TOTAL	24	26	24	22	21	24	21

CONCEPT / CATEGORY	COMP A/C	PANCAKE ENGINE	ROTATING AIRFOIL	ROTATING WING	VTOL LIFTER	TUBE FAN	ACTUATOR DISK
PROPULSION	3	1	3	3	1	3	3
STRUCTURES	3	3	1	2	3	2	2
DESIGN COMPLEXITY	3	2	2	2	3	2	1
STABILITY & CONTROL	3	1	1	2	2	1	1
CONVERSION	2	3	3	2	3	2	2
HOVER EFFICIENCY	3	1	1	3	1	1	2
HIGH-SPEED POTENTIAL	3	3	3	3	2	3	2
CTOL/VTOL CAP	1	3	3	3	3	3	1
MULTIMISSION CAP	1	1	2	1	3	3	1
TOTAL	22	18	19	21	21	20	15

SCORE: GOOD(3), FAIR(2), POOR(1)

FIGURE 1-2. CONCEPT EVALUATION MATRIX

Composite Aircraft- Conceptually, this concept appears to meet all the requirements with relatively little risk. However, it requires two air vehicles which was deemed a violation of the requirements.

Pancake Engine Aircraft- The propulsion system received a poor rating due to untried technology and potential high disk loading. No definition of low-speed control was provided.

Rotating Airfoil- This concept produces lift through the rotation of the wing in a manner similar to a ferris wheel. This concept is analogous to a cyclocrane. Complexity, control during conversion and structural implication of the concept led to poor ratings.

Rotating Wing- A concept similar to the stopped rotor/wing, its wing rotates around a circular fuselage, which creates the required lift in conversion. The complexity and limited volume caused this to receive a low rating. It may be suitable for a ground attack vehicle, requiring volume only for a pilot. Stability and control concerns probably make this concept unviable.

VTOL Wing Lifter- This achieves hover through engine exhaust gases blown tangentially over the wing to reduce upper surface pressure. The concept, as presented, had no aerodynamic merit. Even with modifications, stability and control in hover, low wing loading in cruise and power required to hover resulted in a poor rating.

Tube Fan- Large cylindrical fans accelerate air downward providing required thrust for lift. This resulted in high disk loading and questionable efficiency. The structure becomes more complex due to embedding the large fans near the wing root.

Actuator Disk- A rotating disk with guide vanes feed air, through centrifugal pumping, into a series of counter rotating blades rotating on the outside of the craft. Stability and control is questionable at low speed. The concept would be mechanically and structurally complex if it could work.

Results of Initial Selection

The selection of five concepts for further study in Task 1 provided the opportunity to look at the best candidates in greater detail. It also ensured that none of the most promising concepts were prematurely eliminated, especially since only a conceptual, subjective evaluation was initially performed. The selected concepts, shown in Figure 1-3, attained the highest total ratings and include:

Trail-Rotor Convertiplane (TRC)
Folding Tilt Rotor (FTR)
Tilt Rotor
Rotor/Wing
Tilt Wing

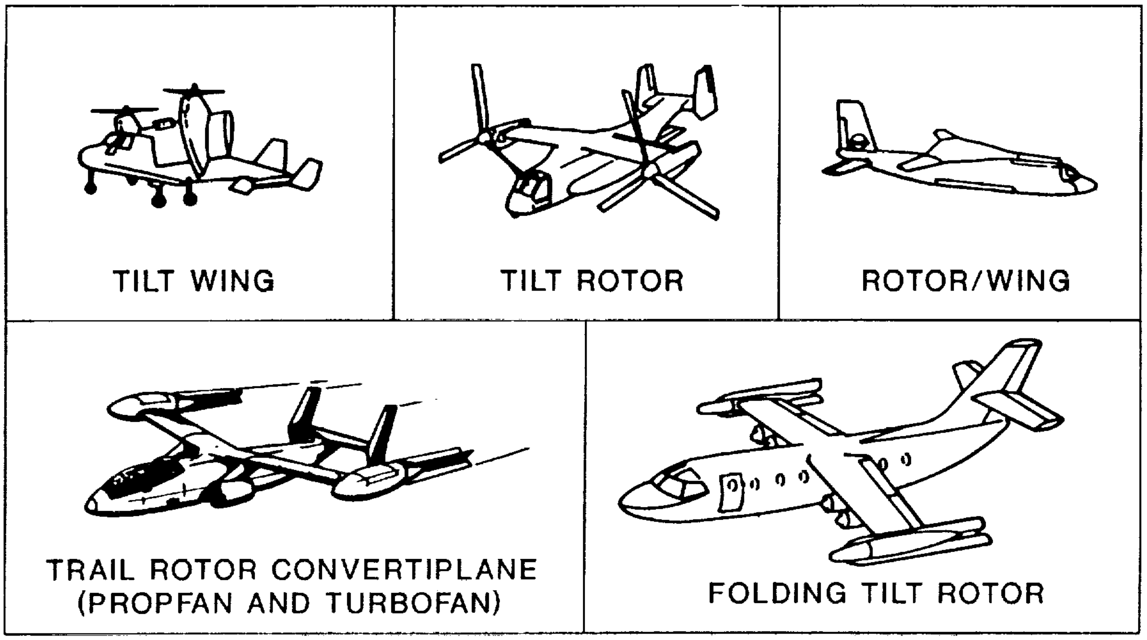


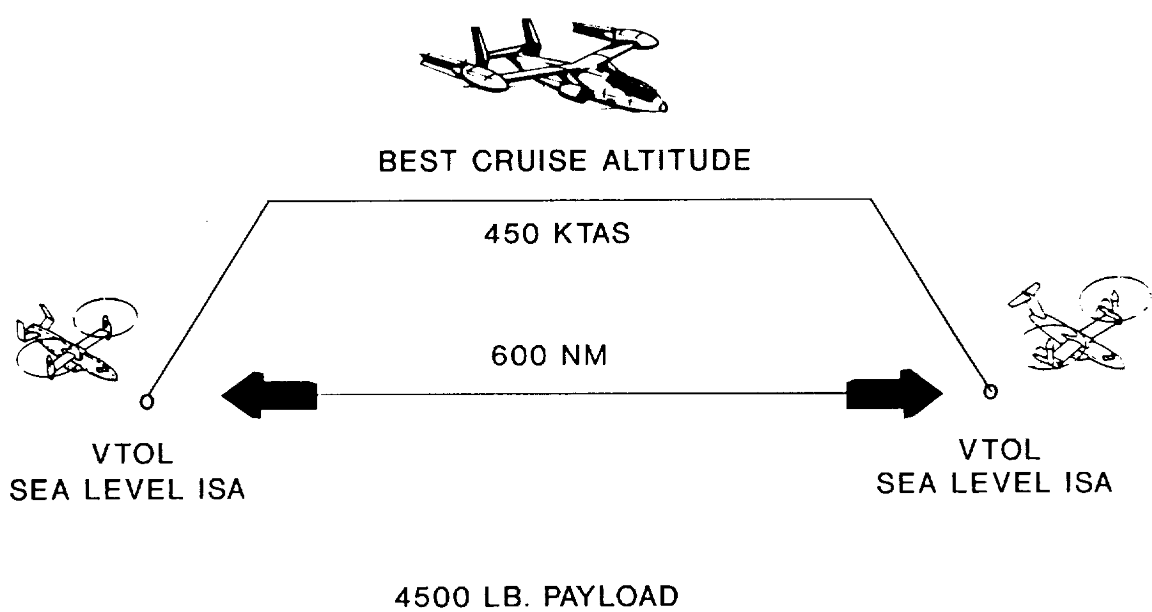
FIGURE 1-3. FIVE CONCEPTS SELECTED FOR TASK 1 EVALUATION

One variation to the Trail Rotor study included assessment of a turbofan versus a propfan for cruise.

CONCEPT SIZING

Generic Mission

A comparative study of the selected concepts must include development of a set of requirements which provide a basis for sizing, while providing a common standard of performance. The generic mission depicted in Figure 1-4 serves this purpose. The mission closely parallels the Task 2 missions in general. The profile consists of a taxi, hover, vertical take off segment of 10 min., followed by a climb to best cruise altitude. Once at altitude, the aircraft completes a 600 nautical mile mission at 450 KTAS. The final leg consists of descent and a 10 minute vertical landing, hover, and taxi. The aircraft carry an unspecified 4500 pound payload which compromises between the Task 2 mission payloads, while the box size represents a more configuration demanding alternative. Arguably, it eliminates a small compact attack configuration, but the cargo/passenger box may pose layout concerns for some concepts. The cruise speed requires some wing sweep to achieve efficient cruise altitudes and represents a significant increase over current high-speed rotorcraft.



Configuration Sizing Assumptions

The limited scope of Task 1 results in a number of assumptions utilized in the configuration sizing. The majority of the assumptions are design parameters chosen to remain constant during the Task 1 sizing exercises, either to simplify aircraft sizing or because determining the actual parameters requires analyses beyond the scope of Task 1. In the more intensive Task 2, these assumptions will be verified and optimized during the final sizing of the remaining concepts.

To account for high-speed aeroelasticity characteristics, wing bending, torsional stiffness and wing structural integrity, the wing aspect ratio is limited to 6 times the cosine of the wing sweep angle. This criteria represents a reasonable limit based on existing V/STOL aircraft.

Assuming a minimum wing thickness ratio of 0.18 ensures wing stiffness in helicopter flight and torsional stiffness required for airplane mode and conversion. This assumes improvement in structural wing design compared to the V-22 and the XV-15 with no weight penalty.

In the absence of a complete stability and control analysis, the tail surfaces are sized by XV-15 tail volume coefficients. For the Folding Tilt Rotor, a canard configuration, the Beech Starship tail volume coefficients size the control surfaces.

Based on V-22 rotor performance, the maximum blade loading (C_T/σ) is 0.18. By providing for a 35% maneuver margin in helicopter flight, the design hover blade loading becomes 0.1333.

The wing download in hover, based on V-22 results, is held constant at 12% hover weight for the Tilt Rotor, Trail Rotor, and Folding Tilt Rotor[2]. The Tilt Wing configuration eliminates wing download. The download used for Rotor/Wing is 5%.

The rotor hover tip-speed is 750 fps for acoustic reasons. In Task 2, this parameter will be optimized for the final concepts.

Excessive wing sweep angles result in a large difference between the locations of the hover and cruise center of lift, which may result in unique longitudinal stability problems. To minimize these problems, the maximum allowable wing sweep angle is restricted to 20°. This limitation influences the optimum cruise altitude for each concept. Further illumination of potential stability problems associated with high sweep angles is presented on page 1-35.

Rotor clearance determines the wing span for all applicable concepts. This method of sizing results in configuration constraints at lower disk loading due to aspect ratio limitations.

A modified version of VASCOMPII was utilized to size all Task 1 concepts but the Rotor/Wing. Because of its unique sizing criteria, the Rotor/Wing was sized by a separate code based on methodology found in references (3,4). Both sizing codes incorporated similar weight estimating equations and mission analysis subroutines.

Weights Methodology

The baseline weight estimation methodology used for the HSR study is documented in the MDHC Weight Estimation Handbook Series. These equations were derived using a wide range of helicopters, from the light scouts to the heavy lift tandem rotors, and a wide range of gross weights from 3,000 lbs to 130,000 lbs.

Starting with this methodology, modifications were made to properly sensitize the equations to V/STOL configurations, particularly tilt rotors. This was accomplished by adjusting and calibrating the equations initially to the V-22 Osprey. This calibration results in a baseline which has the weight penalties associated with the V-22 design built in such as very stiff wing panels.

The difference between Task 1 concepts and the V-22 were identified and the appropriate weight adjustments made. As an example, some concepts required an additional weight penalty due to the requirement for a pressurized fuselage.

Common weight estimation methodology was maintained for all groups where the type of air vehicle had little effect on weight equation form (i.e., body group). As a result, it was possible to use common weight equations for all configurations except the Rotor/Wing's flight controls and wing group where configuration specific weight methods were used.

The weights of the payload, fixed equipment, avionics, and operating items were detailed from the Task 2 missions. As previously stated, a 4500 lb. Payload was selected. The remaining items and their weights are: fixed equipment, 4000 lbs.; avionics, 800 lbs.; operating items, 625 lbs.

Advanced Technology Assumptions- The estimated weight savings due to advanced technology in the year 2010 assumes various advances which are detailed in the initial technology assessment portion of this report (pg 1-28). These advances result in a 25% decrease in the drive system weight, a 15% decrease in the primary structure weights, a 36% decrease in engine weight, and a 10% decrease in the secondary structure and landing gear weights.

Sizing for Optimum Cruise Altitude

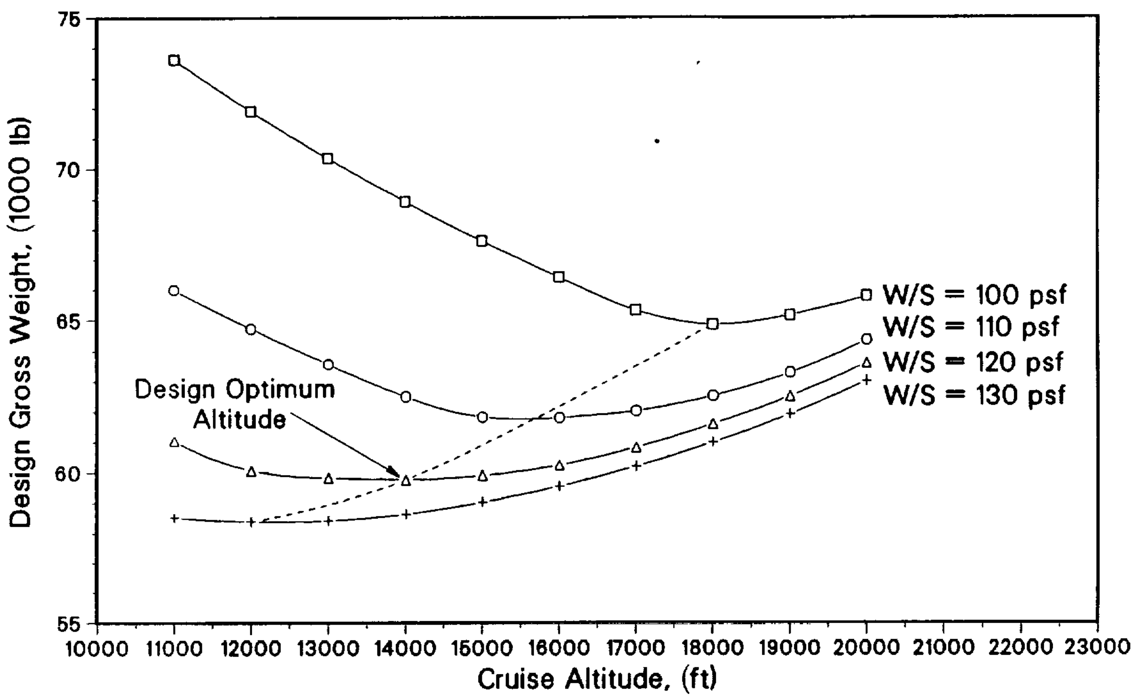


FIGURE 1-5. OPTIMUM CRUISE ALTITUDE DETERMINATION - FOLDING TILT ROTOR

Each configuration was sized to the altitude that yields the minimum gross weight for the design wing loading. Since hover disk loading does not influence this altitude directly, a nominal value is fixed for this trade. Figure 1-5 represents an example showing the optimum cruise altitude sizing plot for the Folding Tilt Rotor. The locus of minimum weight for each wing loading indicates the optimum cruising altitude as a function of wing loading.

For a given wing loading, the altitude for minimum gross weight is a function of the aircraft drag and engine characteristics. For altitudes greater than the minimum weight altitude, the compressibility drag rises because the Mach number and aircraft lift coefficient continue to increase, resulting in a higher gross weight. For altitudes less than the minimum, the aircraft drag increases as the local dynamic pressure increases, resulting in more required thrust, more fuel and higher gross weight. Thus, the optimum altitude represents the point where the compressibility drag begins to rise faster than the dynamic pressure decreases, minimizing the cruise drag and engine size of this altitude.

A significant reduction in the cruise altitude occurs as the wing loading increases. This characteristic results from the drag divergence characteristics of the 18% thick wing section. The requirement for a thick wing with a small sweep introduces stringent drag divergence boundaries that forces the optimum altitude down. Clearly, high-speed rotorcraft require thick airfoils with improved drag divergence characteristics, or wings with increased sweep, or thinner wings for efficient cruise.

Since the optimum altitude is a function of wing loading, choosing the optimum altitude becomes an iterative step in sizing each concept. Only one iteration determines the cruise altitude for each concept, which is then fixed for the remainder of the sizing process. The lowest design gross weight solution leads to higher wing loadings. However, high wing loadings can result in buffeting at high speeds, reduced conversion corridor and excessively high aspect ratios at low disk loadings. For these reasons, a value of 120 psf represents the maximum allowable wing loading. Using this constraint, the example Folding Tilt Rotor's optimum altitude becomes 14,000 ft.

Rotor Parametric Sizing Matrices

For each case, the optimum altitude was determined for a nominal wing loading. This altitude became the concept's design cruise altitude, accounting for compressibility effects and prop cruise efficiency, within the assumptions made. With this parameter fixed for each concept, sweeps varying disk loading and wing loading further defined concept gross weight (Figures 1-6 thru 1-9). Adding constraints to the plots reduced the available design solutions and sometimes prohibited the minimum gross weight solution. Typical constraints placed on the solutions included a maximum allowable aspect ratio, as previously defined, and a maximum wing loading constraint above which high-speed buffet occurs due to shock induced separation, or conversion stall speed exceeded that required for conversion. In some instances, the maximum wing loading shown results in the locus of minimum gross weight solutions, within the cross-hatched boundaries (as in Figure 1-8) and becomes the choice wing loading.

Rotor constraints, in the form of maximum disk loading, occur based on the maximum overturning moments for personnel operating in the vicinity of the aircraft while it hovers in ground effect. For a twin rotor system that maximum is 40 psf[5].

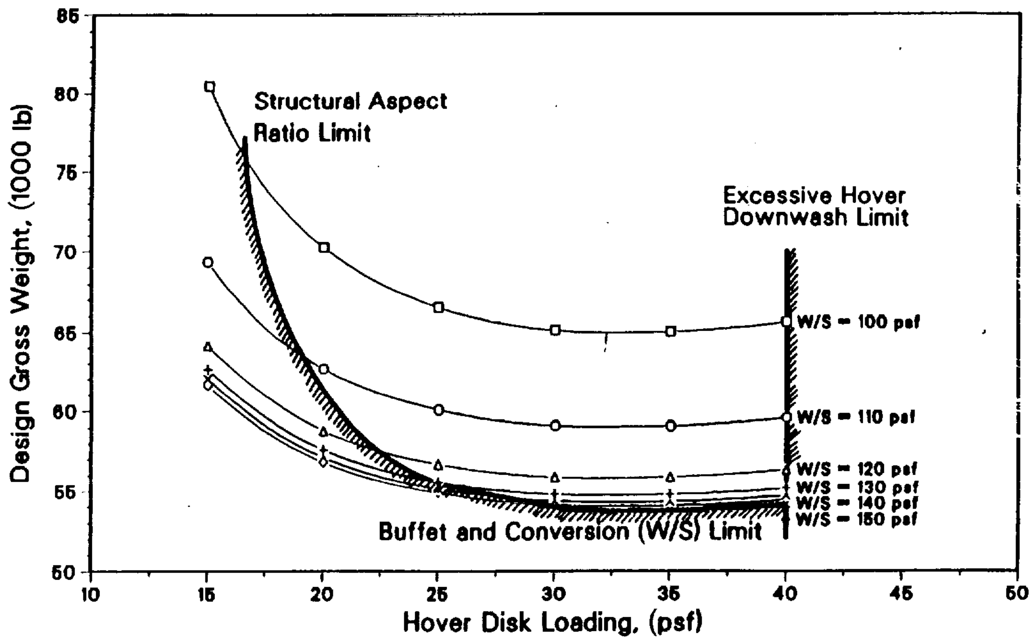


FIGURE 1-6. TURBOFAN TRAIL ROTOR - PARAMETRIC DESIGN MATRIX

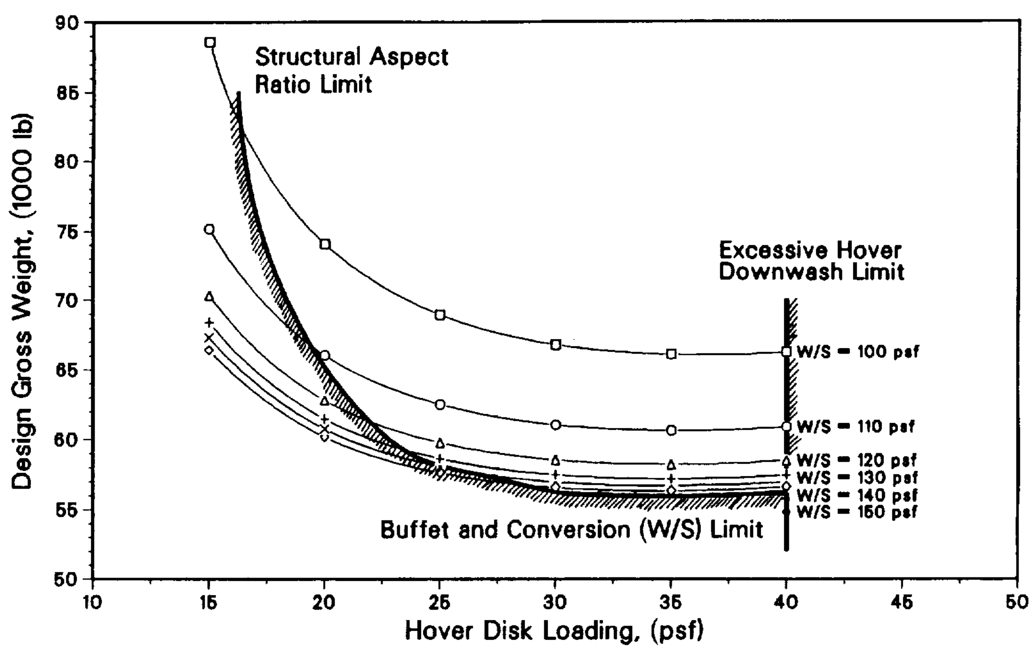


FIGURE 1-7. FOLDING TILT ROTOR - PARAMETRIC DESIGN MATRIX

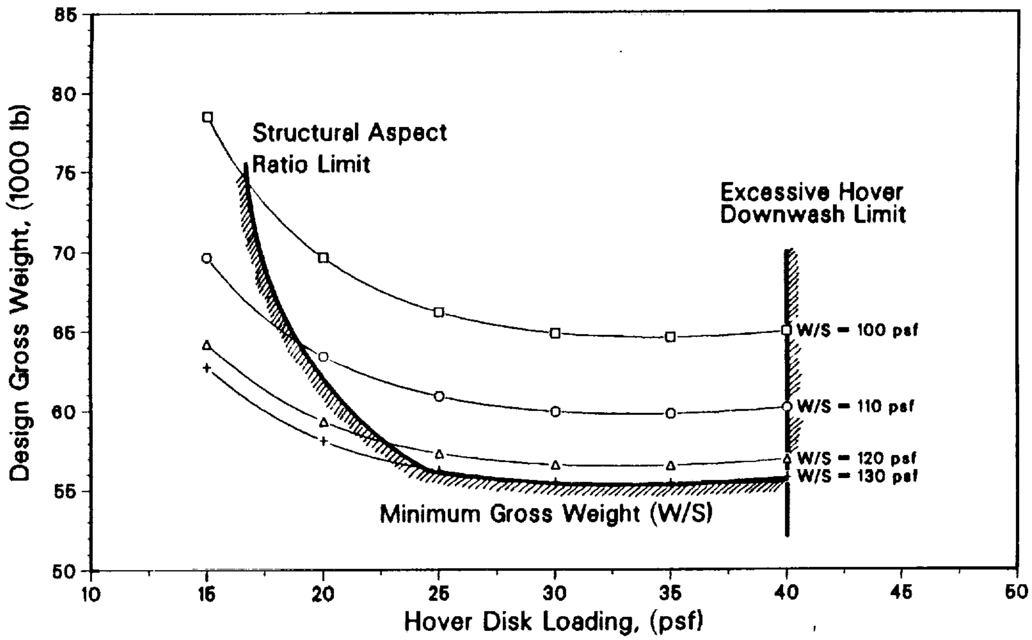


FIGURE 1-8. PROPFAN TRAIL ROTOR - PARAMETRIC DESIGN MATRIX

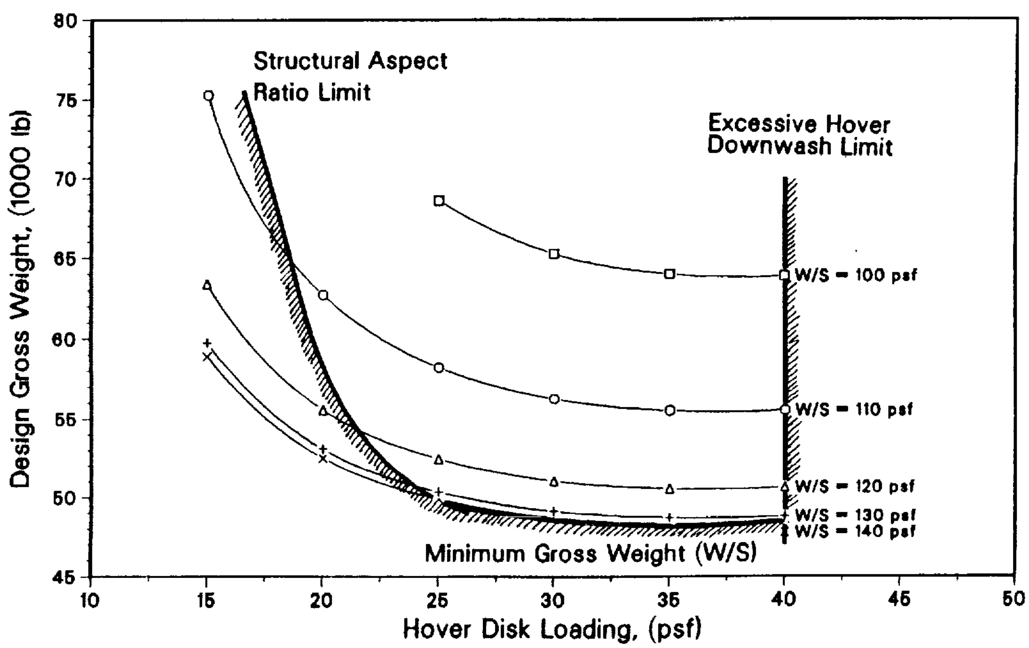


FIGURE 1-9. TILT ROTOR - PARAMETRIC DESIGN MATRIX

Increasing the disk loading results in a lower aspect ratio wing for a constant wing loading which, in turn, results in a lower weight wing. This ultimately reduces the overall structural weight. Since cruise power and not hover power requirements size the concepts, the design is driven to higher disk loadings. The high-speed requirements appear to push the optimized solutions to higher disk loadings because the cruise power requirements are more stringent than for hover. Range may also play a role with aspect ratio determining fuel weight. A long range mission may require higher aspect ratios wings which could drive the solution to a lower disk loading.

The trend of reduced gross weight with increasing wing loading occurs due to reduction in wing size (constant disk loading fixes span). This trend continues until the wing is so small that a weight and induced drag penalty cause the gross weight to increase. These trends are common to all concepts with tip mounted rotors.

Figure 1-10 depicts the sizing trends for the Tilt Wing concept. For a given disk loading, a larger chord to diameter (c/D) ratio results in a higher gross weight design. This occurs due to increased wing area which increases wing weight and drag, thus increasing fuel weight.

The minimum ratio attainable depends on the desired conversion characteristics of the aircraft. Unfortunately, better conversion characteristics result from aircraft with high c/D ratios. Reference 1 indicates .33 as a possible minimum value of c/D, with the use of flaps and leading edge slats. This value was chosen as the limiting value.

For a constant value of c/D, increasing disk loading reduces gross weight, again due to the effect of wing size. Having assumed that the rotor radius defines the wing span, the chord and the span decreased with increasing disk loading, making the wing smaller. Since cruise requirements again size the engines, no weight benefits occur by minimizing hover power using a very low disk loading.

A maximum disk loading constraint of 40 psf is imposed for the same considerations as previously noted.

Figure 1-11 shows the relation of the Rotor/Wing sizing parameters. One of the key design parameters for this concept is the ratio of center-body radius to rotor radius, ξ. As this ratio increases the lifting ability of the rotor system decreases, requiring more power with larger engines. This results in increasing gross weight. The relative power transmission inefficiency of the reaction drive system and the OEI hover requirements size the engines for this concept. Therefore, one would like to minimize the center-body, except that some minimum area is required for conversion. The maximum conversion wing loading, based on the conversion speed of 170 KTAS and an attainable C^L of .6, then constrains and defines the minimum area for the center-body. Two other constraints with regard to the rotor radius occur. The first results from commonalty of fuselage length with the other concepts. This defines the maximum rotor radius. The second constraint, defined by the maximum allowable disk loading for personnel operating in the vicinity of the rotor defines the minimum rotor radius. The annulus based downwash velocity comparable to other concepts defines this boundary.

For constant values of ξ, a high gross weight results at high rotor radius values due to the extremely large wing that ensues. This increases structural weight and adds significant drag in cruise, causing increased fuel weight. Decreasing the radius too much also results in increased gross weight. Here, hover power requirements increase, driving engine weight upward.

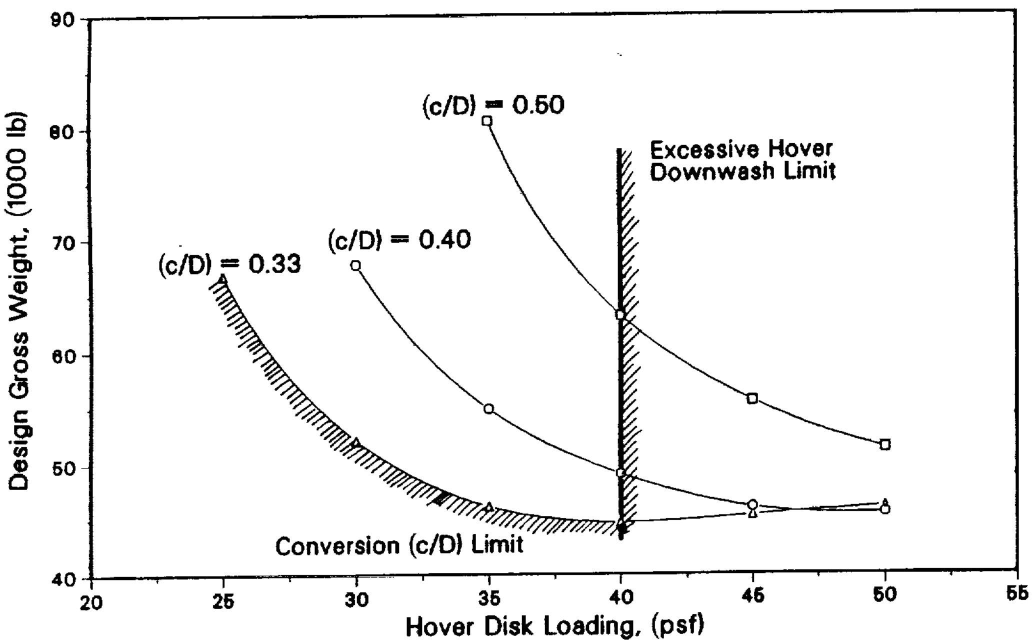


FIGURE 1-10. TILT WING - PARAMETRIC DESIGN MATRIX

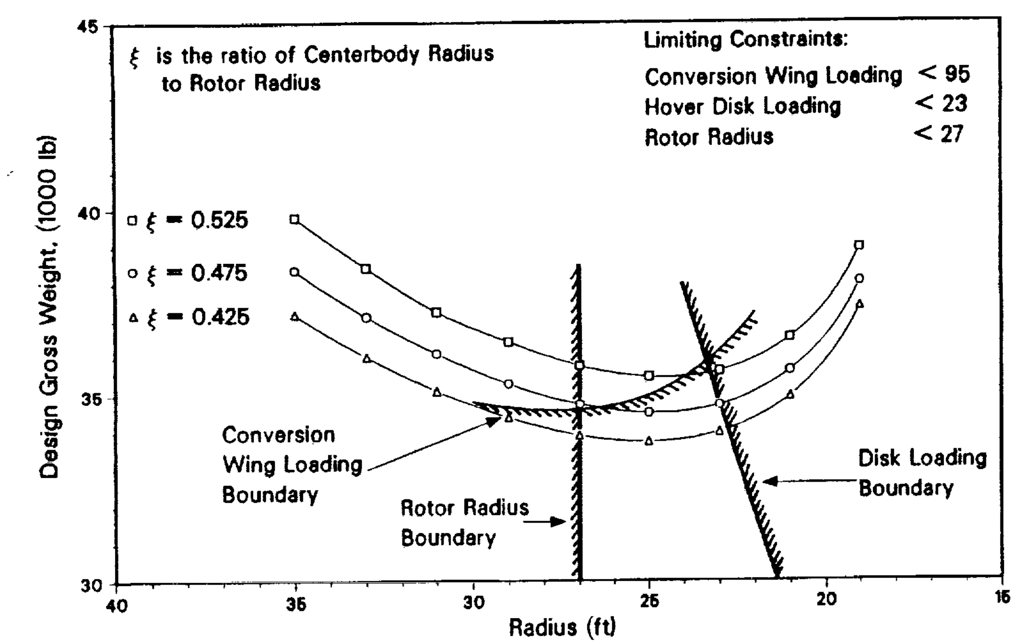


FIGURE 1-11. ROTOR/WING SIZING - PARAMETRIC DESIGN MATRIX

SIZED CONCEPT DESCRIPTIONS

For commonality, each concept consists of a representative fuselage containing a 6x6x20 foot cargo box capable of carrying the required 4500 pound payload. The crew compartment is located forward of the cargo compartment. The fuselage houses the landing gear without sponsors and retains the structure to support the wing and empennage. Only the Rotor/Wing requires a pressurized fuselage due to its relatively high cruise altitude.

Trail-Rotor Convertiplane General Description

The Trail Rotor Convertiplane (TRC) (Figure 1-12) is a vertical or short takeoff and landing configuration consisting of twin rotors mounted at the tips of fixed wings. The TRC utilizes side by side rotors for helicopter operations, while for high-speed operation, the rotors tilt aft and fold into the trailing position. A convertible turbofan engine provides power to the rotor in hover and cruise thrust for high-speed operations.

DESIGN GROSS WEIGHT	56,660	LB
POWER REQUIRED	13,173	LB/ENGINE
MISSION FUEL	10,578	LB
PAYLOAD	4,500	LB
DISK LOADING	25	LB/FT²
WING LOADING	120	LB/FT²

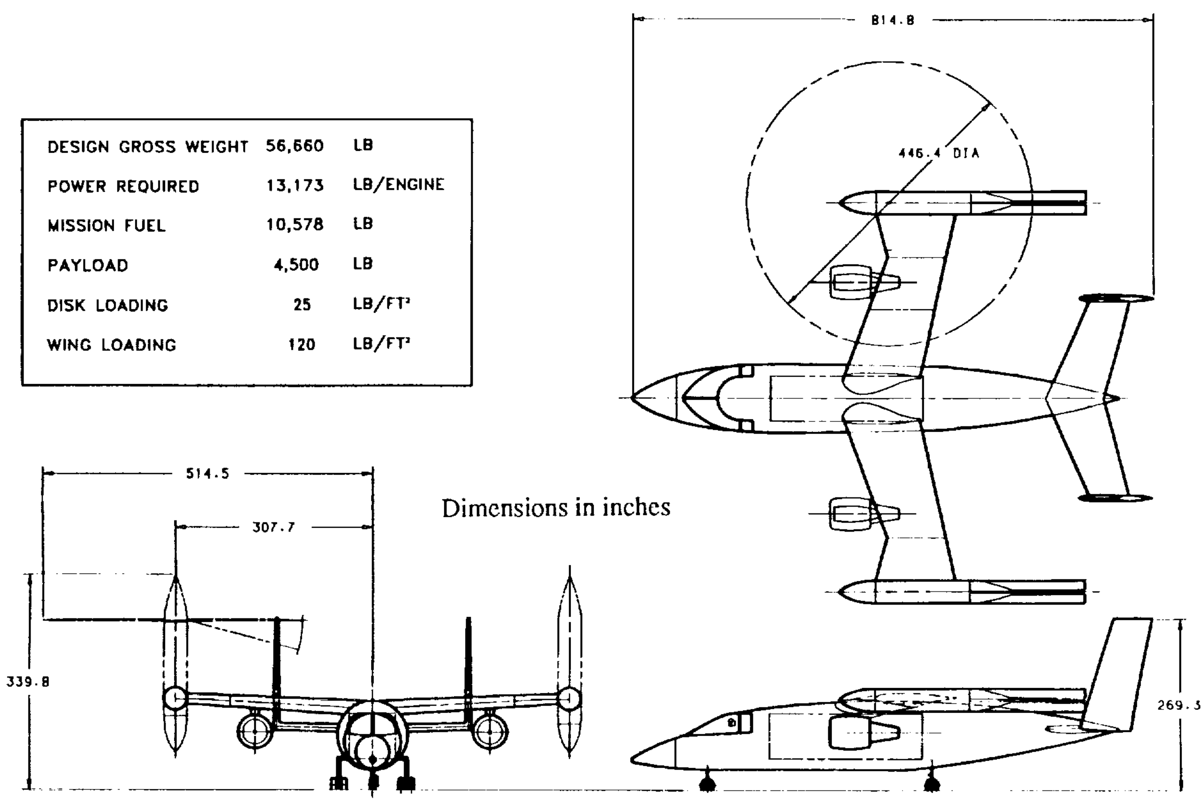


FIGURE 1-12. TRAIL ROTOR CONVERTIPLANE FINAL CONFIGURATION

Wing- The wing incorporates an aft sweep of 20° to meet the cruise speed requirement of 450 KTAS with an 18% thick wing. The chord extension at the tip allows the conversion axis to fall within the wing planform. Without the extension, the desired conversion axis locates in front of the wing leading edge at the tip. This unusual planform weighs more than a conventional swept wing. The wing retains sufficient volume to carry the mission fuel in the inboard sections.

Rotor/Pylon- The TRC rotor is a five blade configuration with a diameter of 37.2 feet. The rotor, positioned vertically for helicopter operations utilizes a fully articulated hub with offset flapping hinges.

Empennage- The empennage of the TRC consists of the horizontal and vertical tail surfaces. The sweep of the horizontal tail surface ensures higher M_{DD} than the wing and provides pitch stability for the aircraft. The twin vertical tail configuration replaces an overly large single tail.

Trail Rotor Convertiplane Conversion Description

The conversion sequence of the TRC requires a good balance of wing and rotor aerodynamics. The transition from helicopter to fixed-wing flight occurs at speeds from 130-180 KTAS. The conversion process is stoppable and reversible at any point and is depicted in Figure 1-13.

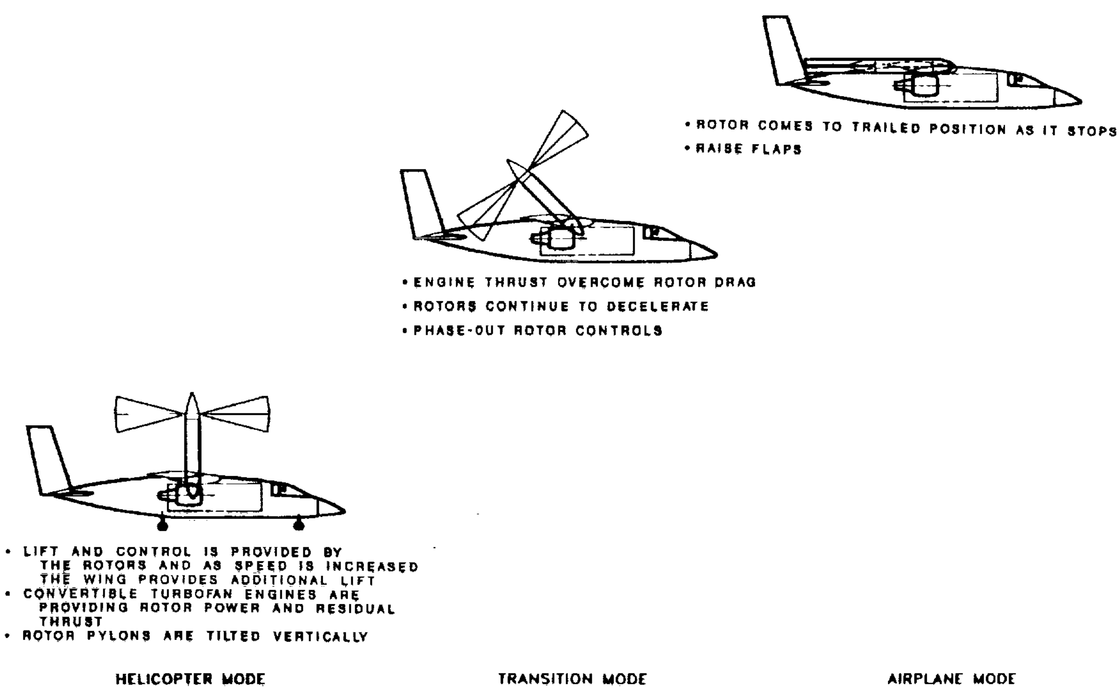


FIGURE 1-13. TRAIL ROTOR CONVERSION SEQUENCE

Prior to conversion, the TRC flies in compound helicopter mode with the rotors operating at hover RPM. In this flight mode, the two convertible engines produce both shaft power to drive the rotors and engine thrust for forward propulsion. The rotors and wing share the aircraft lift evenly. At around 150 KTAS, the pilot enters conversion by pitching the body up and setting the rotor collective to achieve autorotation. At this point, he engages the automatic rotor control system (ACS) and declutches the rotors from the engines. As the rotor pods tilt aft, the ACS maintains an autorotative state by scheduling the rotor collective, cyclic and rotational speed. Once the ACS takes authority, the pilot's rotor controls phase out, and he relies upon conventional airplane control surfaces to trim the aircraft. During transition, the pilot maneuvers with fixed-wing controls, and the rotor reacts to the aircraft response. Once the pod has tilted to 90 degrees, the blades feather and the rotor cones to a trailing position. The transition from fixed-wing to helicopter flight follows the reverse process.

The conversion sequence presents several trade-off study areas. First, although operating the rotors in autorotation throughout transition requires no shaft power, the high rotor thrust aft increases the aircraft drag. Should this conversion drag become critical in engine sizing, the rotor thrust, and therefore the drag, can be reduced by providing 10 to 30% hover power to the rotors and operating the engines in a partial-power mode. Second, because the rotors will eventually stop, the conversion process will pass through rotor resonance. This point must not only be identified, but also investigated to determine the implications of stopping and reversing the conversion process near resonance. Third, a redundant and fail-safe ACS system is required to achieve a successful conversion.

Folding Tilt Rotor General Description

Dimensions in inches

DESIGN GROSS WEIGHT	59,776	LB
POWER REQUIRED	13,291	LB/ENGINE
MISSION FUEL	11,464	LB
PAYLOAD	4,500	LB
DISK LOADING	25	LB/FT^2
WING LOADING	120	LB/FT^2

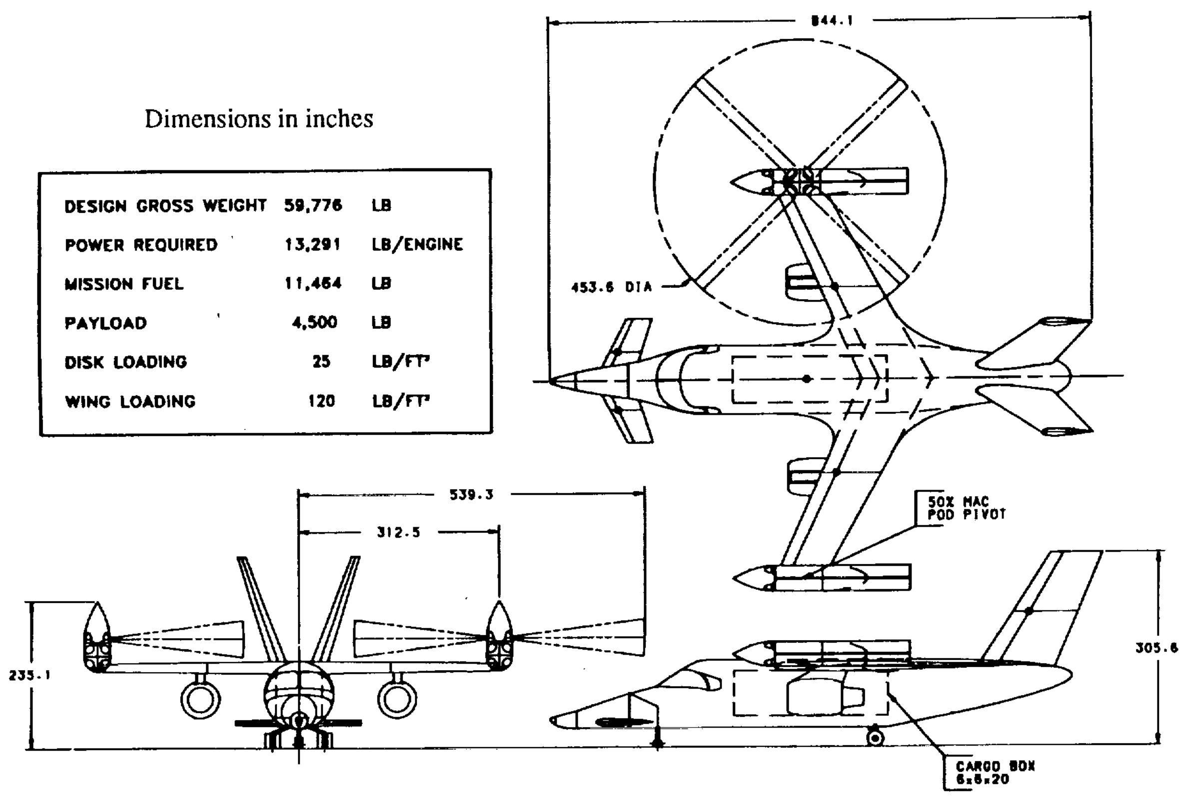


FIGURE 1-14. FOLDING TILT ROTOR FINAL CONFIGURATION

The Folding Tilt Rotor concept (Figure 1-14) uses similar flight modes for hover and loiter as a conventional tilt rotor. The rotor nacelles are vertical for hover/low speed flight and then convert to the horizontal position for high-speed cruise. Two interconnected convertible turbofan engines provide cruise thrust and rotor power. Conversion to high-speed flight is accomplished by increasing thrust to the fan of the convertible engine and reducing rotor thrust. The blades feather and stop, index and fold aft along the nacelle. The rotor aerodynamically stops and spins up to eliminate high-torque clutches and brakes.

Wing- The wing incorporates 20° of forward sweep to delay the drag divergence Mach number. This places the wing aft of the aircraft c.g. and requires a canard to provide longitudinal stability. The canard is sized to place the wing-body aerodynamic enter aft of the aircraft c.g., providing positive static margins.

Rotor Nacelle/Pylon- The rotor nacelle is designed to offer the cleanest aerodynamic configuration. The rotor blades fold flush with the surface of the nacelle, in sculptured recesses. The fold hinge extends from the surface of the nacelle to allow the rotor blades to fold flush.

Canard- The canard is swept aft greater than 20° to exceed M_{DD} of the wing. The variable incidence canard provides longitudinal stability and control during cruise flight. Since it must provide positive lift, its design requires that it stall prior to the wing.

Vertical Tail- The vertical tails provide directional stability with one engine out.

Folding Tilt-Rotor Conversion Description

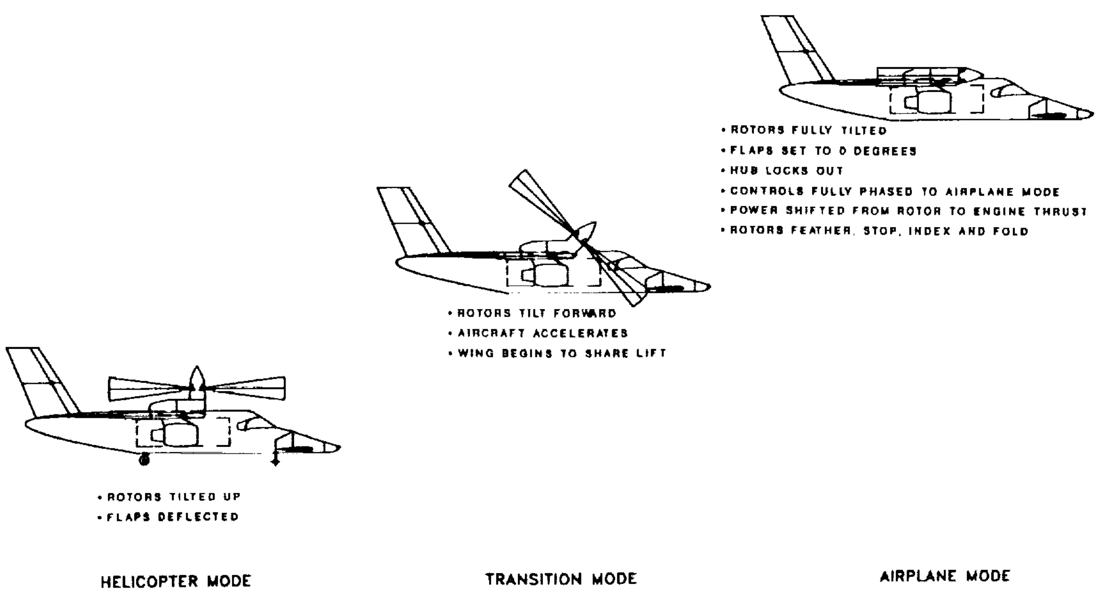


FIGURE 1-15. FOLDING TILT ROTOR CONVERSION SEQUENCE

Conversion of the Folding Tilt Rotor (FTR)(Figure 1-15) from helicopter to fixed-wing flight will be fully automated to minimize pilot work-load. From helicopter mode, the pilot accelerates to a conversion speed of 120 kts at which the wing can support the aircraft. During this time, the nacelle rotates forward as with a conventional tilt rotor, driving the aircraft with the rotor. The pilot has the option of continuing in this mode for moderate speed cruise (possibly maximum range) or, for high-speed cruise, beginning the rotor folding sequence. At this point, the pilot engages the automatic rotor control and actuating system and assumes control of the aircraft solely through conventional airplane control surfaces. Once engaged, the automatic system transfers thrust from shaft power to engine thrust, disengages the rotor by decreasing rotor-blade pitch and actuates rotor clutches. After declutching the rotor, the control system drives the rotor-blade pitch slightly past the fully feathered position. This creates the force opposing the blade rotation to stop the rotor. Once the rotor control system detects reverse rotation, electrohydraulic units apply rotor locks. With the blades locked in their correct azimuthal positions, the blades fold onto the pod and are then restrained for high-speed flight. The pilot then retracts the flaps and accelerates.

As with other configurations that stop the rotor in axial flight, possible unsteady critical loads and excessive dynamic response could develop during transition. Furthermore, the conversion sequence includes a point at which the rotor frequency matches the wing resonance frequency. Both of these major issues not only could alter the transition sequence, but could also affect the ability to stop and reverse the conversion sequence at any point during conversion. Wind Tunnel tests have confirmed the feasibility of stopping and folding a full scale rotor[6].

Tilt Rotor General Description

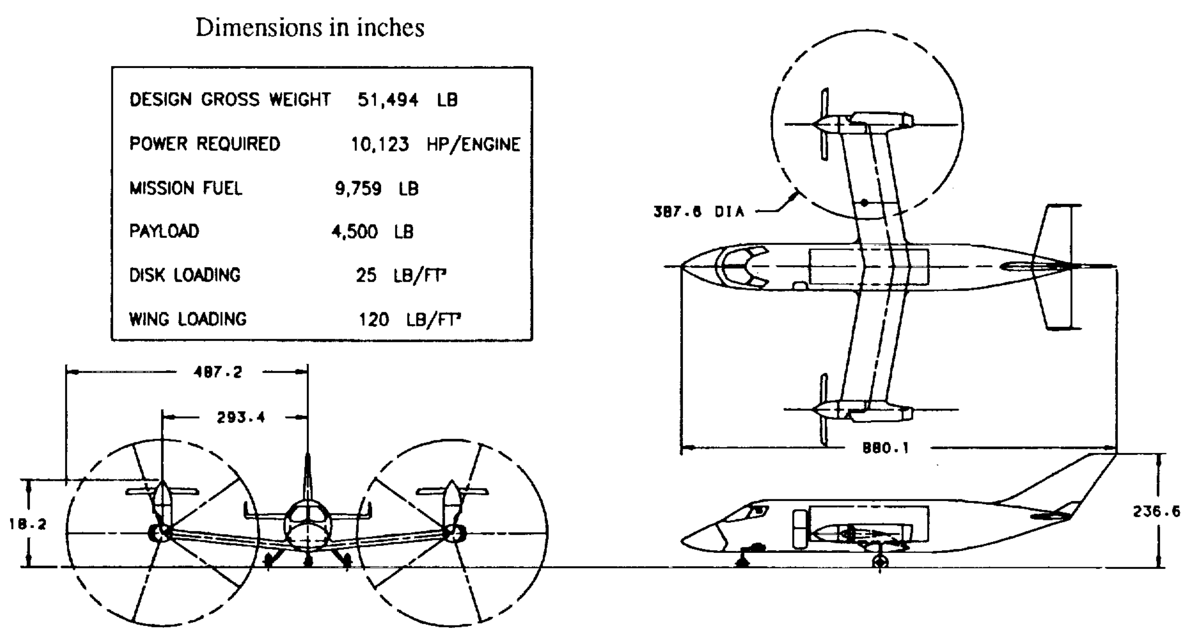


FIGURE 1-16. TILT ROTOR FINAL CONFIGURATION

Figure 1-16 shows the general description of the Tilt Rotor Concept. The aircraft has two 32.3 foot diameter rotor systems and engine transmission nacelles that are mounted on each wing tip. Two turboshaft engines power the rotor systems. The aircraft operates as a helicopter when taking off and landing vertically. Once airborne, the nacelles rotate 90° forward (the engines remain horizontal) converting the aircraft into a turboprop airplane for high-speed, fuel-efficient flight. The rotors are synchronized by means of an interconnecting transmission shaft that runs through the wing between the two nacelle mounted transmissions. This shaft also provides power transmission from one rotor to the other in case of an engine failure. A two-speed gear box allows reduction of rotor RPM in cruise to improve propulsive efficiency at high speeds. The drive system is sized to allow for the increased torque.

Wing- A 10° forward sweep provides blade flapping clearance, minimizes rotor overhang distance from the wing torsional axis, and increases M_{DD} of the 18% thick wing. The low wing enables incorporation of wing dihedral that allows the rotor nacelle centerline to be normal to the ground plane in the vertical position. It also lowers the vertical c.g. location.

Empennage- The tail surfaces are swept aft 14° to exceed the M_{DD} of the wing.

Tilt Rotor Conversion Description

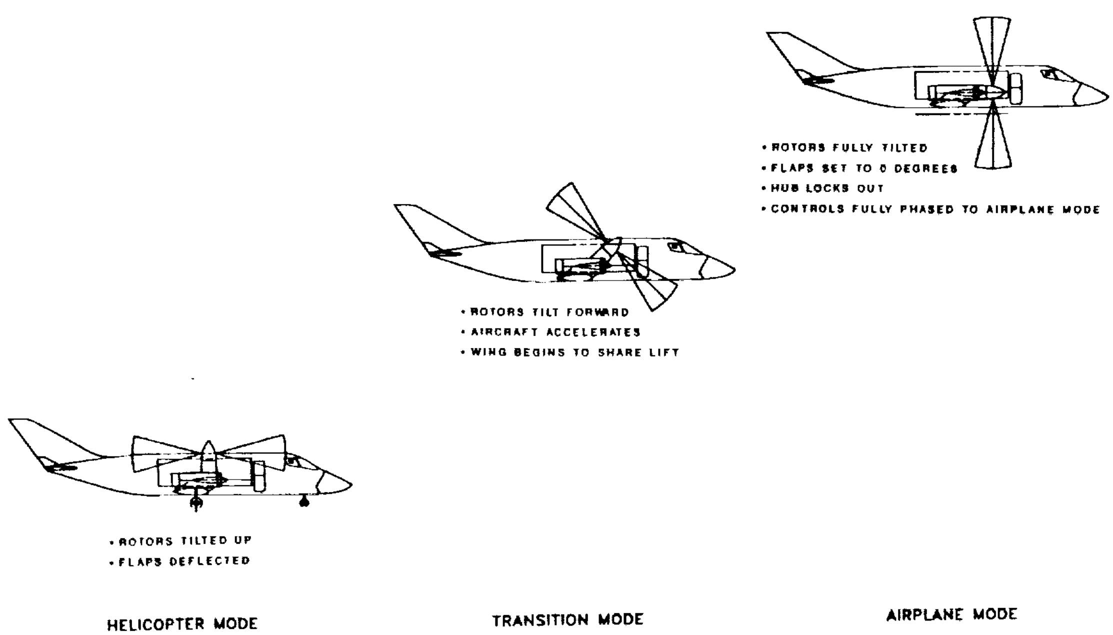


FIGURE 1-17. TILT ROTOR CONVERSION SEQUENCE

Both the XV-15 and V-22 have demonstrated conversion and the continuous lift sharing that occurs between the rotor and wing during transition. The pilot can achieve forward flight in helicopter mode by tilting the rotor pods slightly forward, thereby maintaining a level body attitude. When the Tilt Rotor reaches conversion speed, the pilot tilts the pods forward. As the pods tilt forward, the lift component of the rotor decreases, but because of the forward acceleration achieved by tilting the rotor forward, the wing lift increases. Thus, throughout transition, the rotor and wing continually share the aircraft lift. This lift sharing increases the versatility of the configuration during conversion. Furthermore, the single propulsion device allows a single control system that couples helicopter and fixed-wing flight controls.

Although the concept has a proven conversion sequence, a high-speed Tilt Rotor's configuration might require alteration of the sequence. Based on the rotor capabilities, the conversion sequence should be investigated to identify any possible difficulties.

Cyclic control of the rotors allows control of the Tilt Rotor in helicopter mode. Tilting the pods also provides pitch control capability while differential thrust sallows an alternate means of roll control. Control in fixed wing mode depends on conventional airplane control surfaces. Figure 1-17 depicts the conversion sequence.

Rotor/Wing Description

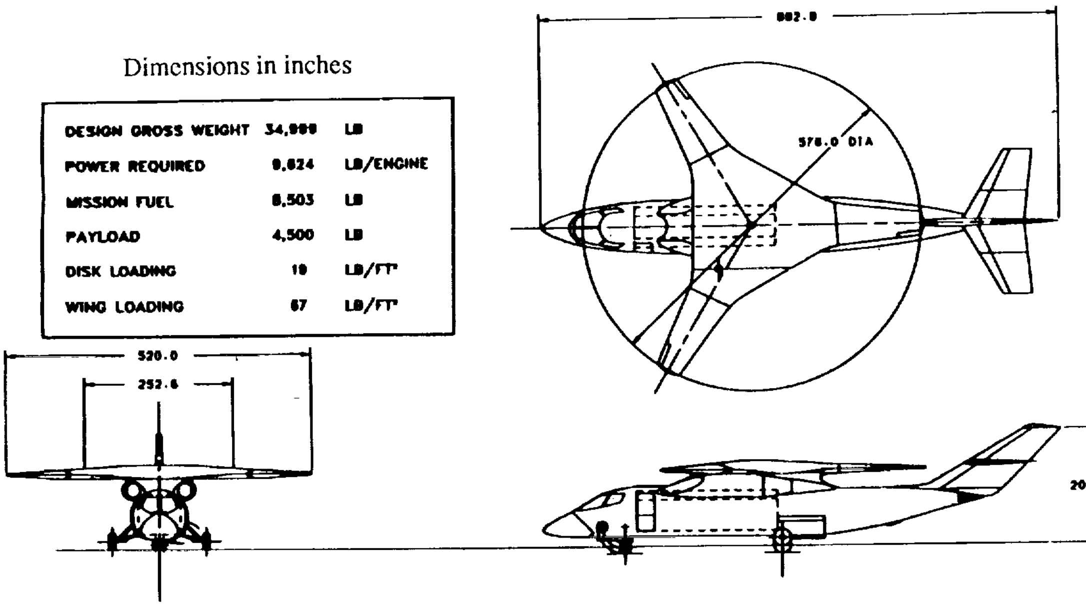


FIGURE 1-18. ROTOR WING FINAL CONFIGURATION

The Rotor/Wing (Figure 1-18) is a warm-cycle, reaction-drive rotor with a large triangular hub and short-span, wide-chord blades. The rotor stops and assumes the role of a wing in airplane mode. It provides the advantages of hovering efficiency, low downwash velocity, and flying qualities of the helicopter for vertical and low-speed flight, combined with the high-speed capability of the jet airplane.

Empennage- The empennage consists of the vertical and horizontal stabilizers. It is sized based on preliminary volume coefficients derived from wind tunnel tests completed in the 1960s.

Rotor/Wing- The Rotor/Wing, consisting of a large center-body and three blades, provides lift for both helicopter and cruise flight. It represents a compromise between a good hovering rotor and a good wing. Sizing the center-body to provide all the lift during conversion at 170 knots with a wing loading less than 95 lbs/ft^2 results in a nose up pitch attitude of about 15°. The blade radius provides a disk loading below 20 lbs/ft^2. The t/c ratio at the blade root is 20%, representing a maximum for the wing. This critical point results from sizing the minimum diameter torque tube to insure that the required mass flow of the engine exhaust gases reaches the blade tips. This defines the thickness of the section at the blade root, and along with the t/c ratio, specifies the chord. The cruise wing loading is low at 65 psf. A circular arc symmetric airfoil provides required performance regardless of direction, allowing in-plane stopping of the rotor. Cyclic and collective pitch control is achieved through feathering hinges located at the juncture of the center-body and blades.

Propulsion- The Rotor/Wing uses a non-conventional propulsion device for the rotary wing portion of the mission. This propulsion utilizes two standard low bypass ratio turbofan engines to produce exhaust gases that are expelled at the tip of each rotor blade via ducting. The high velocity gas propels the Rotor/Wing in the direction of rotation. A diverter valve redirects the exhaust from the rotor, aft, creating cruise thrust after conversion. Engines provide the cruise thrust required for the aircraft in a conventional manner. Hover conditions size the engines rather than cruise as is the case with other concepts. A small thruster in the tail cone provides yaw control during low-speed helicopter flight.

Rotor/Wing Conversion Description

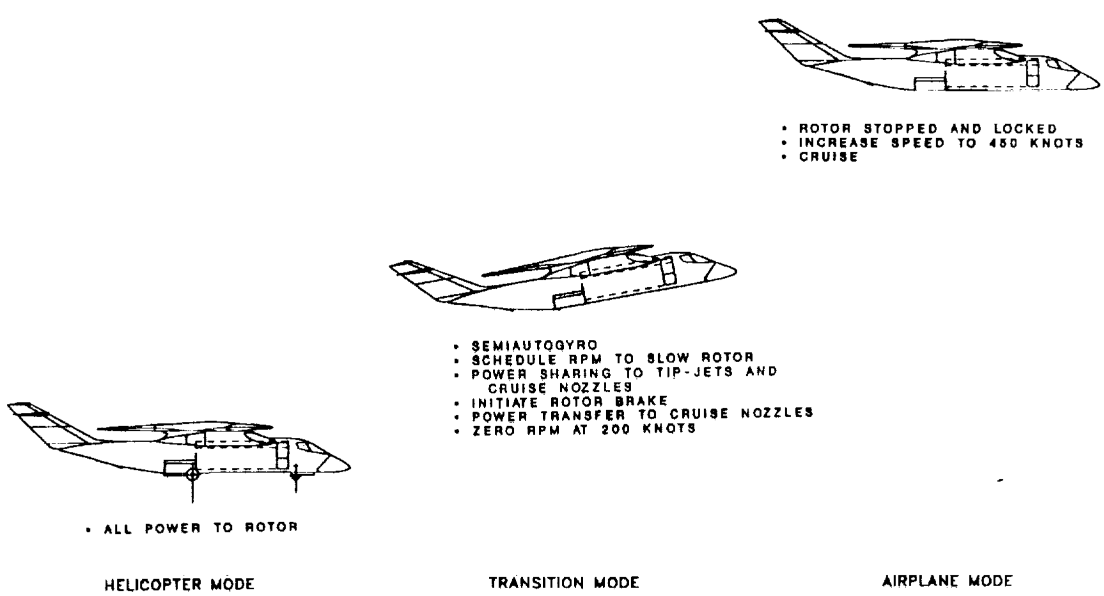


FIGURE 1-19. ROTOR/WING CONVERSION SEQUENCE

The Rotor/Wing conversion process (Figure 1-19) from helicopter to fixed-wing flight requires the rotor to be slowed and stopped. In helicopter mode, the Rotor/Wing flies as a conventional helicopter, achieving it's forward velocity from a nose down pitch attitude. For control in this flight regime, it uses a yaw reaction-control valve, rotor cyclic and collective, tail elevons and rudders. When the aircraft achieves a conversion speed of 150 KTAS, the pilot engages the power diverter and pitches the aircraft up from its negative attitude. The power diverter directs half of the exhaust gas from the rotor tip-jets, aft, to provide the aircraft forward thrust. This accelerates the Rotor/Wing into semi-autogyro flight. Once the aircraft accelerates to around 200 KTAS, the pilot engages an aerodynamic rotor brake, which signals the power diverter to channel all gas horsepower into forward thrust, closes the tip nozzles, deactivates the yaw-control valves, and engages an automatic control system to schedule rotor collective and cyclic as the rotor slows. When he engages the rotor brake, the pilot must pitch the aircraft such that the large center-body provides lift for the aircraft until the rotor stops. Once the rotor stops, the blade and center-body locking mechanisms engage, the pneumatic rotor seals inflate, and the aircraft accelerates to cruise speed. Conversion from fixed-wing flight to helicopter mode follows the reverse process.

The single lifting body of the Rotor/Wing represents the source of two technical difficulties with this conversion sequence. First, since the center-body must lift the aircraft from the time when the pilot engages the rotor brake until the rotor/wing stops, its attitude is critical. Therefore, at this point in the conversion, the pilot has little maneuver margin. Second, one of the more documented problems with the three-bladed rotor/wing is the center of lift oscillation as the rotor slows during the conversion[7]. This center of lift movement results in an annoying aircraft oscillation during the last few revolutions and requires scheduled rotor control inputs to reduce the effect to tolerable levels. Setting the blade pitch to provide zero lift helps to simplify conversion over a configuration such as X-Wing, which requires the blades to provide continuous lift throughout conversion. Here, the center-body provides all the lift required, removing the requirement for azimuthal lift balancing. Although these problems do not jeopardize the feasibility of conversion, they may present technical difficulties that hinder the aircraft's efficiency during transition.

Tilt Wing Convertiplane General Description

The Tilt Wing configuration is a twin engine, twin rotor V/STOL aircraft. It operates like a helicopter with the wing in the vertical position but with less efficiency due to higher disk loading. For high-speed flight, the wing tilts to the horizontal position and operates at an efficiency that is somewhat less than the standard turboprop airplane. The Tilt Wing was designed with rotors at the wing tips to eliminate the pitch fan mechanism. Typical Tilt Wing aircraft of the past utilized the propeller with beta controls to operate in a helicopter mode of flight[8]. This type of configuration requires a pitch fan for aircraft stability and control. Figure 1-20 depicts the configuration.

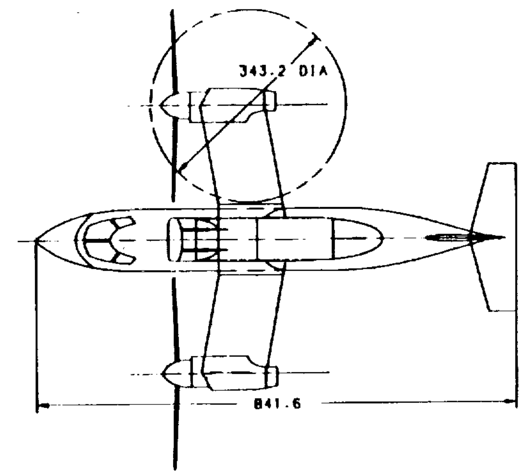
Wing- The wing is designed with a 10° forward sweep for rotor blade clearance. The wing is designed to pivot about the 60% wing MAC allowing the wing box structure to be completely carried through the span of the wing. The engine cross shafting will be carried through the wing quarter chord. The wing carries no fuel due to large tilting angles the wing must make for hover/low speed and high-speed cruise. The large chord results from conversion wing stall considerations. High lift devices on the wing include 30% chord, double-slotted, full-span Fowler flaps and full-span, leading-edge slats.

Rotor/Pylon- The rotor is designed with 5 rotor blades having a diameter of 28.6 ft. This results in a disk loading of 35 psf. The rotor system provides the stability and control of the aircraft in hover and low speed thereby eliminating the pitch fan seen on similar Tilt Wings. The penalty is higher complexity and weight than the standard propellers with beta controls. However, elimination of the pitch fan offsets this weight disadvantage. The rotors rotate inboard down. A two-speed gear box allows reduction of rotor RPM during cruise to maintain propulsion efficiency.

Empennage- The empennage consists of a conventional horizontal and vertical tail configuration.

DESIGN GROSS WEIGHT	45,218	LB
POWER REQUIRED	9,359	HP/ENGINE
MISSION FUEL	9,102	LB
PAYLOAD	4,500	LB
DISK LOADING	35	LB/FT²
WING LOADING	120	LB/FT²

Dimensions in inches



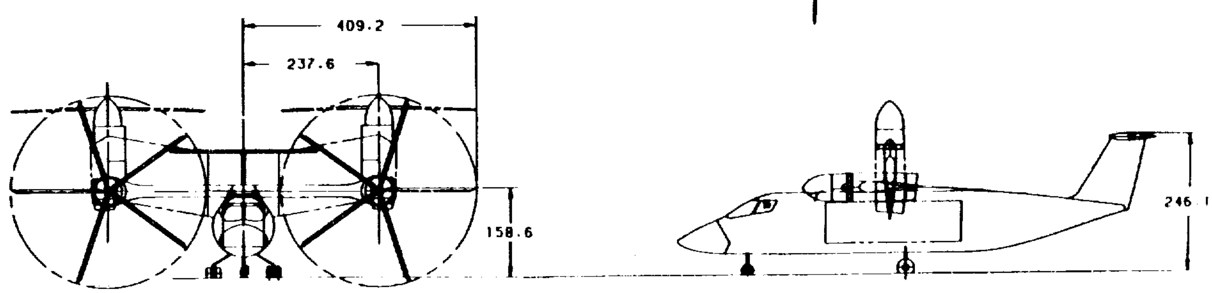


FIGURE 1-20. TILT WING FINAL CONFIGURATION

Tilt Wing Conversion Description

The Tilt Wing configuration alleviates download on the wing in hover by always keeping the wing edgewise to the propeller slip stream. However, this configuration can exhibit wing stall during decelerating descent, resulting in additional power required and control problems during conversion. The Tilt Wing converts from helicopter flight to fixed-wing flight by tilting the wing forward (Figure 1-21). The XC-142 and CL-84 successfully demonstrated conversion[9, 10].

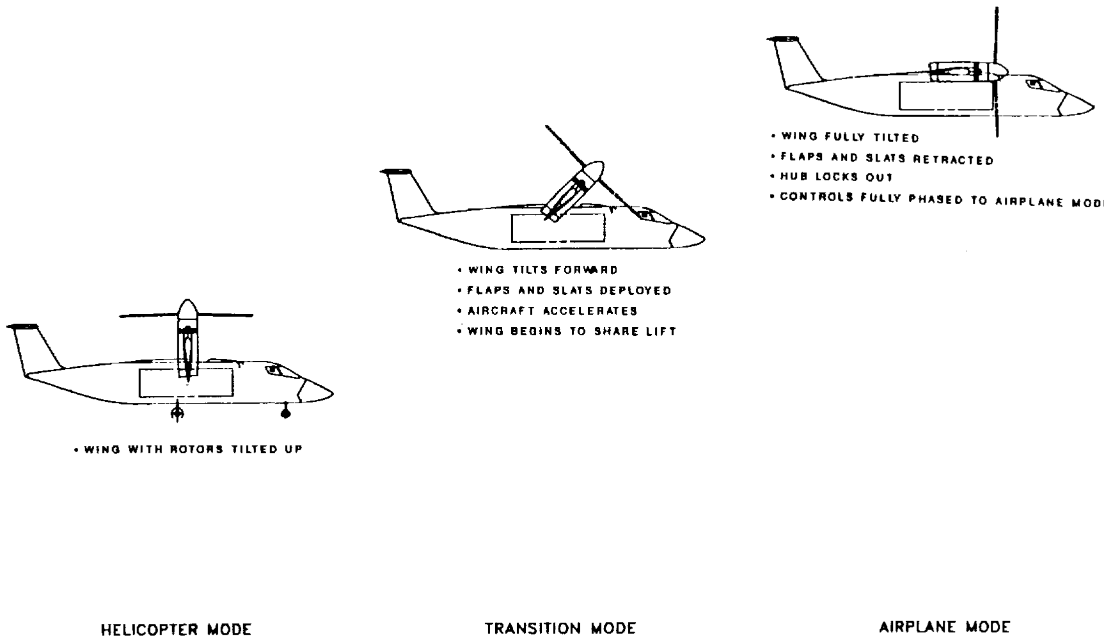


FIGURE 1-21. TILT WING CONVERSION SEQUENCE

Conversion during descent at large angles presents the greatest potential for wing stall. In this condition, propwash over the wing is at a minimum and the wing incidence angle is increasing. This combination can result in severe buffeting due to separated flow over the wing. Experimental evidence indicates that descent angles of up to 15° are achievable with proper designs[11]. This does not limit the utility of the concept, but rather introduces operational constraints.

Several design features can be incorporated to alleviate the wing stall problem. The most basic of these corrections is to increase the blade chord, which, for the same lift, reduces the section angle of attack. Experimental evidence suggests that a wing-chord to propeller diameter (c/D) of at least .5 reduces conversion power to acceptable levels[12]. Adding leading-edge slat and slotted flaps may allow a decrease in this ratio to about .33[1].

Cyclic control of the rotors provides control of the aircraft during helicopter flight. This locks out in airplane mode, with control accomplished using conventional airplane control surfaces.

INITIAL TECHNOLOGY ASSESSMENT

Assessing technology consists of identifying current levels of technology and predicting improvements achievable for a 2010 production aircraft. This implies that demonstration of the technology occurs about 2003. These dates are based on engine technology development consistent with the IHPTET Phase III milestones. Due to the nature of Task 1 and the large number of concepts investigated, the assessment necessarily is broad in scope. Where applicable, goals of existing technology programs represent assumed advanced technology levels, consistent with the time frame specified above.

Structures & Materials

Significant advances in structures and materials technology will enhance the development of high speed rotorcraft. Areas of technology development include: (1) optimized use of composite structures, (2) fail-safe design concepts, (3) manufacturing methods, and (4) new materials. All of these technology areas will contribute to improved structural performance resulting in low weight, damage tolerant, and durable structural designs.

Tailoring composite structures for stiffness and strength minimizes material and fabrication costs, as well as reduces weight. Application of adhesive bonding technologies for structural joining, will minimize the use of mechanical fasteners. Solid laminate skins will also allow optimized designs for improved structural performance.

Hybridization of materials will improve damage tolerance and durability, and local application of multiple materials will be used to tailor stiffness and strength. Incorporation of fail-safe design approaches, such as delamination arrestment concepts, will further reduce structural weight.

Advances in manufacturing technology will significantly reduce fabrication costs and will greatly improve the reproducibility of composite structures. Thermoplastic fabrication techniques, such as roll forming, will be available for large scale application. Employment of integral concurring methods will minimize the number of assembly operations required.

Hybridization of materials will improve damage tolerance and durability, and local application of multiple materials will be used to tailor stiffness and strength. Incorporation of fail-safe design approaches, such as delamination arrestment concepts, will further reduce minum-lithium (Al-Li) alloys under development show greater stiffness and lower densities than conventional aluminum alloys.

The above advances in structural materials and technologies have the potential to reduce component weights between 10-25% depending on the particular system and application. Several examples have shown actual weight savings such as the Army's ACAP and Marine V-22 programs. Weight savings through the use of composites have also been demonstrated on components of the F-16, L1011, A310, and many other aircraft. Preliminary design studies leading to full scale development of the Superteam's LH and McDonnell Douglas Helicopter Company's MD-900 have shown potential weight savings on the order of 15-22%. In addition, conceptual design studies for the Air Force's SOF and ATT air vehicles have identified potential weight savings of 20-25% due to the use of composites. For the HSR study, a slightly less optimistic approach has been taken; 15% weight savings in primary structure and 10% weight savings in secondary structure. The confidence level in attaining these weight savings is high due to lessons learned from the ACAP/V-22 programs, improved composite manufacturing techniques, and true composite design utilizing the beneficial attributes of different composite materials.

Propulsion

Propulsion technology assessment is based upon information obtained from:

1. Current Production Engine Data
2. NASA Contract NAS3-25459, Precursor Convertible Engine Study, by Allison
3. NASA NA3-25460 Precursor Convertible Engine Study, by General Electric (GE)
4. Pratt and Whitney Convertible Engine Data
5. Integrated High Performance Turbine Engine Technology (IHPTET) program Joint
6. Turbine Advanced Gas Generator (JTAGG) program

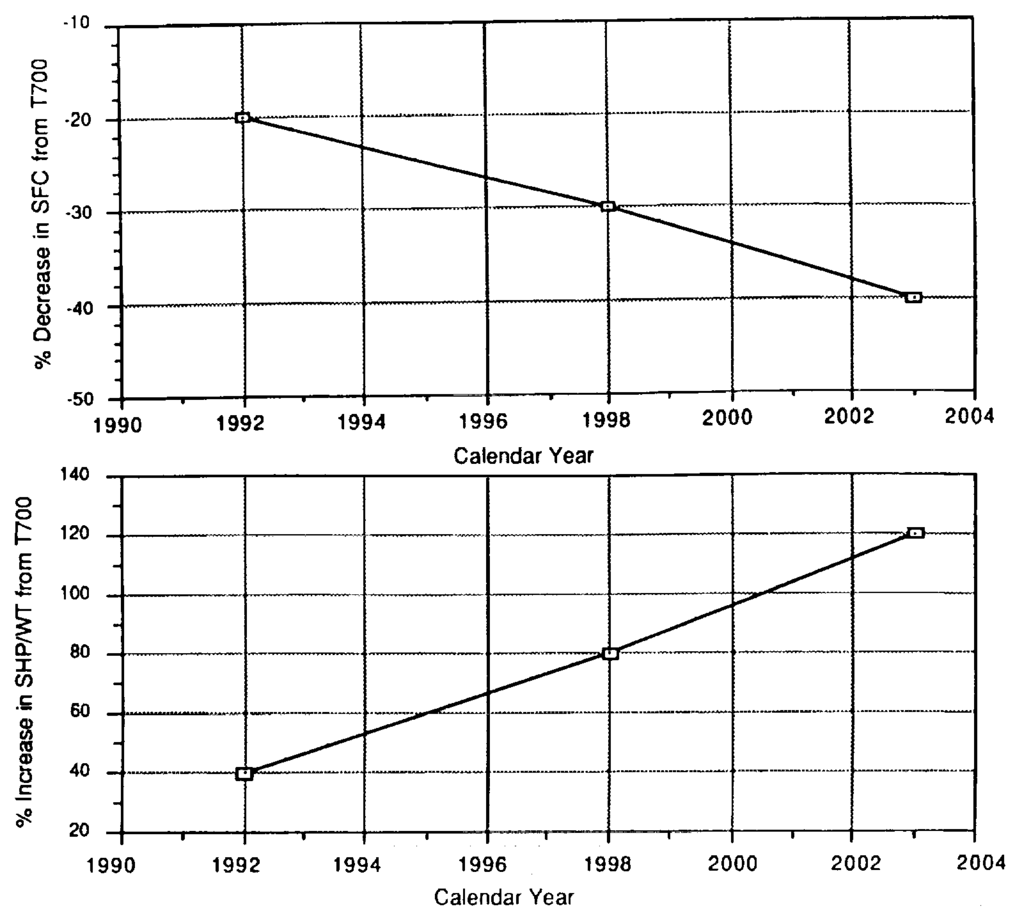


FIGURE 1-22. JTAGG SFC AND SHP/WT GOALS (T700 BASLINE)

The selected high-speed configurations require convertible engines, tilting engines, or turbofan engines. The technology for tilting engines is available in the Allison T406 turboshaft engine utilized on the V-22. Convertible engine feasibility has been demonstrated by GE in a ground test of a modified General Electric TF34 turbofan engine with variable inlet guide vanes[13]. Other feasible convertible engine configurations consist of: variable pitch fan, VIGV-VEGV fan, clutched fan, and propfan. However, there are no currently funded convertible engine development programs. Therefore, the available engines for three of the five configurations are the Allison T406 family of turboshaft engines (6150 SHP to 13000 SHP) for the Tilt Rotor and Tilt Wing configurations and current production low bypass ratio turbofan engines for the Rotor/Wing configuration. The Folding Tilt Rotor and the Trail Rotor require Convertible engines which do not exist today.

Convertible engine technology must be developed over the next fifteen years for the Folding Tilt Rotor and Trail Rotor configurations. The key technologies to be developed (depending upon convertible engine configuration) are: high power, light weight torque converters and clutches, and engine conversion control system(s). Current engine technology must be developed to achieve the JTAGG goals of specific fuel consumption improvement of 40% and engine power-to-weight improvement of 120% over T700 technology (Figure 1-22). This will enable mission effectiveness improvement for all high-speed rotorcraft configurations. To meet these goals the Department of Defense and NASA are funding research and development of engine components under the auspices of the IHPTET program.

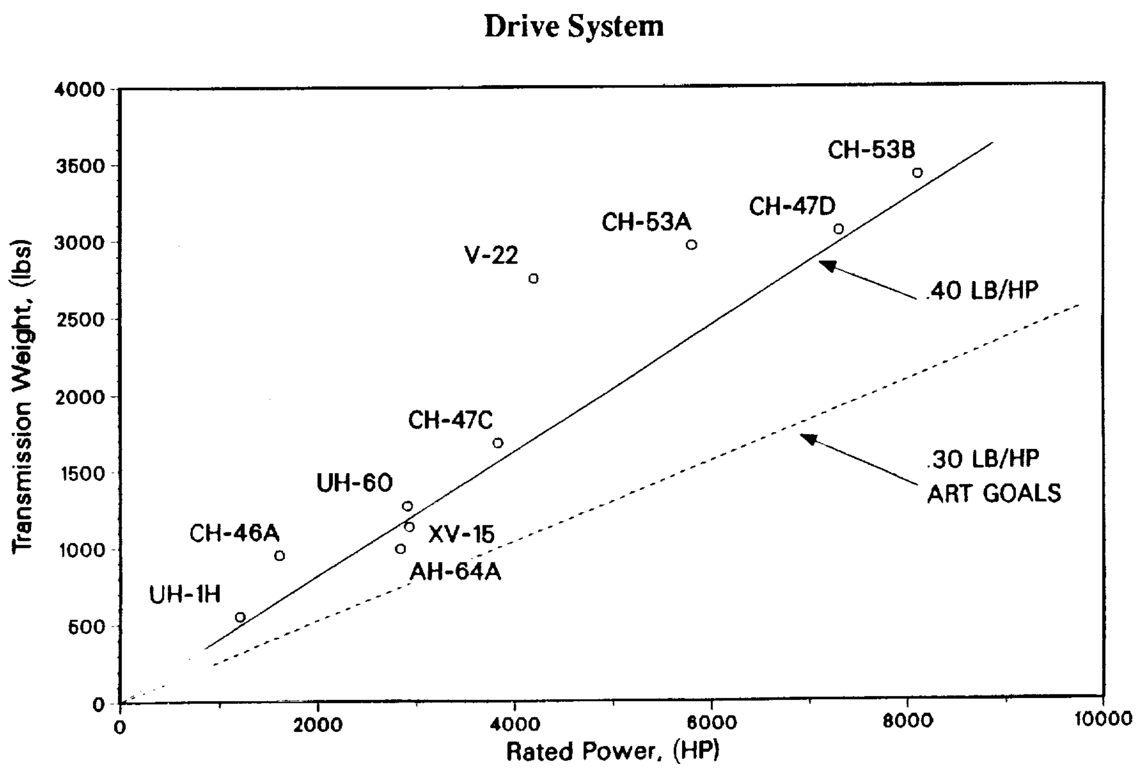


FIGURE 1-23. DRIVE TRAIN WEIGHT TRENDS

Drive System technology assessment is basd upon information obtained from:

1. Current Production Helicopter Drive Systems Designs
2. V-22 Drive System Design
3. Advanced Rotorcraft Transmission (ART) Program[14]

The Folding Tilt Rotor, Trail Rotor, Tilt Wing, and Tilt Rotor configurations require cross shafting, reduction gearboxes, speed increasers, and angle gearboxes. The technology for these drive systems currently exist and is demonstrated in the V-22 development program. Current drive system weight-to-power ratio is .40 lbs/hp as shown in Figure 1-23. The Rotor/Wing, does not require gearboxes or cross shafts, while there is a requirement for ducting, it is substantially lighter in weight. Significantly, it possesses a power transmission efficiency of about 50%.

Future mechanical drive system technology is dependent upon the Advanced Rotorcraft Transmission (ART) program which has goals of:

1. 25% Reduction in drive system weight
2. 5000 hours MTBR
3. 10dB reduction in noise

Based upon a recent ART Program Review in October 1989, there is indication that the 25% reduction in weight and 5000 hours MTBR is achievable. To meet these goals, transmission component technology must be developed in the areas of gears (high pitch line velocity), shafts (high-speed and supercritical), ceramic bearings, housings, seals, positive engagement clutches, advanced lubrication systems, and gearbox diagnostics. Additionally, analytical tools and manufacturing methods require further development to complement component development. All these goals are directly applicable to high speed rotorcraft designs. The weight-to-power goal of .30 lbs/hp is anticipated for 2010 IOC high-speed rotorcraft transmission designs. Drive system efficiency will increase a negligible amount due to new lubricants and gear and bearing materials. Future drive system technology development is considered to be of medium risk.

Figure 1-23 depicts the transmission weight trends for current and advanced rotorcraft transmissions based on rated power transmission. Representative rotorcraft are plotted for comparison. The V-22 falls above the current technology line due to the high torque resulting from reducing RPM in cruise. Helicopters with relatively constant tip speeds fall close to the .4 lb/hp line. High-speed rotorcraft will likely not follow the current trends, but a reduction in weight of 25% will account for advanced technology gains in this area.

Aerodynamics and Acoustics

High-Speed Airframe Aerodynamics- Airframe aerodynamics in high-speed cruise affect the success of a high-speed rotorcraft. For high-speed forward flight, the major emphasis in airframe aerodynamics is to increase the drag divergence Mach number of the wing. Other configuration-dependant design requirements may limit both wing thickness ratio and the maximum allowable sweep, leaving mainly wing loading and altitude to define the compressibility drag of the wing in high-speed cruise. Additionally, airframe integration of such complex configurations may create adverse aerodynamic interference at high speeds.

Rotor Acoustics and Aerodynamics- Both acoustics and aerodynamics define the capabilities of the rotor in helicopter flight. Acoustic signatures limit the tip speed for civil and military operations. For the configurations that utilize the rotor for helicopter flight only, the maximum blade loading determines the capabilities of the rotor, while Figure of Merit indicates relative efficiency. However, for configurations that utilize the rotor for both helicopter and forward flight, like the Tilt Rotor and Tilt Wing, the cruise propulsive efficiency significantly influences the design. Additionally, rotor performance and rotor/airframe interactions in hover become important for low-speed handling qualities and maneuvering capabilities. Hover down-load varies between concepts, from near zero for Tilt Wing to 12% for the tilting/folding rotor concepts.

Collectively, the current technology in aerodynamics and acoustics requires creative design to satisfy high-speed requirements. A 450-kt speed requirement of the high-speed rotorcraft competes with current subsonic transport aircraft. However, the added complexity of a low-speed mission limits the available parameters with which to optimize the aircraft. A 450 KTAS rotorcraft will take aerodynamics and acoustics to the limit of current technology, and to ensure the success of an aircraft with such capabilities, advanced technology must show significant improvements over current state-of-the-art.

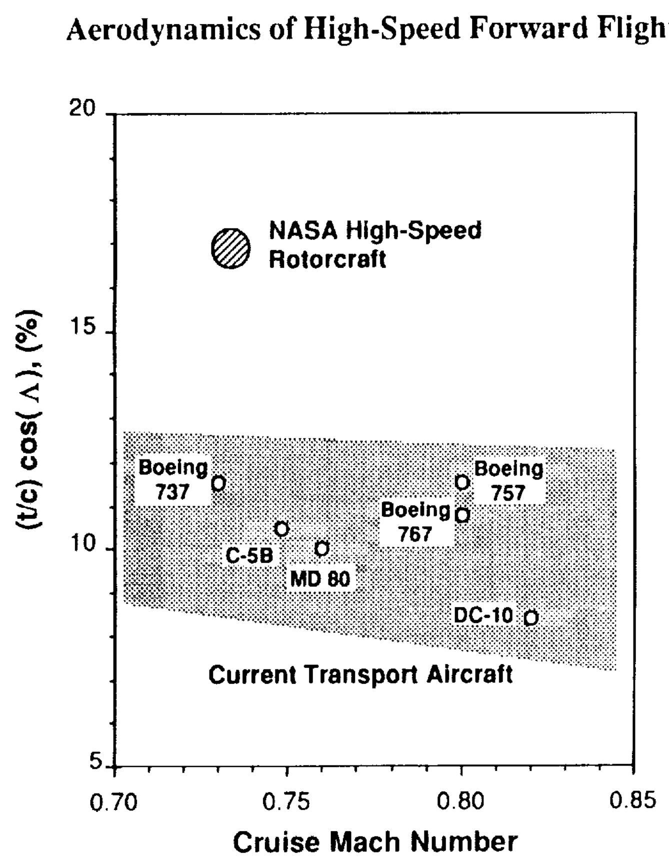


FIGURE 1-24. HIGH-SPEED AIRFRAME AERODYNAMICS

Configuration requirements of high-speed VTOL aircraft dictate the aerodynamic technology required to obtain 450-kt flight. Figure 1-24 shows a survey of existing high-speed subsonic transports revealing the basic dilemma for high-speed rotorcraft. Minimizing wing weight, while maintaining required stiffness to tolerate wing bending and torsional moments, drive the wing thickness-to-chord ratios considerably higher than found conventional transport aircraft. Limiting the wing sweep to 20° on concepts incorporating tilting rotor pods at the wing tips causes the wing design point to lie far from the locus of existing transports. This implies that, without structural breakthroughs to reduce thickness, the wing airfoil section design requirements are considerably more stringent than requirements for current state of the art transports.

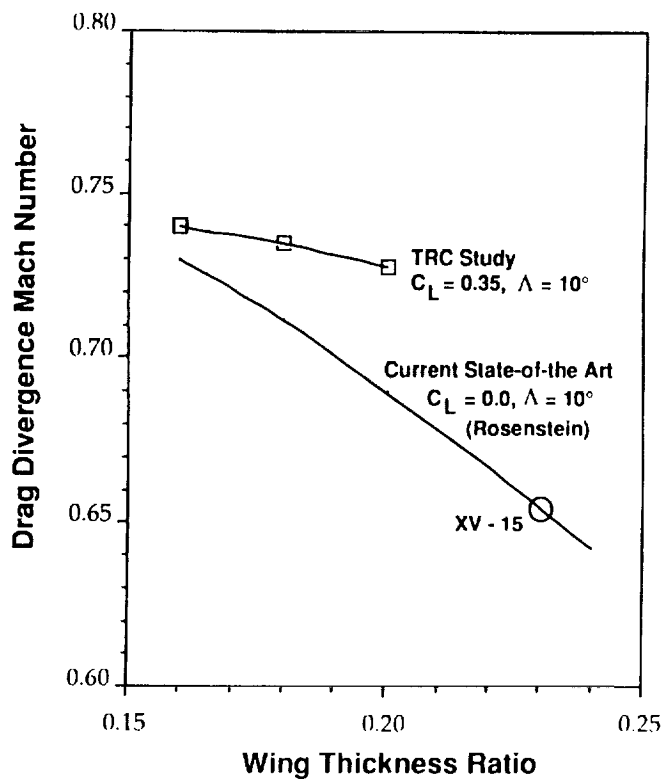


FIGURE 1-25. M_{DD} BOUNDARIES OF HIGH-SPEED ROTORCRAFT WING AIRFOILS

During the initial concept evaluation of the Trail Rotor Convertiplane (TRC), McDonnell Douglas Corporation (MDC) initiated a task to design an 18% airfoil section capable of flying at 0.735 Mach number at 0.35 lift coefficient. A series of airfoils were tested in the Boeing Wind Tunnel and demonstrated improved characteristics as shown in Figure 1-25[15]. However, achieving 450 KTAS with a design using the TRC airfoil and wing sweep limits of 20° still places constraints on wing loading and maximum altitude. Removing these design constraints relies on further improving the TRC section. Further investigation into the trades required for wing thickness, sweep, weight and aerodynamic improvement must follow this study.

Prop/Rotor Performance

Feasibility of any configuration that employs a single propulsive device for both hover and for high-speed forward flight relies on the efficiency of the lifting/propulsive device in both flight modes. Which design condition is more important depends on both the configuration and the mission. Since the disk loading, and thus the hover power is low, the 450 KTAS cruise requirement sizes the engine on most of the configurations. Low propulsive efficiencies in cruise result in larger engines and in heavier aircraft. Although low hover efficiency will not resize the engines, it results in more fuel used during helicopter flight and could be important, if a mission requires a large segment in helicopter mode. Even though the cruise propulsive efficiency has greater impact than the hover Figure of Merit, the resulting rotor design should not penalize the performance in one flight mode to obtain exceptional performance in the other.

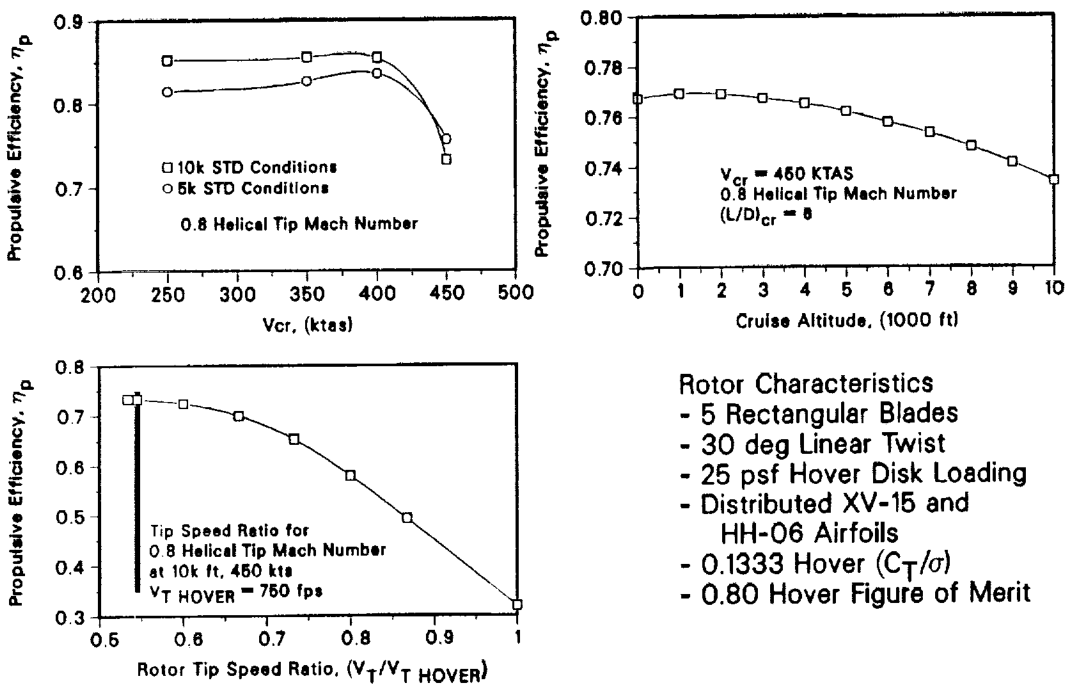


FIGURE 1-26. PROP/ROTOR CRUISE PERFORMANCE

A preliminary study investigated the effects of cruise velocity, altitude, and tip speed on propulsive efficiency to identify the limitations on forward speed capability of a prop/rotor with advanced airfoils. Figure 1-26 shows the results of this study. At around 400 KTAS the rotor reaches an "efficiency divergence". Above this speed the propulsive efficiency decreases very rapidly for a constant helical tip Mach number of 0.8. This occurs due to the airfoils reaching drag divergence Mach number at relatively high C_L. The effect of altitude is less severe, reflecting the speed of sound change. For prop/rotors to operate at these speeds, a reduction in tip speed must occur. Assuming a representative hover tip speed of 750 fps, obtaining a propulsive efficiency of .725 requires reducing the tip speed by 45%. Further reduction results in little gain. This lower tip speed results in the blade sections operating at more optimum angles of attack with respect to drag divergence, and therefore with better efficiencies. Reducing the rotational speed on a direct shaft-driven rotor will force the engine to operate at non-optimum conditions, increasing the fuel flow for cruise. One way to maintain the engine efficiency in cruise is to employ a two-speed gear box to keep the engine rotating at the same optimum speed. The two-speed gear box adds complexity and weight to the drive system, thus, requiring a trade-off.

Besides the performance benefits of lower tip speeds, reasonable acoustic levels require lower tip speeds. Limiting the helical tip Mach number to 0.8 to ensure good acoustic signatures, requires significantly reduced tip speed at 450 KTAS.

Developing advanced airfoils with improved drag divergence characteristics or employing tip sweep seem to be the only ways to improve propulsive efficiencies in high-speed (above 450 KTAS) flight without resorting to elaborate schemes to reduce rotor radius. This requirement may conflict with hover requirements, thus posing a difficult problem. The tip-speed reduction requires a two-speed gear box to maintain good engine performance. The fuel weight saved by improved efficiency more than offsets the weight penalty of the two-speed gear box.

This study uses XV-15 rotor characteristics (modified at the tip) as a baseline[16]. Using current technology airfoils results in a rotor with a hover figure of merit of 0.8 and a propulsive efficiency of 0.725 for a 450 KTAS cruise at 10,000 feet. The 10,000 feet design point represents the optimum tilt-rotor design. At cruise altitudes much greater than 10,000 feet, required power increases significantly.

Conversion Axis - Ceter of Gravity Relationship

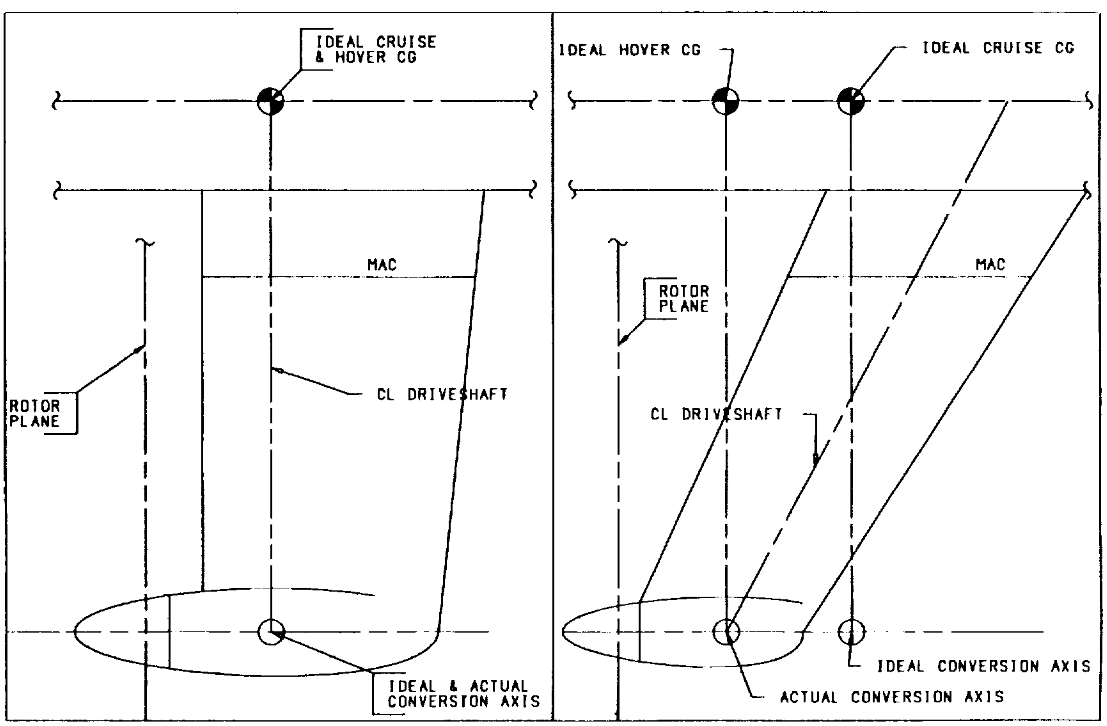


FIGURE 1-27. CONVERSION AXIS - CENTER OF GRAVITY RELATIONSHIP (geometry exagerated for purposes of illustration)

The conversion axis - center of gravity relationship is of primary concern for the Folding Rotor, Tilt Rotor and Tilt Wing concepts. Since wings for these concepts use relatively thick airfoil sections (approximately 18%), highly swept wings are required for high speed flight to avoid drag divergence, ensure rotor blade flapping clearance, and to minimize rotor overhang distance from the wing torsional axis. As illustrated in Figure 1-27, wings with little or no sweep allow the required conversion axis to lie within the wing planform and accommodate the static margin of the aircraft. This allows the use of a conventional wing/tail configuration such as the V-22. As the wing is swept forward or aft, the ideal conversion axis that accommodates the static margin lies outside of the wing planform causing difficulty in providing a drive path or requiring offset/skewed gearing to match the center of gravity and conversion axis. If offset/skewed gearing is eliminated due to complexity, the conversion axis will lie forward and exceed the static margin of the aircraft as illustrated in figure 1-27 for forward swept configurations. For aft swept wings the conversion axis will lie aft and exceed the static margin of the aircraft. The static margin constrains the center of gravity in a cruise condition, which may conflict with the conversion axis requirements on highly swept wings for any tilt concept. Resolving this conflict requires the use of large, highly loaded horizontal tails and/or canards. This problem appears worse for an aft swept Trail Rotor, where the static margin will always be forward of the conversion axis representing an unstable configuration without a large uploaded horizontal tail. The forward swept folding tilt rotor appears more promising due to the center of lift located aft of the conversion axis. The configuration is easily made stable through the use of a canard. However, the effect of the canard on rotor performance or rotor on canard performance remains to be determined and could cause unforeseen problems.

By taking advantage of several possible design ideas below, these critical relationships can be resolved without placing unrealistic constraints on the configuration. Using higher strength materials allows thinner sections and decreases the required wing sweep. This will help to align the conversion axis and center of lift. Incorporation of advanced active flight controls will increase the allowable center of gravity travel for the highly swept forward or aft configurations. The method of tilting rotor pylons and wings could be changed to make allowances for the center of gravity shift and the center of lift for both hover/low speed and cruise flight.

Rotor/Wing Helicopter and Airplane Flight Requirements

The Rotor/Wing promises the advantages of the helicopter for low speed flight combined with the high-speed capability and cruise efficiency of the jet airplane. The fundamental compromise associated with the Rotor/Wing concept is between the conflicting requirements of conversion and rotary wing flight modes.

The Rotor/Wing concept utilizes the center body of the rotor disk to provide a lifting surface during conversion. The conversion requirements dictate that the center surface be as large as possible, so that conversion can occur at lowest possible flight speed. The helicopter mode requires that lift- producing blades sweep as much of the disk as possible. These conflicting requirements are shown qualitatively in Figure 1-28.

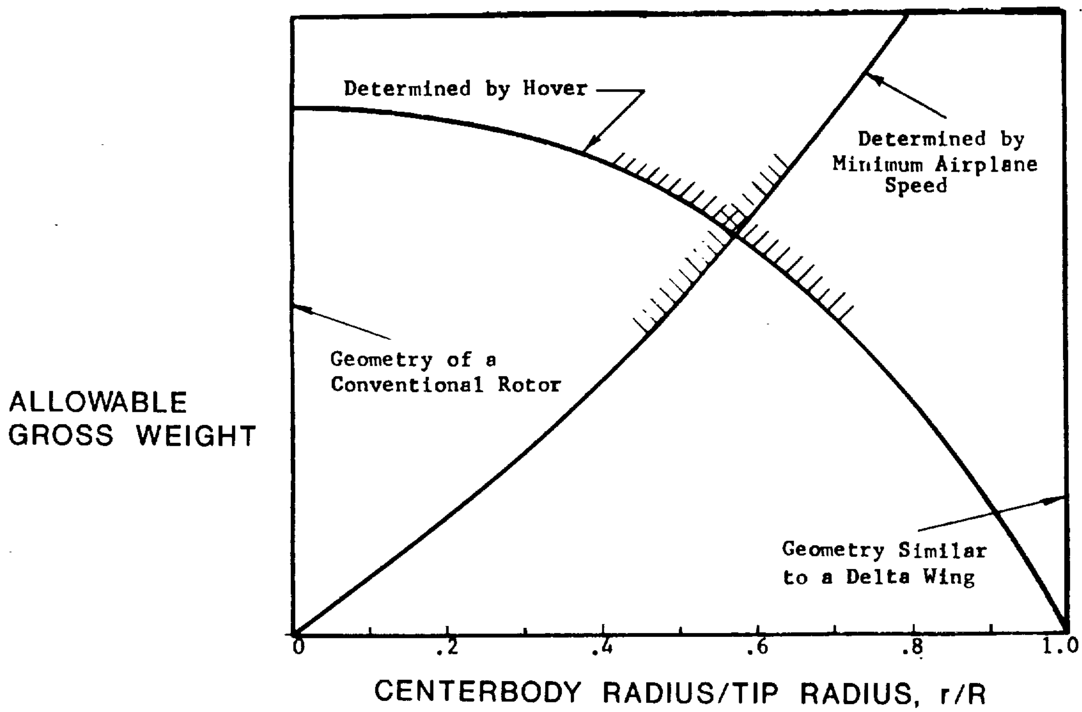


FIGURE 1-28. CONFLICTING HELICOPTER AND AIRPLANE FLIGHT REQUIREMENTS

The horizontal scale of this figure, center-body radius to blade tip radius, represents the configurative geometry of the Rotor/Wing. The left and right hand margins represent two conflicting requirements, helicopter on the left and airplane on the right.

The Rotor/Wing's lifting ability is depicted on the vertical scale. The downward sloping curve represents the lifting ability in hover flight for constant installed power. The larger the blade span in proportion to the total radius, the greater the lifting capacity in hover. As the center-body area increases and blade span decreases, the hover lifting ability decreases until at the right hand margin, no lift can be produced by the bladeless center-body. The lifting ability of the center-body surface during conversion determines the upward sloping curve. At the left margin, there is no surface area to produce lift, but as the surface area increases, the lifting ability in this mode increases rapidly. The two lines represent limits of the conflicting requirements above which the Rotor/Wing concept cannot operate.

The configuration with the largest lifting ability and within the constraints imposed by these requirements lies at the intersection of the two curves. This intersection lies between r/R ratios of 0.4 and 0.7. The exact location of the apex depends upon the power installed, the hover atmospheric conditions, the blade chord and conversion speed.

Dynamics and Aeroelasticity

Each of the five rotorcraft concepts being considered, should be considered from an aeromechanical perspective. More appropriately, in view of the need for full authority automatic flight controls to manage each vehicle during conversion, an aeroservoelastic approach should be used. Some problem areas, such as surface flutter or divergence, are shared by most or all five concepts while others, such as wing/rotor interactions and rotor instabilities, are applicable only to some or one of the designs.

Divergence and Flutter- With the exception of the Rotor/Wing concept, all the designs incorporate large rotor or proprotors located at the end of a medium-to-high aspect ratio wing designed for cruise efficiency. The addition of this large tip inertia to the wing can reduce the rotational frequency coalescence with a primary wing bending mode. The Folding Tilt Rotor and Trail Rotor, additionally, imply a fairly large center of gravity shift aft at the tips when the rotors fold, exacerbating the flutter problem. A fundamental design compromise must be made between increased torsional stiffness, pushing toward thicker wings, and airplane mode efficiency, for which thinner sections are desired. The very high wing stiffnesses required to allow for "jump" (>>1g) vertical takeoffs, however, could obviate the need for this compromise, as could an advanced active electrohydraulic flutter suppression system[17].

The Tilt Rotor, Tilt Wing and Rotor/Wing share a forward swept wing design in the airplane mode, which can lead to wing divergence at high speeds. For the Rotor/Wing, which, of necessity, has a substantial inboard structure to support and enclose the reaction drive ducting, and for the Tilt Wing, which has more propeller-like proprotors and therefore needs less wing sweep, this probably will not be a problem. The Tilt Rotor, on the other hand, especially the Folding Tilt Rotor, require significantly more forward wing sweep to avoid wing-rotor contact at reduced RPM under high loads. Again, a compromise must be made between increased torsional stiffness and airplane mode efficiency. Another possibility is to build in a beneficial bending-torsion couplings in the wing structure using advance tailored composite materials. Wing divergence should not be a problem for the aft-swept Trail Rotor design.

Rotor/Proprotor Instabilities- The Tilt Wing and two Tilt Rotor designs, which are stiff in-plane (i.e., the fundamental in-plane modal frequency is greater than the rotational frequency) could share the problem of whirl mode instabilities, which occur when the thrust vector motion couples with wing torsional bending. Engineering cures for this problem, however, are well established from the XV-15/V-22 program and include both particular design features to reduce the tilt of the thrust vector and active suppression of the motion using cyclic pitch[18]. A major advantage of the stiff in-plane arrangement, however, is that it eliminates the possibility of ground or air resonance instabilities.

The Trail Rotor concept might use a soft in-plane rotor to reduce rotor weight. Since this rotor would tilt aft, not forward, and be under light loading at the time, whirl mode instabilities are probably not a concern here. However, as mentioned above, the soft in-plane rotor is subject to ground and/or air resonance and, unlike a standard helicopter, in a Trail Rotor design the wing and fuselage flexibility will play a large role in the couple motions. Again, careful wing and rotor design is required to remove this possibility. Because the wing participates strongly, however, it may be possible to actually use the vertical wing motion to introduce additional damping by coupling together the blade lag motion with the strongly damped collective flap motion.

Both stiff in-plane and soft in-plane rotors can be subject to flap-lag-torsion instabilities in forward flight. The source and severity of this type of instability is highly dependent on the exact rotor design, especially the built in geometric and structural couplings in the rotor blade motions. It is, therefore, outside the scope of this preliminary concept review, but must be carefully investigated for each idea during the design phase.

The two folding concepts, the Folding Tilt Rotor and the Folding Trail Rotor, must undergo large rapid reductions in rotor rotational speed and finally stop the rotors at fairly high vehicle airspeeds. Control and stability of the rotor during the tilting and folding portions of the conversion from rotor-borne to wing-borne flight and vice versa are almost unexplored areas, both experimentally and analytically. They entail, therefore, higher technical risk than either the Tilt Wing or the standard Tilt Rotor concept. Analytical tools capable of realistically simulating this type of environment are only now beginning to become available and are not yet verified. Most probably, this type of design will require advanced automatic rotor control and stability augmentation systems throughout the conversion process.

TECHNOLOGY TRADE STUDIES

Measures of Effectiveness

Establishing a means of comparative analysis between the concepts requires a derivation of measures of effectiveness. These measures evaluate the concepts beyond the vehicle attributes of weight, speed, range and payload. Grouping these attributes together establishes parameters which evaluate the overall vehicle effectiveness. These measures allow combinations of strong and weak attributes to further define the effectiveness and economy of a concept. For instance, a high-speed, fuel inefficient concept may be more economical than a slower, fuel efficient one. Examining the individual attributes independently may not resolve the economics of the problem.

Five measure of effectiveness (MOE) establish a baseline for a comparative evaluation of the concepts:

1. Lift/Drag (L/D)- This ratio depicts the lifting efficiency of a particular aircraft. A high value results in less thrust required for a given gross weight, indicating more economical operation. This parameter varies with both gross weight and drag changes.

2. Productivity- A measure of the capability of the aircraft to deliver large amounts of payload in a given time, either by large amounts per sorties or small amounts through many sorties defines productivity. Normalizing by the empty weight provides a further indication of economy, since maintenance and acquisition costs generally follow the trend in empty weight. It is defined as payload x velocity/empty weight.

3. Payload Delivery Efficiency (PDE)- This indicates the efficiency of delivering payload from a cost point of view. A higher value implies greater payload delivery for less fuel, hence less cost. Besides cost, it also reflects the degree of logistics support required for an airlift mission. It is defined as payload x range/fuel required.

4. Payload/Range: A measure of the concept's ability to trade payload for fuel, this parameter demonstrates range flexibility. At the same gross weight, range is extended by replacing payload with fuel.

5. Specific Range: This measures a concept's range efficiency at a specified gross weight and altitude. The concepts' MOE were used to conduct three trade studies to initially assess the effects of technology on the concepts. The initial trade study compared the concepts at current levels of technology; the second examined the effect of each advanced technology on each concept; and finally, the last trade study compared all the concepts at advanced levels of technology.

Current Technology Study

Productivity- For a given mission, the weight empty influences this measure of effectiveness the greatest.

Figure 1-29 depicts productivity versus flight speed for each of the concepts. For a specified configuration, these values of productivity were computed at design gross weight, for the generic 600-nm mission flown at the optimum altitude. The calculations reflect fuel and range allowances for take off, climb, descent, and landing with 10% fuel reserves.

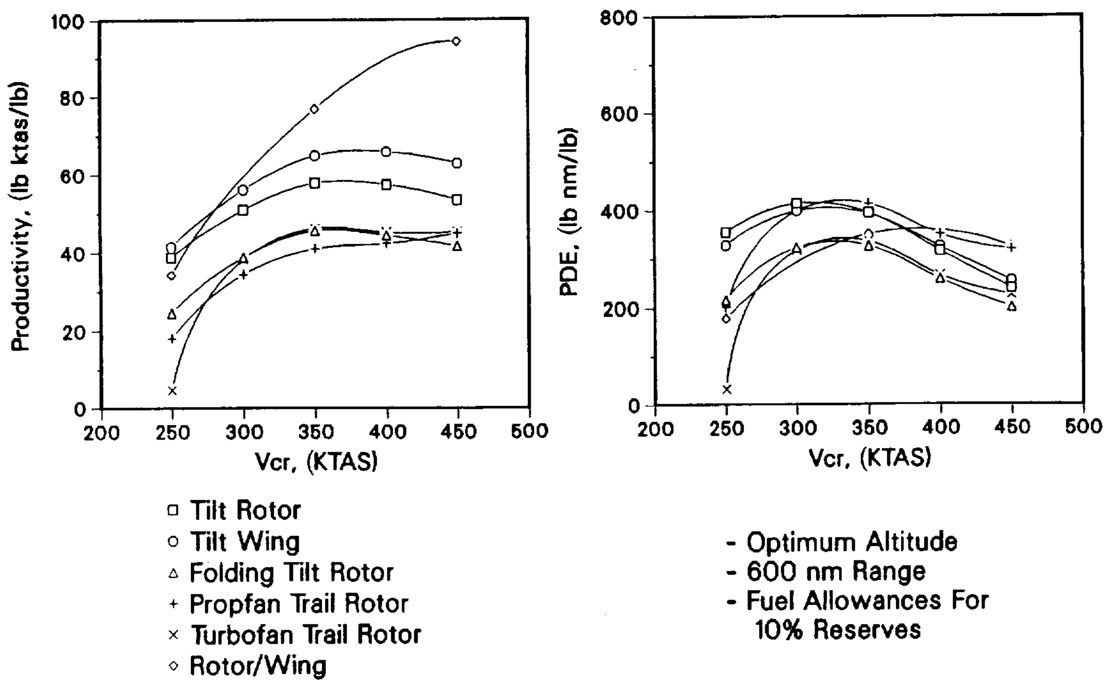


FIGURE 1-29. MEASURES OF EFFECTIVENESS - CURRENT TECHNOLOGY

The graph shows that the Rotor/Wing is the most productive at flight speeds greater than 250 KTAS, followed by the Tilt Wing. The Weights Summary tabulated in Appendix A shows these configurations have the lightest weight empty, substantiating the strong influence of empty weight on productivity. Since the Tilt Rotor weighs slightly more than the Tilt Wing, its productivity is less than that of the Tilt Wing. The folded-rotor concepts, Folding Tilt Rotor, Turbofan Trail Rotor and Propfan Trail Rotor, are the least productive because their dual propulsive devices increase their weight empty.

Payload Delivery Efficiency- For a given mission radius, the PDE is most affected by the fuel efficiency of the configuration. The payload delivery efficiency, depicted as a function of flight speed for each of the concepts, is based on design gross weight and 600-nm mission flown at the optimum altitude for each configuration. The useful load, fuel plus payload, is held constant for each configuration, and the mission fuel reflects allowances for take off, climb, descent, and landing with 10% reserves.

The Propfan Trail Rotor and Rotor/Wing have the greatest PDE for flight speeds greater than 350 KTAS because of their high-speed cruise efficiency. At low speeds, the Rotor/Wing's PDE is poor, while the Tilt Wing and Tilt Rotor have the greatest PDE. However, the rotor's propulsive efficiency decreases as flight speed increases, and the PDE of these concepts also decreases. The Folding Tilt Rotor and the Turbofan Trail Rotor have the poorest payload delivery efficiencies due to high equivalent flat plate area and the inability to fly at drag reducing, higher altitudes.

Cruise Lift-to-Drag Ratio: The lift-to-drag curves depicted in Figure 1-30 are computed versus velocity for each concept in its cruise configuration and includes zero-lift, induced, and compressibility drag contributions.

The Rotor/Wing has the greatest lift-to-drag ratio in cruise, primarily because the concept has the cleanest configuration. These values compare favorably to estimates of full scale L/D based on wind tunnel test reports. The difference in the (L/D) with increasing weight. At high cruise-speeds, the induced drag is small compared to the zero-lift drag, and therefore, as aircraft weight increase, (L/D) increases also. For example, the Tilt Wing and Tilt Rotor have about the same cruise drag, but since the Tilt Rotor weighs more, its (L/D) is greater.

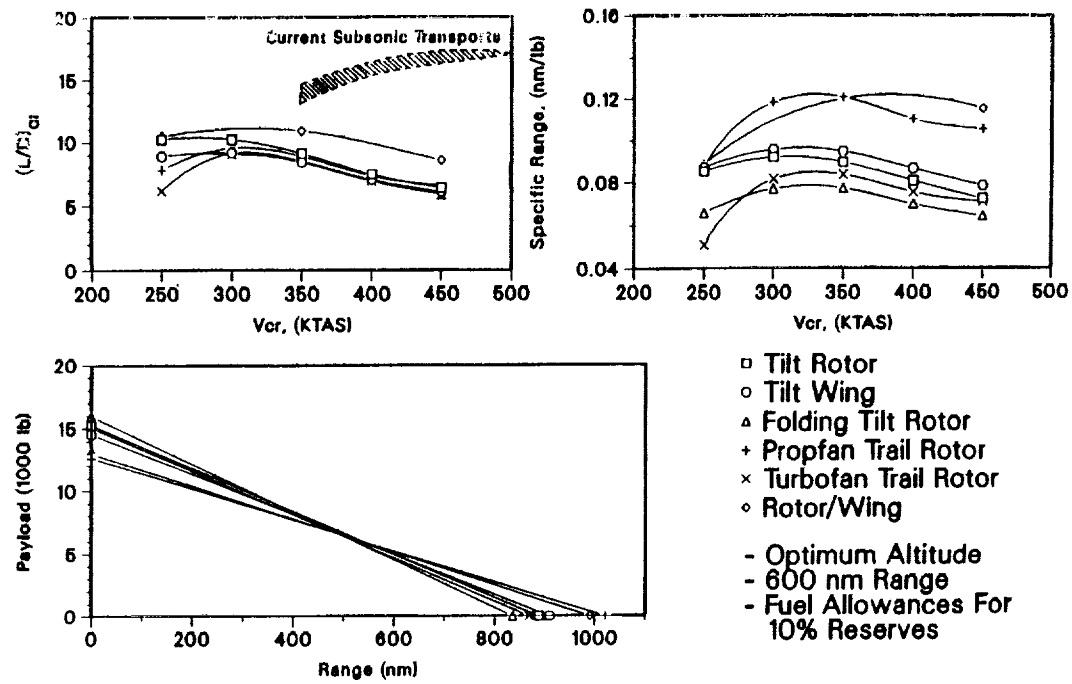


FIGURE 1-30. PERFORMANCE INDICES - CURRENT TECHNOLOGY

Specific Range- Specific range refers to the fuel economy of the aircraft in the distance it can fly per pound of fuel. The figure shows the relationship of specific range with cruise speed for each of the configurations. The specific range curves are based on design gross weight and engine characteristics at the optimum cruise altitude of each aircraft.

As with the payload delivery efficiency, which relies heavily on fuel efficiency, the Rotor/Wing and the Propfan Trail Rotor display the greatest specific range at higher cruise speeds where the low bypass ratio turbofan engine of the Rotor/Wing and the propfan are most efficient. At low speeds, the Tilt Wing and Tilt Rotor have good specific range values due to their high propulsive efficiencies. As the speed increases, turbofan engine performance improves, thus, the specific range of the Folding Tilt Rotor and Turbofan Trail Rotor approach that of the Tilt Wing and Tilt Rotor.

Payload/Range- The payload/range computations are based on design gross weight and a mission flown at each concept's optimum altitude. The calculations utilize a fixed design useful load, fuel plus payload, and the range calculations reflect fuel and range allowances for take off, climb, descent, and landing with 10% reserves. The curves do not intersect at the 600-nm range/4500-lb payload design point because the analysis is based on constant engine characteristics determined for the design gross weight.

The Propfan Trail Rotor and the Rotor/Wing have the best payload/range characteristics. Since the obtainable range is a function of the aircraft's specific range, those aircraft with greater specific range values will have better payload/range characteristics. Following the Propfan Trail Rotor and Rotor/Wing are the Tilt Wing, Tilt Rotor, Turbofan Trail Rotor, and Folding Tilt Rotor, respectively. The concepts possessing the greatest range capability allow most flexibility in long range missions, particularly for ferry type missions.

Advanced Technology Impact

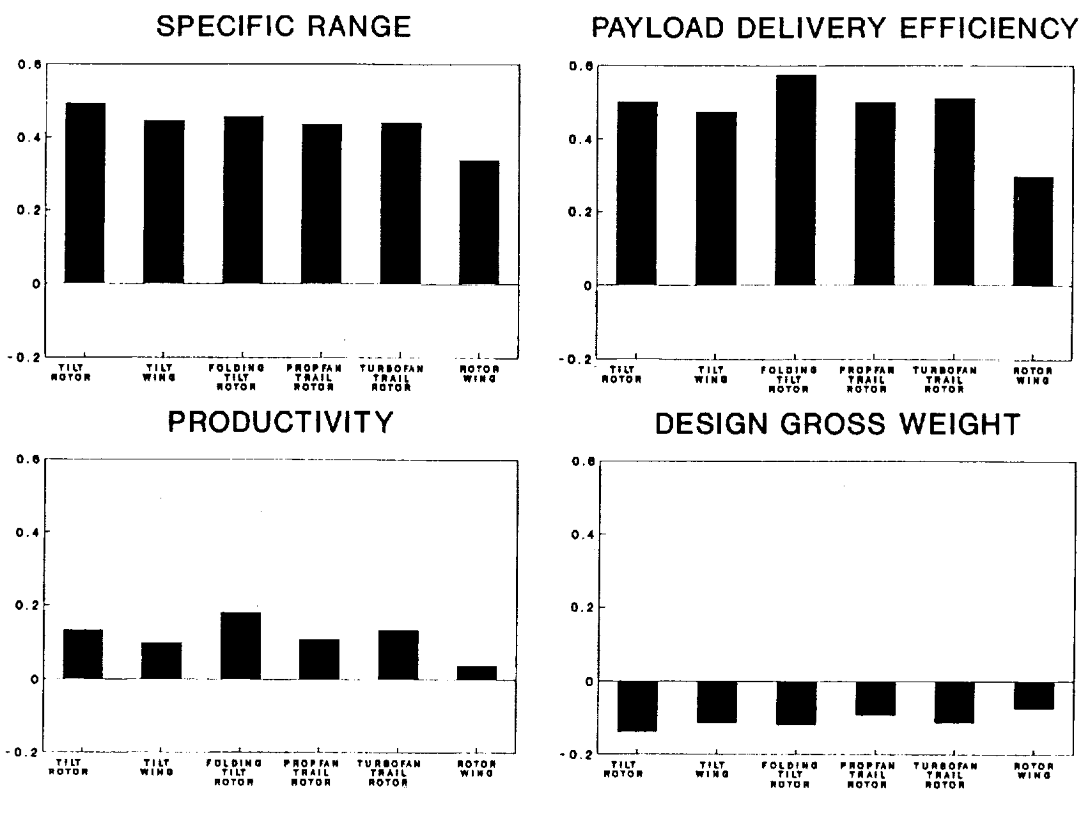


FIGURE 1-31. EFFECT OF REDUCED SFC

The second study examined the effect of each technology area advancement achievable for a 2010 IOC aircraft. Using individual technology areas, and resizing the concept from the baseline current technology, resulted in an assessment of the effect of each technology area on each concept. This allowed a comparative assessment of technology development priority.

Effect of Reduced SFC (-25%)- Reduced SFC, due to advancements in engine technology, significantly affects the attributes of all configurations. Figure 1-31 depicts the relation of a baseline current technology aircraft with one that benefits from improved SFC only. Specific range and payload delivery efficiency show the most significant improvements, since these parameters relate directly to fuel efficiency. Productivity improvements result due to lower empty weight achieved when the structure carries less fuel. The more fuel efficient engines reduce the gross weight of all concepts through the combination of lower structural weight and less fuel weight. For the same percent improvement in SFC, the Rotor/Wing appears less affected. This occurs because a large component of empty weight in the other concepts consists of the drive system. A reduction in overall weight reduces the power transmitted by this system and its weight follows. Therefore, the concepts using drive systems incur the greatest percentage improvement.

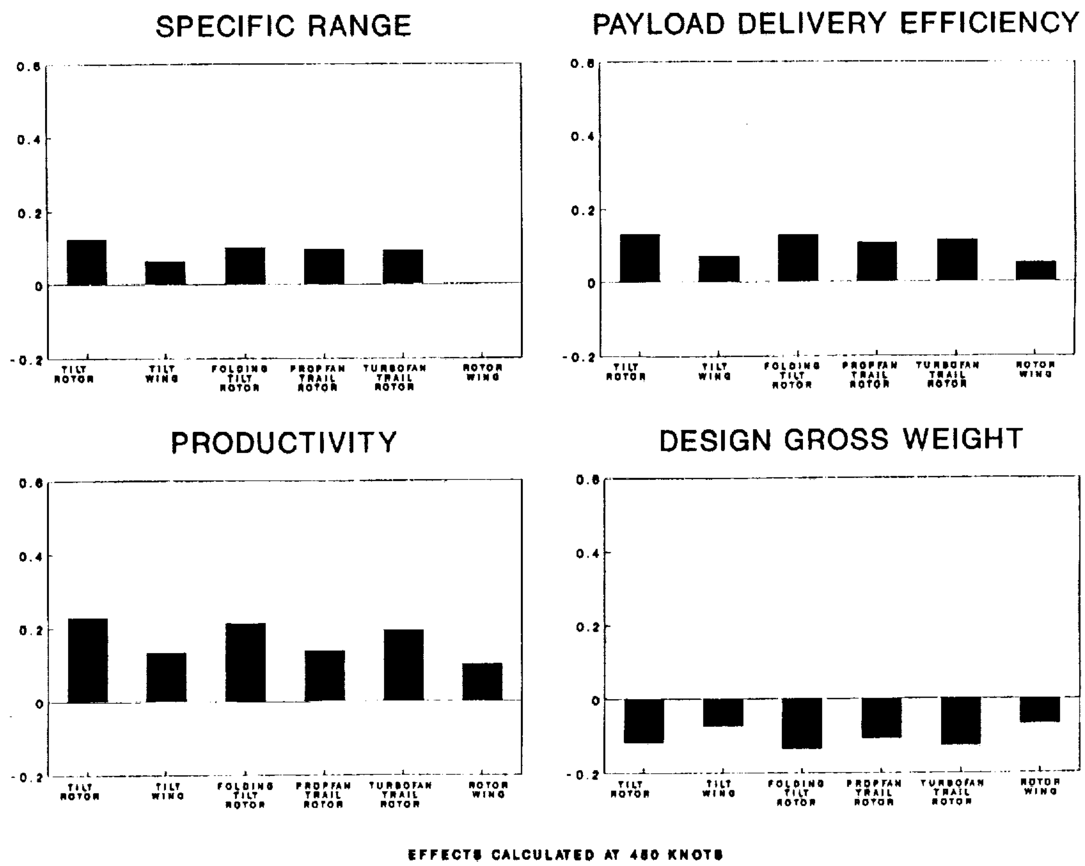


FIGURE 1-32: EFFECT OF REDUCED ENGINE WEIGHT

Improved SFC impacts direct operating costs significantly, due to the large improvements in payload delivery efficiency. Acquisition costs, assuming a $/lb relation, should decrease for all concepts with reduced SFC.

Effect of Reduced Engine Weight (-36%)- Reduced engine weight, due to advancements in engine technology, affects the attributes of all configurations. Figure 1-32 depicts the relation of a baseline current technology aircraft with one that benefits from reduced engine weight only. Specific range, and payload delivery efficiency both increase due to reduced fuel consumption resulting from overall reduced structure weight. This will then reduce power required and resizes the engine to a smaller one. The cascading effect on structural weight is responsible for the improvements in productivity shown.

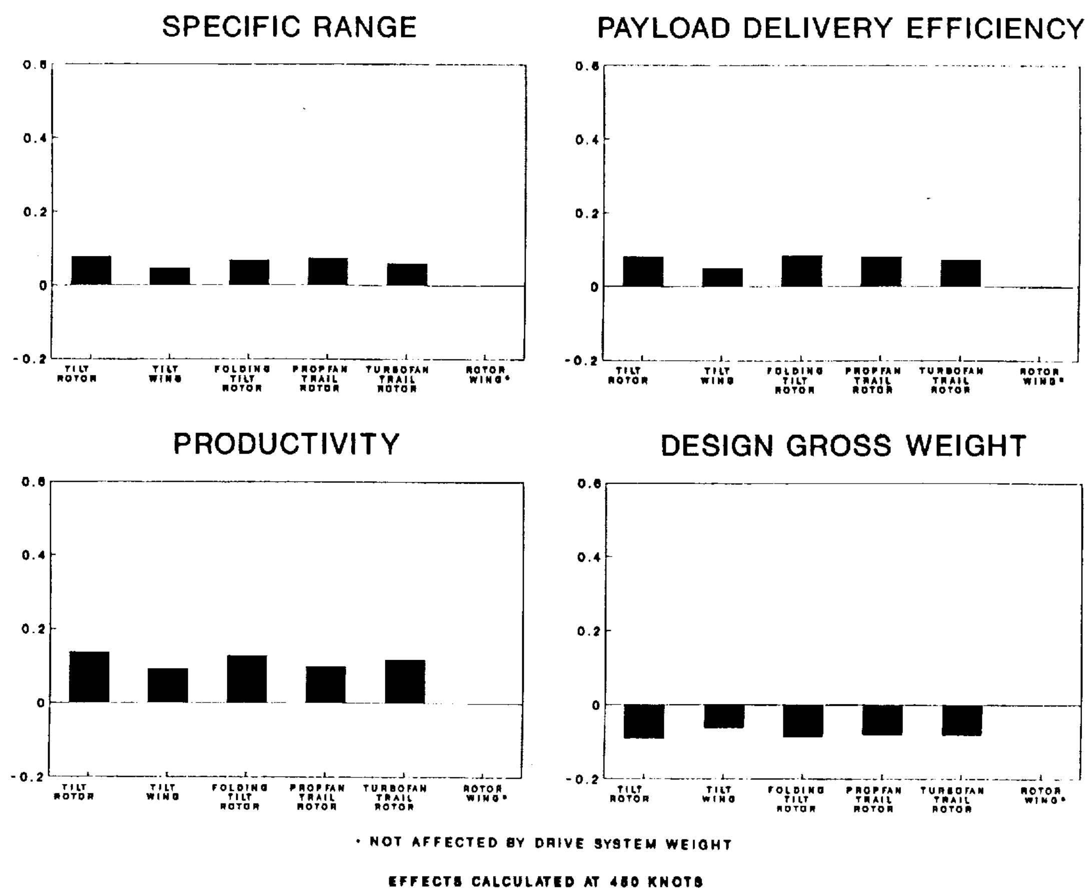
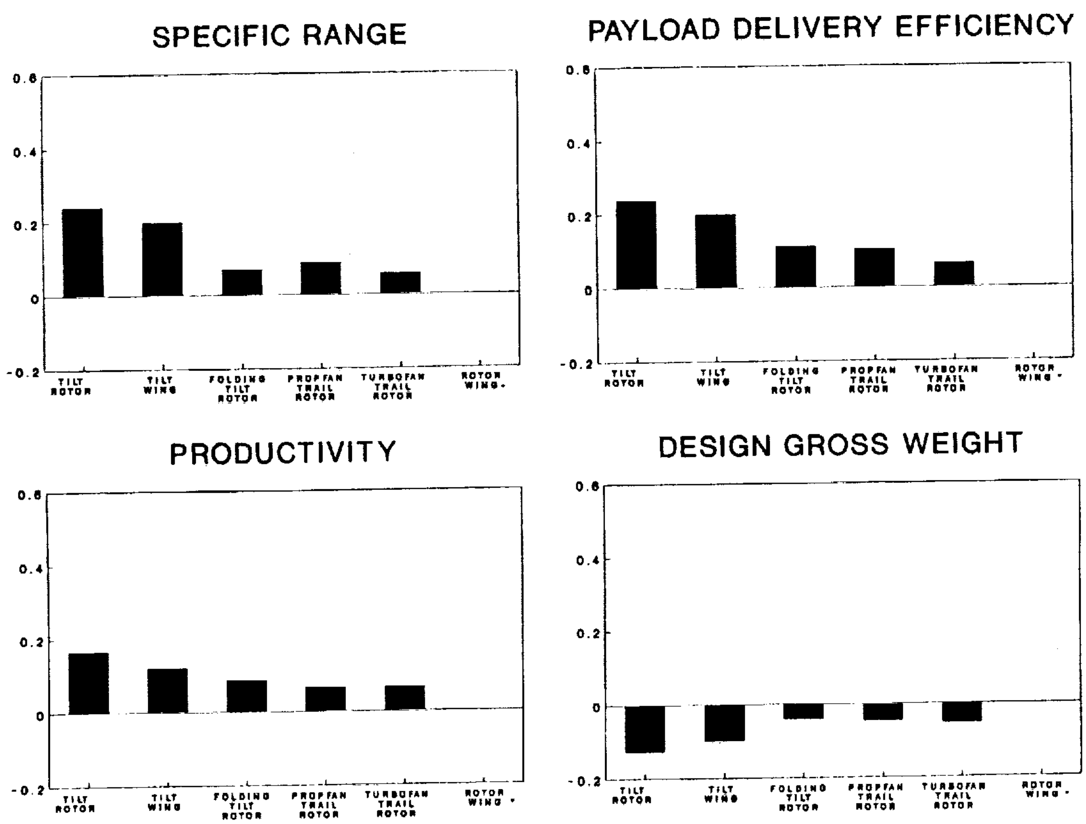


FIGURE 1-33. EFFECT OF REDUCED DRIVE SYSTEM WEIGHT

Effect of Reduced Drive System Weight (-25%)- Reduced drive system weight, due to advancements in component technology, affects all configurations except the Rotor/Wing. This is the result of the Rotor/Wing concept utilizing reaction drive in place of a mechanical drive system. Figure 1-33 shows the relation of a baseline current technology aircraft with one that benefits from reduced drive system weight only. Specific range and payload delivery efficiency increase due to reduced fuel consumption resulting from both reduced structure weight and reduced power requirements. Reduction of power requirements secondarily affects engine size and drive system weight. Productivity improvements result due to lower empty weight achieved.

Effect of Improved Aerodynamics- Improved aerodynamics incorporates two main areas: airframe aerodynamics and proprotor propulsive efficiency. Improvement in both areas directly affects required mission fuel and indirectly affects the weight empty. Figure 1-34 depicts the effect of improved aerodynamics.



* NOT AFFECTED BY IMPROVED AERODYNAMICS

EFFECTS CALCULATED AT 450 KNOTS

FIGURE 1-34. EFFECT OF IMPROVED AERODYNAMICS

Improved airframe aerodynamics includes increasing the wing drag-divergence Mach number at the cruise C_L by 5% at the required cruise speed, reducing thrust and hence fuel. Improving propulsive efficiency of the proprotor by 10% at 450 KTAS reduces the fuel required to accomplish the mission. The reduced fuel consumption for a given mission increases the payload delivery efficiency of all the concepts, with the greatest improvement occurring for concepts driven by proprotors. These concepts benefit through the combination of drag reduction and improved propulsive efficiency.

Aerodynamic improvements do not affect the Rotor/Wing in the context used thus far. Drag reduction may occur to the airframe which improves its efficiency. Unfortunately, unlike other concepts, hover requirements size its engines, so no reduction in engine weight occurs with a reduction in cruise thrust. Any weight savings results from reduced fuel consumption. The addition of circulation control, in fixed wing flight only, would improve the cruise efficiency of the elliptical airfoils and should be relatively easy to accomplish. This possibility was not explored in Task 1.

Specific range and payload delivery efficiency, due to their dependance on fuel show the greatest improvement. Productivity increases as a result of reduced structure weight with less fuel.

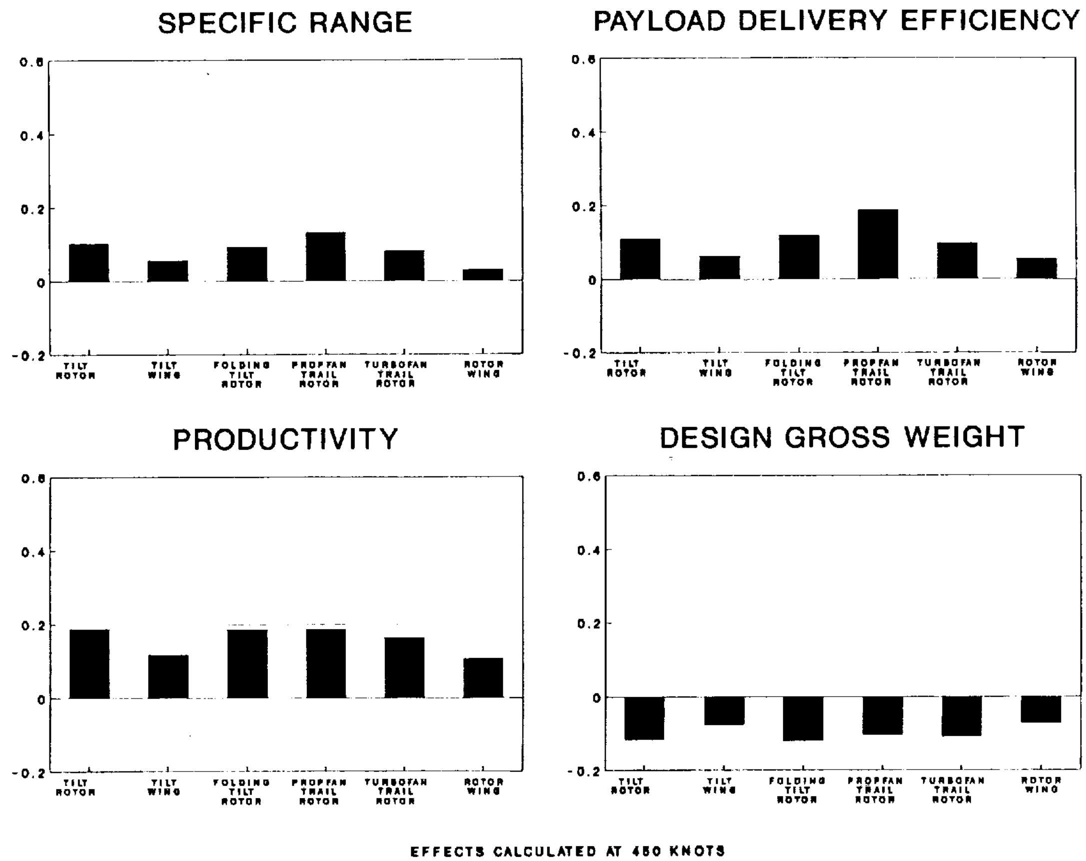


FIGURE 1-35. EFFECT OF REDUCED STRUCTURE WEIGHT

Effect of Advanced Structures- The use of advanced materials and manufacturing techniques affects the vehicle attributes by reducing primary structural weight by 15% and secondary structural weight by 10%. This percentage is an approximate average with various structural components varying more or less depending on their function. Components which require metal obviously can not take advantage of light-weight composite materials.

The reduction in weight empty improves all vehicle attributes (Figure 1-35). A lighter weight empty resizes the aircraft, reducing areas of major drag contributors such as the wing and empennage. As a result, completing the mission requires less fuel which improves both specific range and payload delivery efficiency. Productivity reflects a slightly greater increase due to the inverse relationship with weight empty.

Concepts employing the most complex drive/propulsion systems benefit the most from reduced structural weight. While these systems may not be directly affected, the resulting lower gross weight reduces power required. This in turn, lowers both the propulsion and drive system weights.

The results of this study show that the largest overall impact of reduced structure weight will occur on productivity which indicates maintenance and acquisition cost reductions. Direct operating costs associated with payload delivery efficiency will also decrease.

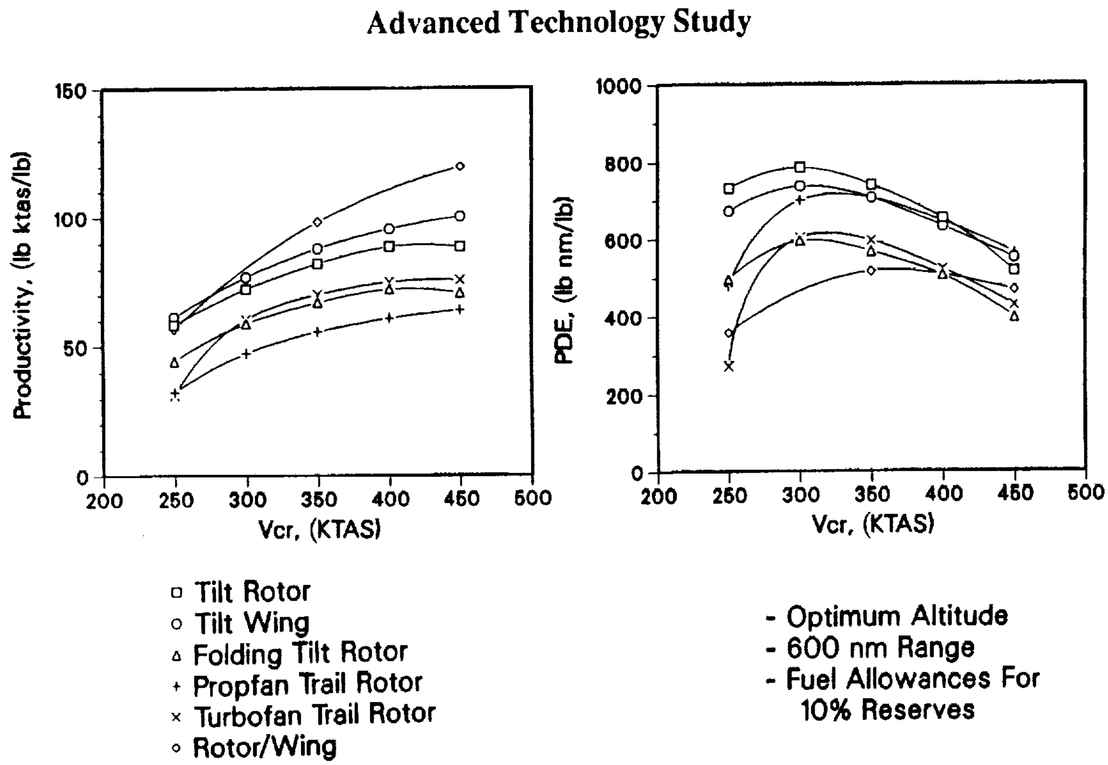


FIGURE 1-36. MEASURES OF EFFECTIVENESS - ADVANCED TECHNOLOGY

The third study compared resized concepts incorporating advanced technology using the MOE described previously.

Productivity- Figure 1-36 shows that productivity trends of the configurations employing total advanced technology. Comparing this chart with the productivity graph for current technology indicates the ranking of concepts remains essentially the same with the Rotor/Wing possessing the greatest productivity, followed by the Tilt Wing, Tilt Rotor, and the Folded Rotor Concepts, respectively. Closer inspection of the two charts reveals some subtle changes.

First, the speed for maximum productivity is greater for the advanced configurations. This characteristic arises primarily because of reduced engine fuel consumption. Second, although the concept productivity ranking is the same, the difference in productivity between the advanced Rotor/Wing and the other advanced configurations is less, a trend that evolves from the advanced technology impact studies.

The 25% drive system weight reduction because of advanced technology reduces the aircraft gross weight by approximately 8% on all configurations except the Rotor/Wing, which has no mechanical drive system. Furthermore, the aerodynamics of the Rotor/Wing is not compatible with the aerodynamics improvements implemented in the other advanced concepts. Thus, two of the five advanced technology trades do not strictly apply to the Rotor/Wing, so therefore, it shows less improvement in productivity with advanced technology.

Payload Delivery Efficiency- Although the advanced configurations show a significant improvement in payload delivery efficiency (PDE), comparing the advanced technology PDE trends with the current technology trends reveals some marked differences. The greatest change is in the concept ranking based on PDE. For flight speeds greater than 350 KTAS, the Tilt Rotor, Propfan Trail Rotor, and Tilt Wing share the best PDE, followed by the Rotor/Wing, Turbofan Trail Rotor, and Folding Tilt Rotor, respectively. Not only does the Rotor/Wing drop in the relative rankings, but the Tilt Rotor and Tilt Wing match the Propfan Trail Rotor's PDE. The advanced Tilt Wing and Tilt Rotor show a 10% improvement in prop/rotor cruise efficiency with a 25% reduction in engine SFC. These two contributions improve the PDE sufficiently to match that of the Propfan Trail Rotor.

As discussed for the productivity trends, the reason for the Rotor/Wing's lower rank exists in the advanced technology trade studies, which are biased toward the other configurations. Although the advanced Rotor/Wing includes a lighter structure and a lighter and more efficient engine, the drive system weight reduction or the aerodynamics improvements considered here do not affect the Rotor/Wing. However, even though the assumed aerodynamic improvements do not apply directly to the Rotor/Wing, the configuration can benefit from more specific configuration modelling to reduce drag and expand the flight envelope. These configuration specific improvements are beyond the scope of Task 1, and therefore the advanced Rotor/Wing does not show great improvements in the measures of effectiveness. The lack of improvement by the Rotor/Wing indicates its relative insensitivity to advanced technology due mainly to its lack of major subsystems to which advanced technology was applied on all other concepts.

Cruise Lift-To-Drag Ratio- The cruise lift-to-drag ratios (L/D) for the advanced configurations show little change from those of the current technology configurations. The smaller (L/D) reduction for the advanced configurations results from the ratio's stronger dependence on aircraft weight. Otherwise, the trends shown in Figure 1-37, remain essentially the same for each concept and for the relative concept ranking.

Specific Range- The specific range trends of the advanced configurations show a significant improvement compared to the current technology trends. This considerable translation in the curves arises from the improved engine fuel consumption, the technology that most drastically affects the advanced configurations. For flight speeds greater than 350 KTAS, the Propfan Trail Rotor shows the greatest specific range, followed closely by the Rotor/Wing.

The Tilt Rotor and Tilt Wing specific range trends include the rotor cruise efficiency improvements, and therefore, their curves lie more closely to those of the Propfan Trail Rotor and Rotor/Wing compared to current technology. The Turbofan Trail Rotor and Folding Tilt Rotor show the poorest specific range values.

Payload/Range- Incorporating advanced technology in the configurations shows some change in their payload/range diagrams. As for the current technology performance, the Turbofan Trail Rotor and the Folding Tilt Rotor have the poorest payload-range characteristics. The trends of the other four configurations are more closely aligned, implying the Tilt Rotor and Tilt Wing reflect more significant improvements than the Propfan Trail Rotor and Rotor/Wing, primarily because of the 10% improvement in prop/rotor cruise performance.

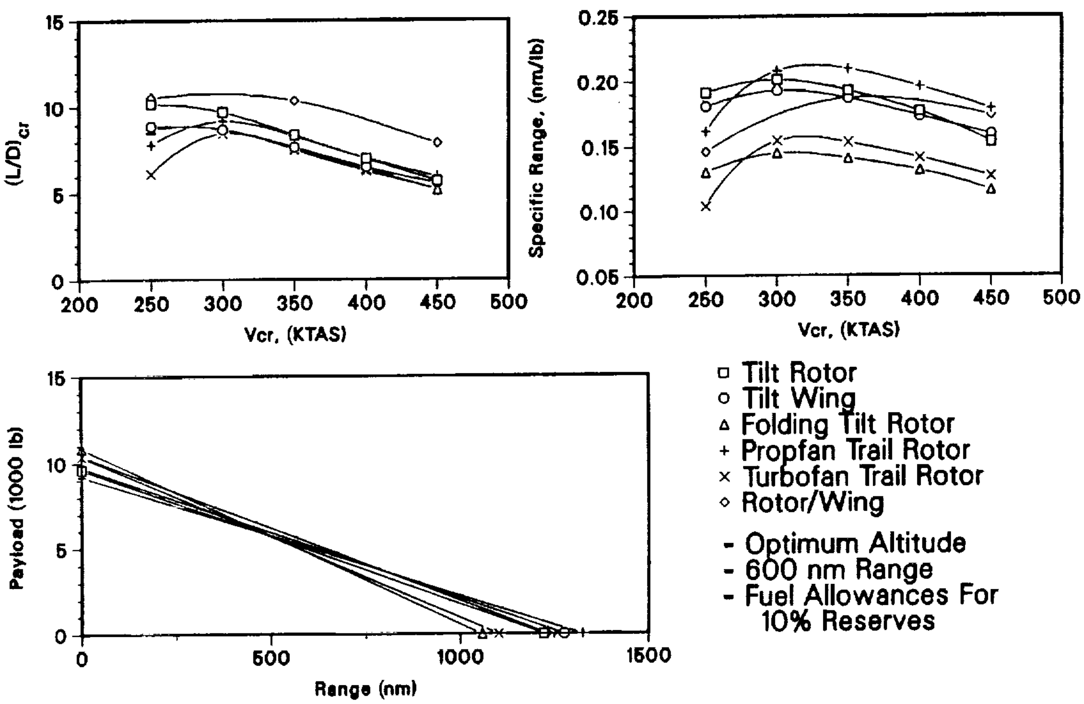


FIGURE 1-37: PERFORMANCE INDICES - ADVANCED TECHNOLOGY

Concept Weight Summary

The following is a general discussion of the major differences between the configurations from a weights perspective for both current and advanced technologies. Figure 1-38 shows this comparison.

Rotor/Wing- Three major groups contribute to the Rotor/Wing's overall lower weight empty. First, it requires no conventional drive system which accounts for between 5,000 and 7,000 lbs in the other configurations. Second, due to the integral rotor/wing structure, the wing group weight replaces the wing, hub and hinge, and blade group weights of the other configurations. This integral structure results in a weight of between 1,500 and 7,000 lbs over the other concepts. The third contributor to the Rotor/Wing's overall lower weight is that the fixed wing and rotor controls are integral by design. Also, it requires only one set of rotor controls as opposed to dual sets in the other configurations. These flight control differences result in a weight saving of between 1,000 and 2,000 lbs over the other configurations.

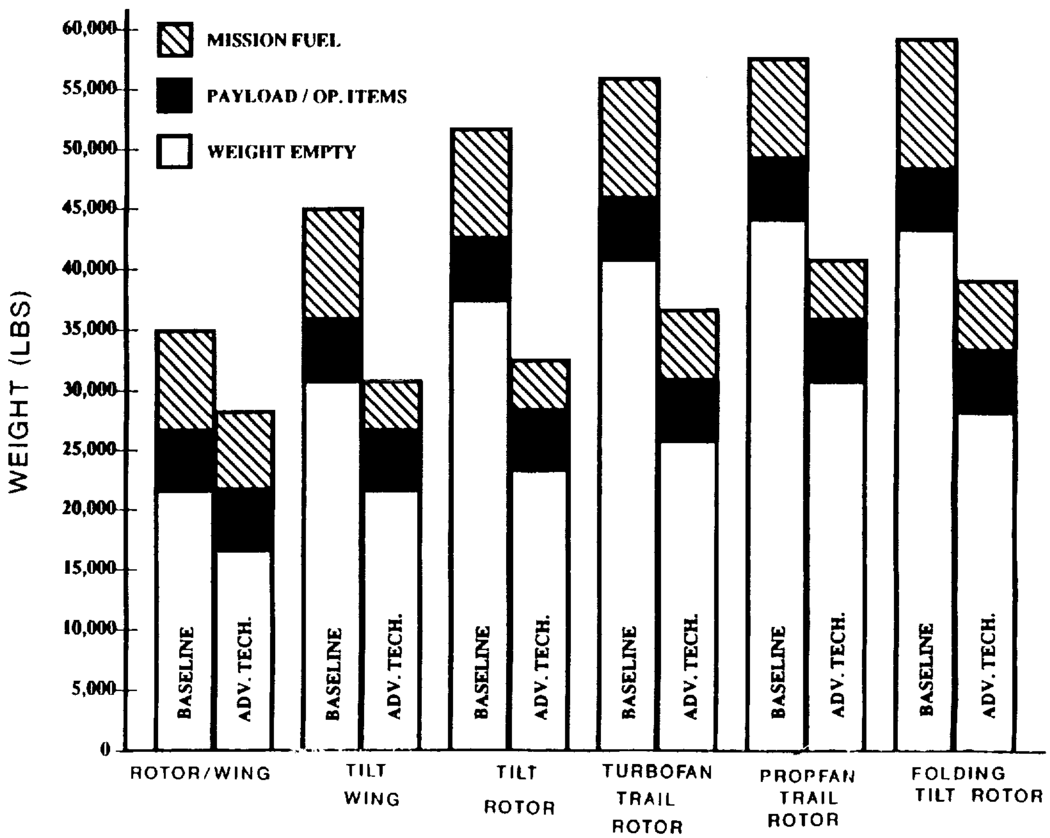


FIGURE 1-38. CONCEPTS WEIGHTS SUMMARY

Comparing the baseline and advanced technology weights, the most significant relationship is that of mission fuel. In the Rotor/Wing's case, the amount of fuel required is not significantly changed due to the fact that the engine is sized for hover and therefore is not directly related to the drag of the vehicle.

Tilt Wing- The single most significant group weight difference for the Tilt Wing versus the other concepts is the wing weight. In analyzing the concepts, it became apparent that the tilt-rotor type wing is designed by jump-takeoff requirements, whereas the wing of the Tilt Wing is designed by forward flight requirements. The forward flight design condition resulted in a decrease in the overall bending requirements, however, it was necessary to increase the chord of the wing for conversion. The effect of increasing the chord while decreasing the bending requirements resulted in a wing weight decrease of between 1,200 lbs and 2,300 lbs over the other configurations with tilt-rotor type wings.

Tilt Rotor- The general configuration of the tilt rotor should be considered similar to the V-22 Osprey with the following changes; there is no requirement for wing folding, there is no loading ramp, the fuselage is pressurized, and the drive system allows for a two-speed rotor gearbox.

Trail-Rotor Convertiplane- There are three weight groups which distinguish the Trail-Rotor Convertiplane from some of the other configurations. First, the main rotor blades are considered to be soft-in-plane or more flexible which results in a weight savings. Second, the Trail-Rotor Convertiplane requires a blade folding system which increase the weight of the hub and hinge group. Third, it requires a convertible engine which increases both the engine installation weight as well as the amount of mission fuel required.

Propfan Trail Rotor Convertiplane- The only difference between the Propfan configuration and the baseline Trail Rotor Convertiplane is the addition of two propeller modules. The increased weight of adding the propeller modules is partially offset by a decrease in mission fuel required, however, the combination resulted in an overall increase in gross weight.

Folding Tilt Rotor- There are two weight groups which make the Folding Tilt Rotor different from some of the other concepts. First, it requires a blade folding system which increases the weight of the hub and hinge group. Second, it requires a convertible engine which increases both the engine installation weight as well as the amount of mission fuel required.

Conclusions Drawn From Trade Studies

The application of advanced technology improves all concepts by every measure. High-speed rotorcraft concepts require large propulsion systems to achieve 450 KTAS cruise. The propulsion system represents the technology area which shows the greatest potential for improving concept effectiveness. By reducing fuel required for the mission, gross weight and empty weight decrease, while economy of the concepts increases. Reduction of engine weight contributes to a lower weight empty as well. Beyond the reduction in fuel and engine weight, secondary effects cascade to result in even greater reductions. As the gross weight decreases, power required also decreases, which results in additional engine and drive train weight reductions.

Improved aerodynamics impacts concepts using proprotors as propulsive devices more than others. Maintaining high propulsive efficiencies at high speeds, significantly improves the effectiveness of these concepts. The ability to achieve this with a rotor also designed for hover may be challenging. Aerodynamics primarily affects fuel consumption, with a secondary structural weight reduction as previously described.

The trade between thick wings for stiffness and sweep for delaying drag divergence represents an extremely important technology assessment. The ability of some of the concepts to fly at more efficient, higher altitudes was severely limited by allowable sweep. Significant gains in aerodynamics must be made to reduce the sweep requirement.

A final conclusion results from the relatively low technology risk presented by the Rotor/Wing, It represents the cleanest configuration from a drag standpoint, so aerodynamic improvements may not affect it to the degree of other configurations. Power reduction impacts the concept less than the others because it does not require a drive system. For this reason, the Rotor/Wing appears less affected overall by technology improvements. While not requiring advanced technology engines, improvements in the cruise efficiency using higher bypass ratio engines may significantly improve its effectiveness. Current propulsion concepts incorporate low bypass ratio engines.

RECOMMENDATION OF CONCEPTS FOR TASK 2

Concept Ranking

Eight parameters comprise the evaluation matrix for ranking the sized concepts. Measures of effectiveness and individual vehicle attributes make up the items to be evaluated. Figure 1-39 depicts the ranking matrix.

CONCEPT / CATEGORY	ROTOR/ WING	FOLDING TILT ROTOR	TURBOFAN TRAIL ROTOR	PROPFAN TRAIL ROTOR	TILT ROTOR	TILT WING
VELOCITY LIMIT (0.83)	5	4.15	4.15	3.32	1.66	2.49
DISK LOADING (1.66)	8.35	10	10	10	10	8.35
PAYLOAD DELIVERY EFFICIENCY (3.33)	20	13.2	13.2	20	16.5	16.5
PRODUCTIVITY (3.33)	20	9.9	9.9	6.6	13.2	16.5
PAYLOAD/RANGE (3.33)	10	3.32	5	10	8.3	6.64
GROSS WEIGHT (3.33)	20	6.6	9.9	3.3	13.2	16.5
SPECIFIC RANGE (1.66)	10	1.67	3.34	8.35	5	6.68
RISK (0.83)	3.32	1.66	1.66	1.66	4.98	4.15
TOTAL	96.67	50.51	57.15	63.22	72.84	77.84
RANKING	1	6	5	4	3	2

FIGURE 1-39. CONCEPT SELECTION MATRIX FOR TASK 2

In some cases, subjective evaluations determined rankings. For instance, since 450 KTAS sized all concepts, the potential limiting speed of each candidate was based on inherent concept limitations and then relative drag values. So, the rotor-driven concepts in cruise naturally have a lower speed limitation than the folded rotor concepts. Next, the folded rotor concepts, due to higher drag, possess lower speed limits than the Rotor/Wing for equivalent available cruise power. Risk represents the other subjective evaluation area. Evidence of previous successful developmental work indicates a level of knowledge and risk associated with a concept. Flight demonstrations, wind tunnel testing to prove feasibility, and lack of required technologies contributed to rankings in this area. An example of lack of required technology, is the convertible engine required for the Folding Tilt Rotor and Trail Rotor. Compared to propulsion systems of other concepts, very little experience exists. General Electric demonstrated feasibility, but no program currently exists to develop and produce the engine. Without it, folding rotor concepts cannot fly unless a propeller is used as a propulsor. While viable, it restricts the attractiveness of folding concepts - their speed capability. The Rotor/Wing's risk ranks ahead of the folding rotor concept due solely to the availability of an engine.

Comparative rankings based on quantitative results of the trade studies comprise the other evaluated areas. Each concept was ranked according to "goodness", allowing ties. The evaluation parameters were weighted according to importance as high, medium, or low. Multipliers (in parentheses) account for the relative weight. A concept ranked best in a given category received 6 points. That value was then multiplied by the weighting factor; the result denotes the final score. One hundred points represents the maximum possible score.

The overall results of the ranking show the concepts finishing in the following order:

1. Rotor/Wing
2. Tilt Wing
3. Tilt Rotor
4. Trail Rotor w/ UDF
5. Trail Rotor
6. Folding Tilt Rotor

Selection for Task 2

MDHC recommended advancing the Rotor/Wing and the Tilt Wing for more detailed study in Task 2.

The Rotor/Wing clearly demonstrates capabilities and concept effectiveness beyond any other concept studied. This results from a cleaner cruise configuration and lighter empty weight. Due to the amount of initial concept exploration in the mid 60's, including whirl stand, wind tunnel, dynamic model conversion, and transonic tests, much is known about this configuration. The XH-17 and XV-9A technology demonstrators incorporated reaction drive rotors in their designs. The lack of required engine technology development, such as a convertible engine, makes the development risk less than any one of the folding concepts. However, desired engine development increases the utility and effectiveness of the concept. As with each of the concepts studies, the Rotor/Wing represents a level of risk associated with it and requires solutions to problems prior to production. As a vehicle to study technology needs, it provides a unique set of technologies not inherent to other concepts. Based on results of this study, the Rotor/Wing appears as a moderate risk concept with high payoff in effectiveness.

The Tilt Wing represents a proven concept. While essentially comparable to the Tilt Rotor in ranking, it potentially offers a lighter weight solution and eliminates the hover download characteristic of tilting rotor concepts. Eliminating the pitch fan using rotors instead of propellers may significantly increase handling qualities and agility in the low-speed regime. It offers a different concept than the Rotor/Wing and one which has not benefited from advanced development, as has the Tilt Rotor.

SECTION II

TECHNOLOGY EVALUATION FOR SELECTED CONCEPTS

INTRODUCTION

The results of the initial concept assessment of Task 1 indicated that the Rotor/Wing and the Tilt Wing offered the best potential for the given generic mission. Folding rotor concepts incurred additional weight and drag penalties in both flight regimes due to carrying two discrete propulsion systems. The chosen concepts provided the opportunity to assess a wide range of technologies required of these widely differing concepts. The missions assigned to the concepts included the military transport mission for the Tilt Wing and the ground attack mission for the Rotor/Wing. The choice of these missions implies suitability of the concepts for the mission. The scope of the contract prevented a detailed analysis to determine the mission best suited for each concept and therefore, mission selection required the use of engineering judgement. A more stringent mission would typically illuminate the technologies that may otherwise go unnoticed. The military missions require more time in helicopter/low speed mode than the civil missions and therefore represent a stringent mix of rotary and fixed wing requirements.

The Task 2 study highlighted the lack of analysis tools available to assess various aspects of high-speed rotorcraft configurations due to their hybrid nature. It also demonstrated lack of data bases available to correlate data from earlier similar concept model or flight tests, although much is available in a narrow design range for both of these concepts. Previous designs did not require the high-speed capability which seriously impact some elements of the configurations.

The approach to identifying technology needs examined more the impact of achieving a capability level, rather than identifying a technique to achieve it. For example, the impact of improving the high-lift capability of a wing assesses the improvement in performance of the Tilt Wing, and stresses the criticality of that technology. The means to achieve that improvement remains unimportant at this stage of study. Assessing the payoff to concept effectiveness does require estimation of the level of improvement possible, so techniques to reach these new levels are implied, but not specified.

CONCEPT SIZING

Design Criteria

Wing Loading and Disk Loading- Three basic flight regimes govern V/STOL aircraft sizing: hover, forward flight and conversion. Good hover performance requires a low disk loading and a high wing loading (for low hover download). Good Cruise performance requires a high disk loading and a high wing loading. Good conversion and reconversion performance, depending on the configuration, usually requires a low wing loading, and in the case of the Tilt Wing, a high disk loading. These criteria are usually accompanied by an operational constraint which limits hover disk loading.

The only limiting criterion placed on disk loading is a maximum allowable disk loading of 40 psf. These values have been determined to create the maximum allowable overturning moment due to rotor outwash for a tilt rotor aircraft.[5] While these values are used for this study, they may be optimistic depending on configuration and location around the aircraft. Due to the sensitivity of the constraint on the size of the vehicles, additional investigation must be accomplished to more fully define the allowable downwash limits in terms of disk loading. Conversion places an upper limit on wing loading. The conversion wing loading values for the Tilt Wing and Rotor/Wing are 90 psf and 65 psf respectively.

Aircraft Structure- Good aerodynamic performance calls for thin wing sections. However, structural criteria which determine aeroelastic properties and load-bearing capabilities limit minimum wing thickness. The load-bearing criteria used on the two aircraft differ in the missions each aircraft flies. The airplane-mode load factors, which size each aircraft, are 2.5 and 3.5 for the Tilt Wing and Rotor/Wing, respectively. The two designs satisfy the specifications in MIL-A-8860 through 8864 and 8870 Airplane Strength and Rigidity.

Mission- The specific missions influence the configuration design more than any other requirement. The military transport mission was applied to the Tilt Wing, and the ground attack mission was applied to the Rotor/Wing. The following descriptions define the two missions.

Military Transport Mission:

* Entire mission at ISA + 15° C.
* 1 minute hover OGE and takeoff at sea level at design gross weight.
* Fly to conversion mode speed and convert to cruise configuration in 1 g flight.
* Climb to cruise altitude to minimize time enroute. Full credit for range.
* Dash at 450 kts. To a radius of 350 n.mi.
* Descend at V_{dive} with no credit for range.
* Convert to hover mode in 1 g flight.
* 15 minute hover OGE at sea level.
* 30 minute loiter at V_{end} in best configuration for loiter.
* Convert and climb to altitude for best range taking credit for range.
* Cruise at $V_{.99}$ max NMPP 350 n.mi. To home base.

* Descend with no credit for range.
* 1 minute hover OGE at sea level.
* Land with 10% fuel reserve.

Ground Attack Mission:

* Entire Mission at 4000 ft., 95° F.
* 1 minute hover OGE and takeoff.
* Fly to conversion speed and convert to cruise at 1 g.
* Cruise out 150 n. mi. at $V_{.99}$.
* Dash 50 n. mi. at 400 kts. TAS. and at IRP.
* Convert to hover mode.
* NOE maneuver including 15 minute hover OGE and 15 minutes at 40 kts.
* Attack targets at IRP for 5 minutes without expenditure of external payload.
* Convert to cruise mode.

Table 2-1 depicts the amount of mission-dependent weight as specified by the statement of work (all values are in lbs.):

Weight in lbs

Weight	Tilt Wing	Rotor/Wing
Payload	6000	3000
Airframe Equipment (not including controls)	3000	200
Mission Equipment (Core avionics & defensive; tactical incl. fire control and visionics)	1500	2000
Armor	400	400
Mission Kit	1000	500
Crew	470	470

TABLE 2-1. MISSION WEIGHT REQUIREMENTS

Control power requirements in hover conform to the Level 1 guidelines of MIL-F-83300 (Flying Qualities of Piloted V/STOL Aircraft). Both the Tilt Wing and Rotor/Wing possess a 1.25g capability in hover (including download). The handling qualities are accounted for conceptually by looking at previous Tilt Wing aircraft and dynamically scaled wind tunnel tests of the Rotor/Wing concept. This allows consideration of adequate handling qualities through the use of aircraft geometries similar to those of previous designs. Tail volume coefficients based on the CL-84, XC-142, for example, will be used to size the empennage of the Tilt Wing. This approach provides a rough idea at what the handling qualities will be, based on those of the aircraft previously flown and tested.

Assumptions

In order to ensure accurate designs, there are certain design boundaries within which the configurations must operate in that are not described in the statement of work design criteria. The following represents a discussion and justification of the assumptions made with each configuration.

Tilt Wing- Three successful Tilt Wing designs provided information useful in the design of a high-speed Tilt Wing. This information forms the basis of assumptions made in the current design effort.

Wing: Conversion wing loading is the single most important factor in the Tilt Wing sizing process. The results of a conversion study indicate that a wing loading to disk loading ratio of 2.57 provides adequate conversion capabilities for a wing with full-span double-slotted fowler flaps and leading edge slats.

Wing thickness to chord (t/c) ratio is another large factor driving Tilt Wing sizing. A wing t/c ratio of 18% was chosen, after a simple analysis, to satisfy the structural and aeroelastic criteria stated above, while maintaining fairly good cruise efficiency. This choice is supported by the XC-142 and the CL-84 Tilt Wing designs which used 18% thick wings.

Drag: There were several assumptions made affecting aircraft performance, the most significant having to do with the calculation of aircraft drag. A standard drag buildup was completed on all of the aircraft components, including sponsons, using skin friction coefficients based on Reynold's number and roughness. Additional fuselage drag due to aft fuselage upsweep was computed using an empirical method developed by Douglas Aircraft. The wing airfoil section used represents a state-of-the-art supercritical section developed under the Navy Medium-Speed V/STOL Program. Wind Tunnel Test results provided the necessary drag data.[15] The sum of all component drag was then incremented by 10% to account for interference and protuberance drag.

VASCOMP II[19] calculated Oswald efficiency factor for the Tilt Wing. Analysis from Douglas Aircraft's DACPROP then determined the decrement in Oswald efficiency factor due to up-at-wingtip propeller rotation.

Propulsion: The assumptions regarding propulsion were selected using well-documented production codes from both Allison (T406 engine) and Douglas Aircraft (prop/rotor performance). Allison's customer T406 engine deck was reduced to VASCOMP II format, and assumed scalable within small ratios. The assumption of scalability appeared valid after final sizing showed the required engine horsepower to be 6411 HP, which is very close to the 6000 HP T406 deck which was used to generate the VASCOMP II engine data. Douglas provided rotor performance in hover and cruise which were implemented in the form of Figure of Merit (0.857 SL Std.) and cruise efficiency (0.790 15,000 ft ISA + 15°). The code used to generate these efficiencies has been validated against V-22 prop/rotor performance, and shows good agreement. The rotor was sized to a sea level ISA + 15° C C_T/σ of .149 which allows for a 1.2 g hover maneuver margin.

A tip speed of 750 fps was chosen at the start of the Task II study, in lieu of a detailed prop/rotor analysis. Subsequent analyses show that a tip speed of 810 fps may increase cruise efficiency and/or increase hover maneuvering capability by reducing rotor solidity for the same C_T/σ. Future high-speed Tilt Wing studies will require trade studies between hover efficiency, hover maneuverability and cruise efficiency.

Empennage: The empennage was sized using existing tail volume coefficients. Initially, a static stability analysis sized the empennage, but results from that analysis produced tail volume coefficients that were much smaller than previously designed Tilt Wings. After some additional research, it was found that low speed and transitional flight sizes the empennage. Thus, the highest tail volume coefficients typical of the CL-84 and the XC-142 were used. They are 1.10 for the horizontal stabilizer and 0.12 for the vertical stabilizer. The horizontal stabilizer uses a NACA 0015 airfoil with an aspect ratio of 4.0, and the vertical stabilizer uses a NACA 0012 airfoil with an aspect ratio of 1.5.

Rotor/Wing- The assumptions made in the design of the Rotor/Wing are supported by extensive studies completed from 1963 to 1969 by Hughes Tool Company on the Rotor/Wing concept. Detailed wind tunnel studies were used to aid in performance estimation along with dynamically-scaled wind tunnel investigations which completed a full transition from helicopter to fixed-wing flight. Analysis also relied on extensive data and methodology relating to reaction drive rotor systems, derived from the XV-9A and the XH-17 research helicopters. Both of these aircraft flew reaction drive rotor systems similar to the Rotor/Wing's in the 1960's.

Wing: The Rotor/Wing configuration has two constraints which determine wing size, the first and more critical being conversion wing loading. Since the centerbody carries all of the lift during conversion, its area must be large enough to carry the Rotor/Wing at 170 kts. This ensures that the rotor carries no load while it stops. Wind tunnel tests of the triangular centerbody demonstrated a lift-curve slope of 0.04/deg. Constraining the attitude of the aircraft to 15 deg. nose-up, further defines the conversion wing loading.

The second factor driving wing loading is rotor blade size. Since the Rotor/Wing must hover, there has to be enough blade area to keep the rotor unstalled. This area decreases the cruise wing loading because two blades and the centerbody comprise the wing.

The root cutout due to the large centerbody makes the ratio of C_T/σ unusable as an indicator of rotor stall. Because of this, a simple strip analysis was used to estimate average C_l as a function of rotor solidity and root cutout. LSAF[20] confirms good hover performance of this rotor, while CAMRAD JA[21] confirms adequate helicopter and autogyro performance.

Drag: The drag buildup for the Rotor/Wing is essentially the same as the Tilt Wing. Extensive data from the 1960's Rotor/Wing wind tunnel tests for both autogyro and fixed-wing flight provided comparative values. The current design achieves L/D ratios approximately 10% greater than the 1960's investigations. The smaller fuselage and the lack of a blade fairing on top of the front part of the fuselage account for this difference. The L/D ratios for autogyro mode obtained with CAMRAD JA analysis correlate well with wind tunnel tests. A 20% thick elliptical airfoil was used for the wing sections at the root. The wing taper and gas ducting determine how the wing thickness is reduced along the span.

Oswald efficiency factor obtained from the 1960's wind tunnel tests help determine induced drag. Since the combination of wing aspect ratio and Oswald efficiency factor determines drag, careful consideration was taken to ensure that aspect ratio, specifically wing area, is defined the same way as in the 1960's analyses. A value of 0.75 for Oswald efficiency factor was assumed.

Propulsion: The Rotor/Wing uses a common propulsion system in all flight modes. For this study, the Pratt & Whitney STF842 turbofan engine is used. Satisfying the gas generator requirement in hover, and the thruster role in autogyro mode and cruise meant selecting a low by-pass ratio. Since these engines are advanced technology engines, the data was converted to current technology using the IHPTET design criteria used in the development engines.

Relations developed in the XV-9A and XH-17 programs determine the total pressure losses from the engine exit to the rotor tip. These losses, coupled with the rotor blade element analysis dictate the engine size.

Empennage: The vertical tail for the Rotor/Wing is sized by the tail volume coefficient determined from the dynamic model tests in the 1960's. The value for this coefficient is 0.137.

The horizontal tail volume coefficient determined by the 1960's tests could not be used, however, because the present design stops the wing with two blades in forward. This creates a forward-swept wing which moves the aerodynamic center of the wing forward. This forward location sizes the horizontal stabilizer for static stability, making it larger than normal.

This dictates a larger horizontal tail which appears to be a reasonable trade off because of several factors. The horizontal stabilizer needs to be slightly oversized for roll control in fixed-wing flight. Also, stopping the rotor forward allows for a shorter fuselage without the need for a blade fairing above the canopy, thus reducing drag. This brings the pilot closer to the rotor shaft improving sensed handling qualities in helicopter and autogyro flight modes.

Weight Estimation Methodology: The baseline weight estimation methodology used for Task 2 is identical to that of Task 1. A discussion of this methodology was previously described in Section I.

Payload, fixed equipment and operating items weights were specified in the proposal. In Task 2 these weight groups varied between configurations due to the different mission scenarios. The Tilt Wing configuration was sized using the weights specified for the military transport mission. The Rotor/Wing configuration was sized using the weights specified for the military attack mission.

A trade-off study was performed to evaluate the weight difference between two engines with cross-shafting versus four engines (two per rotor) without cross-shafting. The analysis considered the weight of the engine installation, gearboxes, and drive shafts. In this particular case, there appears to be some degree of weight savings in going to a non-cross-shafted configuration. Due to a lack of details resulting from the scope of this study, the best estimate of weight savings can only be generalized as a range between 500 and 1000 pounds.

Due to the unique drive system configuration used in the Tilt Wing concept, another means was used to check out the sensitivity of the drive system weight estimation methodology. Sufficient data was available from the drive system schematic drawing, shown in Figure 2-26, to allow an off-line weight analysis on a per item basis. Comparison of the per item weight estimate to the parametric resulted in only a slight difference (+5%) in the total drive system weight. This comparison helped to validate the sensitivity and improve the level of user confidence in the drive system weight estimation methodology.

Sizing

The sizing process for both the Tilt Wing and the Rotor/Wing was a highly iterative process. Even with the assumptions made above, many off-line iterations on each design ensured reaching the optimum design for each mission. VASCOMP II (V/STOL Aircraft Sizing and Computer Program) sized the Tilt Wing using cruise propulsive efficiencies provided from Douglas Aircraft Company (DAC).

A reaction drive rotor code developed by MDHC sized the Rotor/Wing. This code combines reaction drive rotor analyses developed for the XV-9A and XH-17 programs, current MDHC weight methodology, a blade element rotor analysis, and the ground attack mission.

Tilt Wing- Initially, the entire military transport mission segments were input along with the assumptions stated above.

The aircraft cruises at optimum altitude. Cruise efficiency, determined by wing drag and propeller performance, depends on the cruise altitude. For this reason initial estimates of 10,000 ft for cruise altitude, and a wing aspect ratio of 8 were chosen, based on results from Task 1. This initial assumption provided DAC with the necessary information needed for the 'first cut' prop/rotor design.

Additional sizing criteria were used to size the Tilt Wing as follows:

1. The transmission highest power requirement sized the transmission (climb with low tip speed).

2. Engine sizing ensured that the aircraft could hover with one engine out (both rotors still powered) using a 125% contingency factor.

3. Inboard-tip-down propeller rotation decremented Oswald efficiency factor by 0.2.

4. Flight Reynolds number, along with an incompressible wing airfoil lift and drag table, determine wing profile drag.

5. Tests at the Boeing Transonic Wind Tunnel in Seattle provided compressibility drag correction tables.

6. VASCOMP II allowed additional sizing for other mission-dependent criteria, such as crew accommodations, etc.

Mission criteria, assumptions, and additional sizing constraints, with an assumed cruise altitude, complete the sizing matrix. The design point lies in the unconstrained region.

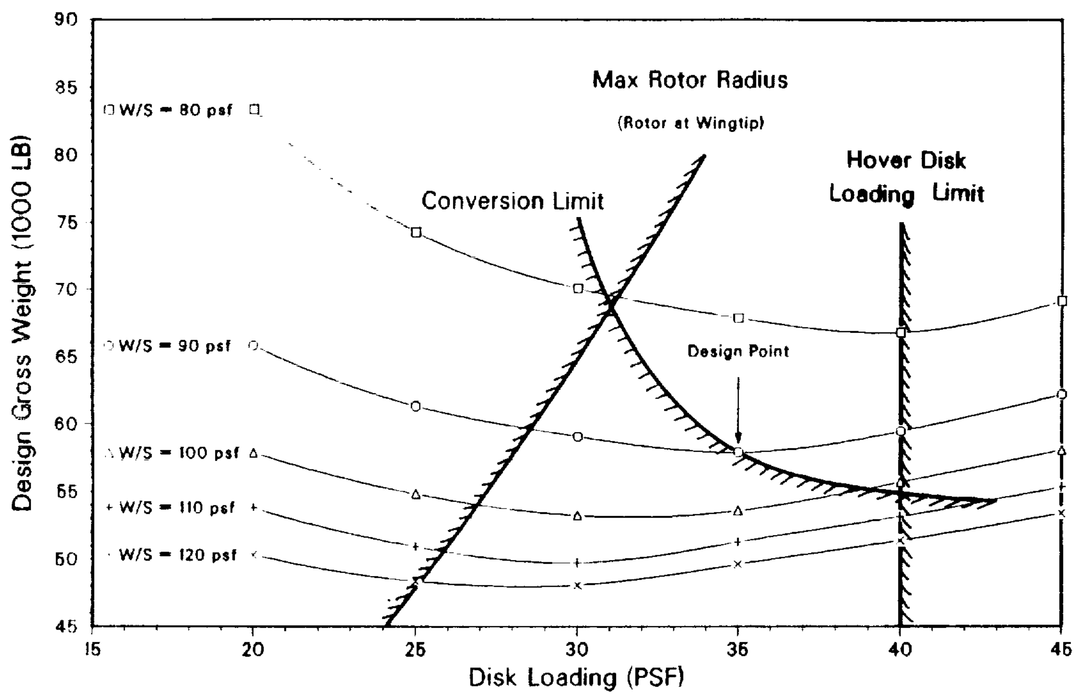


FIGURE 2-1. TILT WING PARAMETRIC SIZING MATRIX

Figure 2-1 shows the results of the sizing exercise. The plot shows design gross weight as a function of disk loading, for five different wing loadings. A Tilt Wing reconversion study provided a wing loading constraint for a given disk loading. Instead of using a fixed chord to diameter ratio as in Task 1, a matrix of points was investigated, varying several parameters. A concurrent conversion sensitivity study determined the conversion boundary on the sizing matrix. This constraint ensures reconversion with at least 8 degrees descent angle at all airspeeds. Two additional boundaries appear in this figure. The first, a maximum rotor radius boundary, places the rotor hub at the wing tip with rotor-fuselage clearance of one foot. Increasing the wing area with the same disk loading results in a portion of the wing outside the rotor slipstream: an unacceptable configuration for a Tilt Wing. The second is based on the maximum disk loading boundary determined by Wernicke[5] to result in overturning moments in ground effect.

Wernicke presents a relationship for the allowable disk loading for a twin rotor helicopter versus gross weight. This shows up on Figure 2-1 as a curve, but far to the right of the design point. For this reason, a disk loading limit of 40 psf was chosen, based on previous twin rotor Tilt Wing Designs. It should be noted that this relationship is presented in reference 5 to be optimistic.

Initial assumptions envisioned the Tilt Wing with two rotors and two engines. A sensitivity study showed no weight advantages with four rotors, but four engines, two for each rotor, and no cross shafting saves about 1800 lbs. While this required the Tilt Wing to hover on two engines, one out in each nacelle, it did not increase the engine size since the cruise requirement of 450 kts still sizes the engines in this case. Thus, it can be concluded that cross-shafting in a Tilt Wing configuration may not be necessary with a demanding high-speed cruise mission. Note that the design point is not optimum. Figure 2-1 shows that a disk loading of 35 psf, which provides a lower downwash and increased hover efficiency, can be achieved for a small penalty in gross weight.

The Tilt Wing sizing process produces a four engine, two rotor aircraft with final sizing parameters shown in Table 2-2:

Gross Weight	57,881 lbs
Max Sea Level Power	25,645 HP, SL STD
Disk Loading	35 psf
Wing Loading	90 psf
Aspect Ratio	7
Hover Tip Speed	750 fps
Cruise Tip Speed	382 fps
Cruise Prop Efficiency	0.79
Flat Plate Drag	18.17
Maximum L/D	10.98
Cruise SFC	0.438
Optimum Dash Altitude	15,000 ft
Optimum Best Range Alt	20,000 ft

TABLE 2-2. CURRENT TECHNOLOGY TILT WING DESIGN PARAMETERS

Additional Tilt Wing information is presented in Appendix B.

Rotor/Wing- Unlike VASCOMP II, the Rotor/Wing code uses the ground attack mission as a separate subroutine. The Rotor/Wing flies the entire mission at 4000 ft 95°. Since optimum altitude does not affect the solution, the iterative process for the Rotor/Wing was less involved than the Tilt Wing.

Unlike the Tilt Wing, no hover Figure of Merit is assumed initially because a blade element analysis determines hover performance. The cruise efficiencies do have to be assumed, however. The required thrust along with the flight conditions then determine sfc using the engine data tables.

The Rotor/Wing uses many of the same sizing constraints as the Tilt Wing:

1. There are no transmission sizing requirements.

2. Engine sizing ensured that the aircraft could hover with one engine out using a 125% contingency factor.

3. All wing drag comes from skin friction coefficients and form factors. A drag coefficient increment of 0.023 is added during cruise at 400 kts for compressibility drag.

4. Various other provisions within the code account for mission-dependent criteria such as crew accommodations, etc.

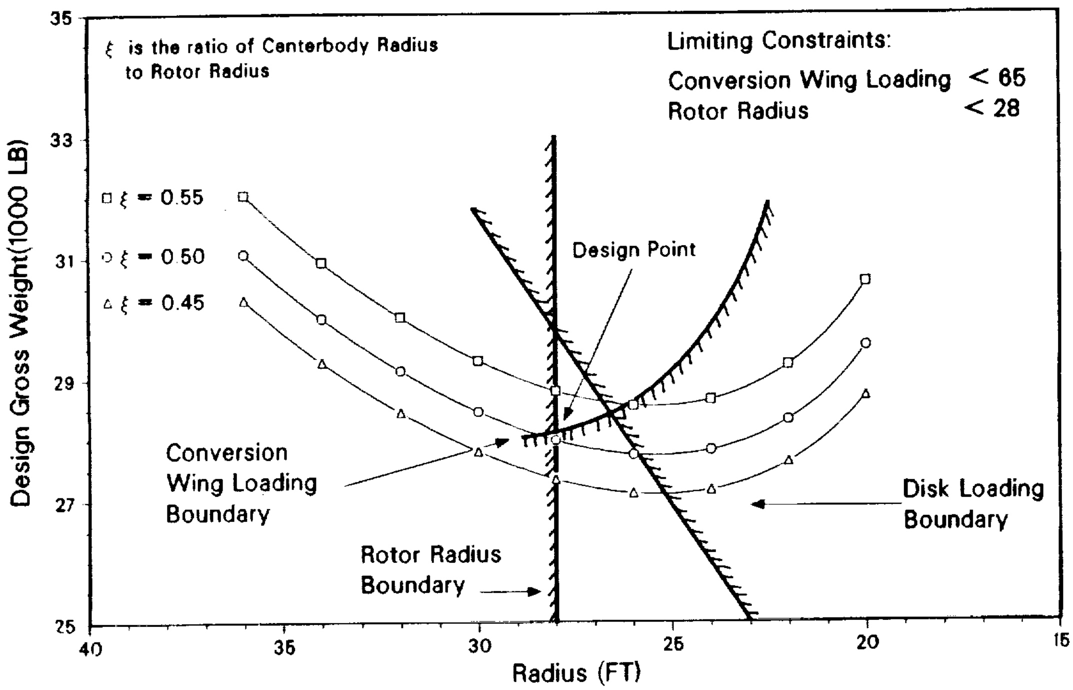


FIGURE 2-2. ROTOR/WING PAMETRIC SIZING MATRIX

For the Rotor/Wing, power required does not equal power available from the engines due to the relative inefficiencies of the reaction drive system. This inefficiency occurs due to friction and heat loses fond in the duct system which tends to require more energy from the gas generator than its shaft driven counter part. The engine is sized, accounting for these losses, based on data available from the XV-9A hot cycle helicopter program. Losses from the engine exit to the blade duct are assumed to be the same as the XV-9A. The blade duct is subdivided into three sections to allow for geometry variations and the losses for each section are computed based on the flow information at the beginning of each section. The tip nozzle efficiency is also assumed similar to the XV-9A. The exit Mach number of the flow is constrained to below sonic conditions and mass flow then matches power available from the exit conditions to that required by the rotor. Since the internal duct size influences the chord size of the blade, for a specified t/c ratio, the sizing process is iterative.

Initial guesses at the gross weight, optimum disk loading, centerbody area, and rotor thickness determine rotor size and performance. The rotor thickness at the root is sized by the amount of mass flow needed at the tip, which is determined by the rotor power required. The blade thickness, rotor radius and tip speed determine average blade lift coefficient. If the lift coefficient is too high (indicating rotor stall), new rotor geometry is needed to keep the rotor unstalled. Because rotor clearance of the vertical tail limits the rotor radius, root t/c controls average blade lift coefficient. Limiting the maximum t/c to 20% produces an optimum rotor tip speed of 650 fps.

Figure 2-2 shows the sizing matrix with the appropriate constraints. Rotor radius and the ratio of centerbody radius, ξ to rotor radius are the dependent parameters which drive the solution. The first represents disk loading, and the second, conversion wing loading. The conversion wing loading of 65 psf occurs at a conversion speed of 170 KTAS and a maximum pitch up attitude of 15°. If ξ becomes to small, the centerbody wing loading exceeds that allowable for conversion. The value is not constant, as a larger rotor radius allows smaller values of ξ without exceeding the conversion wing loading limit. The maximum rotor radius represents a "soft" boundary, as it serves as the maximum allowable radius to avoid striking the vertical tail.

The plot shows a rotor radius boundary of 28 ft (for adequate empennage clearance), a conversion wing loading boundary of 65 psf, and the disk loading boundary which results in overturning moments, in ground effect, for a single rotor.[5] Figure 2-2 shows the optimum solution which satisfies all of the operational constraints. The lowest gross weight solution in this case corresponds to the lowest disk loading, unlike the Tilt Wing. Therefore, no benefit in moving from the design point was perceived. Reoptimization of tip speed revealed no change.

Gross Weight	28,122 lbs
Maximum Sea Level Thrust	12,398 lbs
Rotor Figure of Merit	0.844 (defined as P_{ind}/P_{tot})
Rotor Radius	28.00 ft
Centerbody Radius	14.25 ft
Disk Loading	11.83
Wing Loading	51.98
Aspect Ratio	4.62
Hover Tip Speed	650 fps
Flat Plate Drag	12.34
Maximum L/D	10.92
Cruise TSFC	0.83

TABLE 2-3. CURRENT TECHNOLOGY ROTOR/WING DESIGN PARAMETERS

Table 2-3 shows the aircraft parameters produced by the final Rotor/Wing sizing. Additional Rotor/Wing information is presented in Appendix B.

Concept Weights Summary- A group weight breakdown in a format similar to Mil-Std-1374A Part I can be found Tables 2-4 and 2-5 for the Tilt Wing and Rotor/Wing respectively.

Weight in lbs

		CURRENT	XC-142A	CL-84
GROUP	TILT WING	%GW	%GW	%GW
WING	4431	7.7	6.6	6.9
MAIN ROTOR BLADES	1479	2.6	****	****
M/R HUB & HINGE	2262	3.9	****	****
TAIL ROTOR	****	0.0	0.8	0.5
HORIZONTAL TAIL	1010	1.7	1.6	1.7
VERTICAL TAIL	466	0.8	0.7	1.2
BODY GROUP	4594	7.9	12.9	12.1
ALIGHTING GEAR	1595	2.8	3.2	3.7
NACELLES	1409	2.4	2.9	2.6
(*STRUCTURAL GROUP*)	(17246)	(29.8)	(28.5)	(28.7)
ENGINE	4049	7.0	7.1	10.0
PROPELLER INSTL.	****	0.0	4.0	6.7
PROPULSION SUBSYS	954	1.6	1.4	2.4
FUEL SYSTEM	744	1.3	1.2	1.6
DRIVE SYSTEM & TILT	6759	11.7	7.1	7.9
FLIGHT CONTROLS	3646	6.3	6.8	3.9
(*SYSTEMS GROUP*)	(16152)	(27.9)	(27.7)	(32.5)
FIXED WEIGHT	4900	8.5	8.0	7.1
EMPTY WEIGHT	38298	66.2	64.2	68.3
PAYLOAD	6000	10.4	19.4	13.4
OPERATING ITEMS	1470	2.5	2.0	3.2
FUEL	12113	20.9	14.4	15.1
GROSS WEIGHT	57881	100%	100%	100%

TABLE 2-4. TILT WING WEIGHT BREAKDOWN

To support the validity of the parametric weight analysis, and to serve as a sanity check, the structural and system group weights of the configurations were compared on a percent gross weight basis to vehicles of similar design in Table 2-4. Comparison of the current Tilt Wing configuration to both the XC-142A and CL-84 resulted in significant percent gross weight differences in the areas of the body group and drive system. The decrease in percent body group can be explained by the configuration geometry while the increase in percent drive system is explainable due to the unique configuration and two-speed requirements. The 1960's Rotor/Wing serves as the only vehicle similar to the current Rotor/Wing for comparison. Allowing for vehicle geometry differences and overall evolution of the design, Table 2-5 shows no significant percent gross weight differences.

Weight in lbs

		CURRENT	1966 RW
GROUP	ROTOR/WING	%GW	%GW
WING	3570	12.7	14.0
MAIN ROTOR BLADES	****	0.0	0.0
M/R HUB & HINGE	****	0.0	0.0
TAIL ROTOR	****	0.0	0.0
HORIZONTAL TAIL	882	3.1	1.9
VERTICAL TAIL	356	1.3	1.7
BODY GROUP	2443	8.7	10.7
ALIGHTING GEAR	1066	3.8	3.1
NACELLES	526	1.9	1.2
(*STRUCTURAL GROUP*)	(8759)	(31.4)	(32.6)
ENGINE	1841	6.5	10.8
PROPELLER INSTL.	****	0.0	0.0
PROPULSION SUBSYS	638	2.3	2.5
FUEL SYSTEM	454	1.6	1.3
DRIVE SYSTEM & TILT	0	0.0	3.4
FLIGHT CONTROLS	1578	5.6	3.7
(*SYSTEMS GROUP*)	(4511)	(16.0)	(21.7)
FIXED WEIGHT	3000	10.7	12.7
EMPTY WEIGHT	16354	58.2	67.0
PAYLOAD	3000	10.7	15.3
OPERATING ITEMS	970	3.4	2.3
FUEL	7798	27.7	15.4
GROSS WEIGHT	28122	100%	100%

TABLE 2-5. ROTOR/WING WEIGHT BREAKDOWN

Determination of Vehicle's C.G. and Inertia- With inboard profile drawings it was possible to estimate the vehicle's C.G. and roll, pitch, and yaw inertias. The analysis was performed at the group weight level where the group mass was considered acting as a point load. In the case of weight groups which were distributed throughout the vehicle such as the body group, a simple integration method based on volume was used to obtain an approximate center of the mass. This analysis was conducted for both the hover and cruise conditions of both vehicles.

Tilt Wing: Translation of the vehicle C.G. from hover to cruise is influenced by the composite shift of the following items:

1) Wing, Rotor Group, Nacelles, Engine Installation, Fuel System, Drive system, Flight Controls, and Wing Fuel all shift longitudinally forward and vertically downward.

2) The Landing Gear shifts longitudinally aft and vertically upward.

Rotor/Wing: Due to its unique configuration, the translation of the vehicle C.G. from hover to cruise is influenced by only one item. The landing gear shifts longitudinally aft and vertically upward. This minimal shift in C.G. results in inertia values which are almost identical for hover and cruise.

The resulting inertia values show that the roll and pitch inertias are more sensitive in hover than in cruise as shown in Table 2-6.

Configuration	Gross Weight (lbs)	X (in)	Y (in)	Z (in)	Ixx	Iyy	Izz
					(Slug Feet Squared)		
Tilt Wing (Hover)	57,881	314.8	0.0	126.0	39,912	123,217	83,304
Tilt Wing (Cruise)	57,881	295.6	0.0	87.7	5,235	91,237	86,001
Rotor/Wing (Hover)	28,122	323.2	0.0	87.6	6,895	61,111	54,215
Rotor/Wing (Cruise)	28,122	324.0	0.0	88.9	6,133	60,199	54,066

TABLE 2-6. CONCEPT WEIGHTS AND INERTIAS

Aircraft Description

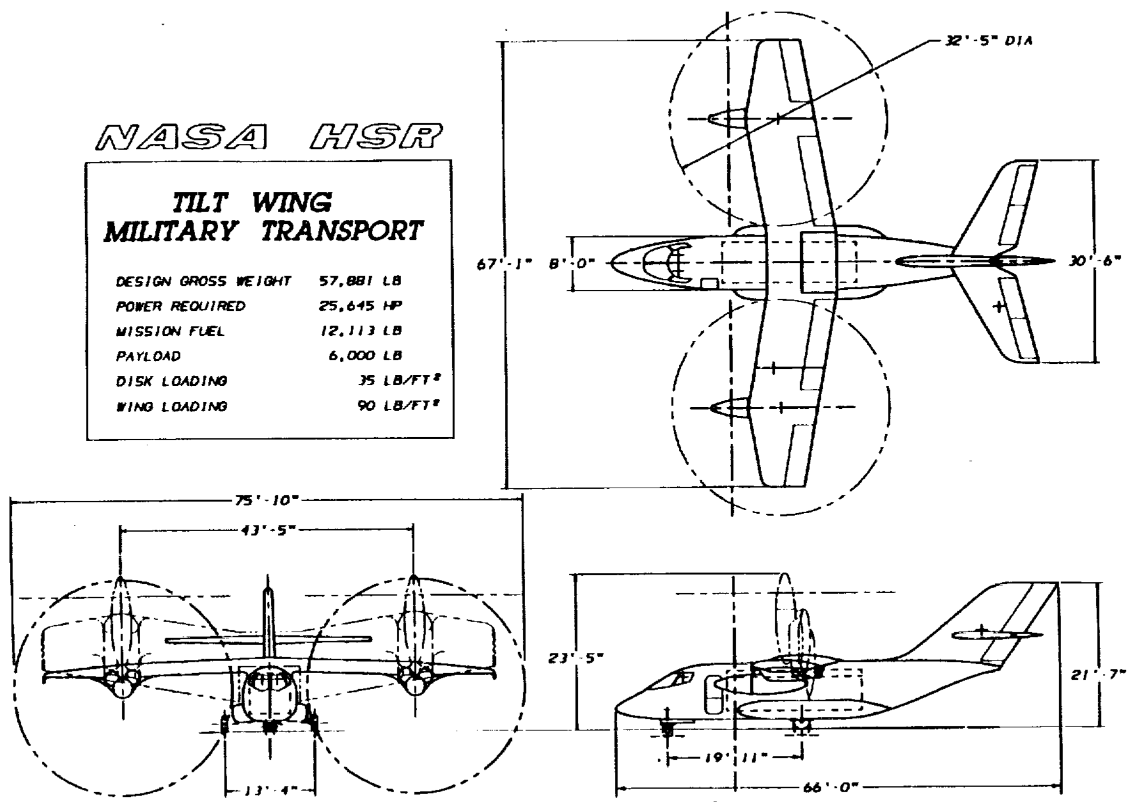


FIGURE 2-3. TILT WING MILITARY TRANSPORT

Tilt Wing General Description- The Tilt Wing is configured as a military transport, and is shown in Figure 2-3. As in conventional tilt wings, the wing tilts upward to a vertical position for low-speed or vertical flight; for high-speed flight the wing tilts to the standard horizontal position. However, this Tilt Wing uses rotors rather than propellers with beta controls; the control provided by the rotors eliminates the need for a pitch fan.

The fuselage for the current Tilt Wing is sized for a 6x6x20 foot cargo bay. The crew station is a two place, side-by-side type with duplicate controls for both. The mission equipment package (MEP) resides behind the right crew station, forward of the cargo bay, with a volume corresponding to the 1500 pound requirement, and is stacked in a five tier arrangement for easy access. Opposite the MEP is the flight crew access door; aft of the cargo bay are the cargo bay doors and ramp. The cargo bay access is configured similar to a C-130 and has the same height (6 foot) as the cargo bay itself. Sponsons on the lower fuselage house the main landing gear, while the nose landing gear is located beneath the crew stations. Fuel cells are fore and aft of the main landing gear in both sponsons. Additionally, two fuel cells are located in the wing.

The high aspect ratio wing consists of ten degrees of forward sweep inboard of the rotor pylons, and ten degrees aft sweep outboard. The wing sweep allows clearance for rotor flapping, and provides some reduction of the effective Mach number on the wing. The high mounted wing has two degrees of anhedral for enhanced maneuverability. Downturned Hoerner wingtips (similar to the A-10) aid in reducing the induced drag. Trailing edge slotted flaperons extend from seventy percent chord to the trailing edge. The wing tilts about a conversion hinge located at fifty percent chord in the local area above the fuselage. Hinging at fifty percent chord reduces the inertia of the tilting wing (versus hinging further aft), hence transmitting reduced loads through the hinge and conversion actuators. Additionally, a minimum of fifty percent chord is considered necessary for the wing torque box carry-through structure. The local wing structure aft of the hinge and directly above the fuselage remains fixed during conversion. Two conversion actuators are provided for redundancy.

The rotor system consists of two five-bladed rotors, with the rotor pylon underslung below the wing. This offset maintains the center of gravity below the center of lift in both flight modes. Additionally, the underslung pylon aids in preserving the wing's flow attachment for improved conversion characteristics. Each rotor is powered by two turboshaft engines, with no cross shafting between the two rotor systems. Each engine provides all of the required power to it's rotor, should the other engine become inoperative (OEI).

The empennage consists of a singular vertical fin with a horizontal tail mounted conventionally. The rudder runs nearly the full span of the fin, with the horizontal tail being notched at the trailing edge to allow full rudder movement. Each half of the horizontal tail has inboard and outboard ailerons.

Rotor/Wing General Description- The Rotor/Wing consists of a Warm Cycle rotor with a large triangular hub and three short-span, wide-chord blades. For vertical and low speed flight, the rotor is powered by reaction driven tip jets, fed by exhaust from the turbofan engines. The rotor autorotates during conversion, and stops to become a swept forward fixed wing for cruise and high-speed flight. For simplicity, use of blunt leading and trailing edge airfoils, and a feathering hinge eliminates the need for circulation control. The Rotor/Wing, shown in Figure 2-4, is configured for the ground attack role. Provisions were made for mounting two AGM-65 Maverick missiles on the lower outboard fuselage (one per side), and include a 20 millimeter gun internally mounted.

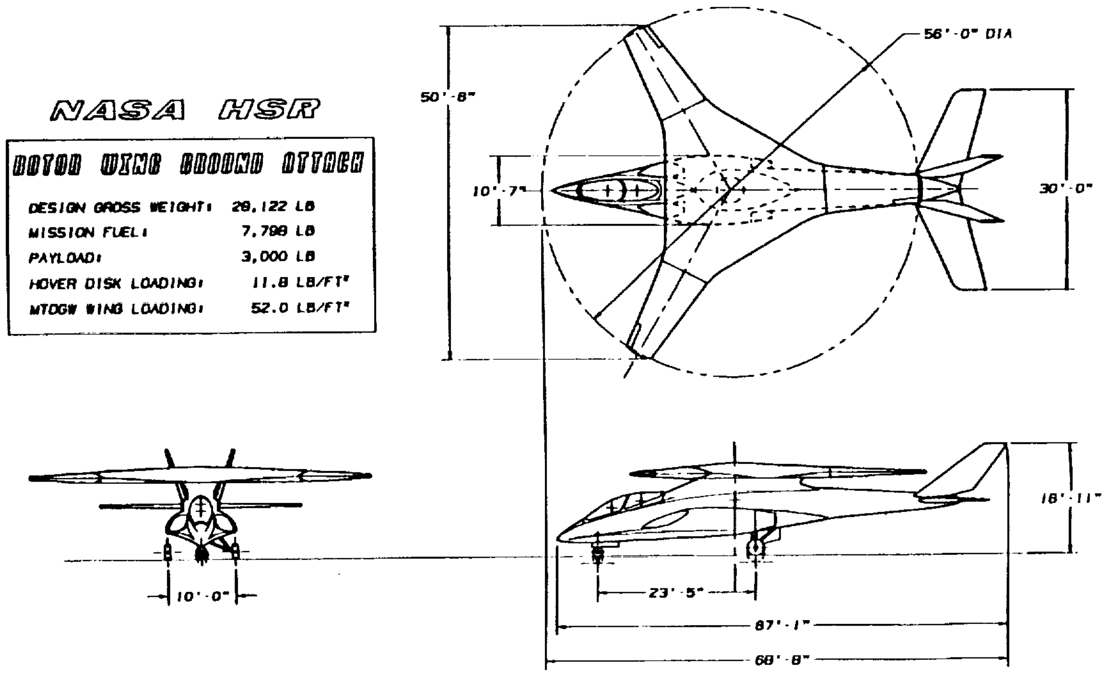


FIGURE 2-4. ROTOR/WING GROUND ATTACK AIRCRAFT

The forward fuselage is sized to accommodate tandem crew stations. Duplicate controls are provided for both stations. The forward fuel cell resides behind the aft crew station; the aft fuselage houses another fuel cell to balance the fuel around the center of gravity. The mission equipment package (MEP) is located above the forward fuel cell. It is stacked in a two tier arrangement and extends to the aft fuel cell, occupying a volume corresponding to the 2000 pound requirement. The 20 millimeter gun lies directly below the forward fuel cell, and the ammunition canister lies to the right of the gun. Outboard of the central fuselage are the turbofan engines (one per side). The engine support structure begins with the inlet just outboard of the aft crew station, and extends to the exhaust nozzle located outboard of the main landing gear. All landing gear is stowed internally, with the nose landing gear housed below the forward crew station.

The rotor/wing is rigidly mounted on the fuselage through bearings that allow only rotational motion, and the blades are similarly mounted to the wing section, allowing only pitching motion. This arrangement provides efficient support of the short, stiff blades, while avoiding the excessive weight and complexity associated with stopping a conventional rotor in flight. The center body also serves as an excellent aerodynamic fairing for the rotor hub, thus providing the aerodynamic cleanliness required for efficient high speed flight. The rotor blades are of elliptical cross section with the thickness to chord ratio (t/c max = 0.2) being the minimum required to house the required reaction drive duct.

The Warm Cycle system that powers the Rotor-Wing provides the simplest possible propulsion system for aircraft with both rotary- and fixed-wing operation. The propulsion system utilizes two standard low bypass ratio turbofan engines (bypass ratio = 1.0). In helicopter mode, the high energy exhaust gases are directed by light-weight ducting to the rotor blade tips, which then propel the rotor in the direction of rotation. During conversion and fixed-wing operation, a diverter valve redirects the exhaust aft, thus providing conventional thrust.

The empennage consists of two vertical fins and a standard horizontal tail. Each of the vertical fins are canted 18 degrees outboard, and are equipped with a rudder. Additionally, a small exhaust nozzle is provided in the lower aft empennage to provide directional control.

Conversion

Conversion of any high-speed rotorcraft concept invariably generates more concern than any other aspect of the flight regime. The specific problems differ between the Tilt Wing and the Rotor/Wing, but equal treatment is given to the conversion of each concept.

$$\alpha_{ind} = \alpha_w - \alpha_{eff} = \tan^{-1}\left\{\frac{w \sin\alpha_w}{V + w\cos\alpha_w}\right\}$$

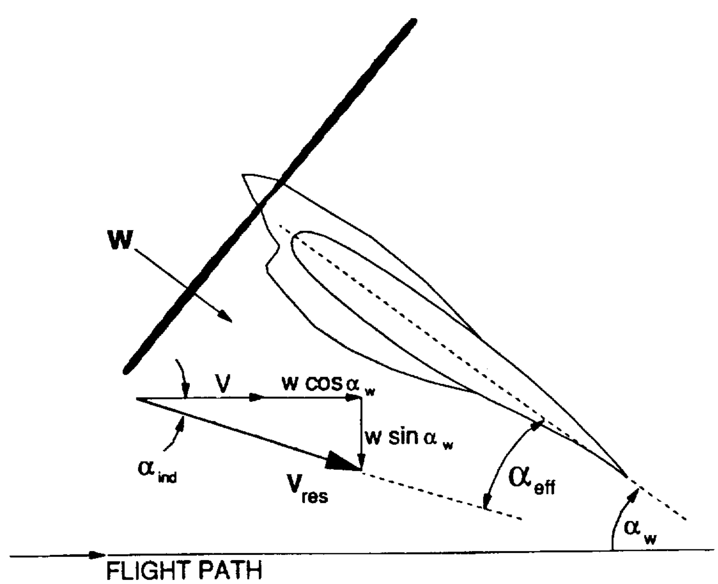


FIGURE 2-5. VELOCITY DIAGRAM DESCRIBING TILT WING CONVERSION

Tilt Wing- Transition from helicopter to airplane mode (conversion) normally occurs while climbing, where transition from airplane to helicopter mode (reconversion) will often occur while descending. Since descending flight requires less thrust, and downwash from the rotors keeps the wing from stalling, reconversion while descending establishes the wing-rotor relationship.

As the wing rotates, it experiences angles of attack from 0 to 90 deg if isolated from the rotors. The downwash from the rotors provides the only means by which the wing remains unstalled. Suppose that Figure 2-5 shows the wing at an incidence angle that is greater than the stall angle of the wing. The rotor slipstream induces a velocity tangent to the wing which depends on disk loading, free stream velocity and rotor angle of attack (assumed equal to the wing incidence angle). Figure 2-5 shows the velocity diagram at the wing with the governing equation which describes the induced angle at the wing in terms of rotor induced velocity, wing incidence and freestream velocity.

For the wing to remain unstalled, the induced angle must at least be equal to the difference between the wing incidence and the wing stall angle.

Examination of the equation in Figure 2-5 shows that for a given wing angle only two approaches can generate the required induced angle at the wing. They are: an increase in the rotor downwash, either by an increase in thrust or disk loading, and/or decreasing the freestream velocity. Notice that c/D, the ratio of wing chord to rotor diameter, appears nowhere in the equation, and therefore, by itself, represents no inherent limit. Notice also that the downwash velocity appears in both the numerator and the denominator, while the freestream velocity appears only in the denominator.

The dilemma becomes apparent when considering hovering flight. The preferred low disk loading rotor induces smaller velocities at the wing which adversely affects conversion. However, using high-lift devices on the wing enables a reduction in stall speed (free stream velocity) and adds induced drag which requires an increase in thrust (hence induced velocity) to overcome. The idea of using high-lift devices to increase descent capabilities has been substantiated by experimental investigations.[12,22] As a result of some preliminary analyses, an independent Tilt Wing conversion study determined the wing and rotor constraints which would provide descent performance typical of previous Tilt Wings.

The results of the conversion study indicate that wing loading to disk loading, for aircraft with similar high-lift systems, is the appropriate parameter which determines descent performance. The proper ratio to use depends on the high lift system. This is contrary to a widely accepted understanding that some fixed value of c/D (which is a form of wing loading to disk loading) determines descent performance. The results of this study predicted the descent performance of the XC-142 which compared reasonably well against flight test data. It also predicted the descent capabilities of the current Tilt Wing to be slightly better than the XC-142.

Figure 2-10 shows a comparison of conversion power with the other flight modes. Recall that maintaining hover tip speed through conversion reduces the efficiency of the rotor. A typical reconversion sequence will take approximately 40 seconds. Figure 2-6 shows a typical reconversion time history for the XC-142.[9]

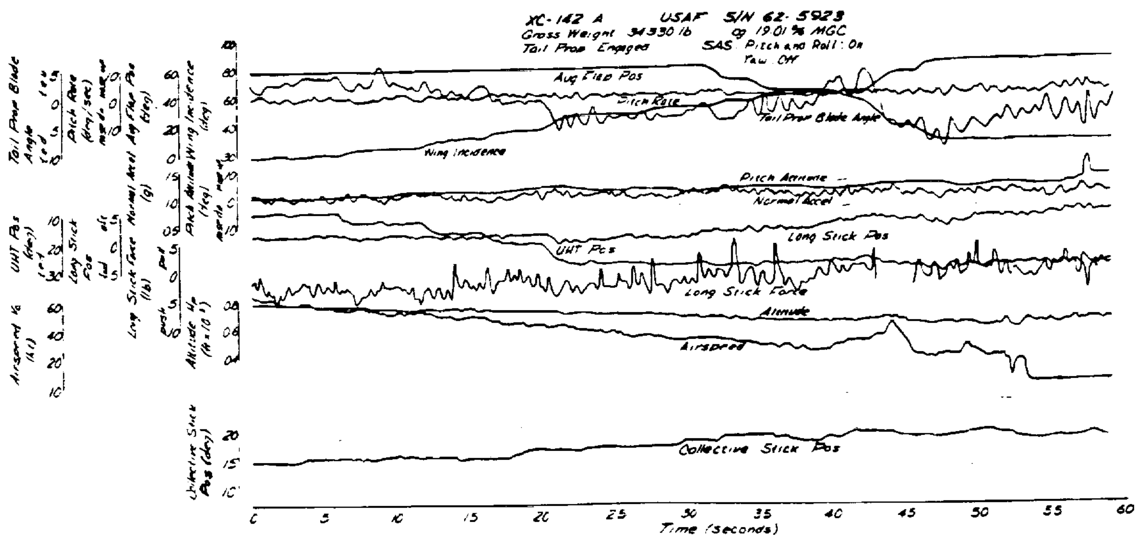


FIGURE 2-6. XC-142 RECONVERSION TIME HISTORY

Since the Tilt Wing uses two bearingless rotors, rotor dynamics during conversion and reconversion are a concern. Whirl mode instabilities, although not analyzed, are accounted for through wing stiffness in the weight equations. Further investigation of rotor dynamics during conversion will analyze whirl mode instabilities. Corio lis forces (which cause the rotor to flap opposite to the direction of rotation) and the required control inputs needed to offset them must also be investigated.

Rotor/Wing- The conversion of the Rotor/Wing requires careful consideration of two areas. They are centerbody lift and high advance ratios (rotor stop and start). Although the Rotor/Wing concept has never flown, extensive wind tunnel tests have investigated conversion fully.

Data from the 1960's wind tunnel tests determined the lift and drag characteristics of various centerbody shapes. The test results show that a triangular centerbody can maintain a lift coefficient of 0.6 at 15°. Although the centerbody could operate at higher angles of attack, 15° represents the maximum practical aircraft attitude during conversion. The lift coefficient and the desired conversion speed of 170 kts, determine the centerbody size.

At moderate helicopter speeds, an analysis using CAMRAD JA indicated that rotor vibration could be a problem.

The results of an analysis using CAMRAD JA show the centerbody and rotor adequate to carry the Rotor/Wing from 80 to 120 kts in autogyro mode. Rotor hub loads, predicted by CAMRAD JA, become excessive above 100 kts in helicopter mode.

The greatest concern during conversion is stopping or starting the rotor in forward flight. As the advance ratio become very large, the rotor vibrations will increase. However, if the blades remain unloaded, the vibration can be significantly reduced using cyclic pitch control. In addition, the three-bladed rotor produces a triangular centerbody. As the centerbody carries lift during conversion, the center of lift oscillates in an elliptical pattern with a frequency three times the rotor rotational speed. Reference 8 presents several suggestions to overcome this problem including cyclic pitch control, elevon deflection, and possibly the use of a four-bladed configuration. Figure 2-7 shows an actual time history of a rotor conversion from autogyro to fixed-wing mode. It should be noted that although basic higher harmonic controls were used, no automatic flight controls were implemented for this conversion. Further investigation will determine the benefits of higher harmonic control, automatic controls, four blades, etc.

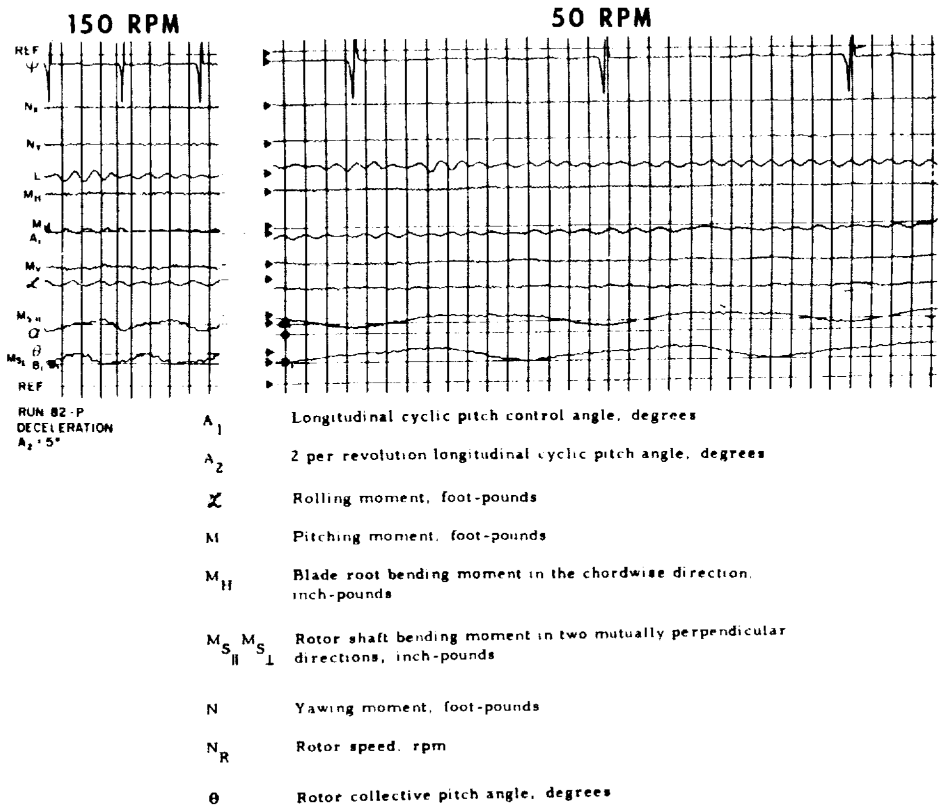


FIGURE 2-7. WIND TUNNEL TEST SHOWING ROTOR/WING CONVERSION FROM HELICOPTER TO AIRPLANE MODE.

Performance

Both the Tilt Wing and the Rotor/Wing demonstrate different levels of performance in helicopter, conversion and airplane mode. Figures 2-8 and 2-9 show the flight envelopes for the Tilt Wing and the Rotor/Wing, respectively. Several different limitations determine the flight envelope on each. Figures 2-10 and 2-11 show the sea level, standard day, composite power curves for the Tilt Wing and Rotor/Wing, respectively.

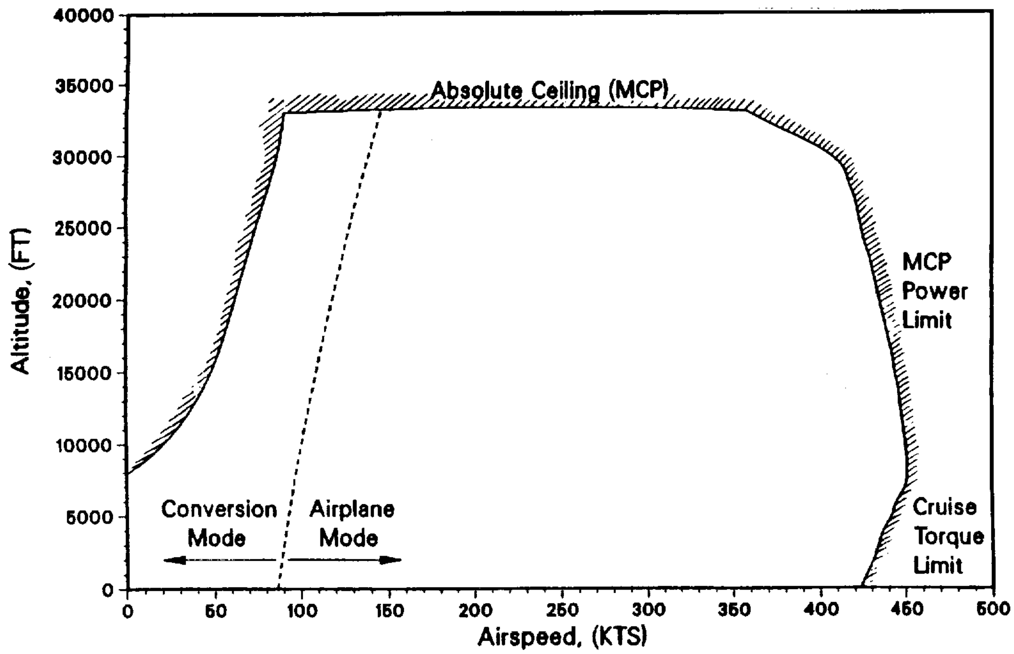


FIGURE 2-8. TILT WING FLIGHT ENVELOPE.

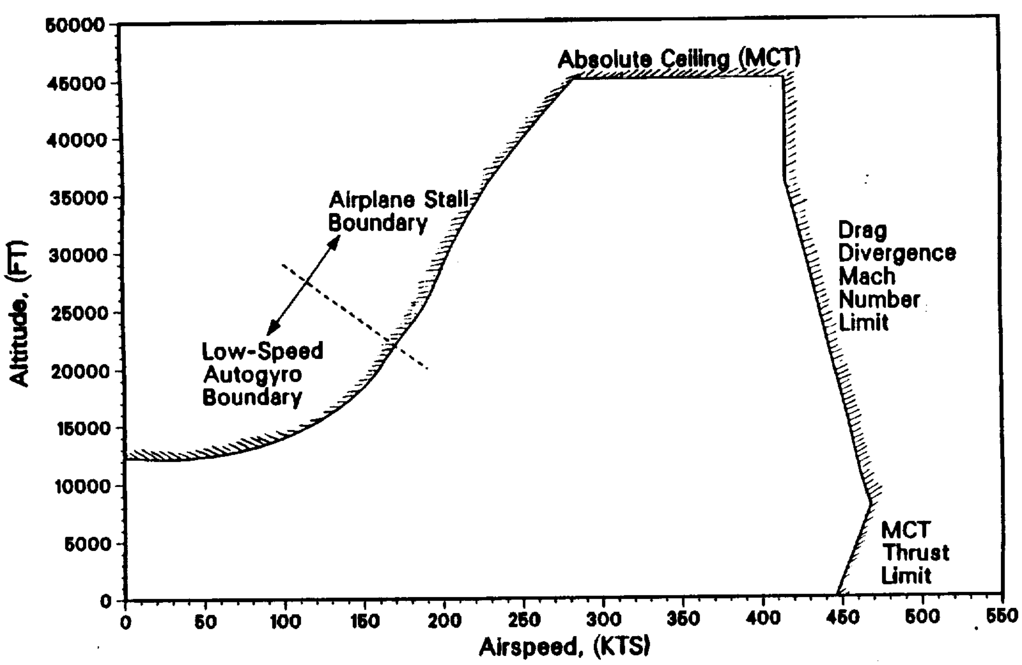


FIGURE 2-9. ROTOR/WING FLIGHT ENVELOPE

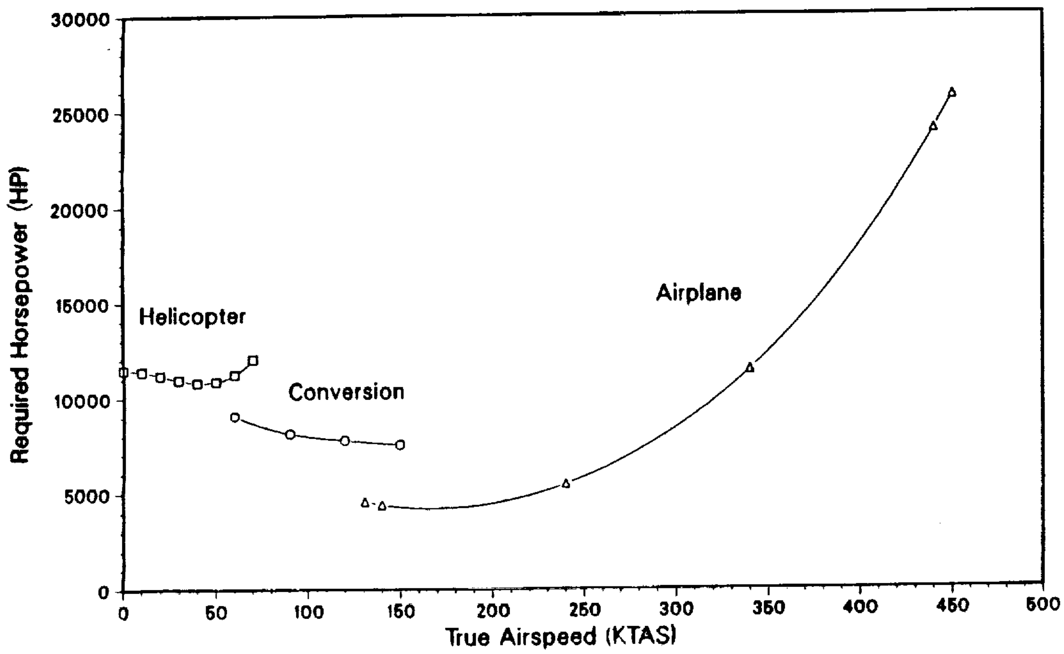


FIGURE 2-10. TILT WING POWER REQUIRED - ALL MODES

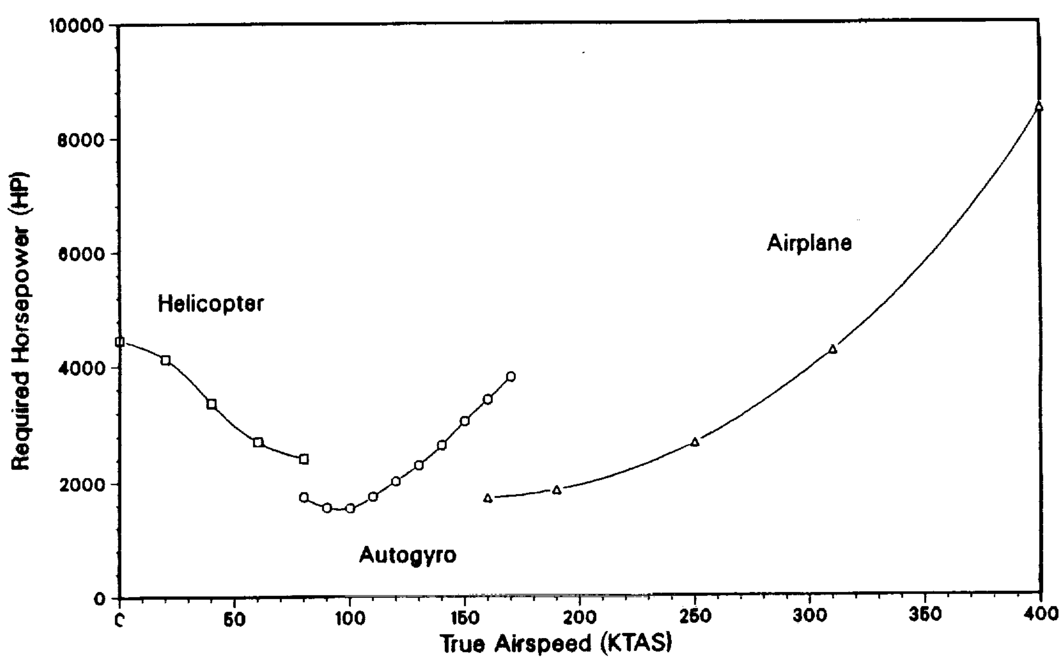


FIGURE 2-11. ROTOR/WING POWER REQUIRED - ALL MODES

Figures 2-8 and 2-9 show that the flight envelopes are shaped at different airspeeds by the different flight regimes. The slope of the low speed boundary is smaller for the Rotor/Wing than the Tilt Wing. Rotor/Wing depends only on its rotor for lift until the rotors are stopped. Thus, air density limits the altitude capability of the Rotor/Wing until the wing can carry load. The Tilt Wing, however, begins loading its wing at the onset of transition. Thus, the Tilt Wing's rotors can be off-loaded very quickly, improving the altitude capability with speed, compared to the Rotor/Wing.

The power curves will be discussed in more detail later in this section. The following section discusses selected plots required in Task 2 which will be used to describe the performance of each concept in each flight mode.

Tilt Wing Helicopter Mode- The Tilt Wing spends virtually no time in pure helicopter mode except for hover. Figure 2-12 shows the non-dimensional power, using V-22 airfoils, as generated by DACPROP. Simple theory also substantiated this data. Figure 2-13 shows hover ceiling as a function of takeoff gross weight. This figure shows that all points are limited by rotor stall ($C_T/\sigma_{max} = 0.18$). Since the Tilt Wing's engines are sized for cruise (checking the power required for hover with 2 engines inoperative and cruise simultaneously), enough power is available to hover at all altitudes until the rotor stalls.

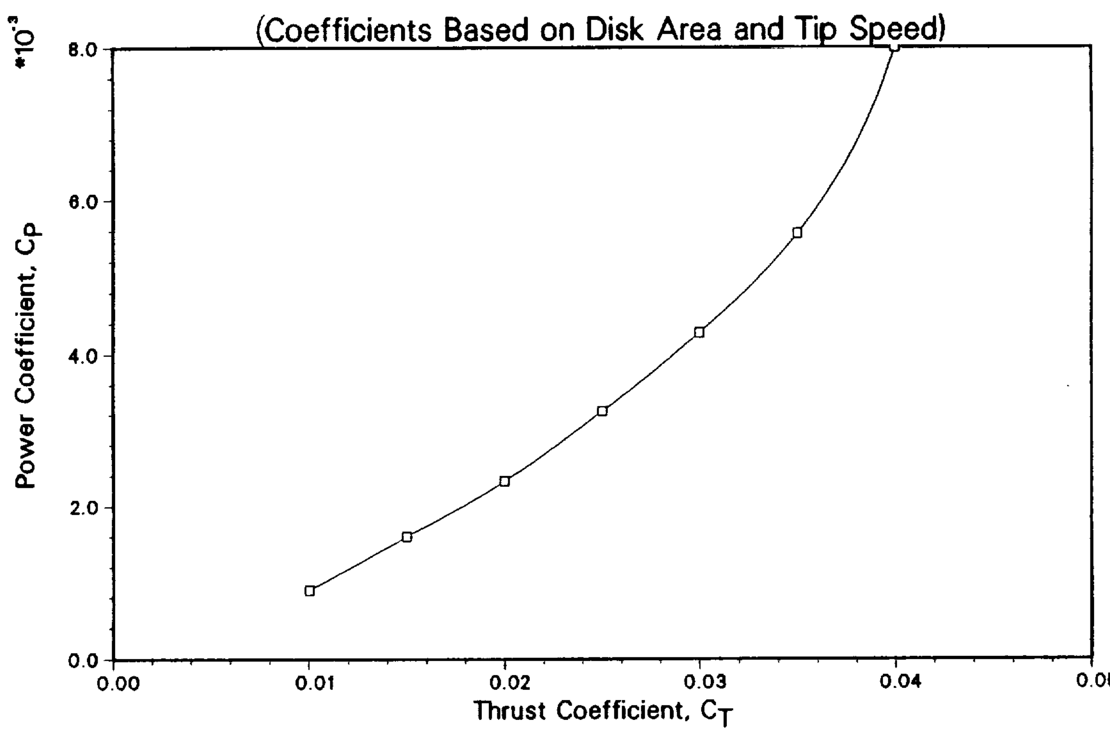


FIGURE 2-12. TILT WING NON-DIMENSIONAL HOVER ROTOR POWER REQUIRED

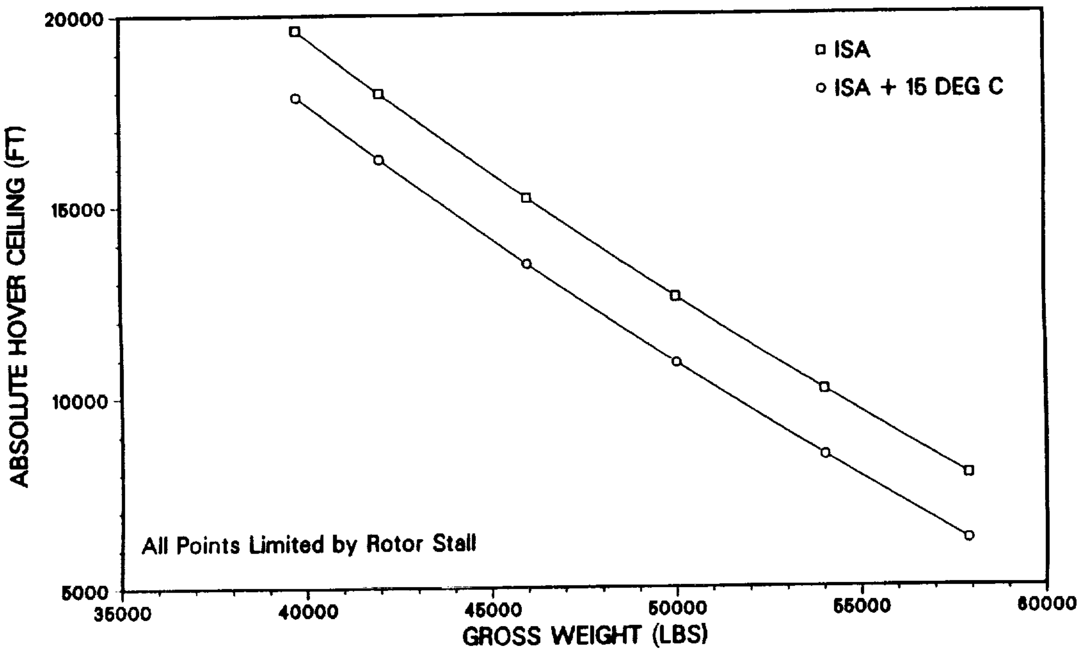


FIGURE 2-13. TILT WING HOVER CEILING

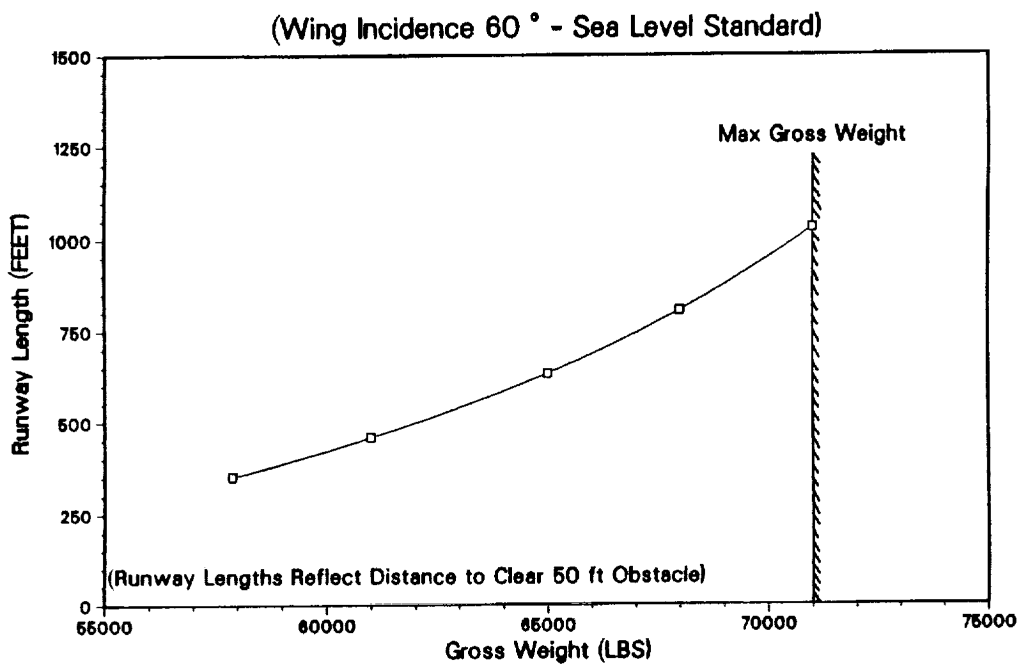


FIGURE 2-14. TILT WING STOL PERFORMANCE - WING AT 60 DEG

Additional Tilt Wing helicopter-mode performance is provided in Appendix B. It should be noted that this data assumes a wing incidence angle of 90 degrees at all velocities. This is not how the Tilt Wing flies, however, so the power required at any velocity greater than zero will be higher than expected due to the large amount of drag from the wing.

Tilt Wing Conversion Mode- Conversion represents a smooth transition from helicopter to fixed wing mode, with one exception. The hover tip-speed is maintained until the wing locks in place (typically 120-150 kts). This, and the added drag for gaps and seals, explains the discontinuity between the power required for conversion and airplane power required at 150 kts as shown in Figure 2-10. Figure 2-14 shows the short takeoff and landing (STOL) performance of the Tilt Wing with the wing at 60 degrees, which is essentially conversion mode. Additional conversion performance information is available in Appendix B.

Tilt Wing Airplane Mode- In airplane mode, drag and propulsive efficiency determine performance. The Tilt Wing drag breakdown is given in Table 2-7. Additionally, Figure 2-15 shows the Tilt Wing L/D at design gross weight (DGW). The cruise performance of the rotor designed for the dash requirement at 15,000 ft. is given in Figure 2-16 for several Mach numbers.

Flat Plate Area in ft^2

Component	Wetted Area	C_f	Form Factor	Flat Plate Area
Fuselage	1377	0.00187	1.48	4.89*
Wing	1318	0.00263	1.47	5.11
Horizontal Tail	461.4	0.00262	1.35	1.62
Vertical Tail	351	0.00264	1.264	1.17
Nacelles	652.8	0.00342	1.36	3.04
Sponsons	255	0.00225	1.206	0.69
				16.52
			10% for Interference and Protuberences :	1.65
			Total :	18.17

* includes 1.08 sq ft for fuselage upsweep

TABLE 2-7. TILT WING DRAG BREAKDOWN - AIRPLANE MODE

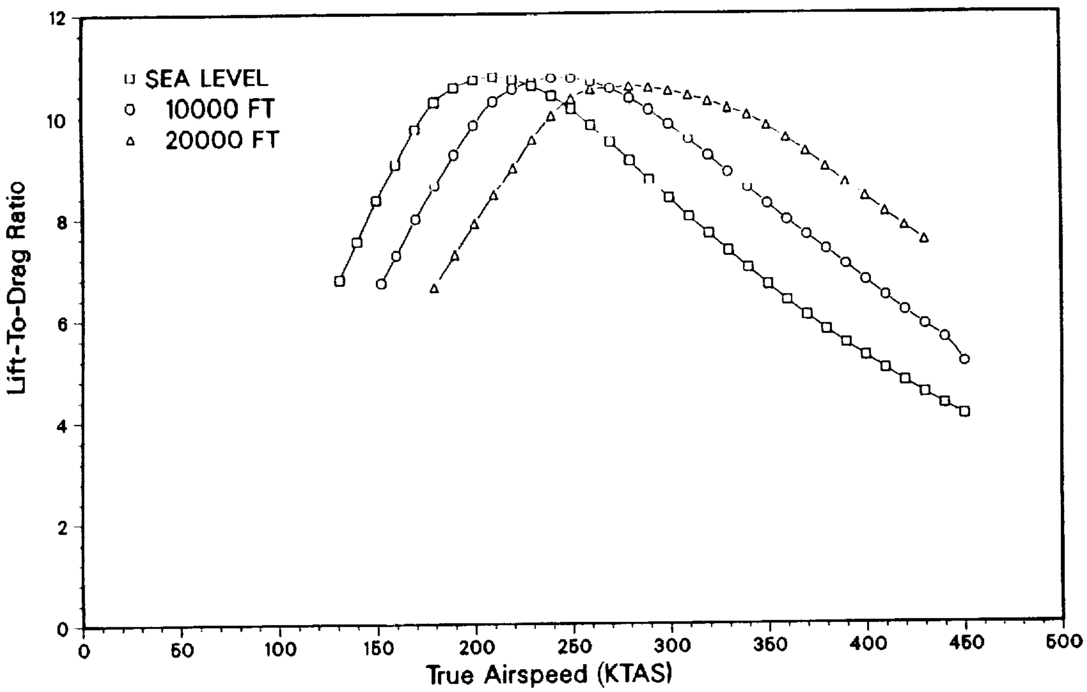


FIGURE 2-15. TILT WING L/D - AIRPLANE MODE

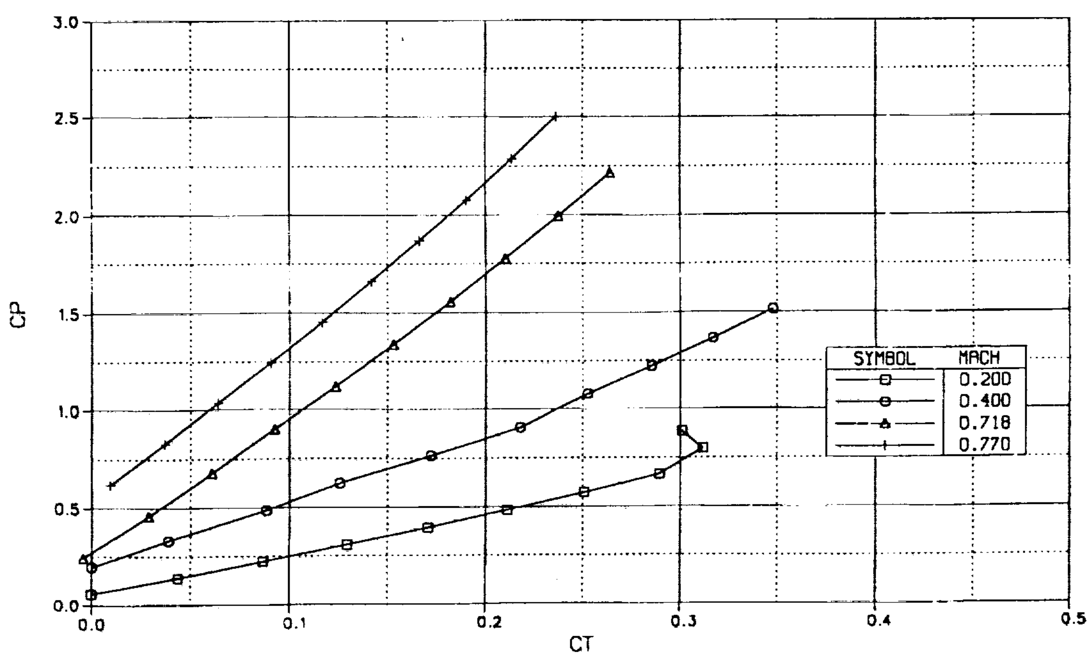


FIGURE 2-16. TILT WING - ROTOR CRUISE PERFORMANCE

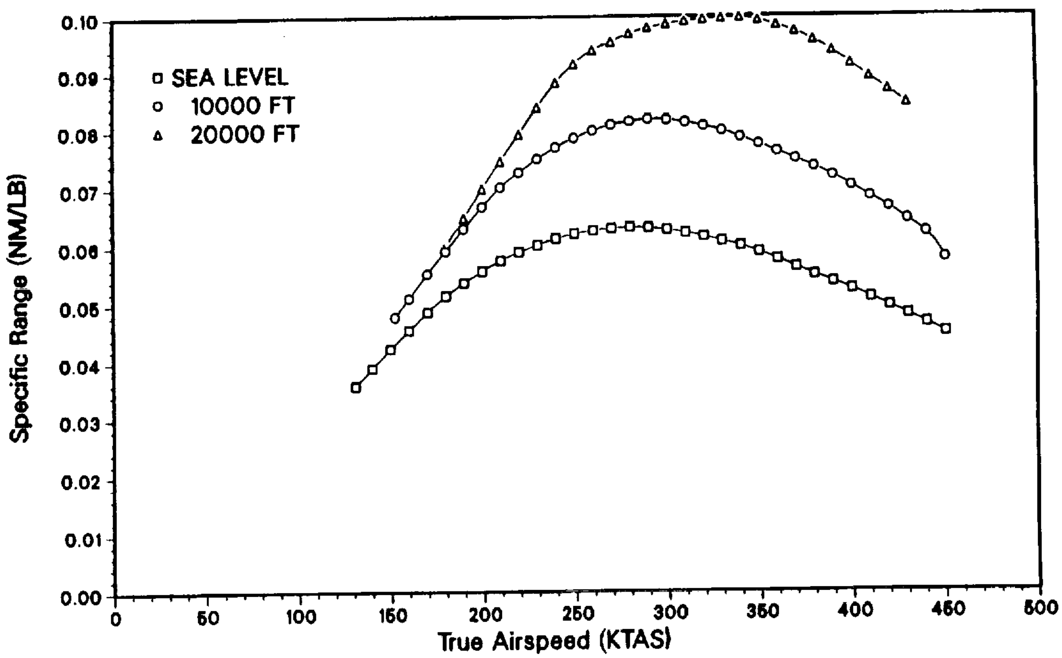


FIGURE 2-17. TILT WING SPECIFIC RANGE

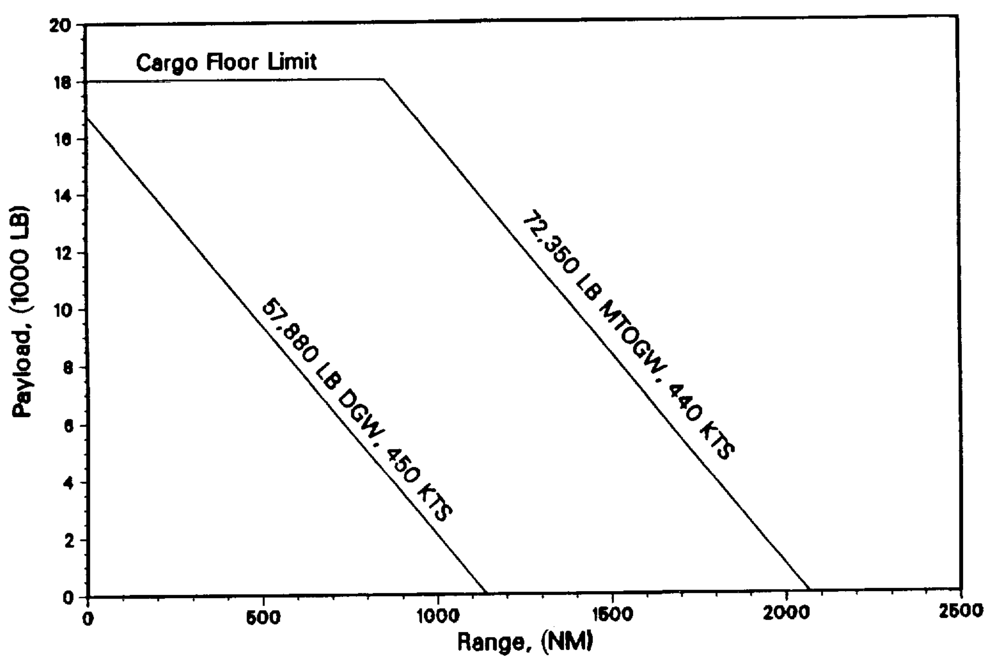


FIGURE 2-18. TILT WING PAYLOAD-RANGE DIAGRAM

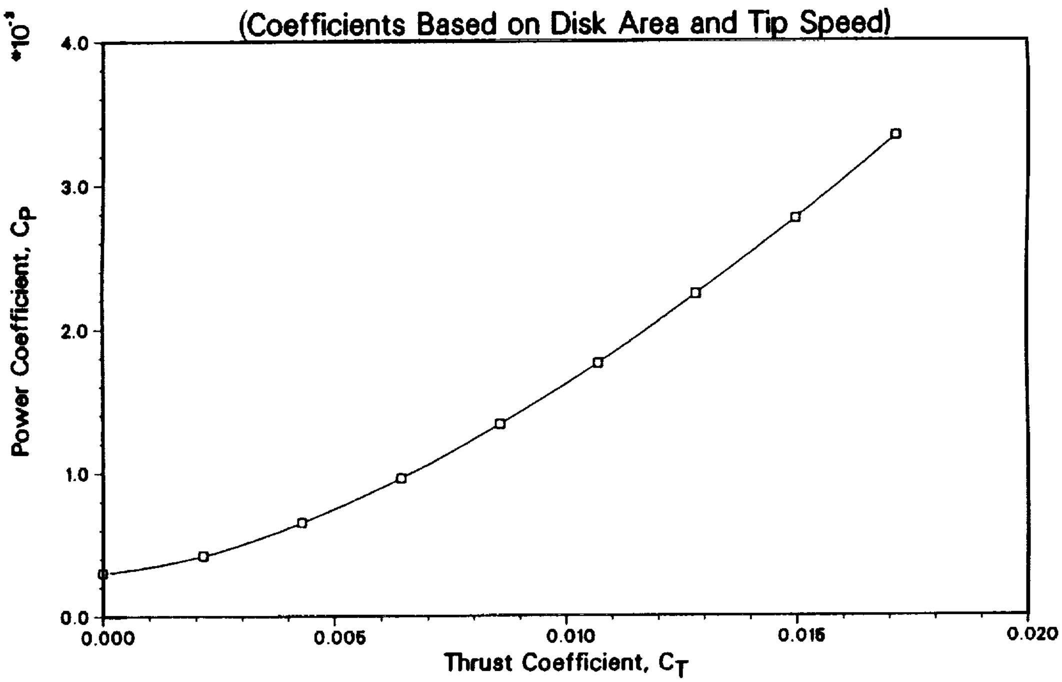


FIGURE 2-19. ROTOR/WING NON-DIMENSIONAL ROTOR HOVER POWER REQUIRED

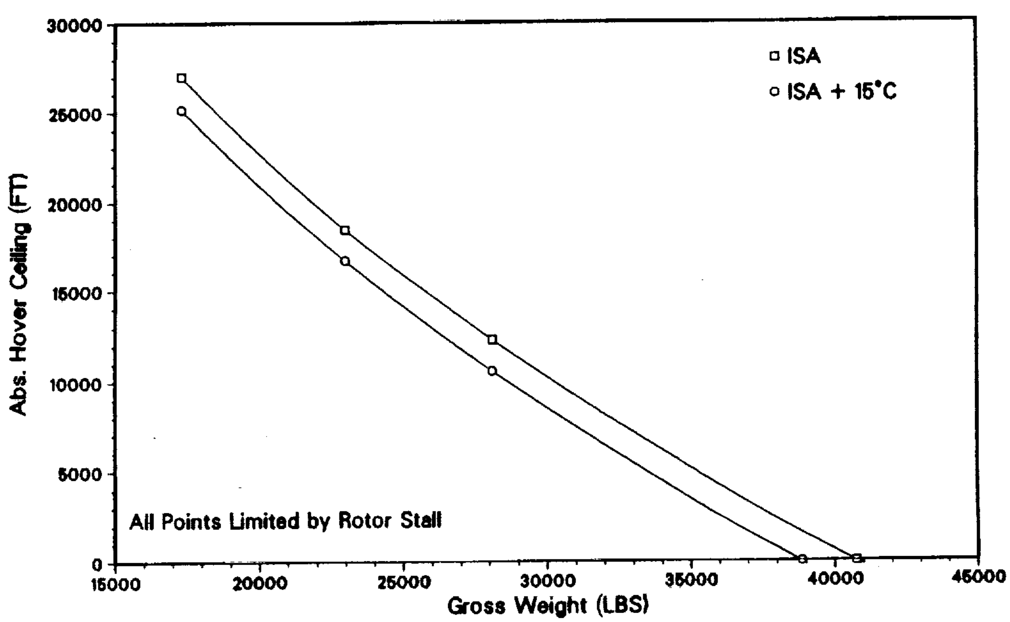


FIGURE 2-20. ROTOR/WING HOVER CEILING

Specific range and payload-range which measure the Tilt Wing's efficiency are presented in Figures 2-17 and 2-18. Neither of the graphs represent any mission characteristics. The payload-range plot represents the payload capacity for a given cruise speed, altitude and range. The specific range plot shows the specific range variation at DGW for different airspeeds, at several different flight conditions.

Rotor/Wing Helicopter Mode- Unlike the Tilt Wing, the Rotor/Wing mission requires about 45 minutes in hover and NOE flight. Figure 2-19 shows the non-dimensional rotor power in hover as predicted by simple theory. Comparison of this data to LSAF and a blade element analysis confirmed the accuracy of this data. The simple analysis also provided the power curves for forward flight in helicopter mode. Figure 2-20 shows the Rotor/Wing hover ceiling at DGW for a standard and hot day. Notice again that all of the points in these curves are limited by rotor stall. This limitation results because of excess power due to the OEI hover requirement and due to minimizing rotor solidity in deference to cruise wing loading. Additional helicopter mode performance is presented in Appendix B.

Rotor/Wing Conversion (Autogyro) Mode- Figure 2-11 shows a discontinuity in the power required between autogyro and the other two modes. The angle of attack needed to trim the Rotor/Wing in autogyro flight increases the L/D ratios from those in cruise. Figure 2-21 shows a comparison of the calculated L/D ratios for the Rotor/Wing to the wind tunnel obtained for a similar configuration in the 1960's. Additional conversion mode performance is presented in Appendix B.

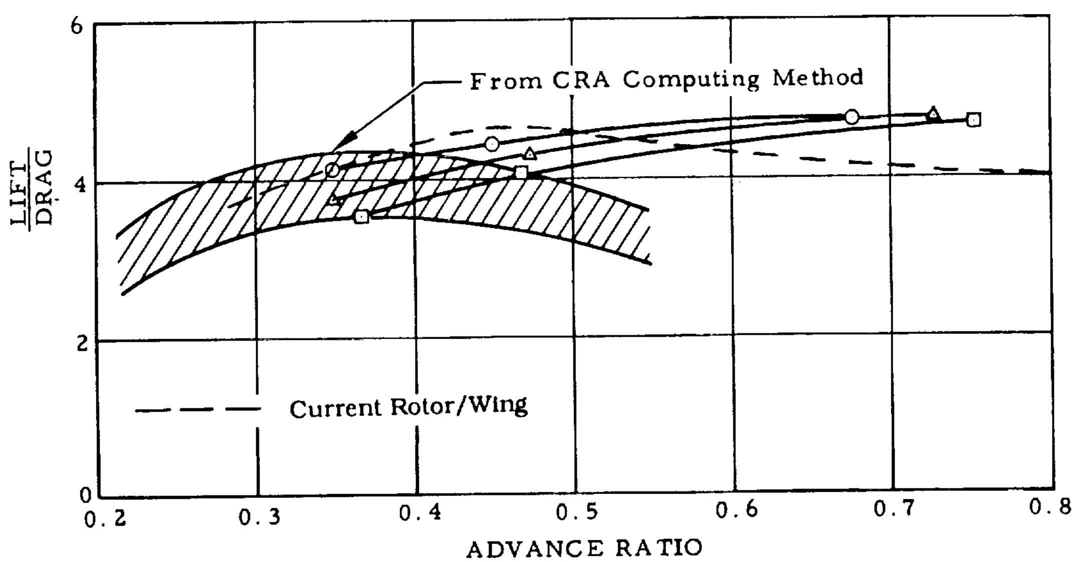


FIGURE 2-21. ROTOR/WING L/D - AUTOGYRO MODE

Rotor/Wing Airplane Mode- Like the Tilt Wing, drag and propulsive efficiency largely determine airplane mode performance for the Rotor/Wing. Table 2-8 shows the drag breakdown in airplane mode. Figure 2-22 presents cruise L/D as a function of forward speed. The maximum values agree favorably with wind tunnel test data from similar models corrected to full scale. The engine data presented previously and in Appendix B provides engine fuel efficiency for different thrust levels and Mach numbers at several altitudes.

Flat Plate Area in ft^2

Component	Wetted Area	C_f	Form Factor	Flat Plate Area
Fuselage	725	0.00187	1.5	2.04
Wing	835.7	0.00235	1.7	4.20
Horizontal Tail	410	0.00251	1.45	1.49
Vertical Tail	256.3	0.00247	1.43	0.90
Nacelles	372	0.00285	1.51	1.59
Mission Drag Increment				1.00
				11.22
10% for Interference and Protuberences :				1.12
Total :				12.34

TABLE 2-8. ROTOR/WING DRAG BREAKDOWN - AIRPLANE MODE

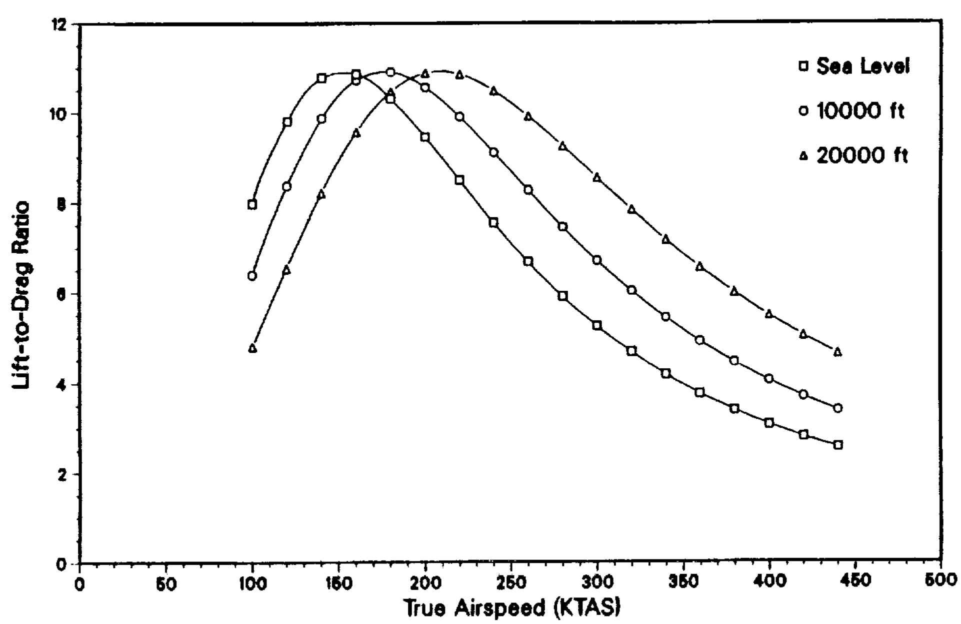


FIGURE 2-22. ROTOR/WING L/D - AIRPLANE MODE

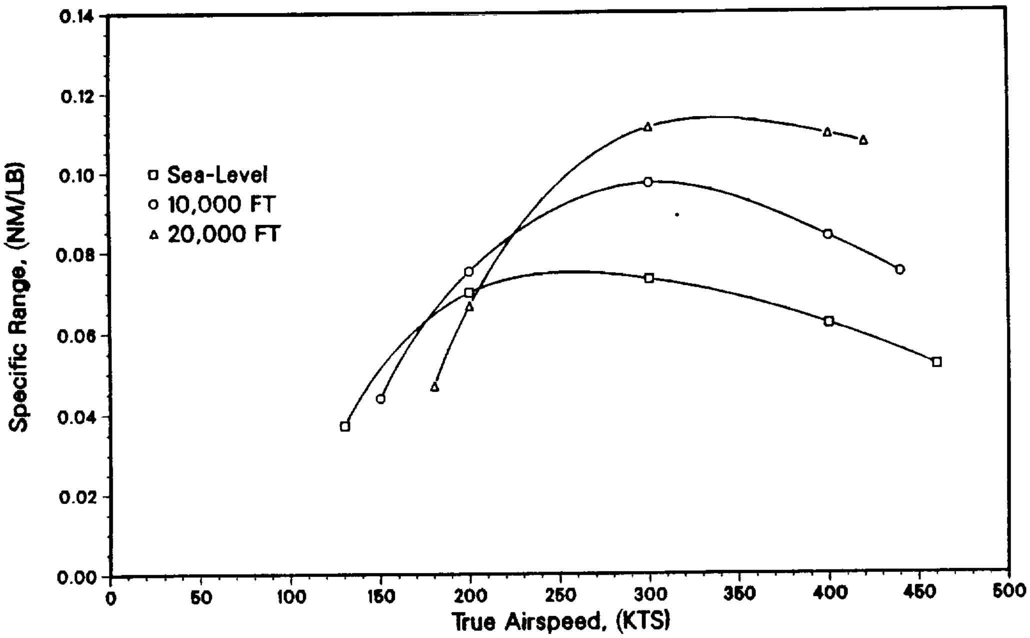


FIGURE 2-23. ROTOR/WING SPECIFIC RANGE

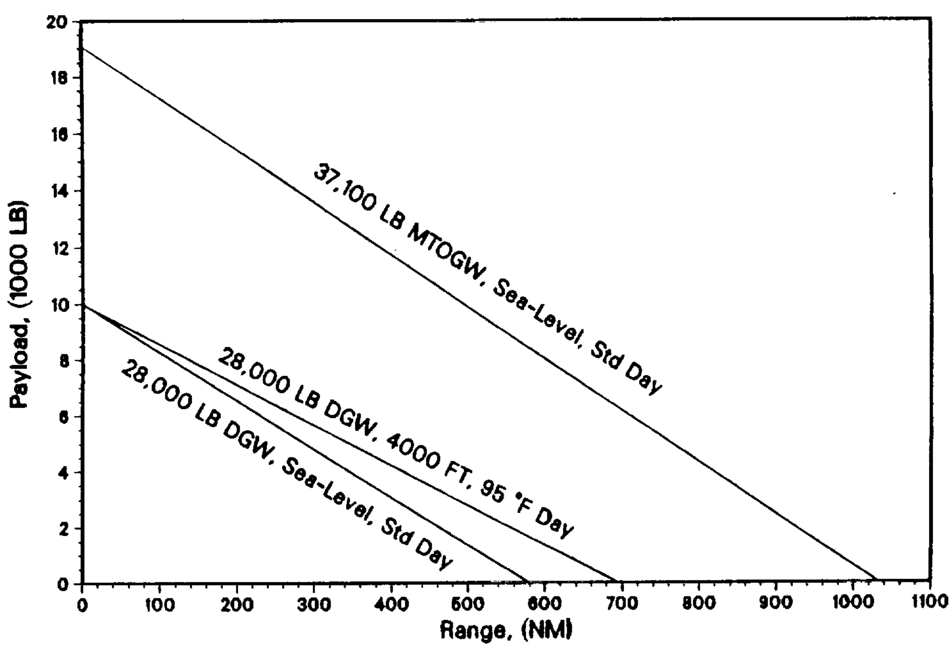


FIGURE 2-24. ROTOR/WING PAYLOAD-RANGE DIAGRAM

The specific range and payload-range plots provide some measures of non mission specific Rotor/Wing efficiency. The specific range and payload-range curves are presented in Figures 2-23 and 2-24 respectively, similar to the Tilt Wing curves presented previously.

In summary, low-speed flight (hover and transition) and high-speed flight both compromise performance. Examination of both Tilt Wing and Rotor/Wing performance leads to a general conclusion. That is, hover and transitional flight tend toward large surface areas, be it rotors, wing or centerbody. High-speed flight, however, tends toward smaller surface areas because of increased dynamic pressure. The need to compromise is obvious, but the point where hover and the high-speed requirements cause the solution to diverge is not. The Task 2 performance analyses seem to indicate that, at present technology, the velocity at which the Tilt Wing begins diverging is about 450 kts. The Rotor/Wing appears to possess more potential for higher speeds, but one reason for this is that the ground attack mission flies at 400 kts for only 50 nm.

Tilt Wing Subsystem Design

Hub- The original Tilt Wing prototypes (CL-84, XC-142, & VZ-2) used variable pitch propellers that were simple to operate but offered little or no lateral or longitudinal control and required additional control thrusters at the tail. Boeing proposed a monocyclic hub which could produce a pitch and/or yaw moment but was only slightly less complex than a full cyclic hub.[8]

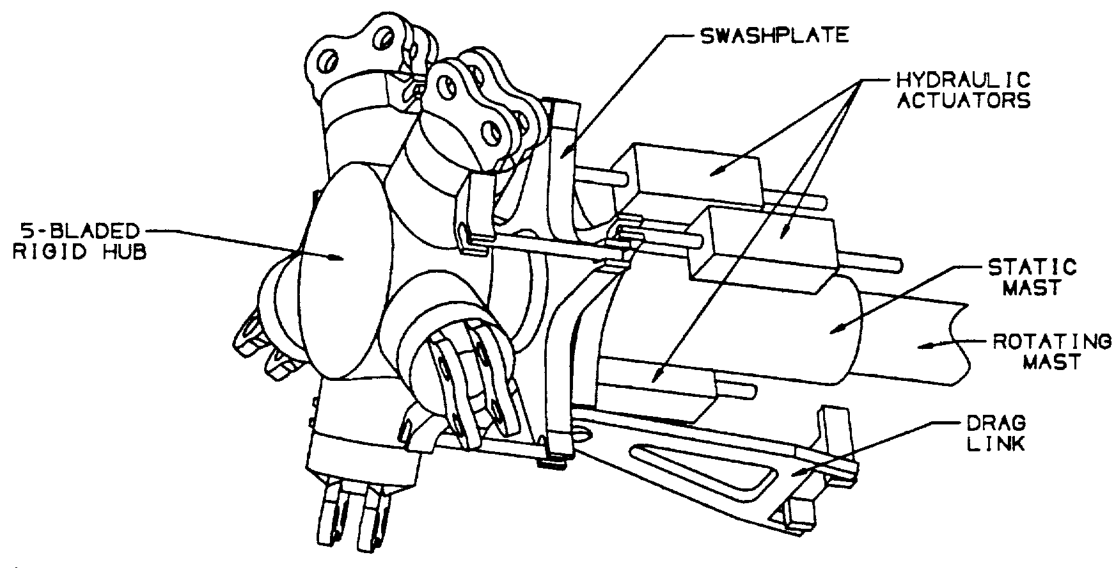


FIGURE 2-25. TILT WING HUB WITH CONTROLS

Figure 2-25 shows the proposed hub which consists of a 5 bladed rigid hub with full cyclic and collective pitch control. This ensures adequate control without the use of a pitch or yaw fan. The virtual flapping axis is located at approximately 5% radius and results from flexibility in the blade root. The total feathering travel of approximately 60 deg. Accommodates the relatively flat pitch at hover and nearly full feathering required in cruise.

The non-rotating swashplate is mounted to a spherical bearing which slides on a static mast. Three hydraulic actuators define the orientation of the swashplate. A torque link mounted to the mast base restricts rotation. The three actuators, used together, provide both cyclic and collective pitch. Simultaneous input from all actuators provides collective control while cyclic uses differential input.

Drive System- Figure 2-26 shows the proposed Tilt Wing drive system which consists of a 5-stage, 2-speed gearbox on each wing. Two 6411 HP engines mounted side-by-side aft of the gearbox provide the required power. Each gearbox consists of shafting with spiral bevel sets from each engine feeding into a 4-stage planetary. Cross shafting between the rotors, which is common on similar configurations, was omitted to reduce weight and complexity. The excessive power required in cruise far exceeds that required for hover and results in engines which provide over twice the power required for hover. Cross shafting was unnecessary because the aircraft can meet the hover requirement with only two of its four engines operating (one on each side).

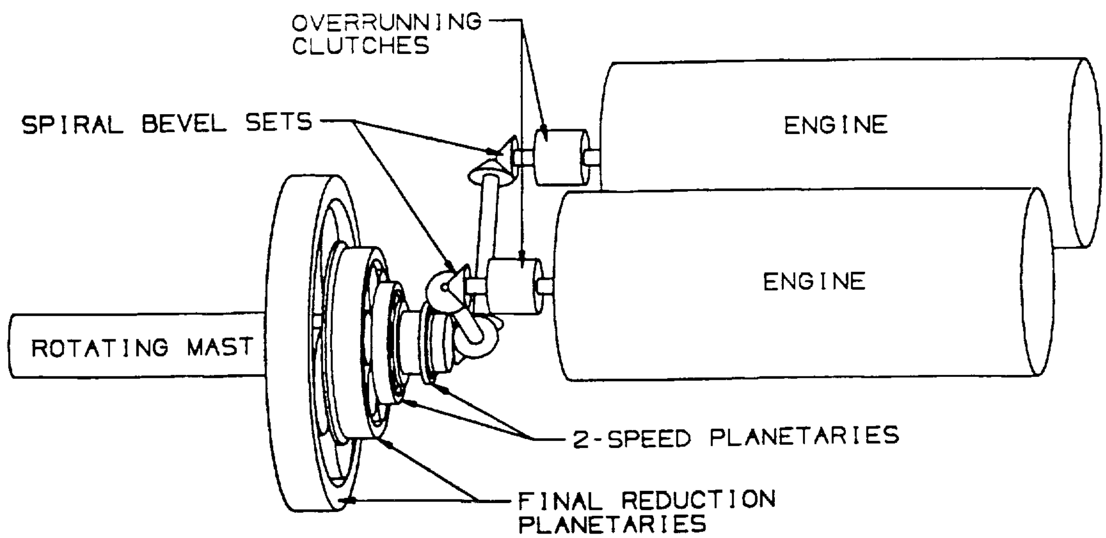
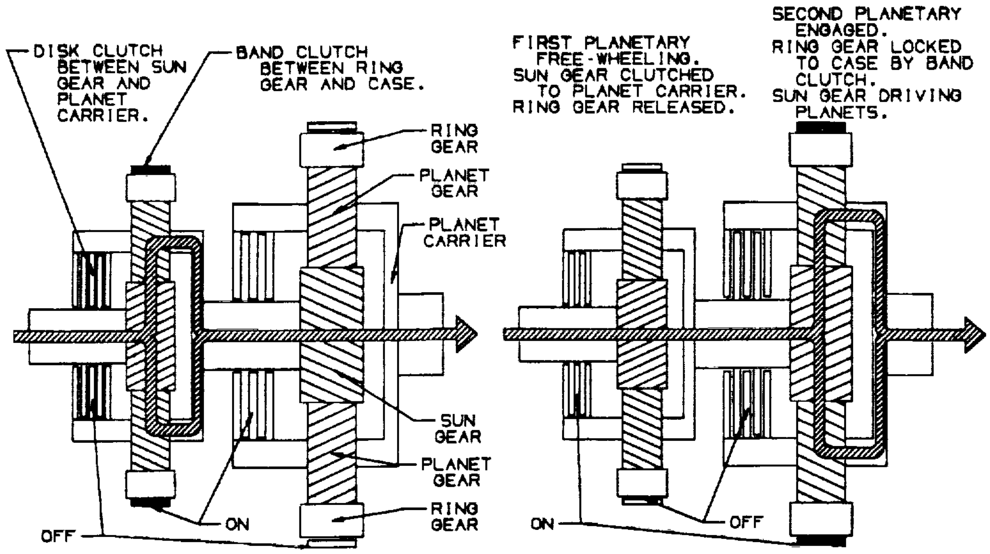


FIGURE 2-26. TILT WING DRIVE SYSTEM

The shafts and associated spiral bevel sets spanning the distance from the engines to the mast axis were sized to carry 6411 HP MCP at 15,000 rpm. Idler gears were also considered for spanning the distance but were found to be too heavy. Analysis of the mission power requirements revealed that the maximum power occurred during climb to altitude. This power level (10650 HP/rotor) subsequently sized the planetary stages. Figure 2-27 shows the two-speed gearbox which is used to achieve two-speed operation. The two planetaries' reduction ratios provide the required cruise and hover rotor rpm. One is engaged for hover (high rpm) and the other for cruise (low rpm). Locking the ring gear to the case engages the planetary and allows the sun to drive the armature. When the planetary is disengaged, the armature and sun gear clutch together and the ring releases, allowing the entire assembly to spin freely yielding no speed reduction.



HIGH SPEED OPERATION.
T PLANETARY TAKES SMALL REDUCTION.
SECOND PLANETARY FREE-WHEELING.

LOW SPEED OPERATION.
FIRST PLANETARY FREE-WHEELING.
SECTION PLANETARY TAKES LARGE REDUCTION.

FIGURE 2-27. TWO-SPEED GEARBOX

Other options investigated for two-speed operation included other planetary configurations and simple helical gearsets. The two-speed transmission was originally designed to have only one disengagable planetary. The intent was to engage this stage for low-speed operation and allow it to free-wheel in high-speed operation. Tip-speed requirements led to a 1.96:1 ratio between hover and cruise rpm. Of the six planetary configurations possible, only one could achieve this ratio, however, it reverses the output rotation direction. This would cause the rotor to spin one direction in hover and the opposite in cruise. The other alternative was to use a simple helical gearset, similar to an automobile manual transmission, but experience has shown the weight penalty to be excessive.

Control System- The proposed Tilt Wing control system combines conventional aileron, elevator, and rudder controls with cyclic and collective pitch control on two separate hingeless rotors. A fly-by-wire system minimizes pilot workload, and reduces weight and mechanical complexity. A triple redundant, double fail operative computer system translates cockpit inputs into actuator outputs to achieve the desired response in all flight modes. This will greatly simplify control during conversion.

Pitch is controlled by the tail plane and elevators in airplane mode. Use of a stabilator is also an alternative. As the wing rotates to vertical, cyclic control of the rotors is phased in for pitch control during vertical flight eliminating the need for the pitch fans on previous designs. The elevators can be active or inactive during vertical flight, whichever is more beneficial.

Yaw control changes from rudder in airplane mode to differential cyclic pitch and ailerons in vertical flight. Differential cyclic for tilting one rotor forward and the other aft in vertical flight has been demonstrated on the XV-15 and V-22.[23] The XC-142 and CL-84 demonstrated that ailerons could significantly enhance yaw control in vertical flight out of ground effect.[8,22]

Roll control shifts from ailerons in airplane mode to differential thrust in vertical flight. Differential collective inputs to the two rotors provides differential thrust as demonstrated bye the XV-15 and V-22.

Cruise flight utilizes conventional fixed-wing controls. Only collective inputs are fed to the blade actuators to make the rotors function as constant speed propellers.

Software Requirements- Three processors and the appropriate transducers will be required to provide a triple redundant system. These processors will be networked such that the operating processor(s) will override the inoperative unit(s). The criteria for override will be contained in software.

The bulk of the software development will be devoted to mixing of the controls during the conversion sequence and phasing the controls to accommodate fixed and rotary-wing flight modes. Each actuator's response to the pilot's input is computed based on the wing position and aircraft velocity. These responses will be determined from algorithms or test data.

Rotor/Wing Subsystem Design

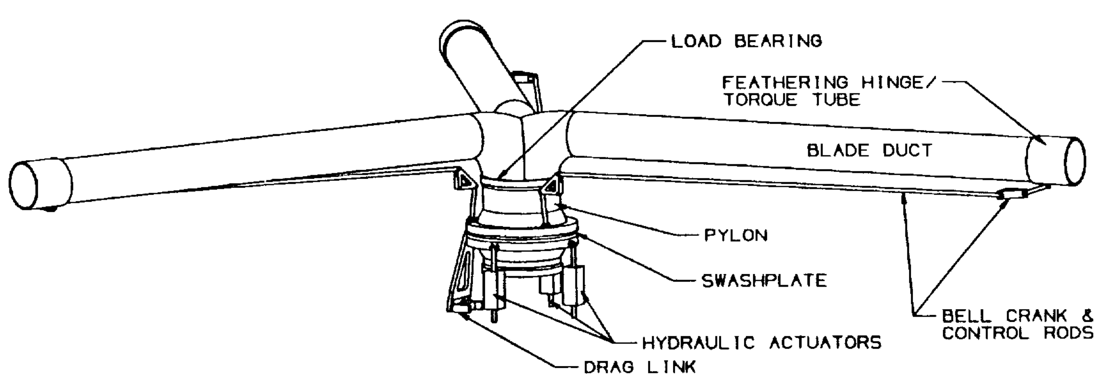


FIGURE 2-28. ROTOR/WING HUB WITH CONTROLS

Hub- The rotor/wing centerbody will act as a rigid hub for the 3 blades. For each blade, the feathering axis is established by a hollow torque tube through which the duct passes. Pushrods and bell cranks will transmit the control inputs from the swashplate out to the pitch horn at the blade root. Swashplate orientation is controlled by three hydraulic actuators driven by a fly-by-wire controller. Figure 2-28 shows the Rotor/Wing hub.

Flight loads are carried by a ring-type load bearing mounted on a pylon structure. The reaction drive duct passes through the center of the pylon to the centerbody. The pylon will incorporate some type of vibration isolation system to reduce airframe loads and improve the dynamic response.

Propulsion System- Figure 2-29 shows the proposed Rotor/Wing drive which system consists of two turbofan engines whose exhaust drives the rotor or provides direct propulsive thrust. A diverter valve directs the flow to either the rotor or the propulsive thrust nozzles.

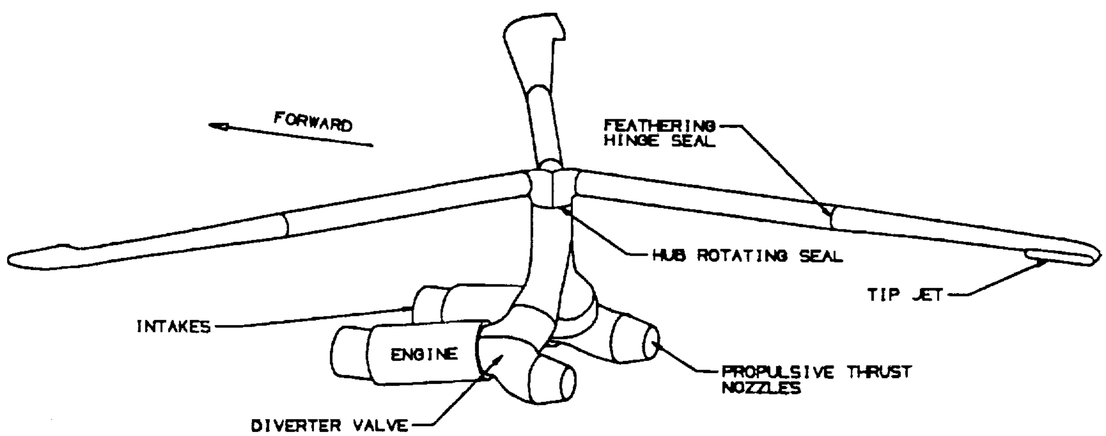


FIGURE 2-29. ROTOR/WING PROPULSION SYSTEM DUCTING

In forward flight, the propulsion system operates like that of a conventional aircraft. The gas from the turbine exit is ducted through the diverter valve to the exhaust nozzle where it is expanded to produce thrust. In hover, the diverter valves rotate 180 deg to direct the exhaust gas flow from each engine into the mast. In helicopter mode, the flow can be split between the rotor and exhaust nozzles to provide the combination of lift and thrust required. In an OEI condition the diverter for the inoperative engine would be set for through-flow thus blocking back flow through the inoperative engine.

The mast duct mates to the rotor system ducts at the hub through a rotating seal. The main duct into the rotor splits into three sections at the hub, one for each 'blade'. Each of these ducts passes through the centerbody to a joint at the root of the variable pitch blade. This represents the minimum duct area and its size significantly affects blade geometry. This duct continues through the blade to the tip where the trailing edge nozzle is located. Figure 2-30 shows the Rotor/Wing tip jet configuration.

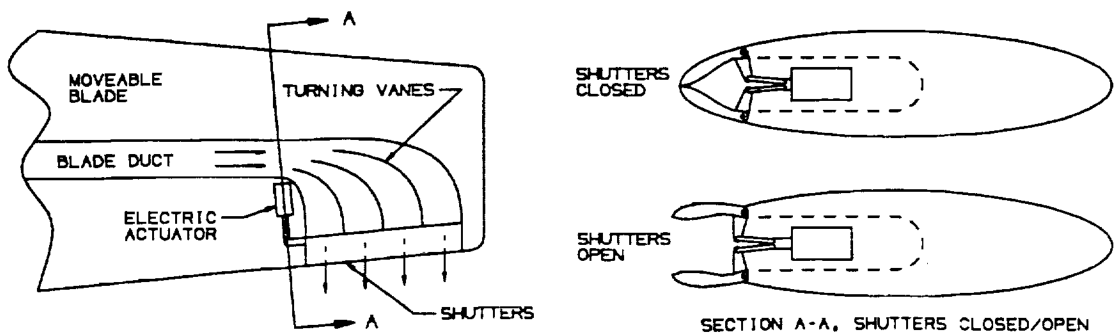


FIGURE 2-30. ROTOR/WING TIP JET

The blade nozzles turn the flow 90 deg. and vent through pressure controlled shutters. The exit area, controlled by an electrical actuator, maintains optimum exit conditions based on internal pressure. When closed, the shutters maintain the outside contour of the airfoil to reduce drag in fixed wing mode.

Control System- The proposed Rotor/Wing control system must provide attitude and directional control in hover, in forward flight with rotor turning, in fixed-wing flight to 450 kts, in auto gyro mode, and during acceleration and deceleration of the rotor during transition. The system uses rudder and elevon control surfaces plus reaction yaw control jets on the tail, and controllable pitch blades on the rotor. Significant anti-torque control capability is not required because the rotor is driven by reaction nozzles at the blade tips and no torque is transmitted to the airframe.

A triple redundant, double fail operative fly-by-wire system translates pilot inputs into control device actuations. The control laws of the system vary depending on the flight mode/conditions.

In vertical flight, cyclic and collective blade control to the rotor are used for lateral and longitudinal control. Reaction jets, using engine bleed air or a portion of the exhaust, are mounted in the tail for yaw control. Partially diverting some of the exhaust to the propulsive thrust nozzles allows augmentation of the rotor propulsive thrust.

In fixed-wing mode, the elevons and rudder on the tail provide yaw, pitch, and roll control with the rotor fixed and blade pitch locked.

For conversion from rotary-wing to fixed-wing mode, exhaust flow diverts from the rotor to the propulsive thrust nozzles. Figure 2-31 shows the Rotor/Wing locking-stopping mechanism. A brake slows and stops the rotor and a locking mechanism engages. During rotor deceleration, the elevons automatically actuate at 3/rev, independent of pilot inputs, to cancel rolling and pitching moments caused by a shifting aerodynamic center.

Conversion from fixed to rotary-wing flight mode reverses this sequence. This capability was successfully demonstrated during wind tunnel tests of previous Rotor/Wing configurations.

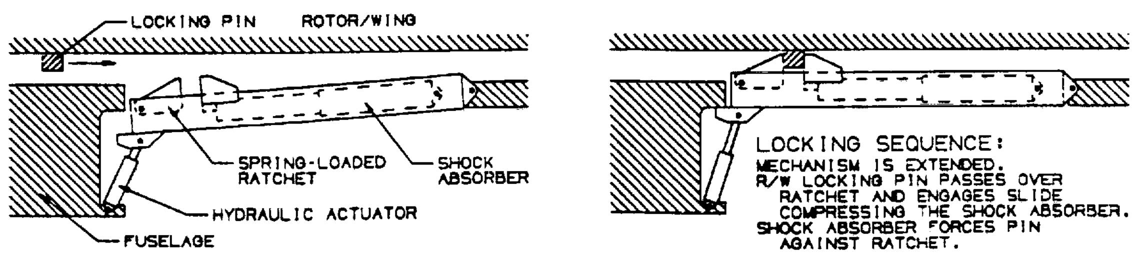


FIGURE 2-31. ROTOR/WING LOCKING-STOPPING MECHANISM

Software Requirements- Three processors and the appropriate transducers will be required to provide a triple redundant system. These processors will be networked such that the operating processor(s) will override the inoperative unit(s) in the case of a failure. The criteria for override will be contained in software.

The majority of the software development effort will be focused on automatic conversion between fixed-wing and helicopter modes. This includes diverting exhaust between the rotor and the propulsive thrust nozzles, phasing cyclic blade control in or out, actuation of the rotor brake and stop, and actuation of the elevons to cancel pitch and yaw moments.

SESITIVITY STUDIES

Mission/Design Sensitivities

The sensitivity of the concepts to changes in mission design parameters helps to identify concept effectiveness and critical technologies. The following section outlines the results of sensitivity studies performed on both the Tilt Wing and the Rotor/Wing. The parameters evaluated include:

50% change in all hover times.

20% change in cruise L/D.

Changing cruise or maximum speeds to 350 or 500 kts.

25% change in characteristics directly associated with increased maneuver capability.

20% change in specific fuel consumption (SFC).

20% change in powerplant installed power to weight ratio (P/W)

Impact of a 5dB reduction in sideline noise at 500 ft.

Results presented concurrently from both the Tilt Wing and the Rotor/Wing sensitivity studies show not only the effect of each variation on the concepts, but on the different missions as well. Gross weight, engine power, maximum L/D, and fuel weight measure the sensitivity. All figures present these results on common scales, except where noted.

Trade in Total Mission Hover Time- Figure 2-32 shows the effect of a 50% increase and a 50% decrease in mission hover time. The sensitivity of both concepts to changes in mission hover time appears to be virtually the same. Both missions require a 15 minute mid-mission hover, and one minute OGE hover at each end of the mission, but the Rotor/Wing engines are sized for hover and the Tilt Wing engines are sized for cruise. The different sizing criteria for the concepts result in a larger change in engine power required for the Rotor/Wing than for the Tilt Wing. So the Rotor/Wing concept demonstrates greater sensitivity to changes in hover requirements.

Trade in Cruise L/D- Initially, it must be noted that Figure 2-33 shows the Tilt Wing data on a much larger scale than the Rotor/Wing. Changes in cruise L/D do not directly reflect changes in cruise drag since it is the ratio of gross weight to drag. Flat plate drag increments control the parasite drag of each aircraft in this study. However, each drag increment increased the fuel required, fuel system weight, etc. So, for each concept, the addition of parasite drag tends to drive up gross weight also. Figure 2-33 shows that changes in L/D occur more easily for the Rotor/Wing's mission than for the Tilt Wing's mission. Longer and faster cruise segments in the Tilt Wing's mission increase fuel weight, etc. more quickly than the Rotor/Wing's, for each increment in equivalent flat plate area.

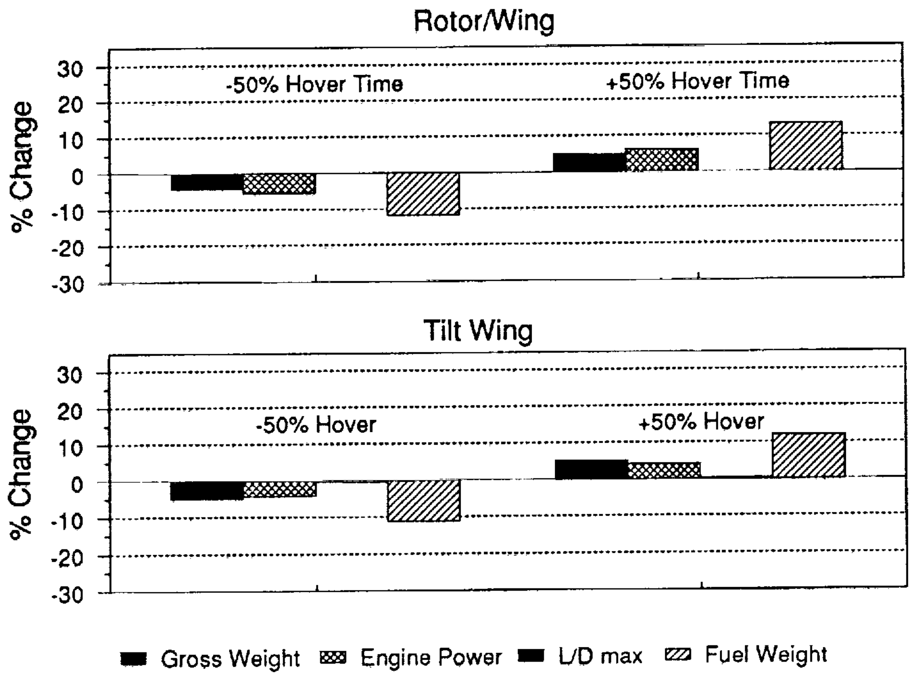


FIGURE 2-32. SENSITIVITY TO CHANGES IN MISSION HOVER TIME

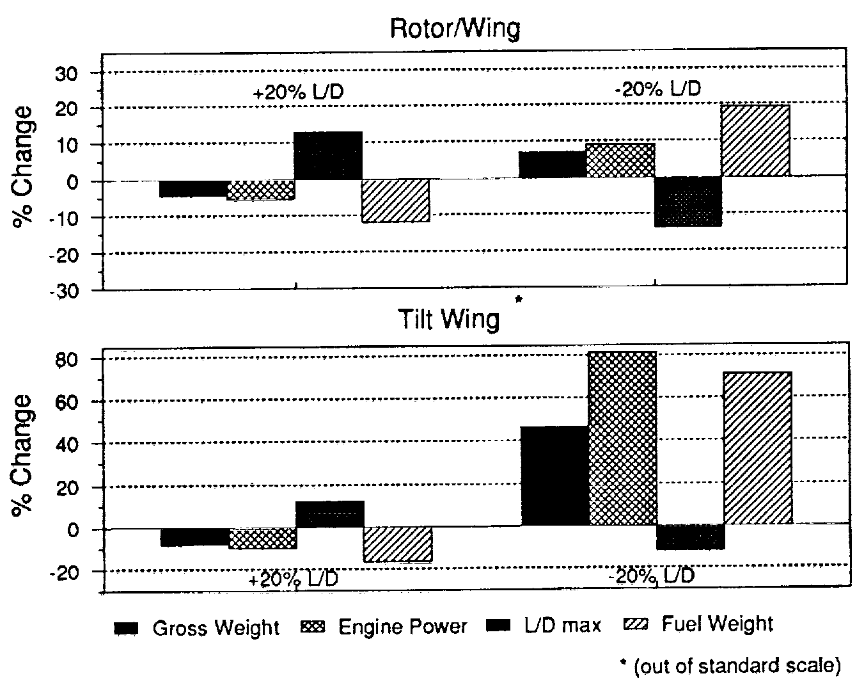


FIGURE 2-33. SENSITIVITY TO CHANGES IN LIFT-TO-DRAG RATIO

Trade in Maximum Cruise Speed- Again, Figure 2-34 depicts the Tilt Wing data on a much larger scale than the Rotor/Wing data. The Tilt Wing appears more sensitive to changes in maximum cruise speed than the Rotor/Wing for several reasons. The Tilt Wing Cruises at 450 kts for 350 nm, while the Rotor/Wing cruises at 400 kts for only 50 nm. The Tilt Wing is propelled by prop/rotors where the Rotor/Wing is propelled by turbofan engines. The efficiency drops off significantly for the prop/rotors after 450 kts, while the turbofan can still maintain efficient cruise at 500 kts. Finally, wing planform and tilting requirements limit wing sweep on the Tilt Wing, while the three-bladed Rotor/Wing incorporates 30 degrees of wing sweep automatically, delaying the onset of drag divergence.

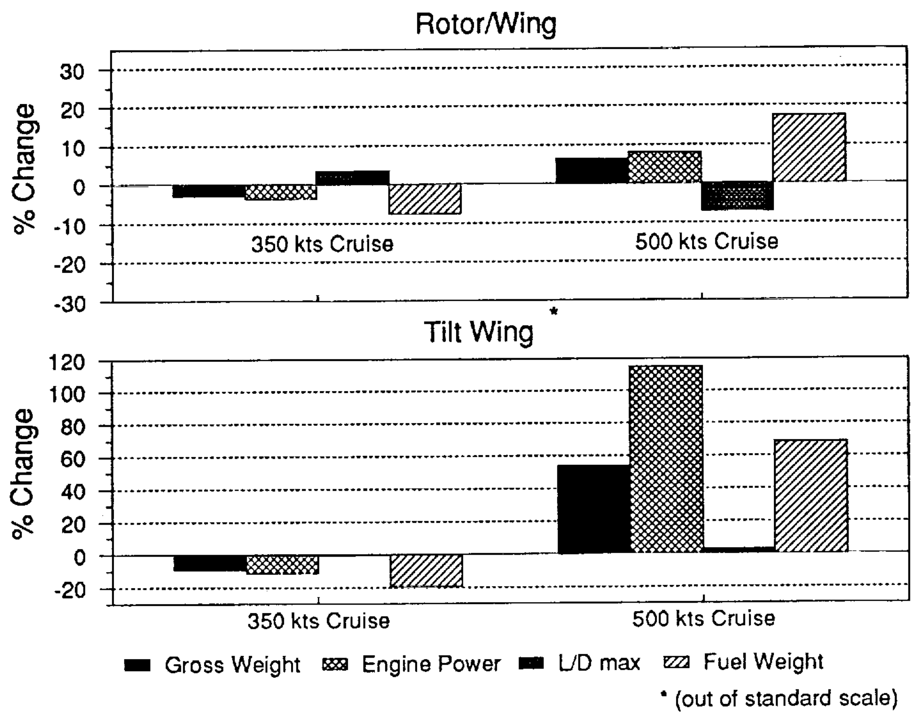


FIGURE 2-34. SENSITIVITY TO CHANGES IN CRUISE SPEED

Trade in Maneuverability Characteristics- The sensitivity of changes in maneuverability characteristics apply to two areas: rotor solidity and wing area. The baseline average hover lift coefficients for the Tilt Wing and Rotor/Wing are 0.89 and 0.70, respectively. Figure 2-35 shows the affect of decreasing rotor solidity, or average lift coefficient (if C_T remains unchanged), by 25%. This figure shows the affect of increasing the hover g capability from 1.25g to 1.56g, and decreasing the hover g capability to 0.94g for both aircraft (realistically, the latter would require additional airfoil development). This change affects the Rotor/Wing engine sizing more than the Tilt Wing, again, because the Rotor/Wing's engines size for hover and the Tilt Wing's for cruise. The large change in L/D for the Rotor/Wing reflects the dual role of the rotor as a fixed-wing in cruise. The fuel weight of each concept is affected essentially the same. The Tilt Wing's gross weight changes more , however, due to a decrease in cruise efficiency. This decrease has a large affect on the drive system weight, which is the largest component weight of the Tilt Wing.

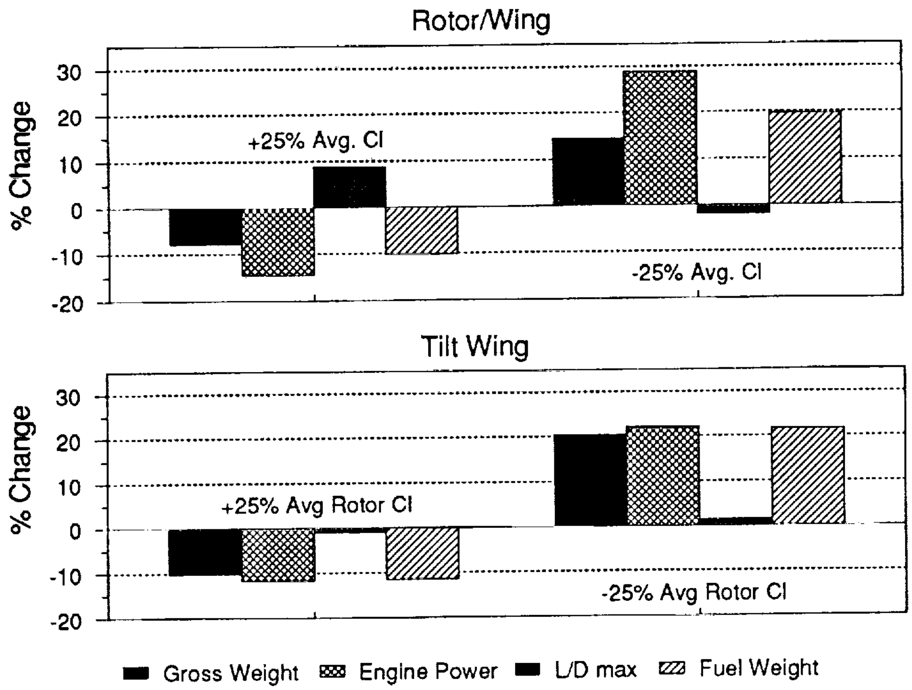


FIGURE 2-35. SENSITIVITY TO CHANGES IN AVERAGE ROTOR LIFT COEFFICIENT

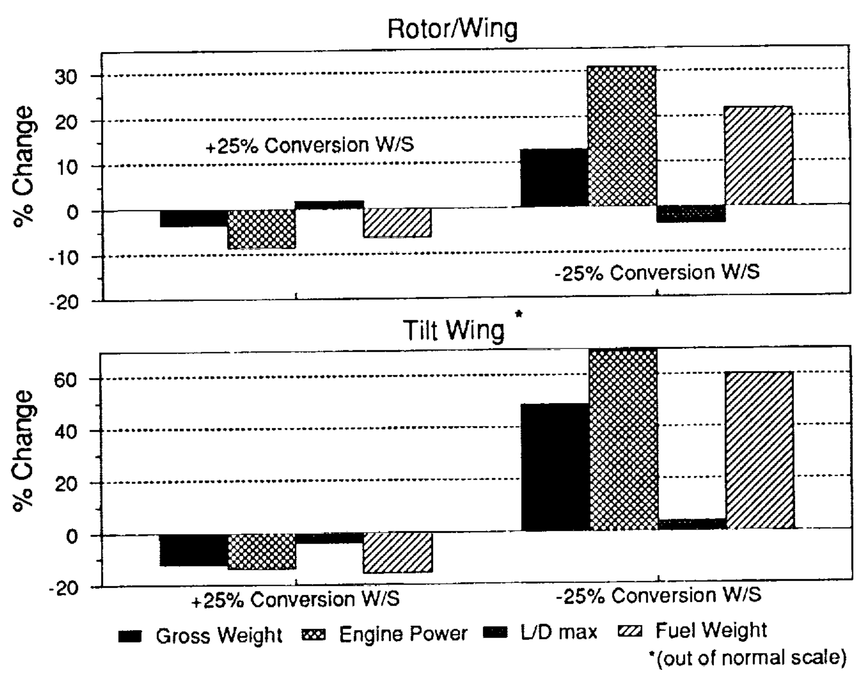


FIGURE 2-36. SENSITIVITY TO CHANGES IN CONVERSION WING AREA

Another maneuverability study reflects changes in wing area. The baseline conversion wing loading for the Tilt Wing is 90 psf. The baseline conversion wing loading for the Rotor/Wing is 65 psf. Changes in conversion wing area affect the flight regime most sensitive to maneuvering flight. In fact, no difference exists between conversion and cruise wing area for the Tilt Wing, and the Rotor/Wing conversion wing area makes up 79% of the cruise wing area. Figure 2-36 shows the affect of 25% change in conversion wing loading. Once again, the Tilt Wing data is on a larger scale than the Rotor/Wing data. Since the disk loading is not changed, the Rotor/Wing experiences large changes in effective rotor area due to changes in the centerbody radius. This accounts for the increased Rotor/Wing engine sizing. Several factor account for the large changes in Tilt Wing gross weight, engine sizing, and fuel weight. The Tilt Wing sees the same change in cruise wing area as it does in conversion wing area. This change not only reflects in the empty weight of the aircraft, but also affects the cruise profile drag. This, in turn affects the fuel consumption and the engine sizing.

Trade in SFC- Figure 2-37 shows that the Tilt Wing and the Rotor/Wing are affected nearly the same by changes in SFC (or fuel flow). Like the mission hover time trade study, variation in SFC affects engine sizing of the Rotor/Wing more than the Tilt Wing. Since the Rotor/Wing engines size for hover, their sizing will be more effected by changes in gross weight than the engines of the Tilt Wing, which are sized for cruise.

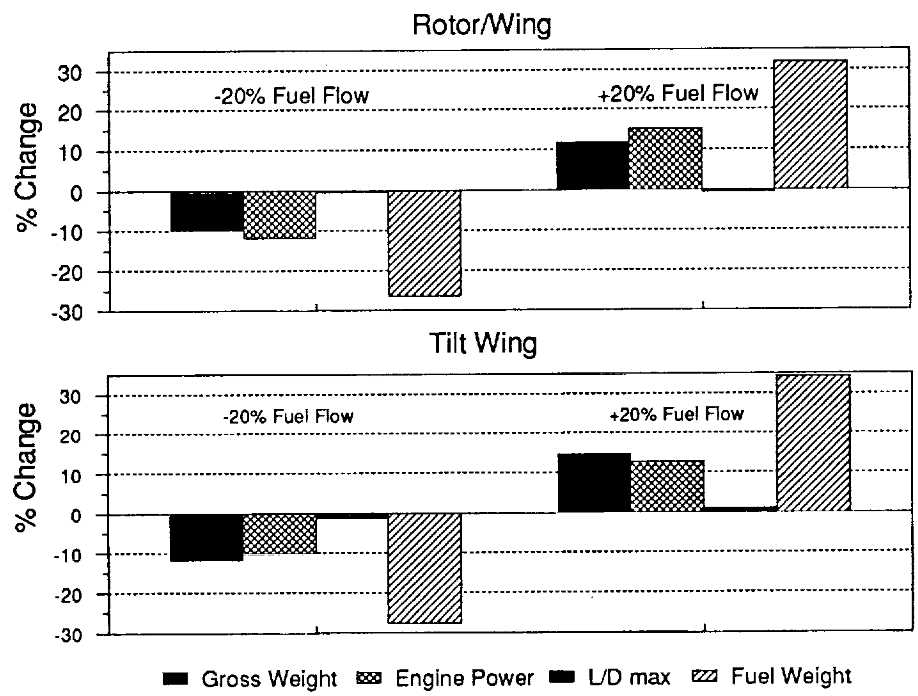


FIGURE 2-37. SENSITIVITY TO CHANGES IN FUEL FLOW

Trade in installed P/W- Figure 2-38 shows the effect of P/W on the Tilt Wing and Rotor/Wing. Changing P/W does not have as large of an effect on the concepts as the other sensitivities, but it does appear to effect the Tilt Wing more than the Rotor/Wing. The engines account for a slightly larger percentage of the gross weight of the Tilt Wing than for the Rotor/Wing (7.00% as compared to 6.55%). Changes in engine weight reflect changes in the engine installation, drive system, etc., while the Rotor/Wing has fewer components affected by engine weight.

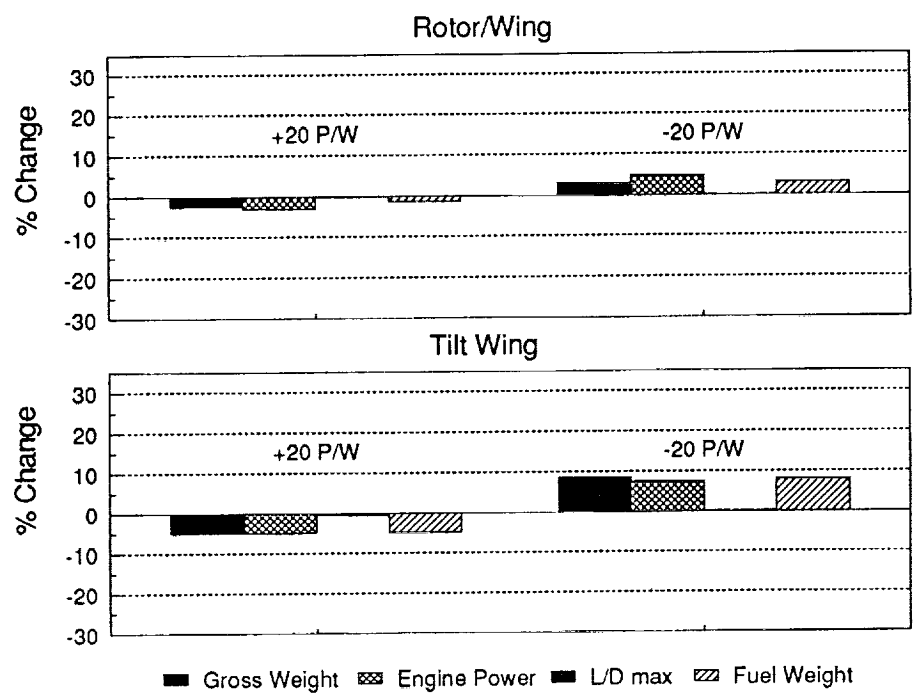


FIGURE 2-38. SENSITIVITY TO CHANGES IN ENGINE POWER-TO-WEIGHT RATIO

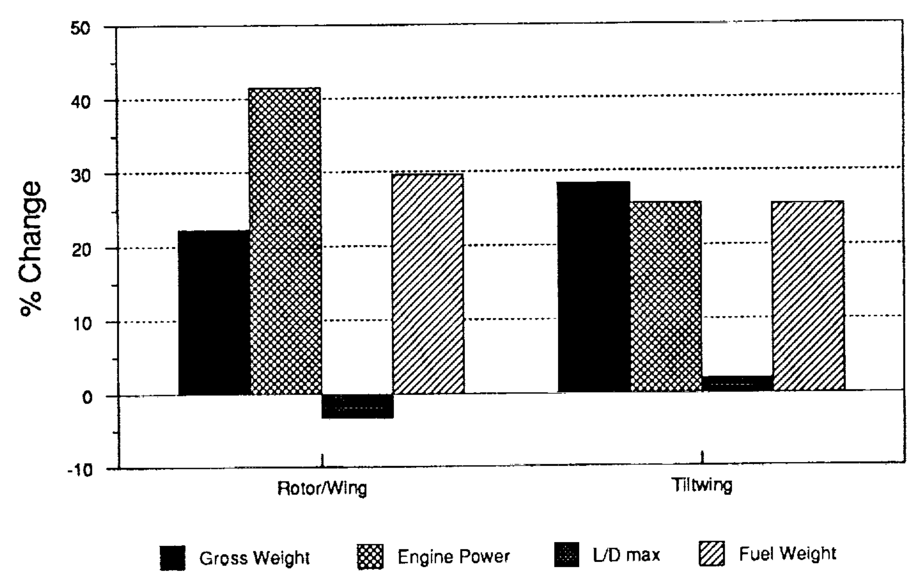


FIGURE 2-39. SENSITIVITY TO A 5 dB SIDELINE NOISE REDUCTION

5dB Noise Reduction: A 20% reduction in tip speed reduces the sideline noise at 500 ft by approximately 5 dB. Figure 2-39 shows the effect of reducing the tip speed 20% on both concepts. Tip speed reduction results in a larger rotor system, because C_T increases, but maximum C_T/σ does not. The same disk loading then requires much higher solidities to keep the rotor from stalling. This affects the engine sizing of the Rotor/Wing more than the Tilt Wing, again due to engines being sized for hover, and the increased profile power due to its resulting high solidity rotor. The reduction in tip speed reduces the prop/rotor cruise efficiency, due to larger solidities needed to prevent rotor stall. This greatly increases the drive system weight, the single heaviest component. For this reason, the Tilt Wing experiences the larger change in gross weight due to tip speed reduction.

Conclusions

The sensitivity studies help to define technology areas which would most benefit each concept at its chosen mission. Several conclusions as a result of the studies are:

1. The largest benefits for these concepts will come from improvements in engine SFC.
2. 450 kts represents the efficient cruising limit for current prop/rotor-driven V/STOL aircraft. Beyond this speed, propulsive efficiency drops dramatically, resulting in greater power required and higher gross weights.
3. The Rotor/Wing concept shows a potential for higher cruise speeds without severe penalties in gross weight.
4. Increases in control surface area (wing, rotor, empennage, etc.) for increased maneuverability or noise reduction result in large cruise efficiency penalties, which may not justify the increase.
5. The Rotor/Wing is the most sensitive to changes in hover time due to its engines being sized by the hover requirement.

Technology Sensitivities

Achievable technologies will determine the potential of both the Tilt Wing and the Rotor/Wing. A brainstorming session produced the technology matrix shown in Table 2-9. The matrix represents six technology areas for the Tilt Wing and five for the Rotor/Wing. Independent application to each concept illustrates the impact of each technology. Application of all technologies indicates the size and shape of future Tilt Wing and Rotor/Wing aircraft.

In Task 1, velocity-dependent measures of effectiveness indicated the effect of each technology. This provided useful information on the efficiency of the aircraft at various speeds. However, Task 1 used a simple mission cruising at 450 knots, bracketed by short hover segments. Task 2 utilizes two different missions for the Tilt Wing and the Rotor/Wing. These missions include longer periods of hover, mingled with dash and loiter segments at speeds varying from 150 to 450 knots. Since the mission of each specifies a payload, speed and range, these parameters remain constant and the measures of effectiveness of Section 1 reduce to those shown in table 2-10.

TECHNOLOGY	ROTOR/WING	TILT WING
Materials & Structure	Overall Weight (-15% Primary Structure) (-10% Secondary Structure)	Overall Weight (-15% Primary Structure) (-10% Secondary Structure)
Propulsion	IHPTET Goals (-30.0 SFC, +120% T/W)	IHPTET Goals (-35.5% SFC, +100% P/W) Cruise Efficiency (+8.3% Cruise Efficiency)
Drive Train	N/A	ART Goals (-20% Gear Box Weight) (-25% Driveshaft Weight)
Aerodynamics	Reduce Cruise Airfoil Drag (-12.3% Drag Coefficient) Increase Conversion Wing Loading (90 psf)	High Drag Divergence (M_{DD} = 0.75) Increase Conversion Wing Loading (120 psf)
Flight Controls	Reduce Empennage Size (-15% Area) Reduce Weight (-10%)	Reduce Empennage Size (-15% Area) Reduce Weight (-10%)
Subsystems	Reduce Weight (-10%)	Reduce Weight (-10%)

TABLE 2-9. ACHIEVABLE TECHNOLOGY MATRIX

These new measures can compare the effectiveness of the vehicles with advanced technology to the baseline vehicles using the same mission. The values presented in table 2-10 represent the measures of effectiveness values for the current technology baseline vehicles and are used as the basis for determining percent improvements of advanced technology over current technology. The definitions of the new measures of effectiveness are as follows:

Gross Weight

Mission Productivity $= W_{pay} / W_{emp}$

Mission Efficiency $= W_{pay} / W_{fuel}$

Specific Range $= V_{dash} / \dot{W}_{fuel}$

Measures of Effectiveness	Tilt Wing	Rotor/Wing
Gross Weight (lbs)	57881	28121
Mission Productivity	0.1509	0.1732
Mission Efficiency	0.4963	0.3847
Specific Range (Nm/lb)	0.0729	0.0782

TABLE 2-10. CURRENT TECHNOLOGY MEASURES OF EFFECTIVENESS

From these baselines, each advanced technology was applied individually to each concept and a sensitivity to achieving the technology goals was assessed.

Technology Weight Factor Assumptions- The general weight assumptions applied in Task II are as follows:

Those structural weight groups which are currently of "conventional" construction will decrease in weight by 15%.

Those structural weight groups which are currently using some level of composites will decrease in weight by 10%.

Drive System: ART goals require a 25% decrease in total drive system weight. For this study assumed only 20% reduction in the gearbox weights but the full 25% reduction in the driveshafts.

Landing Gear: Composite gear design; weight savings of 15%.

Engine: Phase III IHPTET level of technology was assumed.

No weight savings were assumed in the following areas:

1. Rotor Blades
2. Propulsion Subsystems
3. Fuel System
4. Flight Controls

The following figures show the effect of each technology, at the desired technology goal, and also present the effect if the goal is exceeded or falls short by 15%. The figures present this information as a percentage change from the current technology baselines shown above.

Tilt Wing-

General Weight Reduction: Figure 2-40 shows the impact of a general weight reduction (neglecting the drive system, which will be varied separately) reflecting materials and structures technology available in 2003. As expected, the largest gain is in Mission Productivity which indicates the empty weight needed to carry the required payload.

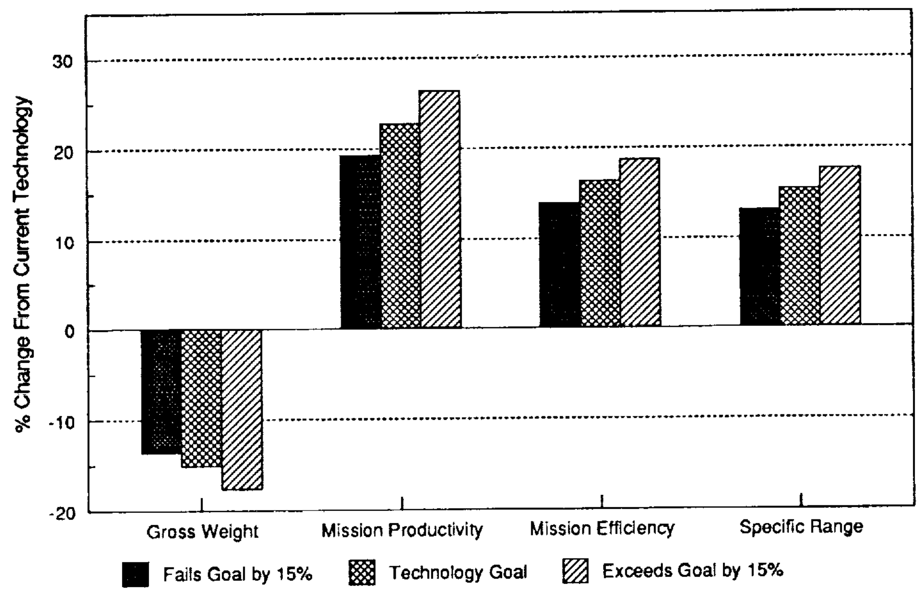


FIGURE 2-40. TILT WING : EFFECT OF A GENERAL WEIGHT REDUCTION

The fairly large change from 15% failure to 15% excess of the goal shows, at least, that the Tilt Wing transport is fairly sensitive to level of materials and structures technology implemented. This seems reasonable because the weight reduction affects virtually every component of the aircraft both directly and indirectly.

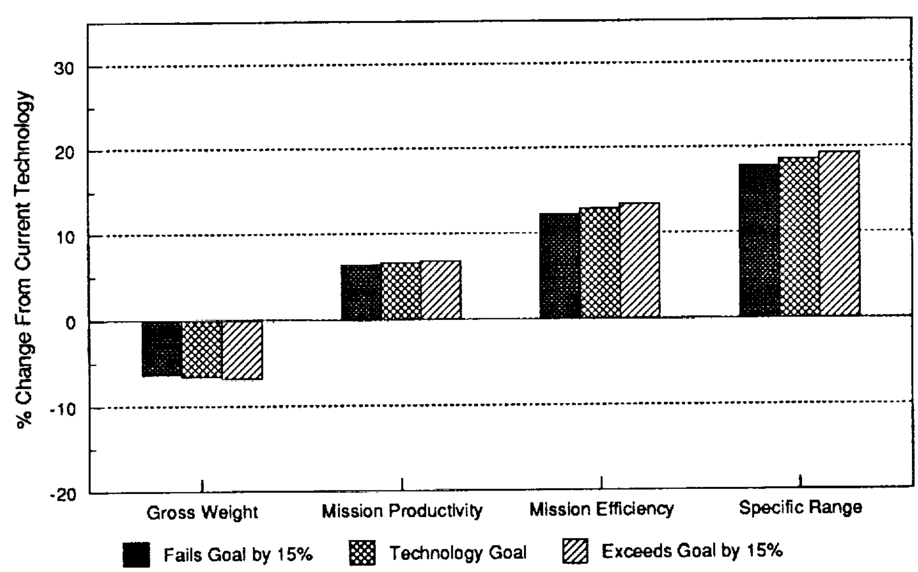


FIGURE 2-41. TILT WING : EFFECT OF A REDUCTION IN WING THICKNESS (18% - 14%) WITH NO CHANGE IN WEIGHT

Wing Thickness Reduction: Reducing wing thickness from 18% to 14%, through an advancement in structures and materials, decreases wing profile drag with no change in wing weight. Figure 2-41 shows the impact of a reduction in wing thickness. This technology uses composites with advanced weaving methods to maintain strength and stiffness. Figure 2-41 indicates that the largest increases are in Mission Efficiency (fuel weight) and Specific Range (fuel consumption).

Reduction in SFC: Figure 2-42 shows the effect of reducing SFC of the Allison T406 turboshaft engine by 35.5% over the current SFC. This value represents Phase III IHPTET goals applied to the T406 by Allison.

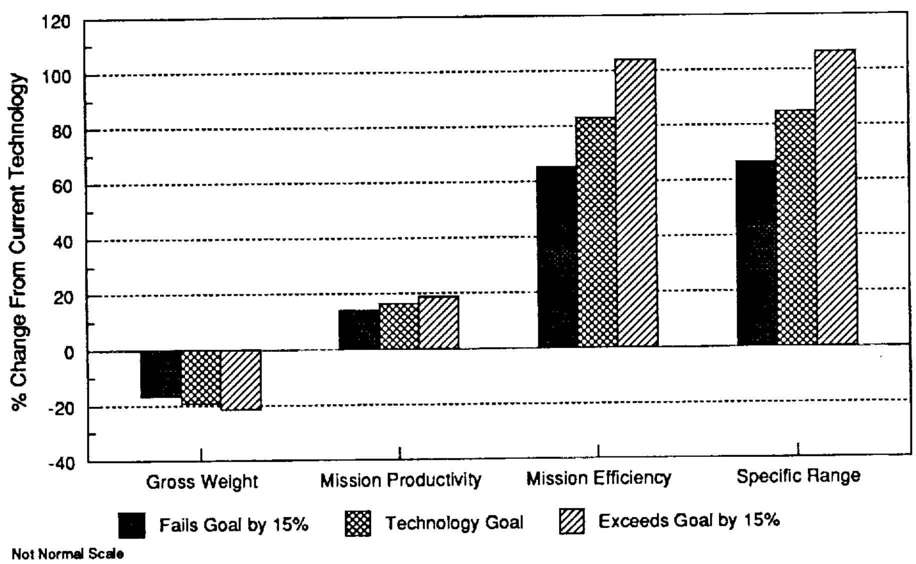


FIGURE 2-42. TILT WING : EFFECT OF A 35.5% REDUCTION IN SFC

The scales of Figure 2-42 are expanded compared to previous graphs. The reduced fuel weight also causes a reduction in empty weight of the same order of magnitude as the general weight reduction, but no component weights were directly reduced. Huge gains in all measures indicate the tremendous impact possible if the IHPTET goals are realized. Although these goals appear to be very difficult to achieve, engine performance remains one of the most significant technology improvement areas.

Increase in Engine Power-to-Weight Ratio (P/W): Figure 2-43 shows the effect of increasing the engine power-to-weight ratio by 100% from the current ratio of 6.3 HP/lb, as specified by the Phase III IHPTET goals.

The four primary engines make up 10.2% of the total empty weight of the current technology Tilt Wing. Increasing the P/W of the engines equates (before resizing) to cutting their weight in half. This means that a 100% reduction in P/W should provide a 5% decrease in empty weight (before resizing). Figure 2-43 shows an almost 20% increase in Mission Productivity reflecting an equivalent decrease in empty weight. This shows a large dependence of the empty weight on the weight of the primary engines due to changes in the weight of the drive system, engine installation, wing, etc.

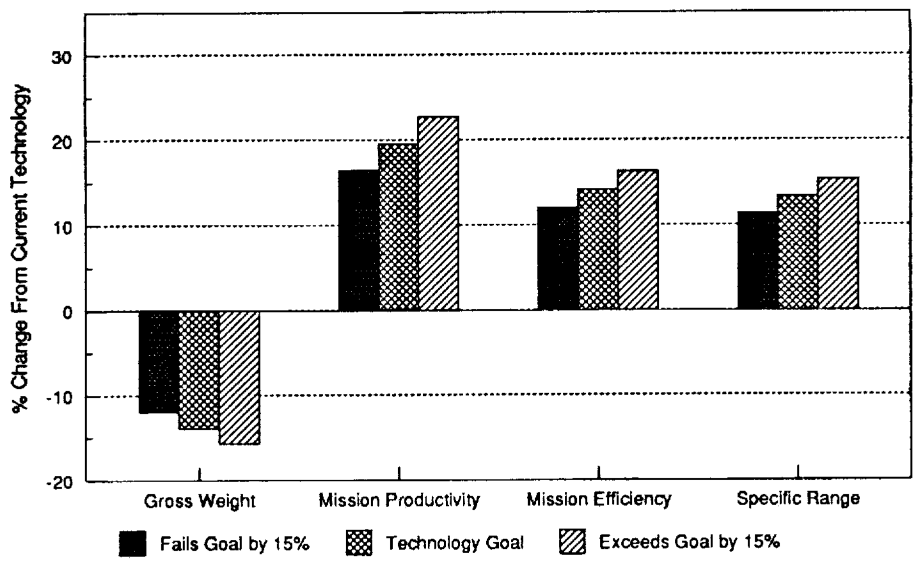


FIGURE 2-43. TILT WING : EFFECT OF A 100% INCREASE IN ENGINE POWER-TO-WEIGHT RATIO FROM 6.3 HP/LB

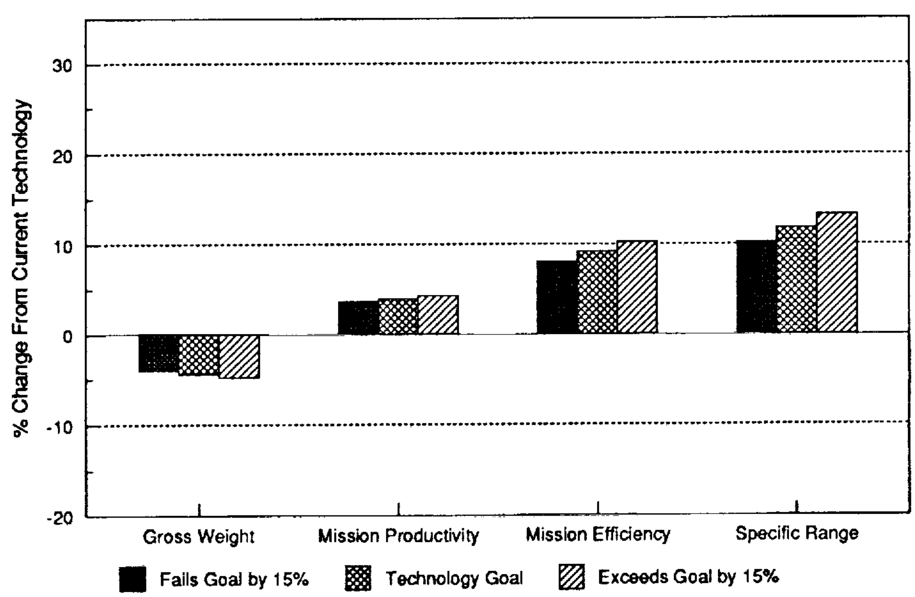


FIGURE 2-44. TILT WING : EFFECT OF AN INCREASE IN CRUISE EFFICIENCY (η_{CR}) by 8.3% to .855

Increase in Prop/Rotor Cruise Efficiency: An 8.3% increase in cruise efficiency, η_{CR}, from a baseline value of .79 at 450 KTAS reflects the application of several advanced technologies. Along with a two-speed gearbox utilized in the current technology design, the rotor will achieve the desired increase in η_{CR} by utilizing counter-rotating rotors, improved planform shapes, and advanced airfoil sections.

Figure 2-44 shows the effect of increasing η_{CR} by 8.3%. As expected, the highest gains are in Mission Efficiency and Specific Range, due to decreased fuel flow. This does not reflect changes in the measures of effectiveness as large as other technologies presented. However, only a slight variation in η_{CR} occurs due to the difficulty in improving it without compromising hover performance. Thin airfoil sections will reduce C_T/σ_{max}, leaving reduced maneuverability margins in helicopter flight mode. The modest gains achieved by this small increase in η_{CR} indicates the sensitivity, hence the importance of this parameter to the effectiveness of the Tilt Wing. The advanced technology coaxial prop/rotor shown in Figure 2-45 also reduces the torque over the current technology prop/rotor which would result in additional weight savings of the drive system. Coaxial rotors also effectively reduce induced power compared to a single rotor of the same diameter.

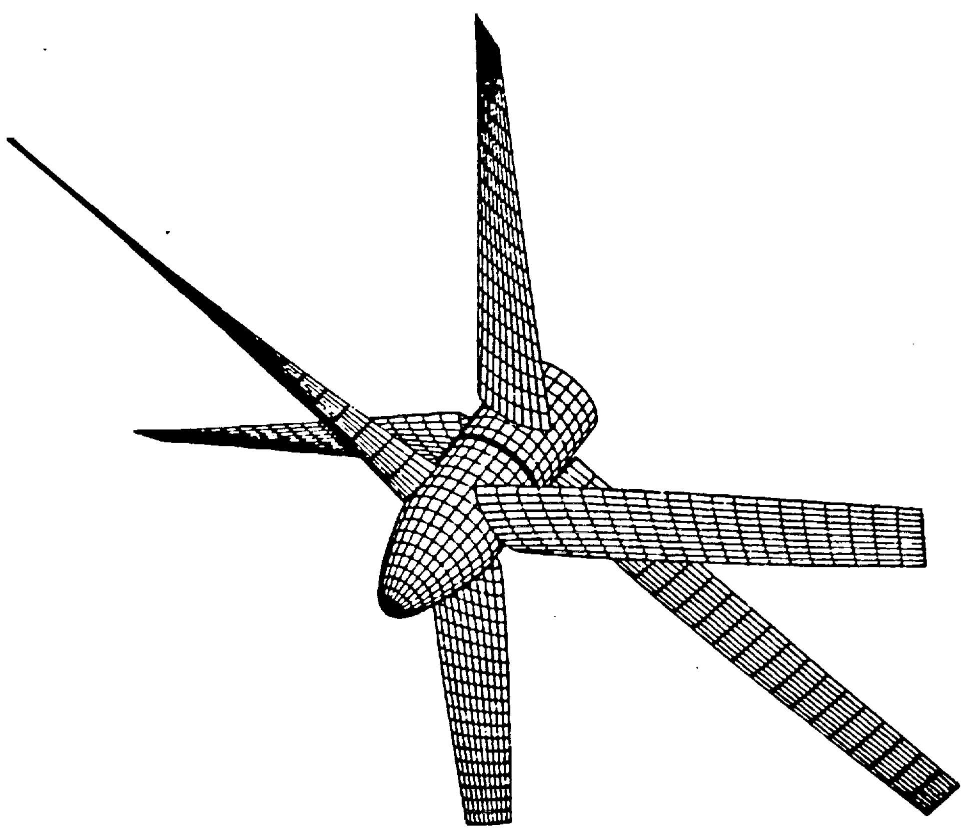


FIGURE 2-45. EXAMPLE OF AN ADVANCED COAXIAL PROP/ROTOR

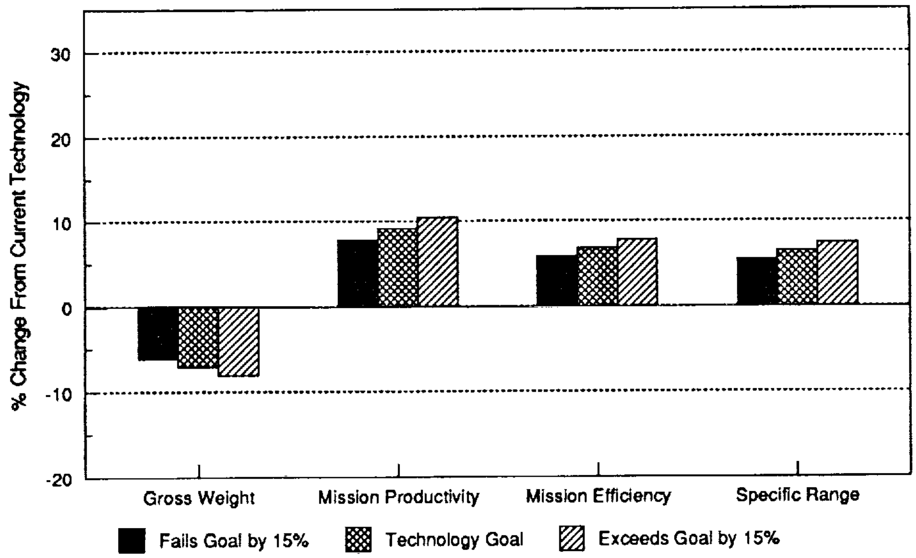


FIGURE 2-46. TILT WING : EFFECT OF A 20% REDUCTION IN GEAR BOX WEIGHT AND 25% IN DRIVE SHAFT WEIGHT

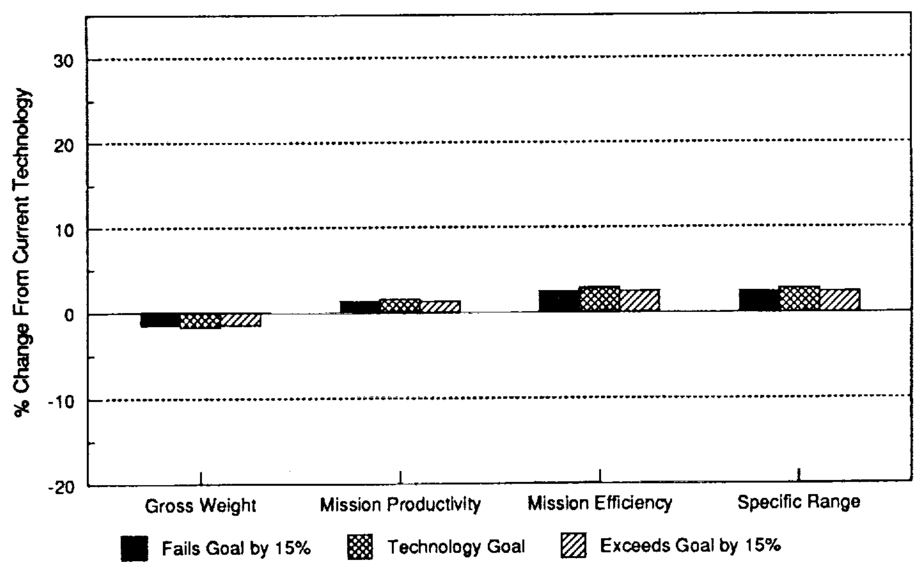


FIGURE 2-47. TILT WING: EFFECT OF INCREASING WING AIRFOIL M_{DD} TO 0.75 FROM 0.714.

Reduction in Drive System Weight: The drive system represents the single heaviest component in the Tilt Wing, mainly due to the two-speed gearbox and the high power requirements in cruise. The Advanced Rotor Transmission (ART) goals dictated a 20%

reduction in total gearbox weight and a 25% reduction in total shaft weight[14]. Based on current progress in the ART program, these goals appear achievable. Figure 2-46 shows the effect of the ART goals on the measures of effectiveness.

Although the drive system represents a larger percentage of the empty weight than the primary engines, the ART goals do not effect the measures of effectiveness as strongly as the IHPTET engine weight reduction. This is for two reasons. The IHPTET goals represent a 50% reduction in engine weight, while the ART goals represent less than a 25% reduction in drive system weight. Also, more Tilt Wing subsystem weights are driven by the weight of the engines than the drive system.

Increase Wing Drag Divergence Mach Number (M_{DD}): The current technology Tilt Wing utilizes a supercritical wing section with a zero-lift M_{DD} of 0.714. Figure 2-47 shows the effect of using an airfoil with the same incompressible lift and drag properties as the current technology Tilt Wing, but with a higher M_{DD}.

The highest Mach number that is achieved during the Tilt Wing's mission is 0.698 at a lift coefficient of 0.20. Thus the wing, although close to M_{DD}, does not exceed it with current technology (see Figure 1-25). Therefore, Figure 2-47 shows only small gains in the measures of effectiveness when the M_{DD} is increased. Increasing the M_{DD} of the airfoil allows cruising at a higher altitude if the wing were the only consideration. Since the prop/rotor must also be considered, the reduction in cruise propulsive efficiency will outweigh the reduction of drag obtained at a higher altitude. The combination of improved wing and prop/rotor efficiency would improve the effectiveness of the aircraft simply by allowing to cruise at higher altitudes. Only increased speed capability will require development of airfoils which delay M_{DD} beyond current capabilities.

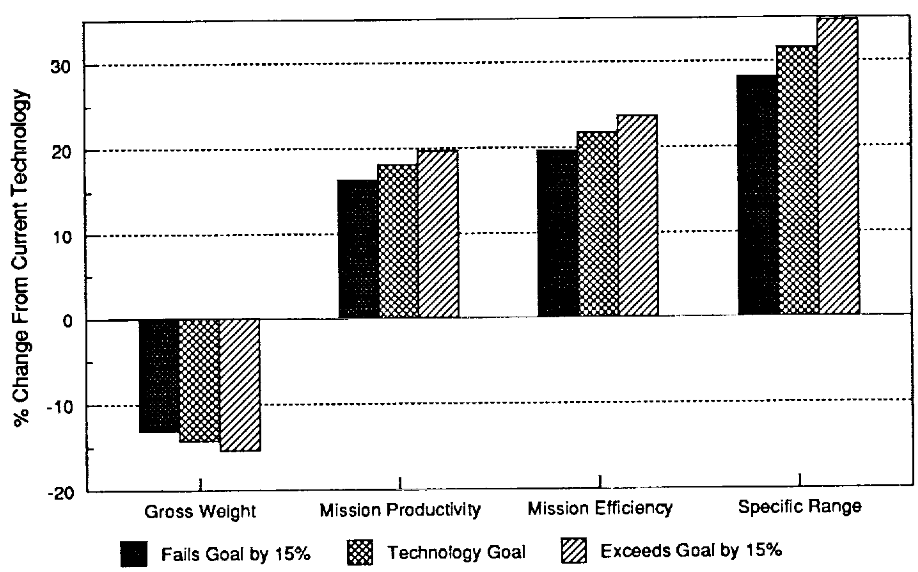


FIGURE 2-48. TILT WING: EFFECT OF INCREASING CONVERSION WING LOADING TO 120 PSF FROM 90 PSF.

Increase in Conversion Wing Loading: The amount of wing area needed to carry the Tilt Wing through conversion, and especially reconversion is generally much more than desired for cruise at high speed. Figure 2-48 shows the effect of increasing conversion wing loading (equal to takeoff wing loading) from 90 psf to 120 psf.

This decrease in wing area results in a huge increase in Mission Efficiency and Specific Range, as the large decrease in cruise drag would dictate. The large increase in Mission Productivity reflects direct reductions in drive system and propulsion weight due to lower cruise power required. In fact, hover sizes the engines in this case, not cruise as before. The exact technology needed to reduce the wing area may arise through several means. Possible solutions include a circulation control wing (utilizing the excess power needed for cruise) or a geared-flap arrangement which allows the wing to move independent of the rotors.

Application of Active Flight Controls: As described in previous sections, tail volume coefficients from previous Tilt Wing designs determined the size of the current technology Tilt Wing. It is estimated that the application of active flight controls will allow a 15% reduction in empennage size. Figure 2-49 shows the results of this reduction.

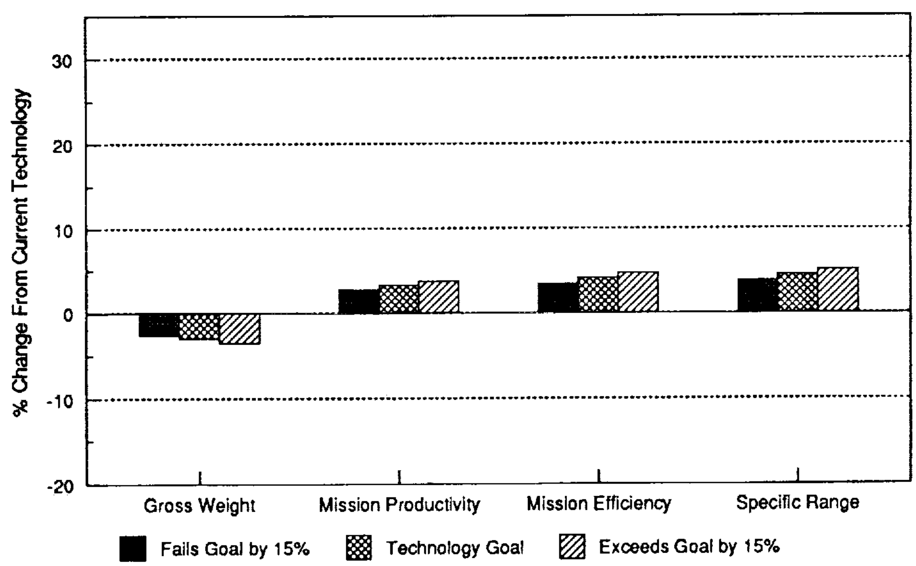


FIGURE 2-49. TILT WING : EFFECT OF REDUCING EMPENNAGE SIZE 15% DUE TO APPLICATION OF ACTIVE CONTROLS.

The effect on the measures of effectiveness is small, but noticeable. Note that the smaller empennage affects Mission Productivity and Mission Efficiency similarly, denoting a reduction in structure weight and an increase in cruise efficiency, due to reduced drag.

Rotor/Wing-

General Weight Reduction: Figure 2-50 shows the impact of a general weight reduction reflecting materials and structures technology in 2003. As with the Tilt Wing, Mission Productivity shows the largest gain.

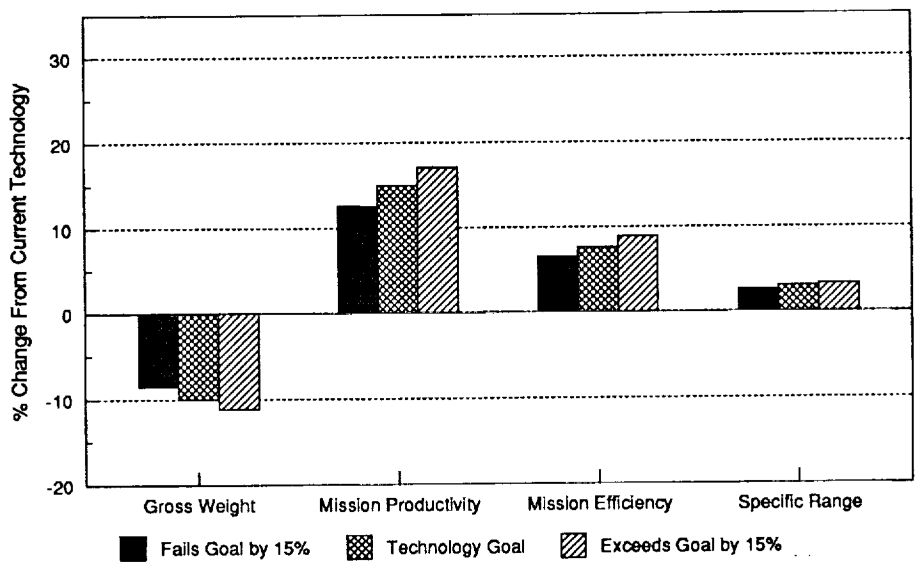


FIGURE 2-50. ROTOR/WING: EFFECT OF A GENERAL WEIGHT REDUCTION

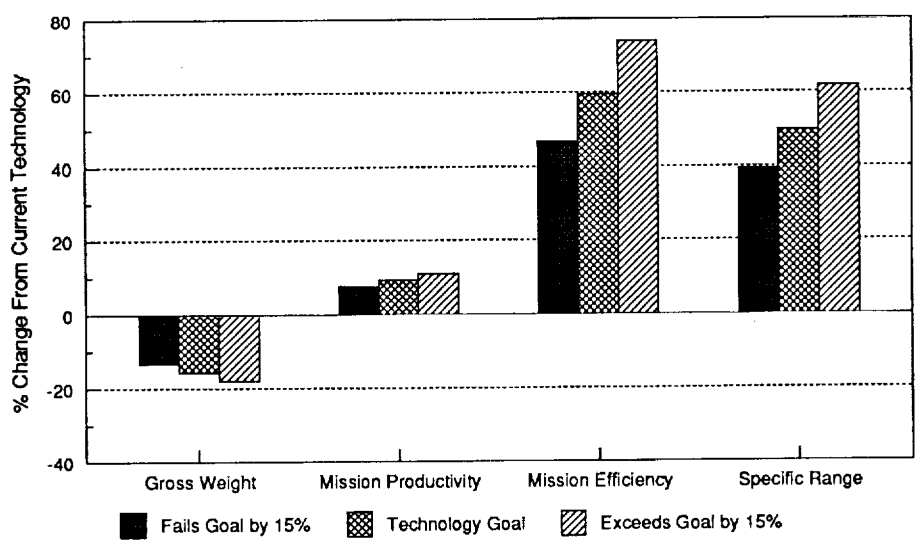


FIGURE 2-51. ROTOR/WING: EFFECT OF A 30% REDUCTION IN SFC

Although the component weight reduction for Rotor/Wing is essentially the same as the Tilt Wing, the effect on the measures of effectiveness is much less. This results because the mission requirements yield a lighter aircraft, thus there is less weight to reduce than was the case with the Tilt Wing. Figure 2-50 shows the result of a general weight reduction on the Rotor/Wing in the ground attack mission. The results indicate a large increase in Mission Productivity, but not as large as the Tilt Wing. This is due to both the ground attack mission and to the Rotor/Wing concept. The Rotor/Wing has fewer subsystems which, compared to the Tilt Wing, are relatively independent from each other in the sizing process. The Mission Efficiency and Specific Range show little variation due to only small changes in the wing and rotor geometry.

Reduction in SFC: Figure 2-51 shows the effect of a 30% reduction in engine SFC from a range of 0.66 in hover to 0.84 in cruise. This reduction satisfies the IHPTET goal for a low-bypass ratio turbofan engine. This technology realizes advancements in both engine technology and in the Rotor/Wing concept which will allow a higher bypass ratio engine. Again, these goals appear very difficult to achieve.

Figure 2-51 is not in normal scale. The reduction in SFC results in huge increases in Mission Efficiency and Specific Range, while resulting in smaller, but substantial, improvements in Mission Productivity and gross weight. The changes in the measures of effectiveness are smaller than seen in Figure 2-42, due mainly to differences in the cruise and duration requirements of the ground attack mission.

Increase in Engine T/W: Figure 2-52 shows the effect of a 120% increase in T/W for the Rotor/Wing. This represents an equivalent 54.5% reduction in engine weight for the same power requirements. The 120% increase in T/W represents the IHPTET for a low-bypass ratio turbofan engine.

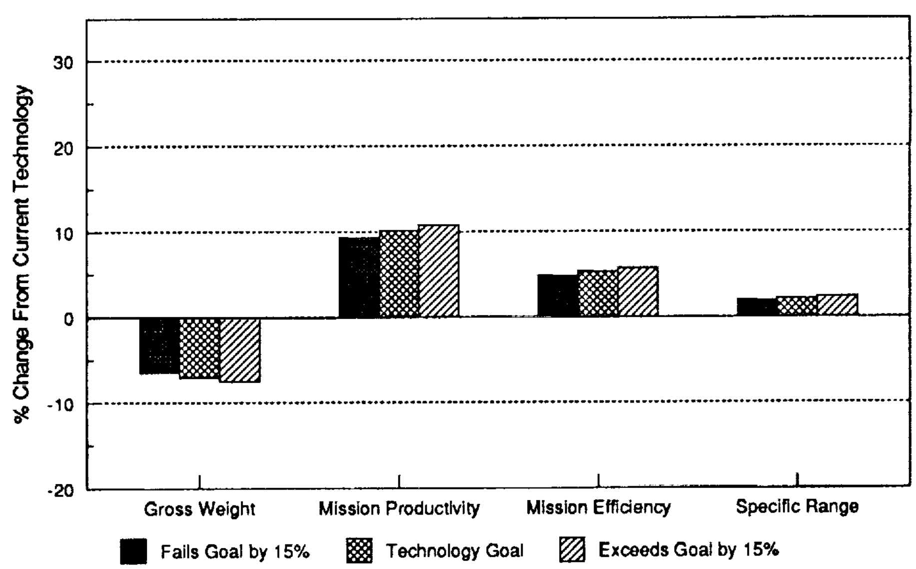


FIGURE 2-52. ROTOR/WING: EFFECT OF A 120% INCREASE IN ENGINE THRUST-TO-WEIGHT RATIO

The larger increase in engine T/W for the Rotor/Wing over the Tilt Wing, produces a smaller change in the measures of effectiveness. The reaction-drive rotor, without a drive train, has fewer parts directly associated with the primary engines. Therefore, the Rotor/Wing's engine weight does not effect as many components as does the Tilt Wing's.

Decrease in Cruise Wing Drag: Figure 2-53 shows a 12.3% decrease in cruise wing drag, which represents the drag of an airfoil with the same 18% thickness, but with a sharp trailing edge. This occurs due to the reduction in the blade drag coefficient from 0.018 to 0.011, noting that the blade area represents only 35% of the wing reference area. The excess power in cruise could allow bleed air to supply boundary layer control (BLC) to the stopped rotor blades and the centerbody. The pressurized ducts in the rotor facilitate the incorporation of a BLC design.

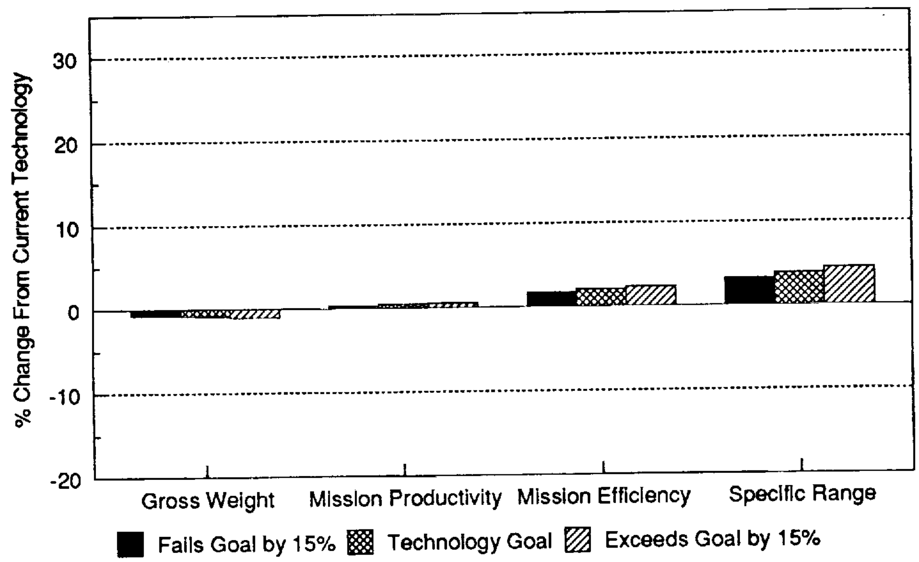


FIGURE 2-53. ROTOR/WING: EFFECT OF A 12.3% REDUCTION IN CRUISE WING DRAG

Figure 2-53 shows almost no effect on any of the measures of effectiveness by decreasing wing drag. The ground attack mission requires a 400 kts dash for only 50 nm. The rest of the mission is hover, 40 kts helicopter mode flight, and 140 kts best range flight. Wing profile drag is not as large a factor as rotor profile drag, or induced drag. Also, the wing represents only 34% of the parasite drag. While large, this percentage reduces the total parasite drag reduction in this case to only 4.18%. This could be more important for a longer range mission.

Increase in Conversion Wing Loading: The conversion wing loading is one of the main considerations when sizing the Rotor/Wing. Unfortunately, addition of high-lift devices or other means of reducing conversion wing loading is not possible. This is because the centerbody rotates while carrying the full weight of the aircraft. Increasing the conversion wing loading from 65 psf to 90 psf requires replacing the centerbody with alternate lifting surfaces. These surfaces provide lift during conversion, carrying the weight of the aircraft, while the rotor stops. Because these surfaces provide lift more efficiently than the centerbody, they can be made smaller, thus reducing drag.

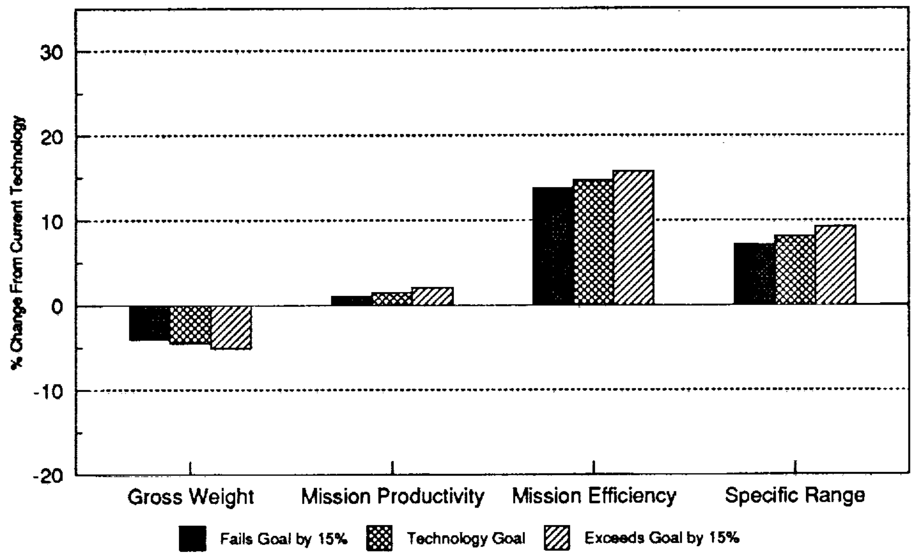


FIGURE 2-54. ROTOR/WING: EFFECT OF INCREASING CONVERSION WING LOADING TO 90 PSF FROM 65 PSF

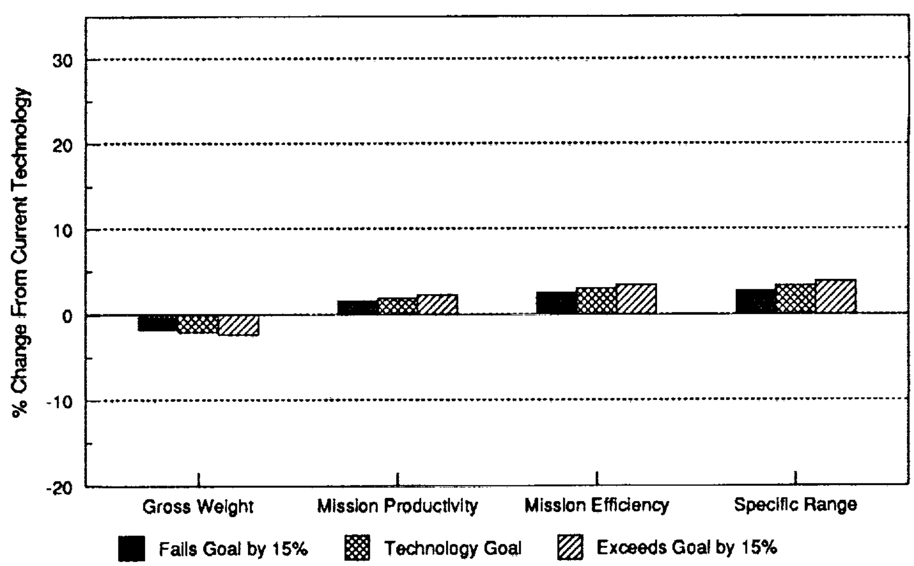


FIGURE 2-55. ROTOR/WING: EFFECT OF A 15% REDUCTION IN EMPENNAGE SIZE

Figure 2-54 shows very little gain in the measures of effectiveness, with the exception of Mission Efficiency (a reflection of less cruise wing area, and therefore, drag). The merit of this configuration lies in aircraft and rotor dynamics during conversion. Since the angle of attack of the lifting surfaces is independent of the rotor disk plane, the rotor is off-loaded in forward flight, reducing vibration. At conversion speeds, the lifting surfaces completely off-load the rotor prior to stopping. This configuration does not require the pitch up into autogyro mode as before, making conversion much smoother and less restricted. Analysis of this configuration using CAMRAD JA shows great promise during conversion, in regards to vibration alleviation. This reduction may also allow a two-bladed configuration (which was previously not considered due to large rotor vibration in helicopter mode), which would further reduce the cruise drag.

Application of Active Flight Controls: Figure 2-55 shows the result of a 15% reduction in horizontal and vertical tail size through active controls. Little effect on the measures of effectiveness is shown, although Mission Efficiency and Specific Range are affected slightly more than gross weight and Mission Productivity. Again, the decrease in tail size does not significantly affect Mission Efficiency or Specific Range because of the ground attack mission. Also, the empennage does not represent a very large fraction of the gross weight, therefore, a 15% reduction in empennage size will not significantly affect Mission Productivity.

Identification of Critical Technologies

The study of achievable technology goals identifies which technology areas will provide the greatest benefit if implemented into the Tilt Wing and the Rotor/Wing. Certainly any advancements in engine technology will increase the effectiveness of both concepts. The engine manufacturers admit that the Phase III IHPTET goals are very aggressive, and therefore actual improvements in fuel economy and T/W may be significantly lower. Increases in allowable conversion wing loading help both concepts, but for different reasons. The Tilt Wing benefits from a decrease in cruise wing drag, and the Rotor/Wing benefits through easier conversion.

The general weight reductions can only be realized if the future concepts use the advanced materials and structures effectively. Current applications of advanced composites have failed to realize weight or cost savings. These advancements, along with the engine advancements will benefit all aircraft concepts, not simply the high-speed rotorcraft concepts. Therefore, the means by which the Tilt Wing and Rotor/Wing become more effective as a transport or ground attack aircraft compared to conventional aircraft, is by reducing the penalty to convert at low speeds from helicopter to fixed-wing flight. The Tilt Wing has shown gains in efficiency over other concepts, and the Rotor/Wing has shown gains in ease of conversion. A different, more cruise-intensive mission would also show significant increases in Mission Efficiency and Specific Range for the Rotor/Wing with a reduced conversion wing loading. The two most successful VTOL concepts currently flying, the Harrier and the Tilt Rotor, do this, but with penalties in hover and high-speed flight respectively. For the Tilt Wing and Rotor/Wing, increasing the wing loading needed for conversion achieves the necessary reduction in those penalties.

The synergistic application of all achievable technologies to the Tilt Wing and the Rotor/Wing results in the following percentage increases in concept effectiveness from current technology, shown in Table 2-11:

	Tilt Wing	Rotor/Wing
Gross Weight (lbs)	30780	21124
Mission Productivity	92%	29%
Mission Efficiency	195%	108%
Specific Range (Nm/lb)	222%	62%

TABLE 2-11. INCREASES IN MEASURES OF EFFECTIVENESS DUE TO ADVANCED TECHNOLOGY

The values presented above do not indicate that one concept is better than the other. They do indicate the improvements that achievable technologies may gain for the Tilt Wing in the military transport mission and Rotor/Wing in the ground attack mission.

Tables 2-12 through 2-15 presented below give a general description of the basic design and performance parameters of the advanced Tilt Wing and the advanced Rotor/Wing. These correspond to tables 2-2 through 2-5.

Gross Weight	30,780 lbs
Max Sea Level Power	3,353 HP, SL STD
Disk Loading	35 psf
Wing Loading	120 psf
Aspect Ratio	7
Hover Tip Speed	820 fps
Cruise Tip Speed	500 fps
Cruise Prop Efficiency	0.855
Flat Plate Drag	9.08
Maximum L/D	9.81
Cruise SFC	0.261
Optimum Dash Altitude	15,000 ft
Optimum Best Range Alt	20,000 ft

TABLE 2-12. ADVANCED TECHNOLOGY TILT WING DESIGN PARAMETERS

Gross Weight Maximum Sea Level Thrust Rotor Figure of Merit Rotor Radius Centerbody Radius Disk Loading Wing Loading Aspect Ratio Hover Tip Speed Flat Plate Drag Maximum L/D Cruise TSFC	21,124 lbs 7,264 lbs 0.63 (defined as P_{ind}/P_{tot}) 28.00 ft 2.80 ft 90 psf 70 psf 13.38 650 fps 11.05 12.93 0.59

TABLE 2-13. ADVANCED TECHNOLOGY ROTOR/WING DESIGN PARAMETERS

Weight in lbs

GROUP	TILT WING
WING MAIN ROTOR BLADES M/R HUB & HINGE TAIL ROTOR HORIZONTAL TAIL VERTICAL TAIL BODY GROUP ALIGHTING GEAR NACELLES (*STRUCTURAL GROUP*) ENGINE PROPELLER INSTL. PROPULSION SUBSYS FUEL SYSTEM DRIVE SYSTEM & TILT FLIGHT CONTROLS (*SYSTEMS GROUP*) FIXED WEIGHT	1207 689 853 **** 67 3786 810 833 (8448) 1059 **** 320 255 2533 1705 (5872) 4900
EMPTY WEIGHT	19220
PAYLOAD OPERATING ITEMS FUEL	6000 1470 4090
GROSS WEIGHT	30780

TABLE 2-14. ADVANCED TILT WING WEIGHT BREAKDOWN

Weight in lbs

GROUP	ROTOR/WING
WING	3682
MAIN ROTOR BLADES	****
M/R HUB & HINGE	****
TAIL ROTOR	****
HORIZONTAL TAIL	899
VERTICAL TAIL	363
BODY GROUP	2039
ALIGHTING GEAR	704
NACELLES	286
(*STRUCTURAL GROUP*)	(7973)
ENGINE	490
PROPELLER INSTL.	****
PROPULSION SUBSYS	546
FUEL SYSTEM	235
DRIVE SYSTEM & TILT	0
FLIGHT CONTROLS	1165
(*SYSTEMS GROUP*)	(2346)
FIXED WEIGHT	3000
EMPTY WEIGHT	13409
PAYLOAD	3000
OPERATING ITEMS	970
FUEL	3745
GROSS WEIGHT	21124

TABLE 2-15. ADVANCED ROTOR/WING WEIGHT BREAKDOWN

Identified technologies which keep the concept from achieving any portion of the defined mission are considered critical.

Tilt Wing- The VZ-2, the CL-84 and the XC-142 have proven the Tilt Wing concept. There is only one major difference between MDHC's Tilt Wing and previous Tilt Wing designs. The technology requires a two-speed gear box, or some other means, to significantly lower the propeller rpm during cruise. The dash requirement, which is significantly faster than any current or previous Tilt Wing of Tilt Rotor aircraft, demands a large reduction in propeller rpm due to high rotor inflow and larger-than-hover power requirements. The two-speed gear box allows the rotor performance to be optimized for both hover and cruise without reducing engine rpm. Without development of this technology, prop/rotor-driven concepts will be prohibitively inefficient at these high cruise speeds.

Rotor/Wing- Realization of the Rotor/Wing concept, although never flown, requires some technologies that have not been demonstrated. All of these relate to conversion. The Rotor/Wing maintains control through use of collective and cyclic pitch control, an elevator for attitude control, and valves for diverting the gas from the rotor tip to the engine.

Reduction of the rotor induced pitch and rolling moments during the first and last few revolutions of starting and stopping the rotor has been demonstrated during model wind tunnel tests. Regardless of the means used to alleviate this, cyclic pitch control to maintain zero-lift on the rotor during conversion represents a critical technology.

During conversion, the hot gas must be diverted from the rotor tip jets to be used as propulsive thrust. The gas diversion schedule which maintains the proper rotor rpm, while providing necessary propulsive thrust is critical to successful conversion.

Finally, a rigid, reaction-drive rotor, which incorporates cyclic pitch control, needs to be fully investigated. Both the XV-9 and the XH-17 demonstrated the feasibility of reaction drive rotors with cyclic pitch control. However, the need for fixed-wing flight puts an added constraint on the Rotor/Wing. The XV-1 utilized a gimballed rotor that locked the gimballed degree of freedom in compound helicopter flight. The Rotor/Wing design will lock and stop in forward flight. The difference in rotor rigidity between these two seemingly similar concepts may provide unforeseen problems in helicopter mode.

In any event, successful conversion of the Rotor/Wing without a critical technology convertible engine, dictates the use of a reaction-drive rotor system with cyclic control. This rotor must also have the ability to stop in forward flight (while fully unloaded) while diverting the gas from the rotor tip to be used as propulsive thrust.

SECTION III

ENABLING TECHNOLOGY PLAN

TECHNOLOGY DEVELOPMENT NEEDS

Introduction

This section assesses the technology development requirements for each of the two concepts. Each technology is described and its impact on vehicle effectiveness assessed. Since the study emphasizes technology development needs, rather than the vehicles themselves, organization of the section is by technology discipline for ease in reference, then divided by vehicle type within the technology. Time lines provide an assessment of the major tasks within each technology discipline, and also identify the institutions best suited to accomplish a specified task. Finally, a summary table of technology development requirements for each concept and those which are common to both are identified, prioritized, and assessed for risk and payoff.

Aerodynamics

Technology Assessment- The following narrative explains the technological goals which require attention to develop an efficient, high-speed Tilt Wing or Rotor/Wing concept.

The Tilt Wing concept flew successfully in several configurations, although it possessed a significantly lower cruise speed than required here. The development of required technologies reflects required improvements as opposed to critical technologies for this concept.

To fly at high-speed and at reasonable altitudes, the Tilt Wing requires development in two areas. **Efficient high-speed flight using rotors requires a design that provides good propulsive efficiencies at flight Mach numbers of .75 for lightly loaded rotors.** Propeller development in the late 1950's achieved propulsive efficiencies of .8 during flight tests at flight Mach numbers of .95 on thin-sectioned propellers.[24] These results indicate that the goal should be achievable. Tip-speed reductions using a two-speed gear box or perhaps a variable diameter rotor reduce the compressibility effects due to the otherwise high tip-Mach number. Combinations of thin airfoils, planform design, and advanced configurations may provide improvement in the high-speed efficiency.

The second area, development of airfoils with high drag-divergent Mach numbers, allows a thicker, lighter weight wing which still provides a high-speed cruise capability. The configuration allows only very slight wing sweep, so airfoil design alone must delay drag divergence. The airfoil requirements will depend to a large extent on the structural design of the wing for minimum thickness. Hence, the drag divergence requirements may significantly ease if the wing can be made structurally thin. A thin wing is preferable to a thicker one because of both compressible and incompressible drag benefits, providing the stiffness requirements are met.

Tilt Wing performance reflects a compromise between conversion characteristics and cruise requirements. Past examples of the concept sacrificed cruise wing loading for reasonable conversion characteristics. This resulted in much more wing area than desired for efficient cruise. Increasing cruise wing-loading would significantly improve cruise efficiency and would lead to greatly reduced gross weight. The literature repeatedly suggests that the use of high-lift systems can reduce the area required of the wing for conversion. While certain chord to diameter ratios appear as limits, the aerodynamics suggests that the wing size required for conversion can be significantly reduced. Delaying the onset of wing stall and/or increasing the lift for a given angle of attack served as the basis for large wing areas on past tilt-wing prototypes. The use of high-lift systems or a means of preventing wing stall by flying the wing, represent two possible ways to reduce the required conversion wing size. **Increasing the wing loading represents the most significant step toward improving the attributes and effectiveness of the Tilt Wing.**

The Rotor/Wing, while never flown, grew out of extensive testing covering a seven year period. Wind tunnel tests included helicopter flight, conversion, and fixed-wing flight modes. Conversion was achieved with a dynamically scaled model. Through these tests, acquired information suggested the feasibility of the concept and identified potential aerodynamic deficiencies. There are no critical aerodynamic technologies that need developing.

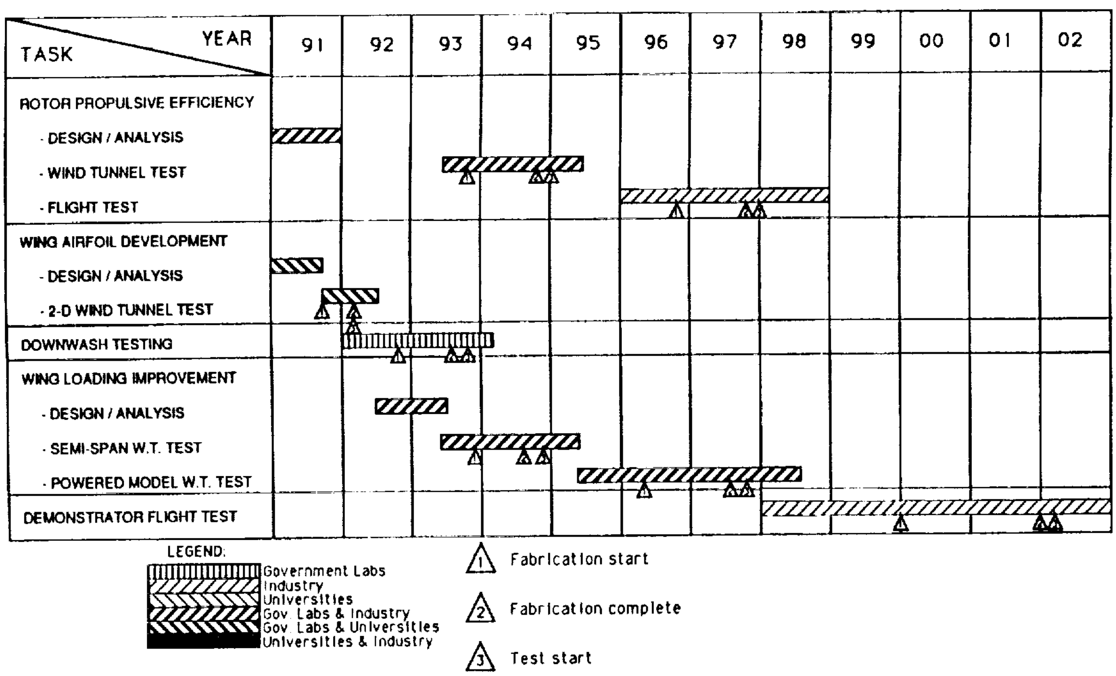


FIGURE 3-1. AERODYNAMICS TECHNOLOGY DEVELOPMENT TIMELINES: TILT WING

As with other concepts, the ability to operate in helicopter and fixed-wing modes necessitates compromise. The Rotor/Wing requires a large center body to carry adequate lift during conversion to support the aircraft. This alleviates the requirements for the blades to provide lift as the rotor stops, thus reducing the amount of asymmetric lift created. It also simplifies the system by eliminating the need for circulation control as required by X-Wing. Despite the advantages of the large centerbody for conversion, it reduces the effectiveness of the rotor in helicopter mode and significantly reduces the wing loading in cruise. The latter effect increases cruise drag and results in poor ride quality at high speeds (although for a close air support mission, the wing loading is comparable to existing CAS aircraft). **Reducing the centerbody size, while maintaining required conversion characteristics will increase the effectiveness of the concept by weight and drag.** Improved aerodynamics of the centerbody or configuration changes could lead to a reduction in the centerbody size.

Operating the blades in both helicopter and fixed-wing modes presents the problem of operating the stopped retreating blade airfoils in reversed flow. The X-Wing solved the problem using circulation control to orient the airfoil in the proper direction. The Rotor/Wing concept uses elliptical sections to ignore the apparent reversed flow over the stopped retreating blade. While this solution works, it results in increased drag due to the lack of a sharp trailing edge. **Developing a scheme to operate as a rotor and still maintain fixed-wing efficiency after stopping would increase the efficiency of the concept by reducing its drag.** Methods to accomplish this include circulation control in the fixed-wing mode only or a mechanically deployable sharp trailing edge.

Required Tools- The analysis tools required to analyze complex high-speed rotorcraft include CFD codes and data base development for code validation.

1. Analysis of tilting wings with new or improved high-lift devices in the presence of a rotor requires complex grid systems. This problem resembles the problem of rotor-body interaction which currently receives attention from researchers. Although, it includes the motion of the rotor-body at the same time. The problem becomes even more complicated if treated in ground effect.

2. High-speed rotorcraft will tend to remain in helicopter mode only a short while due to mission suitability. Additionally, since hover usually does not size the propulsion systems at these speeds, helicopter efficiency assumes a secondary role to cruise. Design of prop/rotors for efficient cruise at high speeds requires more sophisticated analysis than currently exists. The analysis must target low disk loaded prop/rotors in high-speed axial flow.

3. Determining and predicting the effects of rotor downwash requires both experimental and analytical methods. High-speed rotorcraft tend to optimize at higher disk loadings than helicopters and generally consist of multiple rotors. Transport configurations may size to high gross weights. Data from past high-speed rotorcraft prototypes provide only conflicting observations of the effect of high disk loading induced velocities on ground objects. Additional work in this area must be accomplished in order to provide definitive information to use for disk loading limit determination.

4. Validation of analysis codes will require substantiating databases. Some information exists based on previous Tilt Wing and Rotor/Wing configurations, however, these tend to be configuration dependent (narrow range of disk loadings etc.). To achieve a broader understanding of the major parameter dependencies will require model scale development.

5. Historically, handling qualities during low-speed flight and conversion, especially in-ground-effect, determined the success or failure of the concept. In some cases, poor handling qualities resulted in loss of the aircraft, killing the program. To reduce the risk associated with a flying prototype and to aid in selection of future concepts for development, flight simulation models play an important role and need developing along with the concept.

Required Resource Assessment- Most of the basic information required to develop the previously described technology currently exists. Therefore, aerodynamic technology requires no basic research to determine causal relationships. Research institutions such as government laboratories, universities, and industrial research laboratories possess the capabilities to develop computational codes required for analysis. These codes include analysis of tilting wings with high-lift devices in the presence of a rotor and airfoil development. Experimental data bases will require large, probably sophisticated models and will require cooperation between government and industry. Figures 3-1 and 3-2 present time lines of the required aerodynamic technologies and their major subtasks.

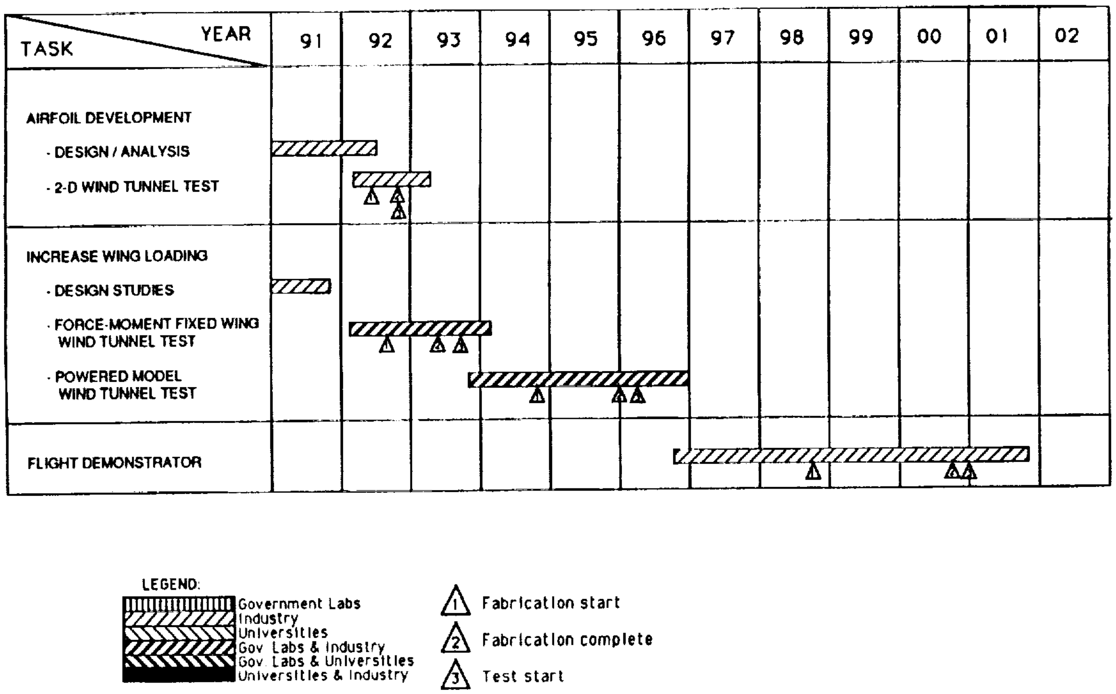


FIGURE 3-2. AERODYNAMICS TECHNOLOGY DEVELOPMENT TIMELINES: ROTOR/WING

Propulsion

Technology Assessment- Both concepts studied require no new propulsion development. Development of both concepts may proceed using engines available today. However, as evidenced from the advanced technology trade studies (Figures 2-40 to 2-55) improved technology engines significantly impact the effectiveness of the concepts and their weight. The IHPTET program currently seeks to improve engine SFC and weight through advances in materials, manufacturing and improved aerothermodynamics. **The relative impact of an advanced technology engine on the attributes of both concept establishes the importance of this research and development area.** The IHPTET goals for the reduction of weight and SFC are depicted in Figure 1-22.

The Tilt Wing using turboshaft engines, requires significantly differing tip speeds in cruise and hover. One solution, advocated previously, suggests the development of a two-speed gear box to maintain constant engine operating RPM while reducing rotor tip-speed in high-speed cruise. Operating RPM significantly affects the efficiency of current engines, limiting practical deviation from 100%. The V-22 reduces engine RPM by about 80% in cruise to reduce rotor tip-speed and maintain good rotor propulsive efficiencies. However, high-speed flight, at 400-450 KTAS requires tip-speed reductions of around 50%, well below that practical for current engines. The two-speed gear box solution, while viable, adds weight complexity and increased maintenance requirements. **Development of a turboshaft engine which operates efficiently over a wide range of operating RPM could provide a much better solution to this problem.**

The propulsion requirements of the Rotor/Wing very significantly between hover and cruise. Hover requires engine exit conditions of high temperature And pressure ratios found with low by-pass ratio engines (B.R. 1). This requirement, and the subsequent engine selection, results in less than optimal engine performance characteristics in cruise. This difference may not greatly affect a configuration designed for a short cruise duration mission, but it becomes increasingly important for long range missions. Efficient cruise dictates using a high by-pass ratio engine. The extent to which these conflicting requirement can be resolved will influence the utility and effectiveness of the concept. The IHPTET program, in seeking to improve SFC, targets some of the improvement through turbofan engines possessing the same engine exit conditions while using higher by-pass ratios. So, this program already seeks to resolve the conflicting requirements previously addressed.

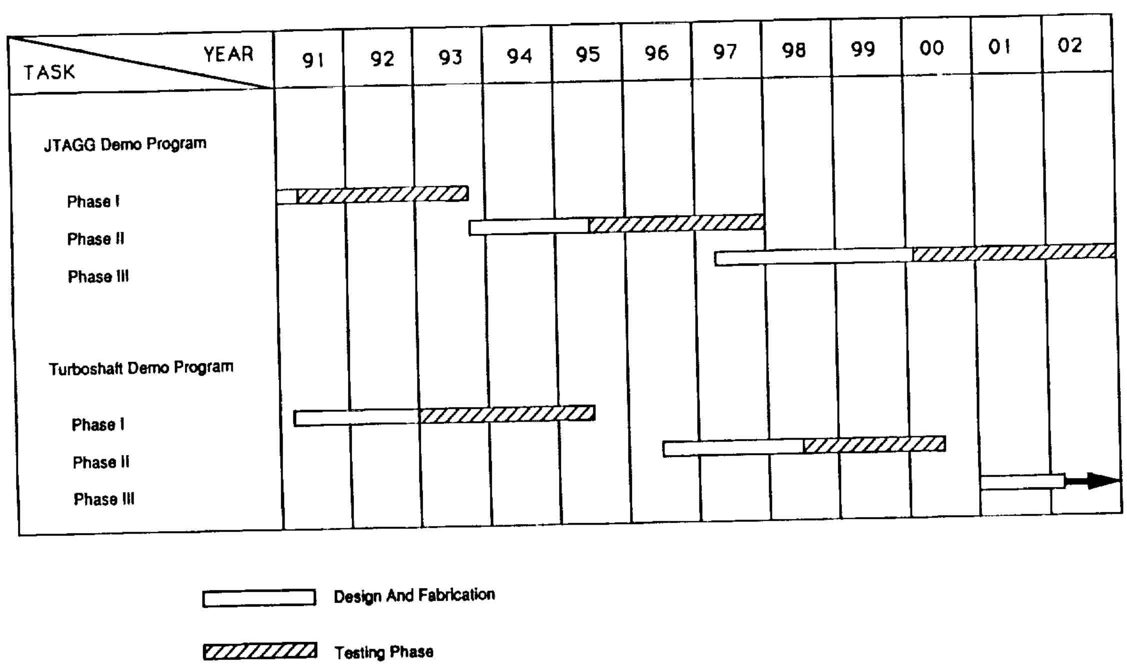


FIGURE 3-3. IHPTET TIMELINE[14]

Tip-turbine driven, ducted fans offer another way to improve cruise efficiency. This type of fan, demonstrated in the XV-5A, fan-in-wing, effectively increases the mass flow of the engine for given engine fuel flow rate, thus improving the overall efficiency of the propulsion system. Additionally, this means of propulsion maintains its drive system independence which makes it so attractive to begin with. Quantifying the effectiveness of this system will require detailed trade studies to examine efficiency, weight, installation concerns and other aspects. However, it represents a viable, low-risk alternative.

Required Tools- Engine development programs such as IHPTET are in place with technology goals as previously described. The participating engine manufacturers defined the resources required to include development of advanced computer predictive codes, experimental materials programs, and configuration design. Further coordination between airframe companies and engine companies will help define the impact of the IHPTET goals to specific applications and identify specific, possibly, unique engine requirements. Detailed discussion of specific tools required is deferred to IHPTET program documentation.

Required Resource Assessment- Successful completion of the IHPTET program will incorporate cooperative efforts from all the major institutions. Basic research into materials properties development of new materials and analysis methods should grow out of efforts at universities and government laboratories from requirements generated by industry. Close association between government and industry will lead to application in the form of engine technology demonstrators. Resources from both of these institutions will be needed to develop, test, and demonstrate the new technology. Engine test facilities and possibly flight demonstrators, as accomplished with propfan development, will improve chances for success. Figure 3-3 depicts the timeline of major IHPTET tasks, culminating in a technology demonstrator by 2003.

Drive Systems

Technology Assessment- The drive systems proposed for the Rotor/Wing and Tilt Wing are proven concepts and are feasible using present technology. The jump from technical feasibility to economic practicality will require improvements in both systems.

Rotor/Wing: Relatively long runs and sharp turns in the Rotor/Wing ducting cause a significant stagnation pressure loss due to viscous effects and thermal losses. Internal flow characteristics and optimized designs must receive further investigation in order to reduce pressure losses throughout the system and identify potential thermal "hot spots". Improvements in the surface condition and contouring of the ducts will minimize viscous effects, while application of materials with low thermal conductivity and thermally reflective coatings promises to reduce thermal losses.

Previous designs used metal ducts hard mounted to the aircraft structure. This eased manufacturing and provided some thermal isolation for the structure, but was a heavy solution. The ability to manufacture ducts integrally within the structure would provide significant weight savings. This will require development of new manufacturing techniques to produce hollow structures capable of withstanding the high temperatures and having suitable insulating properties and surface conditions.

Metal matrix composites exist which meet or exceed the 1050 deg. F temperature requirements for Rotor/Wing ducting.[25] Economical manufacturing processes must be developed to make these materials an affordable option. Thermal barrier coatings on conventional composites (graphite, fiberglass) provide a promising alternative. These coatings demonstrate good insulative and corrosion resistive properties in similar applications. Economical and consistent application techniques require further development.

The Rotor/Wing ducting system uses three types of exhaust seals: one in the diverter valves, one in the mast, and one at each of the blade roots (see Figure 2-29). The AV-8B uses similar seals in its hot gas ducting system, so this does not represent a critical technology. The rotating-trough diverter valve proposed for the Rotor/Wing differs significantly from the turning-vane type used on past designs (Figure 3-4). This proposed valve features equally efficient operation in both diversion directions. Research will be necessary, however, to optimize the geometry to reduce losses at intermediate positions of the trough.

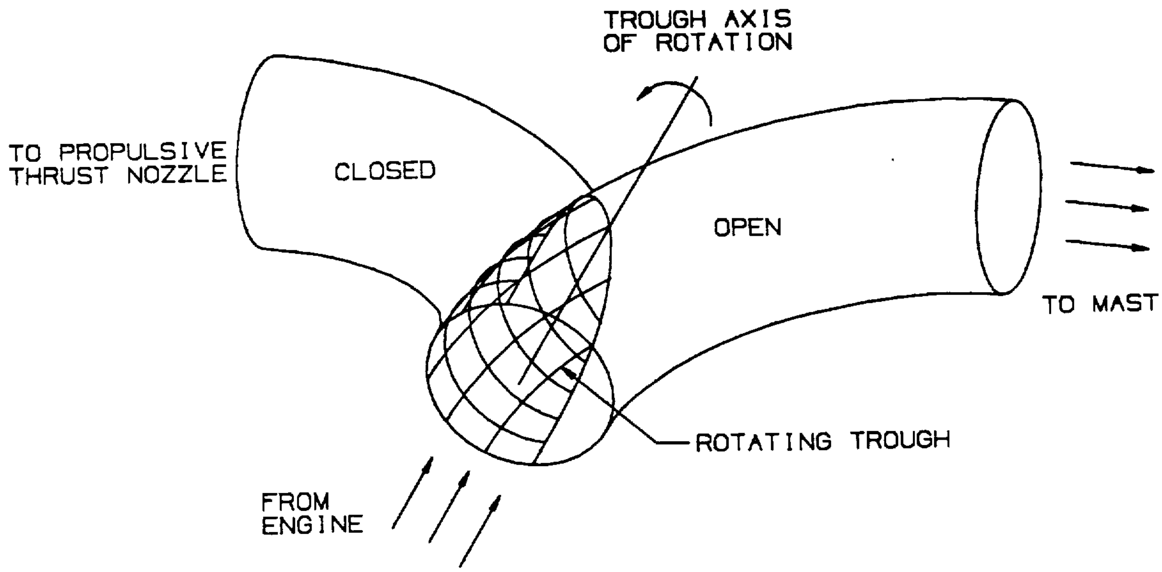


FIGURE 3-4. ROTOR/WING DIVERTER VALVE

Tip-jet geometry has a great deal of potential for optimization. Turning vane spacing, cross sections, and locations are topics that will require further investigation. Jet exit area will need to be controlled based on the pressure and mass flow rate through the duct, especially during OEI situations. A simple system would actuate all three blades simultaneously based on the mass flow rate through the mast. A shutter would vary from closed in forward flight to fully open at max power hover. A more complex approach would cyclically control each shutter independently to maintain fully expanded flow through the entire 360 deg. travel of the blade. This would require an actuator that could operate in a high-G environment at a frequency of 1/rev. The actuator would most likely have to be electrically powered because of its location in the rotor.

Tilt Wing: The Tilt Wing drive system utilizes a conventional transmission with a two-speed capability. The success of the Tilt Wing as a transport or cargo aircraft will be determined by its cost effectiveness. It is essential that the drive system weight and reliability be improved from present standards to improve its chances of acceptance in the market. The Advanced Rotorcraft Transmission (ART) program, currently under way at MDHC to enhance the performance of rotorcraft transmissions, is investigating many technologies to meet this objective.

New gear tooth forms, under development, offer higher load carrying capabilities than those currently in service. Corrosion and wear surface treatments are being investigated which increase scoring resistance. Rough forging of gear teeth improves the potential strength of nonforged teeth by a factor of five. All these will lead to smaller, lighter gears capable of carrying higher loads.

New bearing types and lube systems promise to reduce cost and increase life. Self aligning spherical roller bearings can loosen tolerance requirements reducing manufacturing costs.

Shafts with integral bearing races eliminate the weight of pressed in races. Advanced oil lube systems and even grease gear lubrication promise reduced wear and improved reliability.

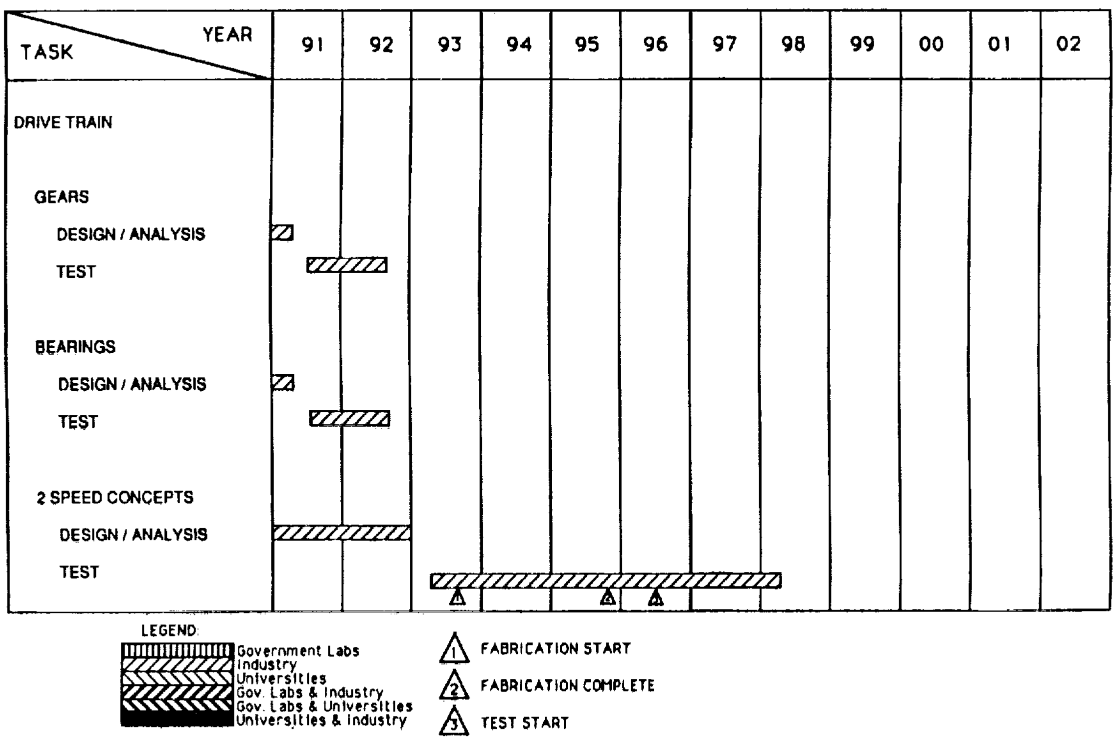


FIGURE 3-5. DRIVE SYSTEMS TECHNOLOGY DEVELOPMENT TIMELINES: TILT WING

Various overrunning and positive engagement clutches for disengaging shut down engines are under development to reduce weight and extend life. Rotor tip-speed limitations to maintain propulsive efficiency require nearly a 2:1 ratio between hover and cruise rpm. A shiftable two-speed transmission, extending the concepts used in automobile automatic transmissions, is the most feasible solution. It is critical that disk and band clutches for a transmission of this type be developed which can handle the torques and speeds found in the Tilt Wing.

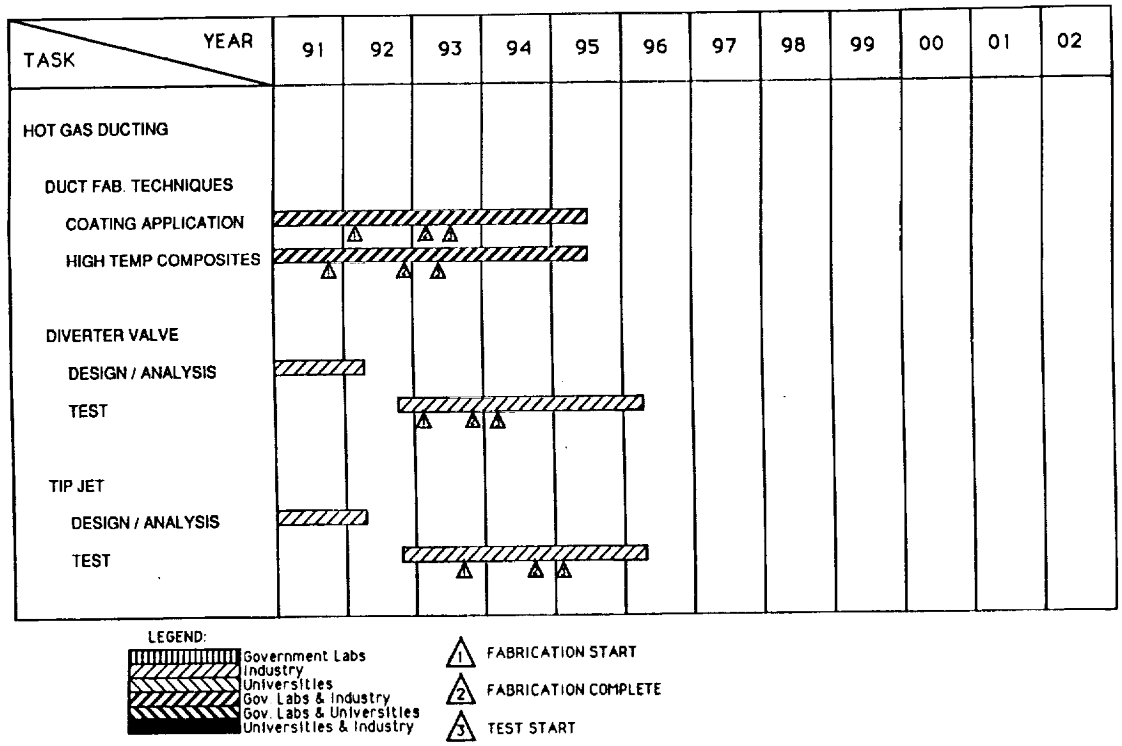


FIGURE 3-6. DRIVE SYSTEMS TECHNOLOGY DEVELOPMENT TIMELINES: ROTOR/WING

Required Tools-

1. Computer programs currently available optimize the size of a given tooth combination or reduction configuration but do not allow comparison of different configurations. Sizing of gearboxes will require optimization routines that process discrete variables, such as number of gearboxes or reduction stages, effectively.

2. Integration of drive train sizing programs with conceptual level CAD programs to generate solid models from sizing program output require development. 3-D models are invaluable in evaluating the feasibility of configurations because they illustrate inconsistencies which present analysis codes are unable to identify. The time required to generate a solid model with any degree of complexity prohibits the number of iterations which would be desirable. Quite often the final configuration of a subsystem is determined early in the design process. However, the specific parameters of the system change continually. Software must be developed to generate the specific geometric entities within the CAD model based on parameters from sizing codes.

3. Subsystems of the future need to be evaluated based on their contribution to the aircraft life cycle cost. Life-cycle cost databases need to be established and relationships developed for all the aircraft subsystems.

4. Testing reaction drive systems will require building full scale test stands. Testing will allow development of experimental data bases and possible parameter variation in which to optimize the duct system.

Required Resource Assessment- As a result of theoretical relationships that have already been established for the technologies previously described, no basic research is required. There is, however, a need for fabrication and testing of component hardware to validate design concepts and develop efficient/affordable manufacturing techniques. Industrial research labs possess the capabilities to build and test components under development. Figures 3-5 and 3-6 show development timelines in the drive system technology areas.

Structures

Technology Assessment- Significant advances in the technology areas of structures and materials will be required to help meet the performance goals of high- speed rotorcraft.

The primary requirement will be to develop thin rotor and wing structures to reduce aerodynamic drag and attain high drag-divergent Mach numbers. Typically, these structural designs will be driven by either a stiffness or a strength requirement. **The judicious application of composite materials in the rotor and wing structures of high-speed rotorcraft is essential in order to meet the design requirements.**

Improvements in the stiffness and strength of composite materials will facilitate the development of rotor and wing structures for the high-speed rotorcraft. **Specifically, the development of higher modulus fibers and increases in the transverse strength of composite materials are required.**

Higher modulus composites are necessary to help meet stiffness requirements with thin wing structures. This is particularly important if aeroelastic stability considerations greatly influence the design requirements.

Composite materials suffer from low strength transverse to the fibers. This leads to significant matrix cracking and delamination in many composite structural designs. Improvements in basic materials processing technology and materials development are required to minimize this undesirable characteristic. Enhancements in materials and processing include the development of higher strength matrix materials and improved fiber-matrix interfacial bonding. In addition, the evolution of new composite material architectures such as three-dimensional weaves and stitched preforms will lead to increased delamination resistance.

Optimal use of composite materials in structural designs for high-speed rotorcraft must be exercised to meet the design goals. Composite materials are often applied in structural designs with a "metals philosophy", i.e., a limited selection of layups (typically quasi-isotropic) are used for which properties are well known. This is done primarily to reduce analysis costs and develop a focused data base for the design methodology. However, this approach limits the potential for weight savings in the design by providing redundant structure for the load requirements.

Composite structures for high-speed rotorcraft must be tailored to carry the necessary loads and provide adequate stiffness to meet aeroelastic constraints. Weight savings are critical to the successful development of these rotorcraft and will be maximized using this approach. In addition, the development of thin rotor and wing structures will be more feasible with the increased design flexibility.

Technology for the manufacture of composite structures will need refinement in order to reduce fabrication costs and improve reproducibility. Thermoplastic composite materials offer numerous novel approaches for fabrication which will require continued development for full-scale production.

Required Tools- Extensive analysis capabilities will be required to examine the stiffness and strength of candidate structural designs.

1. The different stiffnesses and structural coupling effects associated with composite structures must be appropriately modeled to assess stiffness characteristics for aeroelastic considerations. This establishes a requirement for efficient analytical techniques to model the response of composite rotor and wing structures to aerodynamic loads. Advanced finite element modeling techniques provide a comprehensive means of investigating this problem.

2. The failure analysis of composite structures is a difficult task to accomplish. Several reasons contribute to this: (1) modeling the variation of material properties in the individual plies is a formidable effort, (2) accounting for changes in the structural geometry of complex composite structures (eg., stiffeners joined to a wing) presents a challenge, and (3) interlaminar stresses often promote the failure of composite structures and must be analyzed. Thus, advanced three-dimensional modeling techniques are necessary to assess the strength and damage tolerance of candidate composite structures for high-speed rotorcraft.

3. A great deal of scatter (relative to metallic materials) is associated with the strengths of composite materials. Since a number of strength parameters (associated with different failure modes) exist for composites, structural reliability calculations become quite extensive. Probabilistic analysis methods need to be developed and applied for the reliability assessment of composite structural designs.

4. Databases will have to be created to validate the composite structural analysis codes developed. This includes coupon and component tests of representative rotor and wing structures to assess stiffness and strength prediction capabilities. Duplication of full-scale failure modes at this level of testing is mandatory.

Required Resource Assessment- Basic research to improve the stiffness and transverse strength characteristics associated with composite materials is required. Primarily government laboratories and universities should be tasked with this effort. However, the materials industry may also play a role. Universities and the aerospace industry will need to work closely to develop advanced finite element techniques for composite structural analysis. In addition, methodologies for probabilistic analysis of composite structures require attention. Both universities and industry need to contribute to the creation of a composite structures data base for high-speed rotorcraft. Industry will be challenged with the development of proven manufacturing concepts for rotor and wing structures. The development schedule for structures technology is shown in Figure 3-7.

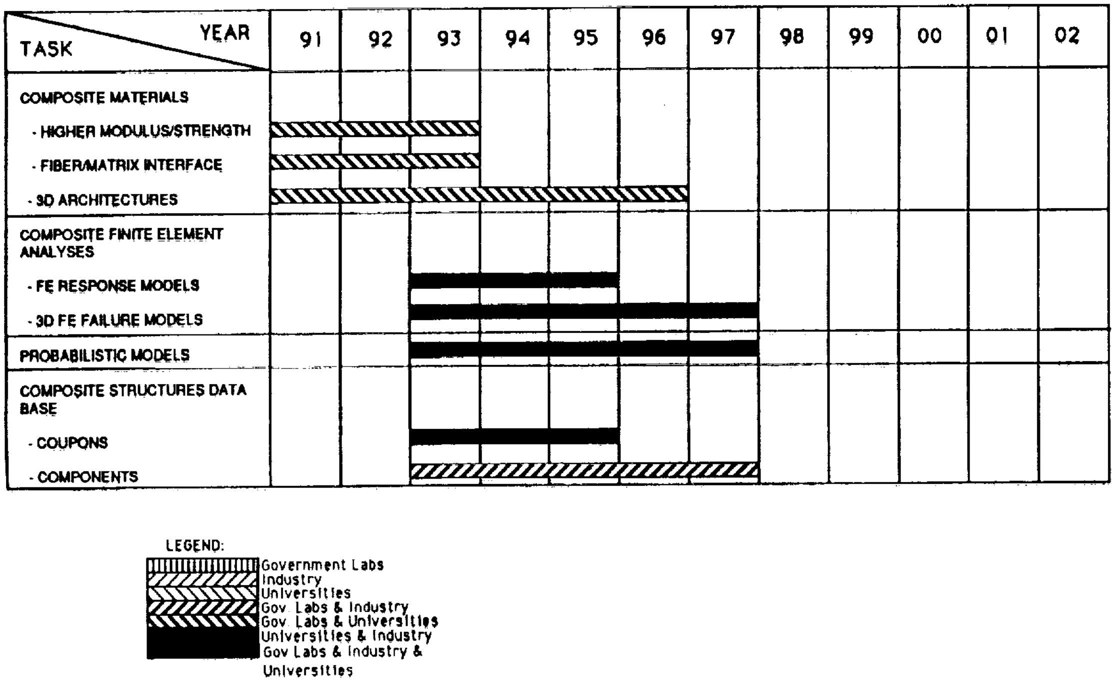


FIGURE 3-7. STRUCTURES TECHNOLOGY DEVELOPMENT TIMELINES

Stability and Control

Technology Assessment- No critical technology needs developing in this area for either concept. **Both concepts would benefit by incorporating active controls.** The use of a fly-by-wire control system allows this option. Active controls would reduce empennage area, thus reducing weight and drag. The effect of this addition, as previously depicted in Figure 2-49, produces only small increases in concept effectiveness. The Rotor/Wing would probably benefit the most from active controls due to the inherently unstable configuration in airplane mode. Additionally, as previously demonstrated through wind tunnel tests in the mid 1960's[7] elevon deflection, during rotor stopping and starting, could provide a means to counter the short term pitch and roll oscillation experienced by the aircraft due to any asymmetric lift produced by the rotor.

Past Tilt Wing configurations experienced reduced yaw control in-ground-effect due to the reduced effectiveness of the wings in close proximity to the ground. The use of spoilers improved the yaw control by killing the wing lift on one side of the aircraft.[22] Using rotor controls such as differential cyclic would improve the yaw control characteristics in all regimes of helicopter flight. This presents a more complicated hub arrangement and requires new control law development over previous Tilt Wing demonstrators, but would significantly improve the low-speed flight characteristics.

Similarly, cyclic control could replace the need for the pitch fan of previous designs. The pitch fan added weight, complexity and drag to previous Tilt Wings. Pitch control, through longitudinal cyclic, would improve the overall effectiveness of the concept. **Trade studies, comparing the benefits of cyclic control against the disadvantages must first be initiated.** Development of this technology requires little risk, as it duplicates technology in place for the V-22 and XV-15.

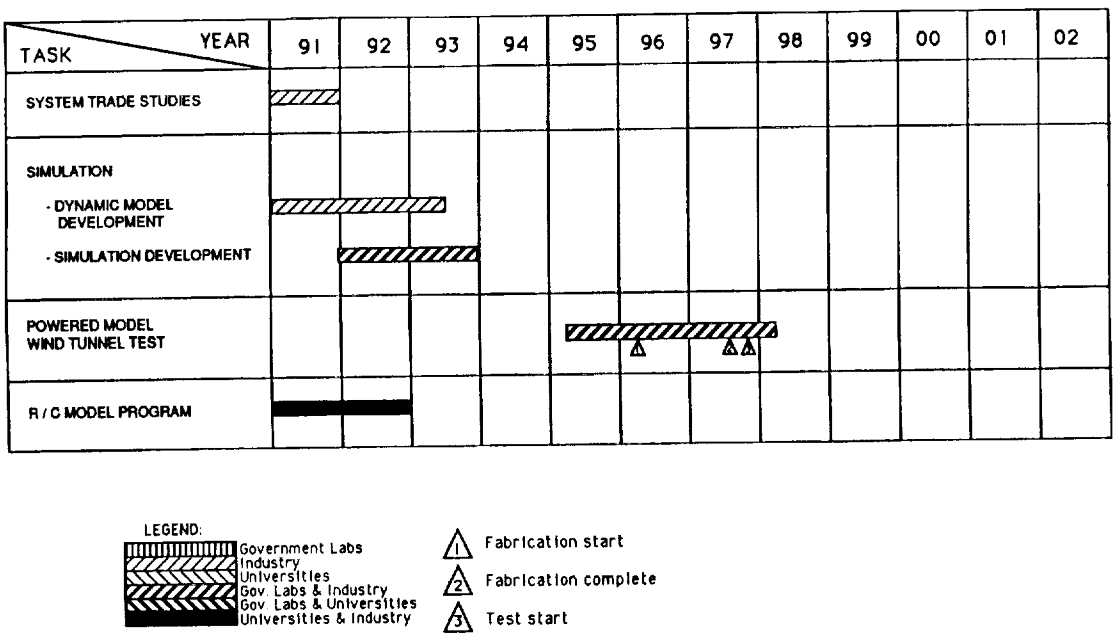


FIGURE 3-8. STABILITY AND CONTROL TECHNOLOGY DEVELOPMENT TIMELINE: TILT WING

Control of the Rotor/Wing in helicopter mode requires use of standard helicopter type controls for roll and pitch. Control moments result from cyclic inputs to the rotor. Yaw control systems will be conventional in control, but evaluation of several concepts for yaw control will be required. Possible configurations include a hydraulically driven tail fan as suggested in early 1960's design studies, an electrically driven tail fan, or a thruster such as found in the NOTAR™ system. Since the yaw control system requires little power (no anti-torque requirements), the system need not be excessively large. **Selection of the appropriate yaw control system requires additional design and trade studies but little in the way of technology development.**

Lateral control of the Rotor/Wing in airplane mode presents a more challenging problem. Previous studies envisioned the use of elevons for lateral control. Wind tunnel tests indicated that the outboard wing panels (blades) could not provide the required control moment when deflected due to flow off the centerbody (aft swept configuration). The forward swept configuration alleviates this problem but may introduce structural divergence or flutter if the outer panels are deflected at high speed. **Development of an effective lateral control system will require technical solutions from aerodynamics, structures and avionics areas.**

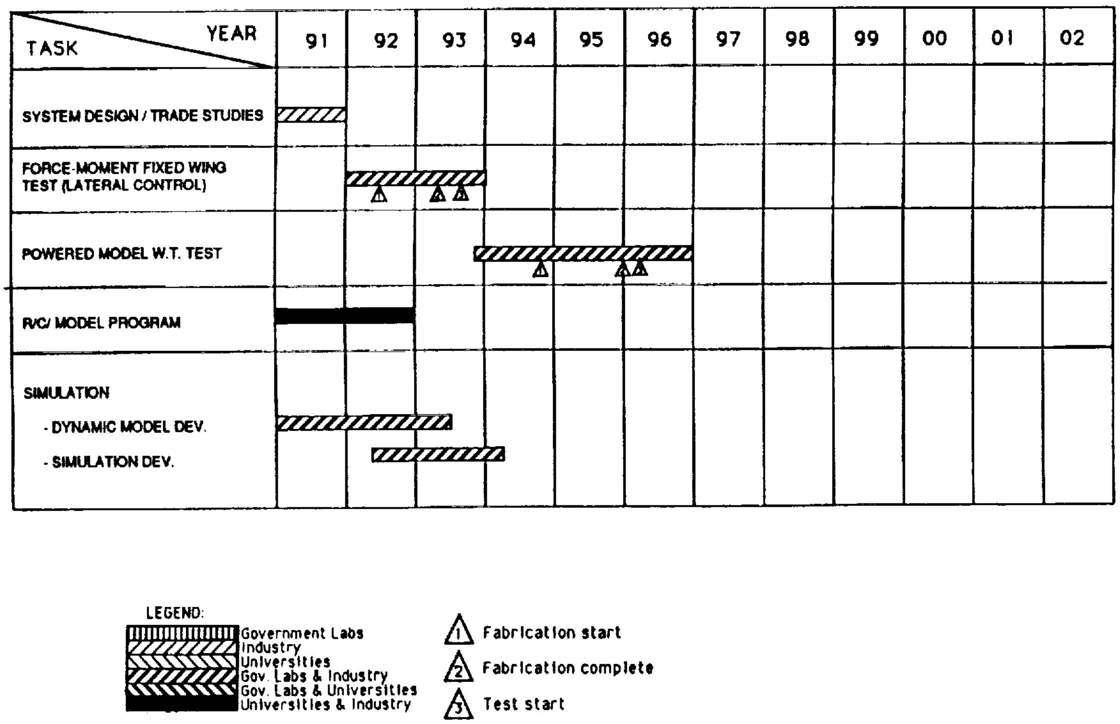


FIGURE 3-9. STABILITY AND CONTROL TECHNOLOGY DEVELOPMENT TIMELINE: ROTOR/WING

Required Tools-

1. For both concepts, flight simulation models will significantly aid development of control laws and in assessing effectiveness of the control systems in all flight modes.

2. Wing tunnel testing must provide important stability and control data for modeling. Testing can be accomplished in existing tunnels.

3. Development of radio controlled models to identify stability and control problems will provide a valuable tool. These models will also provide an inexpensive flight vehicle to try out control system concepts.

Required Resource Assessment- Technology development in this area will rest largely with industry, while government laboratories and resources, and universities will play a supporting, cooperative role. Large-scale wind tunnel models require the use of government wind tunnel facilities to obtain data. Small scale radio controlled model work may best be accomplished with university support. Simulation development and use would most effectively be accomplished by cooperative industry/government laboratory initiatives. The following figures depict timelines required to develop effective stability and control systems.

Control Systems

Technology Assessment- Today's control system technology is sufficiently advanced to meet the needs of the Tilt Wing and Rotor/Wing. There are, however, several areas of development that offer worthwhile improvements.

Self contained pump/actuator packages which eliminate the need for centralized pumps, accumulators, and hydraulic lines are becoming available. These units are self-contained and independent, therefore, damage to one will not degrade or stop performance of the others. Power can be supplied electrically or mechanically. Further development and testing remains to be done prior to system final design.

Digital fly-by-wire control systems are becoming more and more common as their cost and reliability improve. Presently, fly-by-wire systems utilize three independent computers for triple redundancy, and a mechanical or analog electrical backup in case of EMI. Improvements in computer reliability and system survivability may eliminate the need for one or even two of the backup computers, reducing weight and complexity.

The mechanical and electrical backup systems are good candidates for replacement. Electrical backups are susceptible to electrical system failure and mechanical systems are weight prohibitive. Fly-by-light and reduced sensitivity to EMI may eliminate the need for these systems. In the mean time, the emergence of fluidic control circuitry provides a nonelectrical, light weight alternative for backup control. Input signals are transmitted through very small, light weight hydraulic (or pneumatic) lines to the controller whose logic is processed hydraulically (or pneumatically).

Required Tools-

1. Integrated pump/actuator packages need to be certified for use on aircraft. This will require test stands for system evaluation and, ultimately, flight testing.

2. Elimination of any redundancy in the digital control system must be justified by demonstrating acceptable reliability of the remaining components. This will require environmental chambers and vibration test equipment to simulate worst case operating conditions. These simulations will enable identification of and reduction of failure modes and will provide an accurate measure of system reliability.

3. Software must be developed to expedite the analysis and design of fluidic circuits. Circuits must then be built and tested in a "brass board" fashion to validate the software.

4. Development and certification of fluidic backup control systems will require acquisition of component parts from the vendor and laboratory space in which to conduct experiments. Vendor consulting will also be necessary.

5. Simulators will be needed to evaluate the control laws and cockpit integration.

Required Resource Assessment- The theoretical relationships have already been established for the technologies described, therefore, no basic research is required. There is a need for adaptation and testing of new products that are becoming available for use on aircraft. Industrial research labs possess the capabilities to develop and certify commercial hardware. The development timeline shown in Figure 3-10 depicts the control system technology areas with their major milestones.

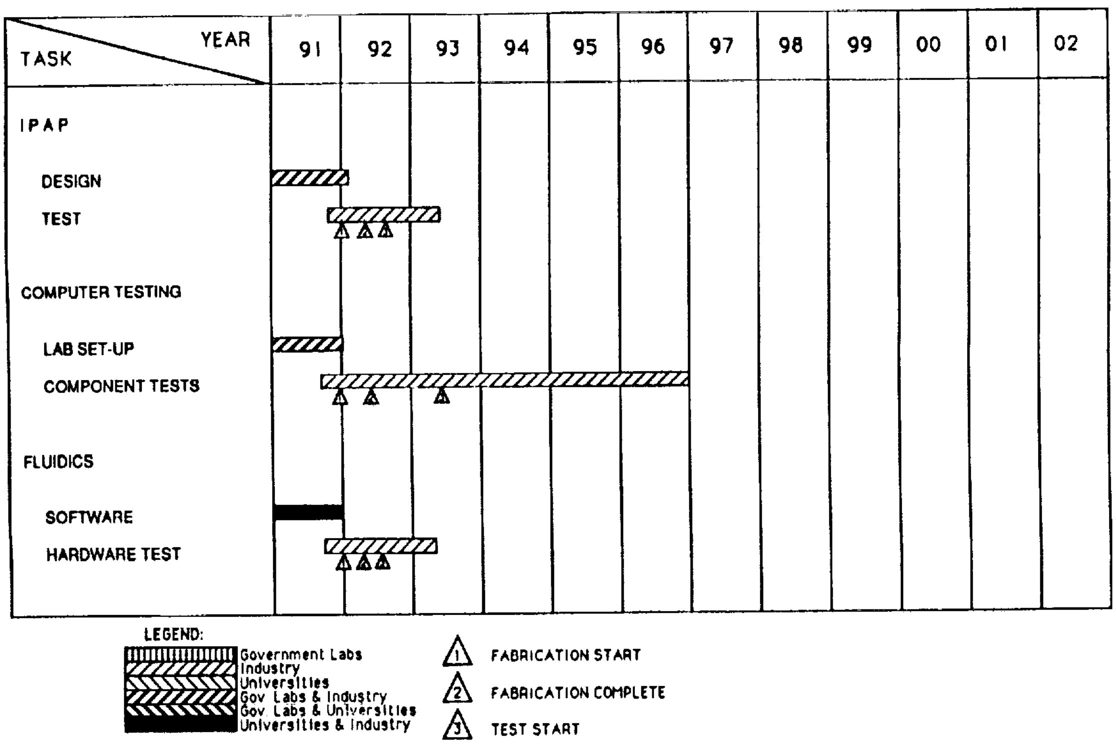


FIGURE 3-10. CONTROL SYSTEMS TECHNOLOGY DEVELOPMENT TIMELINES.

Dynamics

Technology Assessment- The discussion which follows addresses the technologies that will be required to develop Tilt Wing or Rotor/Wing aircraft capable of efficient, safe operations. Since the Tilt Wing concept has been flown in several configurations, the feasibility of the concept is not in question. The question that must be addressed is whether a Tilt Wing aircraft can be designed to achieve high-speed flight. The Rotor/Wing concept, on the other hand, has not flown. However, extensive wind tunnel testing of a rotor/wing concept was carried out in the mid 1960's. These tests included simulations of the helicopter, autogyro, and fixed-wing flight modes, and conversion from the autogyro mode to the fixed-wing mode. Additional analysis and testing has been performed for similar concepts, such as stopped rotors, folded rotors, and the X-wing.

The most critical Tilt Wing flight regime (and the most difficult to model) from a dynamics viewpoint is the conversion from hover to forward flight. **Accurate dynamic analysis of conversion is important for predicting loads, vibration, and stability of the aircraft.** The tilting of the wing coupled with spinning rotors produces Coriolis forces on the rotor blades. These forces are then transmitted to the engines and controls of the aircraft. Furthermore, the tilting of the rotors results in transient changes in what is already an unsteady flow field. The resulting aerodynamic forces and moments are the primary sources for vibratory loads that are transmitted throughout the airframe.

With the use of thin airfoils for the rotor blades and advanced blade planforms to increase the performance of the aircraft, construction methods that employ composite materials will surely be needed to achieve the desired stiffness and strength properties in the rotor blades. **Because of the structural couplings due to material anisotropy that result from the use of composite layups, a rotor dynamic model that includes these effects will be essential.** The fidelity of the dynamic modeling of the structural couplings has a direct influence on the validity of the analysis results.

In order to achieve higher forward speeds, a thinner wing than has been used in the past is being suggested for the Tilt Wing design. A thinner wing may result in some loss of structural stiffness. **To avoid whirl-mode instabilities, careful analysis will be required to determine the couplings between the wing, pylon and rotors.** This will be particularly important if a variable-speed rotor is used on the aircraft. As the rotor speed is changed, the dynamic coupling of the rotor and wing due to gyroscopic and Coriolis forces will change.

The selection of a hub configuration for the Tilt Wing aircraft will require careful consideration of the dynamics and control of the rotors. Among the possibilities available for a hub design are gimballed, articulated, hingeless, and bearingless configurations. The factors that will influence this selection will include the following: (1) method of roll control, (differential thrust or cyclic pitch); (2) aeroelastic stability; (3) hub geometry; and (4) loads and vibration.

The most critical portions of the Rotor/Wing flight regime are the stopping and starting of the rotor. Wind tunnel tests have found that large roll moments were transmitted to the fuselage during the first few revolutions after starting the rotor, and during the last few revolutions before stopping the rotor. These moments were found to be due to the lateral movement of the center of pressure on the rotor and centerbody. **In order to make the Rotor/Wing a viable concept, the transition roll moments must be controlled.** In previous Rotor/Wing designs, the rotor stopped at a high angle of attack, so that the centerbody could develop sufficient lift to support the aircraft. The magnitude of the moments produced during rotor start and stop could be greatly reduced if the need for centerbody lift could be reduced through the use of additional lifting surfaces that are capable of developing lift independent of the rotor. Thus, the centerbody (and rotor) angle of attack could be reduced. The severity of the moments could also be reduced by accelerating and decelerating the rotor quickly through this critical flight regime. To control the moments that are produced, two candidate methods have emerged. The first is to apply cyclic rotor controls in a manner similar to the control of blade pitch on conventional helicopters. A second approach is to use fixed-wing type control surfaces to generate moments that counter the roll moments.

Because of the requirement that any possibility of aeroelastic divergence in the fixed-wing mode must be eliminated, Rotor/Wing aircraft are designed with unusually stiff rotor blades. The vibratory loads produced by the rotor are dependent on the aircraft mode of operation, the blade loading, and the forward speed. **Stiff rotor blades do not greatly attenuate the vibratory loads transmitted to the rotor hub, and therefore are responsible for high vibration levels in helicopter mode and conversion.** Vibration levels during conversion may be reduced if the rotor can be unloaded quickly, and the conversion to fixed-wing mode can be performed at the lowest possible speed. Therefore, the addition of lifting surfaces with controllable angle of attack would allow the rotor to be unloaded at lower speeds, and could significantly reduce vibration levels during conversion. For helicopter-mode operations, higher harmonic control could be used to reduce the vibration levels. Twenty-five years of higher harmonic controls development has shown it to be an effective means for reducing vibrations in helicopters.[26,27] These methods could be adapted for application to the Rotor/Wing.

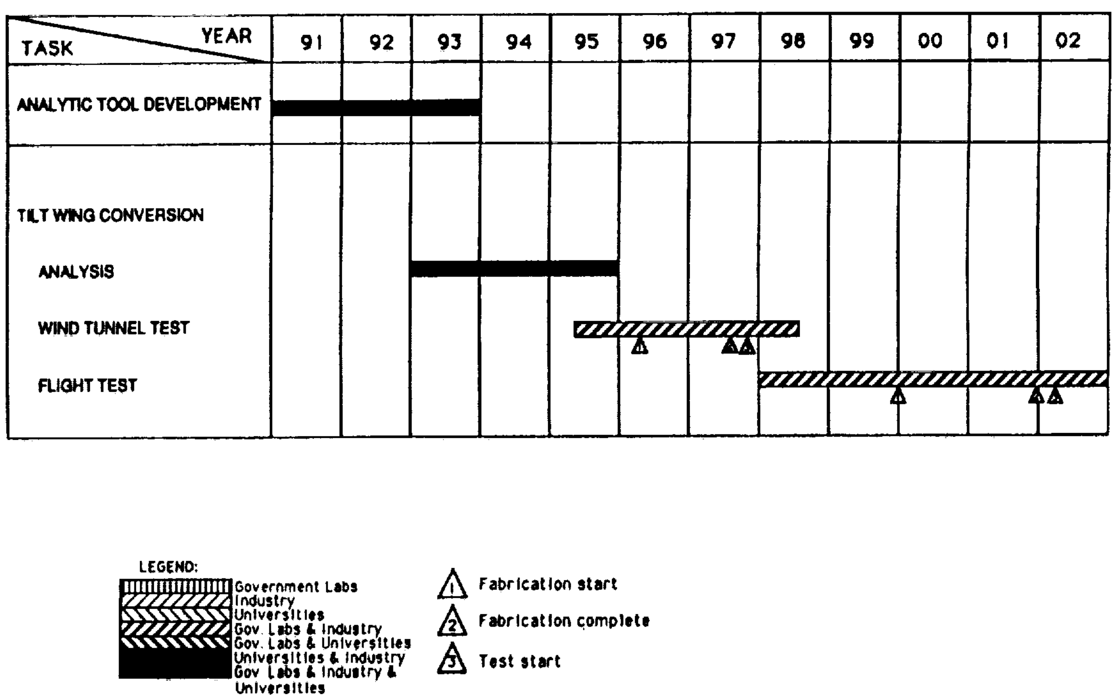


FIGURE 3-11. DYNAMICS TECHNOLOGY DEVELOPMENT TIMELINES - TILT WING

Required Tools- The tools that will be required to perform dynamic analyses of Tilt Wing aircraft in include vibration and loads analyses, and transient dynamics analyses. Some generalized analysis codes exist which can be used for preliminary investigation of the Tilt Wing and Rotor/Wing concepts, and as bases for development of more robust codes. In addition, analysis of flight test and wind tunnel test data from previous Tilt Wing and Rotor/Wing designs is required to validate the results generated by the dynamic analyses.

1. Analysis of the transition from hover to forward flight (and back) will require improved analysis codes that include the effects of rotor-fuselage interactions. The analyses must also model the aeroelastic behavior and rotor-fuselage interference of a coupled rotor and fuselage at high rotor angles of attack. Existing helicopter analyses do not handle the transient dynamics of conversion, and existing multibody dynamics codes can adequately mode neither flexible structures nor the aerodynamic environment. The aeroelastic behavior of the tip-jet driven rotors must also be considered for the Rotor/Wing. Tip jets change the structural behavior of the rotor by eliminating the usual lagging moment and chord-wise shear at the blade root. Also, the rotor wake may be significantly affected by the injection of jet gasses from the blade tip.

2. Safe operation of Tilt Wing and Rotor/Wing aircraft will require the development of control algorithms and hardware for conversion from hover to forward flight. The controls could involve many combinations of both low and high-frequency control of rotor blade pitch and fixed control surfaces, in addition to attitude control.

3. In order to validate the analysis methods developed for Tilt Wing and Rotor/Wing aircraft, data from wind tunnel and flight tests must be collected and cataloged such that it is useful for correlation work. All available data from flight and development testing of the Vertol VZ-2, the Hiller XH-18, the LTV XC-142A, and the Canadair CL-84 could be put into a database, which could then be drawn upon as necessary. Similarly, the wind tunnel data from the extensive Rotor/Wing tests should be collected.

4. Results from previous testing may not provide full coverage of all the technology areas required for the development of a high-speed Tilt Wing or Rotor/Wing aircraft. The lack of coverage may be a result of insufficient testing of the earlier concepts and aircraft, or a result of the infusion of new technology into the design. In either case, dynamic model tests should be undertaken to fill in the experience base, provide insight into specific configurations, and provide analyst and designer alike with a basis on which to make sound engineering judgements.

Required Resource Assessment- As evidenced by the existence of Tilt Wing aircraft, the technology required to design and build such an aircraft is available. However, in order to meet the mission requirements, the technology must be upgraded such that an aircraft can be created which can achieve those requirements. Similarly, analyses and databases sufficient for preliminary investigations of the Rotor/Wing concept already exist. However, more detailed analysis and testing are required. Most research institutions, whether in academia, government, or industry, possess the capability of modifying or creating the computational tools necessary to analyze the dynamics of Tilt Wing and Rotor/Wing aircraft. The government is an obvious choice to coordinate the collection of test data. There would be fewer constraints on them relative to proprietary rights and other privacy issues than on universities or industry.

Furthermore, the government has the facilities to disseminate the data as necessary, on a wider scale. Universities could, however, assist in the creation of the databases for the test data. Testing could most easily be done jointly by the government and industry, with the government providing the test facilities and industry providing the models. Figures 3-11 and 3-12 show timelines required to develop required technology.

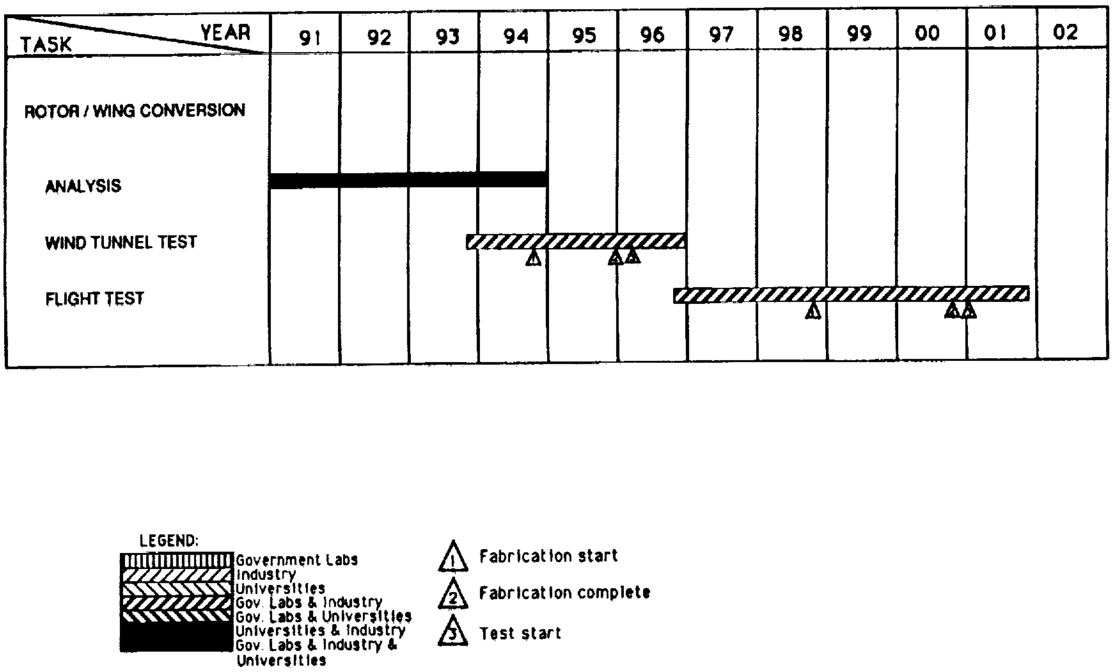


FIGURE 3-12. DYNAMICS TECHNOLOGY DEVELOPMENT TIMELINES - ROTOR/WING

Summary

Two concepts, the Tilt Wing and the Rotor/Wing, were chosen for additional study beyond the Task 1 requirements. These concepts represented low and high risk respectively based on their development to date. The Tilt Wing flew in the mid-'60s while only wind tunnel testing was accomplished with the Rotor/Wing concept in the same time frame. With varied propulsion systems, these two concepts span different technologies while sharing some common technology areas between them and with other concepts. Both concepts' current technology levels allow them to complete their assigned missions with little additional development required. However, application of advanced technology enhances their effectiveness and reduces their acquisition costs. The net effect is to narrow the gap between the high-speed rotorcraft and the fixed wing aircraft in both acquisition and direct operating costs. This occurs due to reduced weight empty and fuel required to accomplish the mission. Both productivity and payload delivery efficiency increase with both concepts after application of advanced technology. Further, application of advanced technology affects the total airvehicle synergistically, compounding the effectiveness.

Realistic sizing of both concepts in Task 2 centered around their ability to convert. Conversion analysis, completed in more depth concurrently with Task 2 allowed better understanding of the problems associated with both concepts and emphasized the optimistic constraints imposed on the sizing matrices of Task 1. Future studies must require more emphasis on conversion as a first step. Despite the optimism of Task 1 results, one of the major areas to concentrate application of new technology evolved from the desire to improve the conversion characteristics of the two concepts.

The Tilt Wing currently requires a large wing to ensure reasonable reconversion flight envelopes; this directly conflicts with the high-speed requirement. Past reports found in available literature indicate certain values of chord to diameter ratios must be adhered to for successful conversion. Since wing stall ultimately limits the capability of the Tilt Wing to reconvert, the capabilities of the wing became the chief area of concentration. Improving the stall characteristics or improving the high-lift capabilities provided the conceptual solution to the problem. Conventional high-lift devices provide only limited improvement in the high-lift capabilities of a wing. A circulation control wing enables large increases in C_{Lmax} and therefore allow reduction of wing size to achieve the same conversion envelope. This application of technology enables matching more closely the requirements for conversion and high-speed flight, while significantly increasing the effectiveness of the concept.

The Rotor/Wing suffers from a similar problem, in that successful conversion requires a large centerbody, which, inefficiently, provides lift. Due to its inefficiency, it requires a large area, which must be moved through the air at high speeds. Additionally, the three-bladed configuration exhibited center of lift oscillation during conversion wind tunnel tests. Reconfiguring the concept allowed for a smoother conversion sequence using more efficient, reduced area, lifting surfaces. This improved the conversion characteristics, while again, more closely matching conversion and high-speed requirements.

Unfortunately, high-speed rotorcraft must fly efficiently at low speeds on the same lifting surface as at high speed. Efficient hover dictates the use of a large diameter rotor, while efficient high-speed flight is simplified using a small diameter propeller or propfan. The extent that these two regimes can be matched through intelligent application of technology will specify the effectiveness of the concept and its attractiveness compared to a conventional aircraft. Current concepts compromise these two flight regimes too heavily to make attractive air vehicles. Future technology development must first focus on this fundamental problem.

Both concepts presented in this study do not require additional technology development to fly. The Tilt Wing is a proven concept with exceptional STOL capabilities, well suited as a military transport aircraft. To fly at 450 KTAS will require development of one technology: efficiently reducing rotor RPM in cruise. Achieving this reduction requires a two-speed gear box, an engine that operates efficiently over a wide range of RPM, or a variable diameter rotor. Additional studies in conjunction with engine manufacturers will provide insight into the appropriate direction to pursue. Obviously, much work remains before flight of the Rotor/Wing, to include demonstration of vibration-free conversion, but there are no inherent technology issues which would prevent this, given a development program. Technologies which prohibit a concept from flying its specified mission define critical technologies. Table 3-1 depicts the prioritization of technologies within each discipline and whether they are common to other potential high-speed rotorcraft concepts.

TECHNOLOGY	RISK	PAYOFF	CRITICAL	PRIORITY
DRIVE SYSTEM				
2 SPEED TRANSMISSION	MED	HIGH	YES	1
GEARING	LOW	MED	NO	2
BEARING/LUBE SYSTEM	LOW	MED	NO	3
DYNAMICS				
CONVERSION DYNAMICS	LOW	MED	NO	2
COMPOSITES	MED	HIGH	NO	1
AEROELASTIC STABILITY	MED	LOW	NO	3
FLIGHT CONTROLS				
CYCLIC ROTOR CONTROLS	MED	MED	NO	1
AERODYNAMICS				
HIGH-LIFT WING	LOW	HIGH	NO	1
HIGH M_{DD} AIRFOIL	MED	LOW	NO	3
PROP/ROTOR η_{CR}	MED	MED	YES	2

TABLE 3-1. TILT WING TECHNOLOGY ASSESSMENT MATRIX

TECHNOLOGY	RISK	PAYOFF	CRITICAL	PRIORITY
DRIVE SYSTEM				
INTEGRAL DUCTING	MED	MED	NO	3
DUCT MATERIALS	MED	MED	NO	4
EXHAUST SEALS	LOW	LOW	NO	5
DIVERTER VALVE	LOW	HIGH	NO	2
TIP JET EXIT CONTROL	LOW	MED	NO	1
DYNAMICS				
CONVERSION CONTROL	HIGH	HIGH	YES	1
VIBRATION CONTROL	MED	HIGH	NO	2
AERODYNAMICS				
AIRFOIL DRAG	MED	LOW	NO	2
CONVERSION WING LOADING	MED	MED	NO	1

TABLE 3-2. ROTOR/WING TECHNOLOGY ASSESSMENT MATRIX

TECHNOLOGY	RISK	PAYOFF	CRITICAL	PRIORITY
		CONTROLS		
SELF-CONTAINED PUMP-ACTUATOR PACKAGES	LOW	MED	NO	1
DIGITAL FLY-BY-WIRE CONTROLLERS	MED	MED	NO	3
FLUIDIC BACKUP CONTROLS	LOW	MED	NO	2
		STRUCTURES		
COMPOSITE MATERIALS DEVELOPMENT	MED	HIGH	NO	1
COMPOSITE STRUCTURAL ANALYSES	MED	HIGH	NO	2
COMPOSITE MANUFACTURING	LOW	MED	NO	3
PROBABILISTIC METHODS	LOW	MED	NO	4
		FLIGHT CONTROLS		
ACTIVE CONTROLS	LOW	MED	NO	2
FBW/FBL	MED	MED	NO	1
		PROPULSION		
IMPROVE SFC - PH III IHPTET	HIGH	HIGH	NO	1
IMPROVE T/W AND P/W - PH III IHPTET	HIGH	MED	NO	2
CONSTANT SFC OVER WIDE RPM RANGE	HIGH	HIGH	YES	3

TABLE 3-3. COMMON TECHNOLOGY ASSESSMENT MATRIX

The technology areas which offer the highest payoff and should be pursued for these concepts include the following:

Tilt Wing-

* Feasibility/suitability study of a high-lift wing
* Feasibility trade study of rotor RPM reduction schemes
* Continue IHPTET program

Conduct preliminary design and test of a 450 knot prop/rotor

Rotor/Wing-

* Assess dynamics of stopping a two-bladed rigid rotor
* Assess feasibility of the concept and assess vehicle dynamics during conversion through building and flying a radio controlled model
* Continue configuration studies leading to wind tunnel testing

SECTION IV

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TECHNOLOGY NEEDS FOR HIGH-SPEED ROTORCRAFT

APPENDIX TO FINAL REPORT

PREFACE

Appendix A contains substantiating data to the concepts studied in Task I. Appendix B contains the balance of the performance requirements called for in the statement of work, which is not contained in the final draft. This Appendix presents the performance tasks completed for the Tilt Wing, followed by those completed for the Rotor/Wing. The sequence of the graphs and figures loosely follows the order that the performance requirements are listed in the statement of work.

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PERFORMANCE MODELLING

The performance models which generated the data in Appendix B are, for the most part, simple models which have been substantiated at various points using more rigorous analyses. The following section will discuss the two engine models and the performance analyses used for both the Tilt Wing and the Rotor/Wing in each mode of flight.

Tilt Wing

Engine Model- The engine model used for the Tilt Wing analyses is the Allison T406. An engine deck was provided to McDonnell Douglas Helicopter Company (MDHC) by the manufacturer. This deck is a computer model of the T406 which can be run at a variety of power settings to obtain rotor shaft horsepower (SHP) and fuel flow (FF) for any flight conditions. In order to use this model in the preliminary design process, it was necessary to nondimensionalize the engine data produced by the engine deck using turbine inlet temperature and flight conditions so that the preliminary design sizing program, VASCOMP II, could scale the engine data to the required engine size. This effectively allows use of T406 engine technology without the need for a separate engine deck for each engine size required during the preliminary design process.

Helicopter Mode- The helicopter mode performance was calculated using classical helicopter analysis found in such texts as Aerodynamics of the Helicopter by Gessow and Meyers, and Aerodynamics of V/STOL Flight by McCormick. Specifically, the rotor power was calculated using momentum theory for the ideal power and strip theory for the profile power. Empirical corrections were implemented to account for the effects of compressibility and stall.

These calculations were validated in hover and vertical climb using LSAF (Reference 20 in the main text), an industry standard rotor hover performance program, and in forward flight using flight test data from the MDHC AH-64A Apache. The wing of the Tilt Wing is assumed at 90 degrees (vertical) for all helicopter mode analyses.

Conversion Mode- The conversion mode performance was analyzed using the same basic rotor model used in the helicopter mode analysis. For conversion mode, however, it is important to find the wing attitude which trims the Tilt Wing at all airspeeds. For this reason, a force balance was added which trimmed the aircraft in conversion mode, checking the wing for stall at all airspeeds. The wing stall model uses Weissinger's lifting surface approximation, coupled with momentum theory for the rotor wake effects, to calculate the lift and drag acting on the wing. This model was validated using flight test data from the XC-142. The model predicted the XC-142 wing angle and stall boundaries quite accurately for all critical airspeeds.

Airplane Mode- The Airplane mode performance presented was calculated using the performance subroutines within VASCOMP II. These methods are also classical in nature, with substantial use of empirical relationships (for Oswald's efficiency factor, compressibility drag calculation, etc). The propeller performance was input as efficiencies dependent on the flight condition. The propeller performance analysis was validated using V-22 propeller performance data. It should be noted that the specific range plots presented were run with a constant propeller efficiency.

Rotor/Wing

Engine Model- The engine model used for all of the Rotor/Wing analyses is the Pratt & Whitney STF842 turbofan engine with a bypass ratio of one. Although this engine deck was not available, extensive engine data at different thrust levels and flight conditions along with scaling curves was available in tabular format. This data was encoded and was automated in the preliminary design process using a series of table lookups.

Helicopter Mode- The helicopter mode performance, like the Tilt Wing, was analyzed using momentum and strip theory validated with LSAF in hover and vertical climb. It should be noted that the ideal power was calculated assuming only the rotor annulus area is lifting. Also, 0015 airfoils were used in the strip theory analysis and incremented by 10% to account for the elliptical sections. This procedure was recommended based on the 1960's whirlstand tests conducted at Hughes Helicopter. Likewise, the profile power of the rotating centerbody was calculated using an empirical correction based on the 1960's whirlstand tests. It should be noted that the forward flight plots fail to sufficiently account for the effects of blade stall. These same trends are shown in the 1960's forward flight performance data. This is not considered critical, however, because autorotative flight is initiated at approximately 80 knots. The power required and vibration levels in forward helicopter mode flight have been checked using CAMRAD JA (Reference 21 in the main text).

The reaction drive internal flow analysis is based on the method outlined by Henry in "One-Dimensional, Compressible, Viscous Flow Relations Applicable to Flow in a Ducted Helicopter Blade," NACA TN 3089, 1953. This method employs basic thermodynamic relationships along with empirical corrections based the previous reaction drive rotors. The outcome of this analysis is approximately 50 percent rotor system efficiency. In other words, only 50 percent of the horsepower of the turbofan engine is converted into rotor power.

Conversion Mode- The autoratation data was calculated using basic momentum and strip theory, and was validated using L/D values obtained during the 1960's wind tunnel tests. As stated previously, the vibration levels near conversion speed have been checked using CAMRAD JA. No analysis of rotor stopping has been conducted to date, however, dynamically scaled wind tunnel tests conducted during the 1960's have demonstrated the feasibility of stopping the rotor without the use of any digital controllers.

Airplane Mode- The airplane mode of the Rotor/Wing, like the Tilt Wing, uses classical fixed-wing analysis with empirical corrections where appropriate. The drag values in airplane mode compare favorably with those obtained during wind tunnel tests in the 1960's at Hughes Helicopter.

APPENDIX A - TASK I SUBSTANTIATION

GROUP WEIGHT SUMMARY
(CURRENT TECHNOLOGY)

GROUP	ROTOR WING	TILT WING	TILT ROTOR	TRAILING ROTOR	PROP-TRAIL ROTOR	FOLDING-TILT ROTOR
WING	3000	1880	3169	4102	4141	4239
M / R BLADES	****	1180	1717	1697	1716	2117
M / R HUB & HINGE	****	1779	2655	2913	2946	3601
HORIZONTAL TAIL	540	707	774	865	898	421
VERTICAL TAIL	309	277	438	583	591	745
BODY GROUP	4437	4893	4924	4942	4945	5313
ALIGHTING GEAR	1323	1325	1472	1567	1579	1637
NACELLES	796	1190	1495	1552	1468	1560
ENGINE	2859	2956	3197	5236	4422	5271
PROP. SUBSYS.	745	852	902	1298	1146	1304
PROPELLOR	0	0	0	0	4400	0
FUEL SYSTEM	672	991	1087	1469	1026	1500
DRIVE SYSTEM	0	5373	7446	6814	6701	7075
FLIGHT CONTROLS	1889	2787	2533	3120	3143	3604
FIXED WEIGHT	4000	4000	4000	4000	4000	4000
AVIONICS	800	800	800	800	800	800
WEIGHT EMPTY	21370	30990	36609	40958	43922	43187
PAYLOAD	4500	4500	4500	4500	4500	4500
OPERATING ITEMS	625	625	625	625	625	625
MISSION FUEL	8504	9103	9760	10578	8121	11464
GROSS WEIGHT	34999	45218	51494	56661	57168	59776

Weight in lbs

DRAG BREAKDOWN
FLAT PLATE AREA (SQ. FT.)

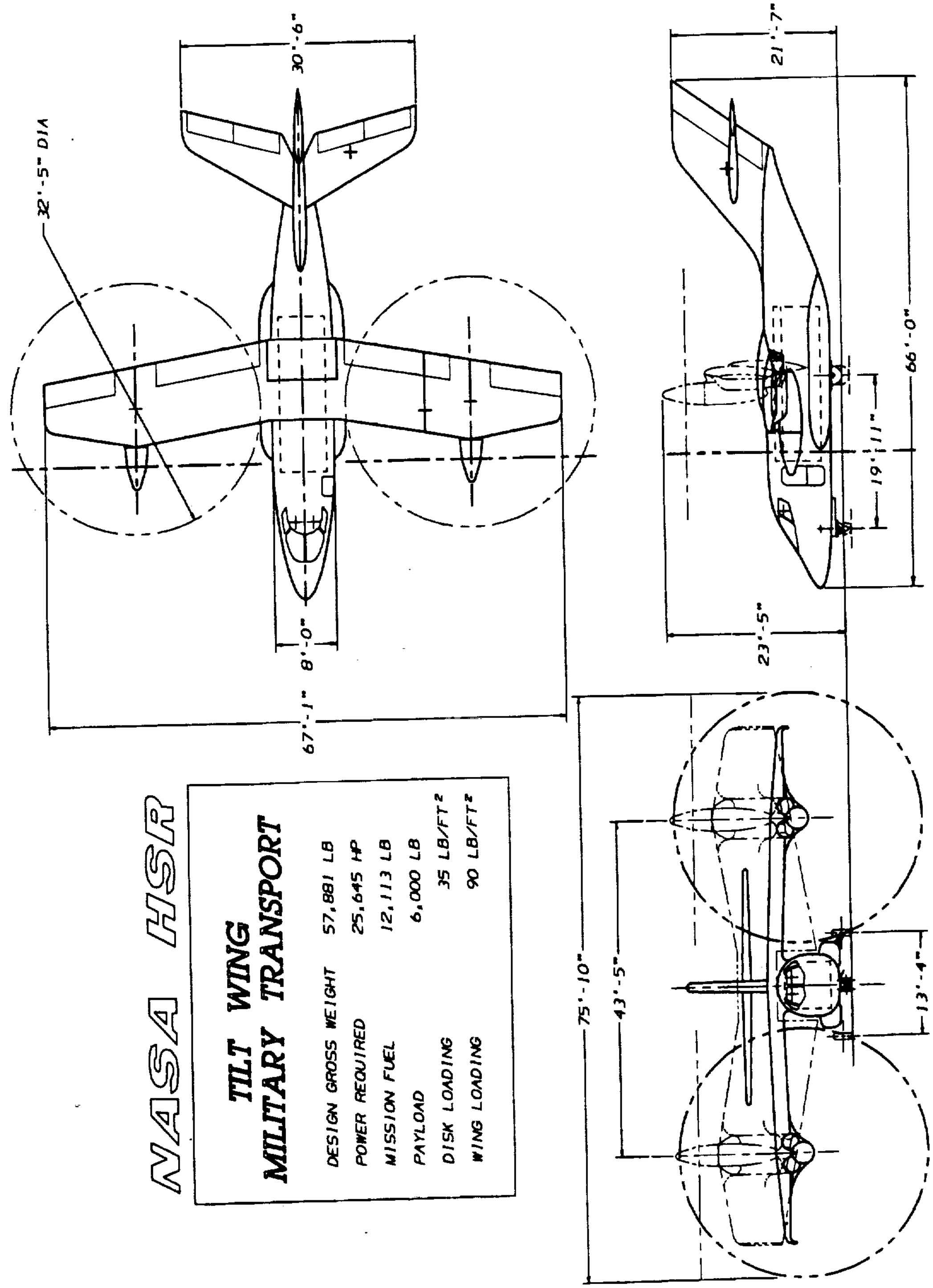
COMPONENT	ROTOR/WING	FOLDING TILT ROTOR	TRAIL ROTOR	TRAIL ROTOR (UDF)	TILT ROTOR	TILT WING
FUSELAGE	2.902	4.145	4.145	4.145	4.145	4.145
WING	4.016	3.537	3.365	3.393	3.213	2.790
HORIZONTAL TAIL	1.017	0.826	1.411	1.466	1.292	1.182
VERTICAL TAIL	0.765	1.685	1.293	1.310	1.064	0.800
ENGINE NACELLES	1.425	1.550	1.550	*****	2.693	2.316
ROTOR PODS	*****	5.070	5.435	5.539	*****	*****
MISCELLANEOUS	1.013	1.645	1.720	1.585	1.241	1.123
TOTAL	11.14	18.10	18.92	17.44	13.65	12.36

MISCELLANEOUS IS 10% OF PRECEDING SUBTOTAL AND ACCOUNTS FOR INTERFERENCE DRAG, PROTUBERANCES, ETC.

GROUP WEIGHT SUMMARY
(ADVANCED TECHNOLOGY)

GROUP	ROTOR WING	TILT WING	TILT ROTOR	TRAILING ROTOR	PROP-TRAIL ROTOR	FOLDING-TILT ROTOR
WING	2163	1095	1626	1759	2439	2260
M / R BLADES	****	687	909	939	1072	1178
M / R HUB & HINGE	****	851	1148	1318	1519	1640
HORIZONTAL TAIL	450	367	323	381	462	187
VERTICAL TAIL	257	137	178	250	298	322
BODY GROUP	3729	4081	4091	4113	4135	4423
ALIGHTING GEAR	961	868	905	992	1085	1040
NACELLES	362	805	1036	1000	995	1000
ENGINE	1378	1312	1293	2699	2363	2693
PROP. SUBSYS.	583	469	464	797	723	796
PROPELLOR	0	0	0	0	4400	0
FUEL SYSTEM	497	631	604	973	724	983
DRIVE SYSTEM	0	2897	3615	3744	4028	3871
FLIGHT CONTROLS	1494	1925	1642	2033	2226	2349
FIXED WEIGHT	4000	4000	4000	4000	4000	4000
AVIONICS	800	800	800	800	800	800
WEIGHT EMPTY	16674	20925	22634	25798	31269	27542
PAYLOAD	4500	4500	4500	4500	4500	4500
OPERATING ITEMS	625	625	625	625	625	625
MISSION FUEL	5896	4756	4655	5345	4684	5772
GROSS WEIGHT	27695	30806	32414	36268	41078	38439

APPENDIX B - TASK II SUBSTANTIATION



TILT WING DRAG BREAKDOWN

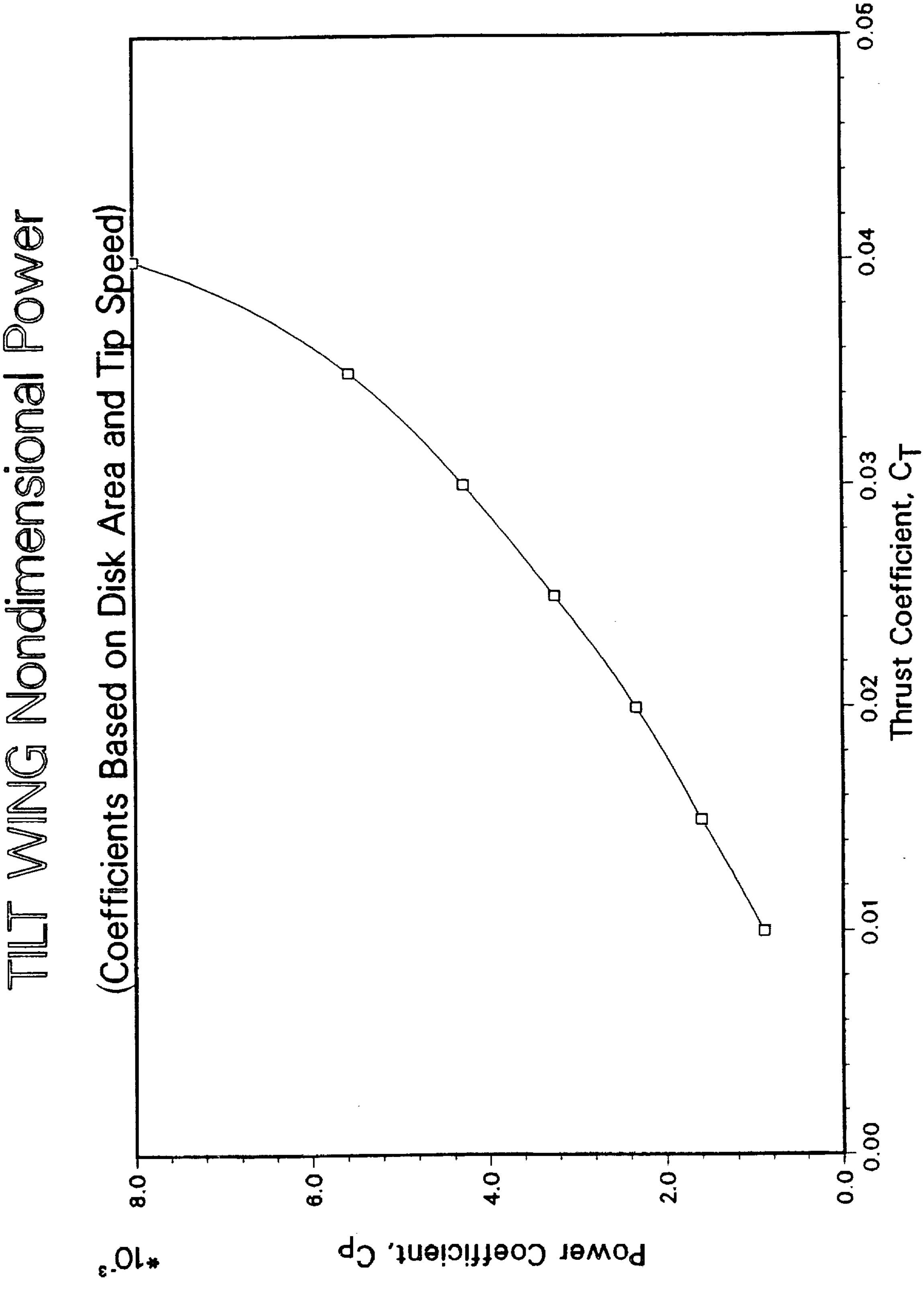
Component	Wetted Area	C_f	Form Factor	Flat Plate Area
Fuselage	1377	0.00187	1.48	4.89 *
Wing	1318	0.00263	1.47	5.11
Horizontal Tail	461.4	0.00262	1.35	1.62
Vertical Tail	351	0.00264	1.264	1.17
Nacelles	652.8	0.00342	1.36	3.04
Sponsons	255	0.00225	1.206	0.69
				16.52
		10% for Interference and Protuberences :		1.65
			Total :	18.17

* includes 1.08 sq ft for fuselage upsweep

TILT WING WEIGHT BREAKDOWN

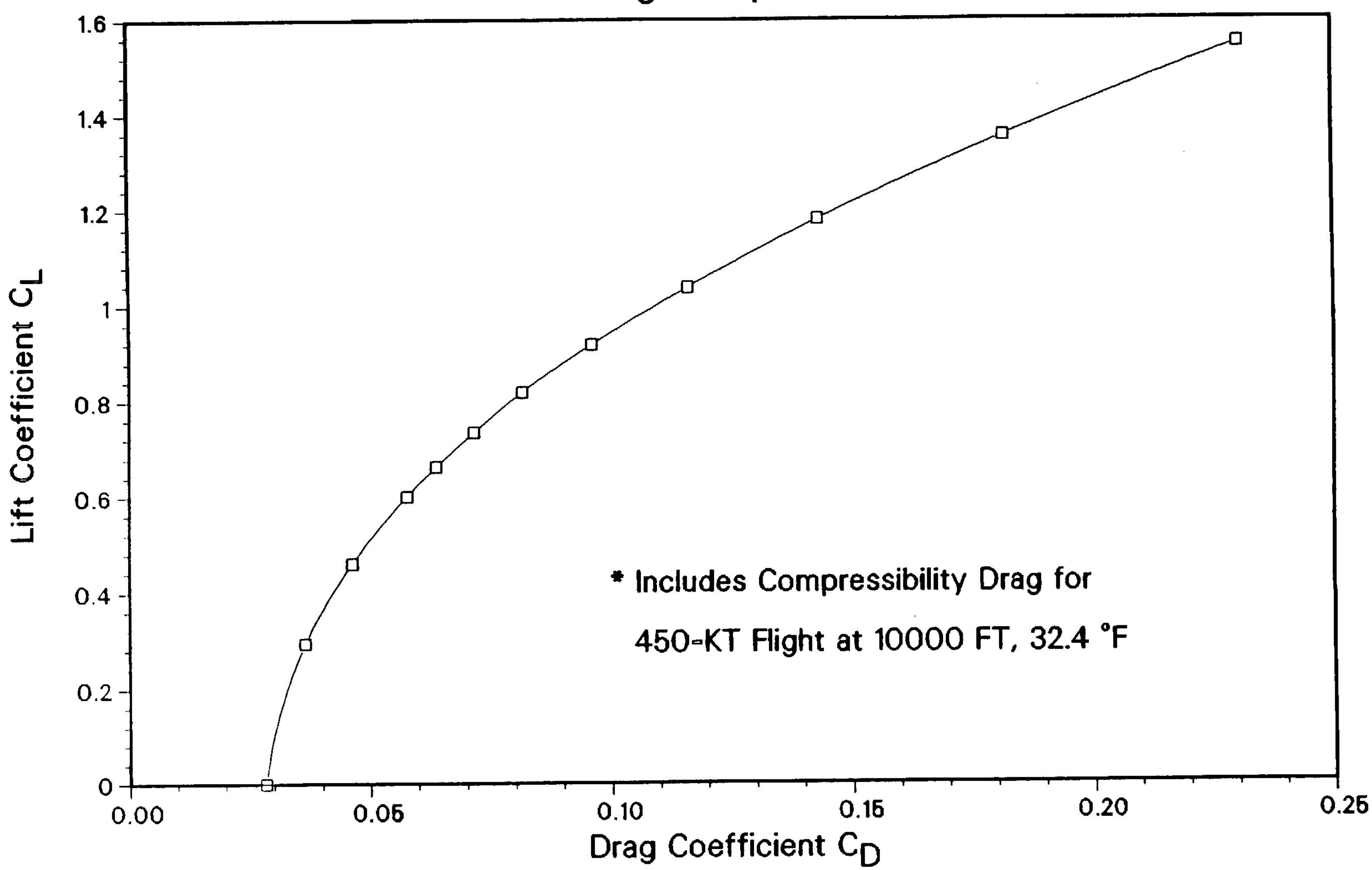
Weight in lbs

		CURRENT	XC142A	CL84
GROUP	TILT WING	%GW	%GW	%GW
WING	4431	7.7	6.6	6.9
MAIN ROTOR BLADES	1479	2.6	****	****
M/R HUB & HINGE	2262	3.9	****	****
TAIL ROTOR	****	0.0	0.8	0.5
HORIZONTAL TAIL	1010	1.7	1.6	1.7
VERTICAL TAIL	466	0.8	0.7	1.2
BODY GROUP	4594	7.9	12.9	12.1
ALIGHTING GEAR	1595	2.8	3.2	3.7
NACELLES	1409	2.4	2.9	2.6
(*STRUCTURAL GROUP*)	(17246)	(29.8)	(28.5)	(28.7)
ENGINE	4049	7.0	7.1	10.0
PROPELLER INSTL.	****	0.0	4.0	6.7
PROPULSION SUBSYS	954	1.6	1.4	2.4
FUEL SYSTEM	744	1.3	1.2	1.6
DRIVE SYSTEM & TILT	6759	11.7	7.1	7.9
FLIGHT CONTROLS	3646	6.3	6.8	3.9
(*SYSTEMS GROUP*)	(16152)	(27.9)	(27.7)	(32.5)
FIXED WEIGHT	4900	8.5	8.0	7.1
EMPTY WEIGHT	38298	66.2	64.2	68.3
PAYLOAD	6000	10.4	19.4	13.4
OPERATING ITEMS	1470	2.5	2.0	3.2
FUEL	12113	20.9	14.4	15.1
GROSS WEIGHT	57881	100%	100%	100%


TILT WING Nondimensional Power
(Coefficients Based on Disk Area and Tip Speed)
Power Coefficient, Cp
*10⁻³
0.0
2.0
4.0
6.0
8.0
Thrust Coefficient, CT
0.00
0.01
0.02
0.03
0.04
0.05

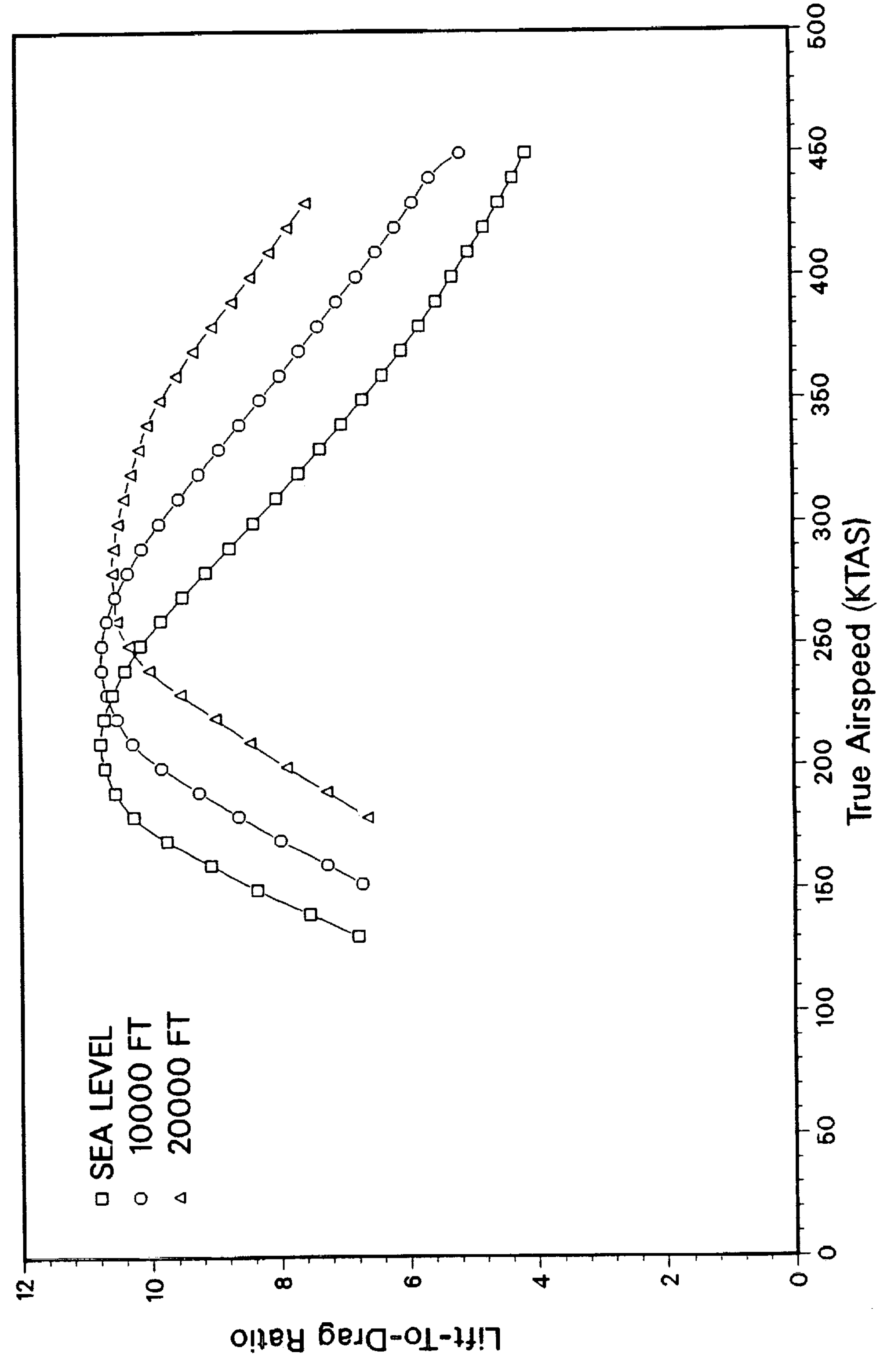
Cruise Drag Polar

Tilt Wing - Airplane Mode



Lift-To-Drag Ratio vs. True Airspeed (KTAS)

Tilt Wing - Design Gross Weight - Airplane Mode



MDHC HSRC PROP/ROTOR FOR MILITARY TRANSPORT TILTWING

T/A=35, VCRUISE= 450 KNOTS, HDES=15,000 FT

ALT. = 0. FT

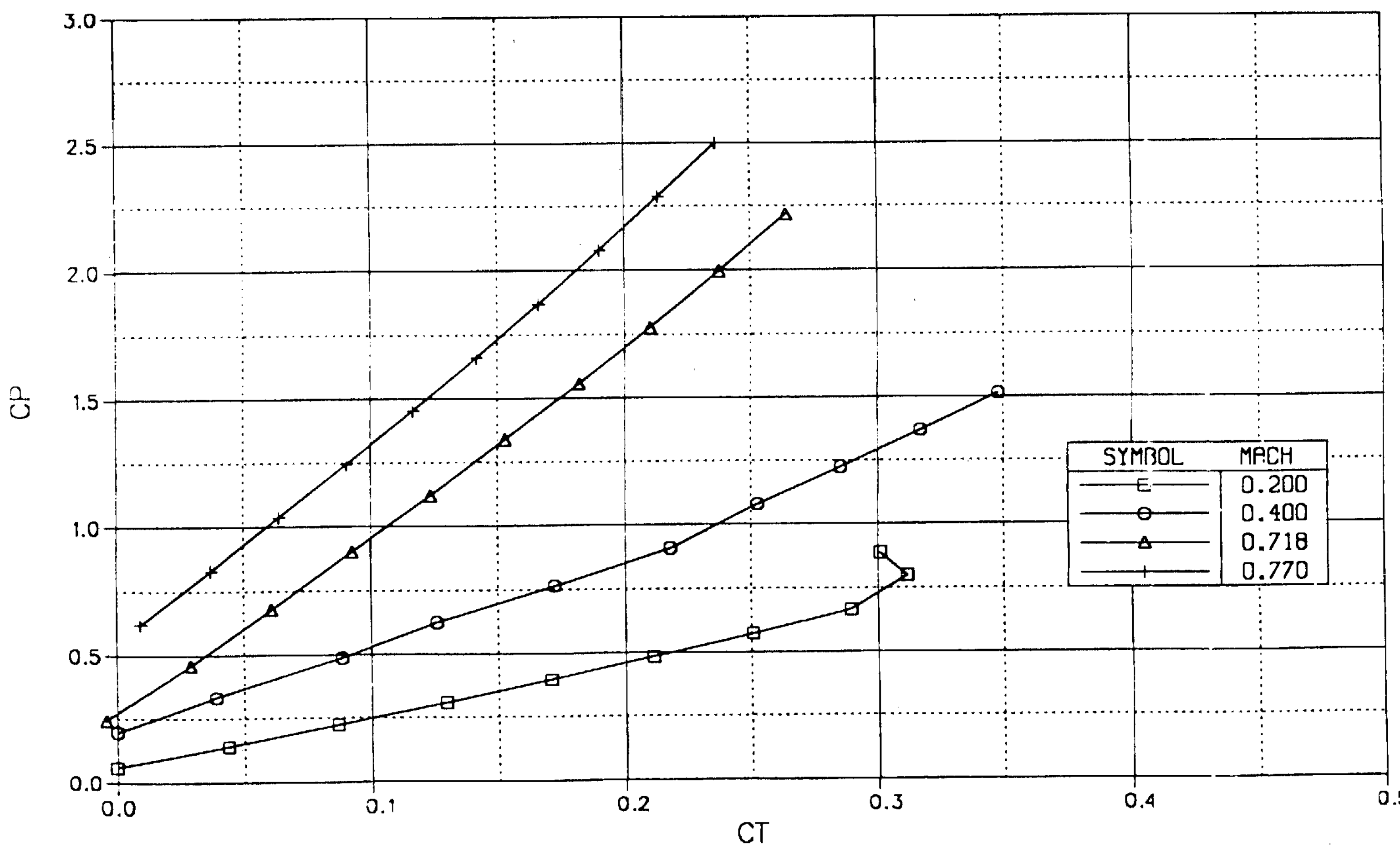
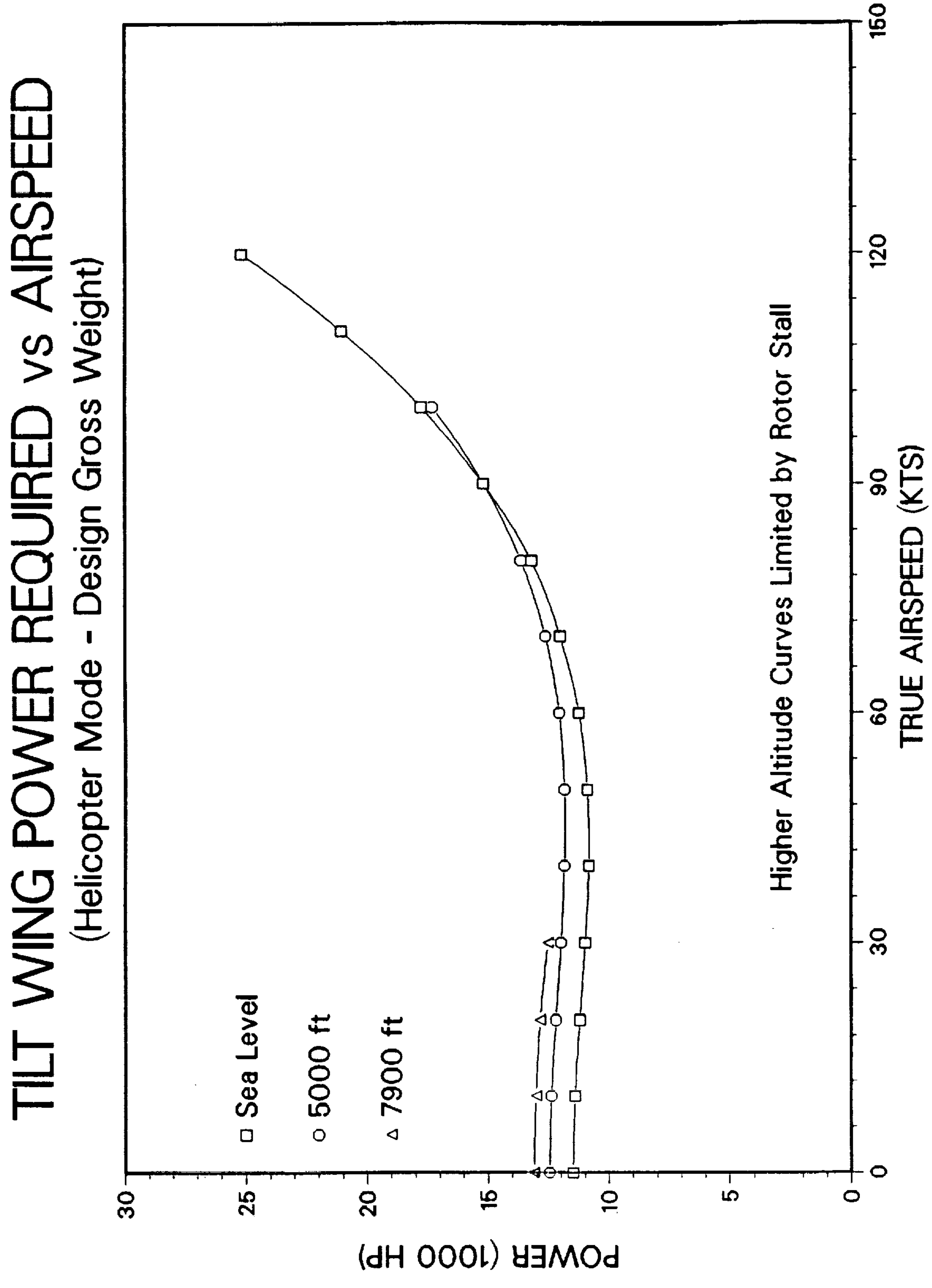
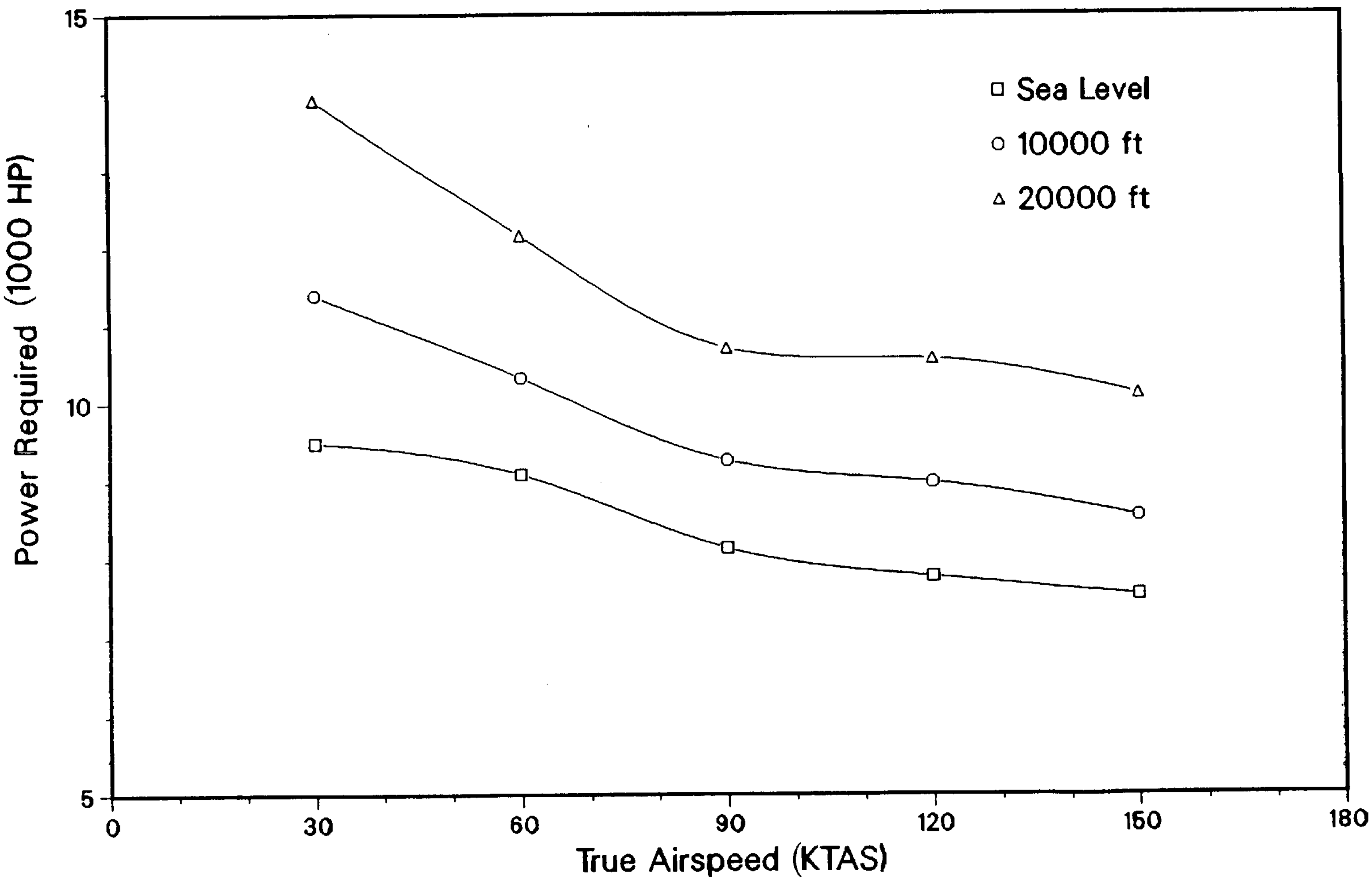


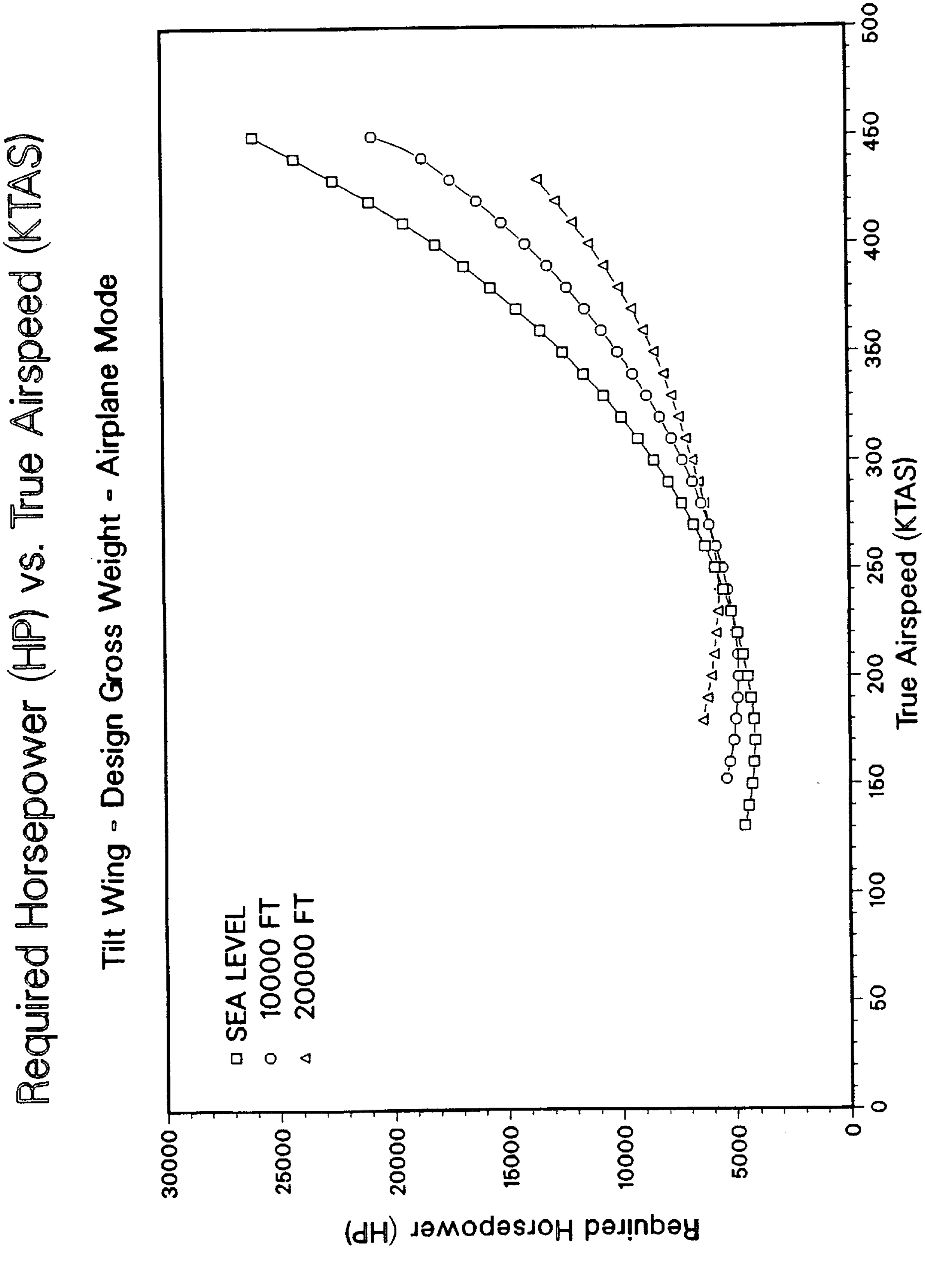
Figure 8 (1 of 4)

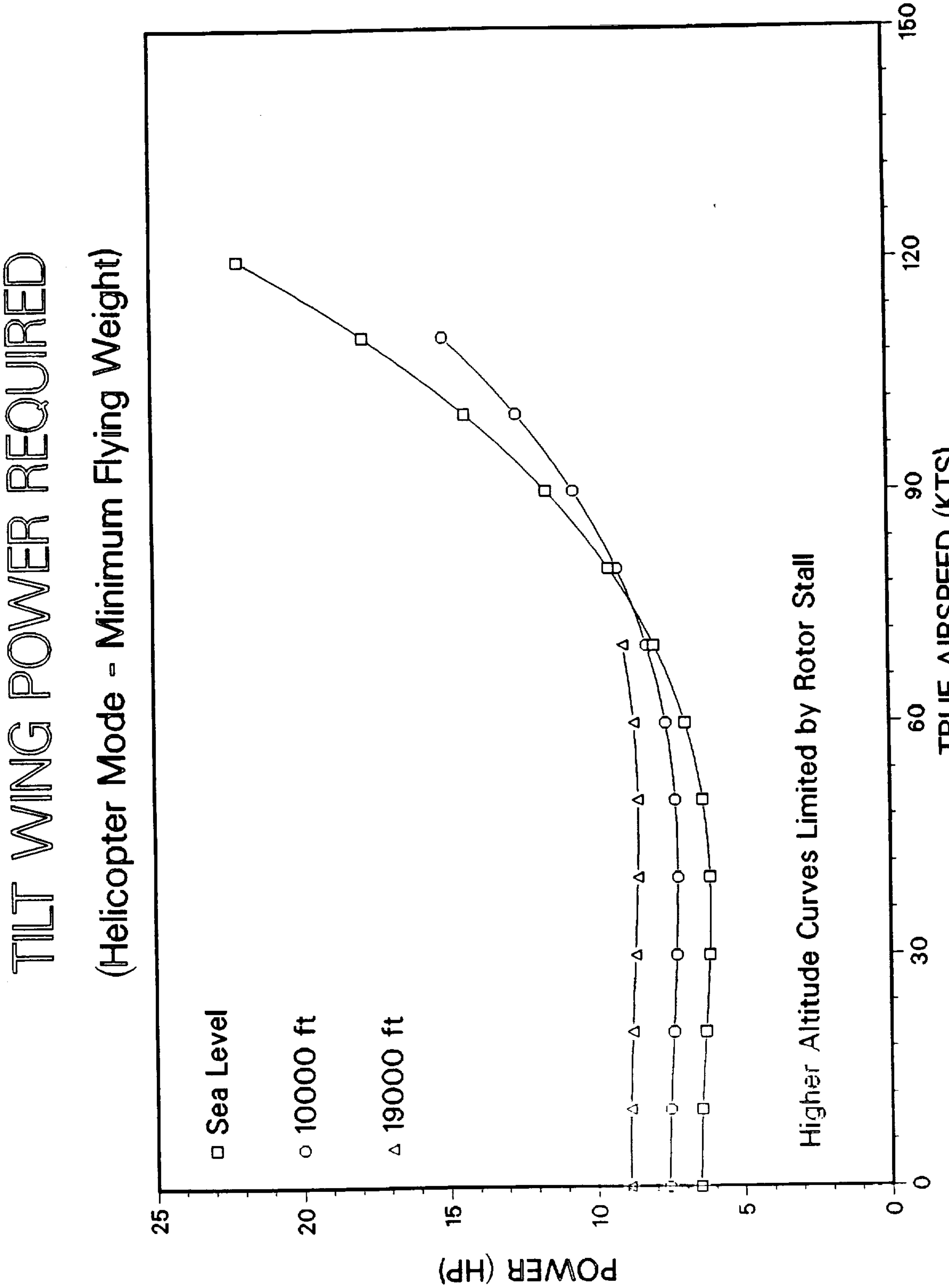

TILT WING POWER REQUIRED vs AIRSPEED
(Helicopter Mode - Design Gross Weight)
Sea Level
5000 ft
7900 ft
Higher Altitude Curves Limited by Rotor Stall
POWER (1000 HP)
TRUE AIRSPEED (KTS)
0
5
10
15
20
25
30
0
30
60
90
120
150

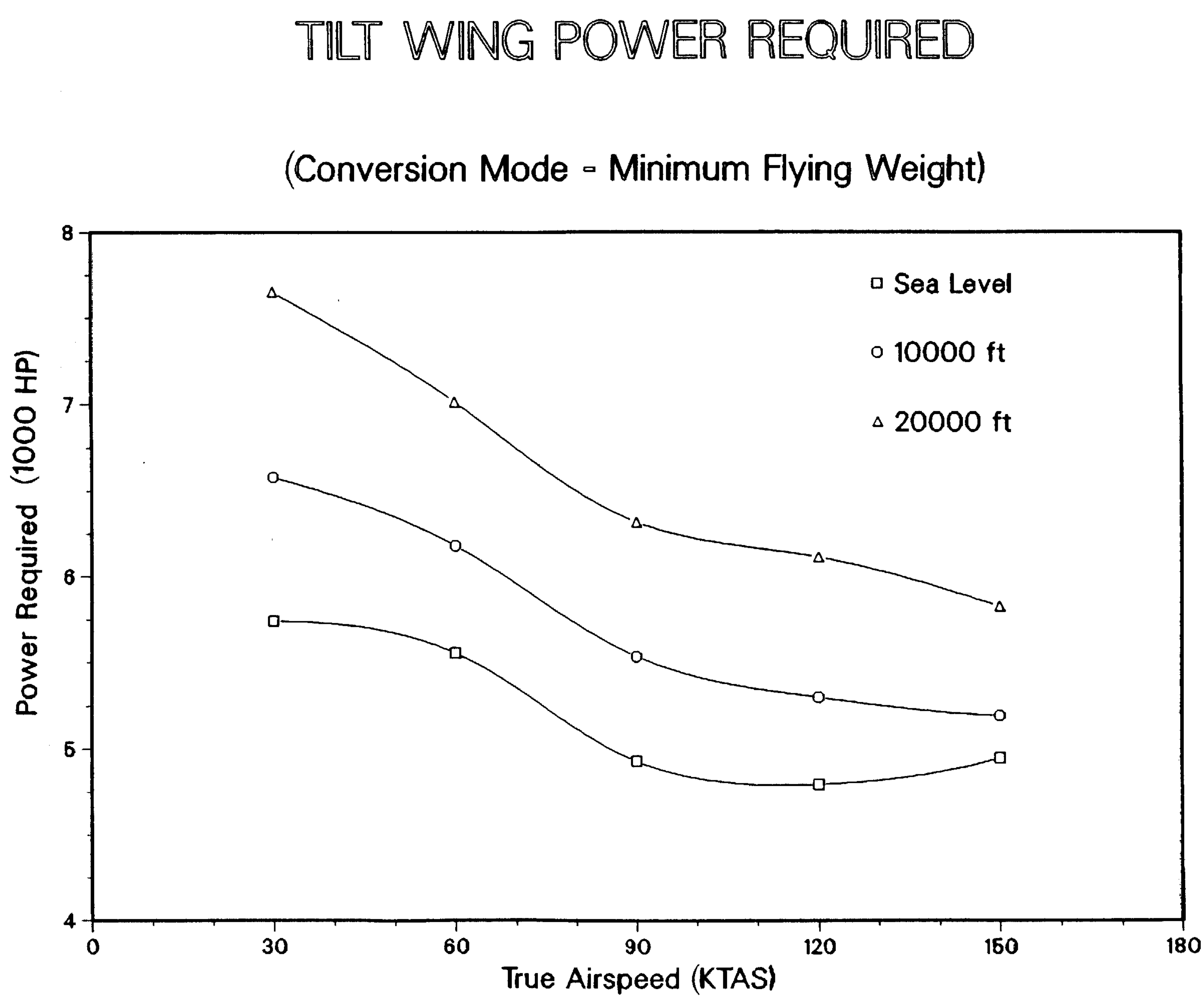
TILT WING POWER REQUIRED

(Conversion Mode - Design Gross Weight)

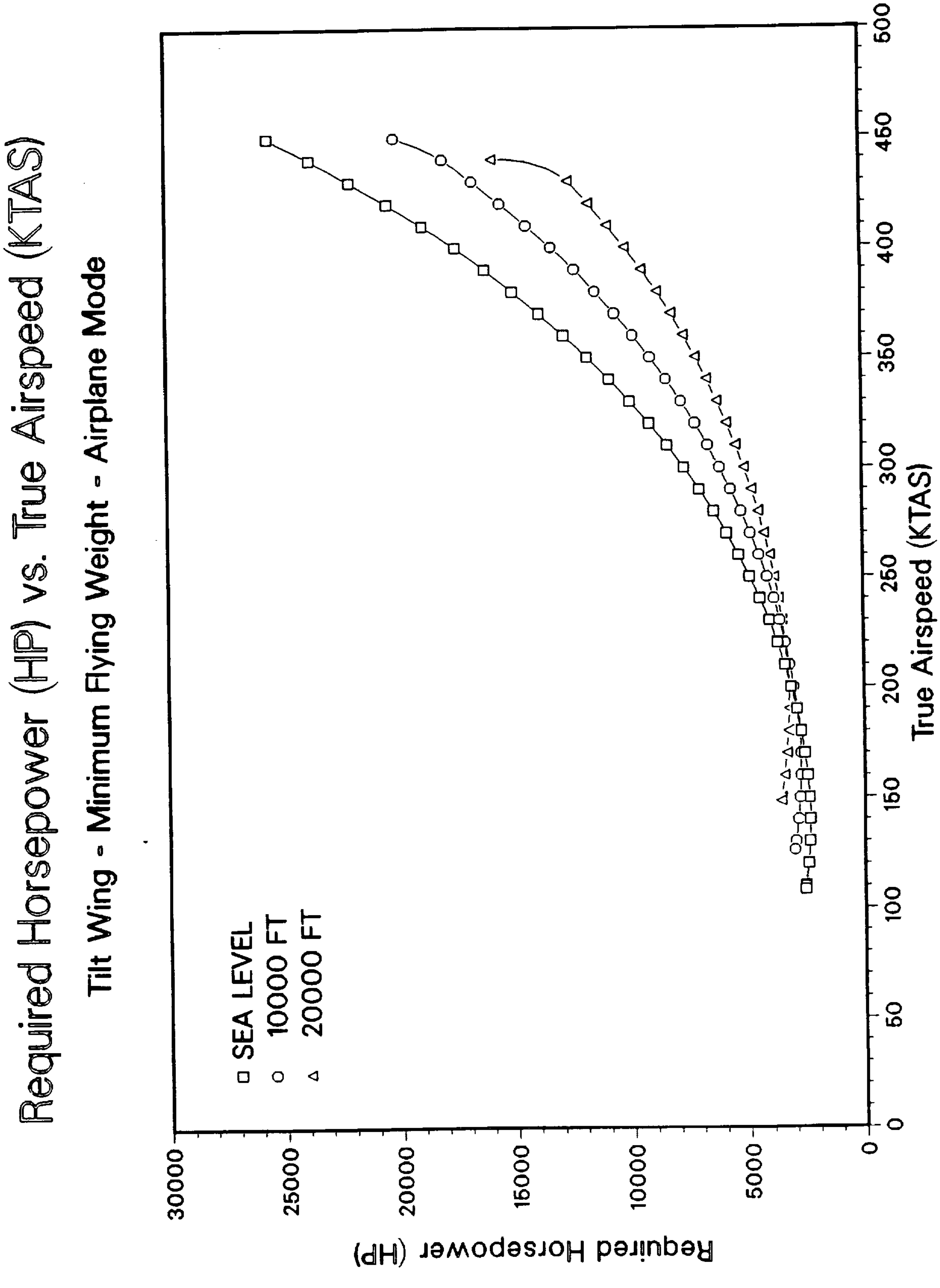



Required Horsepower (HP) vs. True Airspeed (KTAS)
Tilt Wing - Design Gross Weight - Airplane Mode
SEA LEVEL
10000 FT
20000 FT
Required Horsepower (HP)
True Airspeed (KTAS)
0
5000
10000
15000
20000
25000
30000
0
50
100
150
200
250
300
350
400
450
500


TILT WING POWER REQUIRED
(Helicopter Mode - Minimum Flying Weight)
Sea Level
10000 ft
19000 ft
Higher Altitude Curves Limited by Rotor Stall
POWER (HP)
TRUE AIRSPEED (KTS)
0
5
10
15
20
25
0
30
60
90
120
150



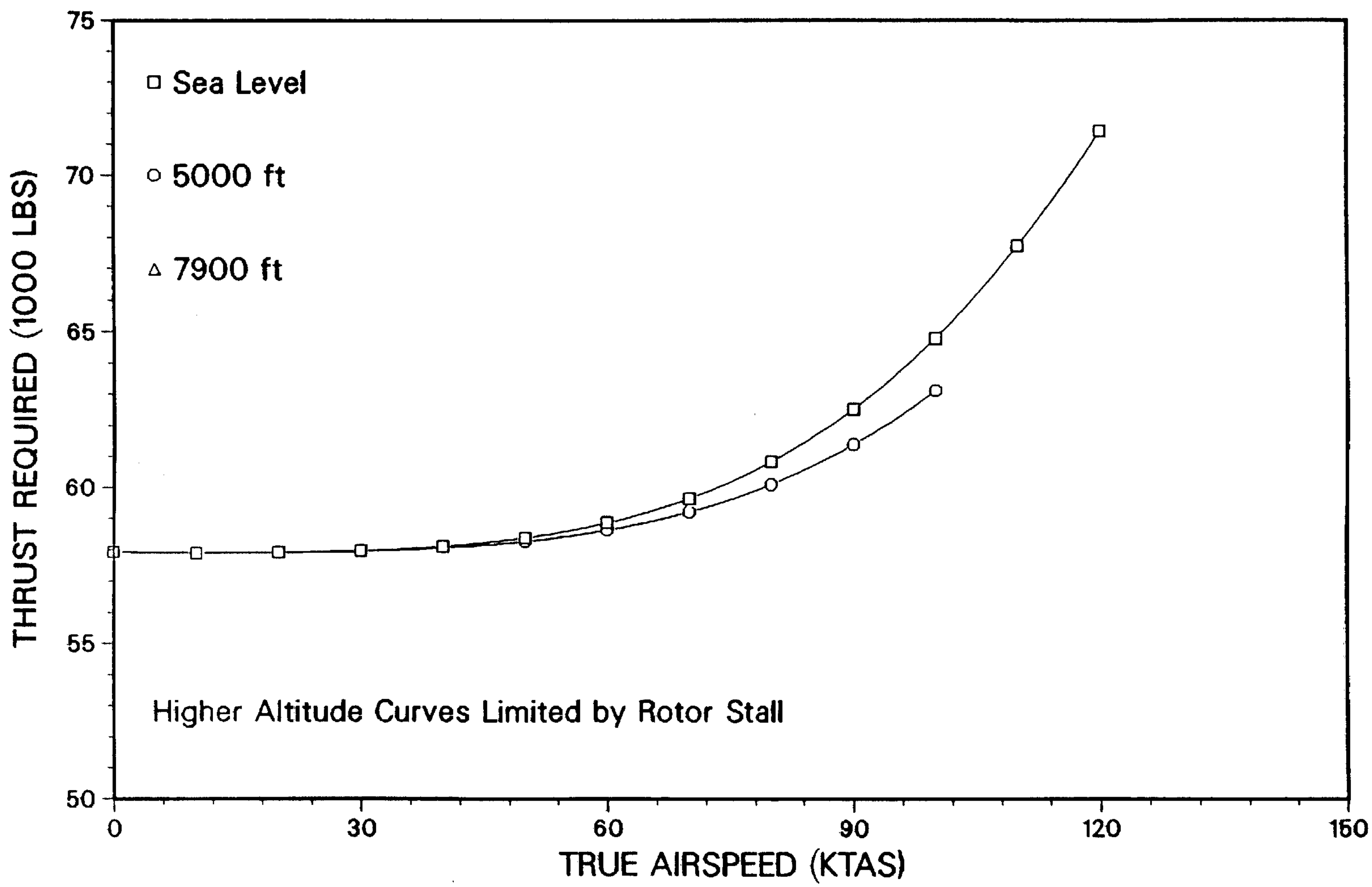
TILT WING POWER REQUIRED
(Conversion Mode - Minimum Flying Weight)
Sea Level
10000 ft
20000 ft
Power Required (1000 HP)
True Airspeed (KTAS)
8
7
6
5
4
0
30
60
90
120
150
180

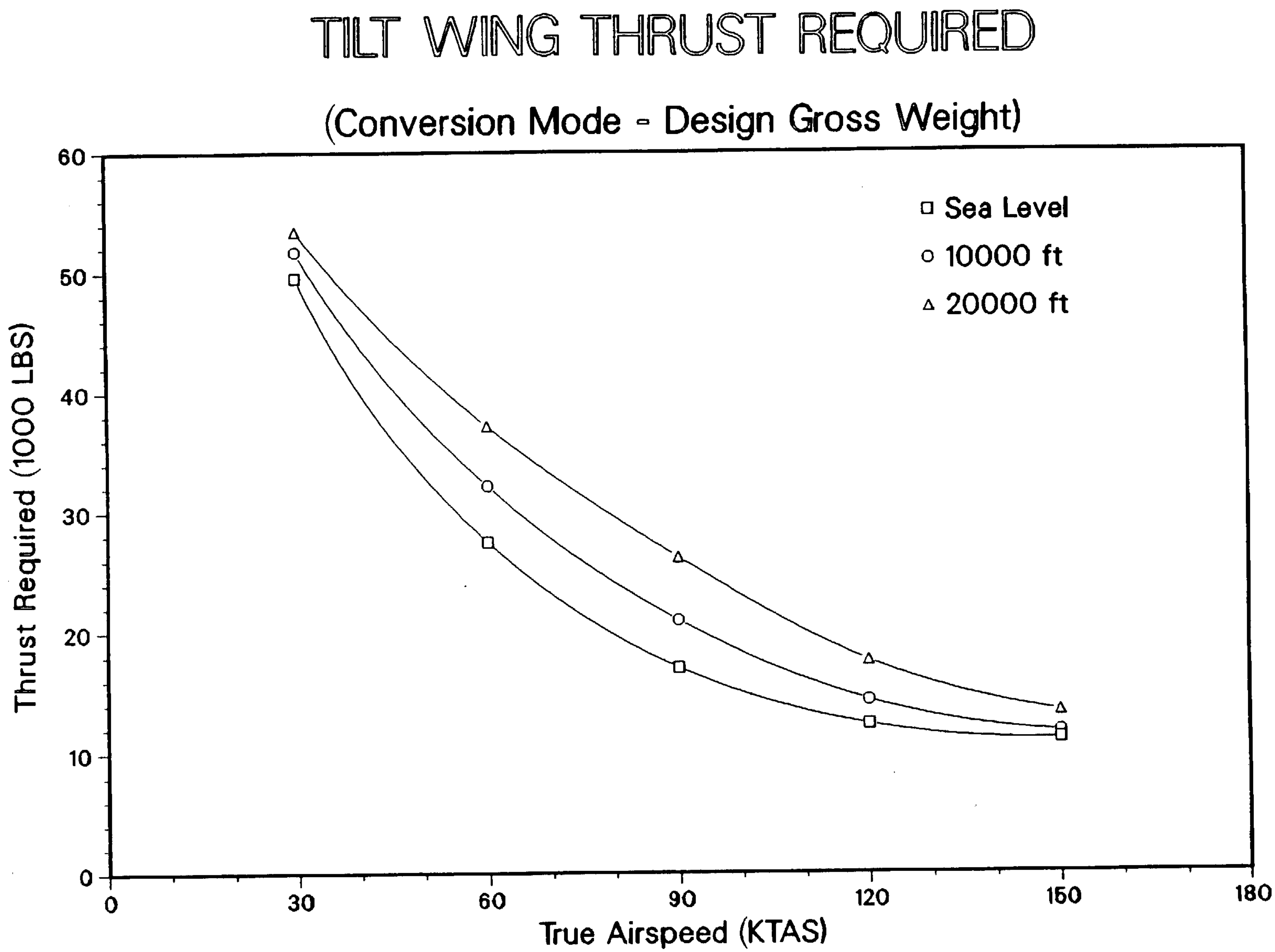


Required Horsepower (HP) vs. True Airspeed (KTAS)
Tilt Wing - Minimum Flying Weight - Airplane Mode
SEA LEVEL
10000 FT
20000 FT
Required Horsepower (HP)
True Airspeed (KTAS)
0
5000
10000
15000
20000
25000
30000
0
50
100
150
200
250
300
350
400
450
500

TILT WING THRUST REQUIRED vs AIRSPEED

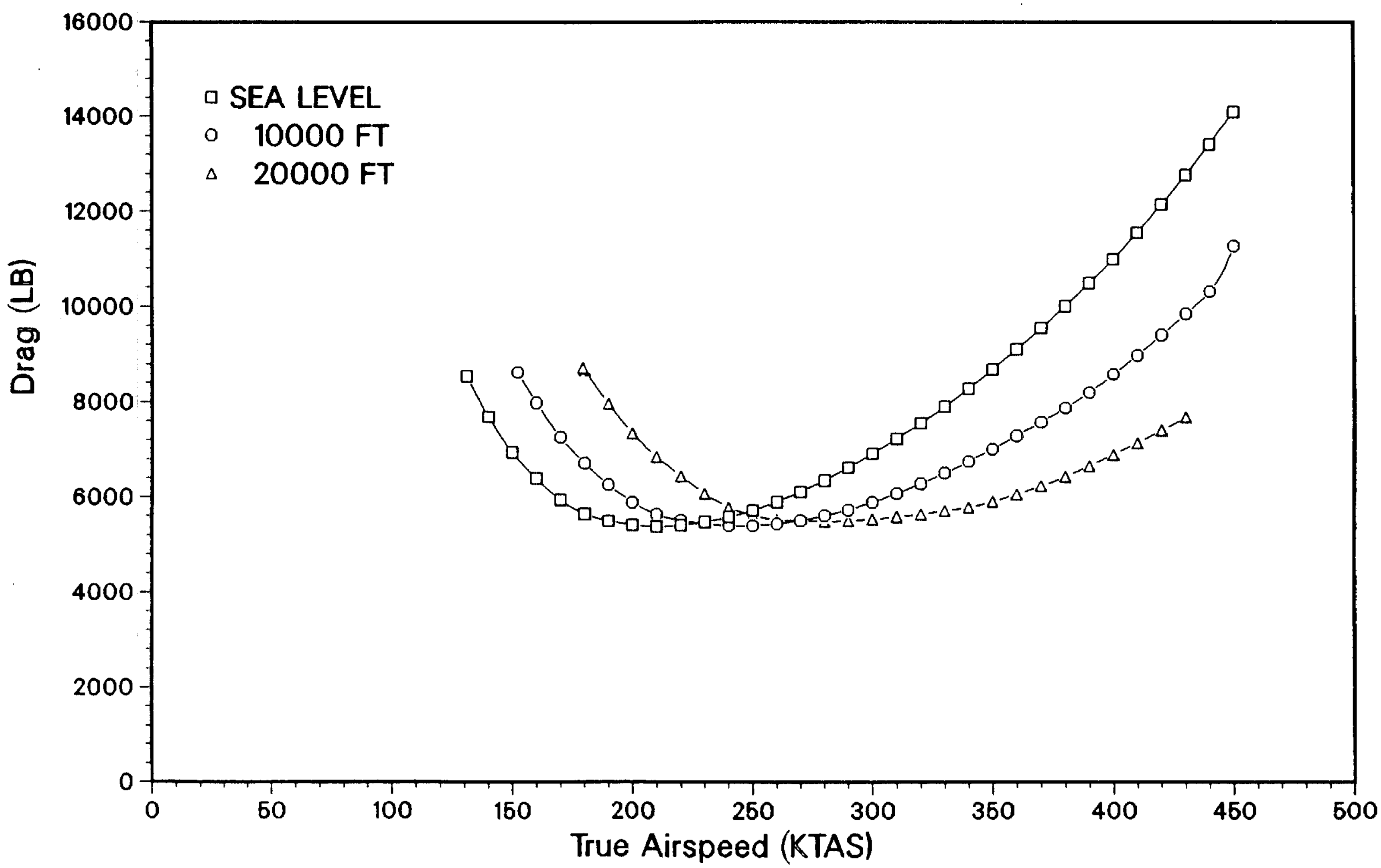
(Helicopter Mode - Design Gross Weight)

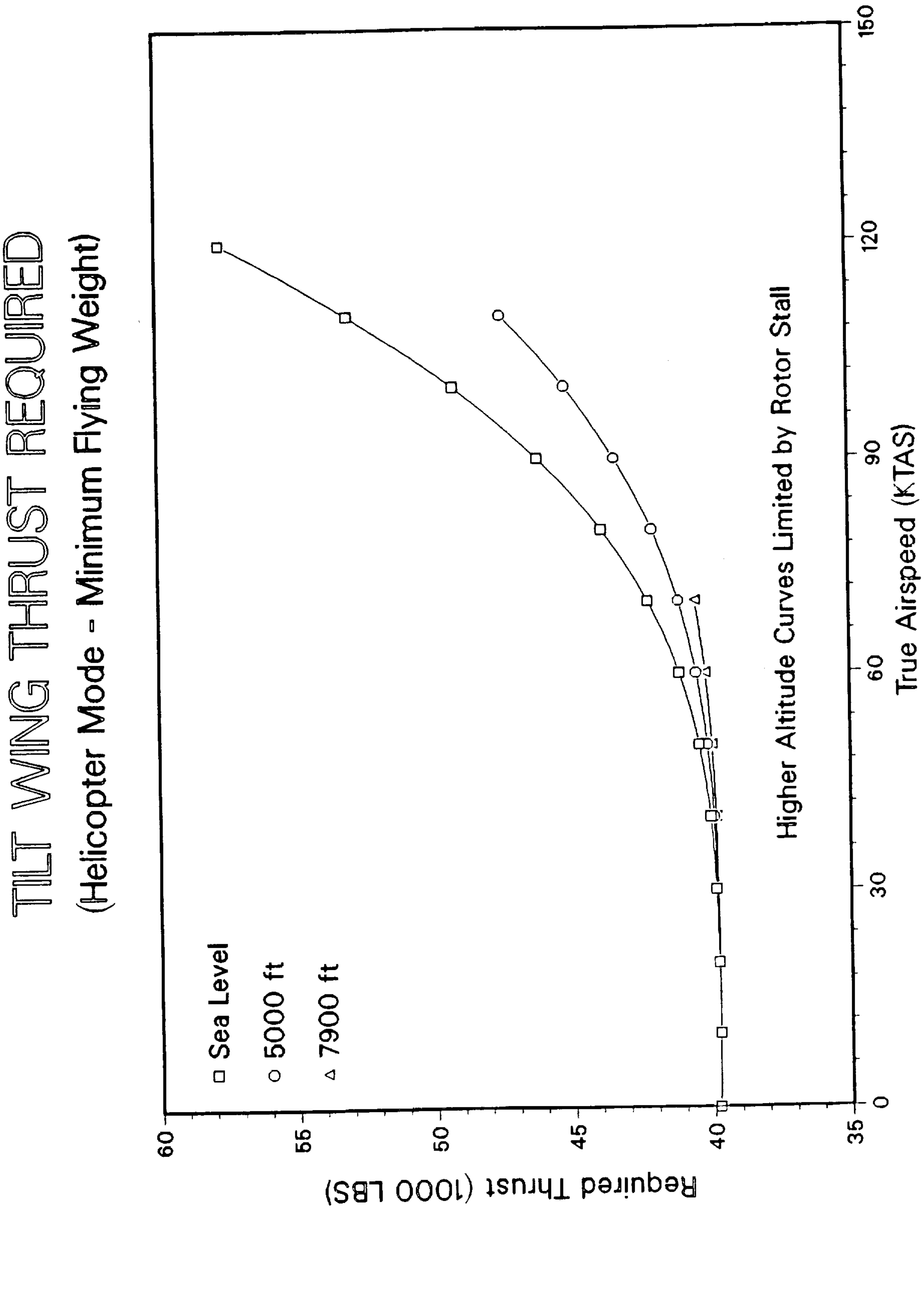



TILT WING THRUST REQUIRED
(Conversion Mode - Design Gross Weight)
Sea Level
10000 ft
20000 ft
Thrust Required (1000 LBS)
60
50
40
30
20
10
0
0
30
60
90
120
150
180
True Airspeed (KTAS)

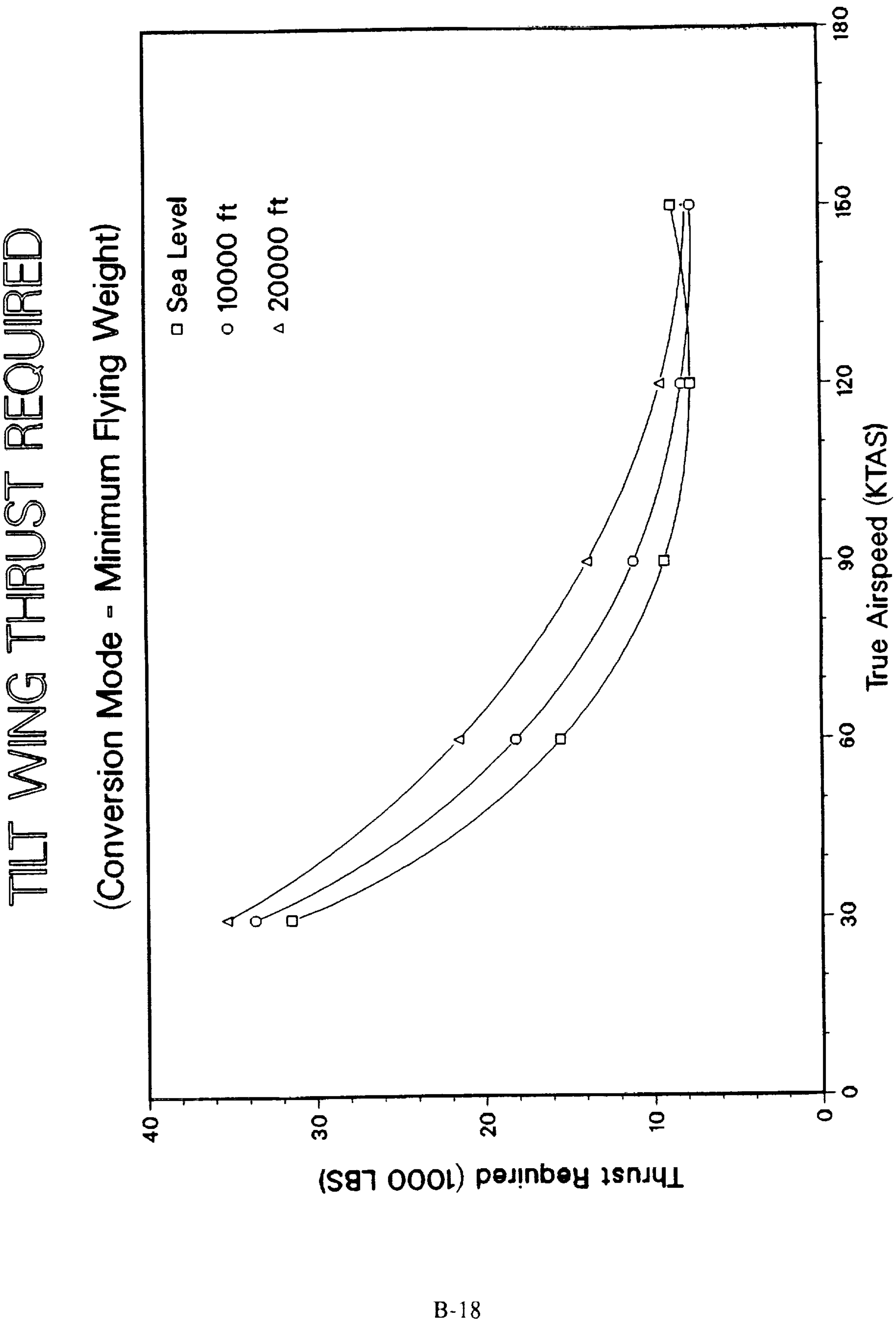
Drag (LB) vs. True Airspeed (KTAS)

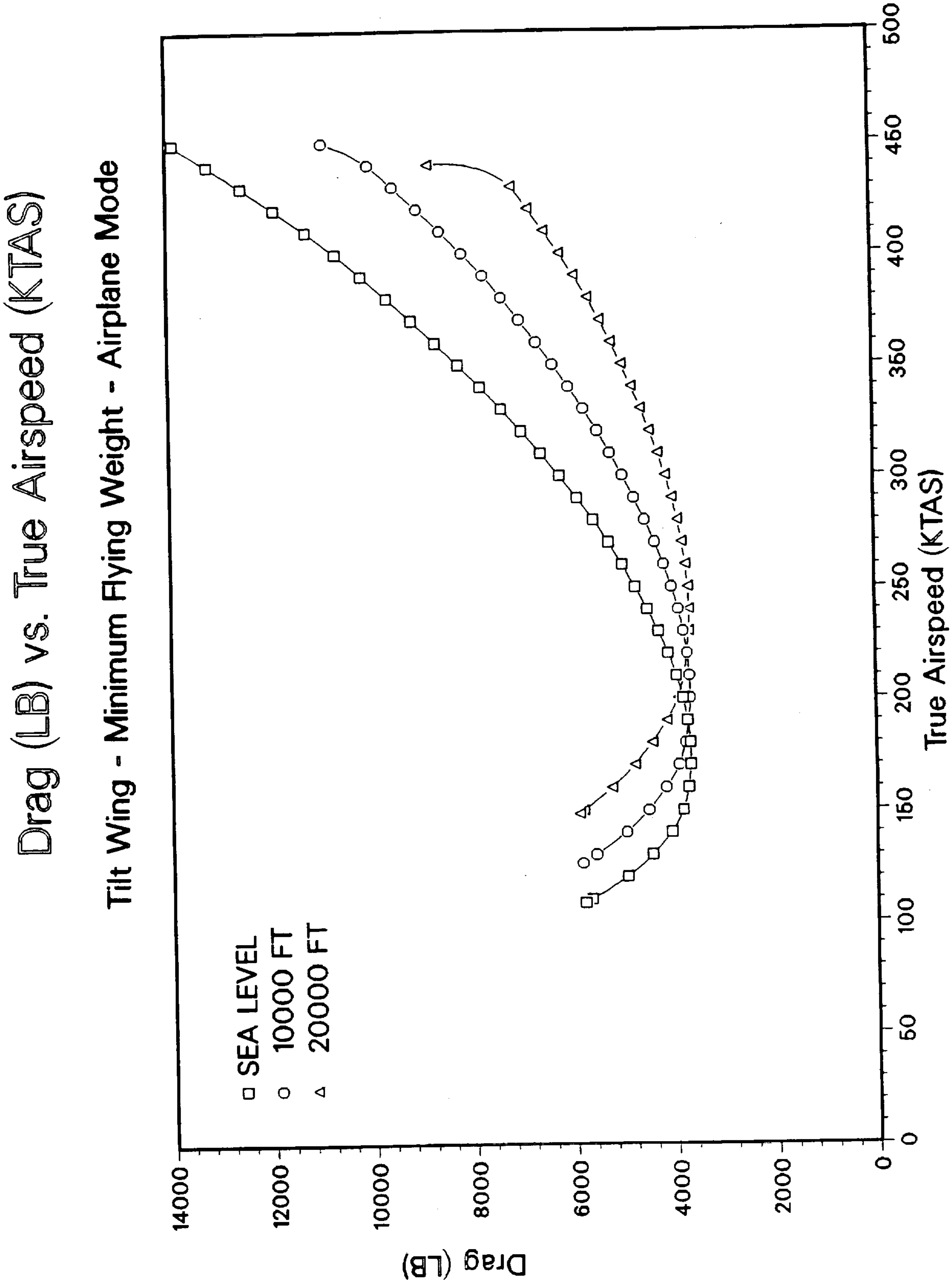
Tilt Wing - Design Gross Weight - Airplane Mode

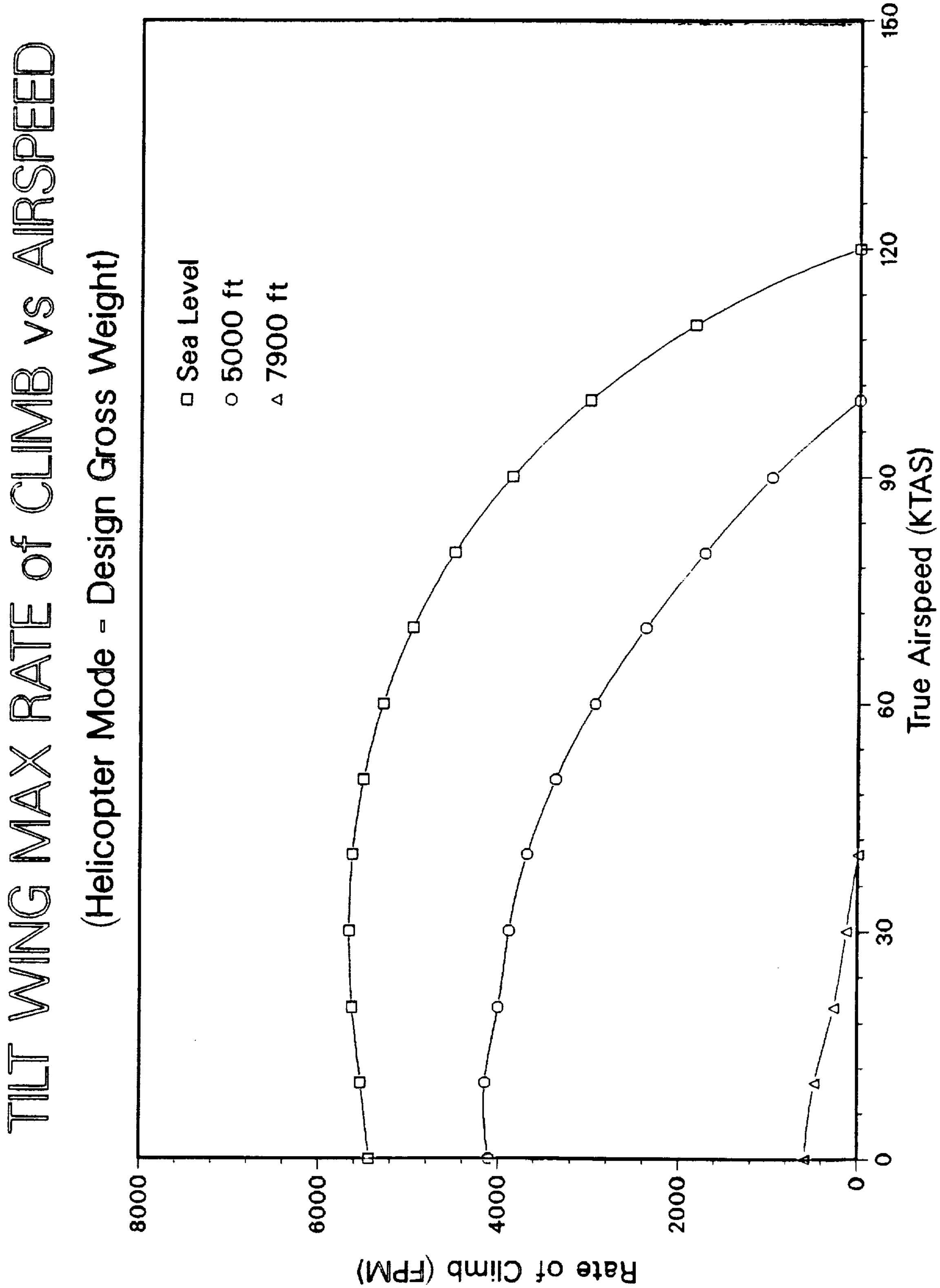




TILT WING THRUST REQUIRED
(Helicopter Mode - Minimum Flying Weight)
Sea Level
5000 ft
7900 ft
Higher Altitude Curves Limited by Rotor Stall
Required Thrust (1000 LBS)
True Airspeed (KTAS)
60
55
50
45
40
35
0
30
60
90
120
150


TILT WING THRUST REQUIRED
(Conversion Mode - Minimum Flying Weight)
Sea Level
10000 ft
20000 ft
Thrust Required (1000 LBS)
0
10
20
30
40
True Airspeed (KTAS)
0
30
60
90
120
150
180

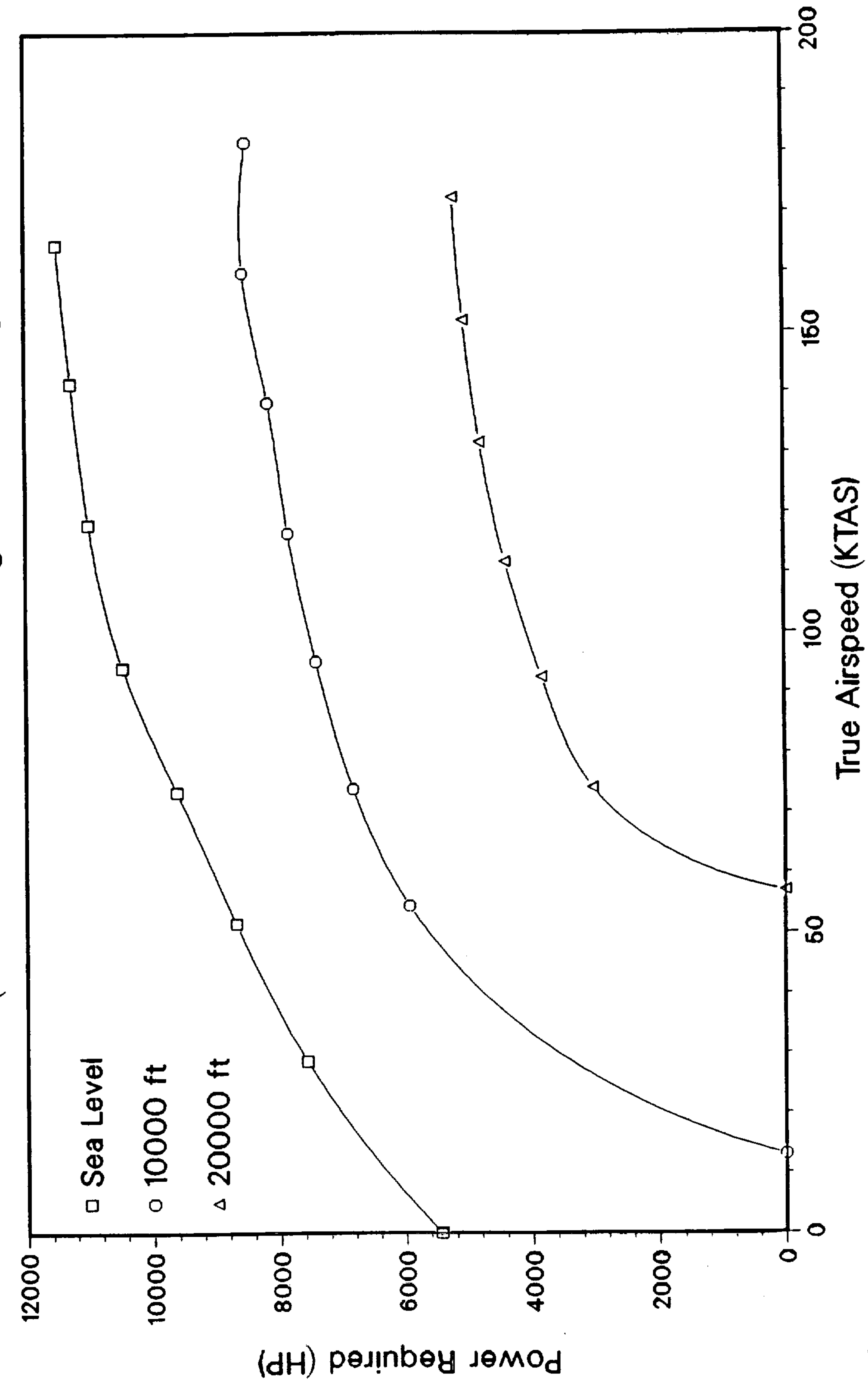

Drag (LB) vs. True Airspeed (KTAS)
Tilt Wing - Minimum Flying Weight - Airplane Mode
SEA LEVEL
10000 FT
20000 FT
Drag (LB)
True Airspeed (KTAS)
0
2000
4000
6000
8000
10000
12000
14000
0
50
100
150
200
250
300
350
400
450
500



TILT WING MAX RATE of CLIMB vs AIRSPEED
(Helicopter Mode - Design Gross Weight)
Sea Level
5000 ft
7900 ft
Rate of Climb (FPM)
True Airspeed (KTAS)
0
2000
4000
6000
8000
0
30
60
90
120
150

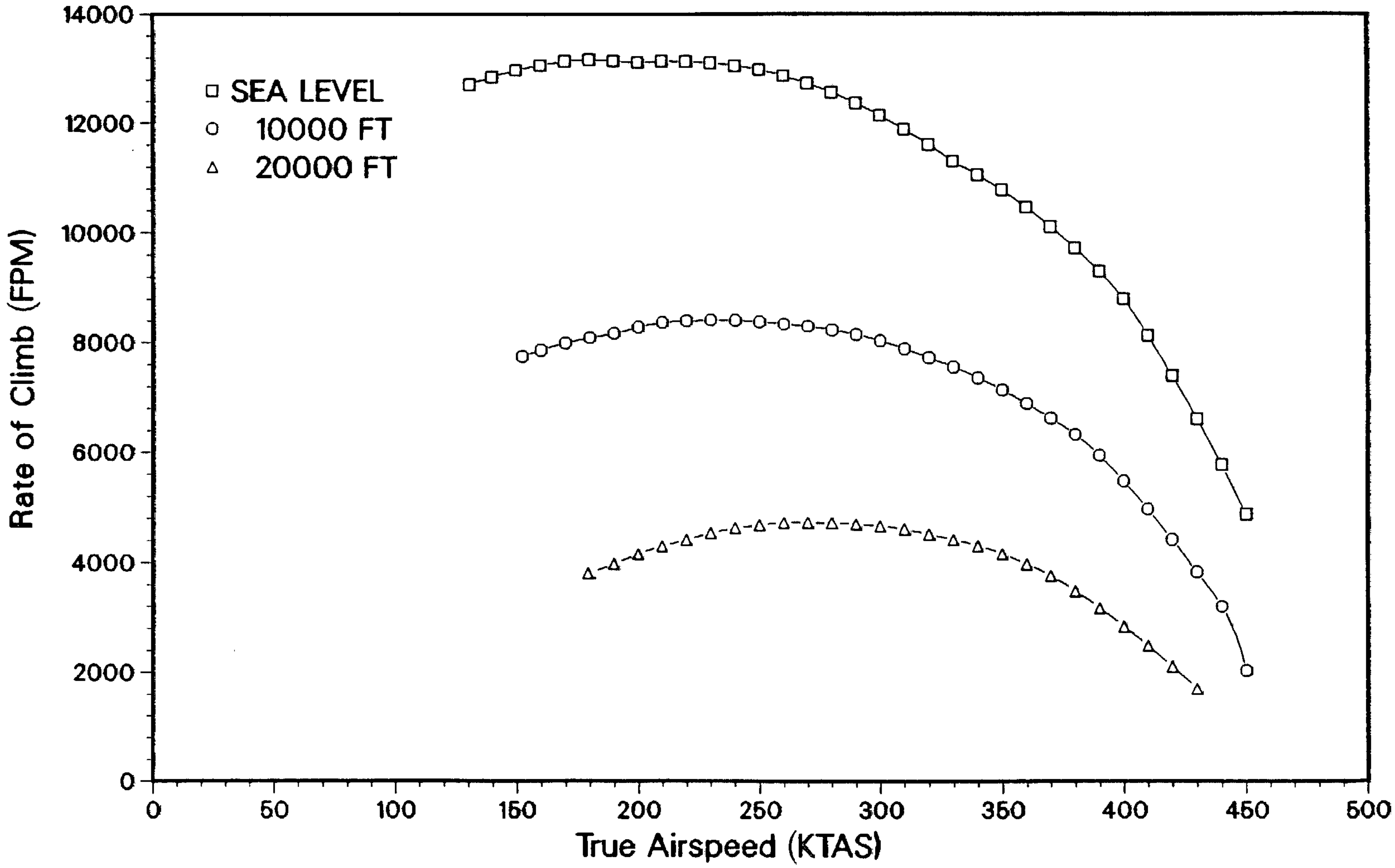
TILT WING MAX RATE of CLIMB

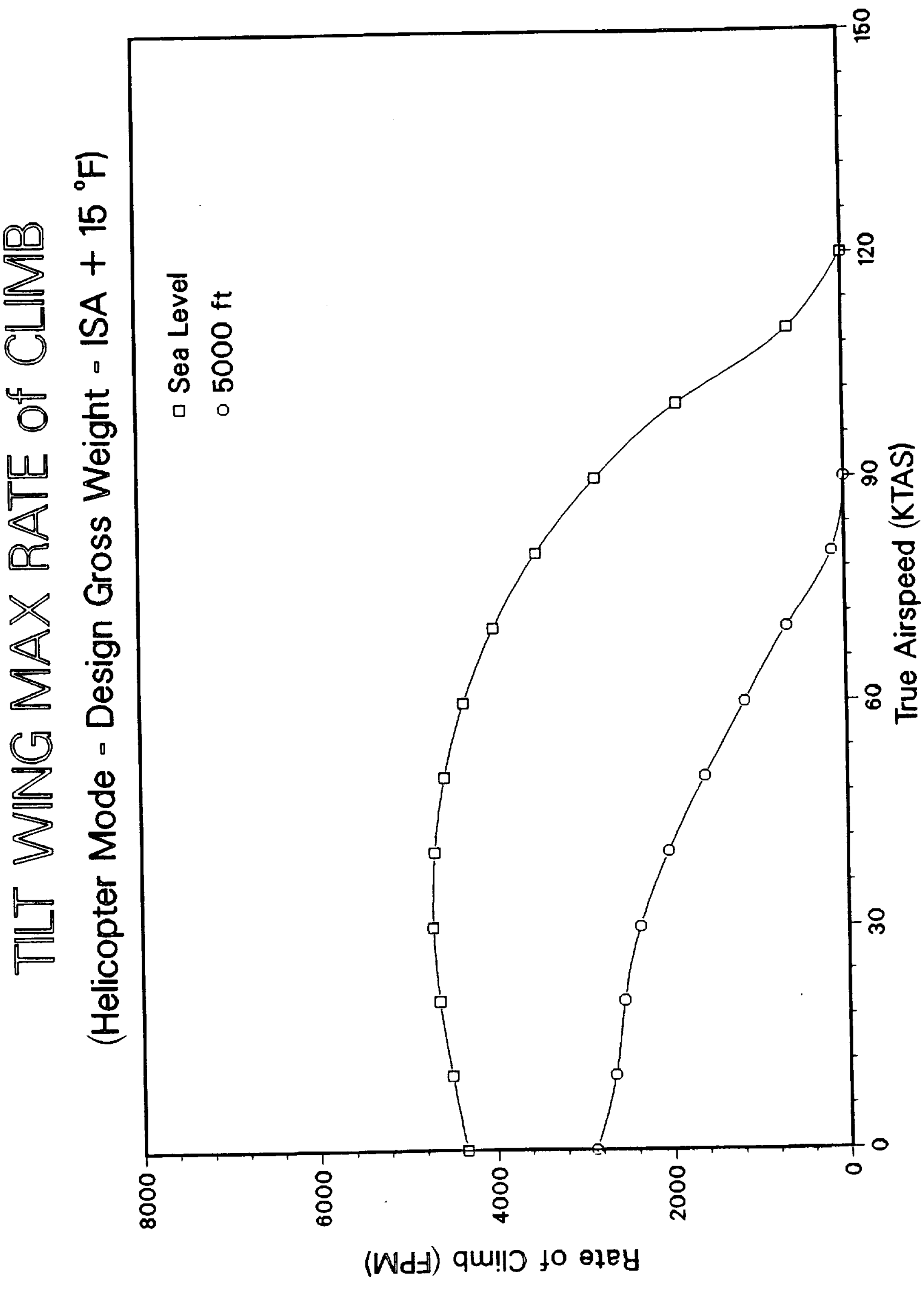
(Conversion Mode - Design Gross Weight)



Rate of Climb (FPM) vs. True Airspeed (KTAS)

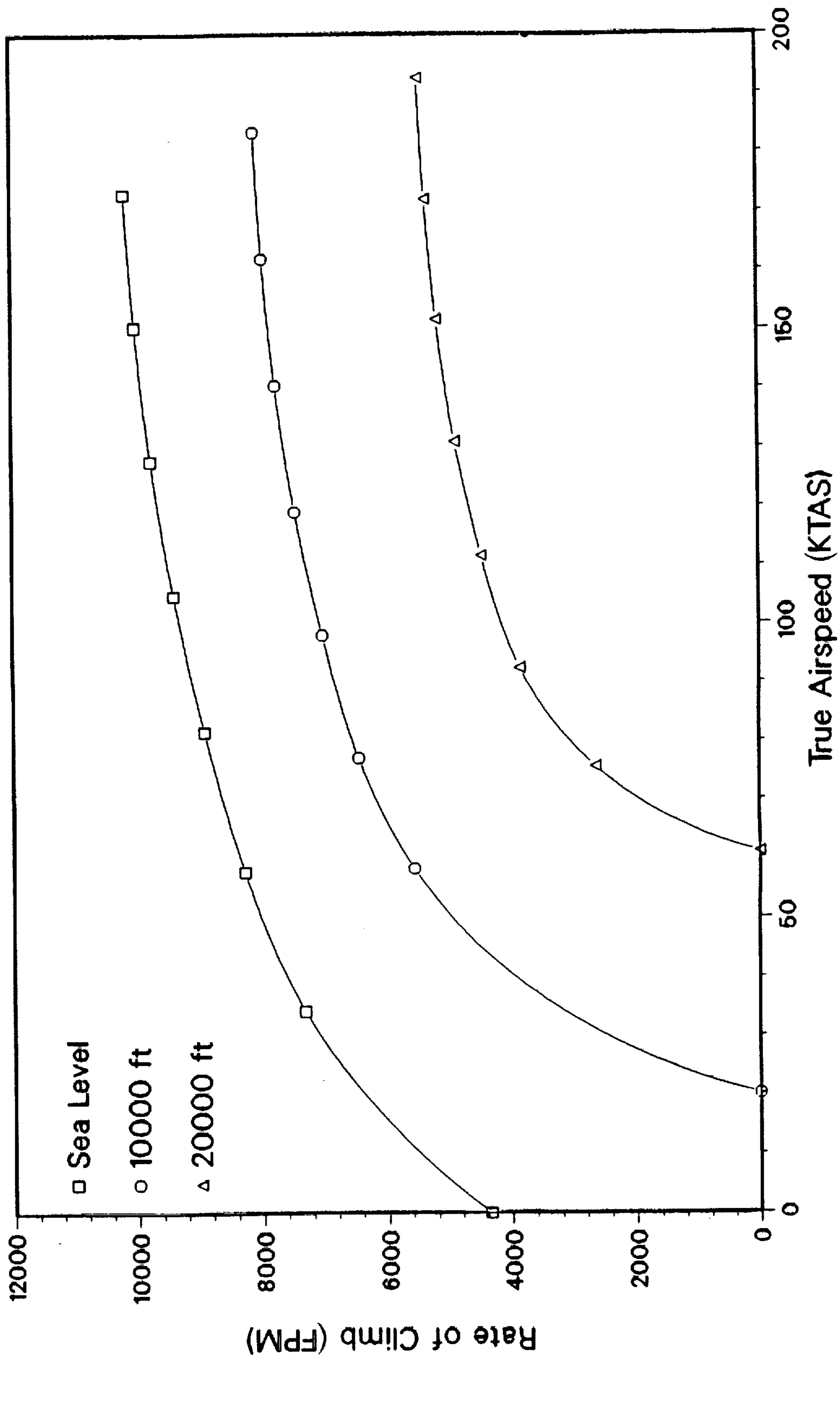
Tilt Wing - Design Gross Weight - Airplane Mode

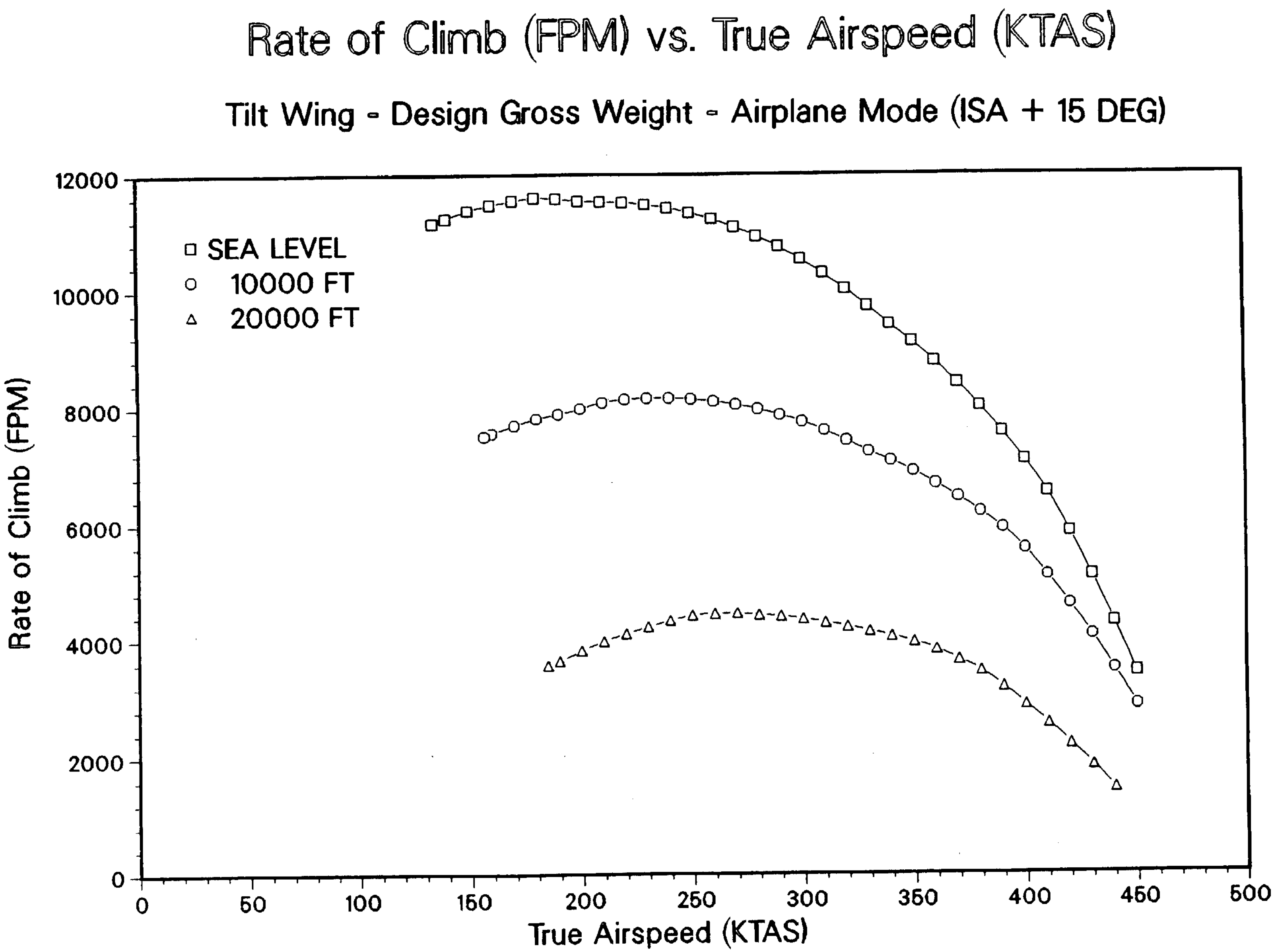



TILT WING MAX RATE of CLIMB
(Helicopter Mode - Design Gross Weight - ISA + 15 °F)
Sea Level
5000 ft
Rate of Climb (FPM)
8000
6000
4000
2000
0
True Airspeed (KTAS)
0
30
60
90
120
150

TILT WING MAX RATE of CLIMB

(Conversion Mode - Design Gross Weight ISA + 15 °F)

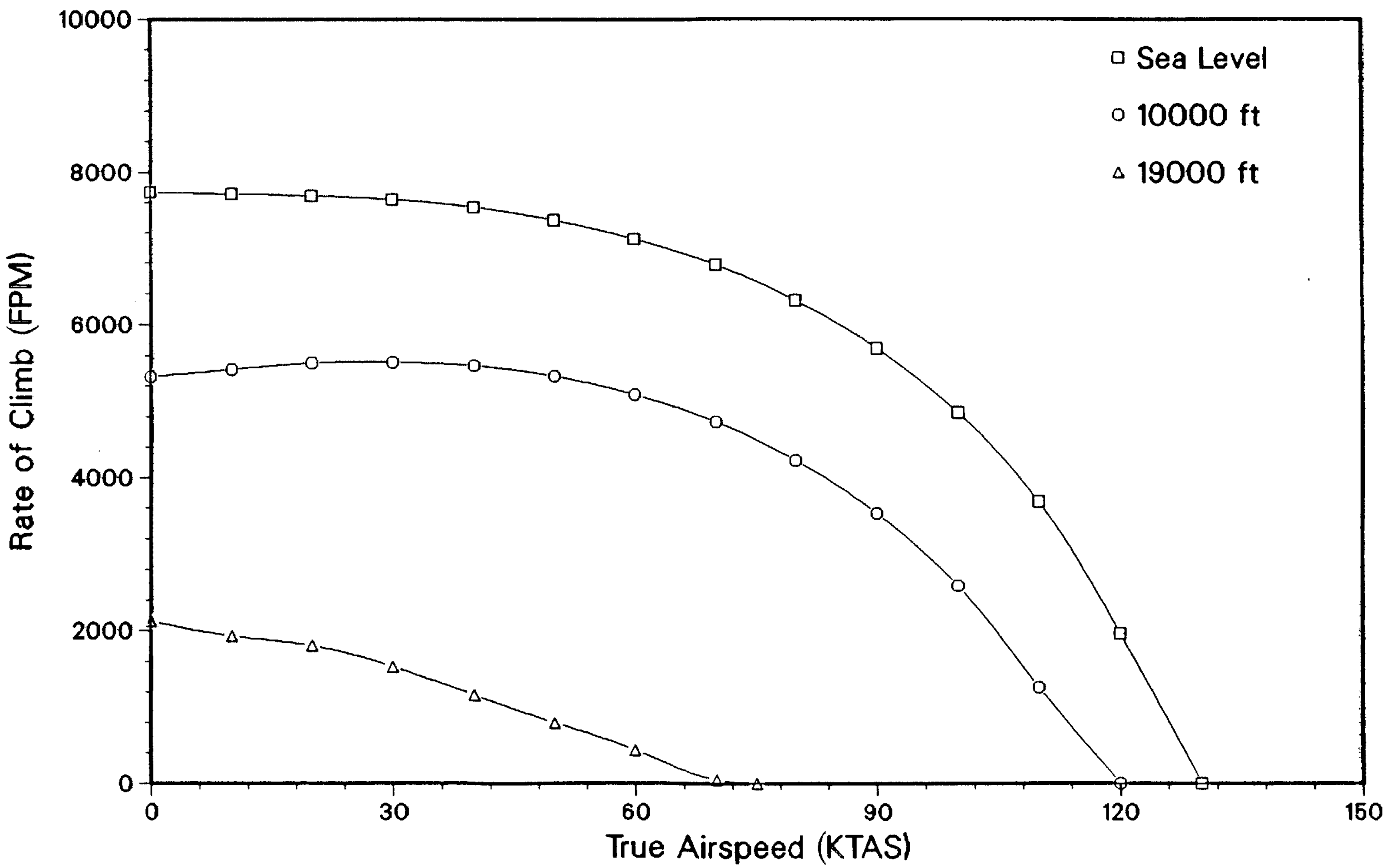


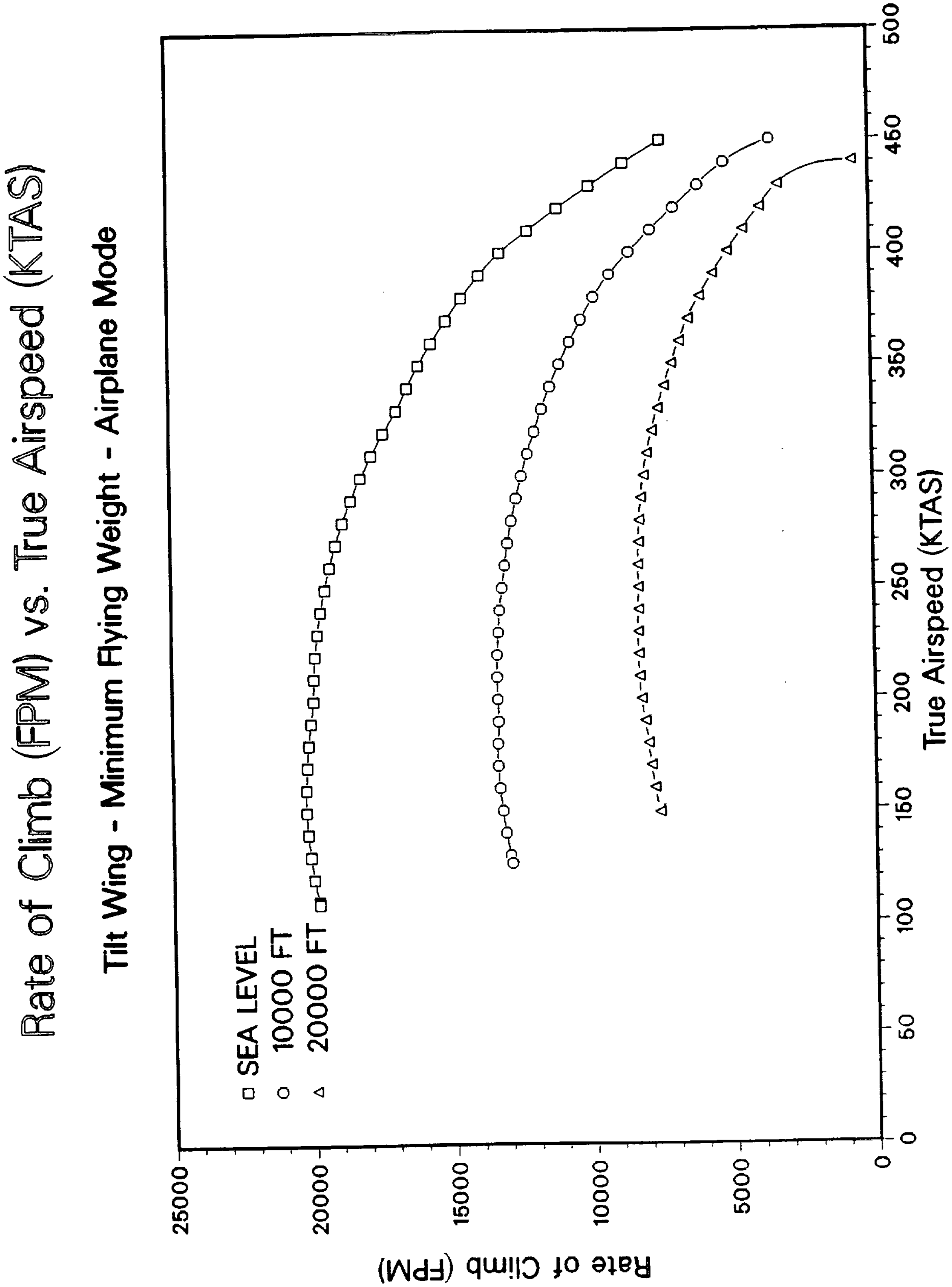


Rate of Climb (FPM) vs. True Airspeed (KTAS)
Tilt Wing - Design Gross Weight - Airplane Mode (ISA + 15 DEG)
SEA LEVEL
10000 FT
20000 FT
Rate of Climb (FPM)
0
2000
4000
6000
8000
10000
12000
True Airspeed (KTAS)
0
50
100
150
200
250
300
350
400
450
500

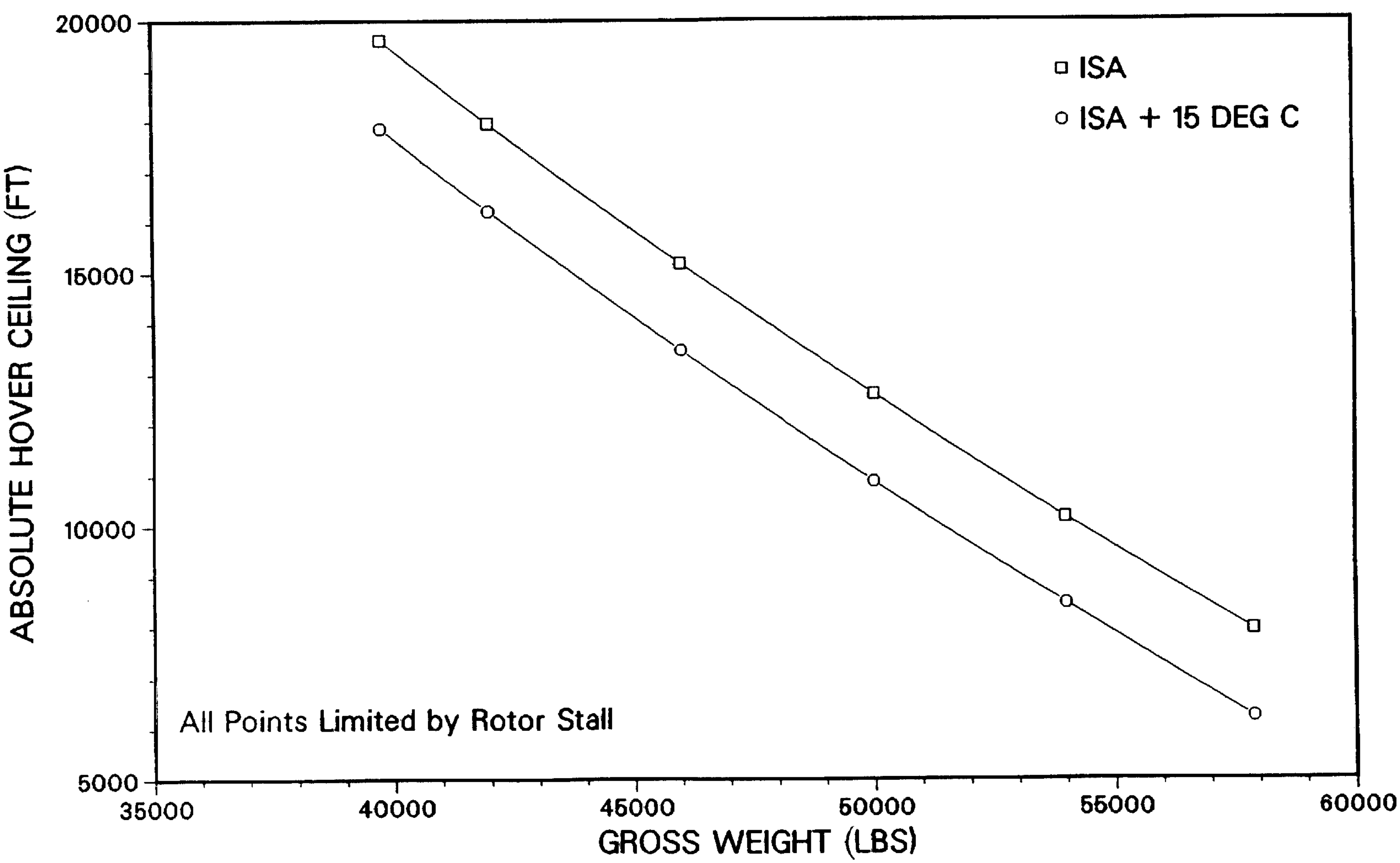
TILT WING MAX RATE of CLIMB

(Helicopter Mode - Minimum Flying Weight)



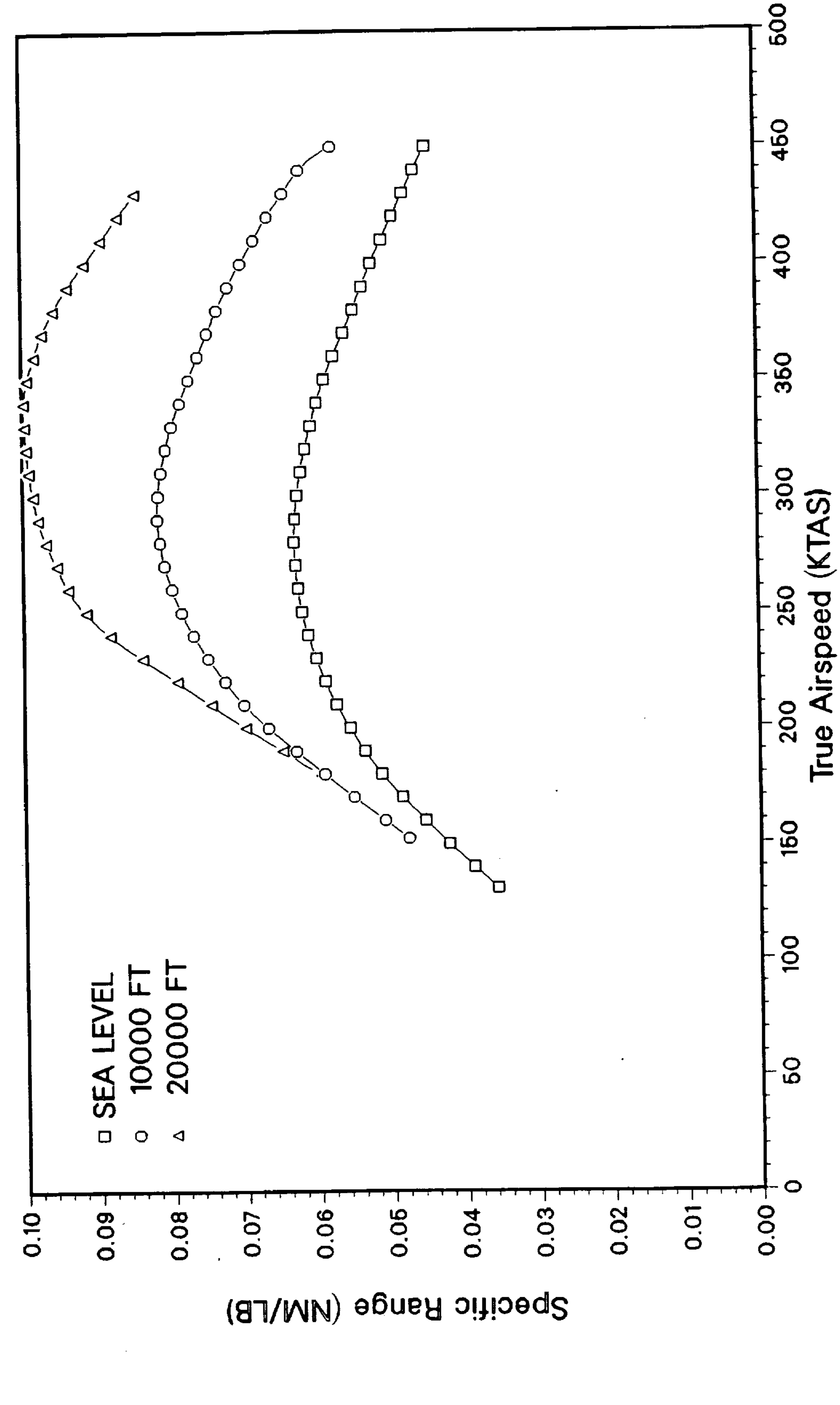

Rate of Climb (FPM) vs. True Airspeed (KTAS)
Tilt Wing - Minimum Flying Weight - Airplane Mode
SEA LEVEL
10000 FT
20000 FT
Rate of Climb (FPM)
25000
20000
15000
10000
5000
0
True Airspeed (KTAS)
0
50
100
150
200
250
300
350
400
450
500

TILT WING HOVER CEILING vs ALTITUDE



Specific Range (NM/LB) vs. True Airspeed (KTAS)

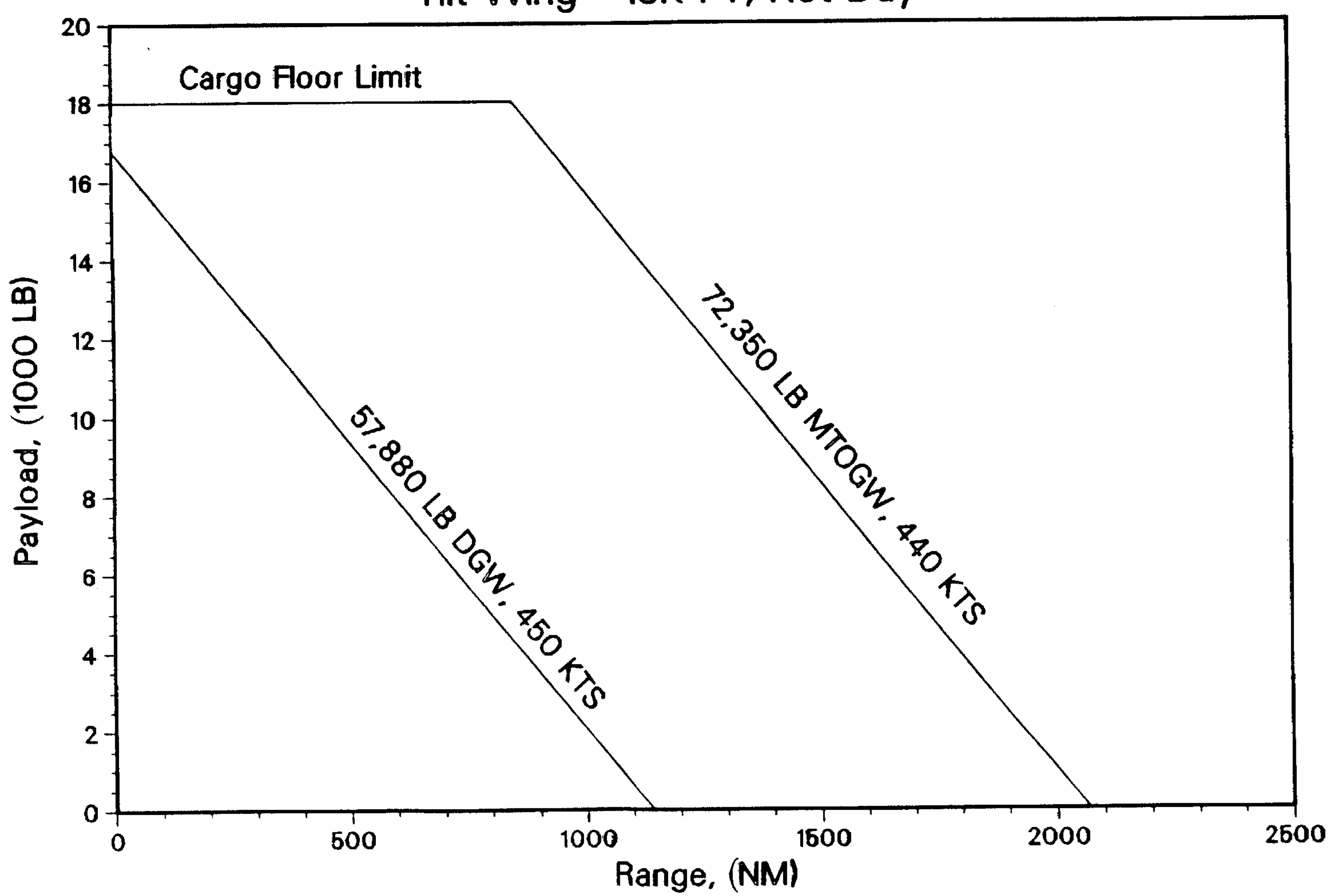
Tilt Wing - Design Gross Weight - Airplane Mode



C-3

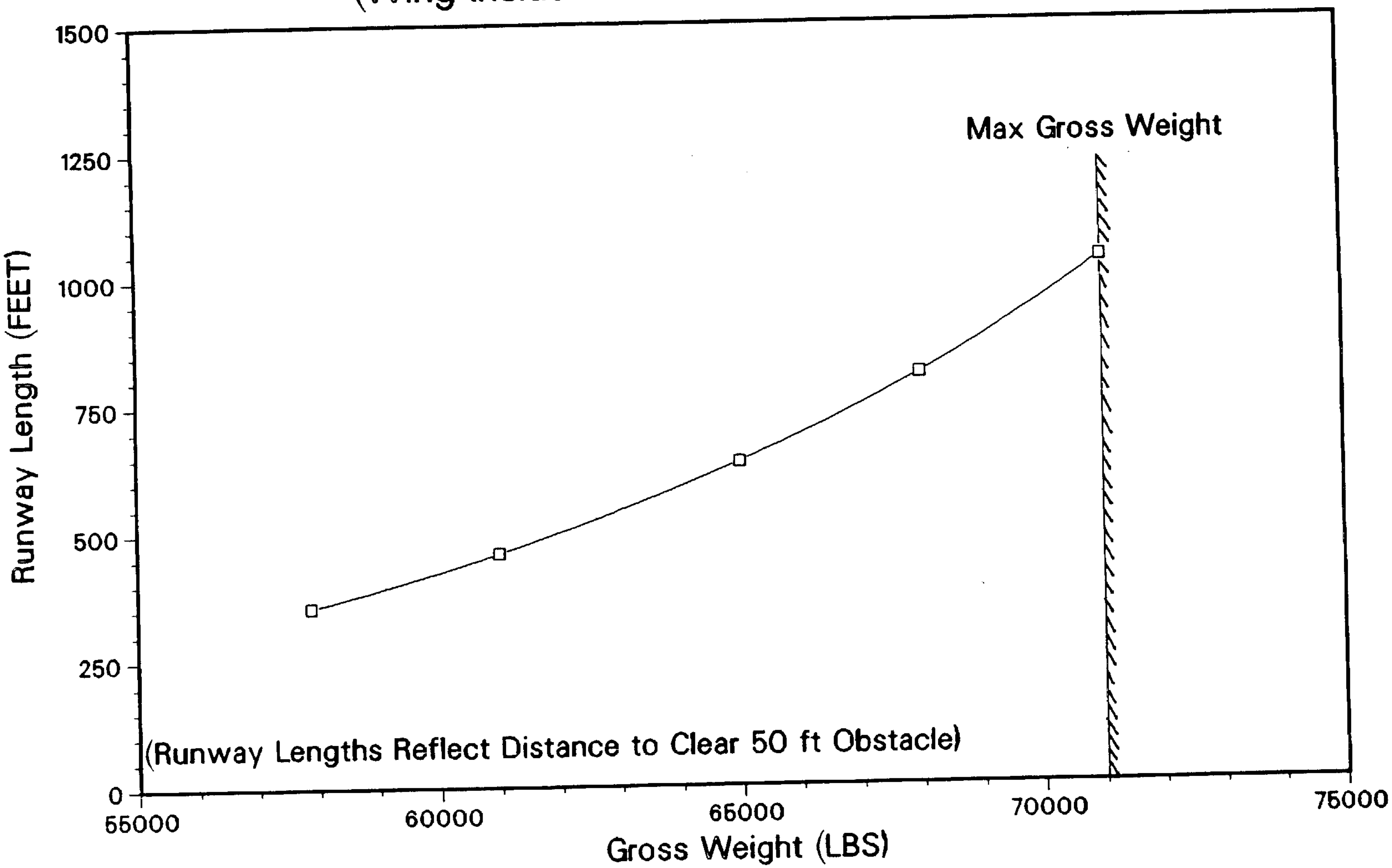
Payload-Range Diagram

Tilt Wing - 15K FT, Hot Day



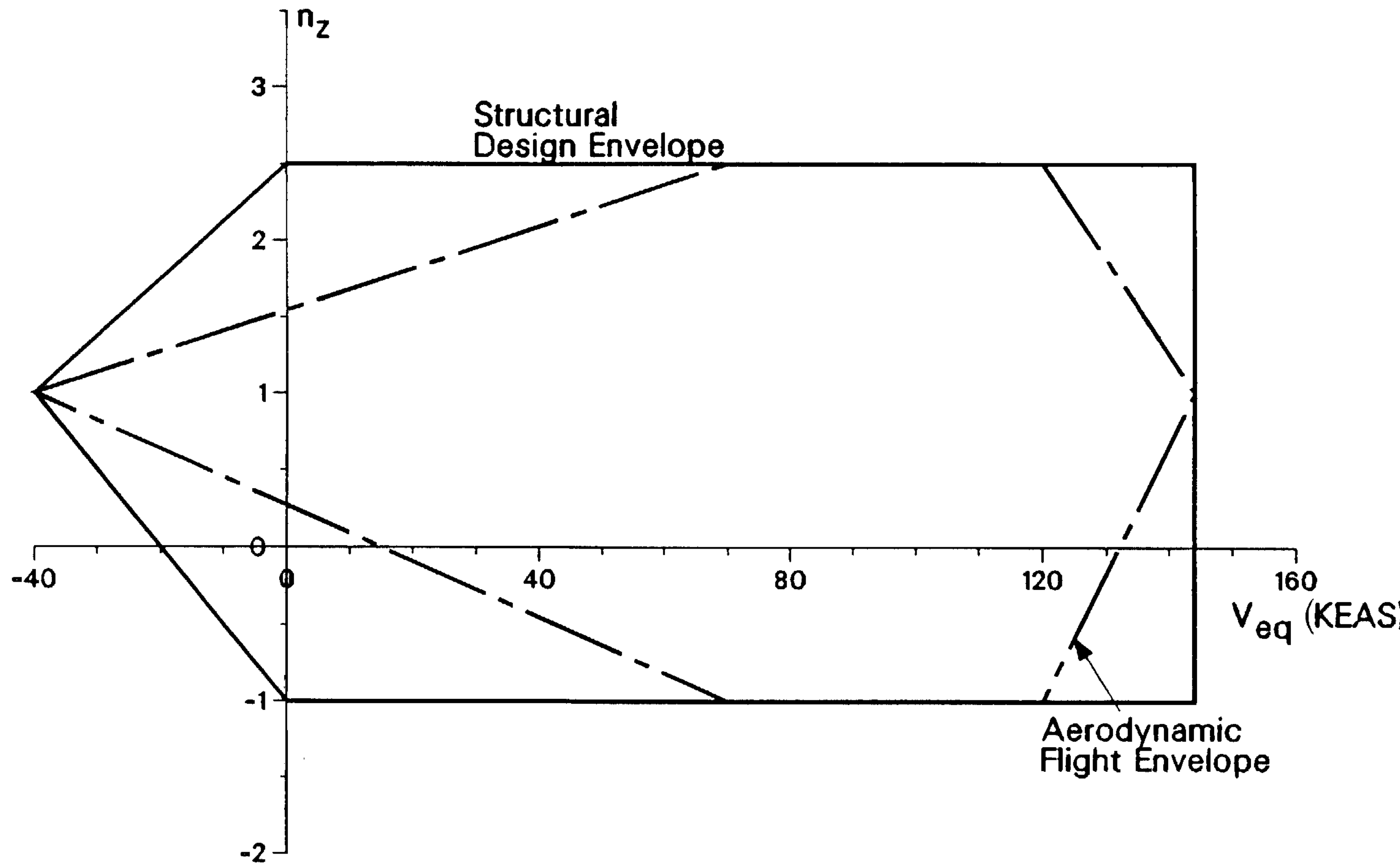
TILT WING STOL PERFORMANCE

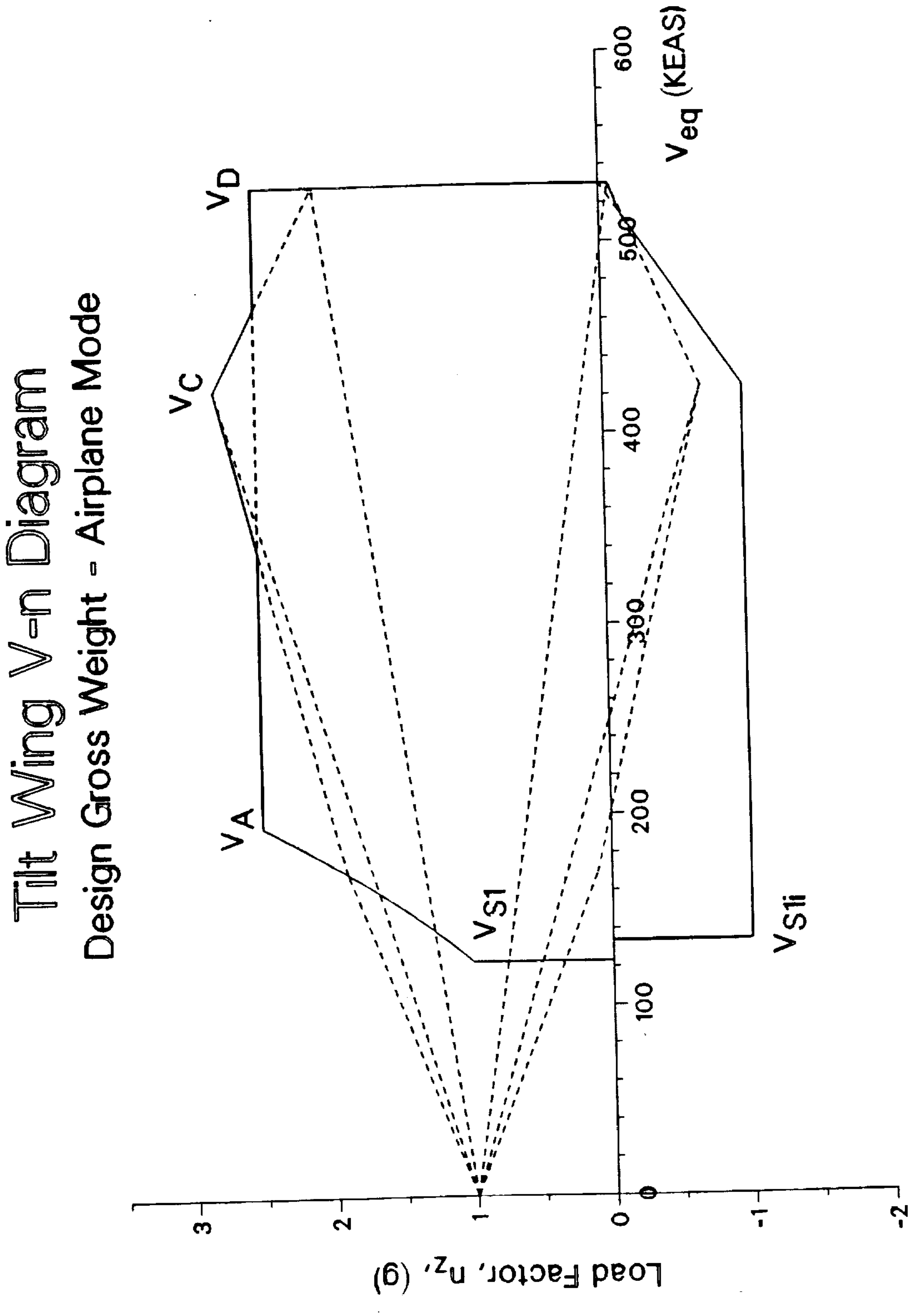
(Wing Incidence 60 ° - Sea Level Standard)



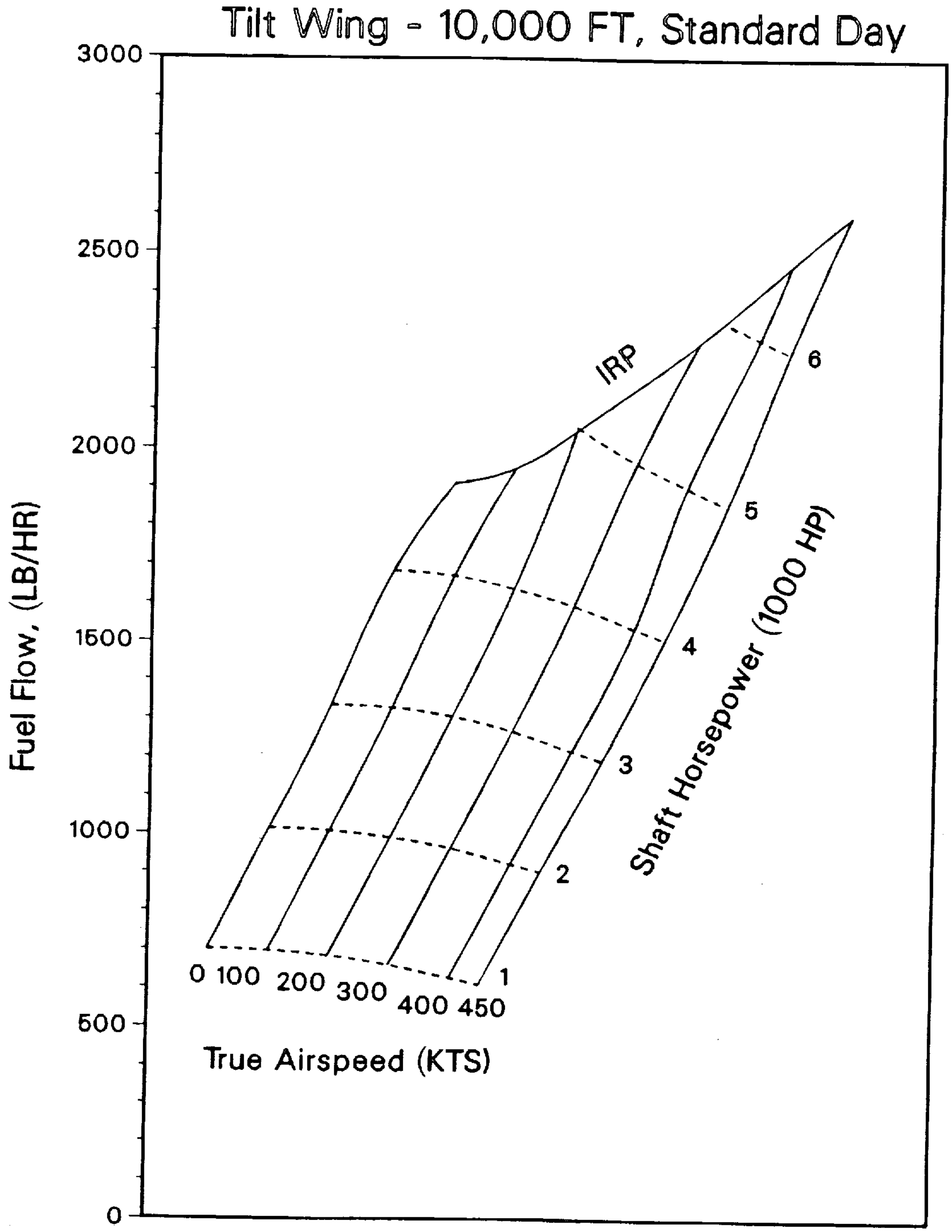
Tilt Wing V-n Diagram

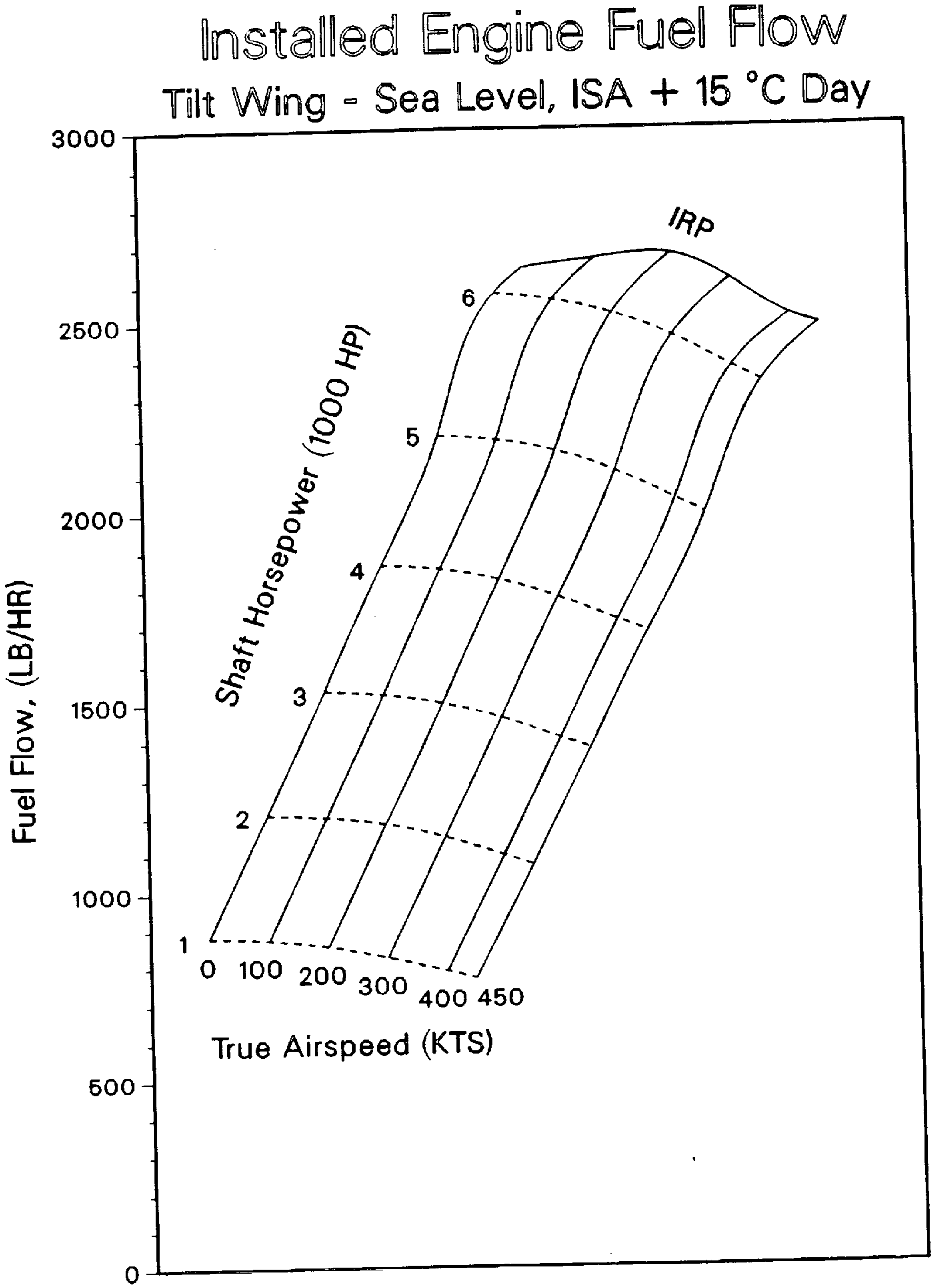
Design Gross Weight - Helicopter Mode




Tilt Wing V-n Diagram
Design Gross Weight - Airplane Mode
Load Factor, n_z, (g)
V_{eq} (KEAS)
V_A
V_C
V_D
V_{S1}
V_{S1i}
3
2
1
0
-1
-2
0
100
200
300
400
500
600

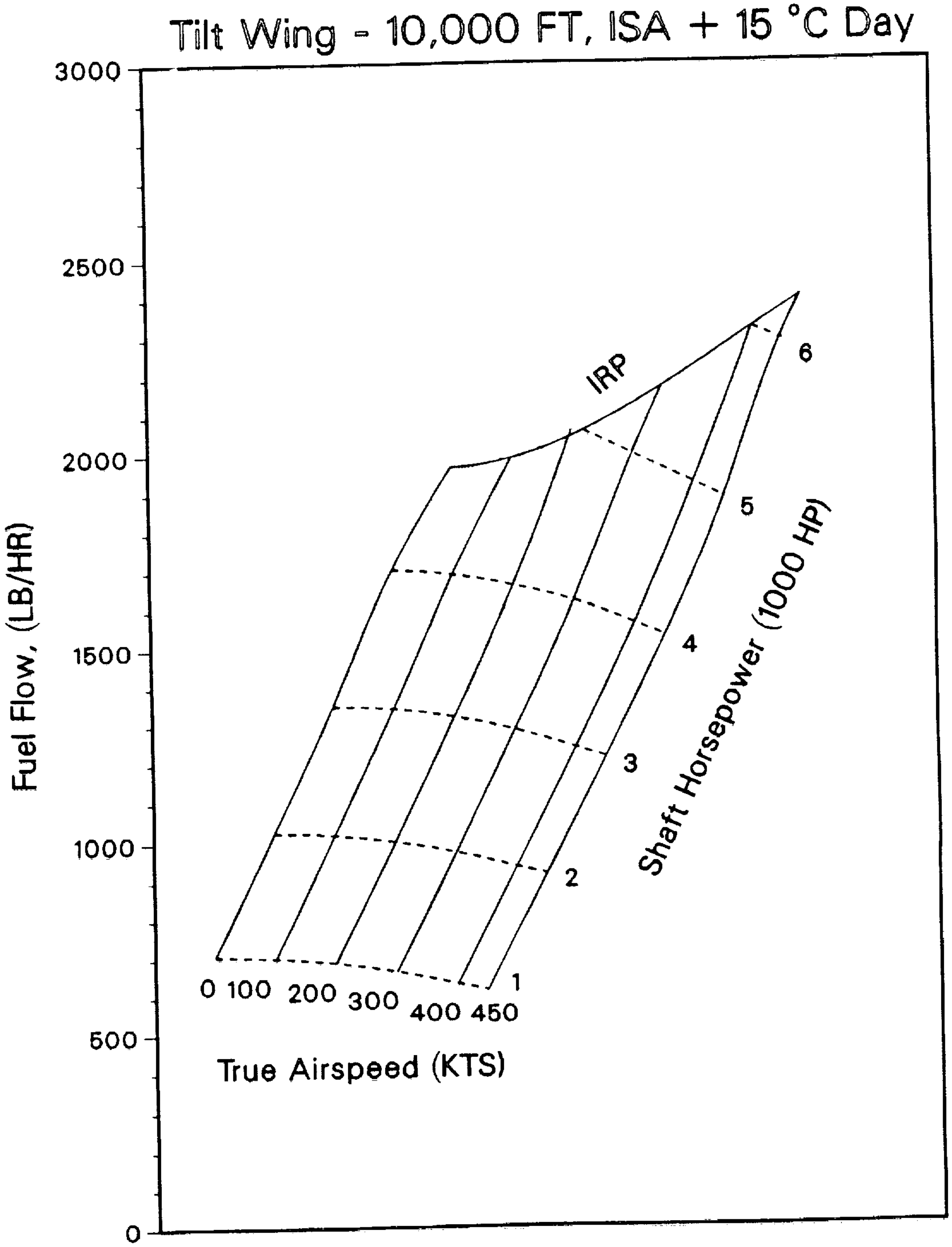
Installed Engine Fuel Flow

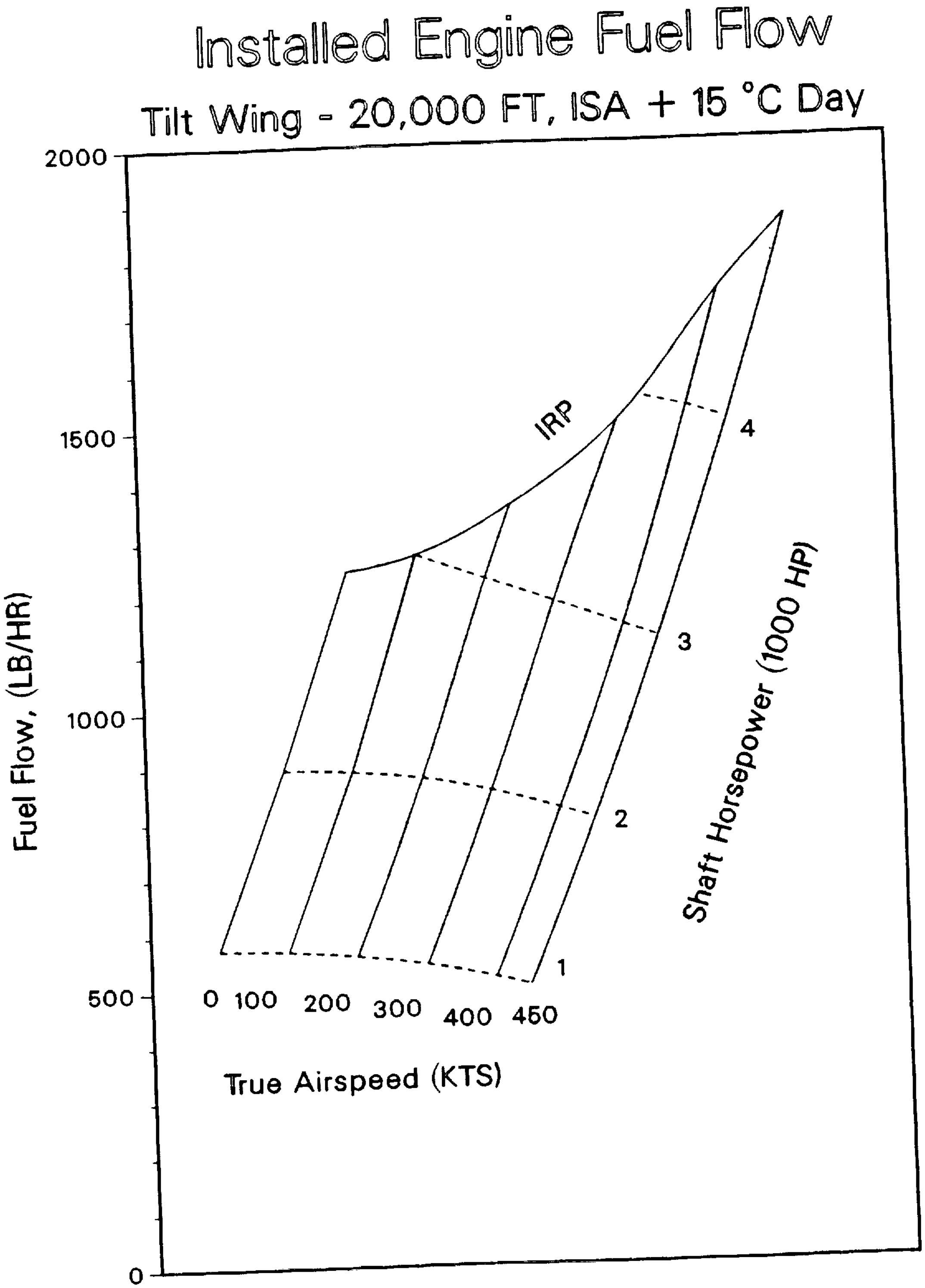




Installed Engine Fuel Flow
Tilt Wing - Sea Level, ISA + 15 °C Day
3000
2500
2000
1500
1000
500
0
Fuel Flow, (LB/HR)
IRP
Shaft Horsepower (1000 HP)
1
2
3
4
5
6
0 100 200 300 400 450
True Airspeed (KTS)

Installed Engine Fuel Flow

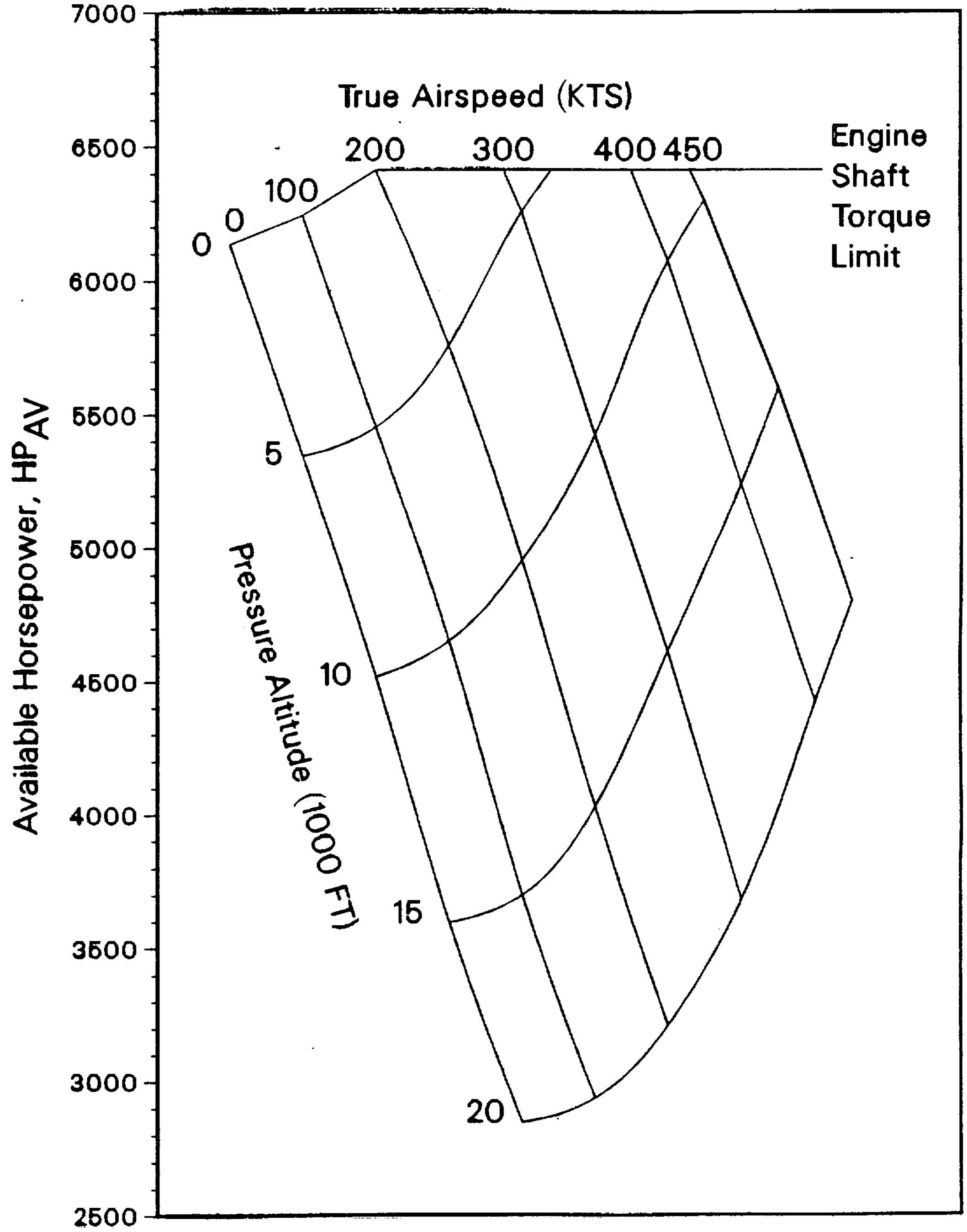




Installed Engine Fuel Flow
Tilt Wing - 20,000 FT, ISA + 15 °C Day
2000
1500
1000
500
0
Fuel Flow, (LB/HR)
IRP
4
3
2
1
Shaft Horsepower (1000 HP)
0 100 200 300 400 450
True Airspeed (KTS)

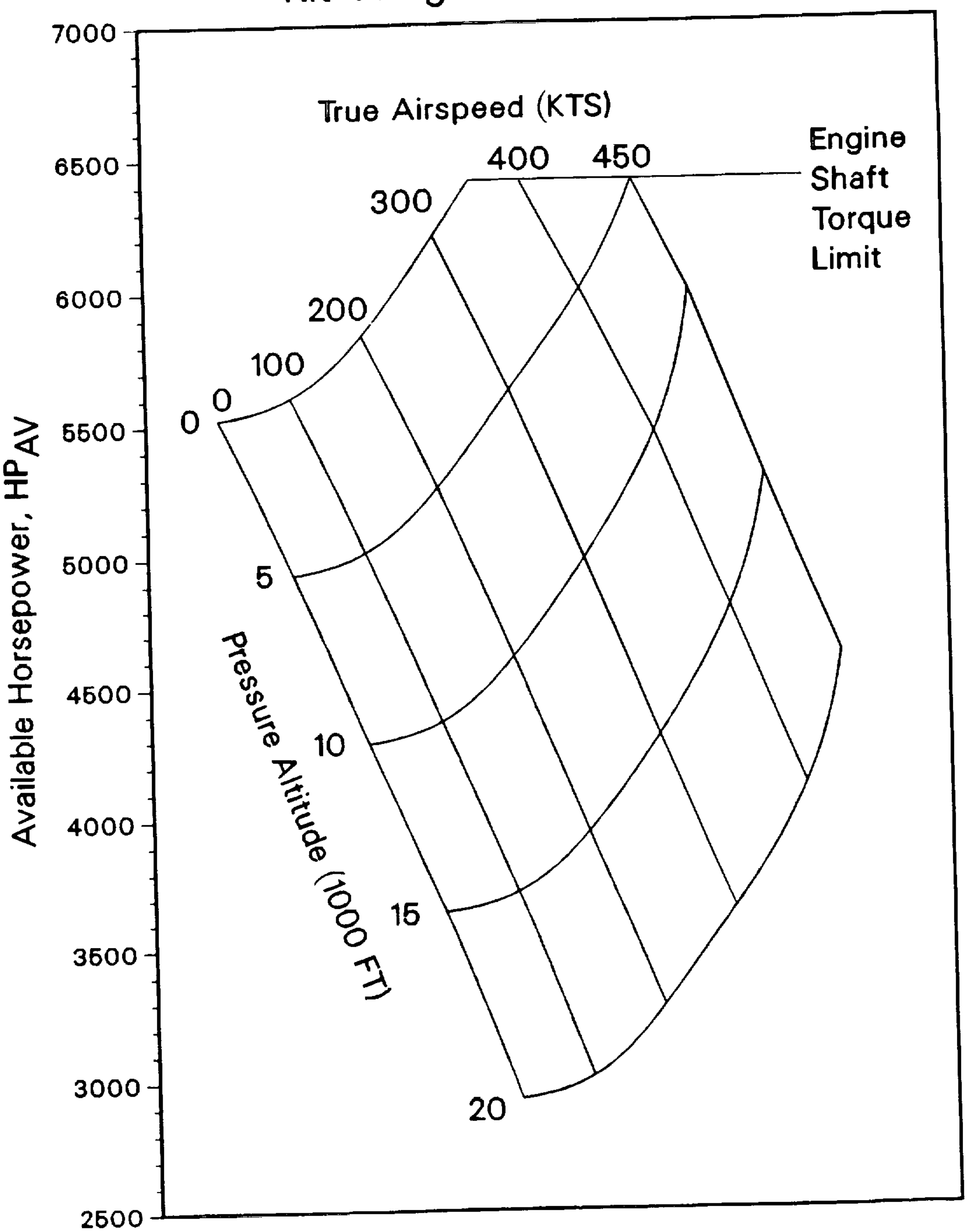
Installed MCP Power Available

Tilt Wing - Standard Day



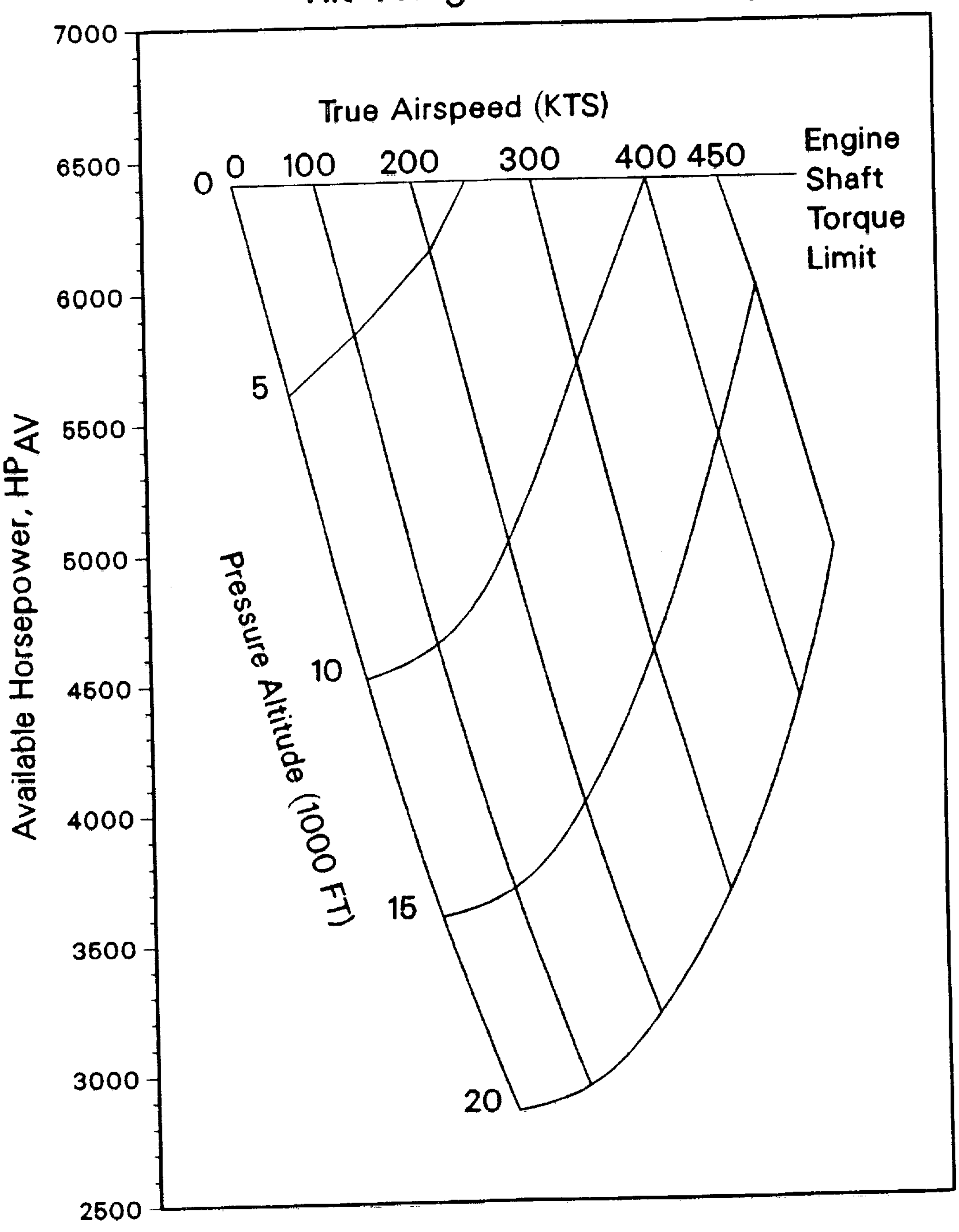
Installed MCP Power Available

Tilt Wing - ISA + 15 °C Day



Installed IRP Power Available

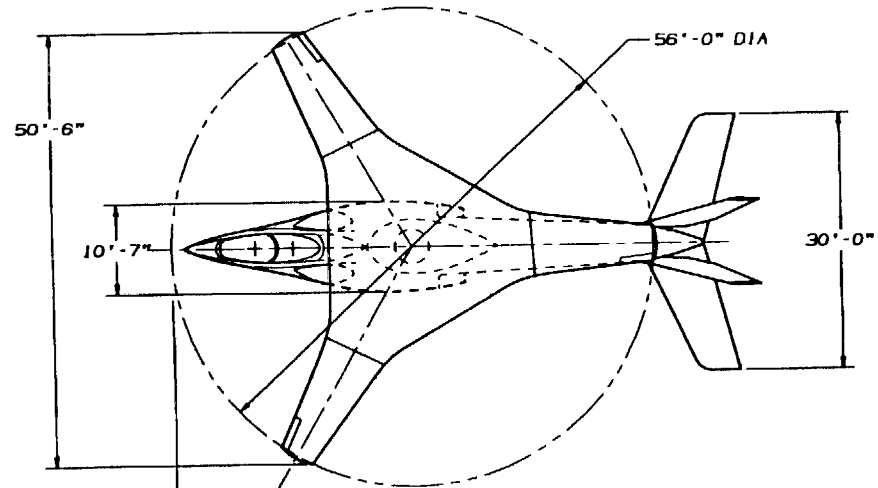
Tilt Wing - Standard Day

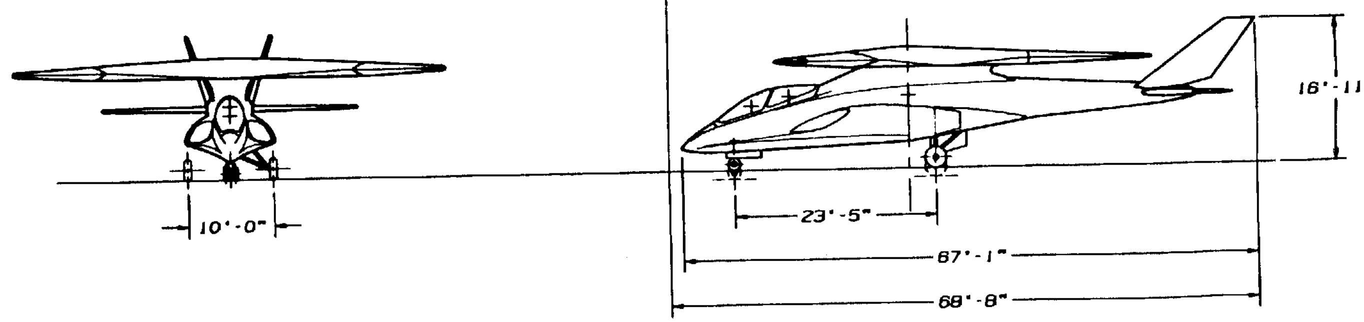


NASA HSR

ROTOR WING GROUND ATTACK

DESIGN GROSS WEIGHT:	28,122 LB
MISSION FUEL:	7,798 LB
PAYLOAD:	3,000 LB
HOVER DISK LOADING:	11.8 LB/FT²
MTOGW WING LOADING:	52.0 LB/FT²





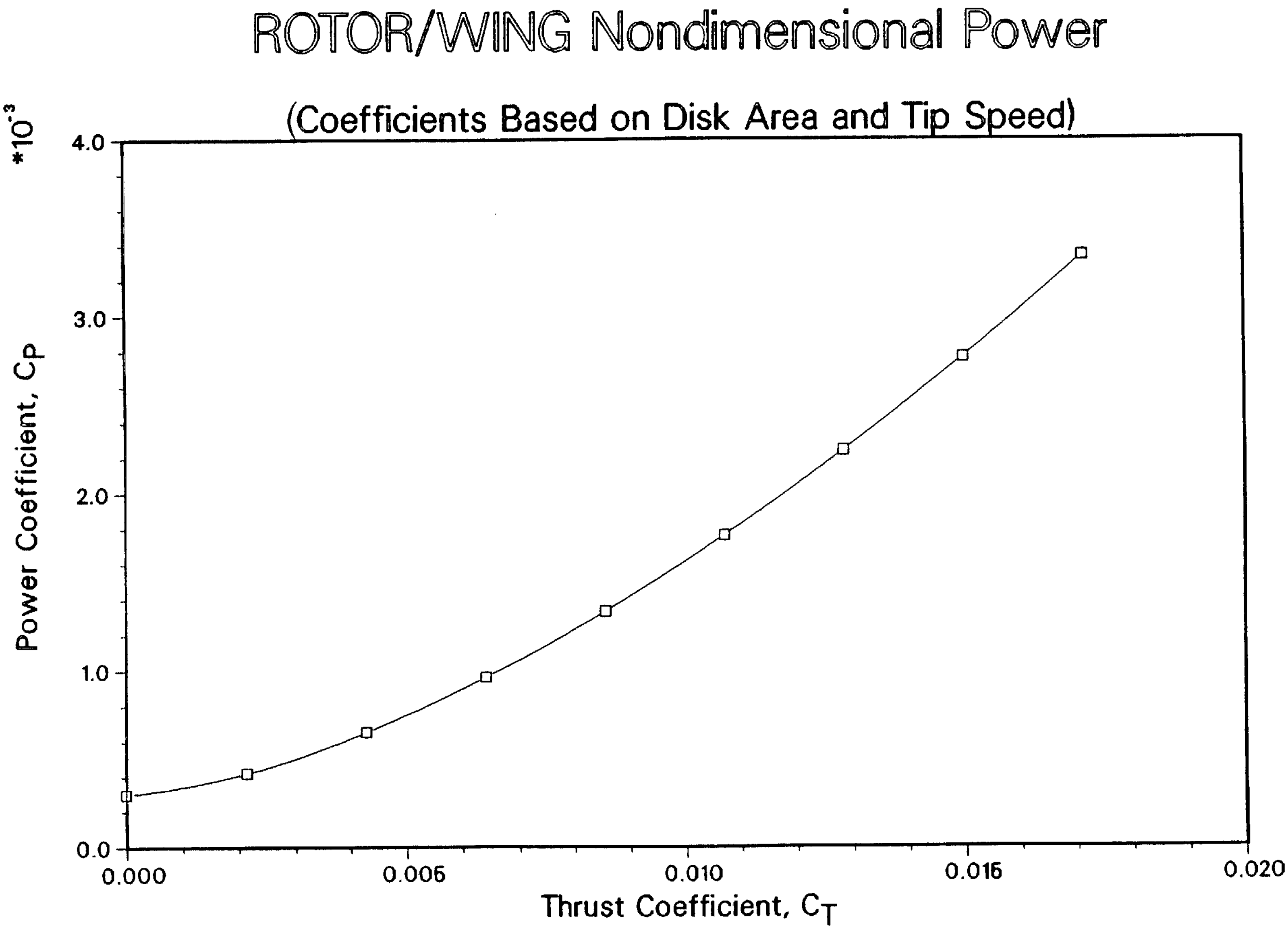
ROTOR/WING DRAG BREAKDOWN

Component	Wetted Area	C_f	Form Factor	Flat Plate Area
Fuselage	725	0.00187	1.5	2.04
Wing	835.7	0.00235	1.7	4.20
Horizontal Tail	410	0.00251	1.45	1.49
Vertical Tail	256.3	0.00247	1.43	0.90
Nacelles	372	0.00285	1.51	1.59
		Mission Drag Increment		1.00
				11.22
		10% for Interference and Protuberences :		1.12
			Total :	12.34

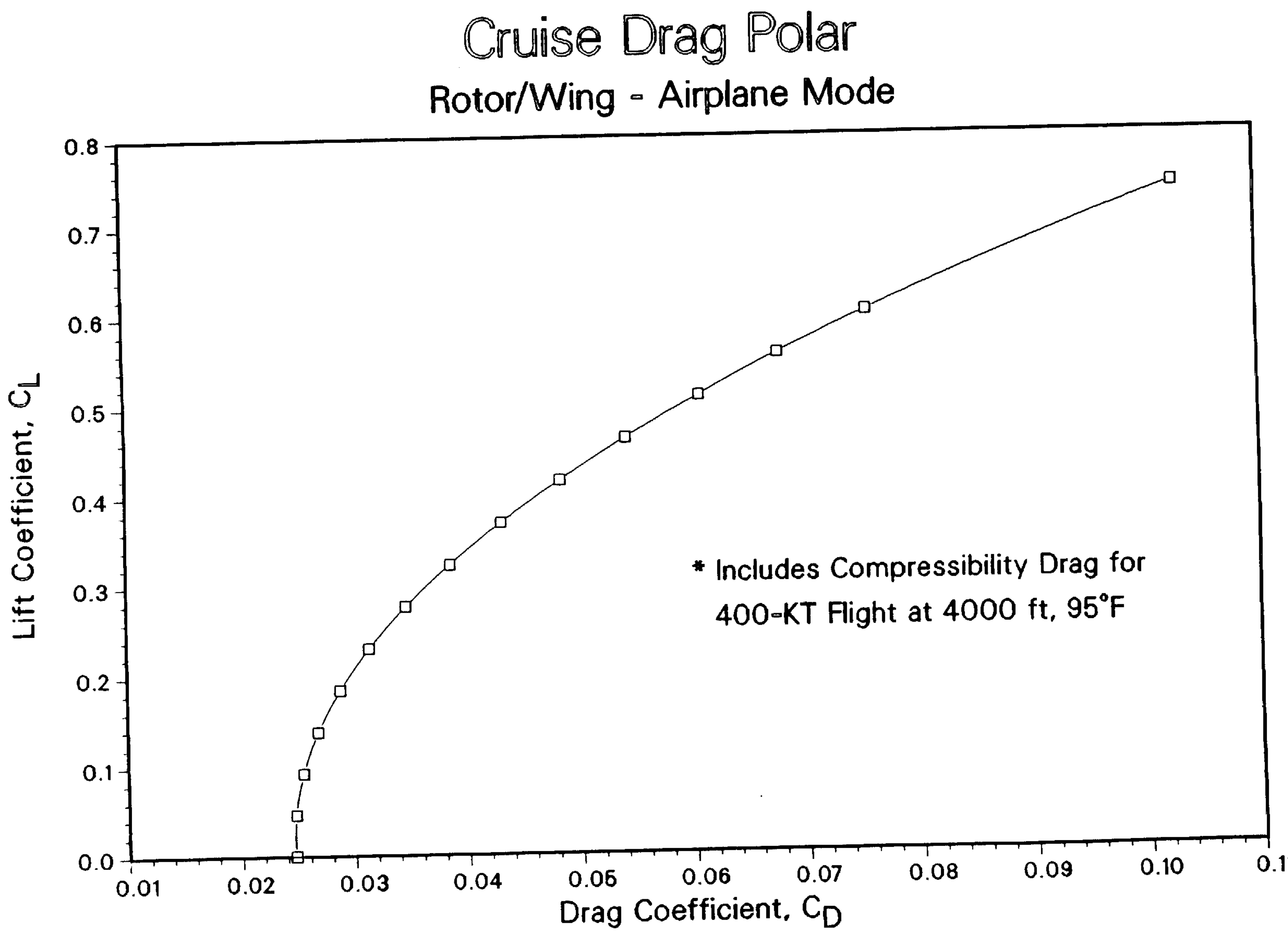
ROTOR/WING WEIGHT BREAKDOWN

Weight in lbs

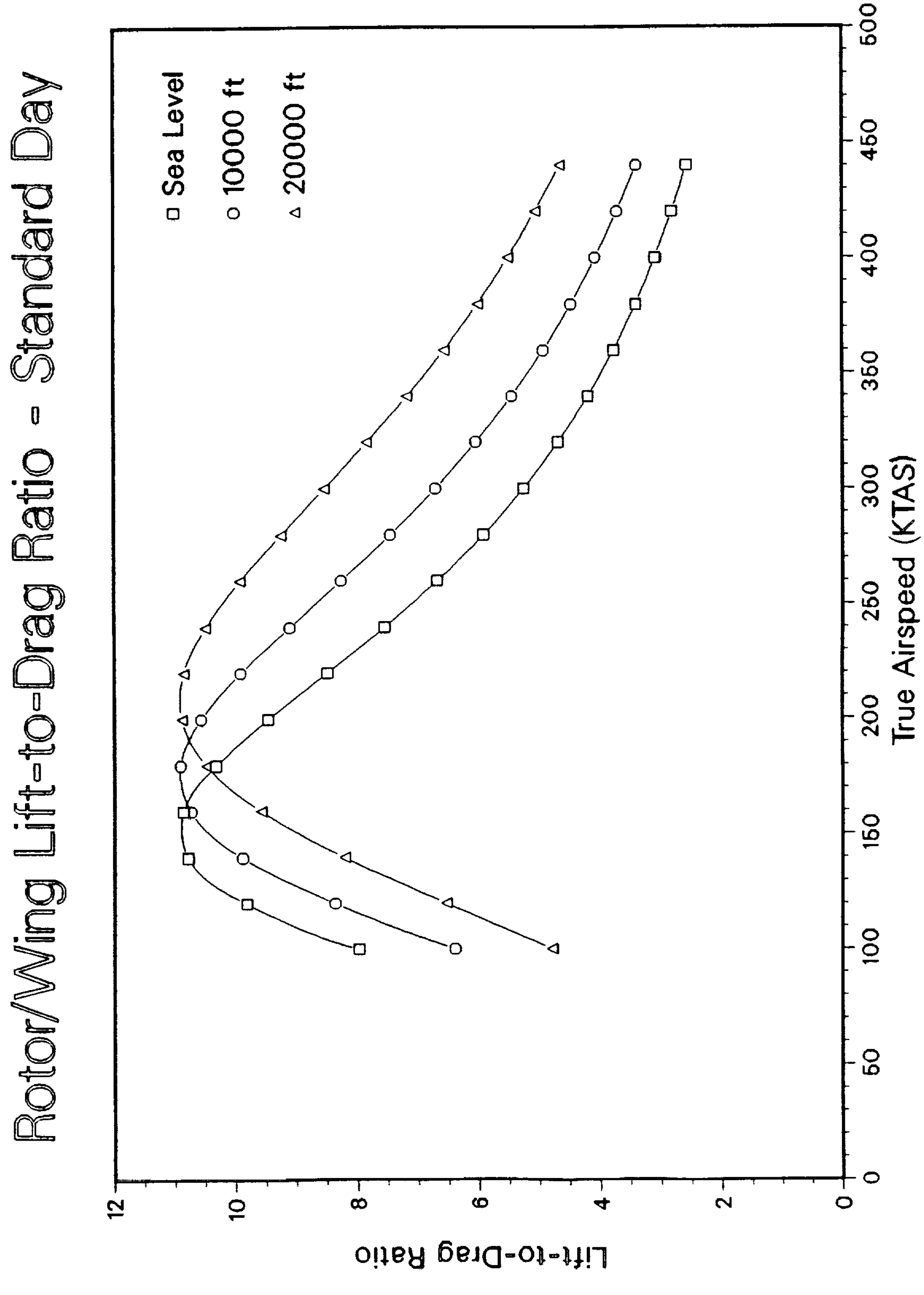
		CURRENT	1966 RW
GROUP	ROTOR/WING	%GW	%GW
WING	3570	12.7	14.0
MAIN ROTOR BLADES	****	0.0	0.0
M/R HUB & HINGE	****	0.0	0.0
TAIL ROTOR	****	0.0	0.0
HORIZONTAL TAIL	882	3.1	1.9
VERTICAL TAIL	356	1.3	1.7
BODY GROUP	2443	8.7	10.7
ALIGHTING GEAR	1066	3.8	3.1
NACELLES	526	1.9	1.2
(*STRUCTURAL GROUP*)	(8759)	(31.4)	(32.6)
ENGINE	1841	6.5	10.8
PROPELLER INSTL.	****	0.0	0.0
PROPULSION SUBSYS	638	2.3	2.5
FUEL SYSTEM	454	1.6	1.3
DRIVE SYSTEM & TILT	0	0.0	3.4
FLIGHT CONTROLS	1578	5.6	3.7
(*SYSTEMS GROUP*)	(4511)	(16.0)	(21.7)
FIXED WEIGHT	3000	10.7	12.7
EMPTY WEIGHT	16354	58.2	67.0
PAYLOAD	3000	10.7	15.3
OPERATING ITEMS	970	3.4	2.3
FUEL	7798	27.7	15.4
GROSS WEIGHT	28122	100%	100%



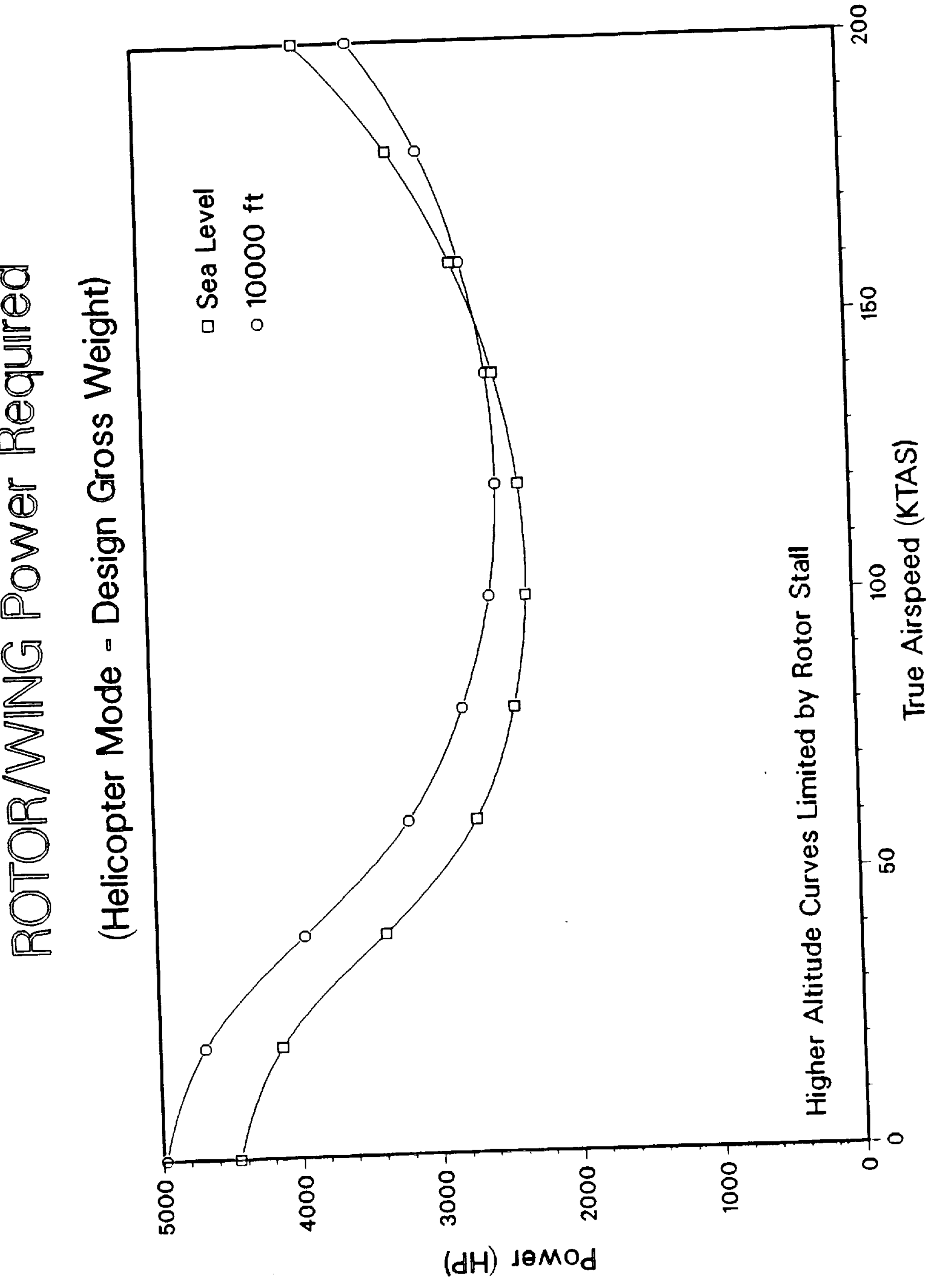
ROTOR/WING Nondimensional Power
(Coefficients Based on Disk Area and Tip Speed)
*10^-3
4.0
3.0
2.0
1.0
0.0
Power Coefficient, Cp
0.000
0.005
0.010
0.015
0.020
Thrust Coefficient, CT



Cruise Drag Polar
Rotor/Wing - Airplane Mode
Lift Coefficient, C_L
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Drag Coefficient, C_D
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
* Includes Compressibility Drag for
400-KT Flight at 4000 ft, 95°F

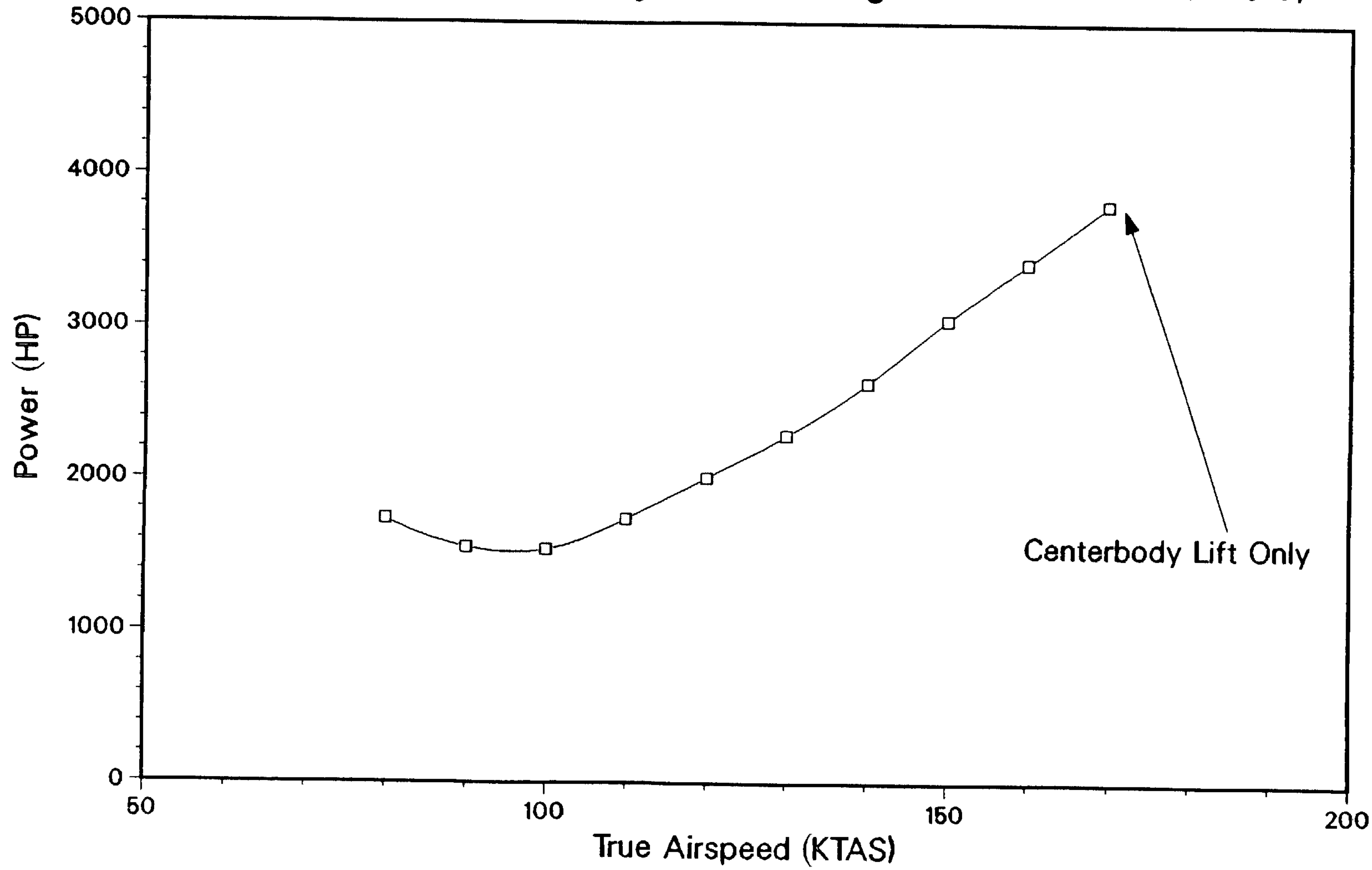


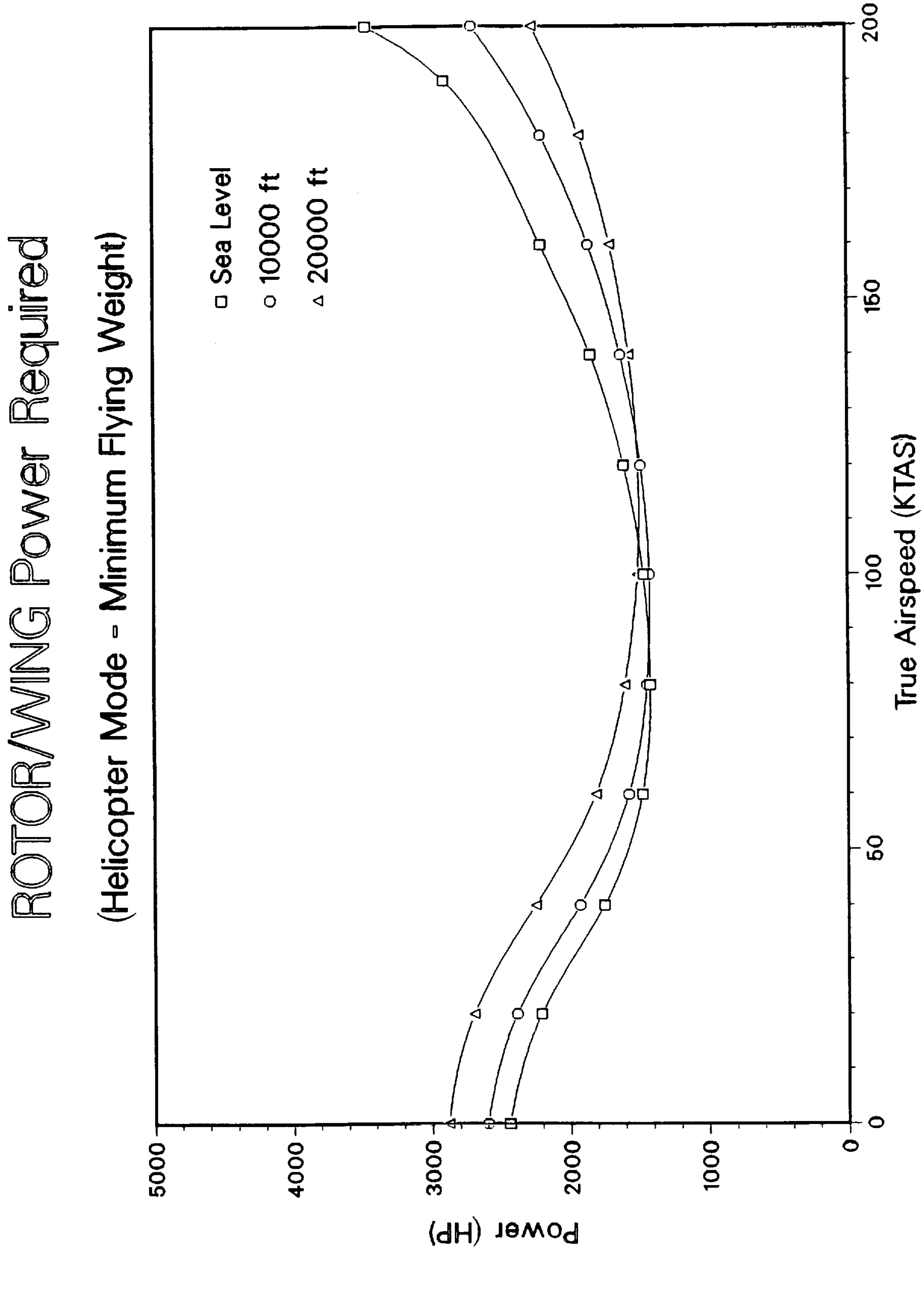
Rotor/Wing Lift-to-Drag Ratio - Standard Day
Sea Level
10000 ft
20000 ft
Lift-to-Drag Ratio
True Airspeed (KTAS)
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400
450
500


ROTOR/WING Power Required
(Helicopter Mode - Design Gross Weight)
□ Sea Level
○ 10000 ft
Higher Altitude Curves Limited by Rotor Stall
Power (HP)
5000
4000
3000
2000
1000
0
True Airspeed (KTAS)
0
50
100
150
200

ROTOR/WING Power Required

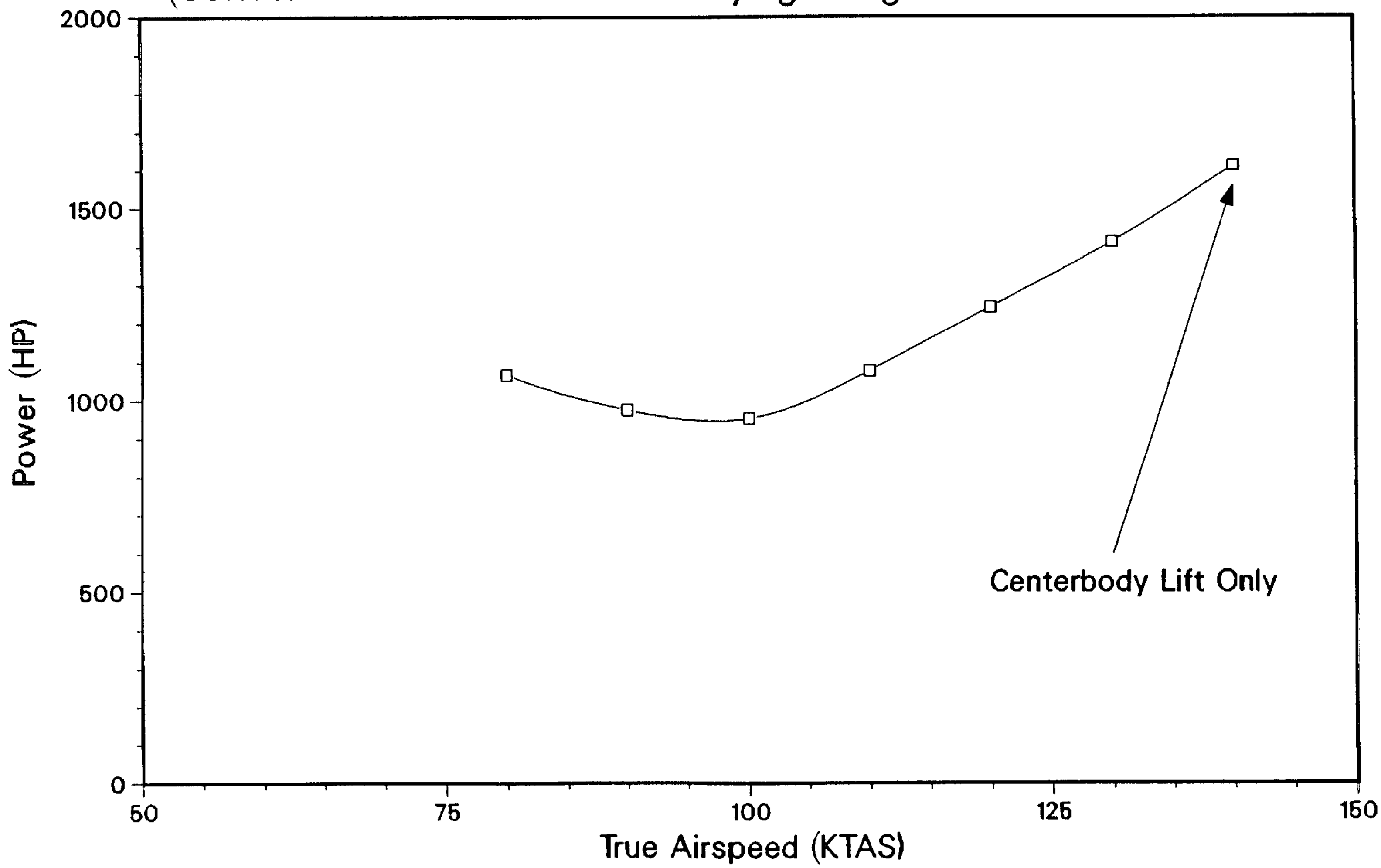
(Conversion Mode - Design Gross Weight - Sea Level Standard)




ROTOR/WING Power Required
(Helicopter Mode - Minimum Flying Weight)
Sea Level
10000 ft
20000 ft
Power (HP)
5000
4000
3000
2000
1000
0
0
50
100
150
200
True Airspeed (KTAS)

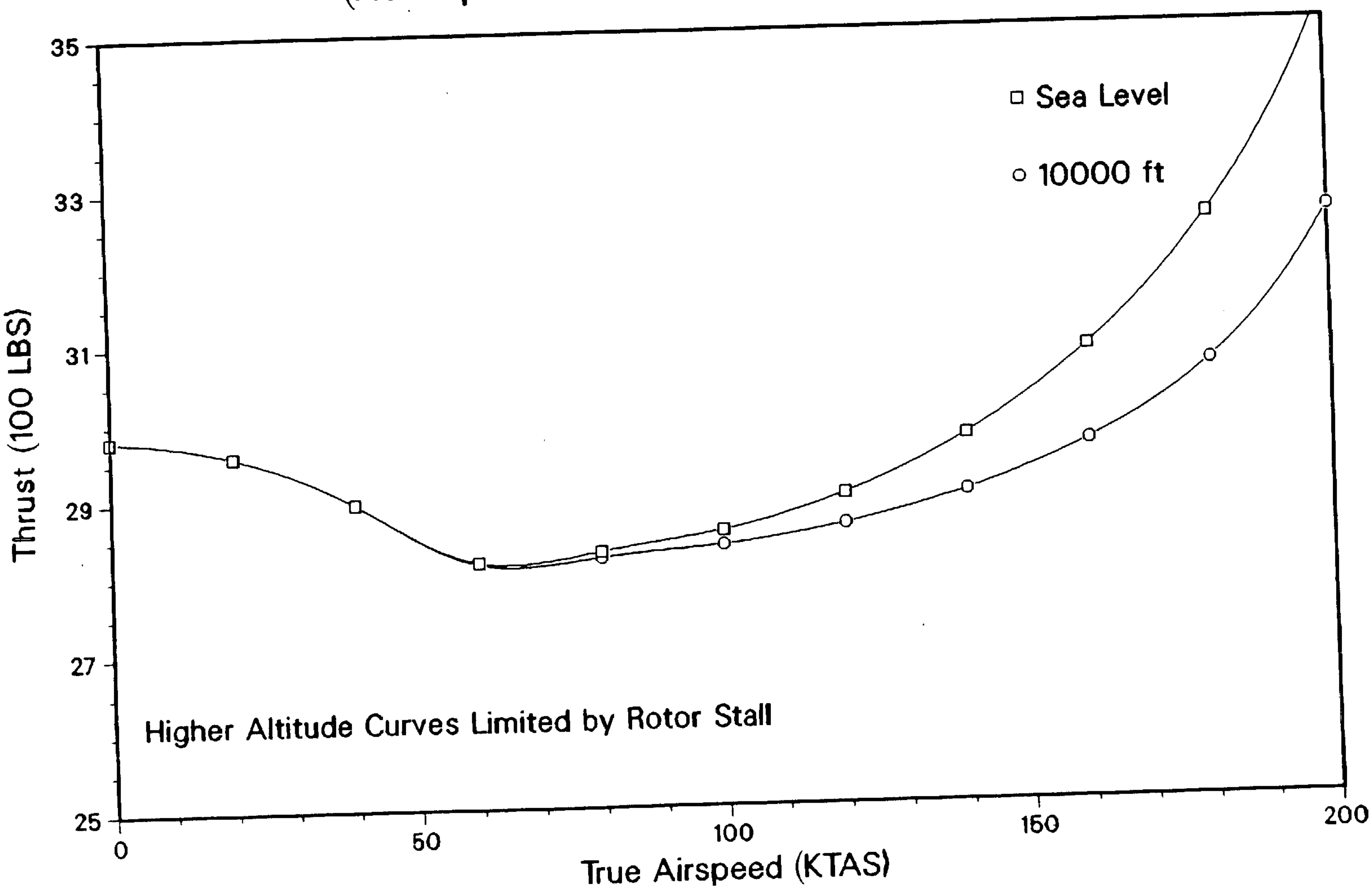
ROTOR/WING Power Required

(Conversion Mode - Minimum Flying Weight - Sea Level Standard)



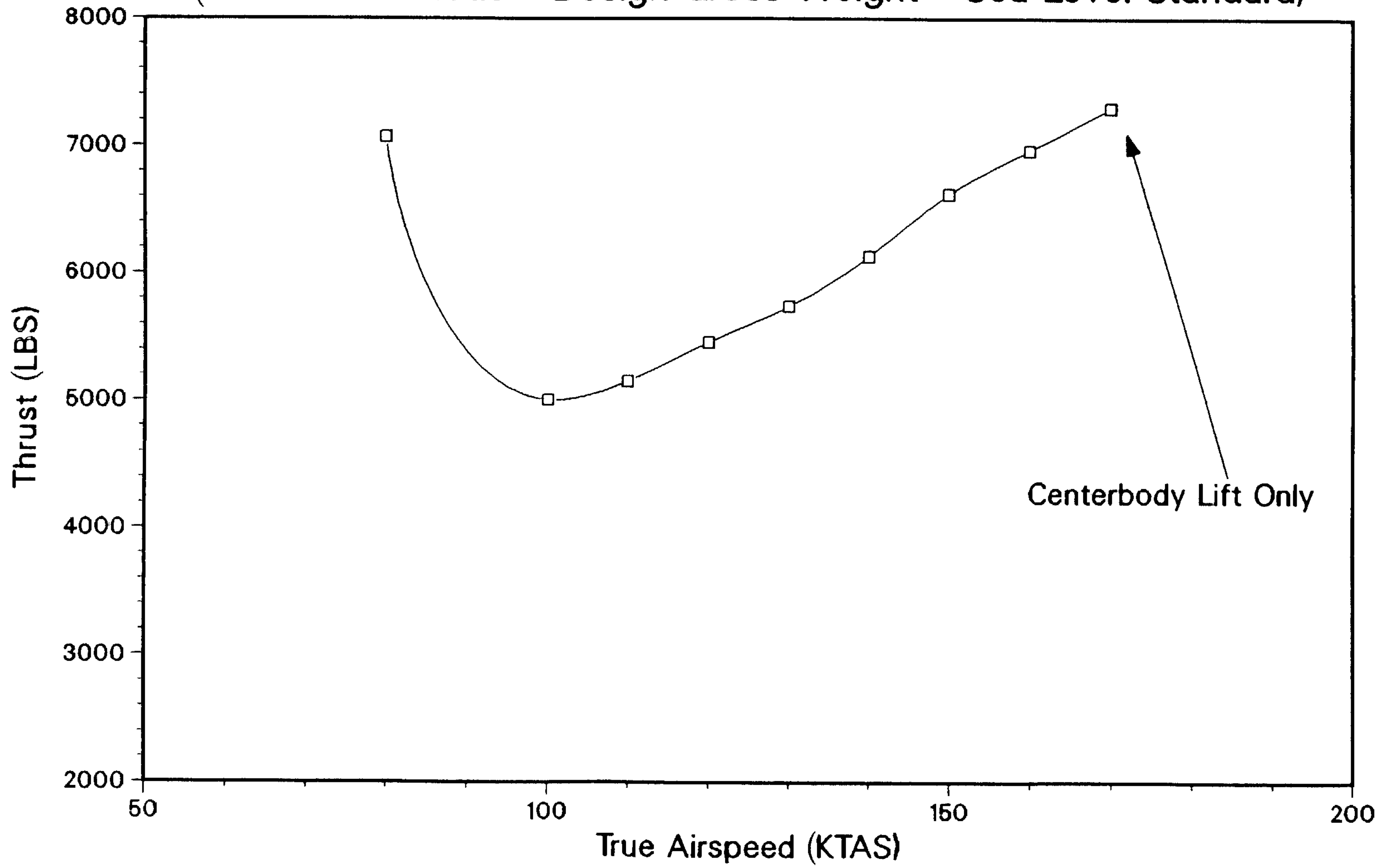
ROTOR/WING Thrust Required

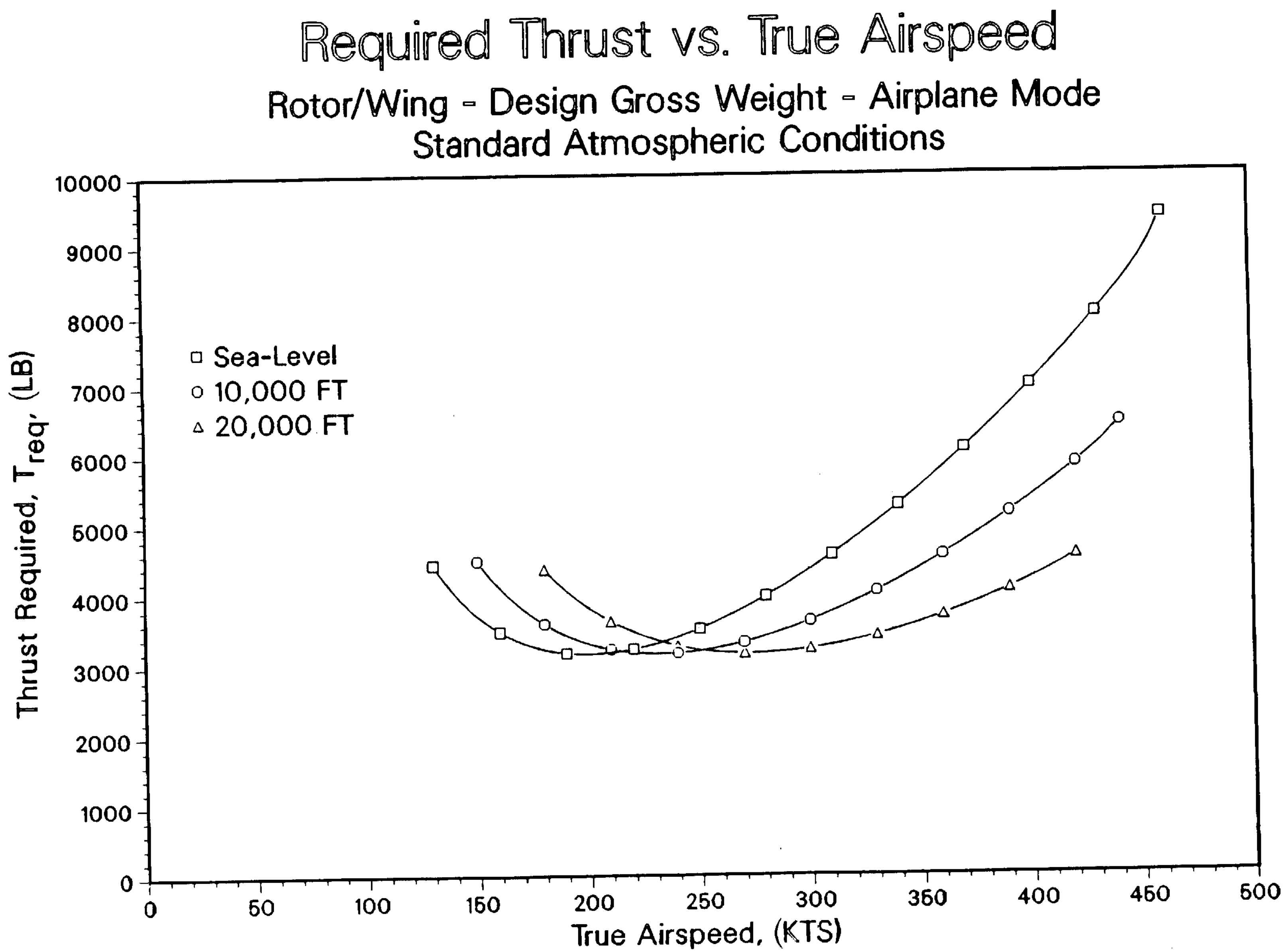
(Helicopter Mode - Design Gross Weight)



ROTOR/WING Thrust Required

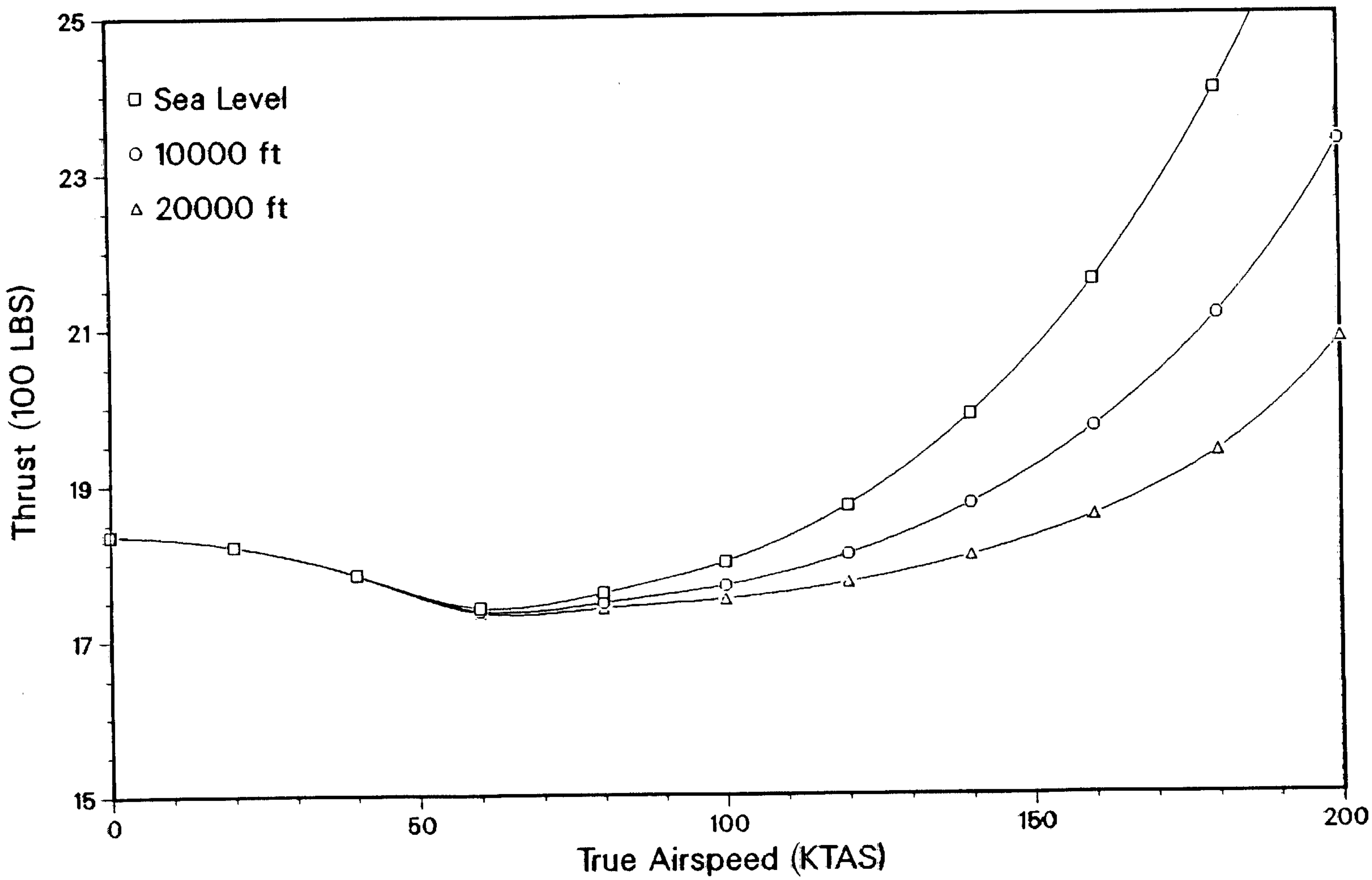
(Conversion Mode - Design Gross Weight - Sea Level Standard)




Required Thrust vs. True Airspeed
Rotor/Wing - Design Gross Weight - Airplane Mode
Standard Atmospheric Conditions
Sea-Level
10,000 FT
20,000 FT
Thrust Required, T_{req}, (LB)
True Airspeed, (KTS)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
50
100
150
200
250
300
350
400
450
500

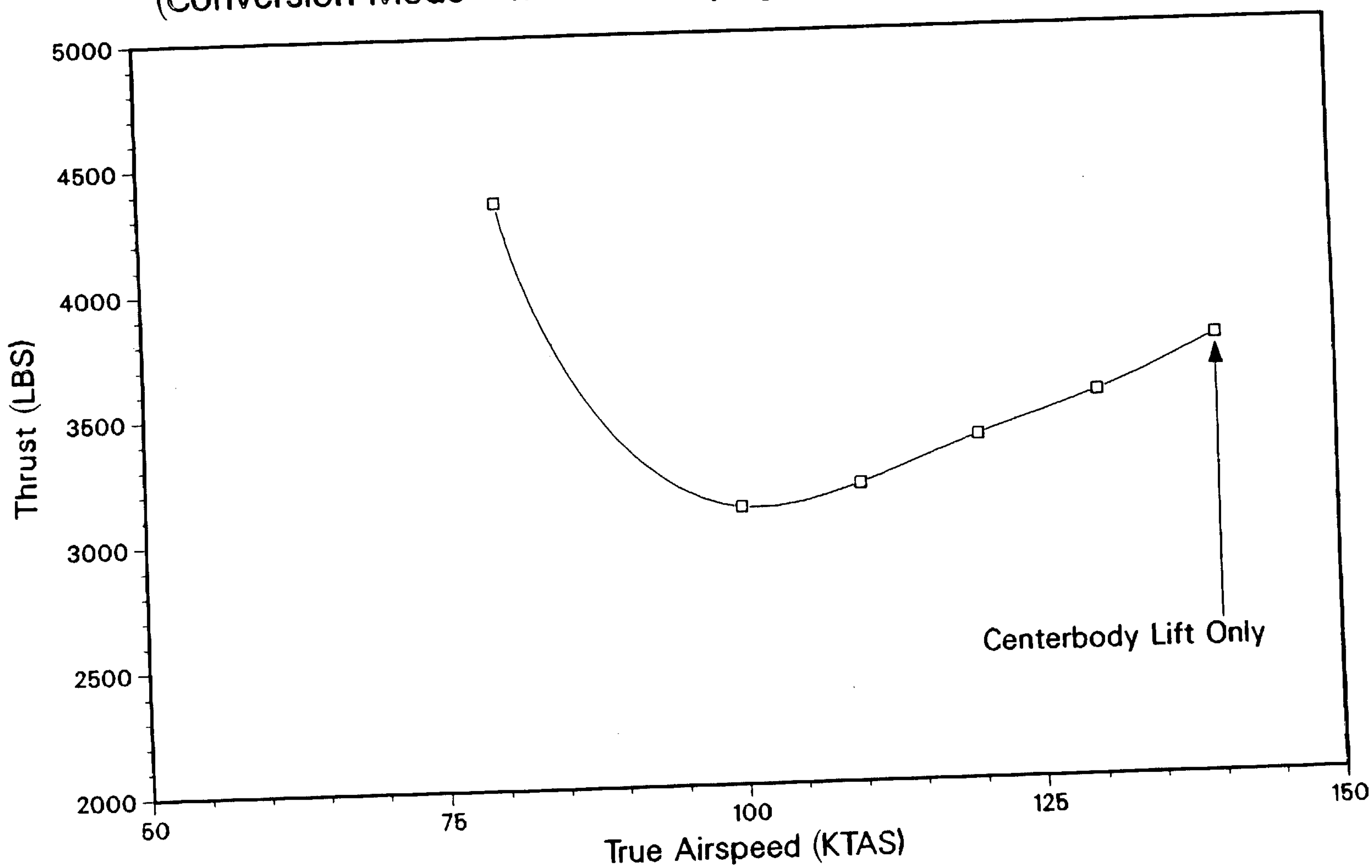
ROTOR/WING Thrust Required

(Helicopter Mode - Minimum Flying Weight)



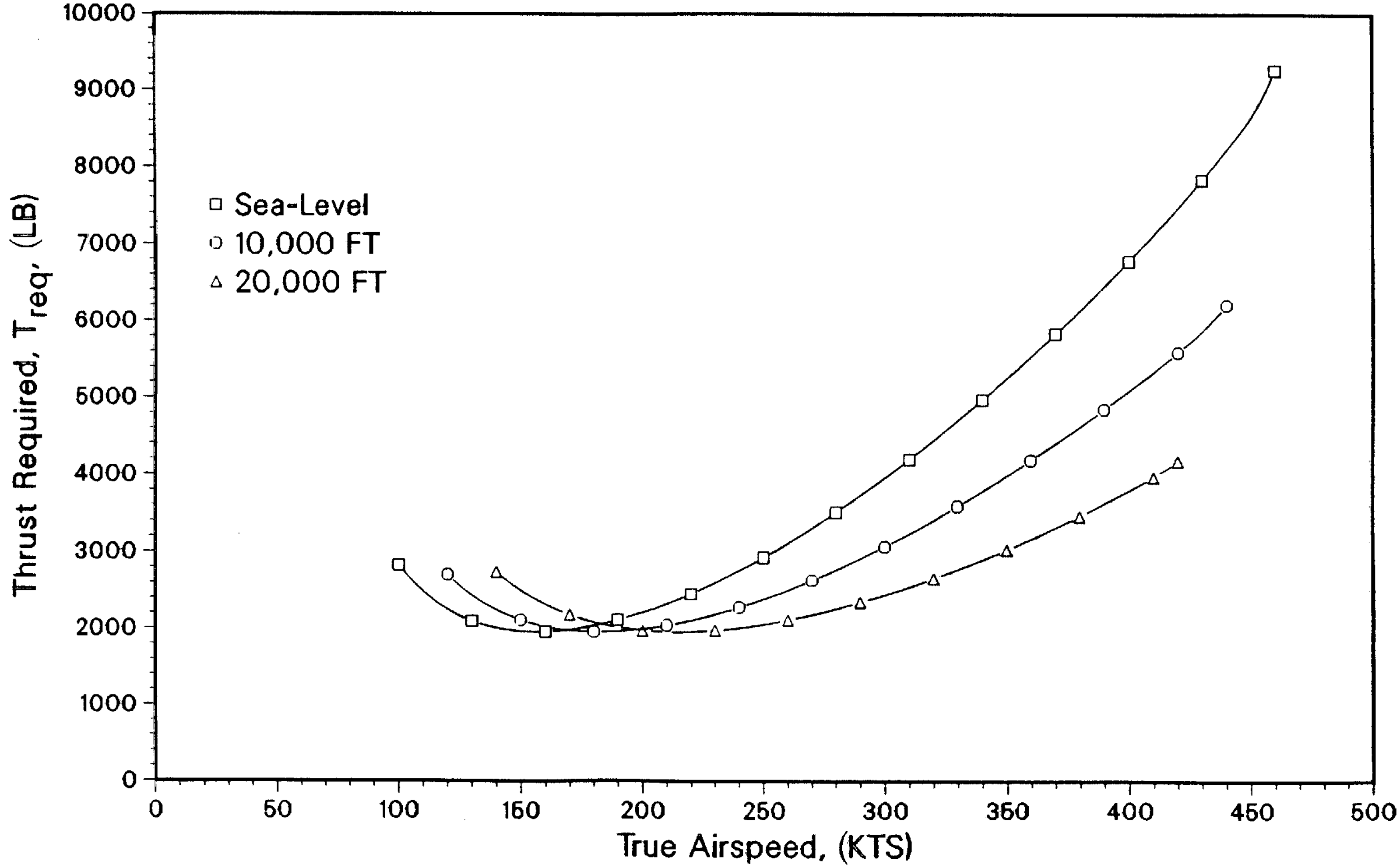
ROTOR/WING Thrust Required

(Conversion Mode - Minimum Flying Weight - Sea Level Standard)



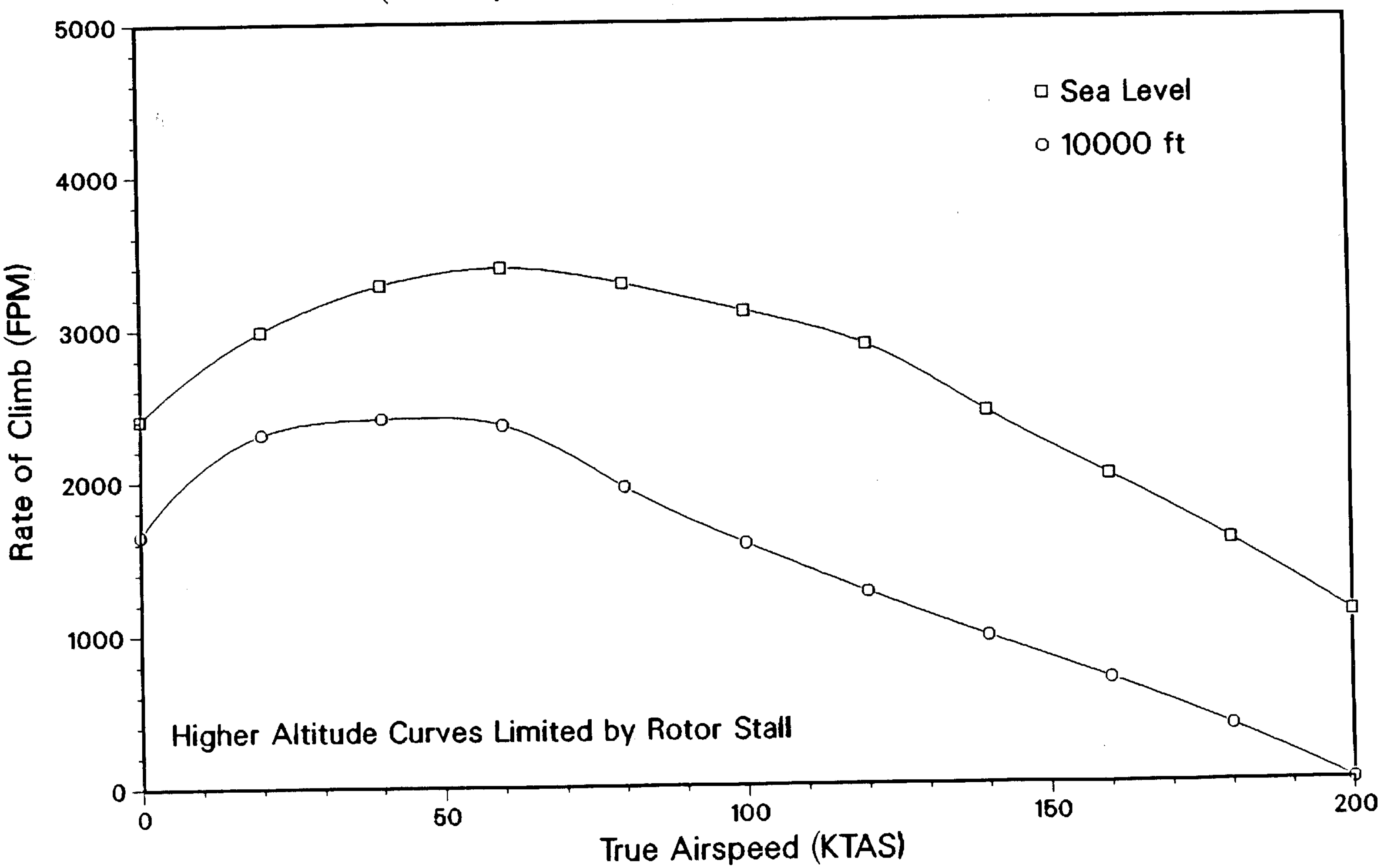
Required Thrust vs. True Airspeed

Rotor/Wing - Minimum Flying Weight - Airplane Mode
Standard Atmospheric Conditions



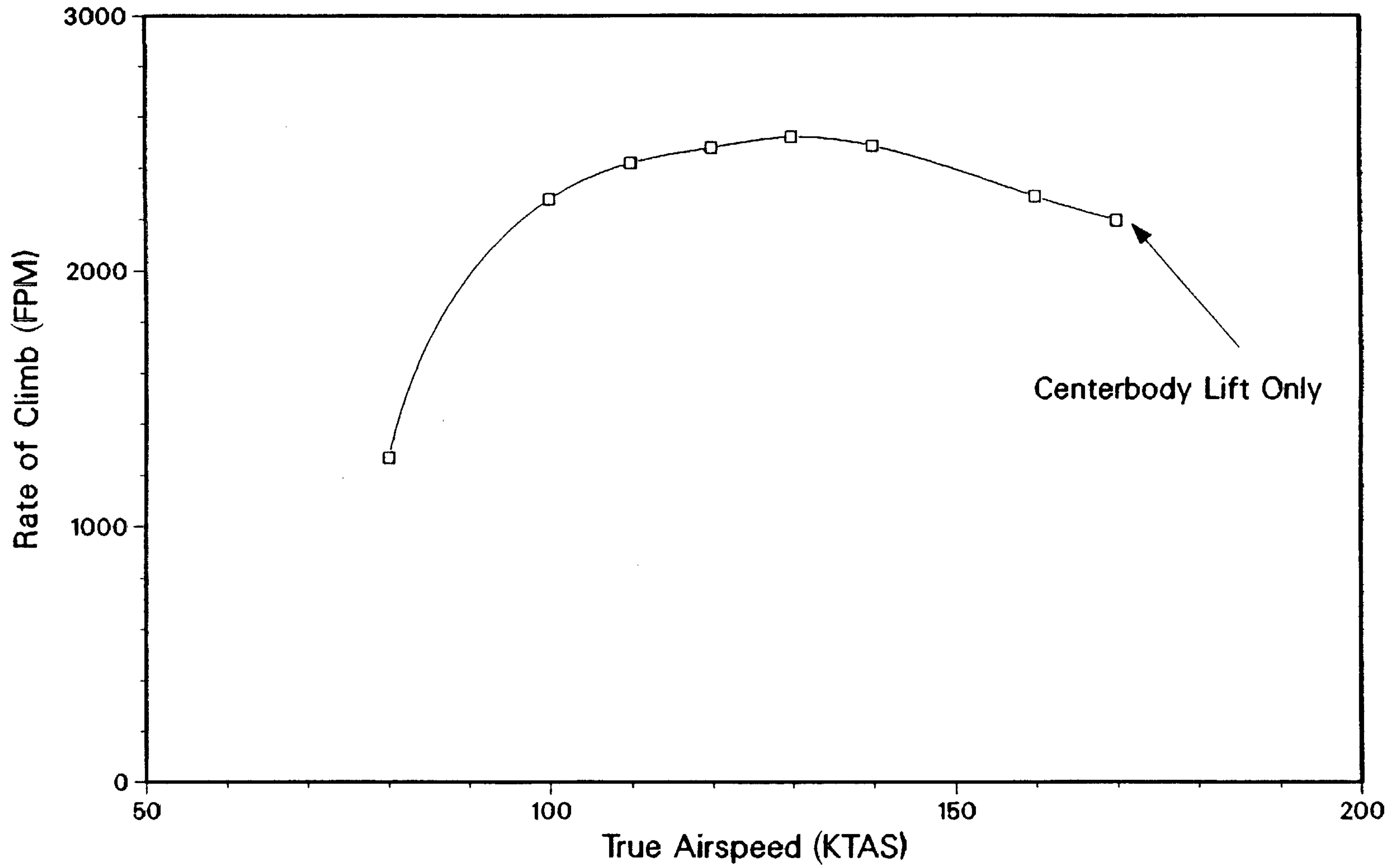
ROTOR/WING MAX RATE of CLIMB

(Helicopter Mode - Design Gross Weight)



ROTOR/WING MAX RATE of CLIMB

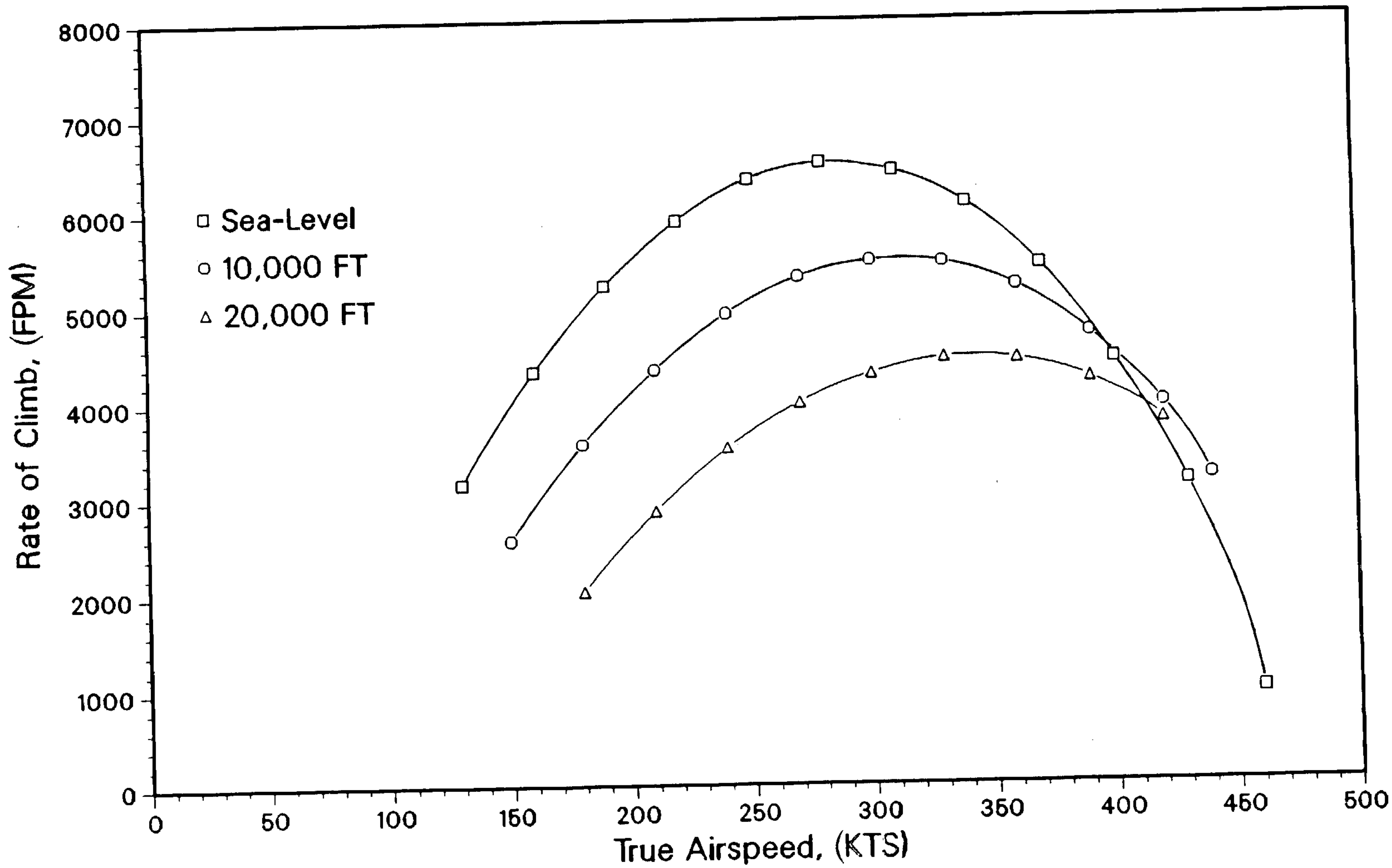
(Conversion Mode - Design Gross Weight - Sea Level Standard)

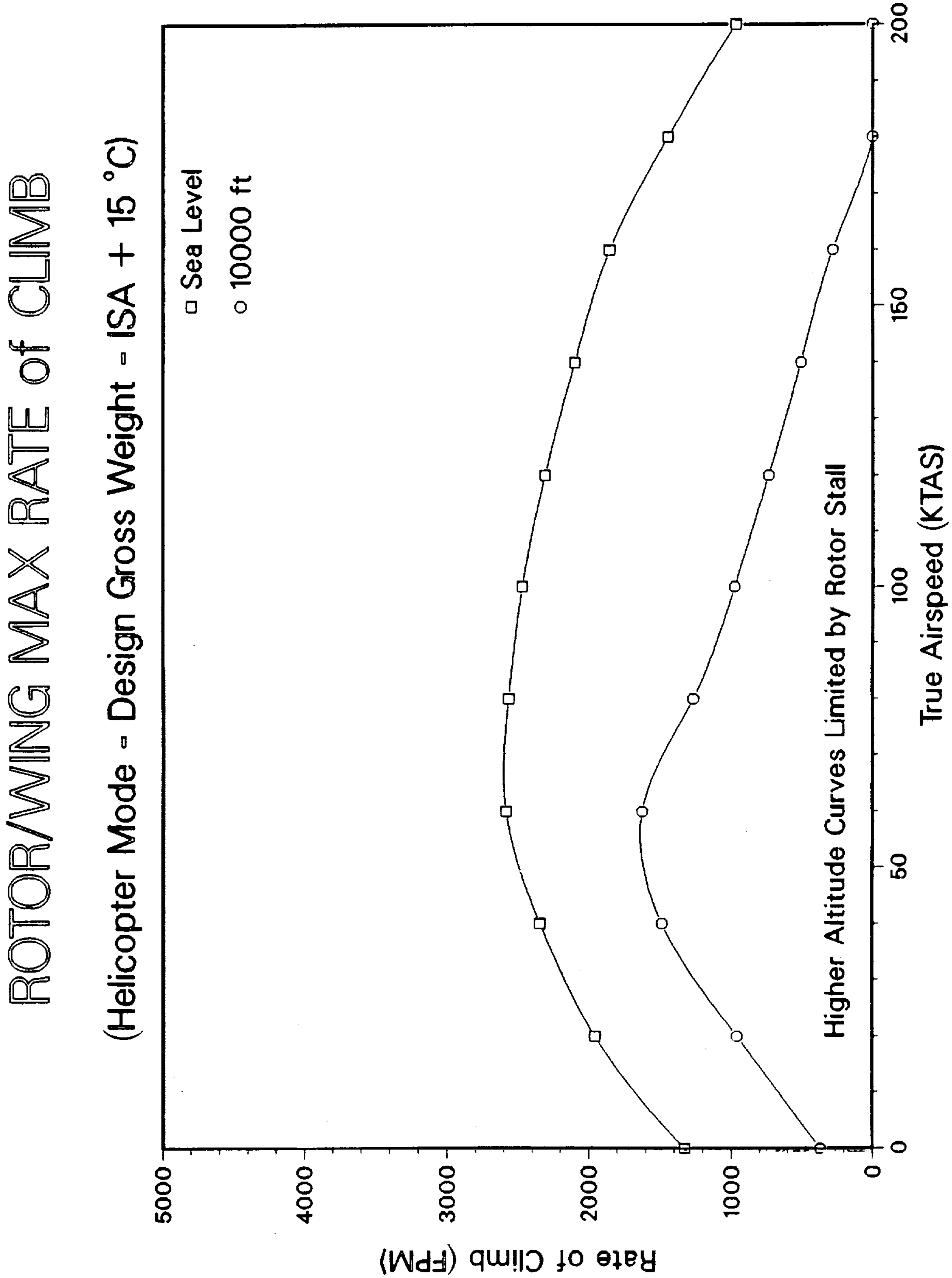


Airplane Mode Climb Rate

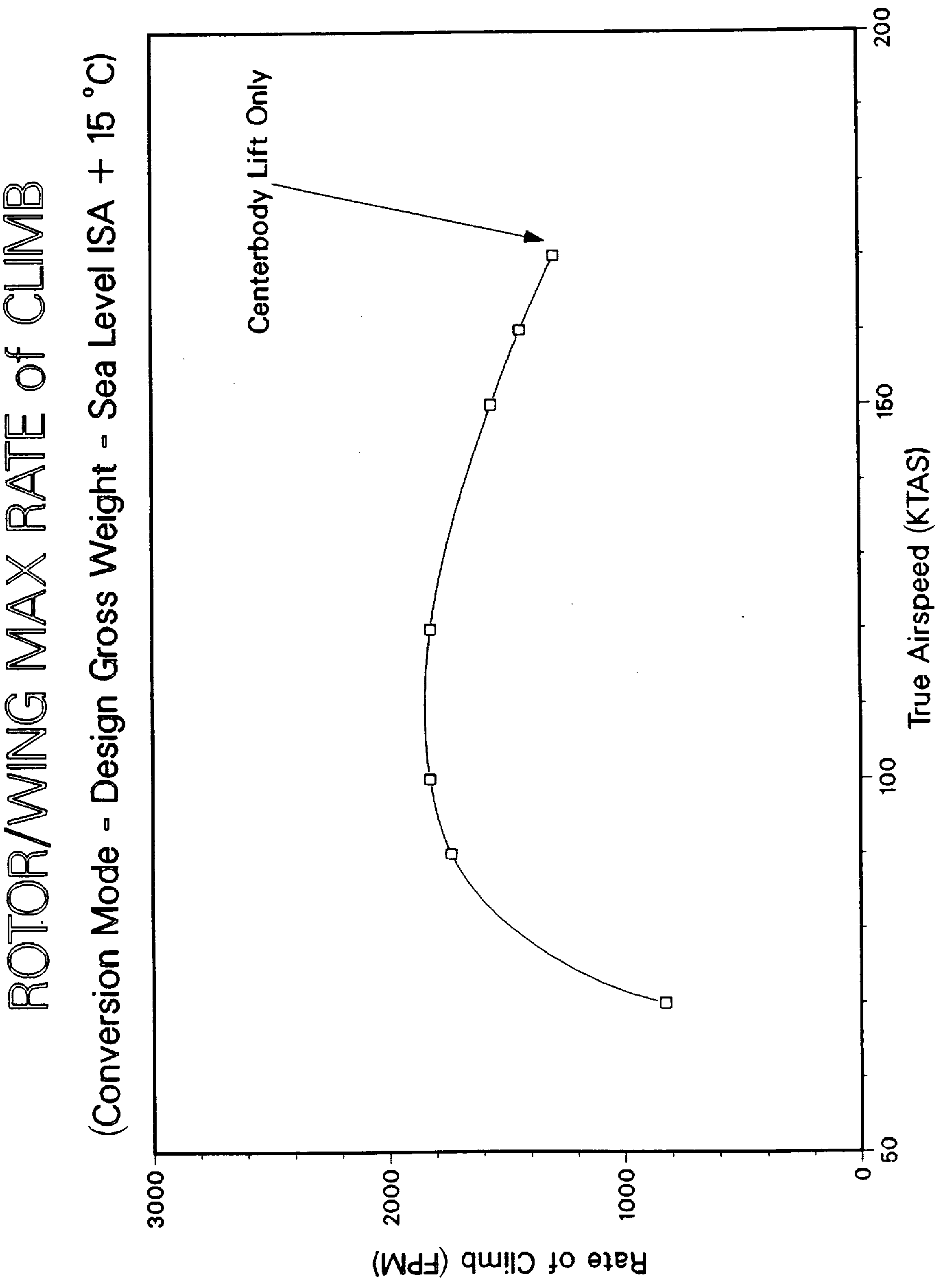
Rotor/Wing - Design Gross Weight

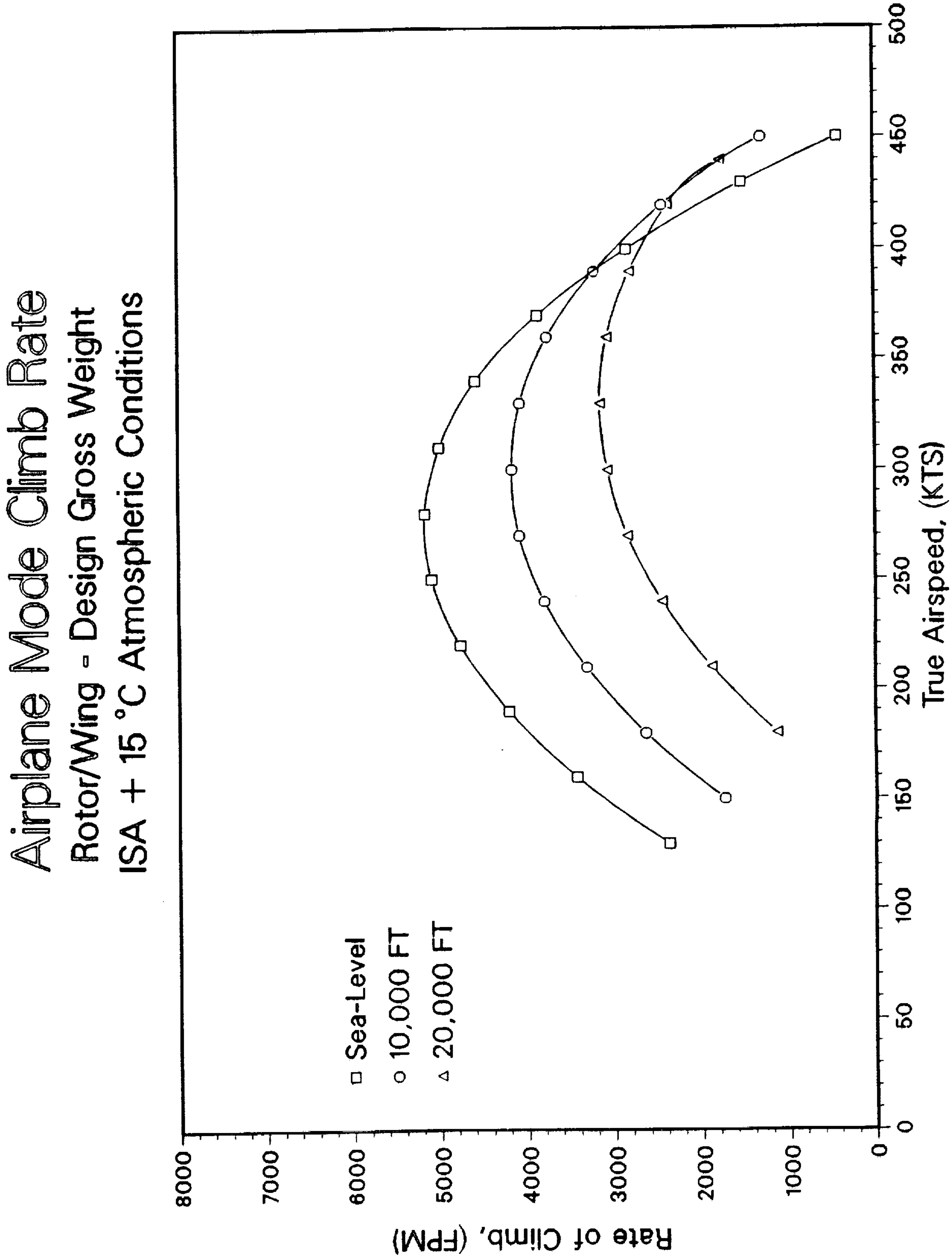
Standard Atmospheric Conditions



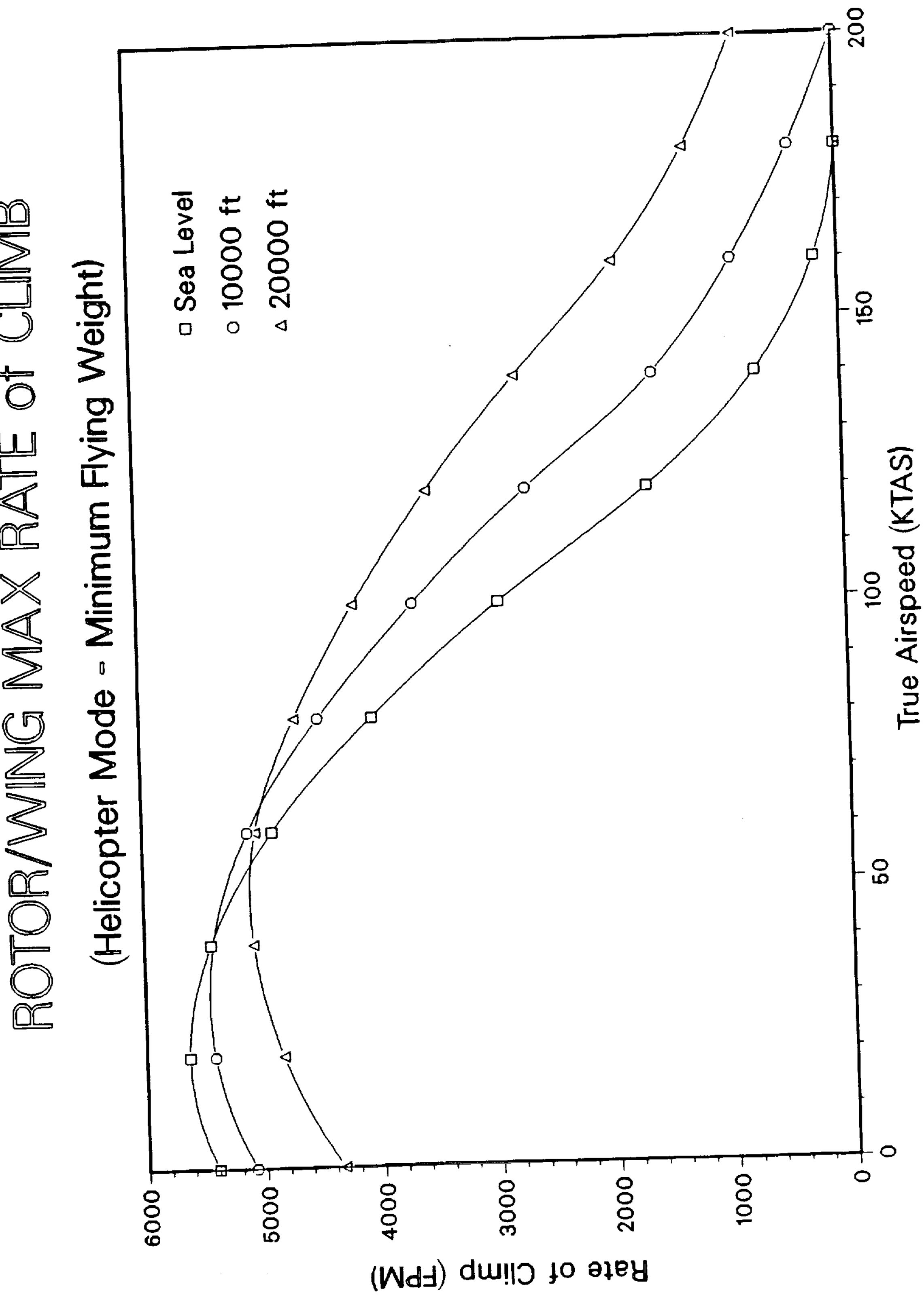


ROTOR/WING MAX RATE of CLIMB
(Helicopter Mode - Design Gross Weight - ISA + 15 °C)
Sea Level
10000 ft
Higher Altitude Curves Limited by Rotor Stall
Rate of Climb (FPM)
True Airspeed (KTAS)
0
1000
2000
3000
4000
5000
0
50
100
150
200

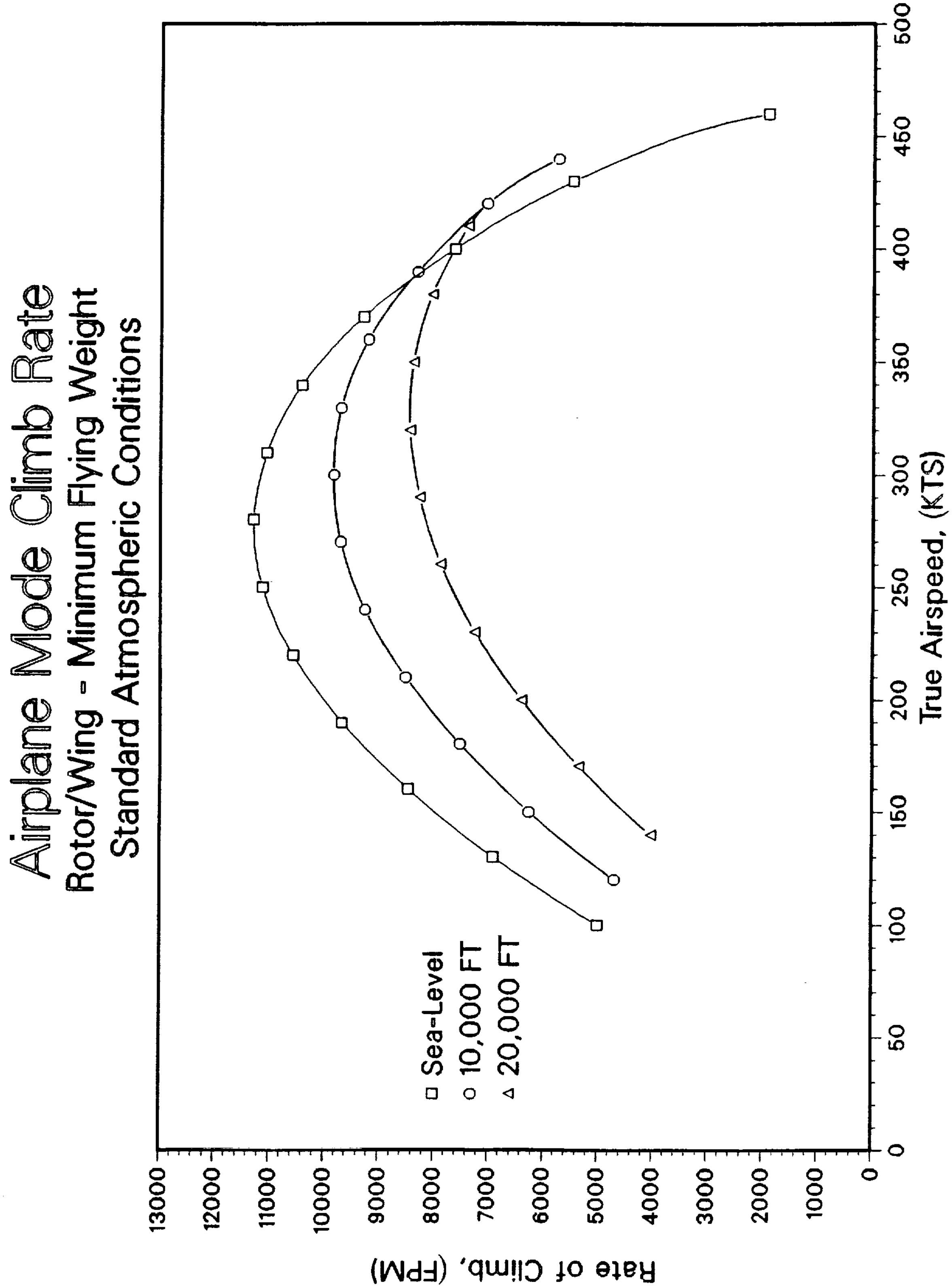

ROTOR/WING MAX RATE of CLIMB
(Conversion Mode - Design Gross Weight - Sea Level ISA + 15 °C)
Centerbody Lift Only
Rate of Climb (FPM)
0
1000
2000
3000
True Airspeed (KTAS)
50
100
150
200



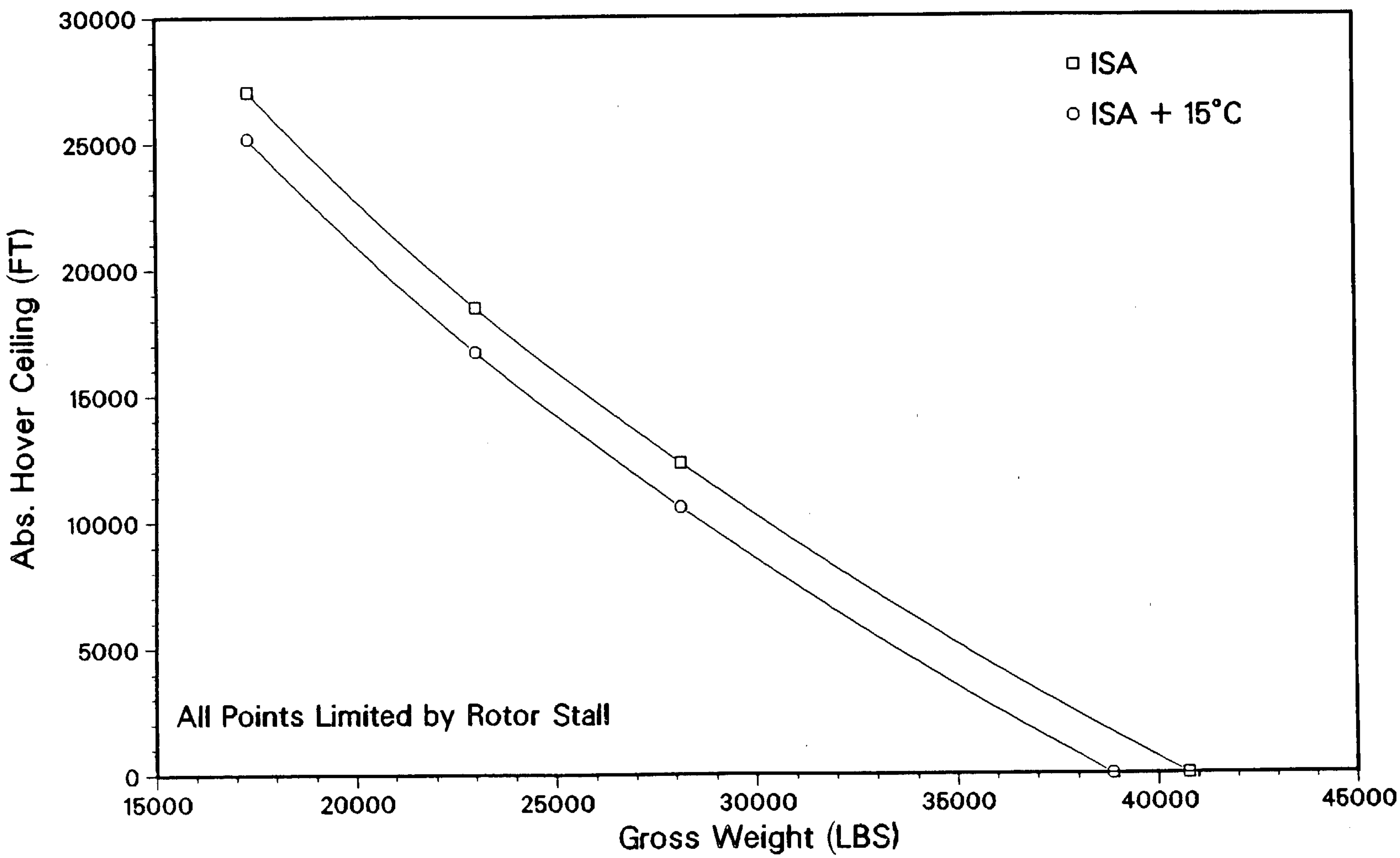
Airplane Mode Climb Rate
Rotor/Wing - Design Gross Weight
ISA + 15 °C Atmospheric Conditions
Sea-Level
10,000 FT
20,000 FT
Rate of Climb, (FPM)
0
1000
2000
3000
4000
5000
6000
7000
8000
True Airspeed, (KTS)
0
50
100
150
200
250
300
350
400
450
500

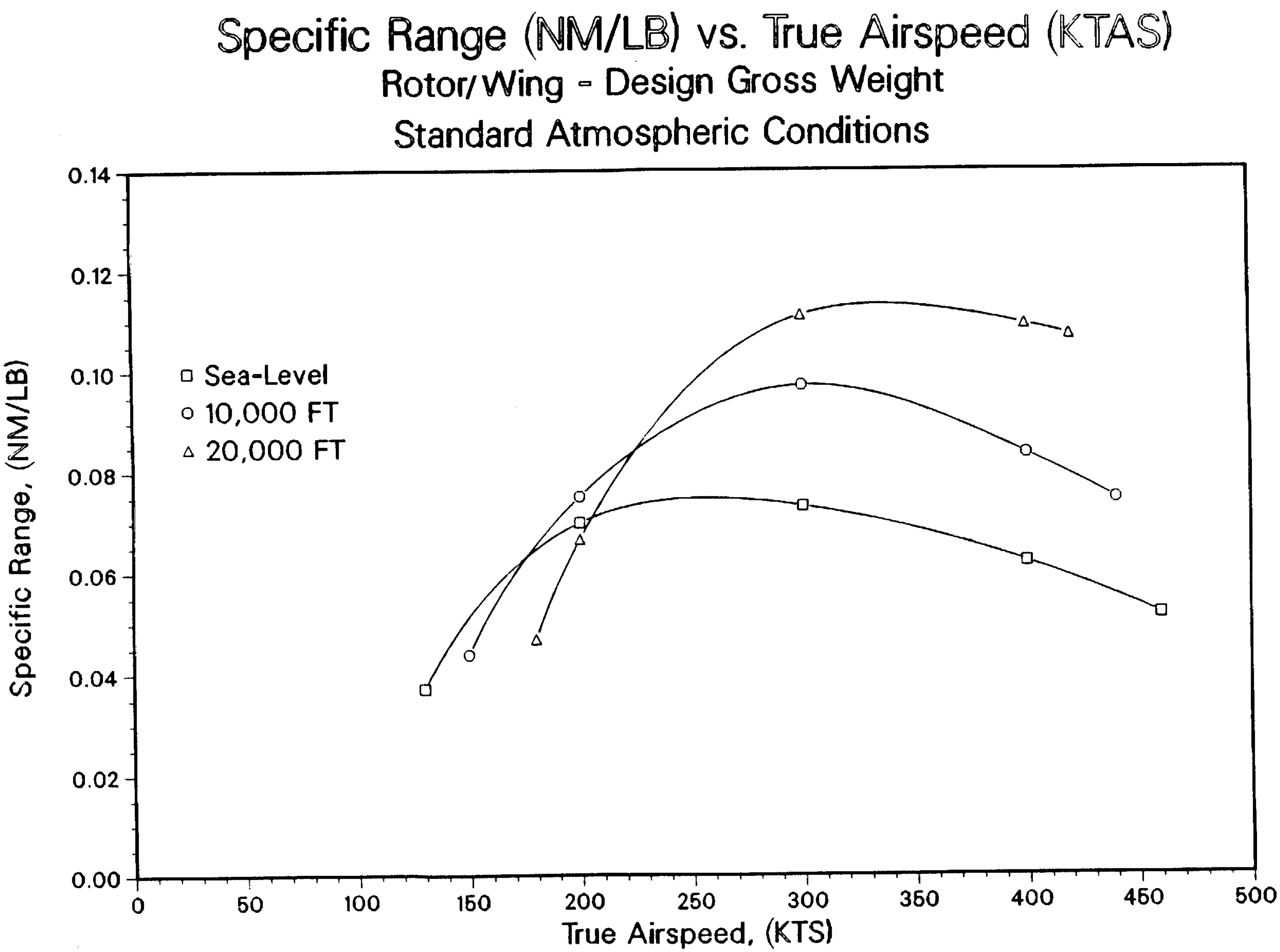


ROTOR/WING MAX RATE of CLIMB
(Helicopter Mode - Minimum Flying Weight)
Sea Level
10000 ft
20000 ft
Rate of Climp (FPM)
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
True Airspeed (KTAS)

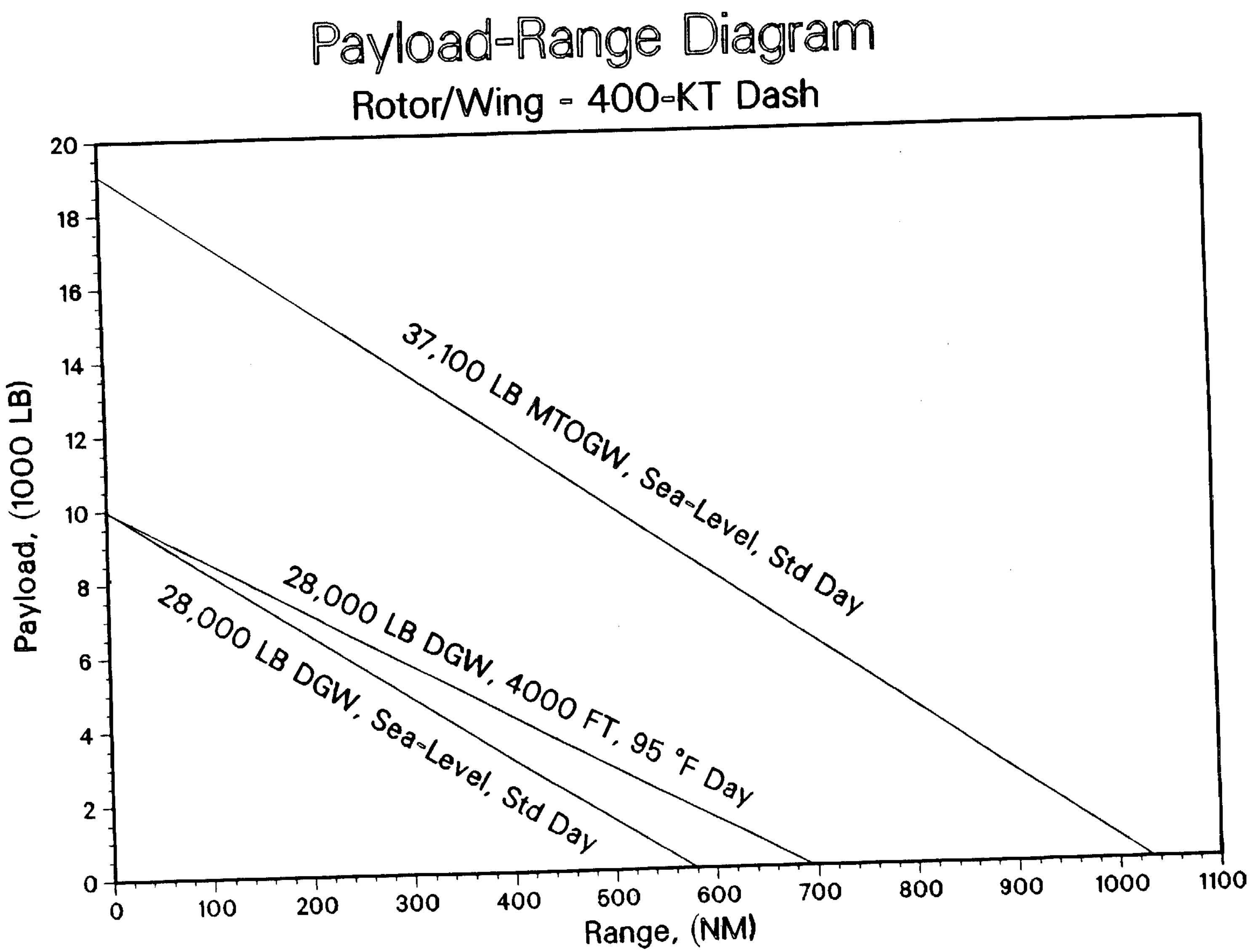

Airplane Mode Climb Rate
Rotor/Wing - Minimum Flying Weight
Standard Atmospheric Conditions
Sea-Level
10,000 FT
20,000 FT
Rate of Climb, (FPM)
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
True Airspeed, (KTS)
0
50
100
150
200
250
300
350
400
450
500

ROTOR/WING HOVER CEILING



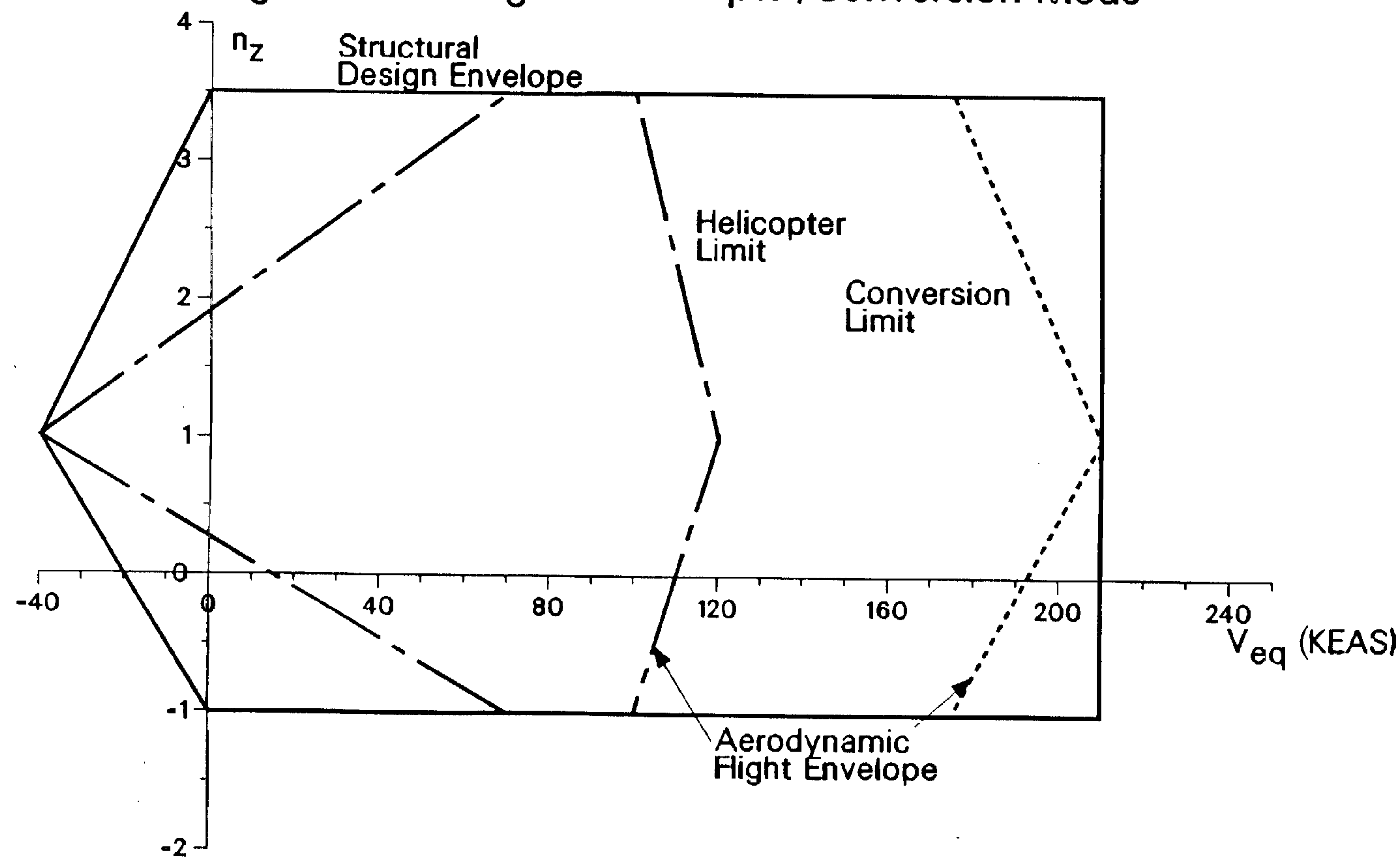


Specific Range (NM/LB) vs. True Airspeed (KTAS)
Rotor/Wing - Design Gross Weight
Standard Atmospheric Conditions
Sea-Level
10,000 FT
20,000 FT
Specific Range, (NM/LB)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
250
300
350
400
450
500
True Airspeed, (KTS)

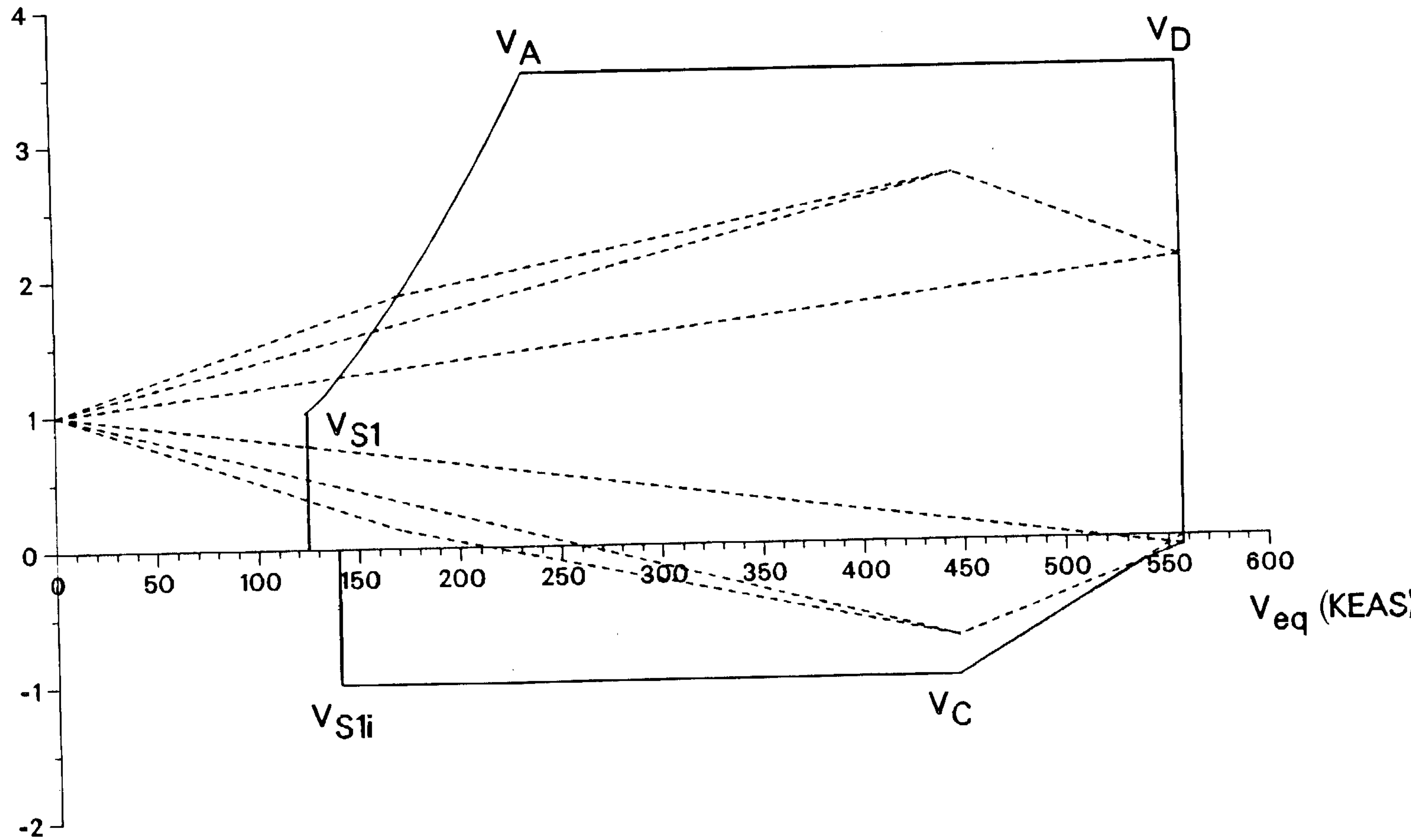

Payload-Range Diagram
Rotor/Wing - 400-KT Dash
37,100 LB MTOGW, Sea-Level, Std Day
28,000 LB DGW, 4000 FT, 95 °F Day
28,000 LB DGW, Sea-Level, Std Day
Payload, (1000 LB)
0
2
4
6
8
10
12
14
16
18
20
Range, (NM)
0
100
200
300
400
500
600
700
800
900
1000
1100

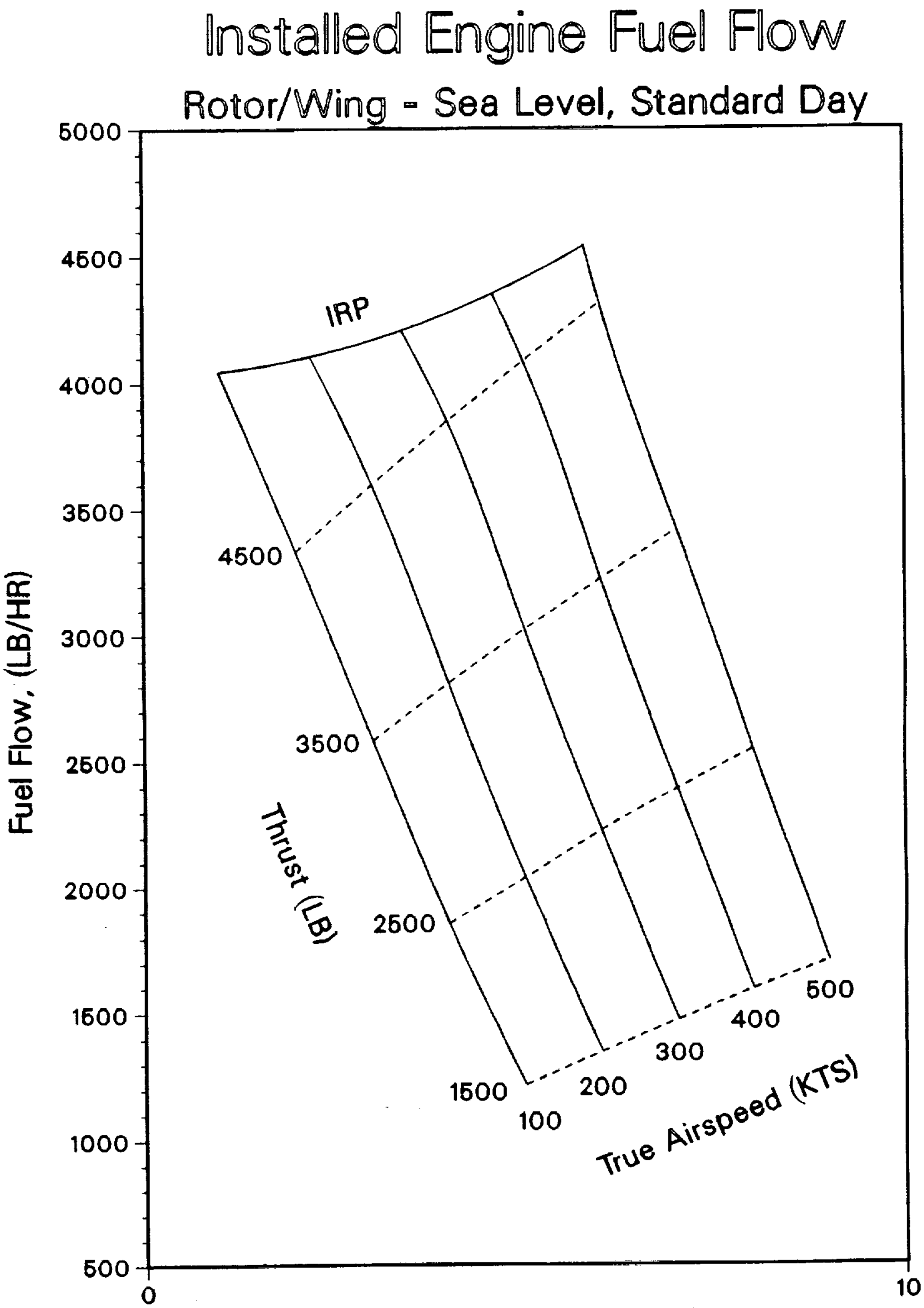
Rotor/Wing V-n Diagram

Design Gross Weight - Helicopter/Conversion Mode

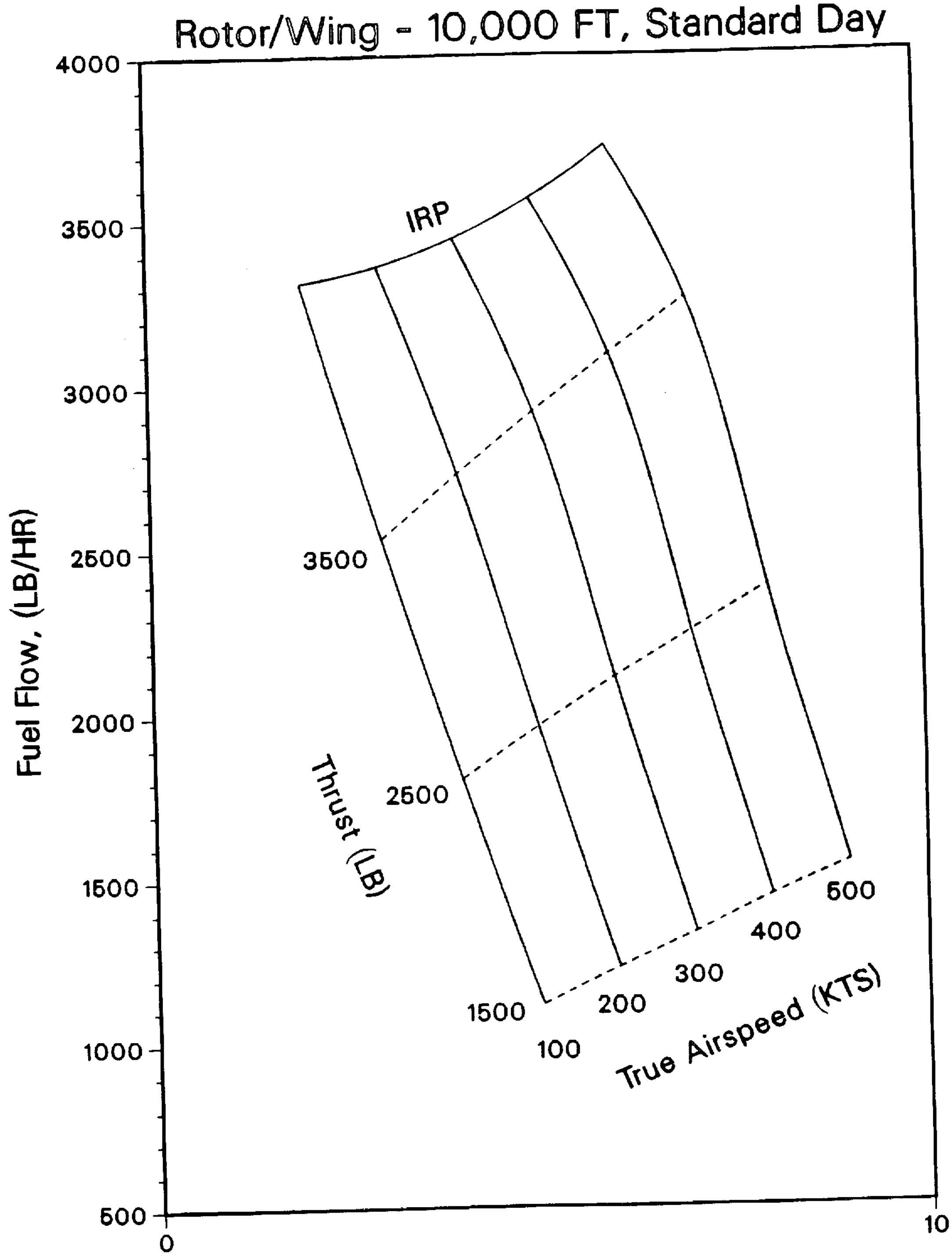


Rotor/Wing V-n Diagram
Design Gross Weight - Airplane Mode

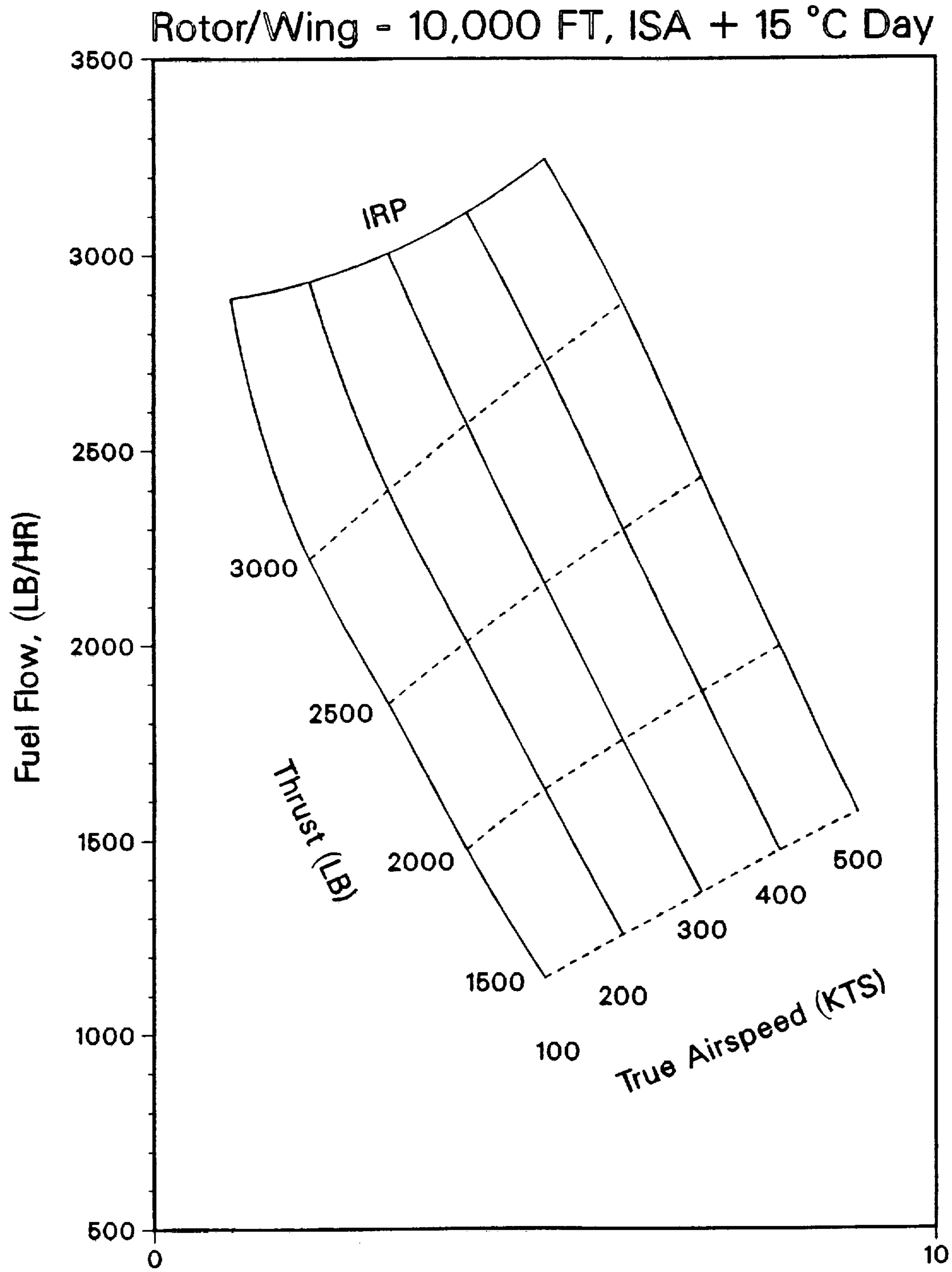



Installed Engine Fuel Flow
Rotor/Wing - Sea Level, Standard Day
Fuel Flow, (LB/HR)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10
IRP
Thrust (LB)
4500
3500
2500
1500
True Airspeed (KTS)
100
200
300
400
500

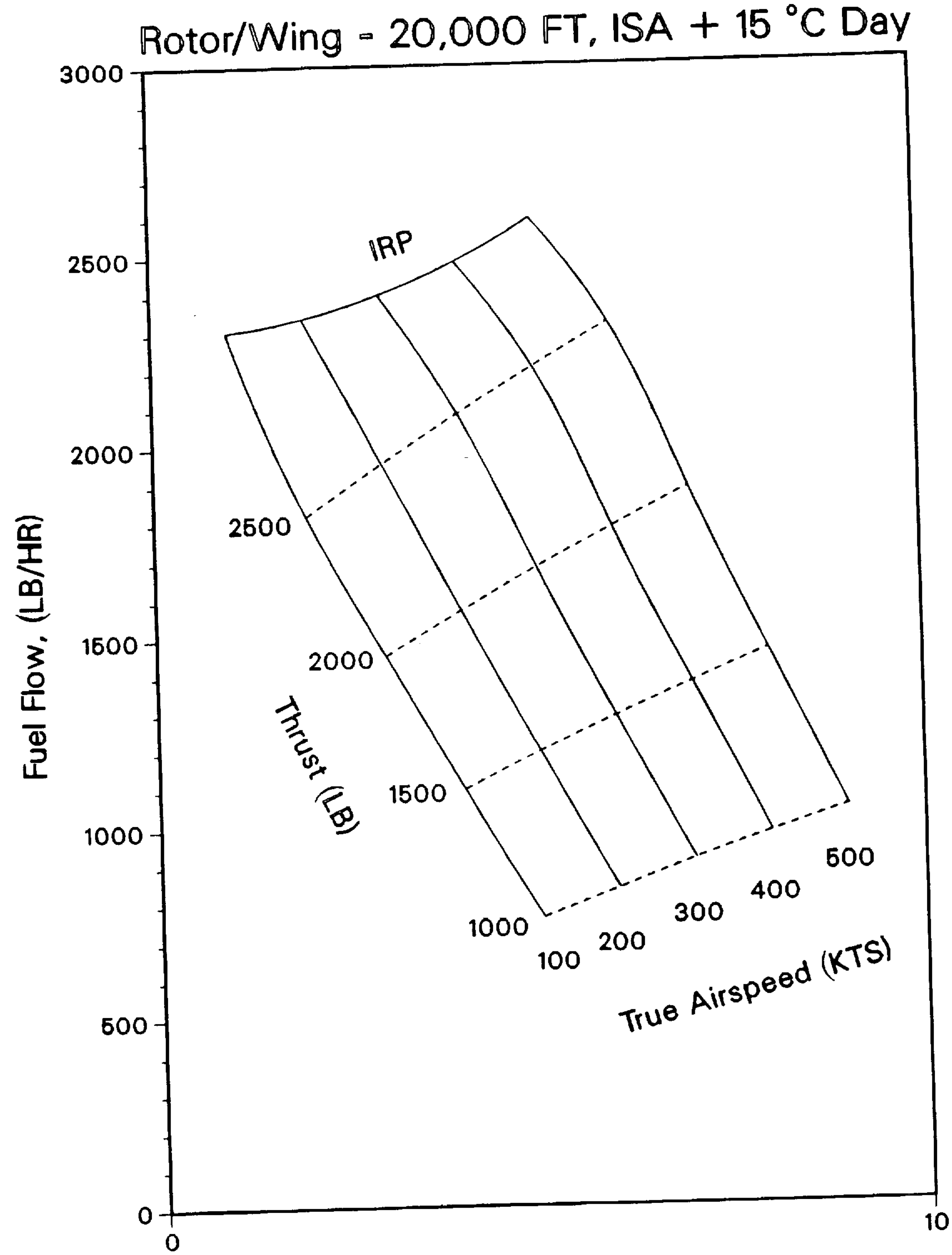
Installed Engine Fuel Flow



Installed Engine Fuel Flow

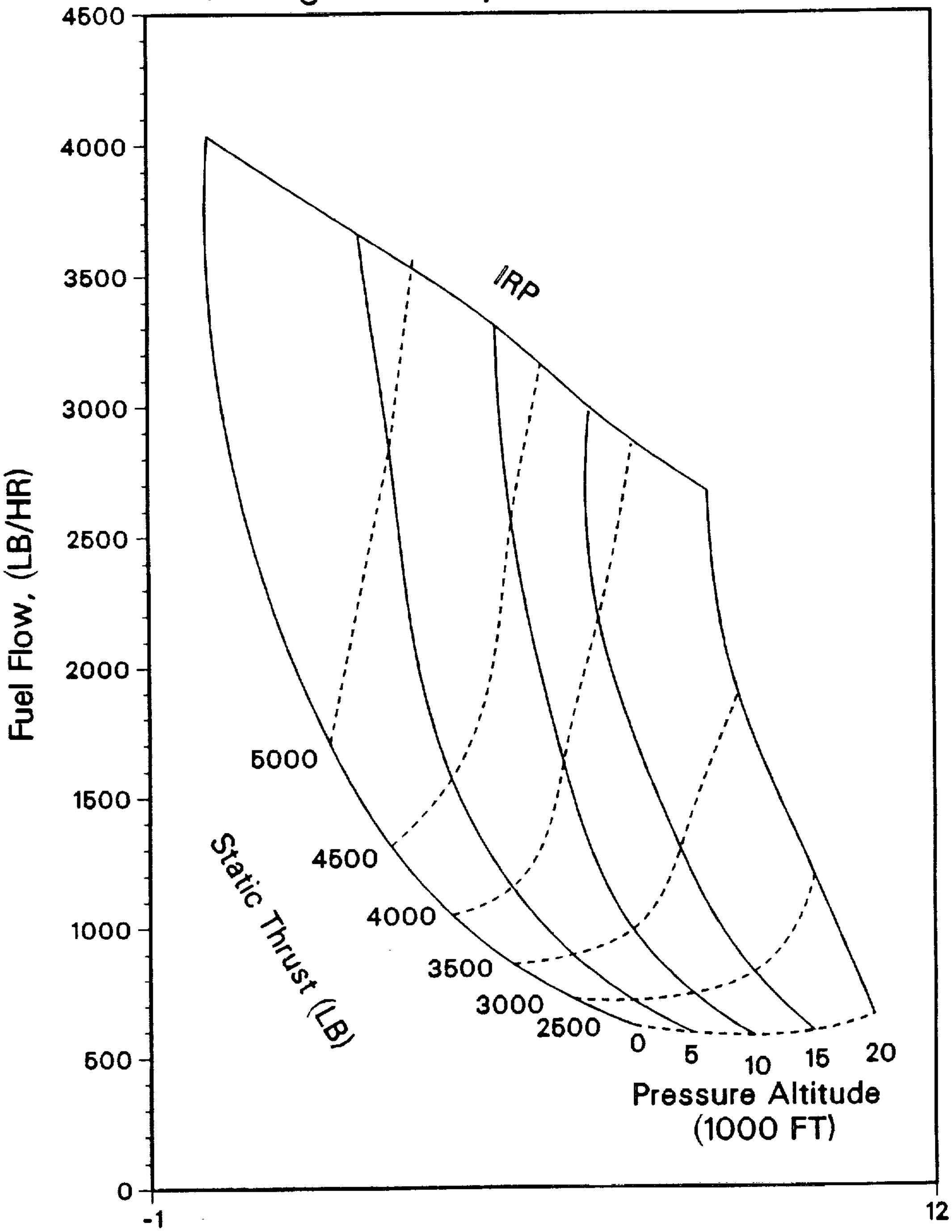


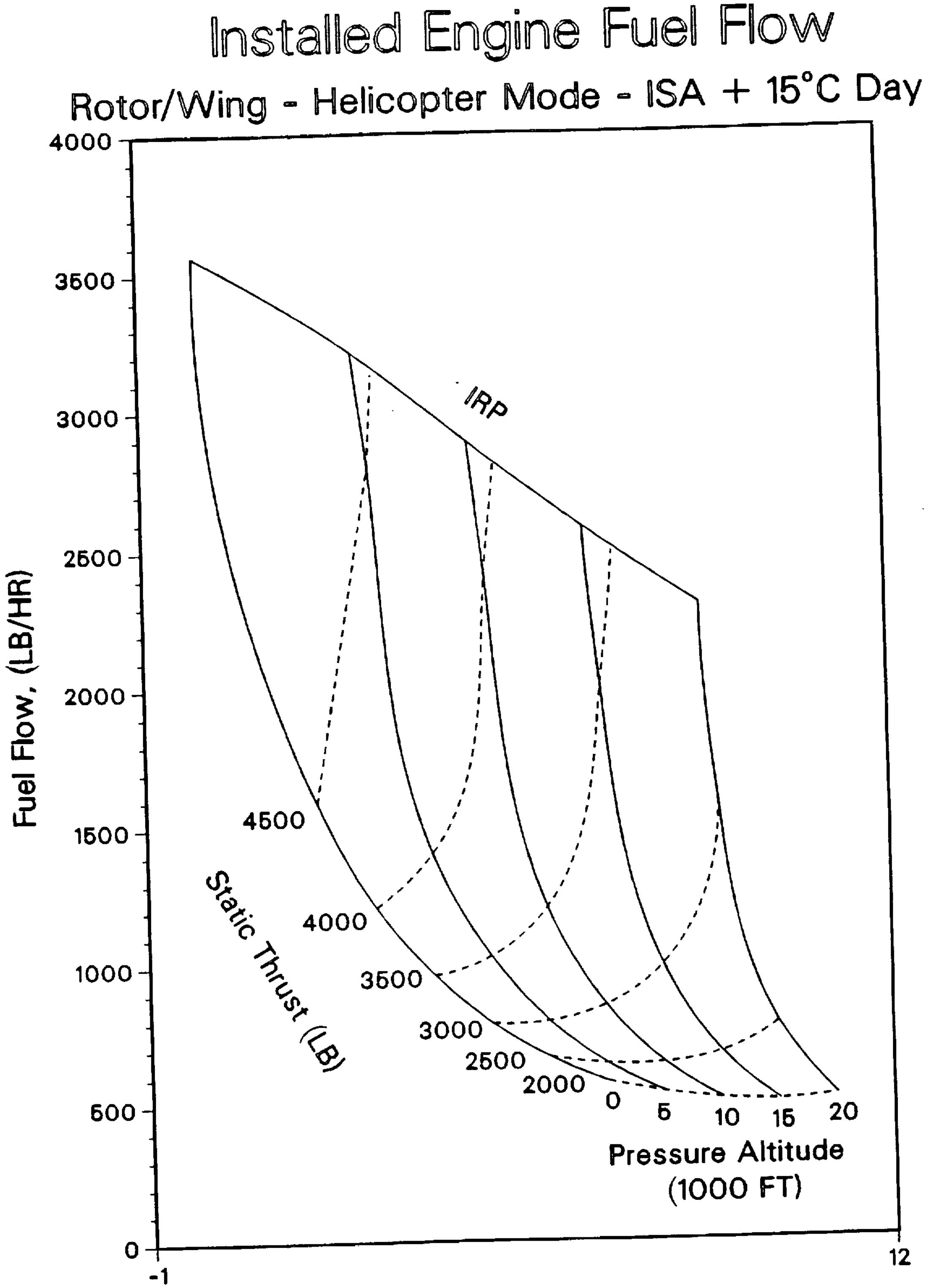
Installed Engine Fuel Flow



Installed Engine Fuel Flow

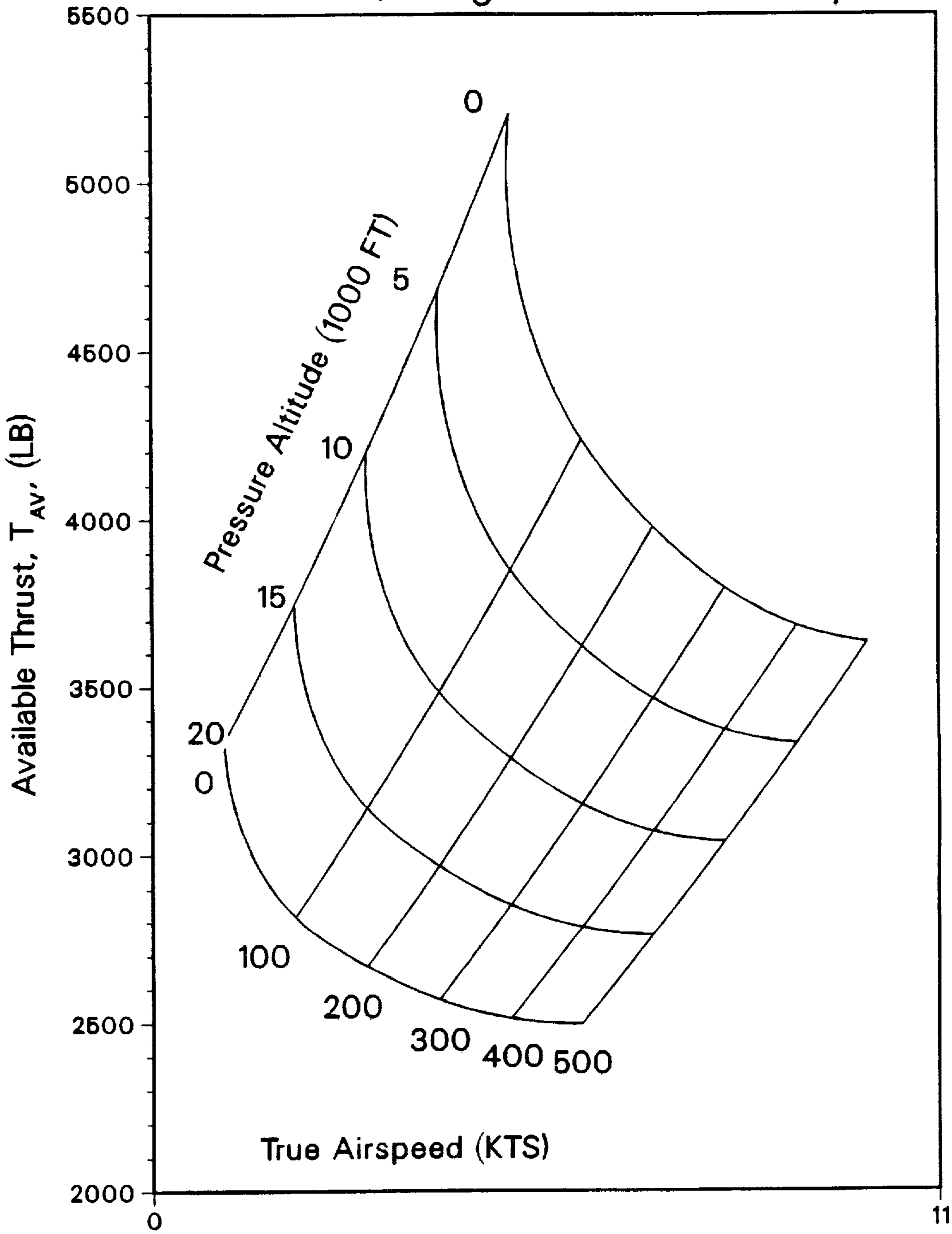
Rotor/Wing - Helicopter Mode - Standard Day

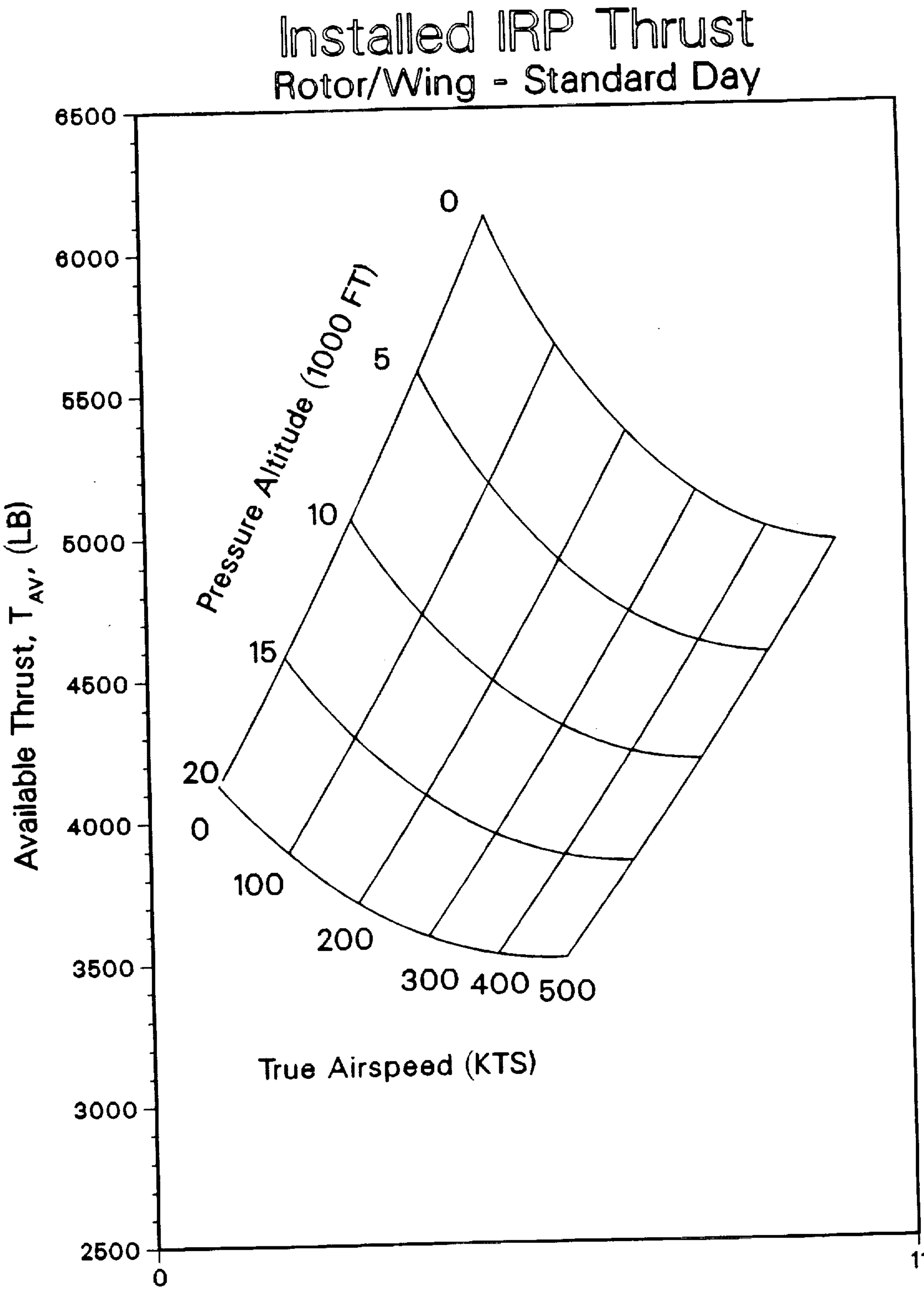



Installed Engine Fuel Flow
Rotor/Wing - Helicopter Mode - ISA + 15°C Day
4000
3500
3000
2500
2000
1500
1000
500
0
-1
12
Fuel Flow, (LB/HR)
IRP
4500
4000
3500
3000
2500
2000
Static Thrust (LB)
0
5
10
15
20
Pressure Altitude
(1000 FT)

Installed MCP Thrust

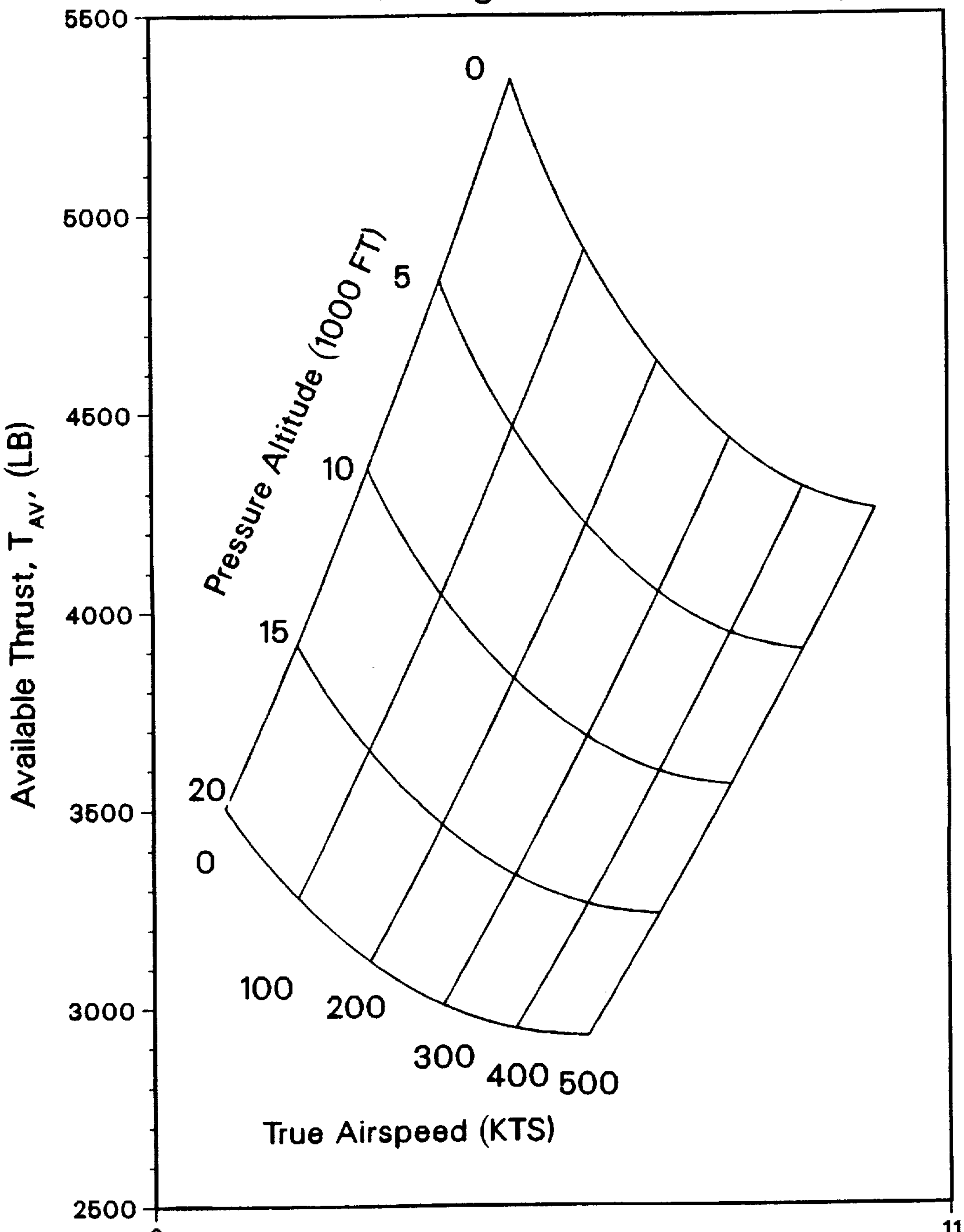
Rotor/Wing - ISA + 15 °C Day




Installed IRP Thrust
Rotor/Wing - Standard Day
6500
6000
5500
5000
4500
4000
3500
3000
2500
Available Thrust, T_{AV}, (LB)
0
11
Pressure Altitude (1000 FT)
0
5
10
15
20
0
100
200
300 400 500
True Airspeed (KTS)

Installed IRP Thrust

Rotor/Wing - ISA + 15 °C Day



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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-177578		

4. Title and Subtitle	5. Report Date
Technology Needs for High-Speed Rotorcraft	April 1991
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
John Rutherford, Matthew O'Rourke, Christopher Martin, Marc Lovenguth, and Clark Mitchell	L9KVAE-FR-91001
	10. Work Unit No. 532-06-37
9. Performing Organization Name and Address	11. Contract or Grant No.
McDonnell Douglas Helicopter Company, Mesa, Arizona	NAS2-13070
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
Ames Research Center, Moffett Field, CA 94035-1000	14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

A study to determine the technology development required for high-speed rotorcraft development was conducted. The study begins with an initial assessment of six concepts capable of flight at, or greater than 450 knots with helicopter-like hover efficiency (disk loading less than 50 psf). These concepts were sized and evaluated based on measures of effectiveness and operational considerations. Additionally, an initial assessment of the impact of technology advances on the vehicles attributes was made. From these initial concepts a tilt wing and rotor/wing concepts were selected for further evaluation. A more detailed examination of conversion and technology trade studies were conducted on these two vehicles, each sized for a different mission. Results of the trade studies indicate the importance of meeting IHPTET goals for both concepts. The tilt wing also benefitted greatly from increased wing loading through improved high-lift capability of its wing. The rotor/wing benefits from increased conversion wing loading leading to reduced drag and more benign conversion characteristics. Finally, proposed technology development times lines are presented for each technology area.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
High-speed rotorcraft, Rotorcraft technology, Tilt wing, Rotor/wing, Reaction drive rotors, Conversion	Unclassified-Unlimited Subject Category - 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	256	A12

NASA FORM 1626 OCT 86

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