NASA Contractor Report 177590

Technology Needs for High Speed Rotorcraft (2)

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ABBREVIATIONS

The following common abbreviations are used throughout this report;

AF	Activity factor
AR	Wing aspect ratio
C	Degrees Celsius
c	Wing chord, ft
Cf	Aircraft drag coefficient, (Cf=fe/GW^2/3)
CFD	Computational fluid dynamics
CG	Center of gravity
Cl	Wing lift coefficient
Clmax	Maximum lift coefficient
Ct/sigma	Nondimensional blade loading
D	Rotor diameter, ft
deg	Degrees
DL	Disk loading, psf
DLF	Design load factor
Dv	Vertical drag, lb
EW	Empty weight, lb
F	Degrees Fahrenheit
FBW	Fly by wire
fe	Equivalent flat plate drag, sqft
FM	Proprotor figure of merit
FMac	Aircraft figure of merit
FSW	Forward swept wing
FUL	Fixed useful load
FW	Fixed wing mode
GW	Gross weight, lb
HOGE	Hover out of ground effect
hp	Horsepower
IHPTET	Integrated High Performance Turbine Engine Technology program
IR	Infrared
IRP	Intermediate Rated Power
ISA	International standard atmosphere
Iw	Wing incidence angle relative to fuselage, deg
Keas	Knots, equivalent airspeed
K ram	Horsepower rise factor due to ram effect
Kts	Knots, true airspeed
lbst	Pounds, static thrust
MAC	Mean aerodynamic chord, ft
MCP	Maximum contiuous power
Mdd	Drag divergence Mach number
MEP	Mission Equipment Package
MOE	Measure of effectiveness
NOE	Nap of the earth flight
OEI	One engine inoperative
PL	Payload, lb

RCS	Radar cross section, sqm or Dbsm
ROC	Rate of climb, fpm
ROD	Rate of descent, fpm
SCAT	Scout-attack
SDGW	Structural design takeoff gross weight, lb
SLS	Sea level standard conditions
STOL	Short takeoff and landing
t/c	Wing thickness to chord ratio
TOGW	Takeoff gross weight, lb
TS	Proprotor tip speed, fps
V	Velocity, fps
Vbe	Velocity for best endurance
Vmax	Maximum operational speed
Vne	Never exceed speed
Vso	Stall speed, flaps extended, power off
VTM	VTOL Trending Model (aircraft sizing program)
VTO	Vertical takeoff
VTOL	Vertical takeoff and landing
WL	Wing loading, psf
XMSN	Transmission
XPORT	Transport
η_p	Propulsive efficiency
η_{HOV}	Nondimensional hover efficiency
η_{LTR}	Nondimensional loiter efficiency
η_{CRS}	Nondimensional cruise efficiency
ρ	Air density, slug/ft^3

Subscripts

FF	Forward flight
H	Hover

High Speed Rotorcraft Concept Abreviations

FTR	Folding Tiltrotor
SHR	Shrouded Rotor
ST RET ROTOR	Stopped Retractable Rotor
ST ROTOR	Stopped Rotor
TD ST ROTOR	Tip Drive Stopped Rotor
TD X WING	Tip Drive X-WING
TR	Tiltrotor
TW	Tilt Wing
VDTR	Variable Diameter Tiltrotor

SUMMARY

This study was broken down into three tasks. The first task was a systematic screening of existing and new high speed VTOL concepts to identify a limited number of the most promising concepts. The most attractive concepts were analyzed in Task II to define their physical characteristics, performance, and sensitivity to technology assumptions. Task III defined the levels of new technology required to enable low risk development of the selected high speed rotorcraft concepts.

From a matrix of 16 VTOL configurations, five were qualitatively found to posses the desired high speed and rotorcraft attributes. The configurations were grouped into three families: tilting propulsor, double propulsion, and shrouded rotor. Within these families 14 distinct concepts were assessed quantitatively in terms of performance and qualitatively in terms of mission attributes and technological risk. The attractiveness of five generic sizing missions were also evaluated for high speed rotorcraft. The following mission-concept pairs were selected for further study in Task II:

Tilt Wing	-	Military Transport
Variable Diameter Tilt Rotor (VDTR)	-	Military Transport
Variable Diameter Tilt Rotor	-	Scout-Attack
Shrouded Rotor	-	Scout-Attack

In general, the tilt wing offered the best overall performance and the VDTR had the best rotorcraft-like attributes. Speed sensitivity results indicated that for maximum productivity, design speeds should be approximately 400 kts and 350 kts for the transport and scout-attack missions respectively. The following technologies were judged to be enabling for each concept:

Tilt Wing	- High speed proprotor, Geared flap control system, Speed-descent buffet boundary expansion
VDTR	- Variable diameter proprotor, Forward swept wing design
Shrouded Rotor	- Rotor-in-wing aerodynamics, Impulse tip drive rotor system, Flight control laws

Weights, structural design, and fly-by-wire controls are enabling technologies common to all concepts. Improvement in generic technologies such as drag reduction, airfoil design, and propulsion systems was important to aircraft efficiency. The shrouded rotor showed poor payload performance and requires more basic research than the others.

INTRODUCTION

The principle goal of this study was to identify promising technologies enabling the successful development of a useful 350 to 500 kt VTOL aircraft with "helicopter-like" low speed and hovering qualities. To attain this goal the study was broken down into three tasks as diagrammed in Figure 1.

In task I, high speed VTOL concepts and mission applications were reviewed in light of new technology. The most attractive concepts were paired with generic sizing missions to be further analyzed in task II. A diagram of this process is shown in Figure 2. Selection was based on a two-stage screening process. The first stage was a qualitative screening based on achievable speed and rotorcraft like attributes. The second stage was a quantitative assessment of performance and a qualitative assessment of mission suitability.

In task II the selected concepts were sized to perform the appropriate missions. Aircraft optimization as well as an analysis of fundamental aircraft performance, characteristics, and sensitivities were made as well. The progression of this work is schematically drawn in Figure 3. Sizing and optimization was an iterative process. Design refinement was continued until a point of diminishing returns was reached. (This is a potential pitfall in a limited study of this nature; a lot of time can be consumed trying to obtain an optimum design. Highlighting and quantifying the important technologies was the aim of this task and not the ultimate refinement of the aircraft design.)

In Task III the most important technologies were grouped into three types: generic, concept-specific, or enabling. Generic technologies are those that are common to all selected concepts. In general, improvements in generic technologies also benefit conventional rotary wing and fixed wing aircraft. Concept-specific technologies are those that must be developed and tailored to the specific high speed VTOL concept. Enabling technologies are those that must be developed to a sufficient level such that the aircraft is viable. For example, the helicopter was enabled by the development of cyclic pitch control technology.

Development plan outlines are presented for each concept-specific and enabling technology with identification of the computational and experimental tools and facilities required.

The sizing and performance analyses in this study were done to a conceptual level based on parametrics and fundamental aerodynamic analysis. Performance was predicated on projected technology levels for the year 2000. Projections were made based on historical trends and the application of modified technologies from related areas. Year 2000 technology is defined as that which has undergone substantial development testing and is ready for implementation into a preliminary design of a prototype production aircraft.

The main body of this report summarizes the results and conclusions of tasks I, II, and III. The reader is encouraged to review the detailed discussion of the mission-concept selection process and aircraft analysis presented in Appendices A and B respectively. The contract required that an interim report be submitted summarizing the selection process results of Task I. This report is in Appendix A. The bulk of the performance and characteristics data is presented in Appendix B. Only the important future technology development information is discussed in the main body of the report. The Task III enabling technology plan results are presented in full since this is the primary focus of the study.

The author wishes to acknowledge the contributions of the following individuals to the content and preparation of this report; Andrew Keith, John Olson, Evan Fradenburgh, Bob Moffitt, Jon Davis, Philip LeMasurier, Jack Landgrebe, and Chris VanBuiten. Thanks also go to General Electric Aircraft Engines and Allison Gas Turbines for their help in the propulsions area. And special thanks to Jack Sutton for his work in the critical area of weights analysis.

TASK I

Mission - Concept Pair Selection Summary

Many attempts have been made in the past to combine the desirable low speed qualities of the helicopter with the high speed and efficiency of the airplane. This is a desirable goal but one that has proven very difficult to attain. All attempts have suffered from the same affliction: the combined requirements of hover and high speed flight necessitate significant performance and design compromises. The result is a degradation in both low speed and high speed handling qualities and performance to a point of impracticality. The primary difficulties encountered in high speed VTOL design are:

Low payload fraction, primarily due to a high empty weight fraction

Complexity required to perform a conversion between low and high speed flight

Degraded helicopter-like qualities, primarily due to higher disk loadings and control system inadequacies.

Over the last five decades, attempts to achieve a successful high speed VTOL have met with increasing success. The illusive goal of a 350- to 500-kt rotorcraft becomes ever closer as technology progresses. Materials, propulsion systems, flight controls, aerodynamics, and a host of other technologies have greatly improved in just the last 10 to 15 years. The synergistic interaction of these technologies applied to a viable concept may result in a successful flight vehicle by the year 2000 for a mission that values both high speed and VTOL operation.

The goal of this study is to identify the most promising concepts and technologies enabling a 350- to 500-kt VTOL with rotorcraft-like qualities. Task I focused on concept selection. This was structured as a process of elimination from a wide field of concepts. Before this was done some key fundamental physical impacts of a high speed design requirement were reviewed.

Aircraft design speed and physical size have opposite effects on aircraft payload efficiency. As design speed increases for a given gross weight, the empty weight fraction increases and payload fraction decreases due to the greater installed power, transmission, and fuel requirements. Almost all transport aircraft, helicopter and fixed wing in production today have empty weight fractions between 0.46 and 0.65. This indicates that a high speed rotorcraft must also be within these limits to be economical unless there are overriding requirements for VTOL that produce their own economic benefits.

Aircraft size has the opposite effect of design speed on payload efficiency. As an aircraft grows in design weight, the empty weight fraction for a given speed requirement reduces. This is why larger aircraft tend to be faster. Size compensates for the increased weight of propulsion components by square-cube effects which cause wetted area and corresponding weight and drag to increase more slowly than gross weight.

Aircraft in the 400- to 450-kt regime are generally larger than 25,000 lb gross weight. Based on this global trend it appears that an economical high speed rotorcraft needs to have an empty weight fraction below 0.65 and at a gross weight no less than 25,000 lb. By helicopter standards this is a large machine. Very few helicopters over this weight are currently used in civil applications.

A price must be payed to provide an aircraft with VTOL capability and efficient high speed cruise. The price is useful load. In both hover and cruise there is some part of the aircraft that is either under-used or operating at reduced efficiency. For example a tilt rotor has oversized, underutilized propellers in cruise and a wing creating negative lift, or download, in hover. An efficient high speed rotorcraft will be one that minimizes these inherent penalties.

As speed increases more installed power is required. With the installed power levels required to fly at 400 to 600 kts aircraft can hover at disk loadings much greater than the 5 to 10 psf of helicopters. The AV-8B for example hovers at a disk loading well over 1000 psf. From a performance standpoint it is advantageous to design for these high disk loadings because it reduces the size and weight of the hover lift system.

Unfortunately, this directly conflicts with the desired goal of rotorcraft-like low speed qualities. One of the most beneficial attributes of the helicopter is the ability to land in unprepared fields. As disk loading increases this ability generally becomes proportionatly more and more impractical due to ground erosion and wake interaction with personnel. Disk loading limits had to be set for this study. These are summarized in Table 1.

An acceptable disk loading is very dependent on surface type. For this reason two sets of criteria were established. These limits were determined by reviewing References 1 through 6. As a surface becomes more and more loose an acceptable diskloading becomes lower and lower. For this study surfaces were characterized as either firm or loose. Over "firm" surfaces, characterized as those like wet sand or dirt, packed dirt, sod or any prepared surface, disk loadings of up to 50 psf can be easilly tollerated. "Loose" surfaces which include water, loose dirt, sand or gravel are significantly elevated into the wake at much lower disk loadings. A disk loading of 15 psf was judged to be a limit for these kinds of surfaces.

Personnel can only tollerate a ceartain amount of force and overturning moment before ballance is lost. An average was used based on the above references. Looses surface personnel limits were reduced by 25% due to the poorer footing often available.

Table 1. DOWNWASH ENVIRONMENT LIMITATIONS

		Firm Surface Operations	Loose Surface
Personnel limits	Overturning Moment	300 ft-lbs	225 ft-lbs
	Body Force	100 lbs	75 lbs
Surface Failure Limits	Disk Loading	50 psf	15 psf

A minimum of two mission-concept pairs were to be selected from a large field of candidates. The contract specified three generic sizing missions: a military transport, scout-attack (SCAT), and a civil transport. The contractor was encouraged to include others for evaluation. It is important to note that a high speed rotorcraft will only be successful for missions that value both high speed and VTOL capability. A special operations forces (SOF) mission and an anti-submarine warfare dipping sonar (ASW) mission were included because they both require high speed and VTOL capability. Mission takeoff gross weight (TOGW) sensitivities were assessed for each mission as a function of performance variables. These variables were operational empty weight fraction, cruise efficiency, loiter efficiency and hover efficiency. For a given percentage of change empty weight fraction had the largest effect. Based on this the most detailed efforts in the remainder of the study were directed to the quantitative assessment of weights.

The SOF and ASW missions were the most sensitive to the performance variables. This was due to the very long range typical of a SOF mission and the large percentage of mission time spent in hover during an ASW dipping sonar mission. These missions were the most difficult to satisfy with any of the low disk loading, high speed concepts, and therefore were eliminated at this point in the study to permit concentration on the other missions. It is likely that the very long range SOF mission will have to accept high hover disk loadings and the long endurance ASW mission will have to sacrifice speed for hover efficiency.

The military places a high value on VTOL capability. It is expected that they will be the first to pay the additional price for a high speed VTOL. The civil transport mission profile is essentially the same as the military transport. Cargo or passengers are transported over a distance at the best possible efficiency. This led to the selection of the military transport as one of the generic sizing missions. It is also representative of a civil transport mission. The SCAT profile was selected for the other generic mission because it represents a distinctly different gross weight category and set of operational requirements and would therefore expose any significant technology need differences.

All high speed concepts can be categorized as one of 16 types. These are summarized in Figure 4. Of these, only five types were judged to have adequate high speed and rotorcraft-like qualities. These are the rotor, propeller, and ducted fan tilting thruster types, and the rotor and ducted fan double propulsion types.

Within these five configurations, 13 separate types were identified. They were grouped into three families. These are listed in Table 2.

Table 2. CANDIDATE HIGH SPEED ROTORCRAFT CONCEPTS

Tilting Thruster	Stopped Rotor	Buried Rotor
Tilt rotor	X Wing	Fan in wing
Tilt wing	Tip drive X Wing	Rotor in body
Tilt duct fan	Stopped rotor	
VDTR	Tip drive stopped rotor	
Folding tilt rotor	Stopped/retractable rotor	
	Stowed rotor	

In order to down-select the most promising concepts their relative 'goodness' was determined by a measure of both attributes and performance. Attributes were assessed on a qualitative basis, performance was quantitative.

Different missions place different value on individual aircraft attributes. Eleven important attributes were identified: cost of ownership, cabin size, noise & vibration, maneuverability & agility, survivability, observables, downwash environment, shipboard compatibility, ease of conversion, and overload STOL capability. Attribute importance to each mission and the quality of each attribute for each concept was rated by a number of individuals experienced in VTOL design and operation. These inputs were averaged and a relative ranking of concept attractiveness for each mission was defined. All five generic missions were evaluated.

For the military transport mission the folding tilt rotor, tilt rotor, and VDTR had nearly the same ranking for the best overall attributes. This was due mainly to their rotorcraft-like low speed handling qualities and relatively low disk loadings. The tilt wing was second. Its low speed qualities are slightly inferior and it suffers from a naturally higher design disk loading. The stopped rotor concepts were generally less attractive. Their rotor support structure and transmission system take up a lot of valuable cabin space. Stopped rotor concepts are also inherently difficult to transition and the tip drive versions are noisy. The buried rotor family was not a viable option for the transport mission.

The shrouded rotor concept showed the best attributes for the SCAT mission. Its excellent agility due to low inertia about all axes, naturally good low observable qualities, and high speed were responsible for this result.

Performance analysis was done on a parametric basis. Experimental reports of past concepts' weights and aerodynamics were reviewed. Because experimental and research activities involving these concepts were done at different times, the differing technology levels had to be normalized, in this case to the 1980 time frame. From this point, equal levels of technology improvement in weights, aerodynamics, propulsion, etc. were applied for the year 2000. The engine technology level assumed was that expected of the IHPTET phase II engine development program. Weights and aerodynamics were based on extrapolated historical trends plus projected finite improvements based on anticipated technology advances. For each mission TOGW was estimated based on the projected year 2000 technology.

A numerical ranking of attributes and performance was developed for each aircraft-mission combination. If an aircraft had an ideal mission attributes level it would have received a value of one. Each aircraft was evaluated against this ideal based on the averaged ratings. Ideal performance was defined as having a payload fraction of 25% of TOGW. As expected, all aircraft fell short of these goals.

Figures 5 and 6 plot the results of the attribute-performance ranking. An ideal aircraft would be positioned in the upper right corner. Aircraft to the upper left trade performance for better attributes, aircraft to the lower right trade attributes for better performance. The curved line labeled 0.5 is a line of constant product, ie. relative attribute multiplied by relative performance.

For the transport mission the tilt wing appeared to offer the best combination of attribute and performance ratings followed by the tip drive stopped rotor and a grouping of the folding tilt rotor, tilt rotor, VDTR, and stowed rotor.

For the SCAT mission the shrouded rotor marginally had the best attributes but the worst performance. The performance of the tilt wing, tilt rotor and VDTR were relatively close and their attribute ratings were nearly the same.

The final selection criterion considered was relative risk of development. This was done by a group of experienced engineers familiar with the current states of technology. These results are graphically displayed in Figures 7 and 8. A single numerical rating consisting of the product of relative attributes and performance was plotted against relative development risk. The far left, or lowest risk, was defined as equivalent to that undertaken to develop an advanced helicopter. Risk was assessed as a balance of two factors. Each concept has its own experimental history of relative success. Some were obviously more successful than others in attaining high speed and rotorcraft attributes. This relative past success constituted the first risk factor. The second factor involved an assessment of the technology advancement required to enable the concept.

There has never been a manned stopped rotor prototype. A large amount of risk would be entailed in the design of a vehicle in this family. As a result, its overall rating is not as good as more proven concepts.

The folding tilt rotor in each mission falls short in overall rating for about the same level of risk as the tilt rotor and VDTR. These latter two are close in overall rating for each mission. The tilt wing had the best overall rating for the transport mission and was close to the tilt rotor and VDTR for the SCAT mission. The VDTR and tilt rotor were judged to be riskier than the tilt wing because they require a more involved technology effort to develop proprotors and aeroelastic technologies.

The tilt rotor, even though it has a one-piece blade compared to the VDTR blade, was judged to be somewhat riskier. At the high helical tip Mach numbers encountered by these proprotors a tilt rotor must use a combination of thin airfoils and significant sweep on a relatively high aspect ratio blade. This is very difficult to design. Aeroelastically, proprotor and wing stability is difficult to maintain. The variable diameter rotor in its retracted state is only at 65% of its extended diameter and tip speed. This makes it very attractive for high speed operation. The price for this advantage is mechanical complexity. However, complexity is a natural evolution of more sophisticated designs. For example, the flap system on todays modern airliners is extraordinary. The trailing and leading edges of the wing are a myriad of flaps, slats, spoilers, and jack screws. All of these are necessary to reconfigure the wing for low speed. Swing wing aircraft are another example of a variable geometry solution. The VDTR solution also accomplishes its goal by changing geometry.

Conceptual designs indicate that a disk loading of 25 psf is the minimum that could be tolerated by a 400- to 450-kt tilt rotor solution with values closer to 30 psf more likely. A solution in the 15 to 20 psf disk loading regime is possible for the VDTR. This is more in line with the rotorcraft-like attributes sought by this study. The VDTR's of this study were sized at a compromise disk loading of 20 psf. This lowers the structural technology level required to maintain a stable proprotor-wing system in cruise. There are solutions at 15 psf for both the transport and SCAT but they incur a 4% and 13% TOGW penalty respectively.

Based on these results the tilt wing and VDTR were chosen for the military transport. The tilt wing has the lowest risk and best performance. This is at the expense of some rotorcraft-like attributes, The VDTR has the best attributes but sacrifices some simplicity and payload performance. The selection of these two concepts brackets the best performance and attributes that can be expected from a future high speed rotorcraft transport.

The VDTR was selected over the tilt rotor for the SCAT mission for the same technological and attribute reasons as for the transport. Observables are an important design consideration for a SCAT design. The VDTR gives more latitude in tip speed selection and has more volume available for RCS treatment in the 3 blades-per-proprotor vs. 4 or more for a tilt rotor.

A long standing problem of past shrouded configurations has been the strong body pitch-up moment at moderate forward airspeeds. This problem has been investigated in separate research by Sikorsky. It was found that moment control by the use of cyclic pitch control on a rigid rotor in a duct is actually magnified by mutual aerodynamic interactions. This has been measured to be powerful enough at moderate speeds to counter the pitch-up moment and obviate the need for an auxiliary fan like that used on the XV-5A and other similar aircraft. The shrouded rotor's agility in low speed rotor borne flight is projected to be excellent with the rigid rotor and duct magnification.

Even with the shrouded rotor's very good SCAT mission attributes its poor payload performance gave it an inferior overall rating. However it was decided to carry it into task II as a contractor option concept and redesign it as a tip driven rotor. This was expected to significantly improve useful load. Analyses beyond the scope of task I were also performed to quantify its inherent maneuverability, agility, and speed advantages.

TASK II

Aircraft Performance, Characteristics, and Sensitivity to Technology Summary

Task II involved refining the designs selected in Task I, performing a configuration trade analysis to find minimum mission TOGW, defining aircraft performance and characteristics, and evaluating sensitivity to various technologies and design variables.

Each transport and SCAT design vehicle was designed to the same set of design guidelines. This ensured that performance and characteristic differences were concept and not capability dependent. The mission profiles used are listed in Table 3.

Table 3. GENERIC SIZING MISSIONS

Military Transport

6000 lb Payload
Entire Mission ISA+15 deg C

HOGE 1 minute, SL
Climb to cruise altitude, full credit for range
Dash 450 kts out to 350 nm
Descend to SL, no credit for range
HOGE 15 minutes SL
Loiter Vbe, 30 minutes, SL
Climb to best range altitude, full credit for range
Cruise 99% best range power, 350 nm
Descend to SL, no credit for range
HOGE 1 minute, SL
10% fuel reserve

Military Scout-Attack

3000 lb payload
Entire mission 4000 ft/95 deg F

HOGE 1 minute
Cruise 99% best range power, 150 nm
Dash 400 kts IRP, 50 nm
NOE maneuvering, 15 minutes, 40 kts
15 minutes HOGE
Attack targets IRP power, 5 minutes
Cruise 99% best range power, 200 nm
HOGE 1 minute
10 % fuel reserve

The tilt wing transport was sized over a range of disk loadings, wing chord-to-diameter ratios (c/D), and cruise altitudes. A disk loading of 50 psf, a c/D of .45, and a cruise altitude of 30,000 ft were selected as the best solution. Mission TOGW was 33,512 lb, span 51.3 ft, and a proprotor diameter 20.7 ft.

The VDTR transport was sized over a range of disk loadings, wing aspect ratios, and cruise altitudes. A disk loading of 20 psf at an AR of 4.0 and a cruise altitude of 25,000 ft was selected. Mission TOGW was 39,839 lb, 18.9 % heavier than the tilt wing. Span was 36.6 ft and the extended diameter 35.6 ft.

The VDTR SCAT was sized at 4000 ft, 95 deg F over a range of disk loadings, wing aspect ratios, and tip speeds. A disk loading of 20 psf at an aspect ratio of 4.0 and a hover tip speed of 800 fps was selected. Mission TOGW was 25,597 lb, span 34.5 ft, and an extended proprotor diameter 28.6 ft.

The shrouded rotor was resized as a tip-driven system and was assessed in terms of its maneuverability, agility, and speed. Redesigned for a 25,000 lb TOGW, it had a payload of only 850 lb as compared to the requirement of 3000 lb. The weight of the louvered covering system and the poor specific fuel consumption of the low bypass turbofan engine was primarily responsible for the poor payload fraction. Maximum speed was at 460 kts at IRP power. The agility of the aircraft was found to be very good in both low and high speed modes. But maneuverability was disappointing. The very low aspect ratio and poor aerodynamic span efficiency of the delta wing created significant induced drag in maneuvering flight. The aircraft was found to have only a 1.7 sustained load factor capability. A qualitative analysis of the transition characteristics, namely a large pitch excursion possibility upon louver closing, and some uncertainty about the rotor-wing lift sharing in the transition regime added to the poor overall aircraft attractiveness. For mission applications where low observability and 450+ kt speeds are important this is a potential solution. However, the infancy of the knowledge places it beyond technology levels projected for the year 2000.

Three views of each aircraft are shown in Figures 9 to 12. The tilt wing uses a pitch control system developed and patented in the late 1960's by Gary Churchill who currently works at NASA AMES. This system eliminates the tail pitch control device used on all previous tilt wing designs. A brief description of this system is provided in Appendix B and a full description in Reference 7. The net savings realized by this system is in the neighborhood of 5% of TOGW. The projected reduction in complexity and vibration is a significant improvement. Improved handling qualities are also cited as an advantage. Yaw control is provided by differential aileron deflection like that used on the XC-142 and CL-84 prototypes.

The VDTR transport and SCAT use the same monocyclic control that is used on a tilt rotor. The transport's forward swept wing is required to increase the drag divergence Mach number of the 21% thick wing. This naturally leads to a canard layout in order to maintain balance. The SCAT's cruise Mach is low enough to allow a 21% thick wing at only five degrees of sweep permitting a conventional layout.The transport has the engines mounted inboard. This reduces drag and increases the natural bending and torsional frequencies of the wing. Relatively high frequencies are required for proprotor-wing aeroelastic stability. The SCAT does not have enough fuselage volume available to do this. A tilting transmission configuration was selected over a tilting nacelle due to required ground clearance.

The full complement of task II analyses were performed for the tilt wing and VDTR transport and the VDTR SCAT. The limited analysis of the shrouded rotor is summarized in Appendix B.

The installed power in all cases was sized by the cruise condition. Each aircraft meets the design hover point with a large dual engine power margin. The tilt wing only falls 1% short of OEI hover capability. The VDTR transport is OEI hover capable up to nearly 3000 ft, ISA+15 deg C. The VDTR SCAT is capable of OEI hover at 84% of design mission TOGW at 4000 ft, 95 deg F. The short field takeoff performance is excellent for all aircraft. Each aircraft can achieve a 40% overload takeoff capability for a field length of less than 500 ft. In general the performance of the tilt wing and VDTR are much like that of a high speed turboprop with outstanding rates of climb. Best specific range is achieved between 25,000 an 30,000 ft altitudes.

The more important technologies came to light as a result of the sensitivity studies. Mission TOGW was determined as a function of both mission and design variables. Sensitivitey was quantified as percent change in TOGW for a given percent change in technology. Mission TOGW was most sensitive to overall weights technology. Propulsive efficiency and L/D were both found to be about half as sensitive as weight technology. Engine SFC, Hp/lb ratio, and aircraft maneuverability were all about one quarter as sensitve.

Mission TOGW sensitivity with speed indicated a sharp rise beyond the design speed. This was primarily due to reduction in propulsive efficiency as higher helical tip Mach numbers were encountered This sensitivity highlighted the need for efficient proprotor operation at high speed. Even at a constant propulsive efficiency mission TOGW climbed considerably beyond 450 kts. This was due to the rapidly increasing size of the propulsion system and fuel required. Based on productivity (defined as payload times speed divided by empty weight) a speed between 375 and 425 kt is optimum.

TASK III

Recommended Technology Development

Critical technologies were characterized as either generic or concept specific. Within these categories a technology could be considered important enough to be termed as enabling. Generic technologies are those that apply to the tilt wing transport, VDTR transport, and VDTR SCAT. Generally these technologies also apply to other high speed VTOL and fixed wing aircraft. Concept specific technologies are those that must be tailored to the concept. Enabling technologies are those that are essential for the concept feasibility. Without the enabling technologies the concept will be less attractive or may not work at all. Critical technologies were identified as a result of the sensitivity studies during configuration selection at the end of Task I.

A summary of the generic and concept specific technologies is presented in Figures 13 and 14. The boxed items in each figure are enabling technologies. Proprotor design and aeroelastic stability proved to be the most important technological areas for all three aircraft.

Generic Technologies

A low empty weight fraction has always been a very important aircraft performance attribute. The inherently higher empty weight fractions of high speed VTOL aircraft make this a prime candidate technology for improvement. Structural weight reduction is accomplished by the incorporation of new materials and more efficient designs. Many aviation performance breakthroughs can be attributed to materials technology. The development of aluminum and composites are two of the most notable. The performance levels of the aircraft in this study were predicated on improved metal and composite materials expected by the year 2000.

Structural weight savings due to better design is often the direct result of better analysis. Refinement and correlation of structural analysis tools enable more accurate prediction of loads and placement of material only where needed. At high speed dynamic loads become dominant. The wing design must be stiff enough to protect the system from instabilities. Loads prediction and the analysis of structural couplings are therefore important.

Even at the assumed year 2000 level of weights technology the transport aircraft of this study are slightly above a historically practical maximum empty weight fraction of 0.65. The offsetting factor is the combined VTOL and high speed cruise capability.

Improved engine efficiency and power-to-weight ratio is beneficial to all aircraft. It is of particular importance to aircraft that require high power-to-gross weight ratios. Turboprop engines generally experience a significant rise in power with increasing Mach number. However, poor inlet design can destroy pressure recovery benefits and cripple an aircraft's high speed performance and specific fuel consumption. The proprotor influence on pressure recovery is larger than that of a turboprop. Proprotors typically have very lightly or even negatively loaded inboard sections. This can significantly disturb the flow field. The application of computational fluid dynamics (CFD) codes to specific inlet configurations with proprotor influence will develop guidelines for designers and help maximize the efficiency levels that can be expected.

The tilt wing and VDTR will not have autorotational characteristics as good as a helicopter. Continued flight or landing with one engine is therefore a critical safety feature. This capability is very sensitive to OEI power margin. The 30 second 140% MCP contingency rating for the tilt wing gives OEI performance better than most helicopters. The VDTR has excellent OEI performance due to it's relatively low disk loading. For the same OEI design criterion the VDTR does not require as great a contingency power ratio.

Drag reduction, like weight reduction, has always been an area of design focus. The major drag contribution to the study aircraft, like all fixed wing aircraft, is skin friction. This is largely dependent on surface finish. Military camouflage paint is not nearly as smooth as the bare metal (or even an enamel) finish found on most airliners. Infrared heat dissipation requirements and mass production compromises roughen up surface texture considerably. The development of a smoother or possibly riblet impregnated finish could produce significant gains. As an example, the Piaggio Avanti is the first business class turboprop to have a 400-kt capability. This is about 70 Kt faster than other aircraft of comparable size and power. Much of this is due to its very smooth flush riveted almost mirror-like finish.

The remainder of aircraft drag is due to form and separation. The avoidance of separation drag is paramount. Even over small areas it can cause a large overall drag increase. Improved CFD analyses to estimate form drag will identify possible areas of local separation before there is a large commitment to design contours and structure.

Fly-by-wire (FBW) control systems are maturing and becoming more common. The Airbus 320 and F-16A are two early examples of successful applications. However it still needs development within the rotary wing industry. With the exception of the V-22 and SA-365N there are no FBW controlled rotorcraft in production development today. Due to the control phasing and mixing requirements of high speed VTOL aircraft a mechanical system would be complicated and difficult to tune. This was the case with fixed wing aircraft back in the 1960's and 1970's. Control can be easily modified with FBW software. A stability augmentation system is easier to superimpose onto a FBW system and easier to route through the fuselage and pivot points.

The observable qualities reduction of military aircraft is receiving more emphasis as new aircraft are designed and the threat to them increases. It is expected that requirements will dictate some degree of low observable technology application on a high speed military VTOL aircraft. Propellers are the most difficult item to 'conceal' in terms of both noise and RCS. All propeller, proprotor, and propfan aircraft will benefit from research expended in this area.

Concept Specific Enabling Technologies

These technologies need to be developed and tested separately before they can be integrated into a full scale design. It is prudent to test subscale models before committing to full scale fabrication. Figures 15 and 16 show the required design and analysis technology discipline and the correlation testing required for each aircraft concept specific issue. Fulfillment of these sub-tasks would enable the main task of configuration model testing and full scale design. In the case of the forward swept wing VDTR transport, a semi-span proprotor-wing aerodynamic/dynamic model test is recommended to correlate with the coupled aeroelastic predictions before an entire aircraft is modeled. Various facilities within the United States adequately fulfill the computational and experimental requirements for the development of these recommended technologies. No need for significant capitalization expenditure is foreseen.

For each concept specific and enabling technology the major development tasks are mapped out as a function of time in Figures 17 and 18. These time lines are notional. They assume a dedicated effort that would start in 1991. A true schedule would require manpower estimates, facility scheduling, funding profiles, and many other considerations beyond the scope of this report. These time lines are intended to give an indication of sequence, time, and effort required. Each technology's importance, goal and development approach is discussed in the following paragraphs.

Proprotors: TW and VDTR XPORTS, VDTR SCAT

A successful proprotor design is crucial to the viability of all three designs. Maintaining a respectable propulsive efficiency at the moderate design cruise tip Mach conditions is the most difficult aspect of the design challenge. This will require tailoring of airfoil sections, planform, and twist distribution to strike a good compromise between cruise and hover efficiency. The degree of success of the proprotor will dictate to a large degree the performance capabilities of the aircraft.

Figure 19 illustrates the projected propulsive efficiencies of the tilt wing and VDTR proprotors as a function of cruise Mach number. The design of the tilt wing proprotor will borrow from existing propeller, propfan, and proprotor experience. It is really a hybrid between these three types of propulsors. Based on the sensitivity studies cruise efficiencies in the high 70 to low 80 percent range need to be attained. Hover FM values are less critical, with values in the mid to high 70 percent range acceptable. The aerodynamic performance would first be estimated using rapid blade element lifting line analyses. Design refinement will then need to be done using lifting surface calculations which are becoming more common. This is needed because of the complex blade geometries.

Both the tilt wing and VDTR transport proprotors will require specifically designed airfoils with high drag divergent Mach numbers (Mdd). These sections would most likely employ supercritical airfoil design characteristics. Existing design codes should be sufficient for this work.

The tilt wing proprotor will require the design and testing of light weight blades and a bearingless or hingeless retention system. The aeroelastic structural requirements of the tilt wing proprotor-wing system is less critical than a tilt rotor or VDTR but more critical than a turboprop or propfan installation. Hingeless or bearingless proprotor stability will most likely be the more difficult requirement to meet. No experimental data exist in this speed regime for proprotors. Before any full scale design can be undertaken, data on stability needs to be developed from both analytical and experimental investigations. Existing whirl mode flutter calculation and finite element techniques are adequate to estimate initial boundaries and loads. The blade aerodynamics needed for the dynamics analysis will have to come from aerodynamics analysis.

The development of a variable diameter rotor is of course an enabling technology for VDTR aircraft. The same aerodynamic and structural methodologies previously discussed would be used to model the variable diameter rotor. However, a rotor dynamics code would have to be modified to handle the change in diameter as a function of time.

Along with the design of the variable diameter rotor a sequencing system needs to be designed to ensure symmetric retraction as a function of nacelle angle. This safety system must be incorporated into a VDTR design to be considered enabling. This could be accomplished mechanically or electronically. A mechanical system was patented by Sikorsky in the 1970's. However, an electronic system would be feasible with today's technology. The design itself is not expected to be very difficult and could be done using today's methods.

Forward Swept Wing Design: VDTR XPORT

Beyond airfoil Mdd the coefficient of drag rises exponentially. Sustained speeds beyond Mdd require disproportionately large increases in power. Tilt rotor aircraft require thick wing sections of over 20% to efficiently react torsional and bending loads. At the cruise Mach numbers of interest in this study the VDTR wings must be swept forward to stave off wing compressibility drag rise. This makes static divergence stability much more difficult to attain. Figure 20 shows how airfoil Mdd increases with wing sweep. Both the VDTR and tilt wing thicknesses are plotted. A combination of sweep and supercritical wing design are required to meet the VDTR cruise Mach condition with some margin. The tilt wing is able to do so with out sweep because of the lower thickness requirement for structural stability.

Forward swept wing design would build on the work done on the X-29. However, the addition of a proprotor at the tip makes this a new and much more difficult design challenge. The dynamic response of the variable diameter rotor needs to be well investigated in order to understand its structural dynamic requirements. The retracted blades will increase the stability of the proprotor at high speeds. If its natural stability is good enough at high speed a thinner wing could be used, requiring less forward sweep. If a 17% thick wing could handle the dynamic and static loads adequately the VDTR transport could employ a conventional wing arrangement.

Tilt rotors in general will be precluded from the 450 Kt speed regime until forward swept wing with proprotors technology can be developed. The aeroelastic tailoring capabilities of composites are used to counter the naturally unfavorable wing pitch-flap coupling. A combination of codes capable of handling this kind of structure with high speed proprotor dynamics is needed in order to calculate the response and loads of the coupled system. Validation of this method would be a primary aim of a semi-span dynamics test.

Geared Flap Control System: TW XPORT

Undesirable qualities of tilt wings with tail pitch fans are drag, weight, complexity, and the requirement to pitch the entire fuselage in order to develop longitudinal force. The geared flap control system addresses these factors. The geared flap system drives and maintains wing position by using the wing flaps as a servo tab. In hover the flaps pivot the wing and move the tip path plane as if it were a helicopter rotor in response to longitudinal stick inputs. Longitudinal pitch motion is therefore much more rotorcraft- like. Geared flap system investigations are currently being conducted at NASA AMES and show good promise. Figure 21 is a mechanical schematic of the system. This can be accomplished mechanically however, an electronic sensing and feed-back system would be a much better performing system and could be done using today's technology. Reference 7 provides a full description of the geared flap control system and the reader is encouraged to consult this for a more thorough understanding. The challenge is to develop the system such that it behaves with acceptable handling qualities. This involves control law and geometry definition through simulation and model testing. A remote control free flight model may be a good way to assess the dynamic stability and maneuvering characteristics of an aircraft utilizing geared flap control.

Speed-Descent Buffet Boundary Expansion: TW XPORT

Past tilt wings exhibited satisfactory descent performance but room for improvement exists. For the tilt wing to become fully accepted it is desirable to increase the speed-descent buffet boundary envelope. Figure 22 shows the speed-rate of sink regions where various degrees of buffeting are encountered. This plot was derived from XC-142 flight test results. The buffeting is the result of flow separation off the wing. This is experienced in low power conditions such as descent and deceleration. A typical fixed wing approach angle is 3 degrees, and STOL landing like that performed by a DASH-7 turboprop is 7.5 degrees. The tilt wing can adequately perform these approaches. Transport helicopters operationally attain their highest descent angles in an autorotative state. A UH-60A at 16,450 lb in 60 kcas autorotation descends at 2280 fpm, which is a 20-degree descent angle. This may seem like a shallow angle but to the pilot it feels steep and rapid and to the unaccustomed passenger rather uncomfortable. Approaches at this angle are infrequently flown.

The total lift of a tilt wing remains fairly constant as the buffet regions are penetrated. No sudden pitch down like that associated with a fixed wing is experienced. The aircraft just begins to shake. Ride quality progressively degrades as the angle of descent increases. Handling qualities eventually begin to degrade deep into this region. However, test points indicate that this occurs at descent angles steeper than those at which transports usually operate. The reduction or elimination of buffet at typical maximum transport aircraft approach angles will remove one of the tilt wing's compromises.

A large amount of high angle of attack research has been completed in the last decade. Application of this knowledge as well as theoretical and experimental research on specific wing configurations and devices will be the means by which the goal of reduced buffet is attained. Separation is a difficult phenomena to predict. Much of what is known about post stall aerodynamics is derived from test. It is expected that the development of buffet alleviating geometries will be derived in the same fashion. New computer codes using massive parallel processing are starting to model viscous and unsteady wake effects. In the future, time dependent stall behavior predictions will become more accurate.

Concept Specific Technologies

Super Critical Wing Section Design: TW and VDTR XPORTS

The wing of the tilt wing must be straight or at most only slightly swept. The VDTR wing must be thick to react large static and dynamic loads. The best way to increase Mach capability is to increase the drag divergence Mach number of the airfoil. This is typically done by thinning the airfoil. However, structurally it is desirable to maintain a thick section to retain torsional and bending rigidity. This conflict naturally leads to the use of a super critical section. The design of a new and specific section tailored for a 400+ kt aircraft is necessary. Such a section would have to accommodate the use of leading edge devices and large slotted or fowler type flaps. It must also operate in a periodic wake environment and not in clean flow as is the case with fixed wing aircraft. The use of existing airfoil design codes should be sufficient to attain the desired performance goals.

Variable RPM Propulsion System: TW XPORT

In order for a tilt wing proprotor to work well in the 400+ kt regime it is necessary to reduce RPM. The goal of 80% RPM operation is only about 4% more than the V-22's reduction capability. It would be desirable to attain 75% RPM operation. Reduced RPM raises difficulties in dynamics, power transmission, and subsystem power supply operation. Engines must also be designed to handle variable RPM operation. Engines currently designed for continuous operation a 100% power turbine speed only loose 4 to 6 percent of their rated power at 80% power turbine speed. Engines specifically designed for slowed operation could reduce this to about 2 to 3 percent.

RCS, Acoustic, and IR Signature Reduction: VDTR SCAT

SCAT aircraft mission success is a strong function of its detectability. Designs with emphasis on low RCS, acoustic, and IR emissions require configuration tailoring. The transports will also require low observable emphasis but the level of treatment on the SCAT design is expected to be sufficiently greater to constitute concept specific technology. Reductions will stem from both generic and specific research areas. The concealment of the proprotor in terms of RCS and acoustics is the most difficult challenge. The suppression of IR returns is a difficult task because the design must efficiently handle both the low inflow environment of hover and the high inflow environment of cruise. The V-22 has accommodated this by having a variable geometry exhaust nozzle.

Technology Development

Accurate aerodynamic performance and structural behavior predictions of the designs proposed herein will be difficult with today's methodologies. When new and unusual configurations are experimentally tested, inadequacies inevitably show up. For example proprotor performance predictions based on helicopter codes were noticeably pessimistic at higher blade loadings. It is expected that similar anomalies will surface as high speed rotorcraft proprotors, airfoils, structures and control systems are developed. The key to understanding phenomena is theoretical research correlated with experimental results.

Most of the enabling concept specific technologies can be boiled down into three fundamental technology areas: aerodynamics, structures, and flight controls. These are shown in Figure 23 with the corresponding applications. Basic research investment into these disciplines, not even specifically directed to high speed rotorcraft, will build the foundation for accurate predictive tools for high speed rotorcraft applications. Conversely, efforts invested into tackling the difficult nature of the aerodynamics, structures, materials, and flight controls of high speed rotorcraft will enable more accurate predictions on simpler physical situations found on more conventional helicopters and fixed wing aircraft.

CONCLUSIONS

Based on the results of this study the tilt wing and VDTR concepts appear to be best suited for high speed rotorcraft missions. Both satisfy the selection requirements. The tilt wing achieves the best overall performance at the expense of some attributes, and the VDTR possesses the best overall attributes at the expense of some performance. The control of these aircraft (albeit the geared flap control system) is well proven. Their operational success rides primarily on achievable economics. The shrouded rotor concept appears to be viable but impractical for the SCAT mission. Overall performance is like that of a high speed turboprop. Each aircraft has very good OEI capability compared to todays helicopters. Based on a measure of productivity, a design speed of 375 to 425 Kt appears to be optimum.

The technology required to enable these concepts are within reach by the year 2000 if concerted development is begun in the early 1990's. The most important fundamental technologies are aerodynamics, structural design, and flight controls. Improved aerodynamic prediction capabilities will enable reduced drag, improved high Mdd airfoils, and efficient proprotor performance at both high helical Mach numbers and static conditions. Structural design, with an emphasis on materials, will enable better empty weight fractions. Flight controls work must center on the implementation of FBW systems and appropriate control laws.

The most important concept specific technologies are tilt wing proprotor design, tilt wing speed-descent envelope expansion, geared flap control system, variable diameter proprotor design, and VDTR forward swept wing design. Improvement in these areas is dependent on improved aerodynamic methodologies, structural dynamics methodologies, and FBW control systems.

TECHNOLOGY NEED FOR HIGH SPEED ROTORCRAFT

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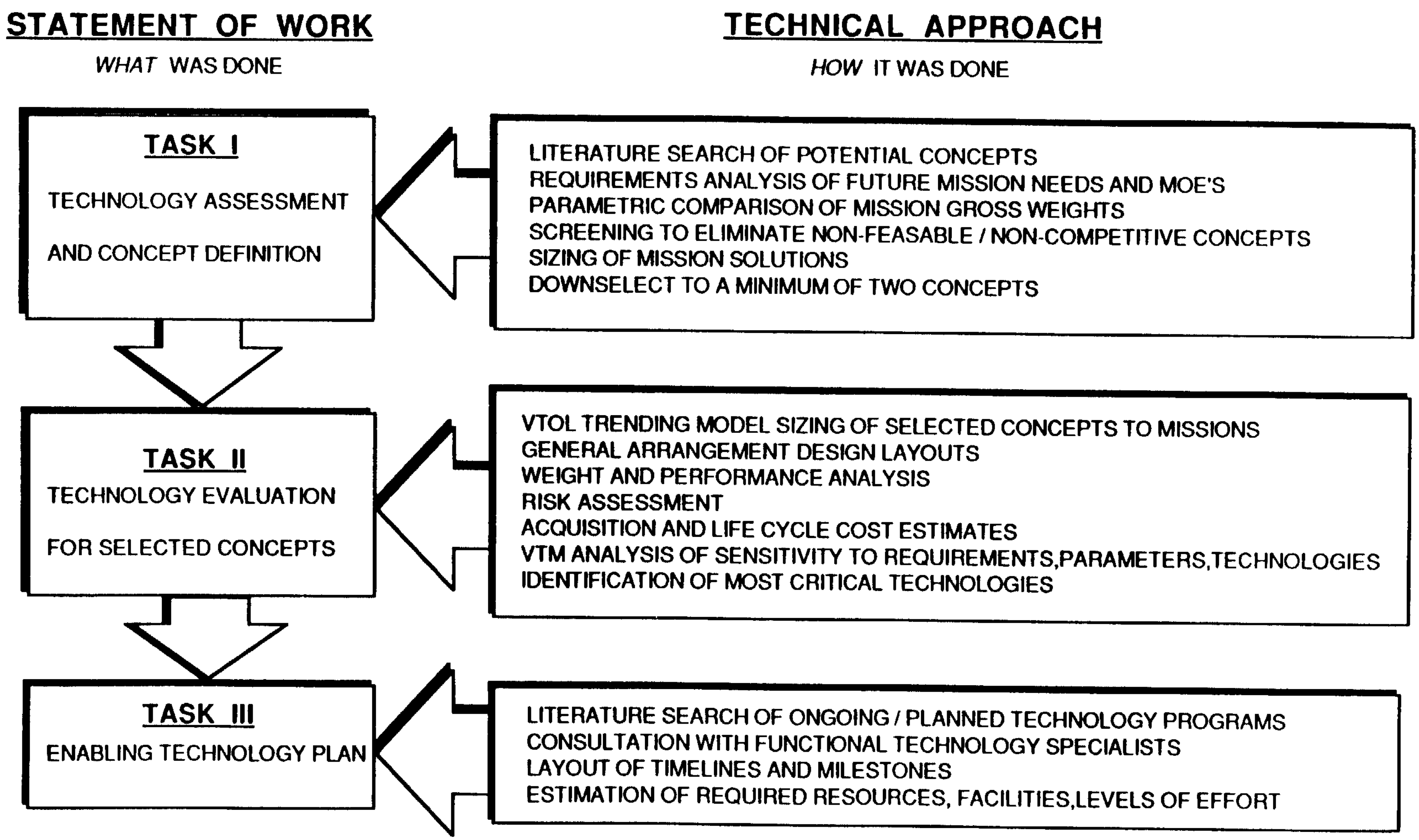

Figure 1. 'Technology Needs For High Speed Rotorcraft Study' overview

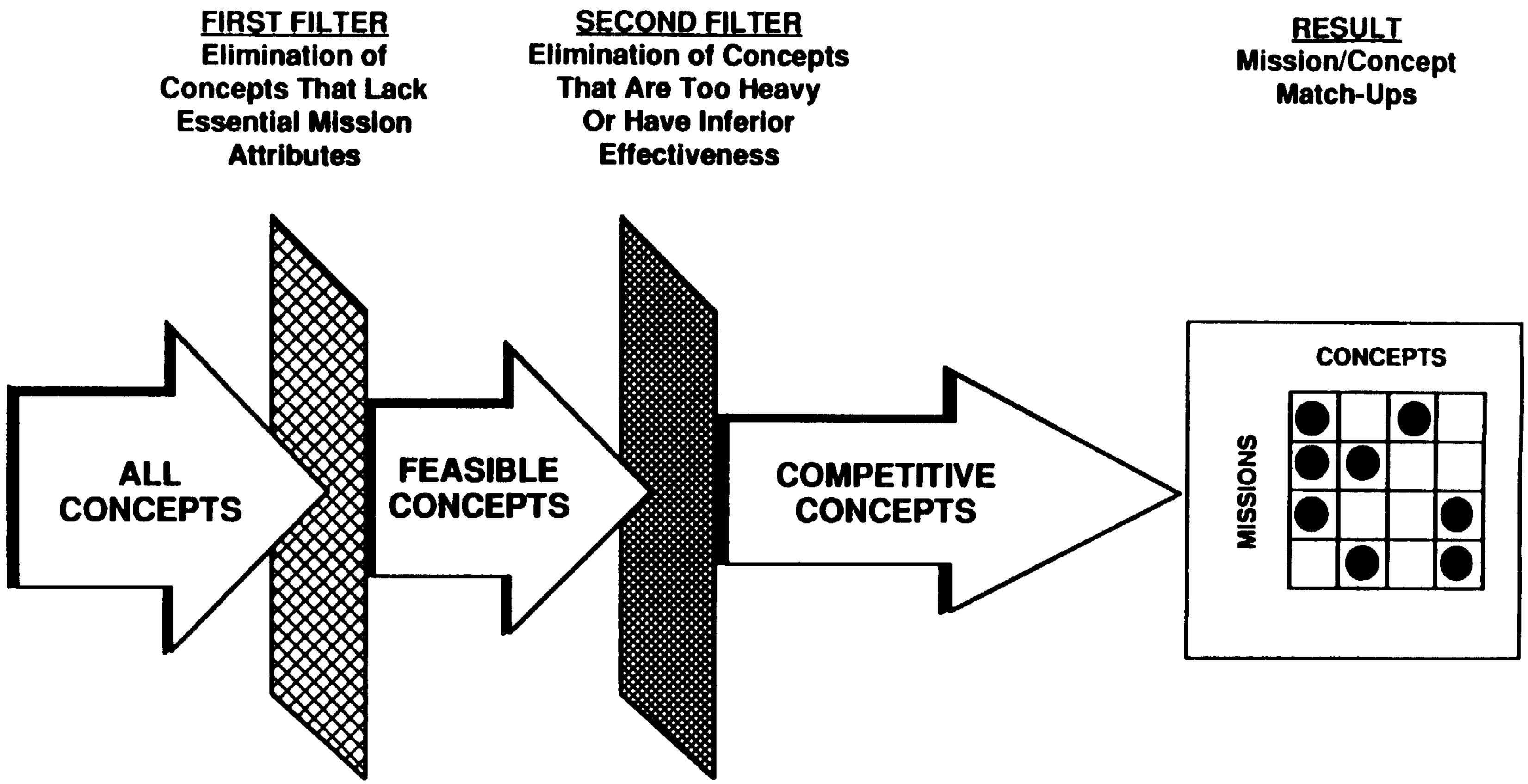

Figure 2. Mission-concept pair selection process

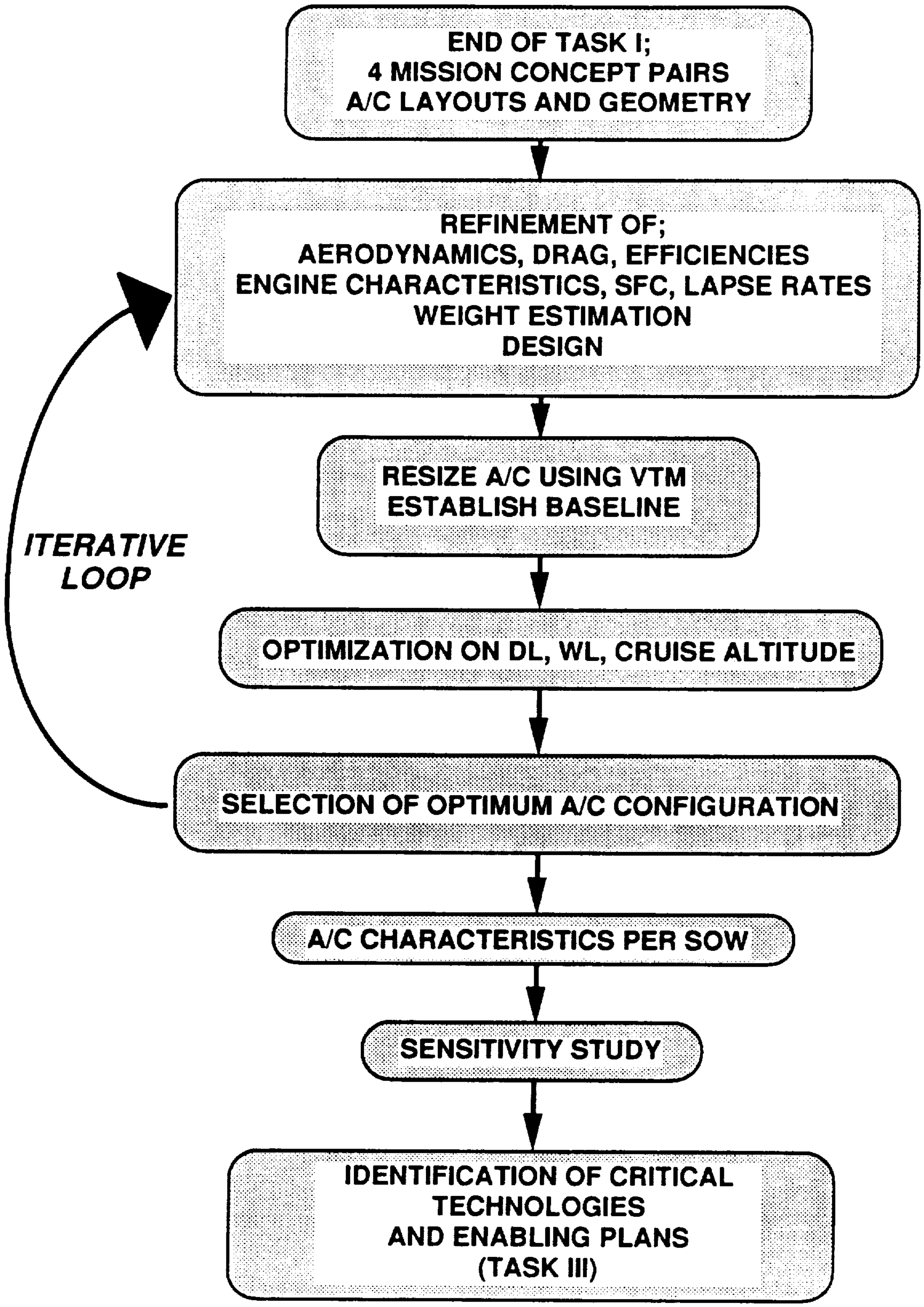

Figure 3. Task II progression of work

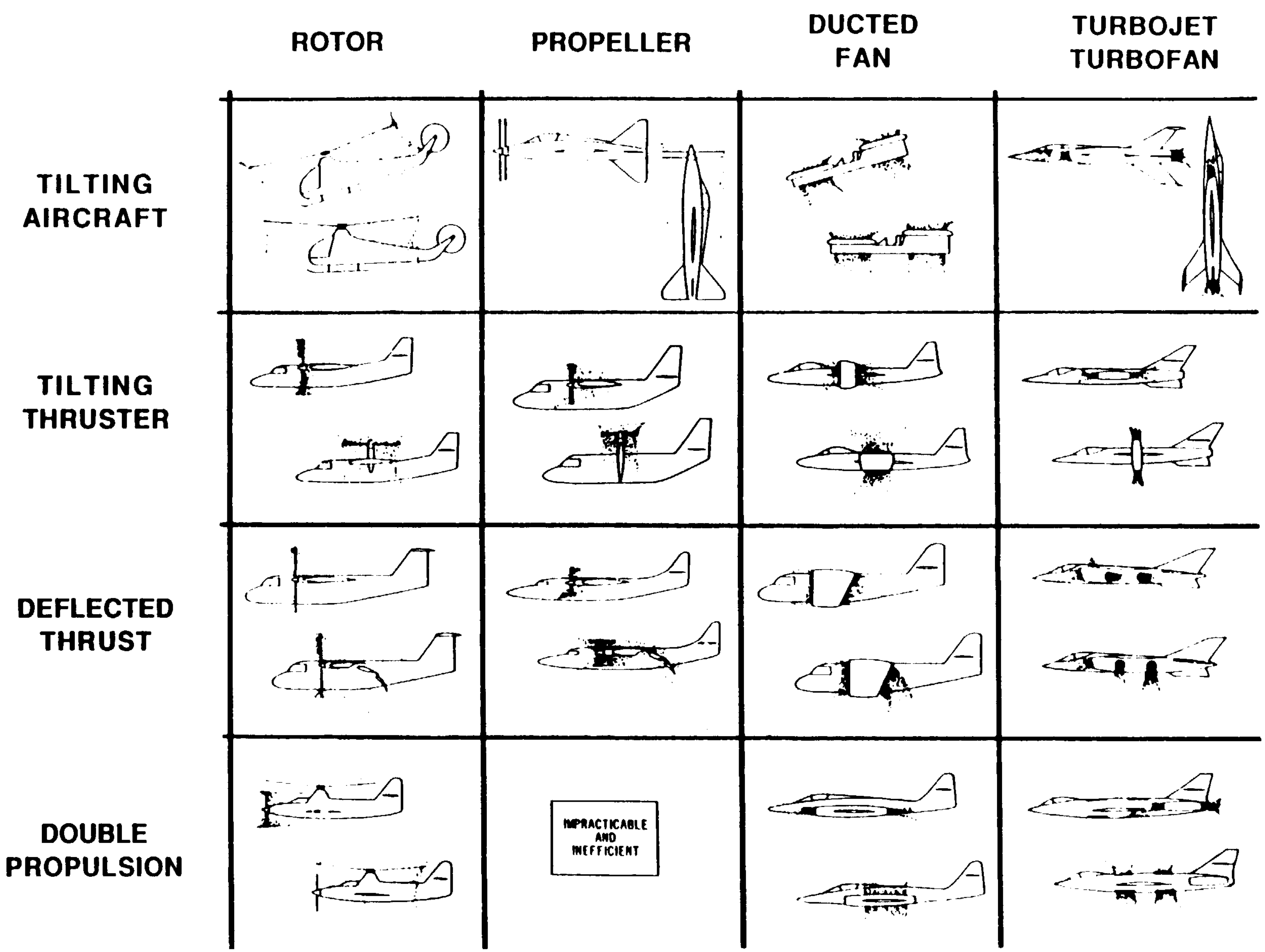

Figure 4. Matrix of VTOL configurations

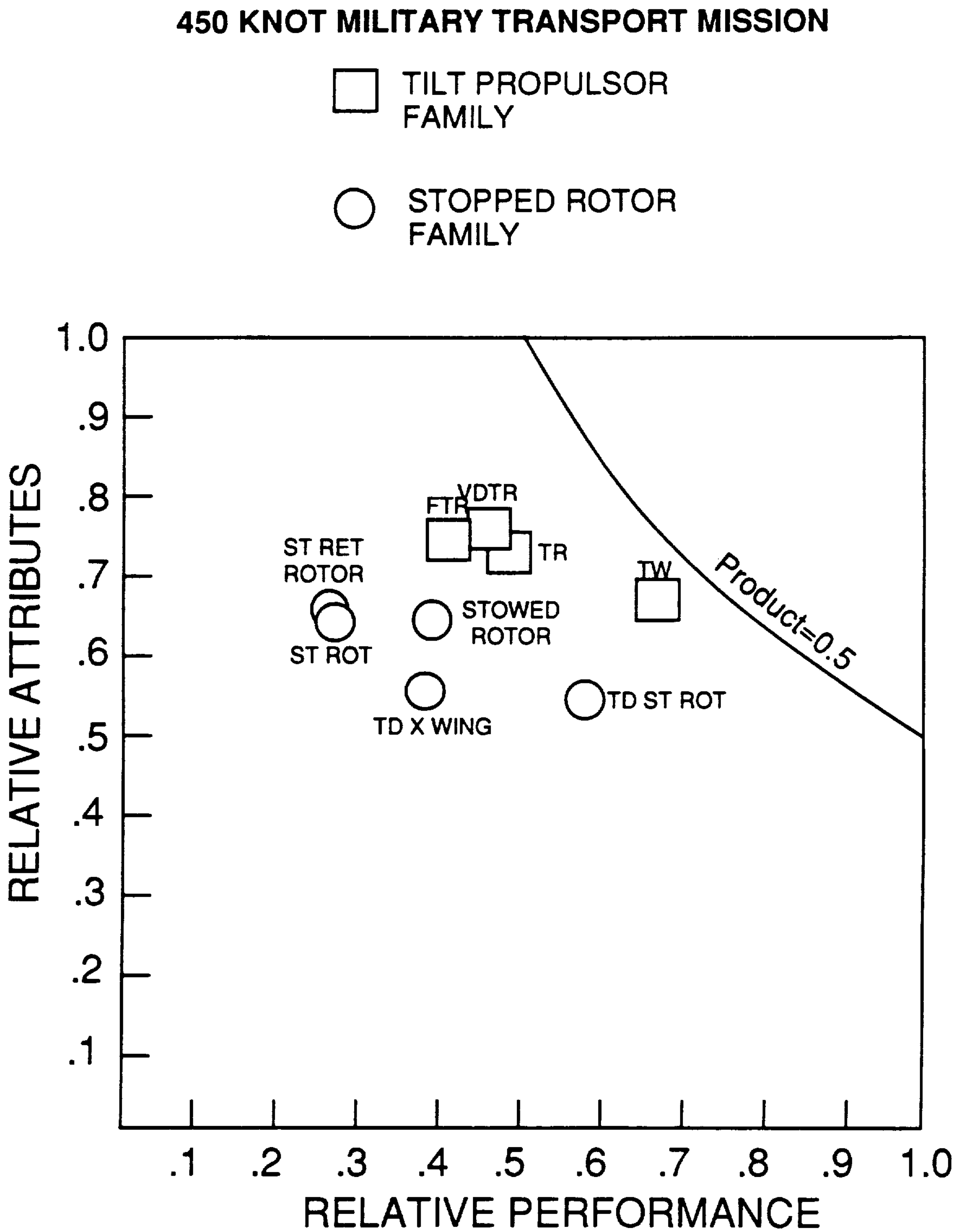

Figure 5. Relative attributes vs. relative performance

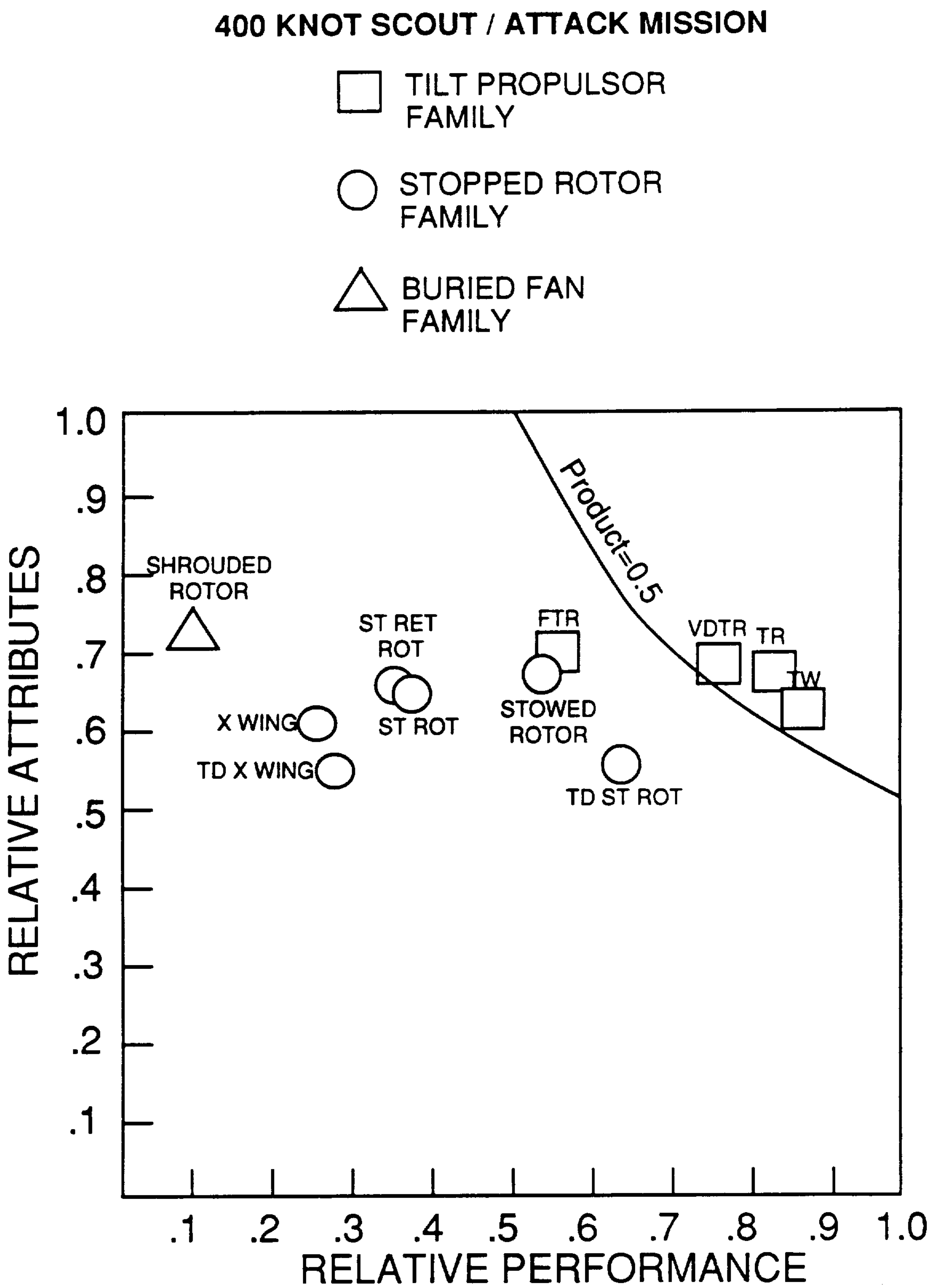

Figure 6. Relative attributes vs. relative performance

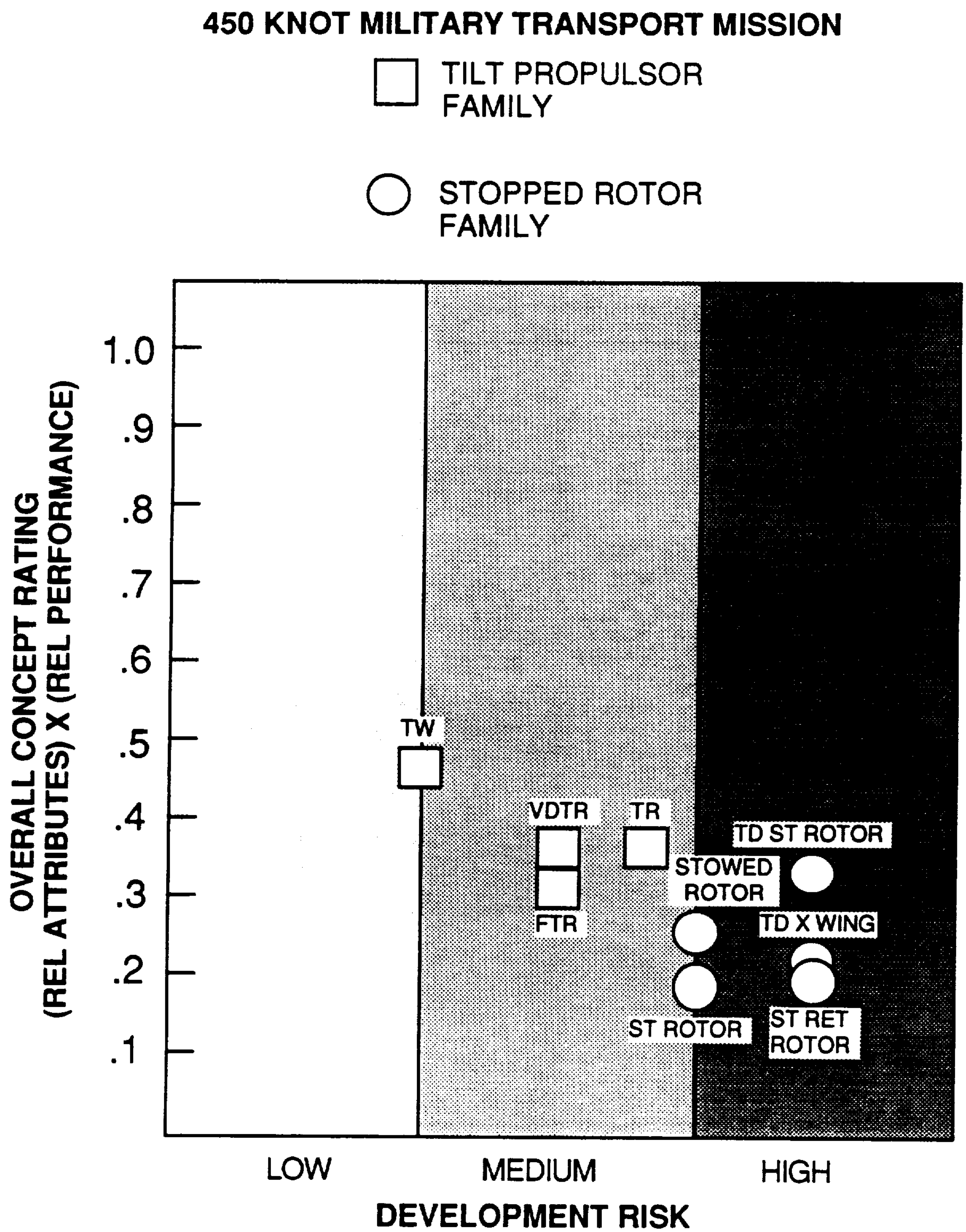

Figure 7. Overall concept rating vs. development risk

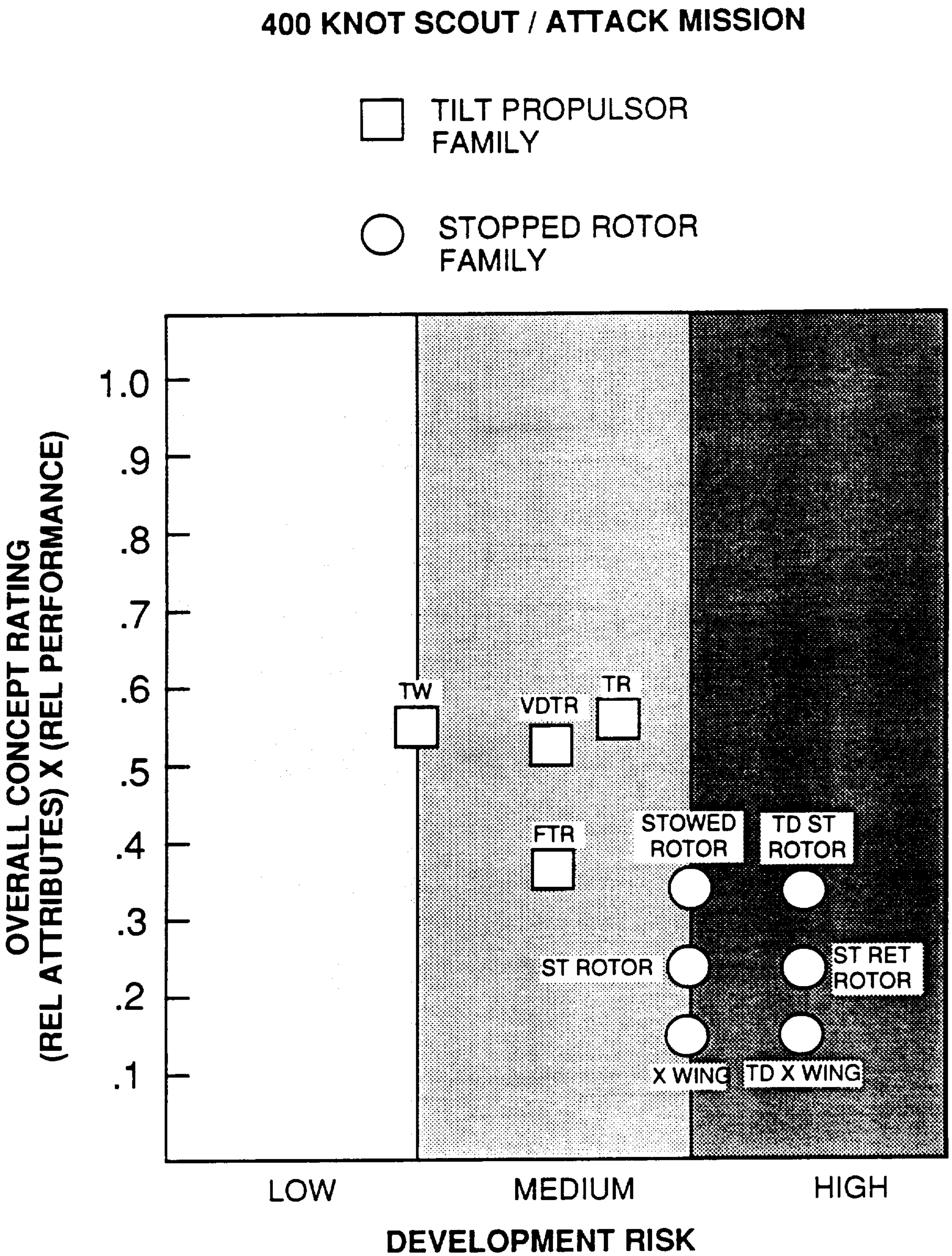

Figure 8. Overall concept rating vs development risk

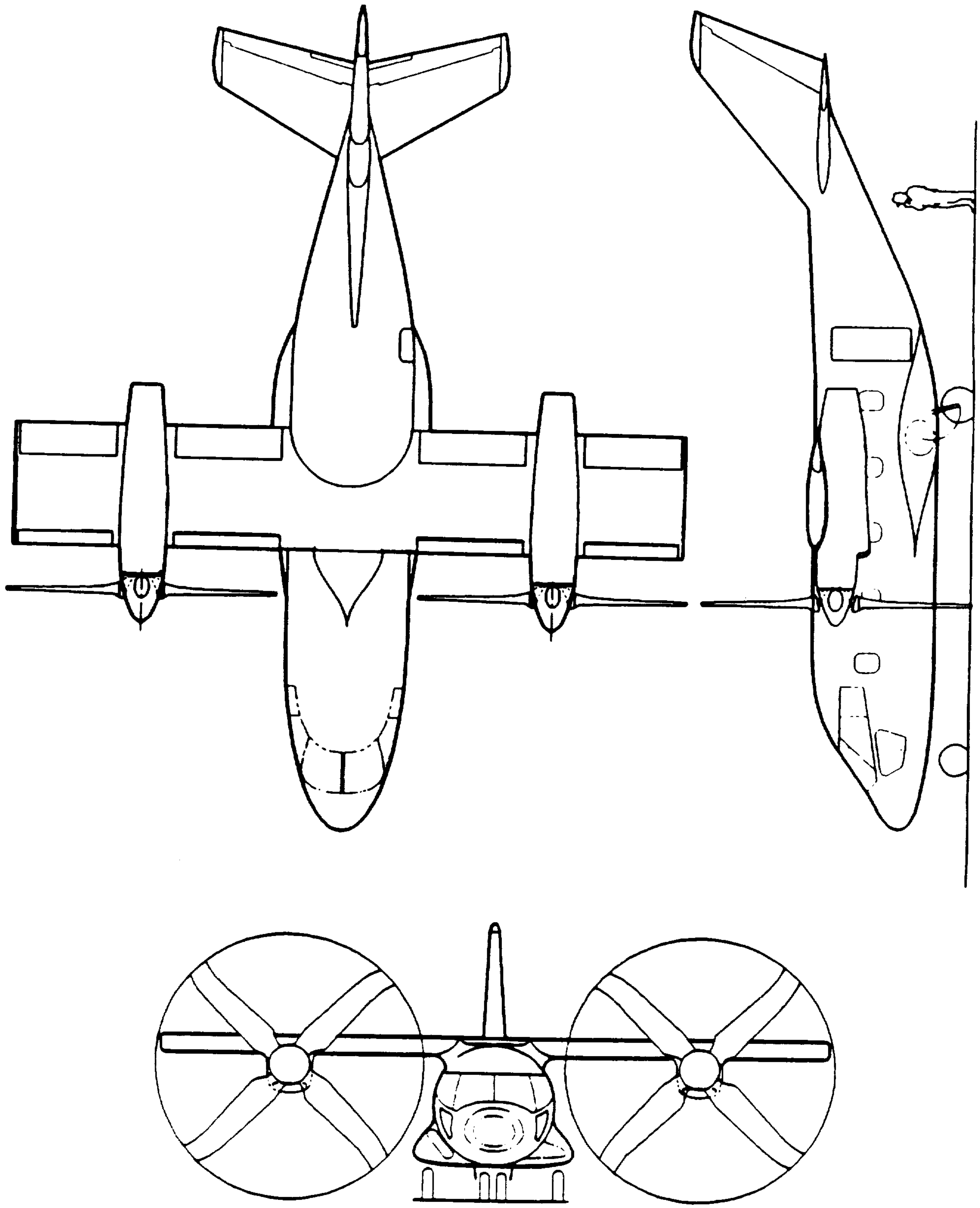

Figure 9. Tilt wing transport configuration

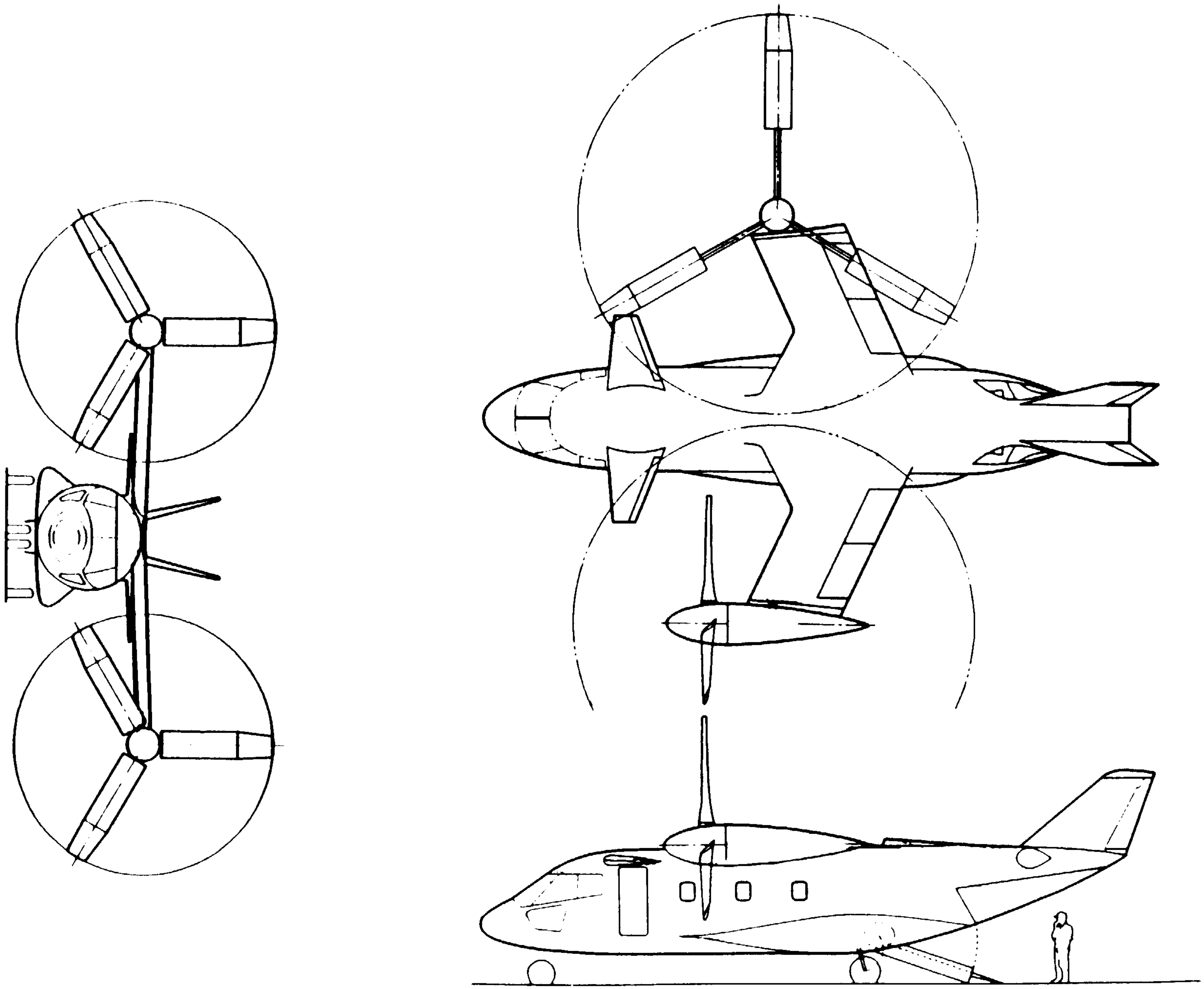

Figure 10. VDTR military transport configuration

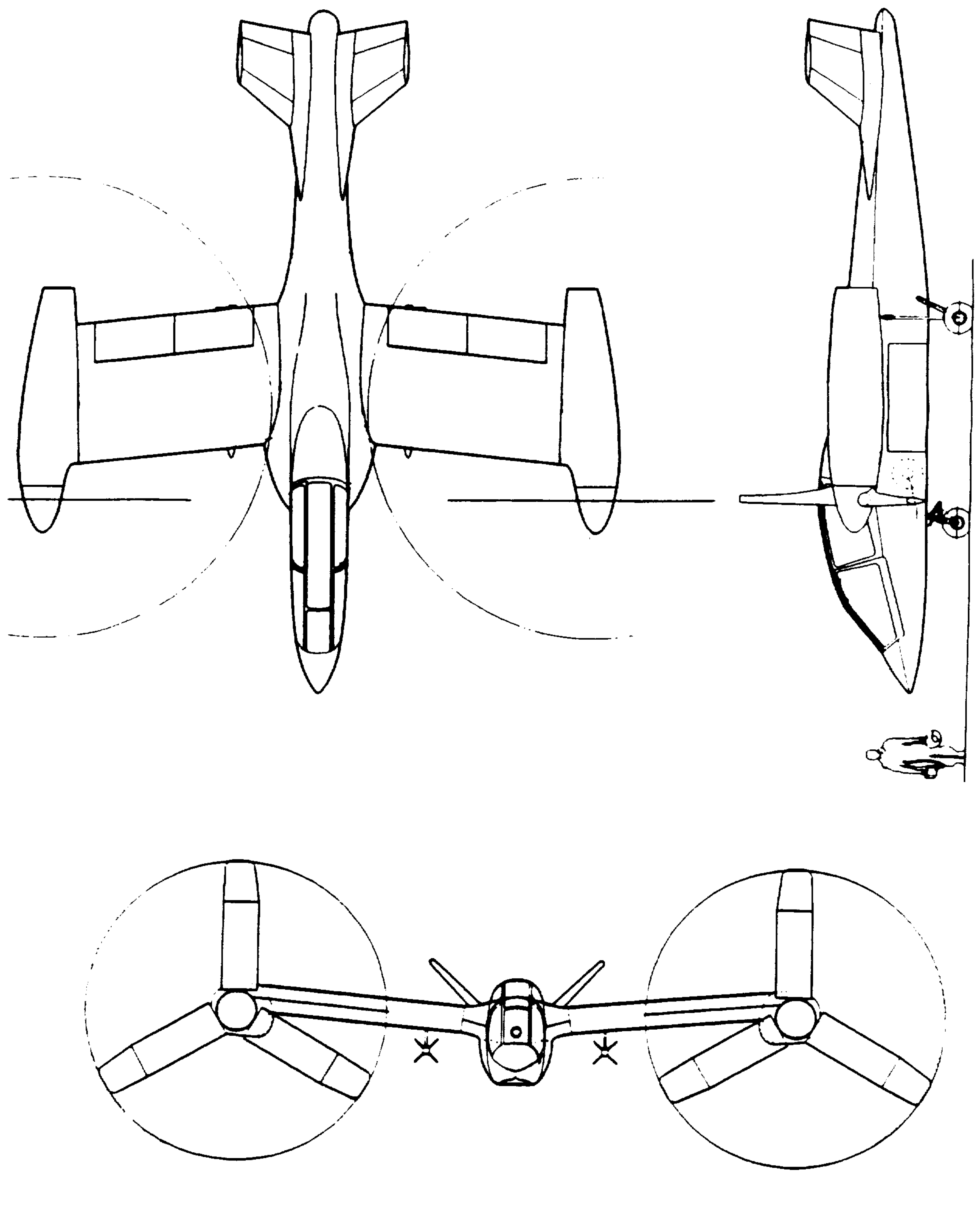

Figure 11. VDTR SCAT configuration

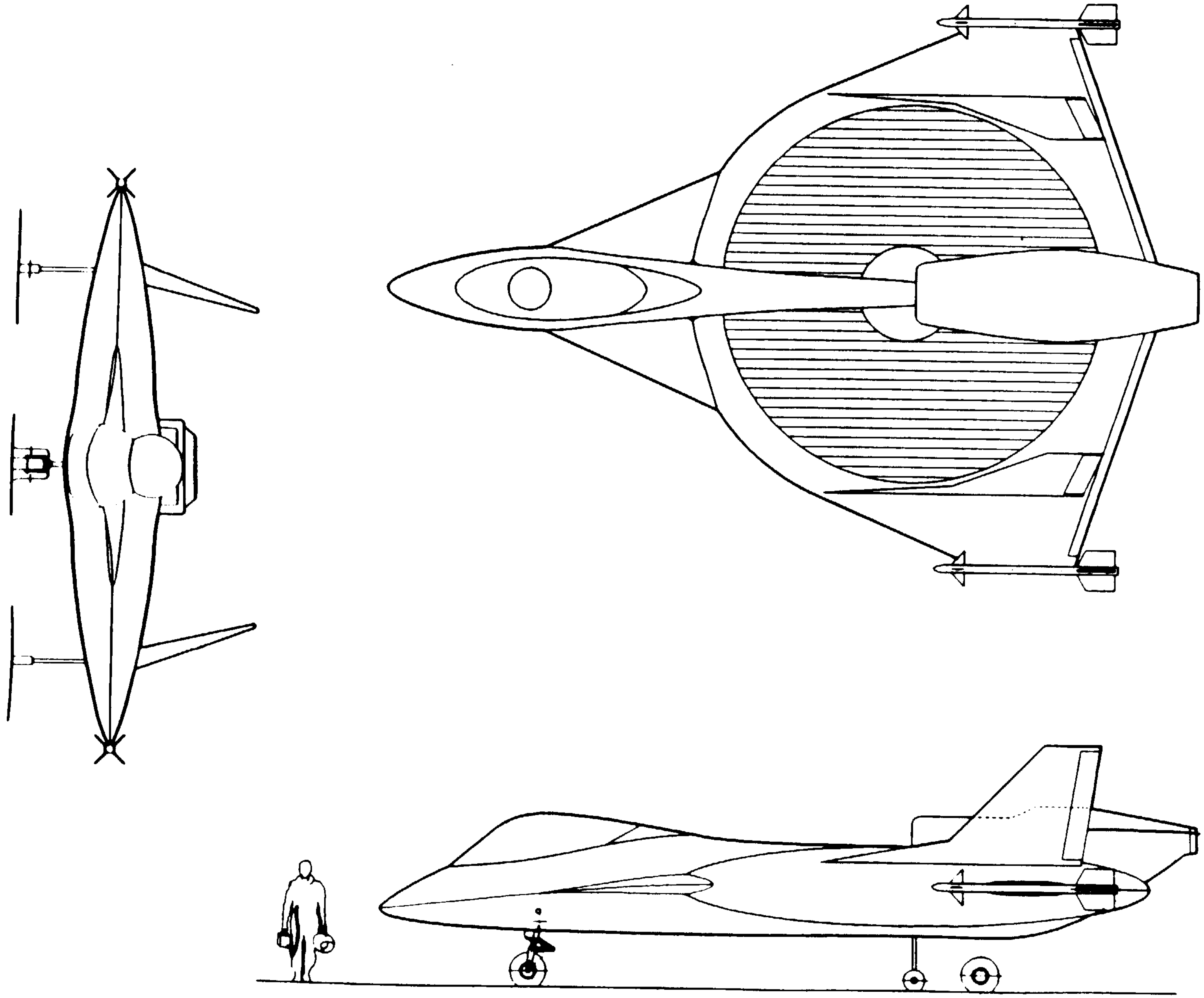
Figure 12. Shrouded rotor SCAT configuration

ENABLING TECHNOLOGIES

WEIGHT REDUCTION	Materials, structural analysis
ENGINES TRANSMISSIONS	Improved SFC, Hp/lb ratio Good pressure recovery High contingency ratings
DRAG REDUCTION	Low drag surface finishes Improved CFD analysis
FLIGHT CONTROLS	Fly by wire control systems
OBSERVABLES	Propeller RCS and noise reduction

Figure 13. Generic high speed rotorcraft technologies

☐ ENABLING TECHNOLOGIES

HIGH SPEED PROPROTORS Performance & Stability Variable Diameter System High Critical Mach Number Airfoils	TW, VDTR
FORWARD SWEPT WING DESIGN Stability at Minimum Weight	VDTR XPORT
GEARED FLAP CONTROL SYSTEM	TW
SPEED-DESCENT ENVELOPE EXPANSION	TW
WING SECTION DESIGN Thick Sections with High Critical Mach Numbers	TW, VDTR
VARIABLE RPM SYSTEM	TW
RCS, ACOUSTIC SIGNATURE REDUCTION	VDTR SCAT

Figure 14. Concept specific technologies

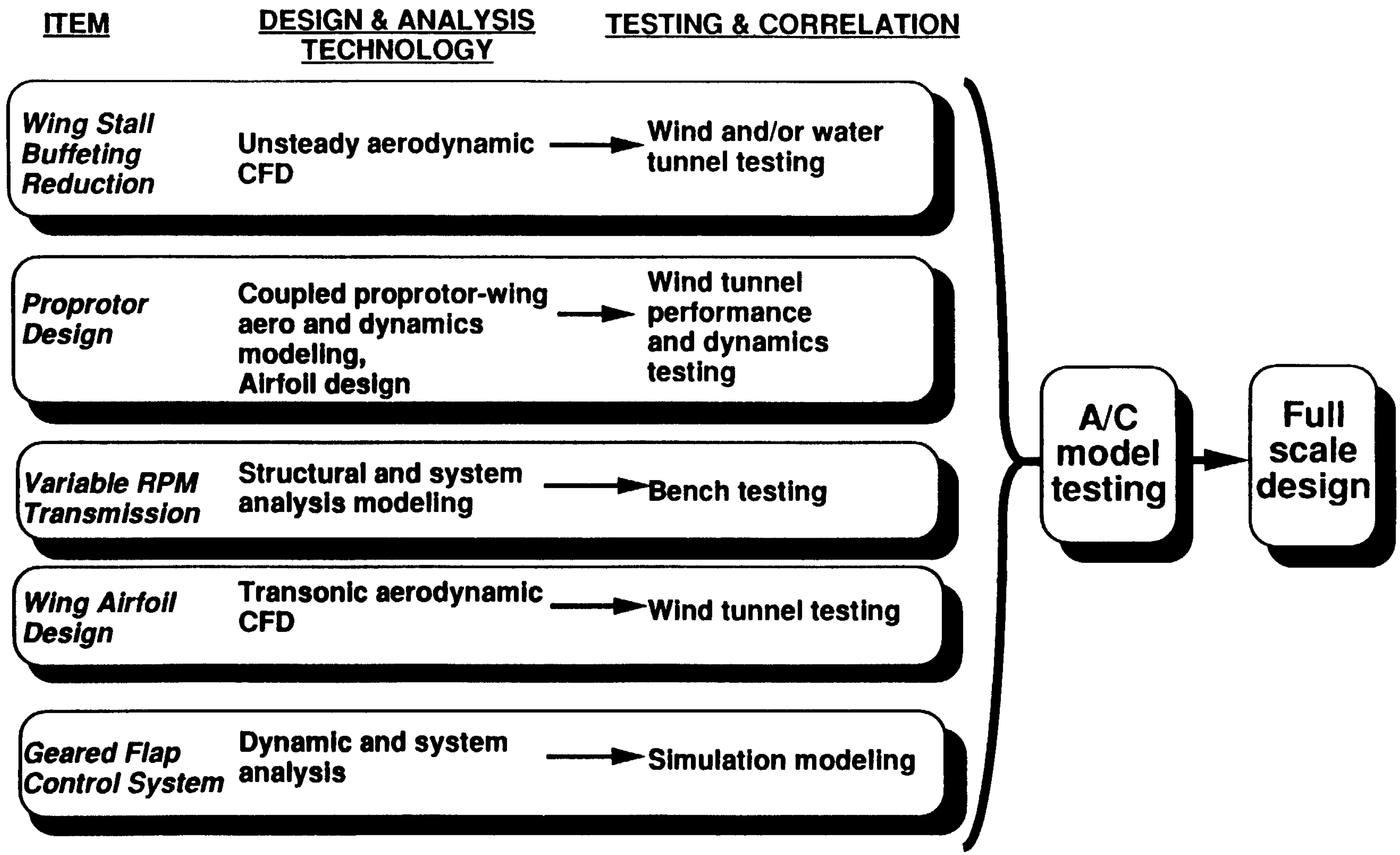

Figure 15. Development tasks to enable 450 kt tilt wing

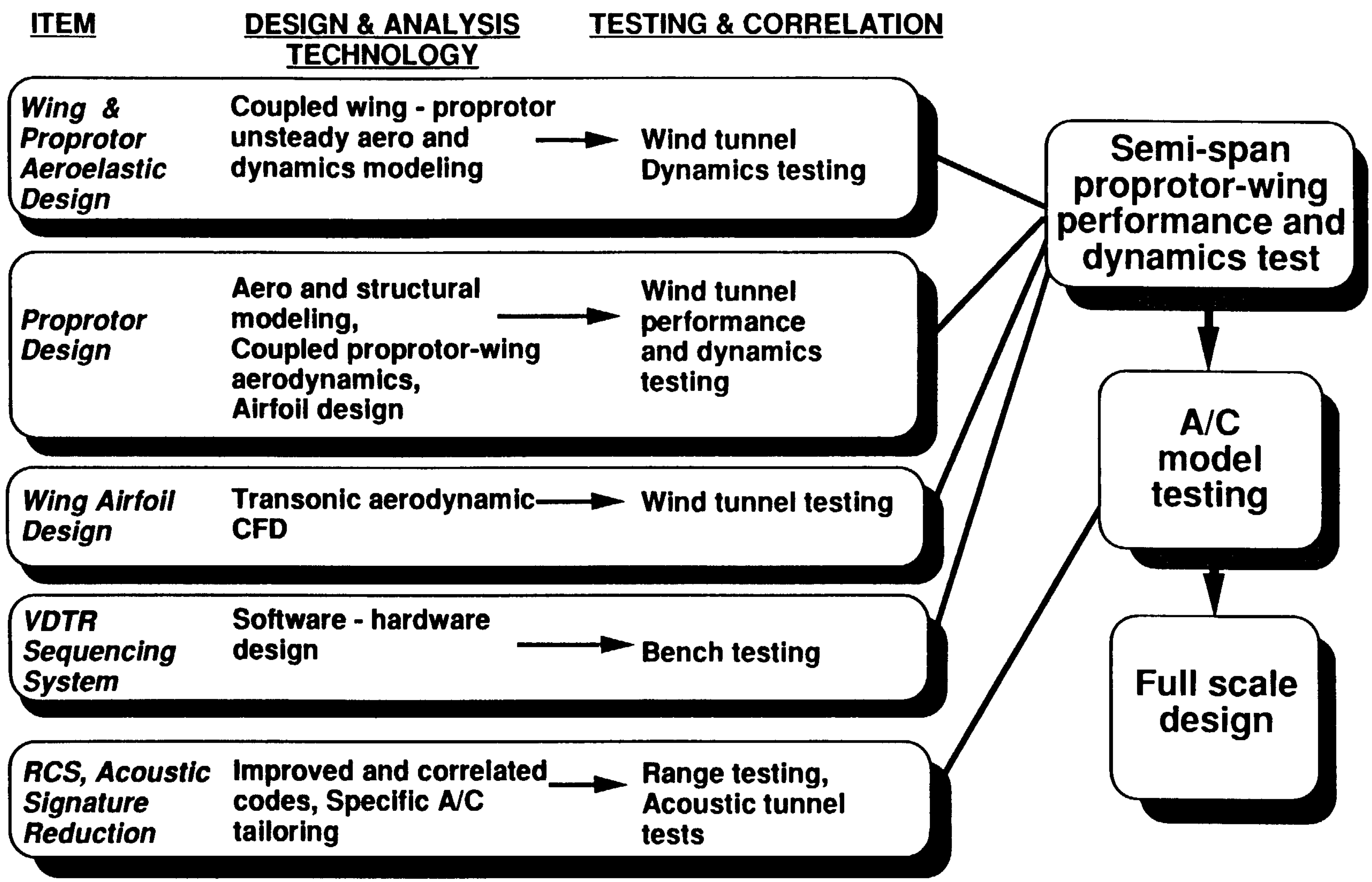

Figure 16. Development tasks to enable 400-450 kt VDTR

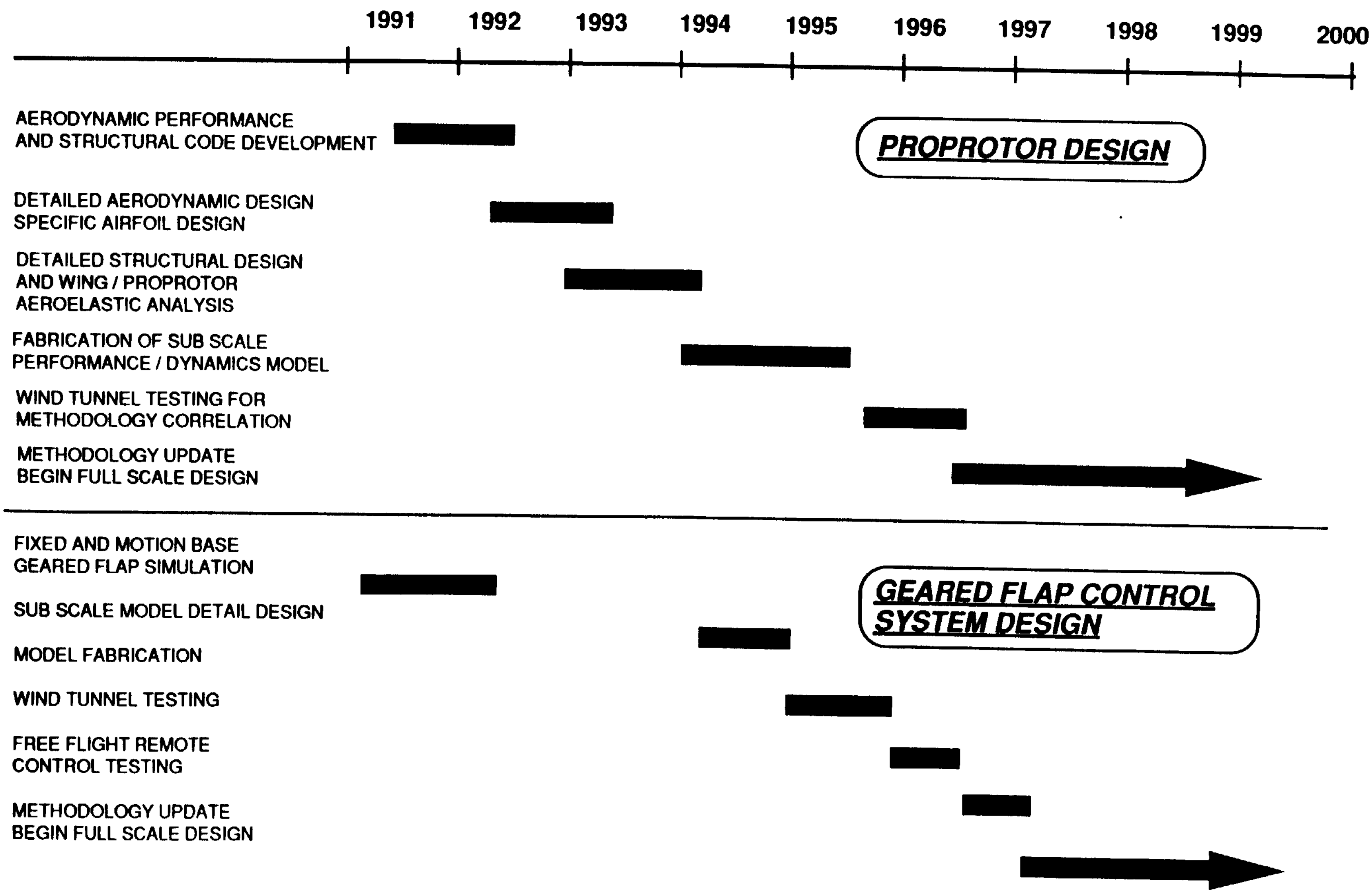

Figure 17. Technology development plan for 450 kt tilt wing

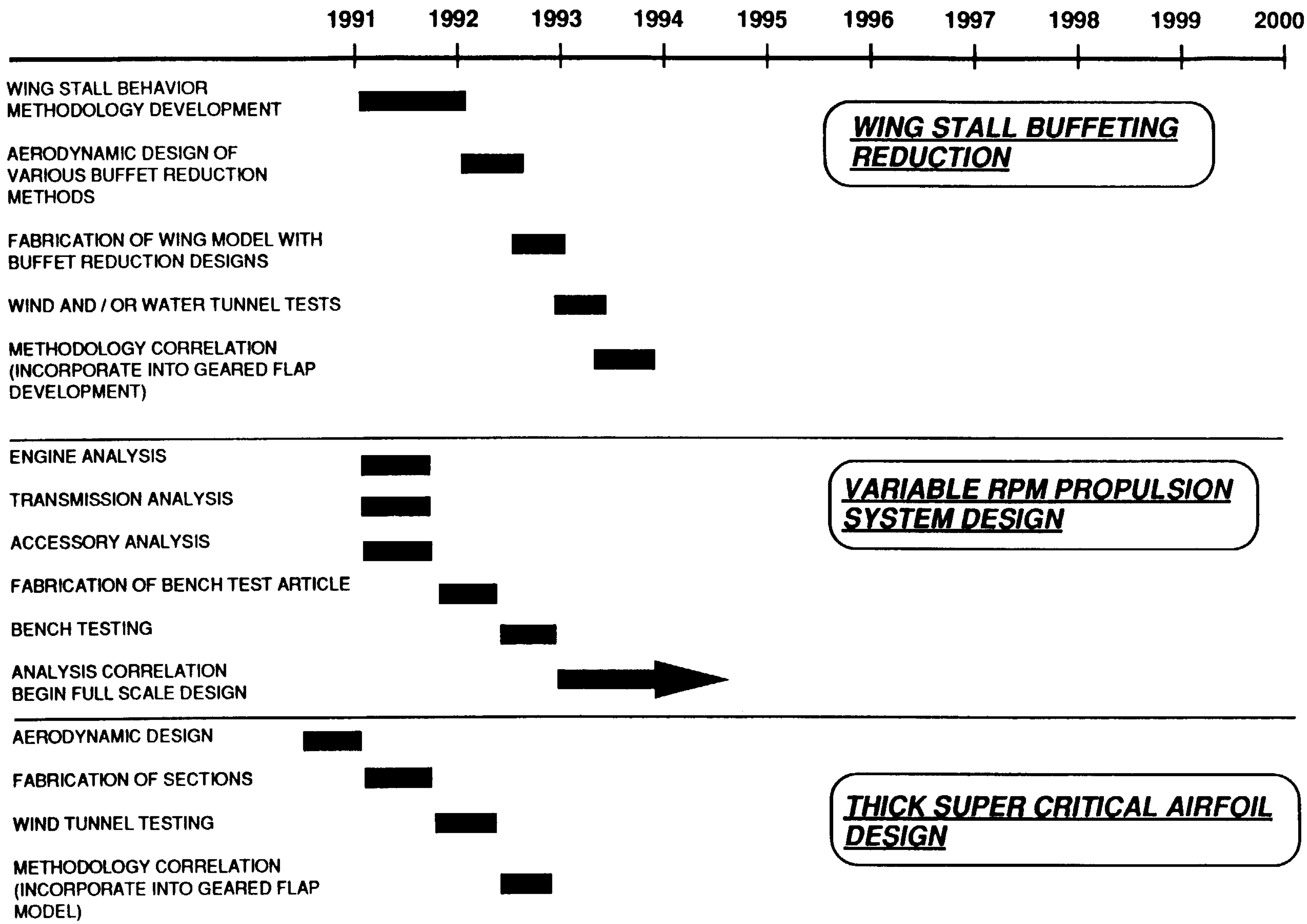

Figure 17. continued

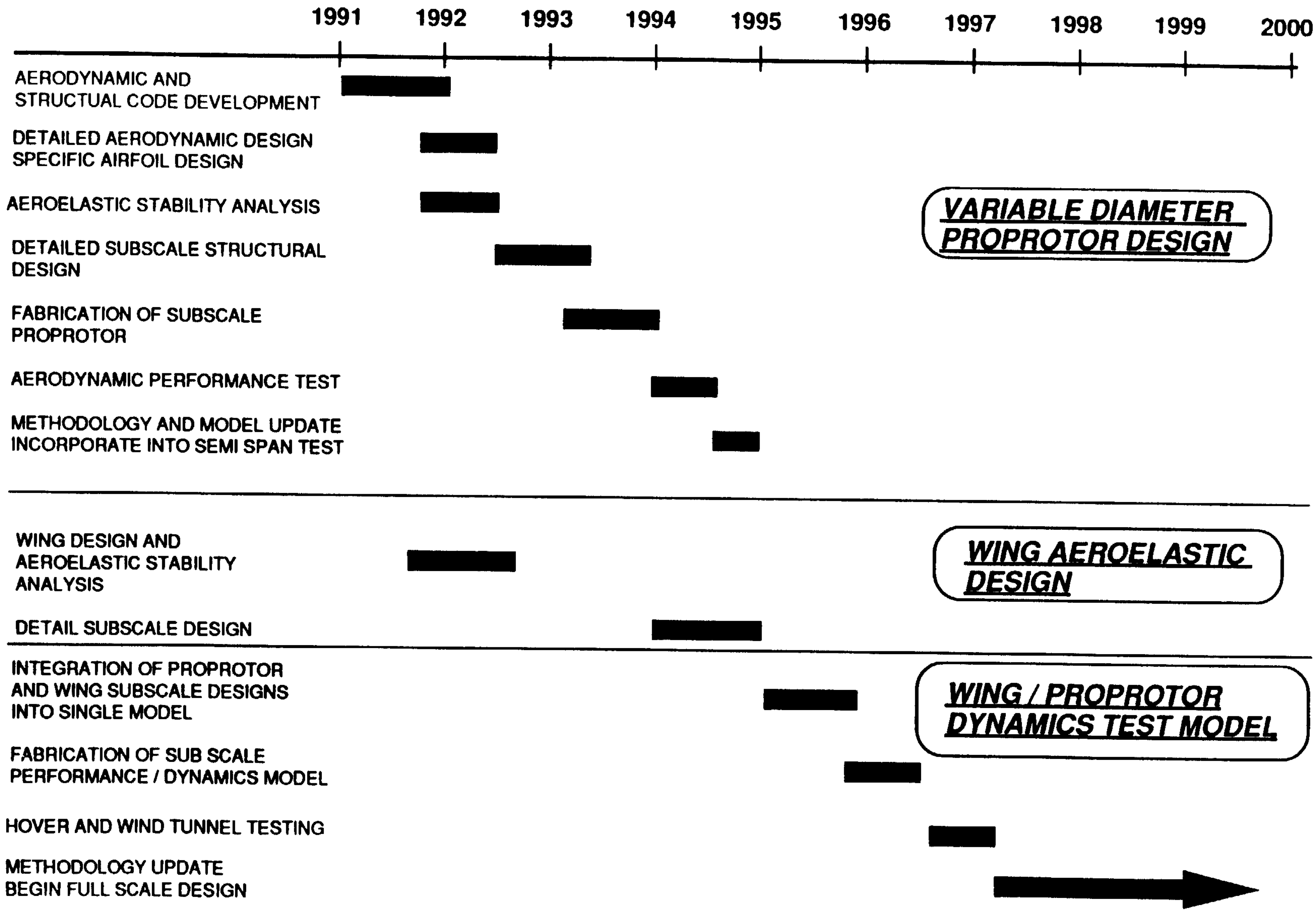

Figure 18. Technology development plan for 400-450 kt VDTR

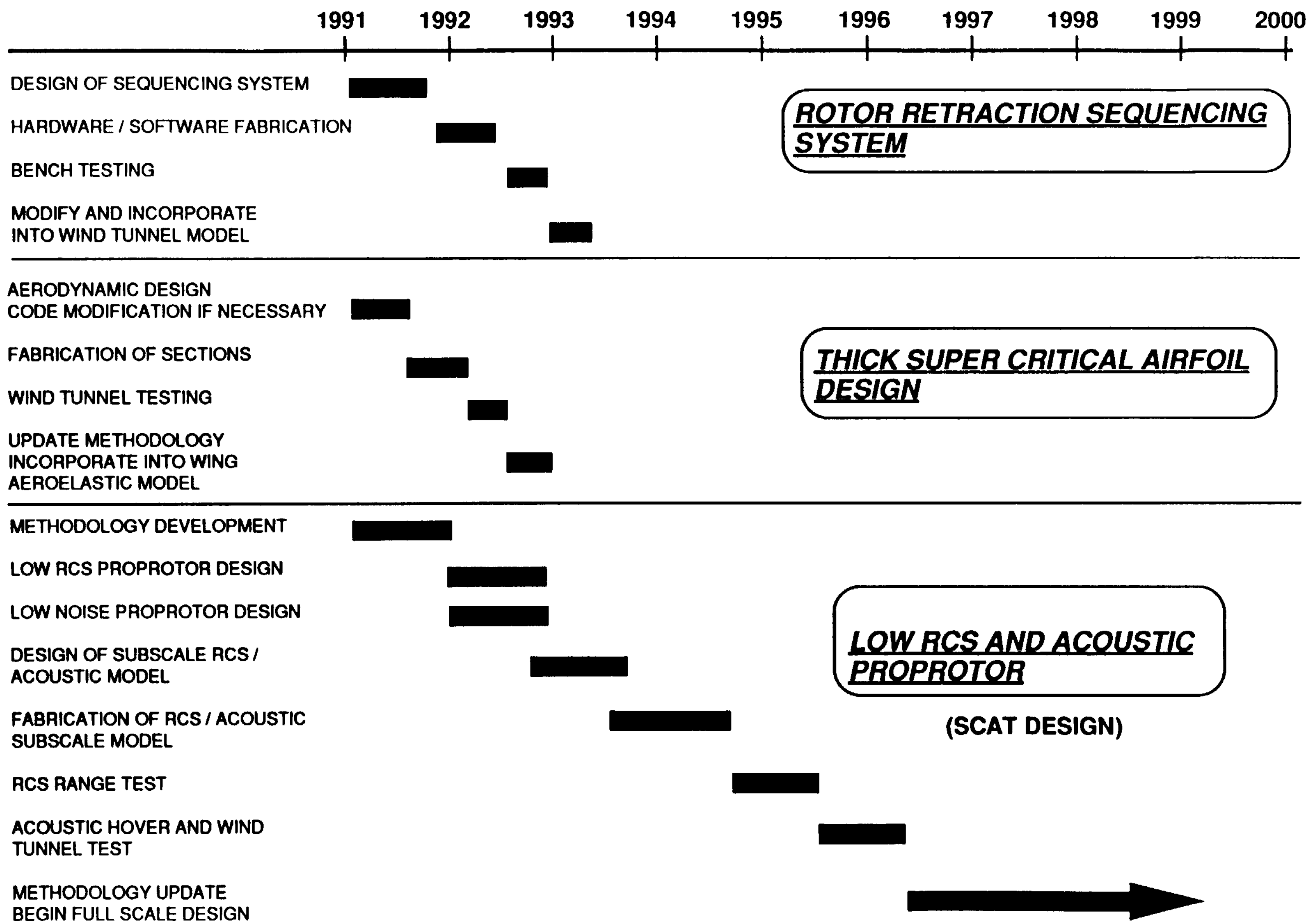

Figure 18. continued

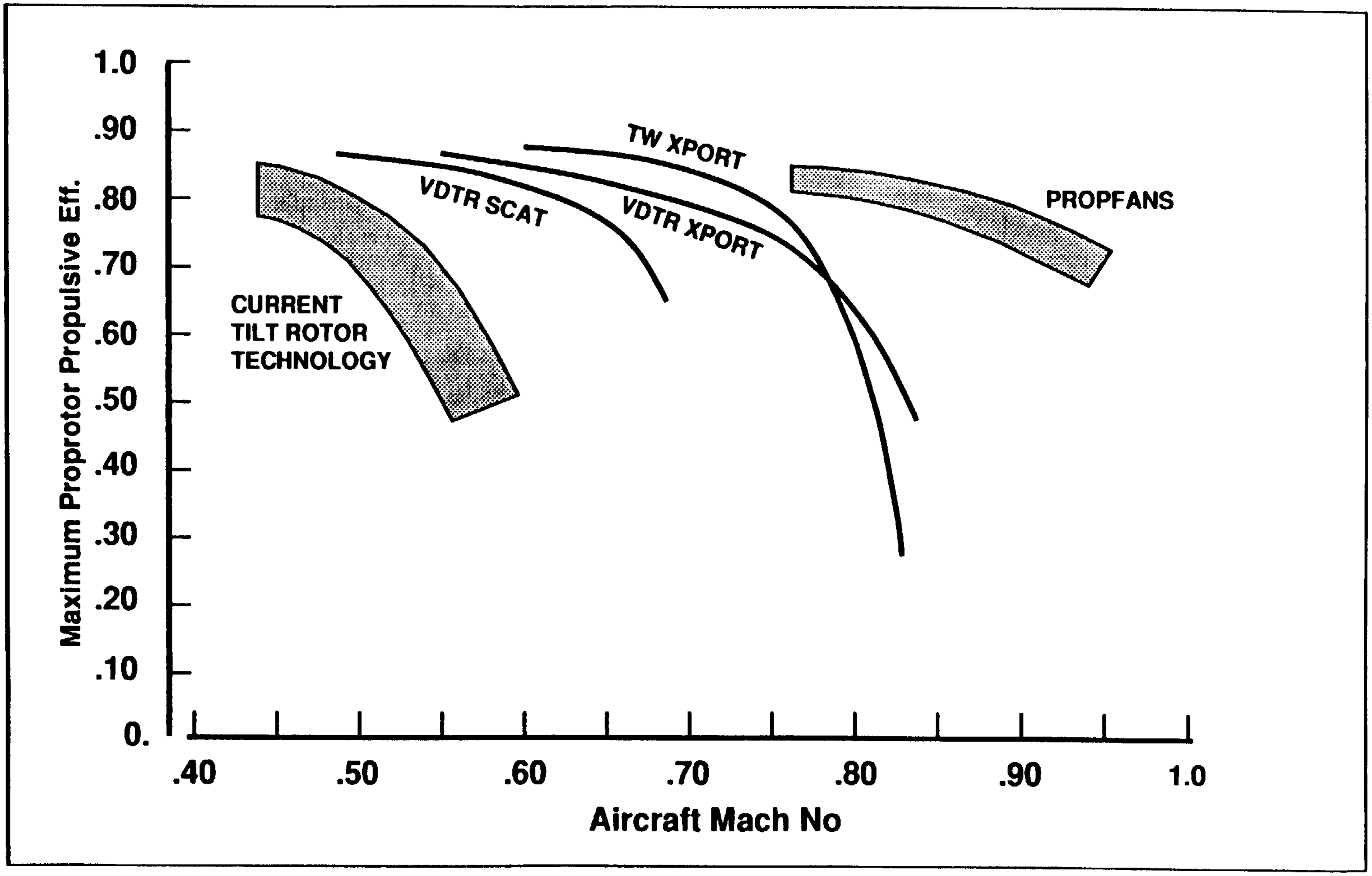

Figure 19. Proprotor maximum propulsive efficiency vs. flight Mach No.

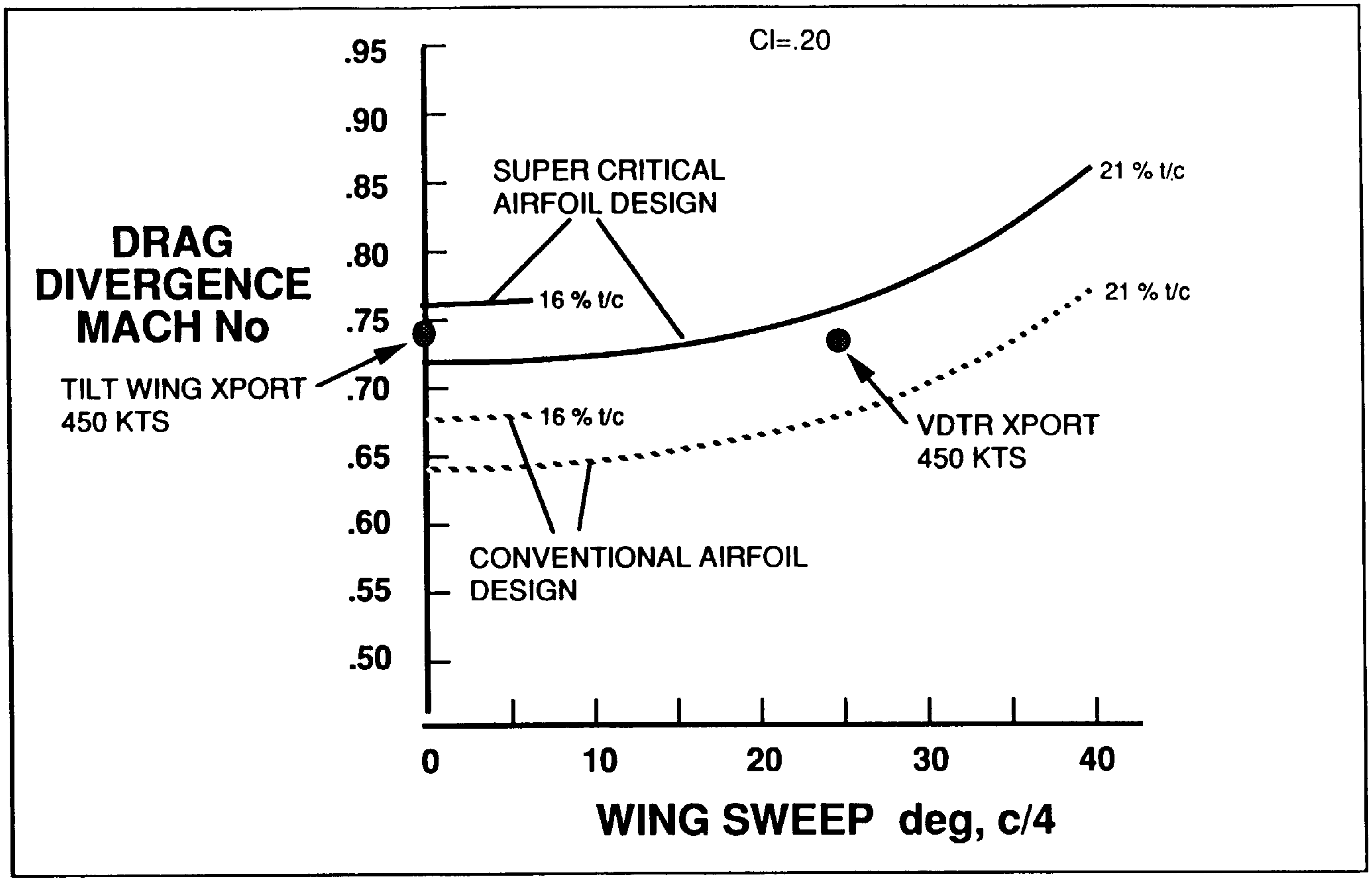

Figure 20. Drag divergence Mach No. vs. wing sweep

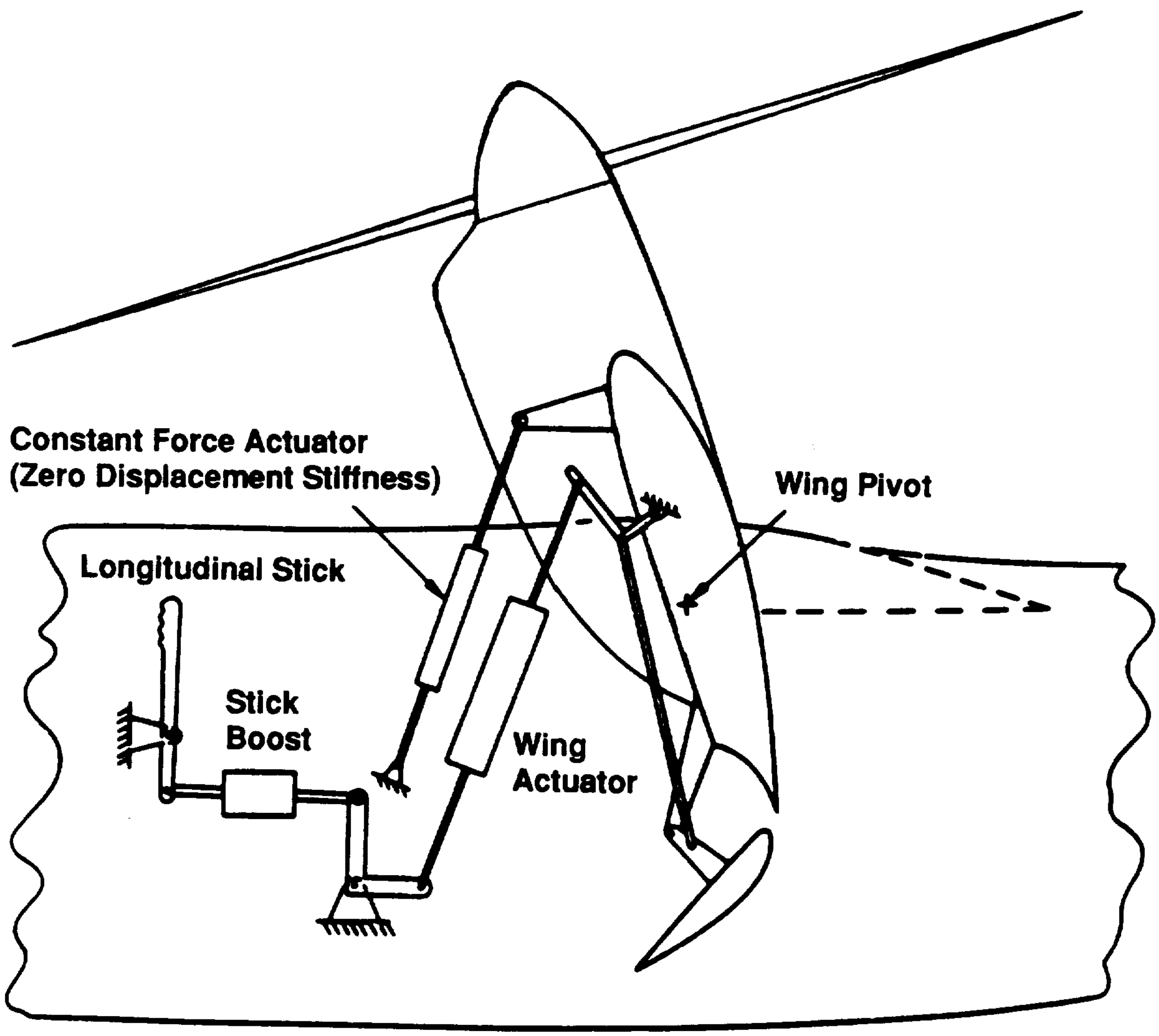

Figure 21. Schematic of geared flap control system

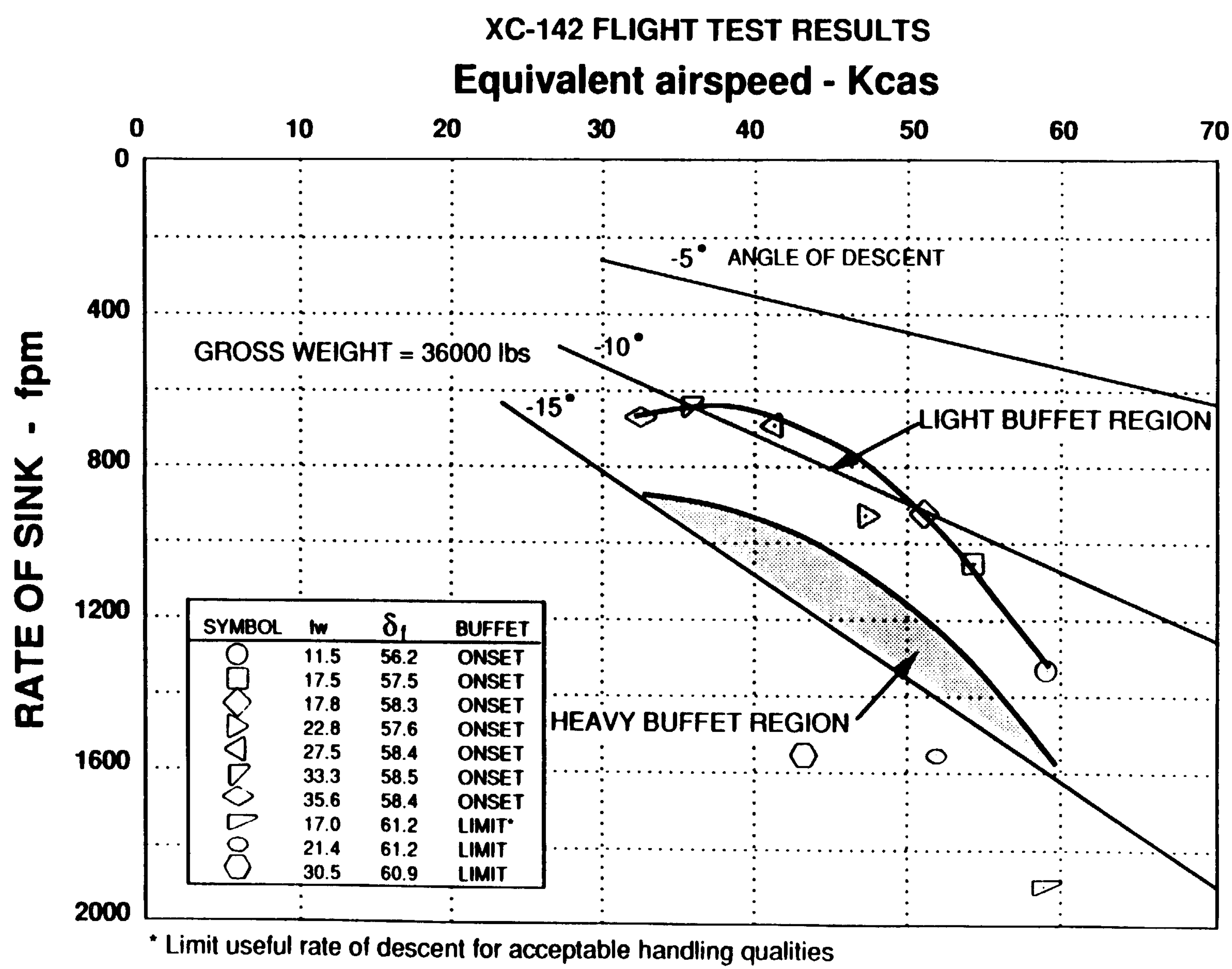

Figure 22. Speed-descent buffet boundaries

KEY FUNDAMENTAL AREAS OF TECHNOLOGY INVESTMENT REQUIRED TO ENABLE HIGH SPEED ROTORCRAFT

AREA	TECHNOLOGIES	APPLICATION
AERODYNAMICS	CFD ANALYSIS EXPERIMENTAL TECHNIQUES	PROPROTOR DESIGN AIRFOIL DESIGN BUFFET REDUCTION DRAG REDUCTION
STRUCTURES	MATERIALS LOADS ANALYSIS AEROELASTIC ANALYSIS	WE / GW FRACTION PROPROTOR DESIGN WING DESIGN
FLIGHT CONTROLS	FBW CONTROLS CONTROL LAWS	PRIMARY FLIGHT CONTROLS GEARED FLAP CONTROL

Figure 23. Fundamental technology summary

APPENDIX A

Task I Interim Report

Section 1. Introduction

The principle goal of this study is to identify technologies that have the most promise of enabling successful development of a useful 350 to 500 knot VTOL aircraft with "helicopter like" low speed and hovering qualities. To attain this goal the study has been broken down into three tasks as diagrammed in Figure A-1.

In Task I, high speed VTOL concepts and mission applications are reviewed in light of new technologies. The most attractive concepts are paired with sizing missions to be carried into Task II for further study. The efforts in Task II will concentrate on refinement of these designs for their respective missions. Specific technology requirements will be identified. Task III will develop an enabling technology plan for these technologies. This plan will outline the respective efforts and facilities required for technology development to a point of application in the year 2000.
Task I was an eight month effort. The fundamental elements of Task I are listed on the right side of Figure A-1.

Section 2. High Speed Rotorcraft, Historical Perspective

Many attempts have been made in the past to combine the desirable low speed and hovering qualities of the helicopter with the high speed and efficiency of the airplane. A few of these are illustrated in Figure A-2. These attempts have had varying degrees of success. High speed VTOL aircraft can be categorized as illustrated in Figure A-3. In general, this categorization is a function of the relative diameter of the thrust-producing device(s) and the means by which vertical thrust is converted into forward thrust. Within this matrix, Figure 4 lists the more notable examples of each configuration. In addition to this, some promising new or unflown configurations are listed in Figure A-5.

In general, all of these aircraft suffer from the same affliction. The combined requirements of hover and high speed flight necessitate significant performance and design compromises. The result is a degradation in both the desired low speed helicopter qualities and high speed aircraft qualities and performance to a point of impracticality. The primary difficulties encountered in high speed VTOL design are:

Low payload fraction, primarily due to high empty weight fraction.

Increased complexity to perform a conversion between low speed and high speed flight.

Degraded helicopter qualities primarily due to high disk loading and control system compromises.

The illusive goal of a practical 350 to 500 knot rotorcraft becomes ever closer as technology improves. Materials, engines, flight controls, aerodynamics and a host of other technologies have greatly improved over the last five decades since the helicopter first flew. The synergistic interaction of these technologies applied to an inherently viable concept for a mission that values both high speed and VTOL efficient capability may result in a successful flight vehicle.

Section 3. Fundamental Effects of High Speed Requirements on Aircraft Design

A high speed requirement significantly affects aircraft design, regardless of whether it is a rotary or fixed wing vehicle. Generally, a high speed requirement manifests itself into a larger vehicle to do the same mission. A review of fixed wing empty weight fractions as a function of design cruise speed reveals two prevalent trends. One, most successful transport aircraft have an empty weight fraction between 0.45 and 0.60 with a few as high as 0.65. Two, size plays an important role in offsetting the weight penalty associated with increased speed. Figure A-6 is a plot of the empty weight fraction of various transport aircraft as a function of speed. Gross weight trend lines were identified and are superimposed as shown. The weight effect appears to be logarithmic in nature.

Fighter attack aircraft are plotted in the same manner in Figure A-7. Successful aircraft of this type that weigh less than 100,000 pounds generally had a higher empty weight fraction, between 0.60 and 0.73. The size effect is found to be more pronounced between the 10,000 and 100,000 pound gross weight trend lines than for the transport aircraft. Overall, these trends indicate that a larger, fighter-type high speed rotorcraft may be the most practical in terms of meeting performance goals.

Among past high speed VTOL aircraft there is a recognized trend of increased hover disk loading as design cruise speed is increased. Helicopters are approximately 150 knot vehicles and have disk loadings on the order of 8 to 14 pounds per square foot (psf). The AV-8B at the other end of the spectrum can fly over 500 knots and has a hover disk loading over 1000 psf. Both are successful designs in part because the installed power is matched to both the design hover and cruise conditions. For a given takeoff criterion if there is excess installed power in hover, then the hover lift device is oversized and imposes penalties terms of weight, complexity and high speed performance. As the installed power increases to fulfill a high speed requirement, the higher the disk loading becomes for an efficient design.

A simple numerical example illustrates this trend as a function of speed, size and design conditions. Equations 1 and 2 relate familiar performance parameters to the installed power required for cruise and hover respectively. The lapse rate effect is taken as being proportional to the density ratio.

CRUISE $$HP_{inst} = 1/2\, \rho_{FF} V^3 Cf(GW^{2/3})(1/\eta_p)(1/550)(\rho/\rho_{FF})K_{RAM} \quad (1)$$

$$K_{RAM} = f(\text{Mach No.})$$

HOVER $$HP_{inst} = \frac{GW\sqrt{DL}}{550\, FM_{A/C}\sqrt{2\rho_H}}(\rho/\rho_H) \quad (2)$$

By equating the cruise and hover powers, one can find the disk loading required for an installed power match. Figure A-8 illustrates the relationship between speed and size for two sets of design conditions. For the given nominal values of aircraft hover figure of merit, drag coefficient and propulsive efficiency, one can see that most of the resultant disk loadings are much greater than typical helicopters. There is a sharp increase in disk loading as design speed increases, and a notable decrease as the aircraft becomes larger.

"Helicopter like" qualities necessitate a downwash environment that does not severely impair personnel operations around the aircraft or cause excessive damage to the ground surface. Disk loading limitations based on these criteria cannot be calculated in an exacting manner. In an effort to establish limits, References 1 through 6 were consulted. Based on the test results and conclusions in these reports, the limits listed in Table A-1 were established. Personnel mobility limits are fundamentally a function of the force and overturning moment on the body. These values are a function of disk loading, gross weight, number of rotors and orientation.

Surface failure is a function of downwash velocity, which is directly related to disk loading. Surface failure occurs at different velocities for different surfaces. Figure A-9 is taken from Reference 3. It was found to be generally representative of the surface failure results of References 1 through 6. Surfaces that could be termed as loose, such as sand, water spray and crushed rock, start to fail at disk loadings greater than 15 psf.

Firm surfaces, such as sod, hard pocked dirt and prepared surfaces are very resistant to failure. In between, "semi loose" surfaces such as wet sand and particularly wet dirt have broad ranges of failure. Judgment based on this data led to the imposed limits shown in Table A-1.

Given the results presented in Figure A-8 and the disk loading limits of Table A-1, high speed rotorcraft designs may well be overpowered in hover in order to maintain an acceptable disk loading.

Section 4. Task I Mission-Concept Pair Selection Process

The realm of aviation encompasses a vast number of aircraft and missions. At this time there are no successful 350-500 knot rotorcraft and no specifically identified missions for them. In an effort to identify what kind of missions a high speed rotorcraft attractively fulfills and to identify what concepts do this most effectively, an analysis framework leading to mission-concept selection was developed. This approach, shown in Figure A-10 converges separately from a mission side and a concept side.

Mission selection starts in block one with a summary of rotary and fixed wing missions. Those that value both high speed and VTOL capability are chosen and grouped into generic profiles to be used for concept sizing. Operational attributes such as noise, vibration, and maneuverability are defined and rated as to their importance for each specific mission.

Concept selection in block two starts with a summary of past, present and potential future VTOL concepts. On a qualitative basis concepts are selected that appear to have 350 to 500 knot capability and helicopter like qualities. These selected concepts are then rated for the same attributes defined for the missions. The detailed progression of the elements contained within each block are covered in sections 5 and 6.

Mission concept pairing is performed on the basis of two independent selection criteria in block 3, based on attributes, and the other based on performance. The results are combined, evaluated and the most attractive mission concept pairs are chosen for further study in Task II.

Section 5. Mission Selection

The only missions that a high speed rotorcraft will compete successfully for are those that place high value on both high speed and efficient VTOL capability. If high speed is not necessary, a helicopter will usually be the most cost effective solution. If a runway is available an airplane or STOL type aircraft will be used. The price for high speed and VTOL is not cheap so strong requirements for both must be present.

To identify potential high speed rotorcraft missions existing rotary wing, fixed wing, and civil missions were identified. From this list, missions that value high speed and VTOL capability were grouped into generic mission sizing profiles. Figures A-11, A-12, and A-13 diagram this process. As can be seen there is a lot of overlap in general mission requirements, and five generic mission profiles were identified. Three of these, military transport, scout attack, and civil transport are the NASA designated missions. Two additional distinct profiles were seen as having high value for both high speed and VTOL capability. These are the Navy dipping sonar ASW mission and the special operations forces (SOF) mission.

An Outer zone anti-submarine warfare mission appears to be a good candidate for a high speed rotorcraft. Currently the U.S. Navy performs this mission with P-3 Orions and S-3 Vikings from land and carrier based stations. This mission requires long ranges and endurance. Both these aircraft go into a loiter mode of operation as sonobuoys are dropped on station. Both aircraft are capable of attack as well with an assortment of torpedoes and depth charges. Helicopter dipping sonar ASW operations are limited to what is called the inner zone, within approximately 50 nm radius from the carrier group. Dipping sonar is a more sensitive means of submarine detection than sonobuoys. Sikorsky specialists in ASW indicated that high speed would be quite valuable for dipping sonar missions. Increased probability of detection would be roughly proportional to the speed increase. In hostile waters dipping sonar helicopters sweep in front of the carrier battle group as it travels. If a rotorcraft could reach each dipping point in less time, the area ahead of the group could be swept faster and allow greater steaming speeds for the carrier group. In the future, the use of dipping sonar is expected to increase due to the ever quieter submarines being launched. For these reasons a long range endurance ASW mission appears attractive for a high speed rotorcraft.

The SOF mission is similar to a military transport mission but places even higher value on speed and VTOL capability. The primary differences are the mission range and cruise ambients. A SOF mission requirement typically involves a long radius of action of about 500 nm conducted at relatively low density altitudes (compared to fixed wing operation), typically 4000 ft, 95 deg F. Because these differences are significant enough to possibly require a different aircraft concept than the military transport, this mission is chosen as a fifth generic profile. A detailed description of the five missions is provided in Table A-2.

For sizing and performance evaluation of concepts, the five generic missions are adequate. However, the attractiveness of a concept is not only a function of performance, but also of its operational attributes. Table A-3 lists what attributes were determined to be most important to the range of missions considered. These attributes differ not only for each generic mission profile, but also for each specified mission.

Mission attributes rating was performed for fourteen specific missions. Each attribute was rated for each mission on a scale of zero to three; zero for unimportant or no requirement, three for critical to mission success. The final rating matrix in Figure A-14 is the averaged result of a consensus of individuals with design, operational analysis, and flight experience.

Section 6. Initial Selection of Candidate Concepts

The concepts selected for Task II analysis were arrived at by a process of elimination, first by a qualitative screening, and then on the quantitative basis discussed in section 8. This filtering process is diagrammed in Figure A-15. Starting with the matrix of high speed VTOL concepts illustrated in Figure A-3, each configuration that lacked the inherent "rotorcraft like" attributes discussed in section 1 was eliminated.

The right hand column of Figure A-3 represents all direct lift concepts. A number of these have been built and tested the most successful of which is the Harrier and the improved version, the AV-8B Harrier II. This is the only high speed VTOL aircraft in production today.

Unfortunately, direct lift vehicles are not at all suited for extended low speed operation. These concepts have severe downwash environments. The temperature and velocity of the exhaust can exceed 1200 deg F and 1800 fps. This is not consistent with the desired soft footprint requirements of this study. In addition, the noise levels of direct lift aircraft greatly exceed the damaging sound pressure levels for unprotected personnel near the aircraft. Low speed control power and handling qualities are also inherently poor as compared to rotorcraft. For these reasons, this concept was eliminated from further investigation in this study.

The top row of Figure A-3 represents all concepts that tilt the entire aircraft forward to develop propulsive force. Even though the helicopter has cyclic flapping the aircraft is basically of this type. The helicopter's top speed is limited by a number of factors: compressibility, retreating blade stall, and high drag. For decades, designers have attempted to achieve speeds over 200 knots with pure helicopters without much success and it appears they will always be limited to speeds less than about 200 knots. Helicopters with auxiliary propulsion can attain higher speeds; however, this is a double propulsion concept which is categorized separately.

Tail sitter aircraft using propellers or duct fans have been flown. The Convair XFY-1 and locked XFV-1 Pogo were found to behave adequately as airplanes, but very poorly as VTOLs. These aircraft were designed to enable VTOL capability but not for extended low speed operation. The most obvious low speed compromise made is the very unnatural reclined position of the pilot in hover and transition. This characteristic is obviously unacceptable with respect to the concept attributes sought in this study. For these reasons, concepts summarized in the top row of Figure A-3 were also eliminated from further study. This leaves nine candidates configurations to be looked at individually.

The double propulsion propeller configuration has no practical benefit. With a propulsion device the size of a propeller it is much more efficient aerodynamically and structurally to tilt it than to have one as a lifting device and another as a propulsive device. There are no known examples of such a configuration.

The deflected duct thrust is an unusual configuration of which there are few examples. The most noteworthy example is the Piasecki Ring Wing, which is comprised of two large diameter duct fans attached to a conventional fuselage. The diameter of the ducts were slightly larger than the fuselage height. This configuration has a couple of significant deficiencies that make it rather unattractive. Low hovering efficiency can be expected due to relatively high disk loading and large turning losses. The inherent control power of this arrangement is also poor.

The remaining two deflected thrust configurations, the deflected rotor and deflected propeller systems, appear to be ill suited to the desired goals of the study for similar reasons. The Ryan VZ-3 and Fairchild VZ-5 are examples of these configurations. They both were significantly lacking in low speed qualities. The 90-degree aerodynamic turning efficiency of a wing is poor. The VZ-3 was a 2600 pounds aircraft with 1000 installed horsepower. Even at a gross weight to horsepower ratio of 2.6:1 it could barely hover. Helicopters and tilt rotors typically have gross weight to horsepower ratios of 7.5 and 5.5 respectively. From a complexity standpoint, this concept is probably no simpler than a tilting concept, and has no noteworthy performance benefits in hover or forward flight.

There have not been any successfully flown deflected prop rotor concepts. However, Kaman proposed and wind tunnel tested such a concept. The Kaman K-16B was actually a hybrid of a deflected slipstream and tilt wing aircraft. Under a Navy contract, Kaman built and installed the wing system on the fuselage of a Grumman Goose aircraft. The wing would tilt only up to 50 deg. The remaining 90 deg of thrust deflection was accomplished by turning the prop rotor slipstream. The 50 deg limit was imposed to eliminate the low thrust wing stall envelope boundaries associated with tilt wing aircraft. The Kaman K-16B is really more of a tilt wing than a deflected thrust concept. Tilt wings show good promise and will be covered in more detail in following sections. Both deflected rotor and propeller VTOL concepts have inherently low hover efficiency and control power. Based on past experience with deflected slipstream concepts and their inherent qualities that foreseen technology cannot remedy, these concepts were eliminated from further study.

The remaining five configurations all appear to be capable of 350-500 knot speeds and retain helicopter like qualities. These configurations can be grouped into three families. The three configurations in the tilt thruster row of Figure A-3 are very similar in nature and are grouped as a tilt propulsion family. The discriminating difference is the size and type of propulsor device outboard on each wing. The remaining two double propulsion concepts are rather different in nature even though they are in the same row. It was expected that the relative performance and attributes of each would be dissimilar. There are numerous examples of the double propulsion with rotor configuration. For the speed range of interest only the stopped rotor family concepts are expected to be feasible. Rotating wing concepts are not foreseen as being viable for very high speeds. The other double propulsion configuration is termed the buried fan or rotor family. Within these three families thirteen concepts were identified as having the desired speed potential and helicopter-like qualities. These concepts are grouped respectively in Figure A-16. Sketches of the concepts are shown in Figure A-17.

For speeds up to 300 knots, the tilt rotor concept has proven to be the most successful high speed rotorcraft to date. The XV-15 and MV-22 are the most notable examples. Pushing this configuration to 400 to 450 knots will require advanced prop rotors that operate at relatively high helical Mach numbers and advance ratios. Proprotor whirl mode aeroelastic stability at these high speed will require improved technology in the areas of materials, structures and analysis.

The tilt wing concept was one of the first attempts to combine VTOL and high speed capability. The Canadiar CL-84 and LTV XC-142 were the two most successful aircraft of this type. Both of these prototype aircraft under went extensive flight test evaluation. Overall, the concept was found to work rather well. Even though the CL-84 and XC-142 were both designed and tested in the late 1960s and early 1970's, they reached speeds of about 260 and 320 knots in level flight respectively. Since this era major improvements have been made in engine specific fuel consumption (SFC), engine specific power, structural efficiency, and aerodynamics. In light of this, 400-450 knot speeds appear well within reach of this concept.

All tilt wing aircraft including the CL-84 and XC-142 used an auxiliary thruster in the tail for pitch control. This system proved to be adequate. However, mechanically it is complex and cumbersome. At the desired speeds for this study, the associated drag penalty of a tail rotor may be unacceptable. For the designs considered herein a geared flap control as designed and patented by G. Churchill in 1962, is used instead. This obviates the need for a tail thruster and eliminates the complexity of transmitting power back to the tail. The details of the system are reported in Reference 7.

The most successful of the tilting duct aircraft was the Bell X-22A. This aircraft had a successful flight test program and demonstrated good low speed qualities and 250 knot speeds. Drag and duct geometry are the primary design areas to be addressed for this aircraft. Aerodynamic technology and analysis will be needed to reduce the interference and parasite drag associated with the ducts.

Two unproven but promising high speed concepts are the variable diameter tilt rotor (VDTR) and folding tilt rotor (FTR). In the VDTR concept, the proprotor diameter reduces to approximately 65 percent in cruise flight. The corresponding drop in tip speed significantly reduces the helical Mach number and full rpm can be maintained at all times. The diameter reduction also reduces rotational inertia and relieves the aeroelastic structural requirements of the wing. These benefits are offset by the complexity and weight of the blade retraction mechanisms. The variable diameter system was successfully designed, fabricated and tested by Sikorsky in the early 1970s. System details are reported in Reference 8. No insurmountable problems were encountered during these tests. The system proved to be reliable and free of any adverse dynamic effects.

The FTR can be considered a stowed rotor concept, and offers the greatest speed potential of all the tilt propulsor family members. In hover and low speed flight the aircraft performs just like a tilt rotor. In a conversion speed regime of 225 to 270 knots the proprotors are stopped, indexed and folded back along the nacelles. Propulsion is then provided by convertible engines. This system was designed and tested by Bell in the early 1970s. Details of proposed FTR configurations can be found in References 3 and 9. A variant of FTR, the trail rotor, proposed by McDonnell Douglas Helicopter Company, was considered but was found to offer no advantages in terms of performance or attributes over the FTR concept.

The double propulsion or stopped rotor configurations have received a large amount of attention over the years. All of these concepts require a convertible engine for efficient design and the lack thereof has impeded development of any successful flight vehicles. The use of separate engines for cruise and low speed flight simply imposes too large a weight penalty. Convertible engine designs are approaching feasibility and may be available by the year 2000. Other new technologies coupled with these types of engines may make a stopped rotor concept possible.

The goal of the X-Wing program was to demonstrate a practical stopped rotor concept. Advanced structural, aerodynamic and control systems technology is required. To reduce empty weight and complexity, a warm cycle tip drive X-Wing has been studied by Sikorsky. Tip drive is particularly well suited for this concept because the duct work for the circulation control blades is already in place.

In the 1960s, Hughes Aircraft proposed a three-bladed stopped rotor concept called the rotor wing. The aircraft had a very large triangular hub extending out to approximately 50% of the rotor radius. At the end of each point of the hub, low aspect ratio blades extended out the remaining 50%. In hover the rotor/wing can be driven either mechanically or pneumatically with an appropriately sized anti-torque and directional control device in the tail. Conversion is made by stopping the rotor aerodynamically with cyclic and collective pitch and locking it into position with one blade over the nose. The Hughes rotor/wing used double-ended airfoils on the stub blades. The mechanically driven stopped rotor analyzed herein is of this type. The tip drive stopped rotor concept for this study uses circulation control airfoils in order to reduce profile drag of both the blades and triangular hub in fixed wing flight.

The stopped retractable rotor consists of a 55% radius circular hub, within which there are four extendable blades. The first pair is for hover and are extended in rotary wing flight. As conversion speed is reached, the blades retract into the hub disk. When fully retracted, the aircraft flies as an airplane with a rotating circular wing. Because the wing is symmetric, rotor RPM reduction causes no vibratory loads like those experienced by the X-Wing. When the rotor is locked into place, the second pair of blades is extended at the 90 deg and 270 deg position of the rotor disk. These "blades" are really forward flight oriented stub wings that increase wing aspect ratio and boost cruise efficiency.

The stowed rotor has good speed and range capability in cruise flight by virtue of an unexposed rotor. In low speed flight a rotor with a relatively low disk loading provides helicopter like qualities. These are the attractive qualities that have sponsored a number of design studies. The price for these qualities is complexity and increased weight. Design of a simple stowing system for a low disk loading rotor is not easy. This has proved to be the major stumbling block for stowed rotors. Convertible engines must be employed for this concept as well.

The Buried fan family is divided into two types; fan-in- wing and shrouded rotor designs. The XV-5A was the most successful fan-in-wing aircraft type. This concept's main advantage is its pure airplane-like characteristics in cruise. These qualities are traded for poorer low speed qualities. Control issues in low speed flight were never fully resolved in the XV-5A. Employment of new control methods as well as lower disk loadings could very much improve the low speed qualities of this concept. Weight also proved to be a particular problem for this concept; therefore, structural technologies will be most important.

The shrouded rotor design is similar to the fan-in-wing but houses a single rotor within the fuselage. Many of the control and weight issues are the same. Both of these concepts in this study have tip driven fans similar in nature to the XV-5A.

Because of the effect of the ducts on the wake, the effective disk loading of the shrouded rotor is less than for a free rotor of the same diameter. A duct theoretically does not allow a wake to contract. Therefore, the inflow velocity at the rotor disk is the same as in the far wake. A free rotor has a contracted wake velocity approximately twice that of the rotor inflow velocity. From Reference 4 it was determined that a GW/duct area of 95 PSF was equivalent to a free rotor at 50 PSF.

Each of the concepts was rated for the same attributes described in section 5 for the missions. The final concept ratings listed in Figure A-18 is an average of the ratings supplied by a number of experienced design engineers at Sikorsky familiar with these concepts.

Section 7. Mission-Concept Pairing Based on Attributes

As explained in section 4 the attractiveness of a mission concept pair is a function of both operational attributes and performance. Sections 5 and 6 described the initial mission and concept selection process. This section covers the first element of block 3 in Figure A-10. Each mission and concept was rated for every attribute listed in Table A-4. These results were combined to form a mission attribute rating of every concept, for every mission. The method used to calculate this rating is diagrammed in Figure A-19. The formula used to generate the relative attribute rank is written in the lower right corner of the figure. This equation is simply a ratio of the sum of concept ratings multiplied against each attribute rating, divided by a perfect aircraft (i.e. score of 3) multiplied against each attribute.

All concepts were ranked relative to each other for all 14 specific missions. Appendix A contains these results. It will be noted that for some missions an aircraft will have a score of zero. This occurred when a concept received a very poor rating in a critical mission attribute. For example, the shrouded rotor has a zero score for the military transport missions because it has no significant cabin or ramp loading capability. In general the tilting thruster family had the best attributes for most missions.

The shrouded rotor and fan-in-wing had the best relative attributes for the scout attack missions but were rather poor for all others. This is confirmation that transport type and fighter type missions favor different concepts. After estimating mission performance, these results were combined and discussed in section 9.

Section 8. Sizing of Concepts for Selected Missions

Sizing an aircraft in terms of required takeoff gross weight (TOGW) is an iterative procedure. It involves a coupled analysis between aerodynamic and weights synthesis models. These programs can become very complicated as the number of input variables increases. Given the scope of Task I, a simplified model that uses only the most fundamental mission and performance values was employed. A list of these variables is shown in Figure A-20. The generic mission profile is prescribed so sizing results are only a function of concept performance variables. The fundamental relationship between aircraft size, payload, fixed equipment, crew, empty weight and fuel is expressed in equation 3.

$$TOGW = \frac{PAYLOAD + FIXED\ EQUIP. + CREW}{1 - \frac{WE}{GW} - \frac{FUEL}{GW}} \qquad 3$$

The numerator of the equation is fixed for each mission. The mission gross weight is then only a function of empty weight fraction and fuel fraction. The mission profile is fixed and fuel required is solely a function of concept aerodynamic performance variables.

Equation 3 can be rewritten into an expanded form.

$$TOGW = \frac{PAYLOAD + FIXED\ EQUIP. + CREW}{1 - \frac{WE}{GW} - \frac{RES\ FUEL}{GW} - \left(\frac{HOVER\ TIME}{\eta_{HOV}} + \frac{LOITER\ TIME}{\eta_{LTR}} + \frac{RANGE}{\eta_{CRS}}\right)} \qquad 4$$

Here the fuel requirement is identified for each mission segment. Derivation of the hover, loiter, and cruise efficiencies from familiar performance parameters are given in Figure A-21.

There are two ways to obtain these efficiencies. One is to calculate them as shown in Figure A-21. The other is to assess them parametrically. Fuel flow as a function of gross weight, airspeed and atmospheric ambients is available from flight manuals and other sources. Cruise and hover efficiencies calculated for various aircraft are plotted in Figures A-22 and A-23 respectively. Cruise efficiency is plotted as a function of true airspeed in Figure A-22. There is a vast difference between helicopters and fixed wing aircraft. Large turbofan aircraft have the highest specific cruise efficiency. It is evident that disk loading has a significant effect on hover efficiency. It is also a direct function of engine SFC. Superimposed on the plot is hover efficiency for lines of constant SFC. The apparent SFC value for an indicated aircraft is higher than the SFC expected for the engine of its era. This is due to power losses imposed by tail rotors, download, transmission inefficiency and fixed equipment power requirements.

Upon reviewing the relative performance of helicopters and the few high speed VTOL aircraft in Figures A-22 and A-23, the expected efficiency bounds of high speed rotorcraft can be approximated. A matrix within these bounds and empty weight fractions yields sensitivity plots of mission TOGW. These results were calculated using equation 4 and are shown for all five generic missions in Figures A-24 to A-28. Note that the vertical scale is logarithmic. The mission TOGW was found to be very sensitive to empty weight fraction for all missions. This was particularly true for the dipping sonar and SOF missions. Figure A-29 is an illustration of how dominant the empty weight fraction is. The scout attack mission is roughly five times more sensitive to a percentage change of empty weight fraction than to the aerodynamic efficiencies. It was then very evident that most of the sizing analysis emphasis must be directed to the empty weight derivation of the 13 candidate concepts.

Time and resource constraints did not allow for concept sizing to all five generic missions. Therefore, at this point the merits of each mission were evaluated for further study. The military transport and scout attack mission were selected as the two most suitable missions for further study. Together these two missions constitute a large portion of the expected demand for high speed rotorcraft. They also represent opposite ends of the requirements spectrum in terms of size, weight and mission attributes. The requirements for the civil transport are similar to those for the military transport. The dipping sonar and SOF missions are unique and have special requirements. Selection of these missions could emphasize technologies that are only unique to them. That technology would have a limited payoff because dipping sonar and SOF aircraft do not comprise a large portion of the world VTOL fleet.

High speed, long range cruise and VTOL capability are very valuable for the SOF mission. However, it typically allows for a STOL takeoff with a midpoint hover requirement. These requirements as opposed to a vertical takeoff requirement at mission start can significantly alter an aircraft's design. It is recommended that SOF mission aircraft be looked at separately and designed in concert with the unique requirements for that mission.

Weight Evaluation Methodology

The second filter requirement, which is to quantify the preliminary study results, would involve extensive methodology development if done in the traditional weight prediction manner. Therefore, due to the time constraints and the significant number of evaluations required (13 candidate aircraft with 2 missions each = 26 evaluations), a fraction sizing method was used. A diagram of this method is presented in Figure A-30.

The fraction method starts with a weight empty fraction for the type of vehicle to be evaluated. The baseline weight empty fraction for each candidate aircraft was taken from an existing vehicle where possible and from previous study data. Where no base existed the vehicle was developed from an existing vehicle and adjusted for discriminating features. The propulsion system and appropriate structure were replaced by resized systems to meet the speed, range, and disk loading requirements. The specified mission fixed equipment were added along with a militarization penalty equivalent to a current U.S. Army helicopter. Other adjustments were made if they were perceived to have significant weight impact. The result was a revised weight empty fraction for the air vehicle, reconfigured to perform the mission in the same time frame and at the same gross weight.

Weight reduction due to technology improvements resulted both from weight reduction technology and propulsion system downsizing due to improved aerodynamics.
Aerodynamic resizing includes resized engines, transmission and fuel systems for the specified time frame along with improved engine SFC's. Design and development weight reduction includes improved materials, new development concepts, integration, methods of analysis, and component development and is based on a

continued extension of historical weight technology trends. The gross weight of the vehicle is projected from the expression:

$$TOGW = \frac{PAYLOAD}{1 - \frac{OWE}{GW} - \frac{FUEL}{GW}} \qquad 5$$

Where fixed equipment and crew are in the operating weight empty. Since the fuel fraction generally decreases with increasing gross weight, three iterations were performed. The final weight solution was determined by a performance evaluation of the third weight projection data.

Table A-5 summarizes the sequence of events and sources of data. For consistency all fraction data are based on the design gross weight of the baseline vehicle at a limit load factor of 3.0.

As shown in Figure A-31 aircraft structure (which includes rotor systems, wings, airframe, tail section, and landing gear) trends with gross weight at a slope of one for existing compound vehicles. These are also the areas of least adjustment. It is the propulsion system and fixed equipment items that are essentially replaced. This trend supports the validity of the fraction approach. Fractions also allow consistency of comparison by measure of development risk for systems that have not yet been developed.

Figure A-32 is an example of how the weight build-up of a concept varies using the empty weight fraction approach. A compound transport aircraft in the 1960's, designed to fly at speeds of approximately 300 kts with limited range, had a reasonable payload fraction. This same aircraft reconfigured to fly 500 nm range with a max speed of 450 kts, militarized to current U.S. Army requirements for VTOL aircraft and including the specified fixed equipment of 5900 pounds in weight empty, has extremely limited payload. After adding technology improvements through 1980, the same aircraft can now carry the required payload but not to the desired range. Technology through the year 2000 allows the aircraft to exceed all requirements such that it can ultimately be downsized. All thirteen aircraft were carried through this process for both the military transport and scout attack mission.

Tables A-6 through A-11 provide the details of the fraction weight analysis for each aircraft. The weight empties are developed from a specified baseline for the time frame of development, current time frame, and the year 2000. The significant parameters which sized the propulsion and rotor systems are identified. Three gross weight projections are shown based on fuel variations with gross weight.

Engine weight trends for current technology are shown in Figure A-33. The four types of engines used in the evaluations were shaft, thrust, turbofan and convertible.

Assessed weight reduction was based on the data shown in Figure A-34, which is a historical trend of helicopter weight reduction due to technology. Some major contributing technologies are noted. The compound VTOL aircraft results also follow this trend.

New requirements have consistently been added to newly fielded helicopter designs, resulting in a relatively constant weight empty fraction in spite of weight reduction technology, however, no new requirement penalties were specified for this study. If new requirements are incorporated, the gross weight solutions will be greater than those currently shown. Because equipment group weights trend with gross weight at a power less than one, the more equipment weight transferred from payload to weight empty, the lower the gross weight solution.

Concept mission performance is dependent upon the fundamental aerodynamic performance variables listed in Figure A-20. The final estimated values of these parameters for both current and year 2000 technology are shown in Figure A-35 for the military transport and in Figure A-36 for the scout attack aircraft. It is important to understand the rationalization for each of the values listed in these figures.

Disk loading selection was based on information obtained from a number of sources. The mission gross weight solution is a function of disk loading and there is a value for each military transport aircraft where the disk loading provides a hover/cruise power match. This disk loading was greater than 50 PSF except for the tip drive and stowed rotor aircraft, which were at about 40 PSF.

References 10 and 11 as well as other sources indicate that disk loadings on the order of 15 to 25 yield mission gross weights for tilt rotors. A middle value of 20 psf was selected for the tilt rotor. Folding tilt rotor information is not as plentiful. Reference 12 was found to be the most comprehensive. It indicated feasible disk loadings on the order of 12 to 18 psf. Given the higher speeds of interest and the expected sensitivity of the gross weight solution to a heavier folding rotor system, 20 psf is expected to be closer to an optimum.

The stopped rotor concepts were all determined to be near optimum at about 15 psf. Previous X-wing studies found this value to be appropriate for both shaft and tip driven configurations. Documented work on the tip drive stopped rotor concepts presented disk loadings of about 12 psf for 45000 pound vehicles. Upon reviewing this design and applying experience from X-wing work, 15 psf appeared to be a good value for this concept. Similar conclusions were drawn for the stopped retractable rotor concept. The stowed rotor concept favors the higher disk loadings of a smaller, more easily stowed rotor system. Previous work on stowed rotors from References 8 and 13 indicate disk loadings 8 to 15 psf were most favorable. The higher value was taken given this study higher speed requirement and rotor stowage limitations.

Vertical drag estimates were derived from known values of like aircraft as well as from calculations. Rotor figure of merit estimates were based on information from various studies and tests. Appropriate modifications to these results were made to reflect differences between the data and the specific geometry of a concept. For example, rotor figure of merit data is available in References 14 and 15 for a shaft driven stopped rotor, but not for a tip driven rotor with circulation control. Using X-wing rotor hover information, appropriate changes were made to reflect a tip drive rotor system's performance.

The aircraft figure of merit for all concepts is comprised of the rotor figure of merit, losses associated with vertical drag, anti-torque, and transmission losses. The aircraft figures of merit for the tip drive rotors were modeled as that of a shaft driven rotor with engine SFC degradation to account for the inherent pneumatic losses. These losses and the characteristics of tip drive systems were derived from previous Sikorsky work and Reference 16. For all concepts the aircraft figure of merit and disk loading determine overall hovering efficiency.

The drag coefficient, Cf is defined by equation 6.

$$Cf = fe / GW^{2/3} \qquad 6$$

This definition reflects the recognized square-cubed relationship between wetted area and volume. Drag is generally proportional to wetted area and weight is generally proportional to volume. A plot of equivalent drag area for a drag coefficient of 1.0 (fe) vs. design gross weight with lines of constant Cf is shown in Figure A-37. Drag estimation was derived from this information, Reference 17 as well as a build up drag analysis using Reference 18.

Over 350 knots the propulsive efficiency of a tilt propulsor aircraft is primarily a function of the helical tip Mach number. Propeller efficiency drops off very rapidly as the helical Mach number exceeds the critical Mach number of the tip airfoil. Propfan technology development in the last decade has pushed propeller cruise speeds out to the 450 to 500 knot range. This is made possible by thin swept tips. Blade sweep of about 35 degrees keeps the normal velocity component at the tip subsonic, albeit very high, at approximately Mach .90 to .95. Application of this technology to prop rotors is expected to enable efficient high speed operation. The tilt rotor and tilt wing concepts required thin tips with a drag divergence Mach number of about .80 and sweep on the order of 30 degrees. The variable diameter tilt rotor reduces down to 65% of its diameter in cruise. The corresponding tip speed and helical Mach reduction necessitates only about 20 degrees of sweep. The helical Mach encountered in the SCAT Mission is lower and the sweep needed is reduced to about half.

Wing sweep is needed for the tilt rotor, VDTR and FTR transport aircraft to increase the wing drag divergence Mach number. The wing airfoils are 21% thick and have advanced profiles to delay compressibility drag rise. The tilt wing has a 15% thick section that has a critical Mach number slightly greater than the cruise Mach number.

The engine SFC values were obtained from the results of both General Electric Aircraft Engines and Allison Gas Turbine division's convertible engine studies detailed in References 19 and 20.

The resultant empty weight for the current and year 2000 Technology levels are listed in the last two columns of Figures A-35 and A-36. The areas of technology improvement expected to enable the year 2000 performance levels are summarized in Figure 38.

The X-wing and shrouded rotor concepts were not considered for the military transport mission. Previous experience has shown them to be non-viable for this mission due to space requirements for their respective drive and rotor systems. The tilt duct fan and fan-in-wing concepts were found to be impractical. The installed power required to overcome the drag of the tilt duct fan drove the empty weight fraction to such a high value that no solution closure could be achieved. The fan-in-wing concept, even though it has respectable performance variables, is inherently heavy, and no closure could be made on this solution either.

Section 9. Selection of Mission-Concept Pairs for Further Study in Task II

The combination of attributes, performance, and development risk was used as the final mission concept pair selection criteria. High speed rotorcraft designs of the past have demonstrated that operational attributes can be traded for performance. The same trend was found in the study. In an effort to clearly illustrate these trades, Figure A-39 diagrams how an attribute vs.

performance plot was generated. The vertical axis is simply the relative attributes measure discussed in Section 7. The horizontal axis is a relative performance scale. An 'ideal' performance was defined as an aircraft of 24,000 pounds for the military transport and 12000 pounds for the scout attack mission. These correspond to a 25% payload fraction. The concept gross weight is that found in Section 8. The lines of constant product are lines of relative goodness. For example, a concept with a relative attribute value of 0.70 and a relative performance value of 0.50 would have a product of 0.35. Anywhere along this line the same trade is made between attributes and performance. The design goal is to make this product as large as possible and move to the upper right corner of the plot.

The military transport results presented in Figure A-40 show that, overall, the tilt propulsor family has better performance and attributes than the stopped rotor family. The tip drive stopped rotors' elevated performance level with respect to the other stopped rotors is due to the lighter-weight tip drive system, three blades, and drag reduction attributed to the circulation control airfoils and hub.

The scout attack mission attributes vs. performance results in Figure A-41 are at about the same overall mission attribute level but with more spread over the performance scale. The lower speed requirement and cleaner fighter configuration affected the power required to such a degree that payload fractions closer to the "ideal" goal of 25% were achieved. This result confirms the trends shown in Section 3 concerning the improved empty weight fraction for lower speed and drag configurations. The disk loadings for hover/cruise power match were found to be lower for this mission. The tilt wing disk loading was lowered to 40 psf to satisfy this condition. All the other concepts had a power match within a few psf of their selected disk loadings.

Compared to the stopped rotor concepts, the tilt propulsion family is far superior in terms of performance is generally as good in attributes. The shrouded rotor, even though it has poor performance for this particular mission, has the best attributes.

All of these concepts have different levels of development risk. A different degree of technology was applied to each concept. Some analyzed concepts have been tested as flying prototypes; others only to a conceptual stage. Given these factors, Figures A-42 and A-43 were developed to illustrate the relationship between overall mission performance and development risk. Overall mission performance was quantified by the product of the relative attributes and relative performance. The relative positions of the concepts on the risk scale were established collectively by a number of senior Sikorsky engineers. Development risk was based on the two aforementioned factors, how much technology application was required to obtain the estimated performance levels, and how well understood the concept is in terms of structure, mechanics, dynamics and aerodynamics.

None of the concepts were considered to be low risk. Low risk was associated with developing a new helicopter embodying new technologies. The tilt wing was assessed as the lowest overall risk of the high speed concepts. The XC-142 was designed with early 1960's technology and demonstrated speeds up to 350 knots. Attaining the additional 100 knots with technologies 40 years newer is not considered to be as large a stride as for the other concepts. This is especially true since propfans have demonstrated efficient operation at cruise Mach numbers of .80. A wealth of information is available on tilt wing aircraft. Numerous reports are available on the XC-142, CL-84, VZ-2, and X-18, including model test results and analytical studies. For these reasons and the tilt wing's good overall performance, it has been selected as a concept for further study in Task II. It is understood that it has the most severe downwash environment of all the concepts. However, it is expected to be manageable. Efforts will be made in the Task II design effort to reduce the disk loading to between 30 and 40 PSF.

The conventional and variable diameter tilt rotors were found to be rather close in overall mission suitability. The tilt rotor had slightly better performance and the variable diameter tilt rotor had slightly better attributes. The discriminator between the two is the estimated risk of developing such a 450 knot vehicle. The conventional tilt rotor has inherent characteristics that limit its maximum speed potential.

One limiting characteristic is the necessary substantial rpm reduction. The normal helical velocity component to the tip must be kept below the drag divergence Mach number of the tip airfoil. To accomplish this a conventional tilt rotor must substantially reduce rpm. Gearbox size and weight are primarily a function of torque. As rpm is reduced at higher and higher speeds, proportionately less horsepower can be transmitted for the same torque level. Hence the gearbox become much heavier as the speed requirement increases.

Susceptibility to whirl mode flutter is the other major factor that limits the speed of the tilt rotor. Large prop rotors at high dynamic pressure and advance ratios are difficult to keep static and dynamically stable. In addition to this, the blade tips of the tilt rotor considered herein required 33 degrees of sweep to relieve compressibility effects. Considerable structural and dynamics analysis would be required to design a swept tip proprotor system to operate at 450 knots.

The VDTR operates at 100% rpm at all times. This enables the full horsepower capability of the gearbox to be used. The 35% tip speed reduction requires ten degrees less tip sweep than the conventional tilt rotor. The reduced diameter and rotational inertia alleviate the aeroelastic structural requirements of the wing. These advantages come at the expense of a more complicated retracting rotor system. The variable diameter rotor system has been successfully designed and tested. It is straight-forward and appears to offer fewer "unknown, unknowns" than a high speed conventional prop rotor may present. The VDTR was selected as a second concept for the military transport mission. This gives two different solution types. One that is best for performance, the tilt wing, and one that is best in terms of attributes, the VDTR.

The SCAT mission risk assessment for each concept is the same as for the military transport although the overall performance levels of the various concepts are different. The tilt wing again came out well and at first glance appeared to be an obvious choice. However, it has not been chosen as a concept for the SCAT mission. Upon further review of the comparative analysis, weak points were identified. Crew visibility and external stores suitability are two attributes that were not evaluated for the concepts. A tilt wing completely blocks the crew's visibility of the two rear quarters. Good cockpit visibility is crucial in the combat environment. External store placement is also a problem. For these reasons it was apparent that the tilt wing is not a good choice for the SCAT mission. These two and a number of other attributes could have been added to make a more comprehensive list. However, a conscious effort was made to restrict the number of attributes to a manageable level.

The next best aircraft were the tilt rotor and VDTR. The tilt rotor has slightly better overall performance at the expense of higher risk. This increased risk is due to the same factors cited for the transport mission. The superior attributes and lower risk of the VDTR were judged to outweigh the slight performance advantage of the tilt rotor.

The SCAT mission is a good choice as a generic sizing mission. As part of the study requirements, alternate missions were to be assessed. The prescribed SCAT mission profile is more aligned with a ground attack than to air-to-air. Air-to-Air mission profiles typically involve less hover and NOE time. The SCAT mission attributes were all given the same scale of zero to three. A review of the SCAT mission requirements revealed that a few attributes were much more important than others. The SCAT Mission MOE, kill probability per encounter, is very much a function of;

maneuverability and agility
low observables
low vulnerability and survivability

Of all the concepts studied, the shrouded rotor was rated the best in these attributes. It is a very compact vehicle with low inertia about all three axes. Combined with the control power of a rigid coaxial rotor this makes for a very maneuverable aircraft.

Low observable technology can make a dramatic difference in the operational effectiveness of a combat aircraft. Billions of dollars have been spent on the YF-117, B-2, advanced cruise missile and other programs. The primary justification for these aircraft is their "stealthiness". The LHX is expected to be heavily influenced by these technologies. The shrouded rotor by virtue of the covered rotor system eliminates the doppler and acoustic radar returns associated with the rotor system in cruise. It is expected that the radar, IR, and acoustic signature levels of low observable fixed wing aircraft can be attained by the shrouded rotor concept.

The combination of maneuverability, agility and low observability go a long way to enhance survivability and low vulnerability. The ballistic tolerance of the shrouded rotor concept should be somewhat better than the other concepts. Of distinct advantage is its CTOL capability should the rotor system be disabled. Given the high lift capabilities of the circulation controlled airfoil, such operations may be actually STOL in nature.

All of these qualities make the shrouded rotor concept very attractive from an attributes point of view. However, the performance level was assessed to be relatively poor for the prescribed SCAT mission. This was due to several reasons. The SCAT sizing mission requires a little over 1/2 hour of low speed and hovering flight. This requires a considerable amount of fuel for high disk loading vehicles. A scout attack mission that is primarily air-to-air would require little NOE or hover. Most of the flight would be in high speed and contour flight mode. This reduces the fuel penalties associated with the high disk loading.

A moderate increase in disk loading, perhaps to 120 psf (which is equivalent to a 65 psf free rotor) yields a substantial improvement in empty weight fraction. Since a benign downwash requirement would not be as important for an air-to-air mission a disk loading increase can be tolerated. Most hovering operations would be performed from prepared or semi-prepared surfaces. External load operations would not be a mission requirement. The doors that cover the rotor are heavy. The invention of a lightweight covering in combination with higher disk loading could yield a very performance competitive concept. The shrouded rotor has been selected as a fourth concept to be evaluated for an air-to-air SCAT mission.

The technologies found to be most important to the design of the tilt wing and VDTR are listed in Figure A-45. Weight reduction is very important. There are a lot of mechanisms required for these aircraft. This inherently makes the empty weight fraction high. Materials, structural and aeroelastic analysis will be vital to reducing airframe weight.

The overall propulsive efficiency is important. High efficiency has two substantial benefits. It reduces the fuel required and the weight of the engine and drive system. Development of good efficiency at high helical tip Mach numbers needs to be the emphasis of propeller and variable diameter rotor aerodynamic research. The mechanics of the variable diameter rotor require an investigative effort in order to verify its operation as a proprotor.

Engine technology has consistently been shown to have a significant impact on vehicle performance. Improved SFC and power-to-weight ratios are of particular importance to a high speed rotorcraft because of the high power requirements. Ample reserve OEI power enables engines to be matched for normal operation conditions and eliminates engine oversizing for contingency conditions.

Drag reduction, like propulsive efficiency, reduces fuel burn and power required. Improved CFD and experimental analyses are the most productive ways to accomplish this. Airfoils with high critical Mach numbers will be required for both the wings and proprotor tips of the tilt wing and VDTR.

The VDTR has moderate low observable attributes. A successful battlefield aircraft needs better attributes than are currently expected of a tilt rotor or VDTR. Many technologies in this area have emerged in the last ten years. And more may be expected in the next ten. Application of these is seen as important to the success of a VDTR as a SCAT type vehicle.

The enabling technologies for a shrouded rotor concept have overlap with the tilt wing and VDTR concepts in the areas of weight reduction and engine technology. In addition it needs convertable engine technology to be viable.

The rotor covering, rotor system, and rotor drive are the most important mechanisms to be researched. These are relatively heavy items that must be optimized for the design. Shrouded rotor designs of the past have used rigid folding coverings. Sikorsky is currently investigating flexible coverings that are much lighter. The closely spaced rotor blades need to be stiff. The ABC rigid rotor and X-wing blades are good starting points from which to design a shrouded rotor. Use of advanced materials, dynamic analysis and advanced aerodynamics will be needed to reduce the weight of the system and improve its aerodynamic efficiency. The rotor drive can be either shaft or tip driven. A trade study between the two will be made to determine which system is most attractive.

The aerodynamic environment of a shrouded rotor in low speed flight is not well understood. Control system requirements are difficult to estimate. One particular problem that has plagued shrouded rotors in the past is the control of a large pitch-up moment in low speed flight. This is caused by increased leading edge shroud augmentation and reduced augmentation on the rear. The augmentation difference is caused by the net sum of the local inflow and forward velocity. On the leading edge, the inflow and flight velocities add together and cause lowered local pressure on the leading edge. At the trailing edge, the inflow velocity is in the opposite direction of the forward velocity. Therefore, the velocities subtract, yield a lower net velocity and produce less local pressure drop on the trailing edge of the shroud.

The only ways to counter this problem is to eliminate the augmentation or to change the inflow distribution into the rotor. By the use of cyclic pitch on a rigid rotor, the inflow velocity distribution can be altered enough to lessen the augmentation difference between the leading and trailing edge. This has been confirmed by detailed computational aerodynamic analysis. There is a power penalty associated with this control method because the overall augmentation is somewhat reduced. The power penalty is not of great concern because a high speed rotorcraft naturally tends to be overpowered in hover. This control method is a long way from being perfected and needs more research. It is, however, an apparently viable way of controlling the pitch-up problem.

The use of circulation control on the trailing edge has two benefits: drag reduction and increased negative pitch moment capability. Blowing over a trailing edge coanda surface enables very thick sections to have a drag coefficient of a typical 10% or thinner airfoil. Application of circulation control technology is very appropriate for a shrouded rotor because a relatively thick wing airfoil is required and wing area must be kept to a minimum. The circulation control enables both to be achieved with a low wing drag coefficient. The X-Wing airfoil tests showed circulation control works very well. A significant problem X-wing encountered was the high frequency modulation of the blade blowing. The rate of change of wing trailing edge blowing for the shrouded rotor is at a much lower frequency and in the fixed system, and is therefore relatively easy to implement.

By increasing the blowing on a circulation control airfoil, very high lift and negative moment coefficients can be developed. Both of these are of benefit for the shrouded rotor in low speed flight. The combination of rotor cyclic pitch and circulation control are expected to be powerful enough to control the low forward speed pitch-up phenomena.

Section 10. Conclusions

The design of a practical high speed rotorcraft must entail the use of new technologies. The high speed and low disk loading requirements combine to drive up the gross weight. Larger and cleaner configurations are the most practical in terms of meeting performance goals. Successful high speed rotorcraft will have disk loadings between 15 and 45 psf. Values below 15 do not look feasible.

The only missions that a high speed rotorcraft will be competitive for are those that require both VTOL and high speed. The military transport and scout attack missions have broad application and value both VTOL and high speed. They have been selected as the best missions to analyze in task II. The SOF mission places the most value on VTOL and high speed. In view of the special requirements of this mission it is recommended that a separate design effort be undertaken to formulate a design around the SOF mission profile.

The tilt wing and VDTR concepts offer the most promise for the military transport mission. The tilt wing has the best performance but marginal attributes. The VDTR has the best attributes but inferior performance compared to the tilt wing. The selection of these two concepts bracket the expected overall performance level a high speed rotorcraft can achieve for this mission by the year 2000.

The VDTR and shrouded rotor were chosen as the most attractive concepts for the scout attack mission. The VDTR has the best attributes and performance nearly as good as the tiltrotor. The shrouded rotor has rather poor performance for the mission but its attributes were the best of all concepts. The shrouded rotor would perform better in an air-to-air SCAT mission profile. This profile has been chosen as an alternate and will be used as the design mission for the shrouded rotor.

Table A-1. DOWNWASH ENVIRONMENT LIMITATIONS

		FIRM SURFACE OPERATIONS	LOOSE SURFACE OPERATIONS
PERSONNEL LIMITS	OVERTURNING MOMENT	300 ft-lbs	225 ft-lbs
	FORCE	100 lbs	75 lbs
SURFACE FAILURE LIMIT	DISK LOADING	50 psf	15 psf

Table A-2. GENERIC HIGH SPEED ROTORCRAFT SIZING MISSIONS

MILITARY TRANSPORT / ASW / CSAR MISSION
6000 Lb PAYLOAD

ENTIRE MISSION @ ISA + 15 deg C

HOGE 1 min @ SL
Climb to cruising altitude, full credit for range
Dash 450 ktas out to 350 nm
Descend to SL, no credit for range
HOGE 15 min @ SL
Loiter @ Vbe, 30 min @ SL
Climb to best range altitude, full credit for range
Cruise @ 99% max range power, 350 nm
Descend to SL, no credit for range
HOGE 1 min
10 % fuel reserve

MILITARY SCOUT / ATTACK MISSION
3000 lb PAYLOAD

ENTIRE MISSION @ 4000 ft / 95 deg F

HOGE 1 min
Cruise @ .99 max range power, 150 nm
Dash 400 ktas @ IRP, 50 nm
NOE maneuvering 15 min @ 40 ktas
15 min HOGE
Attack targets @ IRP power, 5 min
Cruise 200 nm @ .99 max range power
HOGE 1 min
10 % fuel reserve

CIVIL TRANSPORT MISSIONS
3000, 6000 lb PAYLOADS

ENTIRE MISSION @ ISA + 15 deg C

HOGE 1 min @ SL
Climb to best range altitude, full credit for range
Cruise 450 ktas or best range speed (which ever is greater) 600 nm
Descend to SL, full credit for range
HOGE 1 min
10 % fuel reserve

Table A-2 CONTINUED, ADDITIONAL HIGH SPEED ROTORCRAFT GENERIC SIZING MISSIONS

ASW DIPPING SONAR MISSION
6000 lb PAYLOAD

ENTIRE MISSION @ ISA + 15 deg C

HOGE 1 min @ SL
Climb to best range altitude, full credit for range
Cruise 350 ktas out to 250 nm
Descend to SL, no credit for range
2.7 hours time on station: 50 % HOGE
50 % @ Vbr
Climb to best range altitude, full credit for range
Criuse 250 nm @ 300 ktas or Vbr (which ever is greater)
Descend to SL, no credit for range
HOGE 1 min
10 % fuel reserve

MILITARY SOF MISSION
3000 lb PAYLOAD

ENTIRE MISSION @ 95 deg F

HOGE 1 min @ SL
Cruise 500 nm @ 400 ktas or Vbr (which ever is greater)
Climb to 4000 ft, full credit for range
NOE maneuvering @ 40 ktas for 15 min
HOGE 5 min
NOE maneuvering @ 40 ktas for 15 min
Descend to SL, full credit for range
Cruise: 500 nm @ 400 ktas or Vbr (which ever is greater)
HOGE 1 min
5 % fuel reserve

TABLE A-3. HIGH SPEED ROTORCRAFT ATTRIBUTES DESCRIPTIONS

COST OF OWNERSHIP	INVERSE OF USEFUL LOAD FRACTION AND OVERALL AIRCRAFT COMPLEXITY
CABIN VOLUME	USABLE FUSELAGE VOLUME FOR PAYLOAD
COMFORT	NOISE, VIBRATION LEVEL, AND GUST SENSITIVITY DURING PRIMARY MISSION LEGS
EXTERNAL NOISE	EXTERNAL AURAL NOISE LEVEL IN CONVERTED AND HOVER MODE
MANEUVERABILITY AND AGILITY	MANEUVERABILITY AND AGILITY LEVEL BEYOND CIVIL AIRCRAFT CERTIFICATION REQUIREMENTS
SURVIVABILITY AND LOW VULNERABILITY	INHERENT ROBUSTNESS AND DAMAGE TOLERANCE
LOW OBSERVABLES	INHERENT STEALTH QUALITIES WITH RESPECT TO NOISE, IR, AND RCS
BENIGN DOWNWASH ENVIRONMENT	DOWNWASH CHARACTERISTICS IN TERMS OF TEMPERATURE, VELOCITY AND PROFILE
SHIP COMPATABILITY	ABILITY TO REDUCE DECK SPOTTING FACTOR
EASE OF CONVERSION	ABILITY TO STOP AND REVERSE CONVERSION PROCESS - CONVERSION CORRIDOR SIZE
OVERLOAD STOL CAPABILITY	INCREASED TAKEOFF GROSS WEIGHT CAPABILITY WITH STOL PERFORMANCE

Table A-4. CONCEPT ATTRIBUTE SCORES SORTED BY RANK FOR EACH MISSION

AIRCRAFT/MISSION SCORES SUMMED FOR AIRCRAFT

Var Diam Tilt Rot	has total sum over all missions of	10.51
Folding Tilt Rot	has total sum over all missions of	10.38
Tilt Rotor	has total sum over all missions of	10.30
Stopped Retract Rot	has total sum over all missions of	9.38
Stowed Rotor	has total sum over all missions of	9.38
Stopped Rotor	has total sum over all missions of	9.22
Fan in Wing	has total sum over all missions of	8.80
Tilt Wing	has total sum over all missions of	8.69
Xwing	has total sum over all missions of	8.54
Tilt Duct Fan	has total sum over all missions of	8.44
Tip Drive Xwing	has total sum over all missions of	7.93
Tip Drive Stop Rot	has total sum over all missions of	7.83
Shrouded Rotor	has total sum over all missions of	7.06

SORTED AIRCRAFT SCORES FOR GIVEN MISSION

Aircraft performing Civil Passenger mission sorted by rank

Var Diam Tilt Rot	0.830
Folding Tilt Rot	0.813
Tilt Rotor	0.806
Tilt Wing	0.731
Tilt Duct Fan	0.710
Stopped Retract Rot	0.696
Stopped Rotor	0.694
Stowed Rotor	0.668
Fan in Wing	0.632
Xwing	0.629
Tip Drive Xwing	0.575
Tip Drive Stop Rot	0.539
Shrouded Rotor	is unviable for this mission

Aircraft performing Civil Cargo mission sorted by rank

Var Diam Tilt Rot	0.836
Tilt Rotor	0.816
Folding Tilt Rot	0.814
Tilt Wing	0.731
Tilt Duct Fan	0.706
Stopped Retract Rot	0.685
Stopped Rotor	0.670
Stowed Rotor	0.651
Fan in Wing	0.619
Xwing	0.602
Tip Drive Xwing	0.567
Tip Drive Stop Rot	0.522
Shrouded Rotor	is unviable for this mission

Table A-4. CONTINUED

Aircraft performing Civil Corporate mission sorted by rank

Var Diam Tilt Rot	0.827
Folding Tilt Rot	0.805
Tilt Rotor	0.800
Tilt Wing	0.717
Stopped Retract Rot	0.714
Stowed Rotor	0.714
Stopped Rotor	0.708
Tilt Duct Fan	0.678
Xwing	0.647
Fan in Wing	0.628
Shrouded Rotor	0.601
Tip Drive Xwing	0.583
Tip Drive Stop Rot	0.555

Aircraft performing Offshore Oil Support mission sorted by rank

Var Diam Tilt Rot	0.827
Folding Tilt Rot	0.801
Tilt Rotor	0.799
Tilt Wing	0.708
Stopped Retract Rot	0.697
Stowed Rotor	0.687
Stopped Rotor	0.681
Tilt Duct Fan	0.678
Xwing	0.624
Fan in Wing	0.610
Tip Drive Xwing	0.591
Shrouded Rotor	0.568
Tip Drive Stop Rot	0.565

Aircraft performing EMS mission sorted by rank

Var Diam Tilt Rot	0.795
Tilt Rotor	0.779
Folding Tilt Rot	0.774
Tilt Wing	0.680
Stopped Retract Rot	0.679
Stopped Rotor	0.675
Stowed Rotor	0.672
Tilt Duct Fan	0.657
Xwing	0.629
Fan in Wing	0.611
Shrouded Rotor	0.594
Tip Drive Xwing	0.571
Tip Drive Stop Rot	0.547

Table A-4. CONTINUED

Aircraft performing Military Transport mission sorted by rank

Var Diam Tilt Rot	0.755
Folding Tilt Rot	0.745
Tilt Rotor	0.737
Tilt Wing	0.676
Stopped Retract Rot	0.670
Stowed Rotor	0.664
Tilt Duct Fan	0.657
Stopped Rotor	0.656
Fan in Wing	0.633
Xwing	0.600
Tip Drive Xwing	0.566
Tip Drive Stop Rot	0.561
Shrouded Rotor	is unviable for this mission

Aircraft performing Navy ASW/ASST mission sorted by rank

Var Diam Tilt Rot	0.701
Folding Tilt Rot	0.699
Tilt Rotor	0.690
Stowed Rotor	0.665
Stopped Retract Rot	0.658
Shrouded Rotor	0.656
Stopped Rotor	0.650
Fan in Wing	0.638
Tilt Wing	0.636
Tilt Duct Fan	0.633
Xwing	0.606
Tip Drive Stop Rot	0.578
Tip Drive Xwing	0.566

Aircraft performing Combat SAR mission sorted by rank

Var Diam Tilt Rot	0.710
Folding Tilt Rot	0.707
Tilt Rotor	0.696
Stowed Rotor	0.666
Stopped Retract Rot	0.659
Shrouded Rotor	0.650
Stopped Rotor	0.647
Tilt Wing	0.637
Fan in Wing	0.635
Tilt Duct Fan	0.621
Xwing	0.605
Tip Drive Stop Rot	0.570
Tip Drive Xwing	0.568

Table A-4. CONTINUED

Aircraft performing Coast Guard SAR mission sorted by rank

Var Diam Tilt Rot	0.741
Tilt Rotor	0.735
Folding Tilt Rot	0.723
Tilt Wing	0.649
Stowed Rotor	0.647
Stopped Retract Rot	0.645
Tilt Duct Fan	0.642
Stopped Rotor	0.631
Fan in Wing	0.610
Shrouded Rotor	0.596
Xwing	0.594
Tip Drive Xwing	0.569
Tip Drive Stop Rot	0.567

Aircraft performing Navy ASW mission sorted by rank

Var Diam Tilt Rot	0.697
Tilt Rotor	0.694
Folding Tilt Rot	0.691
Stowed Rotor	0.653
Shrouded Rotor	0.651
Stopped Retract Rot	0.644
Stopped Rotor	0.640
Fan in Wing	0.633
Tilt Duct Fan	0.628
Tilt Wing	0.628
Xwing	0.603
Tip Drive Stop Rot	0.581
Tip Drive Xwing	0.569

Aircraft performing Army CAS/Air-Air mission sorted by rank

Shrouded Rotor	0.710
Folding Tilt Rot	0.699
Var Diam Tilt Rot	0.691
Tilt Rotor	0.682
Stowed Rotor	0.681
Stopped Retract Rot	0.657
Fan in Wing	0.652
Stopped Rotor	0.645
Tilt Wing	0.638
Tilt Duct Fan	0.609
Xwing	0.608
Tip Drive Stop Rot	0.563
Tip Drive Xwing	0.555

Table A-4. CONCLUDED

Aircraft performing Naval CAS/Air-Air mission sorted by rank

Shrouded Rotor	0.710
Folding Tilt Rot	0.681
Stowed Rotor	0.677
Var Diam Tilt Rot	0.673
Tilt Rotor	0.666
Stopped Retract Rot	0.654
Fan in Wing	0.649
Stopped Rotor	0.638
Tilt Wing	0.626
Tilt Duct Fan	0.607
Xwing	0.597
Tip Drive Stop Rot	0.569
Tip Drive Xwing	0.549

Aircraft performing Army Spec Ops mission sorted by rank

Var Diam Tilt Rot	0.721
Folding Tilt Rot	0.718
Tilt Rotor	0.704
Stowed Rotor	0.670
Shrouded Rotor	0.660
Stopped Retract Rot	0.660
Stopped Rotor	0.646
Fan in Wing	0.625
Xwing	0.605
Tip Drive Stop Rot	0.559
Tip Drive Xwing	0.559
Tilt Duct Fan	is unviable for this mission
Tilt Wing	is unviable for this mission

Aircraft performing Navy Spec Ops mission sorted by rank

Var Diam Tilt Rot	0.712
Folding Tilt Rot	0.711
Tilt Rotor	0.697
Stowed Rotor	0.667
Shrouded Rotor	0.667
Stopped Retract Rot	0.660
Stopped Rotor	0.646
Tilt Wing	0.637
Fan in Wing	0.633
Tilt Duct Fan	0.620
Xwing	0.598
Tip Drive Stop Rot	0.559
Tip Drive Xwing	0.552

TABLE A-5. MISSION TOGW DERIVATION SEQUENCE AND DATA SOURCES

SEQUENCE	DATA SOURCE OR CALCULATION METHOD
Weight empty fraction	Existing vehicle or study
Propulsion system resize	Aerodynamic sizing methodology
Propulsion system weight	Engine weight trends Transmission hover power Fuel requirement
Weight empty fixed equipment as specified in statement of work	
Militarization	Equivalent percent to UH-60A
Discriminating features	Percent equivalent to existing systems adjusted for relative difficulty
Technology	Aerodynamic methodology Historical weight trends
Gross weight iterations	Fuel trend with gross weight
Final gross weight	Aerodynamic sizing methodology

Table A-6. EMPTY WEIGHT FRACTION DERIVATIONS, MILITARY TRANSPORT MISSION, TILT WING/ROTOR CONCEPTS

TILT WING/ROTOR

ITEM	TILT WING XC-142-TYPE WEIGHT	% GW	TILT ROTOR V-22-TYPE WEIGHT	% GW	VAR DIA TILT ROTOR V-22-TYPE WEIGHT	% GW	FOLDING TILT ROTOR V-22-TYPE WEIGHT	% GW
NASA500 2/27/90								
DESIGN GROSS WEIGHT @ LLF=3	37474.00		39500.00		39500.00		39500.00	
PAYLOAD REQUIREMENT	6470.00		6470.00		6470.00		6470.00	
WEIGHT EMPTY	25610.00	68.34	31000.00	78.48	31000.00	78.48	31000.00	78.48
DELETE: FUEL SYSTEM	-462.00	-1.23	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77
ENGINES	-2877.00	-7.68	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94
ERI	-1729.00	-4.61	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32
XMSN	-2871.00	-7.66	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-8.86
AUTO ROTOR FOLD'G WING STOW			-975.00	-2.47	-975.00	-2.47	-975.00	-2.47
EQUIPMENT GROUPS	-3177.00	-8.48	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67
ITEMS INCL IN MILITERIZATION:								
-ARMORED CREW SEATS			-200.00	-0.51	-200.00	-0.51	-200.00	-0.51
-IR SUPPRESSION			-400.00	-1.01	-400.00	-1.01	-400.00	-1.01
ADD: ROTOR FOLD/STOW								
FUEL SYSTEM (10 GAL)	894.00	2.39	1398.00	3.54	1337.00	3.38	1580.00	4.00
ENGINES	3280.00	8.75	3200.00	8.10	2700.00	6.84	1337.00	3.38
ERI	1968.00	5.25	2830.00	7.16	2389.00	6.05	4000.00	10.13
XMSN	2530.00	6.75	3439.00	8.71	3140.00	7.95	3539.00	8.96
AIRFRAME (Q FOR 450 KTS)	260.00	0.69	300.00	0.76	300.00	0.76	1861.00	4.71
DISC LOAD ADJUSTMENT	-20.00	-0.05	-988.00	-2.50	0.00	0.00	300.00	0.76
MILITERIZATION UH-60A	1660.00	4.43	1750.00	4.43	1750.00	4.43	-988.00	-2.50
FIXED EQUIPMENT	3000.00	8.01	3000.00	7.59	3000.00	7.59	1750.00	4.43
ARMOR	400.00	1.07	400.00	1.01	400.00	1.01	3000.00	7.59
AVIONICS/FMC CONTROL	1500.00	4.00	1500.00	3.80	1500.00	3.80	400.00	1.01
MISSION KIT	1000.00	2.67	1000.00	2.53	1000.00	2.53	1500.00	3.80
TRAC ROTOR 2% GW					790.00	2.00	1000.00	2.53
DESIGN FRACT EQUIV TO Vzz	1873.00	5.00		0.00		0.00	0.00	0.00
(DESIGN REQ., EMI, ETC.								0.00
ACABIN VOLUME DELTA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PRESSURIZATION	749.48	2.00	790.00	2.00	790.00	2.00	790.00	2.00
WEIGHT EMPTY RECONFIGURED	33588.48	89.63	34394.00	87.07	34871.00	88.28	35844.00	90.74
WEIGHT TECHNOLOGY TO 1980	-3372.66	-9.00		0.00		0.00		0.00
	30215.82	80.63	34394.00	87.07	34871.00	98.28	35844.00	90.74
AERO TECHNOLOGY TO 2000 AD:								
- XMSN POWER	-405.00	-1.08	-584.00	-1.48	-518.00	-1.31	-245.00	-0.62
-ENGINE POWER	-540.00	-1.44	-639.00	-1.62	-568.00	-1.44	-513.00	-1.30
-FUEL CAPACITY (@10 GAL)	-243.00	-0.65	-486.00	-1.23	-486.00	-1.23	-304.00	-0.77
	29027.82	77.46	32685.00	82.75	33299.00	84.30	34782.00	38.06
WEIGHT TECHNOLOGY TO 2000 AD	-4496.88	-12.00	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00
	24530.94	65.46	27945.00	70.75	28559.00	72.30	30042.00	76.06

Table A-6. CONTINUED

FUEL (2000)	5808.47	15.50	5925.00	15.00	5530.00	14.00	5925.00	15.00
GROSS WEIGHT LESS PAYLOAD	30339.41	80.96	33870.00	85.75	34089.00	86.30	35967.00	91.06

DERIVATION PARAMETERS	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD
HP/GW	0.50	0.42	0.53	0.44	0.50	0.42	0.38	0.33
HP TOTAL	18737.00	15739.08	20935.00	17380.00	19750.00	16590.00	15010.00	13035.00
FUEL (% GW)	22.00	15.50	23.00	15.00	22.00	14.00	20.00	15.00
NO. OF ENGINES	4	4	2	2	2	2	2	2
NO. OF	4	4	2	2	2	2	2	2
INSN HP /PP	9930.61	8341.71	11095.55	9211.40	10467.50	8792.70	6004.00	5214.00
$/HP	.255		0.31		0.31		0.31	
INSN % OF ENGINE POWER	0.53	0.53	0.53	0.53	0.53	0.53	0.40	0.40
DISC LOAD	50	50	20	20	15.00	15.00	20.00	20.00
TYPE OF ENGINES	SHAFT	SHAFT	SHAFT	SHAFT	SHAFT	SHAFT	CONV	CONV

FIRST PROJECTION

PROJECTED GROSS WEIGHT	33983.28	100.00	45393.43	100.00	47230.64	100.00	72336.54	100.00
WEIGHT EMPTY	22245.87	65.46	32114.41	70.75	34148.35	72.30	55016.06	76.06
PAYLOAD	6470.00	19.04	6470.00	14.25	6470.00	13.70	6470.00	8.94
FUEL	5267.41	15.50	6809.01	15.00	6612.29	14.00	10850.48	15.00

SECOND PROJECTION

PROJECTED GROSS WEIGHT	34247.41	100.00	44617.40	100.00	46135.46	100.00	62660.04	100.00
WEIGHT EMPTY	22418.85	65.46	31565.23	70.75	33356.29	72.30	47655.20	76.05
PAYLOAD	6470.00	18.89	6470.00	14.50	6470.00	14.02	6470.00	10.33
FUEL	5358.56	15.65	6582.17	14.75	6309.17	13.68	8534.84	13.62

THIRD PROJECTION

PROJECTED GROSS WEIGHT	34227.28	100.00	44718.06	100.00	46287.51	100.00	65231.49	100.00
WEIGHT EMPTY	22405.67	65.46	31636.47	70.75	33466.26	72.30	49611.29	76.05
PAYLOAD	6470.00	18.90	6470.00	14.47	6470.00	13.98	6470.00	9.92
FUEL	5351.61	15.64	6611.60	14.79	6351.25	13.72	9150.20	14.03

SOLUTION PARAMETERS		2000 AD		2000 AD		2000 AD		2000 AD
HP/GW		0.42		0.44		0.42		0.33
ENGINE HP TOTAL		14375.46		19675.95		19440.76		21526.39
INSN HP		7618.99		10428.25		10303.60		8610.56

Table A-7. EMPTY WEIGHT FRACTION DERIVATIONS, MILITARY TRANSPORT, STOPPED AND STOWED ROTOR CONCEPTS

S T O P P E D   R O T O R S

ITEM	STOPPED ROTOR V-22-TYPE (I)		STOPPED ROTOR RETRACTABLE V-22-TYPE (I)		STOPPED ROTOR TIP DRIVE V-22-TYPE (Y)		STOWED ROTOR V-22-TYPE	
NASA500 2/12/90	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW
DESIGN GROSS WEIGHT @ LLF=3	39500.00		39500.00		39500.00		39500.00	
PAYLOAD REQUIREMENT	6470.00		6470.00		6470.00		6470.00	
WEIGHT EMPTY	31000.00	78.48	31000.00	78.48	31000.00	78.48	31000.00	78.48
DELETE: FUEL SYSTEM	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77
ENGINES	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94
ERI	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32
INSH	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-3.36
AUTO ROTOR FOLD'G WING STOW	-975.00	-2.47	-975.00	-2.47	-975.00	-2.47	-975.00	-2.47
EQUIPMENT GROUPS	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67
ITEMS INCL IN MILITERIZATION:								
-ARMORED CREW SEATS	-200.00	-0.51	-200.00	-0.51	-200.00	-0.51	-200.00	-0.51
-IR SUPPRESSION	-400.00	-1.01	-400.00	-1.01	-400.00	-1.01	-400.00	-1.01
WING	-3371.00	-8.53	-3371.00	-8.53	-3371.00	-8.53	-3371.00	-3.53
ROTOR	-3615.00	-9.15	-3615.00	-9.15	-3615.00	-9.15	-3615.00	-9.15
ADD: ROTOR FOLD/STOW/STOP	790.00	2.00	1185.00	3.00	790.00	2.00	1185.00	3.00
FUEL SYSTEM (10 GAL)	1276.00	3.23	1215.00	3.08	1385.00	3.51	951.00	2.15
ENGINES	4200.00	10.63	4000.00	10.13	3000.00	7.59	3200.00	8.10
ERI	3714.00	9.40	3537.00	8.95	2653.00	6.72	2931.00	7.27
INSH	2500.00	6.35	1910.00	4.84	2211.00	5.60	317.00	4.60
AIRFRAME (Q FOR 450 KTS)	300.00	0.76	300.00	0.76	300.00	0.76	300.00	0.76
ROTOR/WING	5925.00	15.00	6715.00	17.00	4740.00	12.00	3950.00	10.00
WING							2765.00	7.00
DISC LOAD ADJUSTMENT	0.00	0.00			0.00	0.00		
MILITERIZATION UH-60A	1750.00	4.43	1750.00	4.43	1750.00	4.43	1750.00	4.43
FIXED EQUIPMENT	3000.00	7.59	3000.00	7.59	3000.00	7.59	3000.00	7.59
ARMOR	400.00	1.01	400.00	1.01	400.00	1.01	400.00	1.01
AVIONICS/FMC CONTROL	1500.00	3.80	1500.00	3.80	1500.00	3.80	1500.00	3.80
MISSION KIT	1000.00	2.53	1000.00	2.53	1000.00	2.53	1000.00	2.53
TRAC ROTOR 2% GW		0.00		0.00		0.00	790.00	2.00
DESIGN FRACT EQUIV TO Vzz		0.00		0.00		0.00		0.00
(DESIGN REQ., EMI, ETC.								
ANTI-TORQUE DEVICE	395.00	1.00	395.00	1.00		0.00	395.00	1.00
APT DUCTING		0.00		0.00	395.00	1.00		0.00
CABIN VOLUME DELTA	0.00	0.00	0.00	0.00	0.00	0.00	395.00	1.00
PRESSURIZATION	790.00	2.00	790.00	2.00	790.00	2.00	1185.00	3.00
WEIGHT EMPTY RECONFIGURED	36337.00	91.99	36486.00	92.37	32703.00	82.79	36103.00	91.40
WEIGHT TECHNOLOGY TO 1980								0.00
	36337.00	91.99	36486.00	92.37	32703.00	82.79	36103.00	91.40
AERO TECHNOLOGY TO 2000 AD:								
- INSH POWER	-294.00	-0.74	-245.00	-0.62	-247.00	-0.63	-264.00	-0.67
-ENGINE POWER	-616.00	-1.56	-513.00	-1.30	-237.00	-0.60	-395.00	-1.00

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Table A-7. CONTINUED

-FUEL CAPACITY (010 GAL)	-365.00	-0.92	-364.00	-0.92	-365.00	-0.92	-243.00	-0.62
	35062.00	88.76	35364.00	89.53	31854.00	80.64	35201.00	89.12
WEIGHT TECHNOLOGY TO 2000 AD	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00
	30322.00	76.76	30624.00	77.53	27114.00	68.64	30461.00	77.12
FUEL (2000)	5925.00	15.00	5530.00	14.00	6636.00	16.80	3950.00	10.00
GROSS WEIGHT LESS PAYLOAD	36247.00	91.76	36154.00	91.53	33750.00	85.44	34411.00	87.12
DERIVATION PARAMETERS	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD
HP/GW	0.42	0.36	0.39	0.34	0.45	0.40	0.28	0.24
HP TOTAL	16590.00	14220.00	15405.00	13430.00	17577.50	15602.50	11060.00	9480.00
FUEL (% GW)	21.00	15.00	20.00	14.00	22.80	16.80	14.00	10.00
NO. OF ENGINES	2	2	2	2	2	2	2	2
NO. OF	2	2	2	2	2	2	2	2
INSN HP /PP	6636.00	5688.00	6162.00	5372.00	8788.75	7801.25	5861.80	5024.40
$/HP	0.31		0.31		0.25		0.31	
INSN % OF ENGINE POWER	0.60	0.40	0.40	0.40	0.50	0.50	0.53	0.53
DISC LOAD	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
TYPE OF ENGINES	CONV	CONV	CONV	CONV	TB FAN	TB FAN	CONV	CONV
FIRST PROJECTION								
PROJECTED GROSS WEIGHT	78562.87	100.00	76379.26	100.00	44446.09	100.00	50219.10	100.00
WEIGHT EMPTY	60308.44	76.76	59216.16	77.53	30509.14	68.64	38727.19	77.12
PAYLOAD	6470.00	8.24	6470.00	8.47	6470.00	14.56	6470.00	12.88
FUEL	11784.43	15.00	10693.10	14.00	7466.94	16.80	5021.91	10.00
SECOND PROJECTION								
PROJECTED GROSS WEIGHT	65495.06	100.00	64556.70	100.00	43819.79	100.00	48520.98	100.00
WEIGHT EMPTY	50275.34	76.76	50048.70	77.53	30079.10	68.64	37417.32	77.12
PAYLOAD	6470.00	9.88	6470.00	10.02	6470.00	14.77	6470.00	13.33
FUEL	8749.72	13.36	8038.00	12.45	7270.70	16.59	4633.66	9.55
THIRD PROJECTION								
PROJECTED GROSS WEIGHT	69354.26	100.00	67927.32	100.00	43898.12	100.00	48782.30	100.00
WEIGHT EMPTY	53238.32	76.76	52662.35	77.53	30132.88	68.64	37618.89	77.12
PAYLOAD	6470.00	9.33	6470.00	9.52	6470.00	14.74	6470.00	13.26
FUEL	9645.93	13.91	8794.97	12.95	7295.24	16.62	4693.40	9.62
SOLUTION PARAMETERS		2000 AD		2000 AD		2000 AD		2000 AD
HP/GW		0.36		0.34		0.40		0.24
ENGINE HP TOTAL		24967.53		23095.29		17339.76		11707.75
INSN HP		9987.01		9238.12		8669.88		6205.11

Table A-8. EMPTY WEIGHT FRACTION DERIVATIONS, MILITARY TRANSPORT, SHROUDED ROTOR AND X-WING CONCEPTS

ITEM	LIFT FAN: FAN IN WING XV-5A-TYPE		LIFT FAN: TILT DUCT FAN X-22-TY		LIFT FAN: FAN IN FUSELAGE ABC-TYPE (STUDIES)		X-WINGS: X-WING RSRA-TYPE (STUDIES)		X-WINGS: TIP DRIVE X-WING RSRA-TYPE (STUDIES)	
NASA500 2/22/90	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW
DESIGN GROSS WEIGHT @ LLF=3	12667.00		14700.00		15000.00		24000.00		15000.00	
PAYLOAD REQUIREMENT	6470.00		6470.00		6470.00		6470.00		6470.00	
WEIGHT EMPTY	7541.05	59.53	11025.00	75.00	11100.00	74.00	16800.00	70.00	9750.00	65.00
DELETE: FUEL SYSTEM	-112.00	-0.88	-175.00	-1.19	-360.00	-2.40	-176.00	-0.73	-370.00	-2.47
ENGINES	-951.00	-7.51	-1191.00	-8.10	-2195.00	-14.63	-1820.00	-7.58	-2475.00	-16.50
ENI	-359.00	-2.83	-864.00	-5.88	-1100.00	-7.33	-900.00	-3.75	-1240.00	-8.27
INSN/DUCTS	-306.00	-2.42	-1000.00	-6.80	-1553.00	-10.35	-2800.00	-11.67	-775.00	-5.17
AUTO ROTOR FOLDING WING STOW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EQUIPMENT GROUPS	-708.00	-5.59	-1326.00	-9.02	-1200.00	-8.00	-1200.00	-5.00	-1200.00	-8.00
ITEMS INCL IN MILITERIZATION:										
-ARMORED CREW SEATS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-IR SUPPRESSION	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WING/PROP SUPPORT	0.00	0.00	0.00	0.00	0.00	0.00	-175.00	-0.73	0.00	0.00
ROTOR/FANS	-1740.00	-13.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PROP SYSTEM	0.00	0.00	0.00	0.00	0.00	0.00	-716.00	-2.98	0.00	0.00
ADD: ROTOR FOLD/STOW/STOP	0.00	2.00			0.00	0.00	0.00	0.00	0.00	0.00
FUEL SYSTEM (10 GAL)	430.00	3.39	600.00	4.08	700.00	4.67	600.00	3.00	530.00	3.00
ENGINES	1000.00	7.89	200.00	1.36	2200.00	14.67	3000.00	12.50	1640.00	10.93
ENI	410.00	3.24	1600.00	10.88	1100.00	7.33	1500.00	6.25	1000.00	6.00
INSN/DUCTS	196.00	1.55	900.00	6.12	1600.00	10.67	1500.00	6.25	1029.00	2.00
AIRFRAME (Q FOR 450 KTS)	95.00	0.75	147.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
ROTOR/WING	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WING										
LIFT FANS	1748.05	13.80	3500.00	14.60	0.00	0.00	0.00	0.00	0.00	0.00
PITCH FAN	316.68	2.50	600.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00
DISC LOAD ADJUSTMENT	443.35	3.50	1176.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00
MILITERIZATION UH-60A	561.15	4.43	651.21	4.43	0.00	0.00	0.00	0.00	0.00	0.00
FIXED EQUIPMENT •	3000.00	23.68	3000.00	20.41	3000.00	20.00	3000.00	12.50	3000.00	20.00
ARMOR •	400.00	3.16	400.00	2.72	400.00	2.67	400.00	1.67	400.00	2.67
AVIONICS/FMC CONTROL •	1500.00	11.84	1500.00	10.20	1500.00	10.00	1500.00	6.25	1500.00	10.00
MISSION KIT •	1000.00	7.89	1000.00	6.80	1000.00	6.67	1000.00	4.17	1000.00	6.67
TRAC ROTOR		0.00		0.00		0.00	0.00	0.00	0.00	0.00
DESIGN FRACT EQUIV TO Vzz		0.00		0.00		0.00		0.00		0.00
(DESIGN REQ., ENI, ETC.										
ANTI-TORQUE DEVICE	0.00	0.00	0.00	0.00		0.00	240.00	1.00	0.00	0.00
AFT DUCTING		0.00		0.00	0.00	0.00		0.00		0.00
CABIN VOLUME DELTA	380.01	3.00	441.00	3.00	450.00	3.00	720.00	3.00	450.00	3.00
PRESSURIZATION	253.34	2.00	294.00	2.00	300.00	2.00	480.00	2.00	300.00	2.00
WEIGHT EMPTY RECONFIGURED	15098.61	121.20	22478.21	142.12	16942.00	112.95	22953.00	96.14	14539.00	90.87
WEIGHT TECHNOLOGY TO 1980	-1140.03	-9.00	-1323.00	-9.00	0.00	0.00	0.00	0.00	0.00	0.00
AERO TECHNOLOGY TO 2000 AD:	13958.58	112.20	21155.21	133.12	16942.00	112.95	22953.00	96.14	14539.00	90.87

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Table A-8. CONTINUED

- INSH POWER	-30.00	-0.24	-245.00	-1.64	-154.50	-1.03	-264.00	-1.10
-ENGINE POWER	-65.00	-0.51	-513.00	-3.49	-148.50	-0.99	-396.00	-1.65
-FUEL CAPACITY (W10 GAL)	-79.00	-0.62	-464.00	-2.48	-229.00	-1.52	-242.40	-1.01
-FAN EFFICIENCY (10%)	-250.00	-1.97	-500.00	-3.40	0.00	0.00	0.00	0.00
	13534.58	108.85	19533.21	122.09	16411.00	109.41	22050.60	92.38
WEIGHT TECHNOLOGY TO 2000 AD	-1520.04	-12.00	-1764.00	-12.00	-1800.00	-12.00	-2880.00	-12.00
	12014.54	96.85	17769.21	110.09	14611.00	97.41	19170.60	80.38
FUEL (2000)	2280.06	18.00	2058.00	14.00	2400.00	16.00	3840.00	16.00
GROSS WEIGHT LESS PAYLOAD	14294.60	114.85	19827.21	124.09	17011.00	113.41	23010.60	96.38

- INSH POWER	-165.00	-1.10
-ENGINE POWER	-247.50	-1.65
-FUEL CAPACITY (W10 GAL)	-151.50	-1.01
-FAN EFFICIENCY (10%)	0.00	0.00
	13975.00	87.11
WEIGHT TECHNOLOGY TO 2000 AD	-1800.00	-12.00
	12175.00	75.11
FUEL (2000)	2700.00	18.00
GROSS WEIGHT LESS PAYLOAD	14875.00	93.11

DERIVATION PARAMETERS	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD
HP/GW	0.47	0.44	0.39	0.34	0.41	0.36	0.40	0.40	0.49	0.45
HP TOTAL	5953.49	5573.48	5733.00	4998.00	6150.00	5400.00	9600.00	9600.00	7350.00	6750.00
FUEL (% GW)	22.00	18.00	20.00	14.00	21.00	16.00	20.00	16.00	23.00	18.00
NO. OF ENGINES	2	2	4	4	2	2	2	2	2	2
NO. OF ROTOR/FAN	3	3	4	4	1	1	1	1	1	1
INSH HP /PP	0.00	0.00	2293.20	1999.20	3075.00	2700.00	5088.00	5088.00	4116.00	3780.00
0/HP	0.00		0.31		0.25		0.31		0.25	
INSH % OF ENGINE POWER	0.00	0.00	0.40	0.40	0.50	0.50	0.53	0.53	0.56	0.56
DISC LOAD	50.00	50.00	15.00	15.00	40.00	40.00	20.00	20.00	15.00	15.00
TYPE OF ENGINES	THRUST	THRUST	SHAFT	SHAFT	CONV	CONV	CONV	CONV	TB FAN	TB FAN

FIRST PROJECTION

PROJECTED GROSS WEIGHT	-43571.52	100.00	-26860.04	100.00	-48259.57	100.00	178605.94	100.00	93858.00	100.00
WEIGHT EMPTY	-42198.65	96.85	-29569.64	110.09	-47008.04	97.41	143558.99	80.38	70494.22	75.11
PAYLOAD	6470.00	-14.85	6470.00	-24.09	6470.00	-13.41	6470.00	3.62	6470.00	6.89
FUEL	-7842.87	18.00	-3760.41	14.00	-7721.53	16.00	28576.95	16.00	16894.58	18.00

SECOND PROJECTION

PROJECTED GROSS WEIGHT	-37583.94	100.00	-25042.55	100.00	-40267.23	100.00	63895.31	100.00	63366.15	100.00
WEIGHT EMPTY	-36401.09	96.85	-27569.47	110.09	-39224.61	97.41	51351.07	80.37	47588.98	75.10
PAYLOAD	6470.00	-17.21	6470.00	-25.84	6470.00	-16.07	6470.00	10.13	6470.00	10.21
FUEL	-7652.85	20.36	-3943.00	15.75	-7512.62	18.66	6074.24	9.51	9307.18	14.69

THIRD PROJECTION

PROJECTED GROSS WEIGHT	-38141.98	100.00	-25116.87	100.00	-41127.77	100.00	122059.79	100.00	72469.96	100.00
WEIGHT EMPTY	-36941.42	96.85	-27651.26	110.09	-40062.66	97.41	98105.66	80.37	54427.51	75.10
PAYLOAD	6470.00	-16.96	6470.00	-25.76	6470.00	-15.73	6470.00	5.30	6470.00	8.93
FUEL	-7670.56	20.11	-3935.61	15.67	-7535.11	18.32	17484.33	14.32	11572.45	15.97

SOLUTION PARAMETERS		2000 AD		2000 AD		2000 AD		2000 AD		2000 AD
HP/GW		0.44		0.34		0.36		0.40		0.45
ENGINE HP TOTAL		-16782.47		-8539.74		-14806.00		48823.92		32611.48
INSH HP		0.00		-3415.89		-7403.00		25876.68		18262.43

Table A-9. EMPTY WEIGHT FRACTION DERIVATION, SCOUT-ATTACK MISSION, TILT WING/ROTOR CONCEPTS

TILT WING/ROTOR

ITEM	TILT WING XC-142-TYPE		TILT ROTOR V-22-TYPE		VAR DIA TILT ROTOR V-22-TYPE		FOLDING TILT ROTOR V-22-TYPE	
NASA400 2/27/90	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW
DESIGN GROSS WEIGHT @ LLF-3	37474.00		39500.00		39500.00		39500.00	
PAYLOAD REQUIREMENT	3470.00		3470.00		3470.00		3470.00	
WEIGHT EMPTY	25610.00	68.34	31000.00	78.48	31000.00	78.48	31000.00	78.48
DELETE: FUEL SYSTEM	-462.00	-1.23	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77
ENGINES	-2877.00	-7.68	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94
ERI	-1729.00	-4.61	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32
IRSS	-2871.00	-7.66	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-8.86
AUTO ROTOR FOLD'G WING STOW			-975.00	-2.47	-975.00	-2.47	-975.00	-2.47
EQUIPMENT GROUPS	-3177.00	-8.48	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67
ITEMS INCL IN MILITERIZATION:								
-ARMORED CREW SEATS			-200.00	-0.51	-200.00	-0.51	-200.00	-0.51
-IR SUPPRESSION			-400.00	-1.01	-400.00	-1.01	-400.00	-1.01
ADD: ROTOR FOLD/STOW								
FUEL SYSTEM (10 GAL)	894.00	2.39	1215.00	3.08	1215.00	3.08	1580.00	4.00
ENGINES	1900.00	5.07	1900.00	4.81	1900.00	4.81	1458.00	3.69
ERI	1140.00	3.04	1680.00	4.25	1680.00	4.25	3200.00	8.10
IRSS	4678.00	12.48	4937.00	12.50	3942.00	9.98	2831.00	7.17
AIRFRAME (Q FOR 450 KTS)	0.00	0.00	0.00	0.00	0.00	0.00	2677.00	6.78
DISC LOAD ADJUSTMENT	0.00	0.00	-988.00	-2.50	0.00	0.00	0.00	0.00
MILITERIZATION UH-60A	1660.00	4.43	1750.00	4.43	1750.00	4.43	-988.00	-2.50
FIXED EQUIPMENT	2000.00	5.34	2000.00	5.06	2000.00	5.06	1750.00	4.43
ARMOR	400.00	1.07	400.00	1.01	400.00	1.01	2000.00	5.06
AVIONICS/FMC CONTROL	2000.00	5.34	2000.00	5.06	2000.00	5.06	400.00	1.01
MISSION KIT	500.00	1.33	500.00	1.27	500.00	1.27	2000.00	5.06
TRAC ROTOR 2% GW							500.00	1.27
DESIGN FRACT EQUIV TO Vzz	1873.00	5.00		0.00	750.00	2.00	0.00	0.00
(DESIGN REQ., EMI, ETC.						0.00		0.00
CABIN VOLUME DELTA	-1124.22	-3.00	-1185.00	-3.00	-1185.00	-3.00	-1185.00	-3.00
PRESSURIZATION	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WEIGHT EMPTY RECONFIGURED	30414.78	81.16	29984.00	75.91	30767.00	77.89	31998.00	81.01
WEIGHT TECHNOLOGY TO 1980	-3372.66	-9.00		0.00		0.00		0.00
	27042.12	72.16	29984.00	75.91	30767.00	77.89	31998.00	81.01
AERO TECHNOLOGY TO 2000 AD:								
- IRSS POWER	-138.00	-0.37	-881.00	-2.23	-704.00	-1.78	-198.00	-0.50
-ENGINE POWER	-68.00	-0.18	-356.00	-0.90	-140.00	-0.35	-205.00	-0.52
-FUEL CAPACITY (@10 GAL)	-461.00	-1.23	-486.00	-1.23	-486.00	-1.23	-436.00	-1.10
	26375.12	70.38	28261.00	71.55	29437.00	74.52	31159.00	78.88
WEIGHT TECHNOLOGY TO 2000 AD	-4496.88	-12.00	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00
	21878.24	58.38	23521.00	59.55	24697.00	62.52	26419.00	66.88

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TABLE A-9. CONTINUED

FUEL (2000)	4496.88	12.00	4740.00	12.00	4740.00	12.00	6320.00	16.00
GROSS WEIGHT LESS PAYLOAD	26375.12	70.38	28261.00	71.55	29437.00	74.52	32739.00	82.88

DERIVATION PARAMETERS	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD
HP/GW	0.34	0.33	0.28	0.23	0.28	0.23	0.27	0.25
HP TOTAL (MCP * 1.15)	12741.16	12366.42	11060.00	9085.00	11060.00	9085.00	10665.00	9875.00
FUEL (% GW)	20.00	12.00	20.00	12.00	18.00	12.00	24.00	16.00
NO. OF ENGINES	2	2	2	2	2	2	2	2
NO. OF ROTORS	2	2	2	2	2	2	2	2
INSH HP /PP	18347.27	17807.64	15926.40	13082.40	12719.00	10447.75	8638.65	7998.75
0/HP	.255		0.31		0.31		0.31	
INSH % OF ENGINE POWER	1.44	1.44	1.44	1.44	1.15	1.15	0.81	0.81
DISC LOAD	40	40	20	20	15	15	20	20
TYPE OF ENGINES	SHAFT	SHAFT	SHAFT	SHAFT	SHAFT	SHAFT	CONV	CONV

FIRST PROJECTION

PROJECTED GROSS WEIGHT	11716.03	100.00	12195.48	100.00	13620.69	100.00	20272.89	100.00
WEIGHT EMPTY	6840.10	58.38	7262.02	59.55	8516.21	62.52	13559.23	66.88
PAYLOAD	3470.00	29.62	3470.00	28.45	3470.00	25.48	3470.00	17.12
FUEL	1405.92	12.00	1463.46	12.00	1634.48	12.00	3243.66	16.00

SECOND PROJECTION

PROJECTED GROSS WEIGHT	12160.91	100.00	12708.48	100.00	14228.69	100.00	21278.32	100.00
WEIGHT EMPTY	7100.04	58.38	7567.72	59.55	8896.59	62.53	14231.96	66.88
PAYLOAD	3470.00	28.53	3470.00	27.30	3470.00	24.39	3470.00	16.31
FUEL	1590.87	13.08	1670.76	13.15	1862.10	13.09	3576.36	16.81

THIRD PROJECTION

PROJECTED GROSS WEIGHT	12152.94	100.00	12698.44	100.00	14213.78	100.00	21223.28	100.00
WEIGHT EMPTY	7095.38	58.38	7561.74	59.55	8887.27	62.53	14195.13	66.88
PAYLOAD	3470.00	28.55	3470.00	27.33	3470.00	24.41	3470.00	16.35
FUEL	1587.56	13.06	1666.70	13.13	1856.52	13.06	3558.15	16.77

SOLUTION PARAMETERS		2000 AD		2000 AD		2000 AD		2000 AD
HP/GW		0.33		0.23		0.23		0.25
ENGINE HP TOTAL		4010.47		2920.64		3269.17		5305.82
INSH HP		5775.08		4205.72		3759.55		4297.71

Table A-10. EMPTY WEIGHT FRACTION DERIVATION, SCOUT-ATTACK MISSION, STOPPED AND STOWED ROTOR CONCEPTS

STOPPED ROTORS

ITEM	STOPPED ROTOR V-22-TYPE (X)		STOPPED ROTOR RETRACTABLE V-22-TYP (X)		STOPPED ROTOR TIP DRIVE V-22-TYPE (Y)		STOWED ROTOR V-22-TYPE	
NASA400 2.14.90	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW	WEIGHT	% GW
DESIGN GROSS WEIGHT @ LLF=3	39500.00		39500.00		39500.00		39500.00	
PAYLOAD REQUIREMENT	3470.00		3470.00		3470.00		3470.00	
WEIGHT EMPTY	31000.00	78.48	31000.00	78.48	31000.00	78.48	31000.00	78.48
DELETE: FUEL SYSTEM	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77	-700.00	-1.77
ENGINES	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94	-1950.00	-4.94
ERI	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32	-2100.00	-5.32
INSN	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-8.86	-3500.00	-8.86
AUTO ROTOR FOLD'G WING STOW	-975.00	-2.47	-975.00	-2.47	-975.00	-2.47	-975.00	-2.47
EQUIPMENT GROUPS	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67	-5400.00	-13.67
ITEMS INCL IN MILITERIZATION:								
-ARMORED CREW SEATS	-200.00	-0.51	-200.00	-0.51	-200.00	-0.51	-200.00	-0.51
-IR SUPPRESSION	-400.00	-1.01	-400.00	-1.01	-400.00	-1.01	-400.00	-1.01
WING	-3371.00	-8.53	-3371.00	-8.53	-3371.00	-8.53	-3371.00	-8.53
ROTOR	-3615.00	-9.15	-3615.00	-9.15	-3615.00	-9.15	-3615.00	-9.15
ADD: ROTOR FOLD/STOW/STOP	790.00	2.00	1185.00	3.00	790.00	2.00	1185.00	3.00
FUEL SYSTEM (10 GAL)	1458.00	3.69	1337.00	3.38	1550.00	3.92	1276.00	3.23
ENGINES	2800.00	7.09	2800.00	7.09	2400.00	6.08	3000.00	7.59
ERI	2476.00	6.27	2476.00	6.27	2122.00	5.37	2654.00	6.72
INSN	2057.00	5.21	2057.00	5.21	2400.00	6.08	2083.00	5.27
AIRFRAME (Q FOR 450 KTS)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROTOR/WING	5925.00	15.00	6715.00	17.00	3989.50	10.10	3950.00	10.00
WING							2765.00	7.00
DISC LOAD ADJUSTMENT	0.00	0.00			0.00	0.00		
MILITERIZATION UH-60A	1750.00	4.43	1750.00	4.43	1750.00	4.43	1750.00	4.43
FIXED EQUIPMENT	2000.00	5.06	2000.00	5.06	2000.00	5.06	2000.00	5.06
ARMOR	400.00	1.01	400.00	1.01	400.00	1.01	400.00	1.01
AVIONICS/FMC CONTROL	2000.00	5.06	2000.00	5.06	2000.00	5.06	2000.00	5.06
MISSION KIT	500.00	1.27	500.00	1.27	500.00	1.27	500.00	1.27
TRAC ROTOR 2% GW		0.00		0.00		0.00		0.00
DESIGN FRACT EQUIV TO Vzz		0.00		0.00		0.00		0.00
DESIGN REQ., EMI, ETC.								
ANTI-TORQUE DEVICE	395.00	1.00	395.00	1.00	395.00	1.00	395.00	1.00
AFT DUCTING		0.00		0.00		0.00		0.00
CABIN VOLUME DELTA	-1185.00	-3.00	-1185.00	-3.00	-1185.00	-3.00	-790.00	-2.00
PRESSURIZATION	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WEIGHT EMPTY RECONFIGURED	30155.00	76.34	31219.00	79.04	27900.50	70.63	31957.00	80.90
WEIGHT TECHNOLOGY TO 1980								0.00
	30155.00	76.34	31219.00	79.04	27900.50	70.63	31957.00	80.90
AERO TECHNOLOGY TO 2000 AD:								
- INSN POWER	-5.00	-0.01	-5.00	-0.01	-240.00	-0.61	-99.00	-0.25
-ENGINE POWER	-27.00	-0.07	-27.00	-0.07	-237.00	-0.60	-102.00	-0.26

TABLE A-10. CONTINUED

-FUEL CAPACITY (010 GAL)	-121.00	-0.31	-486.00	-1.23	-425.00	-1.08	-334.00	-0.85
	30002.00	75.95	30701.00	77.72	26998.50	68.35	31422.00	79.55
WEIGHT TECHNOLOGY TO 2000 AD	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00	-4740.00	-12.00
	25262.00	63.95	25961.00	65.72	22258.50	56.35	26682.00	67.55
FUEL (2000)	8690.00	22.00	6320.00	16.00	7307.50	18.50	5332.50	13.50
GROSS WEIGHT LESS PAYLOAD	33952.00	85.95	32281.00	81.72	29566.00	74.85	32014.50	81.05

DERIVATION PARAMETERS	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD	FRACTION	2000 AD
HP/GW	0.21	0.20	0.21	0.20	0.30	0.27	0.21	0.20
HP TOTAL	8295.00	7900.00	8295.00	7900.00	11850.00	10665.00	8295.00	7900.00
FUEL (% GW)	24.00	22.00	22.00	16.00	25.50	18.50	19.00	13.50
NO. OF ENGINES	2	2	2	2	2	2	2	2
NO. OF	2	2	2	2	2	2	2	2
INSN HP /PP	6636.00	6320.00	6636.00	6320.00	9598.50	8638.65	6718.95	6399.00
#/HP	0.31		0.31		0.25		0.31	
INSN % OF ENGINE POWER	0.80	0.80	0.80	0.80	0.81	0.81	0.81	0.81
DISC LOAD	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
TYPE OF ENGINES	CONV	CONV	CONV	CONV	TB FAN	TB FAN	CONV	CONV

FIRST PROJECTION

PROJECTED GROSS WEIGHT	24705.30	100.00	18986.70	100.00	13797.56	100.00	18310.73	100.00
WEIGHT EMPTY	15800.13	63.95	12478.83	65.72	7775.01	56.35	12368.78	67.55
PAYLOAD	3470.00	14.05	3470.00	18.28	3470.00	25.15	3470.00	18.95
FUEL	5435.17	22.00	3037.87	16.00	2552.55	18.50	2471.95	13.50

SECOND PROJECTION

PROJECTED GROSS WEIGHT	25850.70	100.00	19927.57	100.00	14417.36	100.00	19214.46	100.00
WEIGHT EMPTY	16532.91	63.96	13097.47	65.73	8124.51	56.35	12979.51	67.55
PAYLOAD	3470.00	13.42	3470.00	17.41	3470.00	24.07	3470.00	18.06
FUEL	5847.78	22.62	3360.10	16.86	2822.85	19.58	2764.95	14.39

THIRD PROJECTION

PROJECTED GROSS WEIGHT	25758.24	100.00	19882.38	100.00	14401.76	100.00	19174.10	100.00
WEIGHT EMPTY	16473.76	63.96	13067.75	65.73	8115.72	56.35	12952.23	67.55
PAYLOAD	3470.00	13.47	3470.00	17.45	3470.00	24.09	3470.00	18.10
FUEL	5814.48	22.57	3344.62	16.82	2816.04	19.55	2751.87	14.35

SOLUTION PARAMETERS		2000 AD		2000 AD		2000 AD		2000 AD
HP/GW		0.20		0.20		0.27		0.20
ENGINE HP TOTAL		5151.65		3976.48		3888.48		3834.82
INSN HP		4121.32		3181.18		3149.67		3106.20

Table A-11. EMPTY WEIGHT FRACTION DERIVATION, SCOUT-ATTACK MISSION, SHROUDED ROTOR AND X-WING CONCEPTS

LIFT FAN

ITEM	FAN IN WING XV-5A-TYPE WEIGHT	% GW	TILT DUCT FAN X-22-TY WEIGHT	% GW	FAN IN FUSELAGE ABC-TYPE (STUDIES) WEIGHT	% GW
NASA400 . 2 90						
DESIGN GROSS WEIGHT @ LLF=1	12667.00		14700.00		15000.00	
PAYLOAD REQUIREMENT	3470.00		3470.00		3470.00	
WEIGHT EMPTY	7541.93	59.54	11016.10	74.94	11340.00	75.60
DELETE: FUEL SYSTEM	-112.00	-0.88	-175.00	-1.19	-320.00	-2.13
ENGINES	-951.00	-7.51	-1191.00	-8.10	-2285.00	-15.23
DRI	-359.00	-2.83	-864.00	-5.88	-1140.00	-7.60
INSB	-177.00	-1.40	-1000.00	-6.80	-1535.00	-10.23
AUTO ROTOR FOLDING WING STOW	0.00	0.00	0.00	0.00	0.00	0.00
EQUIPMENT GROUPS	-708.00	-5.59	-1326.00	-9.02	-1200.00	-8.00
ITEMS INCL IN MILITERIZATION:						
-ARMORED CREW SEATS	0.00	0.00	0.00	0.00	0.00	0.00
-IR SUPPRESSION	0.00	0.00	0.00	0.00	0.00	0.00
WING/PROP SUPPORT	0.00	0.00	0.00	0.00	0.00	0.00
ROTOR/FANS	-1740.00	-13.74	0.00	0.00	0.00	0.00
PROP SYSTEM	0.00	0.00	0.00	0.00	0.00	0.00
ADD: ROTOR FOLD/STOW/STOP	0.00	2.00			0.00	0.00
FUEL SYSTEM (II GAL)	818.00	6.46	600.00	4.08	807.00	5.38
ENGINES	800.00	6.32	200.00	1.36	2000.00	13.33
DRI	328.00	2.59	1600.00	10.88	1000.00	6.67
INSB	120.00	0.95	900.00	6.12	1312.00	8.75
AIRFRAME (Q FOR 450 KTS)	95.00	0.75	147.00	1.00	0.00	0.00
ROTOR/WING	0.00	0.00	0.00	0.00	0.00	0.00
WING						
LIFT FANS W/TRANSMISSION	1040.00	13.00	3500.00	14.60	0.00	0.00
PITCH FAN	73.00	2.50	600.00	2.50	0.00	0.00
DISC LOAD ADJUSTMENT	443.35	3.50	1176.00	8.00	0.00	0.00
MILITERIZATION UH-60A	561.15	4.43	651.21	4.43	664.50	4.43
FIXED EQUIPMENT	2000.00	15.79	2000.00	13.61	2000.00	13.33
ARMOR	400.00	3.16	400.00	2.72	400.00	2.67
AVIONICS/FMC CONTROL	2000.00	15.79	2000.00	13.61	2000.00	13.33
MISSION KIT	500.00	3.95	500.00	3.40	500.00	3.33
TRAC ROTOR		0.00		0.00		0.00
DESIGN FRACT EQUIV TO V22		0.00		0.00		0.00
(DESIGN REQ., ENI, ETC.						0.00
ANTI-TORQUE DEVICE	0.00	0.00	0.00	0.00	0.00	
AFT DUCTING		0.00		0.00		0.00
CABIN VOLUME DELTA	0.00	0.00	0.00	0.00		0.00
PRESSURIZATION	0.00	0.00	0.00	0.00	0.00	0.00
WEIGHT EMPTY RECONFIGURED	12673.43	109.56	20734.39	130.26	15543.50	103.62
WEIGHT TECHNOLOGY TO 1980	-1140.03	-9.00	-1323.00	-9.00	0.00	0.00
AERO TECHNOLOGY TO 2000 AD:	11533.40	100.56	19411.39	121.26	15543.50	103.62

X-WINGS

ITEM	X-WING RSRA-TYPE (STUDIES) WEIGHT	% GW	TIP DRIVE X-WING RSRA-TYPE (STUDIES) WEIGHT	% GW
DESIGN GROSS WEIGHT @ LLF=1	24000.00		15000.00	
PAYLOAD REQUIREMENT	3470.00		3470.00	
WEIGHT EMPTY	16509.60	68.79	9750.00	65.00
DELETE: FUEL SYSTEM	-176.00	-0.73	-370.00	-2.47
ENGINES	-1820.00	-7.58	-2475.00	-16.50
DRI	-507.00	-2.11	-1240.00	-8.27
INSB	-2800.00	-11.67	-775.00	-5.17
AUTO ROTOR FOLDING WING STOW	0.00	0.00	0.00	0.00
EQUIPMENT GROUPS	-1123.00	-4.68	-1200.00	-8.00
ITEMS INCL IN MILITERIZATION:				
-ARMORED CREW SEATS	0.00	0.00	0.00	0.00
-IR SUPPRESSION	0.00	0.00	0.00	0.00
WING/PROP SUPPORT	-175.00	-0.73	0.00	0.00
ROTOR/FANS	0.00	0.00	0.00	0.00
PROP SYSTEM	-716.00	-2.98	0.00	0.00
ADD: ROTOR FOLD/STOW/STOP	0.00	0.00	0.00	0.00
FUEL SYSTEM (II GAL)	812.00	3.00	669.00	3.00
ENGINES	2200.00	9.17	1200.00	8.00
DRI	1100.00	4.58	600.00	4.00
INSB	1711.00	7.13	1088.00	6.00
AIRFRAME (Q FOR 450 KTS)	180.00	0.75	0.00	0.00
ROTOR/WING	0.00	0.00	0.00	0.00
WING				
LIFT FANS W/TRANSMISSION	0.00	0.00	0.00	0.00
PITCH FAN	0.00	0.00	0.00	0.00
DISC LOAD ADJUSTMENT	0.00	0.00	0.00	0.00
MILITERIZATION UH-60A	1063.20	4.43	664.50	4.43
FIXED EQUIPMENT	2000.00	8.33	2000.00	13.33
ARMOR	400.00	1.67	400.00	2.67
AVIONICS/FMC CONTROL	2000.00	8.33	2000.00	13.33
MISSION KIT	500.00	2.08	500.00	3.33
TRAC ROTOR		0.00		0.00
DESIGN FRACT EQUIV TO V22		0.00		0.00
(DESIGN REQ., ENI, ETC.				
ANTI-TORQUE DEVICE	0.00	0.00	0.00	0.00
AFT DUCTING		0.00		0.00
CABIN VOLUME DELTA	0.00	0.00	0.00	0.00
PRESSURIZATION	0.00	0.00	0.00	0.00
WEIGHT EMPTY RECONFIGURED	21158.00	87.78	12811.50	82.70
WEIGHT TECHNOLOGY TO 1980	0.00	0.00	0.00	0.00
AERO TECHNOLOGY TO 2000 AD:	21158.00	87.78	12811.50	82.70

TABLE A-11. CONTINUED

- INSN POWER	-12.00	-0.09	-245.00	-1.67	-98.00	-1.03	-155.00	-1.10	-116.00	-1.10
-ENGINE POWER	-91.00	-0.72	-513.00	-3.49	-112.00	-0.99	-120.00	-1.65	-90.00	-1.65
-FUEL CAPACITY (810 GAL)	-370.00	-2.92	-364.00	-2.48	-227.00	-1.52	-332.00	-1.01	-231.00	-1.01
-FAN EFFICIENCY (10%)	-156.00	-1.23	-500.00	-3.40	0.00	0.00	0.00	0.00	0.00	0.00
	10904.40	95.60	17789.39	110.23	15106.50	100.08	20551.00	84.02	12374.50	78.94
WEIGHT TECHNOLOGY TO 2000 AD	-1520.04	-12.00	-1764.00	-12.00	-1800.00	-12.00	-2800.00	-12.00	-1800.00	-12.00
	9384.36	83.60	16025.39	98.23	13306.50	88.08	17671.00	72.02	10574.50	66.94
FUEL (2000)	2913.41	23.00	1617.00	11.00	3450.00	23.00	4080.00	17.00	2050.00	19.00
GROSS WEIGHT LESS PAYLOAD	12297.77	106.60	17642.39	109.23	16756.50	111.08	21751.00	89.02	13424.50	85.94
DERIVATION PARAMETERS	**FRACTION**	**2000 AD**	**FRACTION**	**2000 AD**	**FRACTION**	**2000 AD**	**FRACTION**	**2000 AD**	**FRACTION**	**2000 AD**
HP/GW	0.39	0.35	0.39	0.34	0.40	0.37	0.22	0.20	0.28	0.25
HP TOTAL	4940.13	4433.45	5733.00	4998.00	6000.00	5550.00	5280.00	4800.00	4200.00	3750.00
FUEL (% GW)	42.00	23.00	20.00	11.00	35.00	23.00	26.00	17.00	29.00	19.00
NO. OF ENGINES	2	2	4	4	2	2	2	2	2	2
NO. OF ROTOR/FAN	3	3	4	4	1	1	1	1	1	1
INSN HP /PP	4001.51	3591.09	4643.73	4048.38	4860.00	4495.50	4276.00	3888.00	3402.00	3037.50
Q/HP	0.30		0.31		0.27		0.40		0.32	
INSN % OF ENGINE POWER	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
DISC LOAD	50.00	50.00	15.00	15.00	50.00	50.00	20.00	20.00	15.00	15.00
TYPE OF ENGINES	THRUST	THRUST	SHAFT	SHAFT	CONV	CONV	CONV	CONV	TB FAN	TB FAN
FIRST PROJECTION										
PROJECTED GROSS WEIGHT	-52587.94	100.00	-37614.76	100.00	-31308.27	100.00	31598.12	100.00	24674.09	100.00
WEIGHT EMPTY	-43962.71	83.60	-36947.14	98.23	-27577.37	88.08	22756.44	72.02	16516.02	66.94
PAYLOAD	3470.00	-6.60	3470.00	-9.23	3470.00	-11.08	3470.00	10.98	3470.00	14.06
FUEL	-12095.23	23.00	-4137.62	11.00	-7200.90	23.00	5371.68	17.00	4688.08	19.00
SECOND PROJECTION										
PROJECTED GROSS WEIGHT	-37138.53	100.00	-30370.12	100.00	-26628.25	100.00	30704.49	100.00	23980.20	100.00
WEIGHT EMPTY	-31048.81	83.60	-29832.11	98.23	-23455.85	88.09	22112.71	72.02	16051.40	66.94
PAYLOAD	3470.00	-9.34	3470.00	-11.43	3470.00	-13.03	3470.00	11.30	3470.00	14.47
FUEL	-9559.72	25.74	-4008.01	13.20	-6642.40	24.94	5121.78	16.68	4458.80	18.59
THIRD PROJECTION										
PROJECTED GROSS WEIGHT	-39914.78	100.00	-31202.34	100.00	-27036.69	100.00	30806.96	100.00	24028.67	100.00
WEIGHT EMPTY	-33369.43	83.60	-30649.44	98.23	-23815.55	88.09	22186.53	72.02	16083.85	66.94
PAYLOAD	3470.00	-8.69	3470.00	-11.12	3470.00	-12.83	3470.00	11.26	3470.00	14.44
FUEL	-10015.35	25.09	-4022.90	12.89	-6691.15	24.75	5150.43	16.72	4474.82	18.62
SOLUTION PARAMETERS		**2000 AD**		**2000 AD**		**2000 AD**		**2000 AD**		**2000 AD**
HP/GW		0.35		0.34		0.37		0.20		0.25
ENGINE HP TOTAL		-13970.17		-10608.80		-10003.58		6161.39		6007.17
INSN HP		-11315.84		-8593.13		-8102.90		4990.73		4865.81

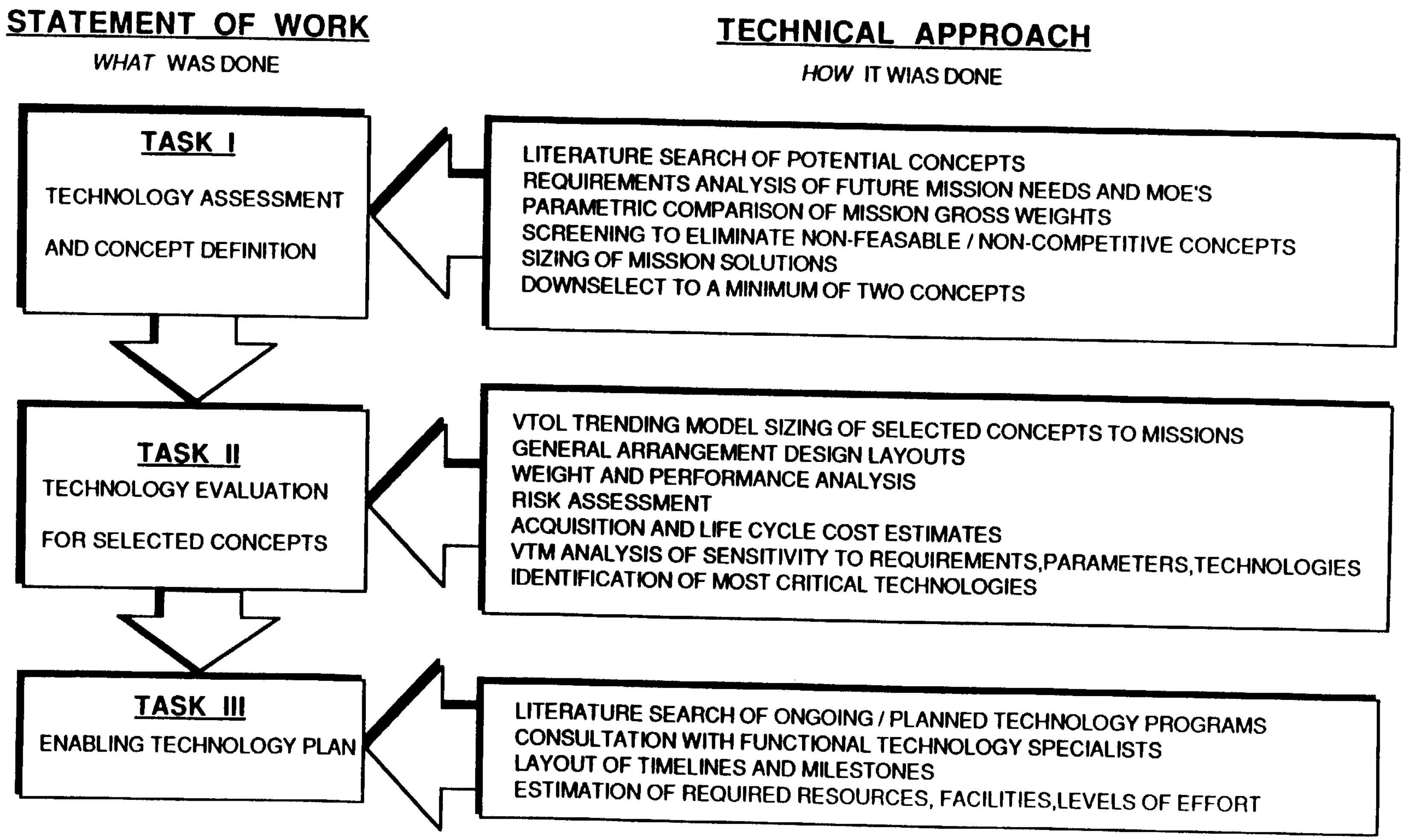

Figure A-1. 'Technology Needs For High Speed Rotorcraft Study' overview

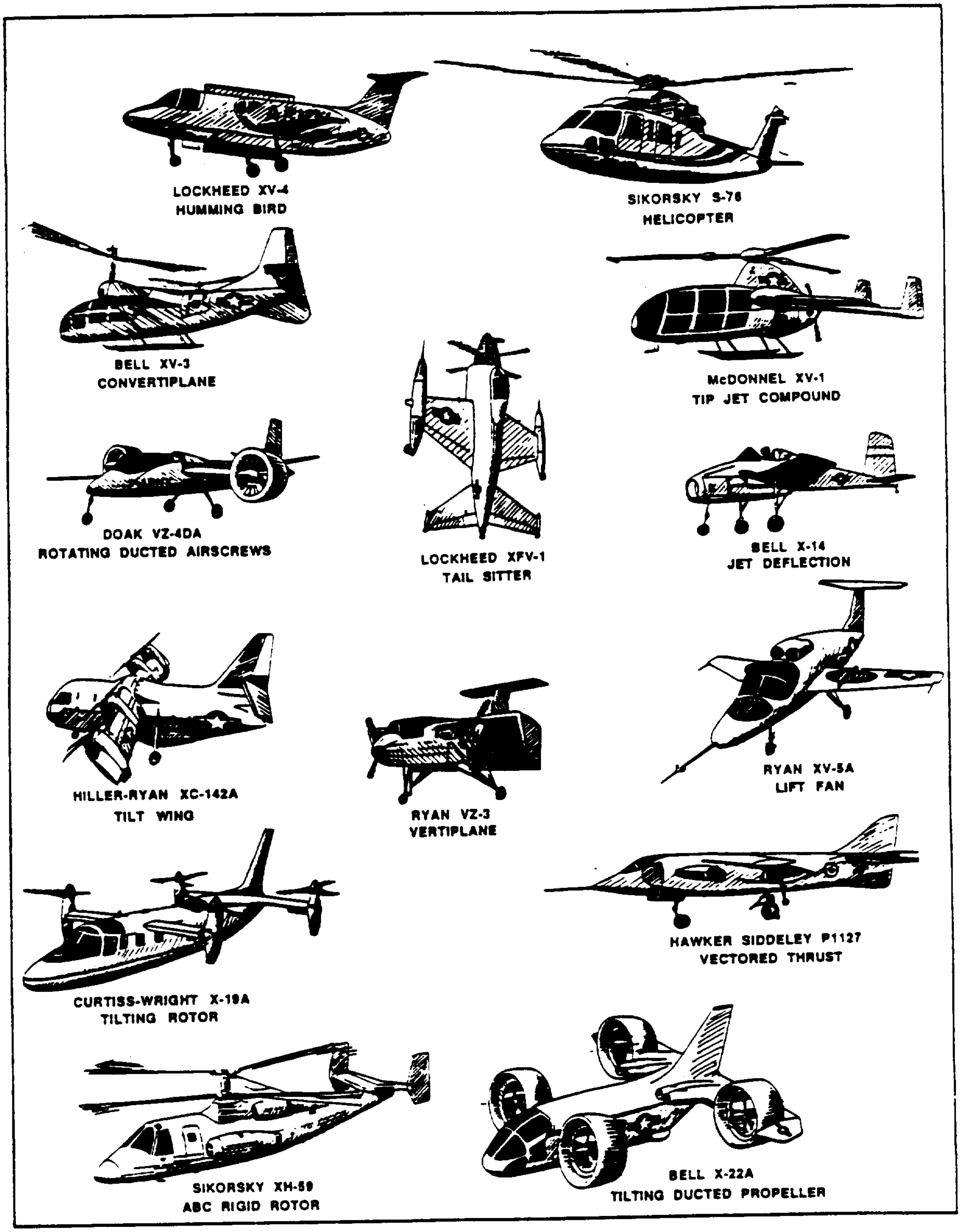

Figure A-2. Examples of VTOL concepts

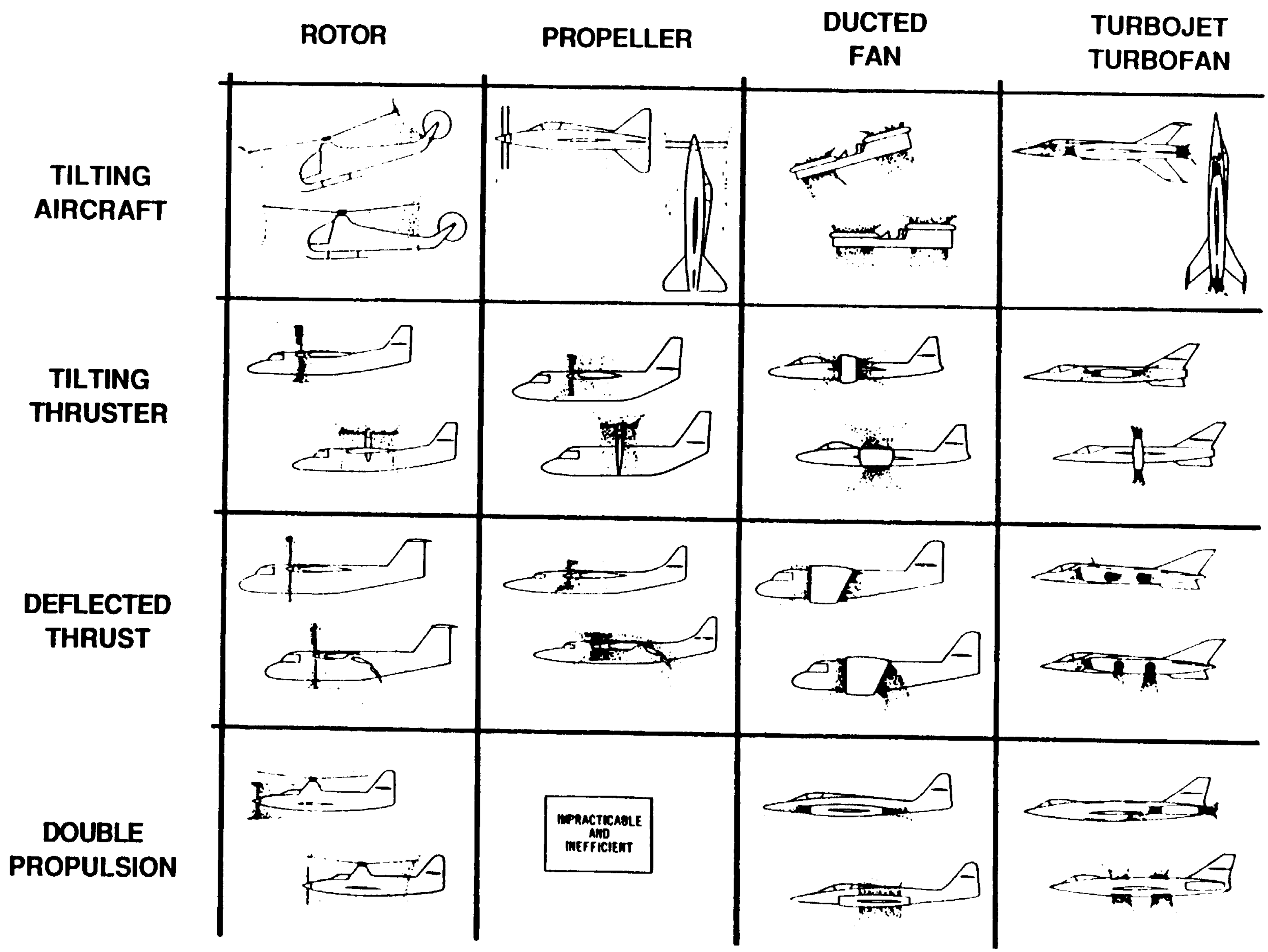

Figure A-3. Matrix of VTOL configurations

	ROTOR	PROPELLER	DUCTED FAN	TURBOJET TURBOFAN
TILTING AIRCRAFT	*ALL PURE HELICOPTERS* *Vmax LESS THAN 250KTS*	LOCKHEED XFV-1 CONVAIR XFY-1	SNECMA 'COLEOPTER'	RYAN X-13
TILTING THRUSTER	BELL XV-3 BELL XV-15 BELL-BOEING V-22	CANADAIR CL-84 LTV XC-142 HILLER X-18 BOEING VZ-2 CURTIS WRIGHT X-19	BELL X-22 DOAK VX-4DA	EWR-SUD VJ-101C
DEFLECTED THRUST		RYAN VZ-3 FAIRCHILD VZ-5	PIASECKI RING WING	HAWKER XV-6A KESTREL BELL XV-14
DOUBLE PROPULSION	FAIREY ROTODYNE SIKORSKY ABC McDONNELL XV-1 LOCKHEED XH-56 PIASECKI PATHFINDER SIKORSKY X-WING		RYAN XV-5 PIASECKI VANGUARD 2C	DORNIER DO-31 LOCKHEED XV-4 SHORTS SC-1 DASSAULT VTOL MIRRAGE 3

Figure A-4. Examples of previous high speed VTOL configurations

	ROTOR	PROPELLER	DUCTED FAN	TURBOJET TURBOFAN
TILTING AIRCRAFT				
TILTING THRUSTER	FOLDING TILT ROTOR VARIABLE DIA TILT ROTOR			GRUMMAN NUTCRACKER GRUMMAN 698
DEFLECTED THRUST				
DOUBLE PROPULSION	STOWED ROTOR STOPPED ROTOR RETRACTABLE ROTOR RET/EXT STOPPED ROTOR			GENERAL DYN.-NASA E-7A

Figure A-5. New and unflown VTOL configurations

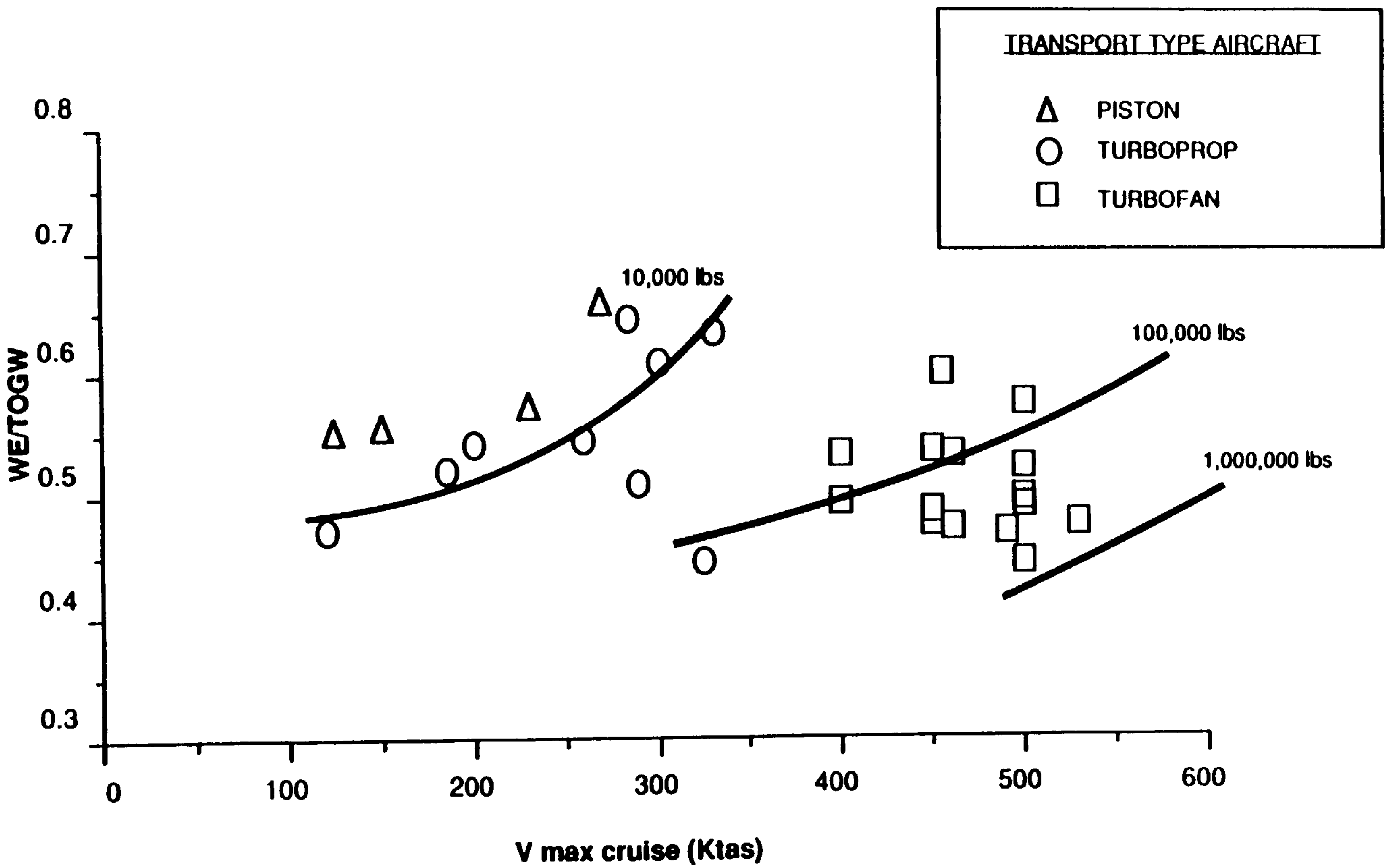

Figure A-6. Weight empty fraction vs. maximum cruise speed for various transports

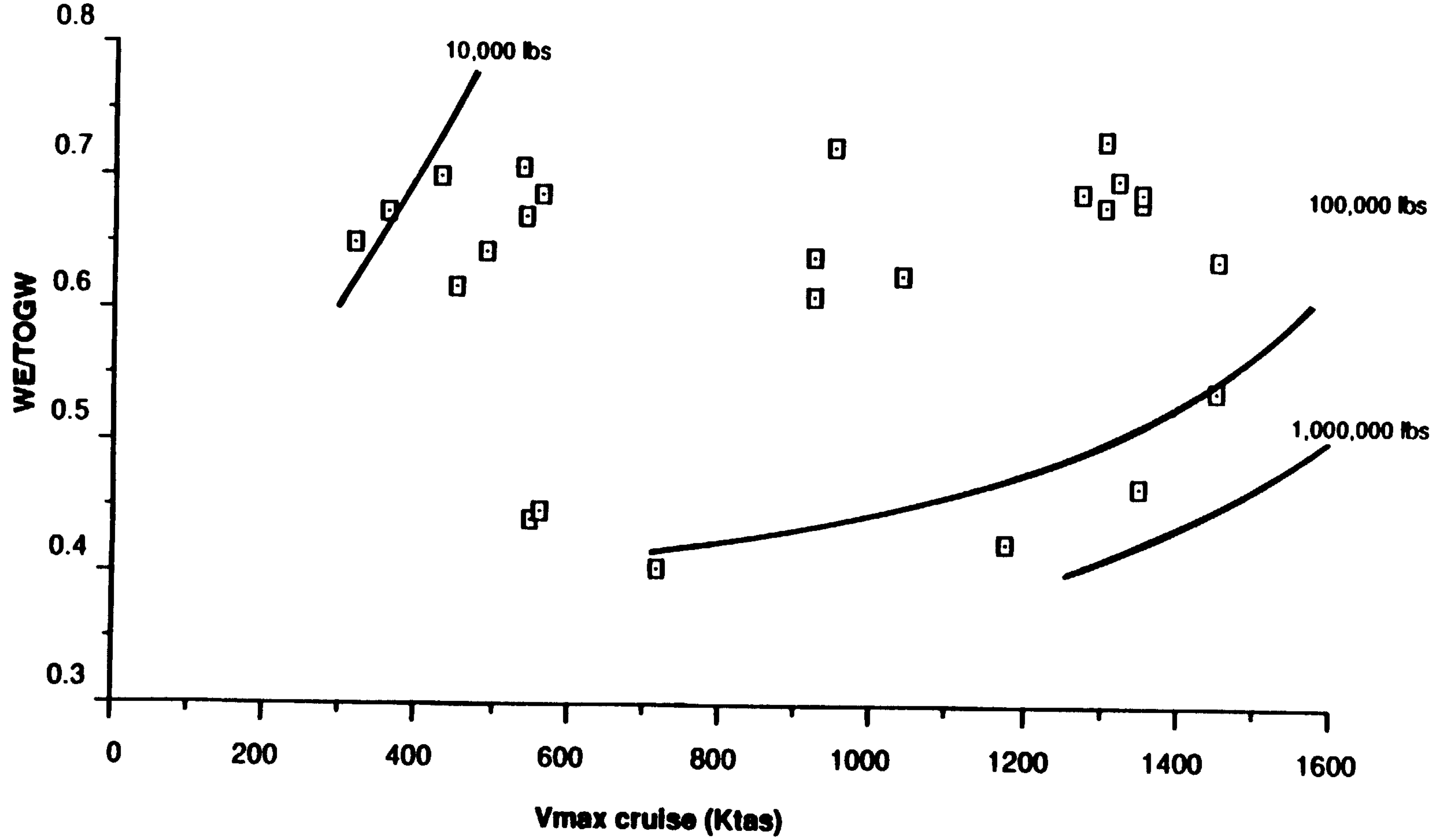

Figure A-7. Weight empty fraction vs. maximum cruise speed for fighter / attack aircraft

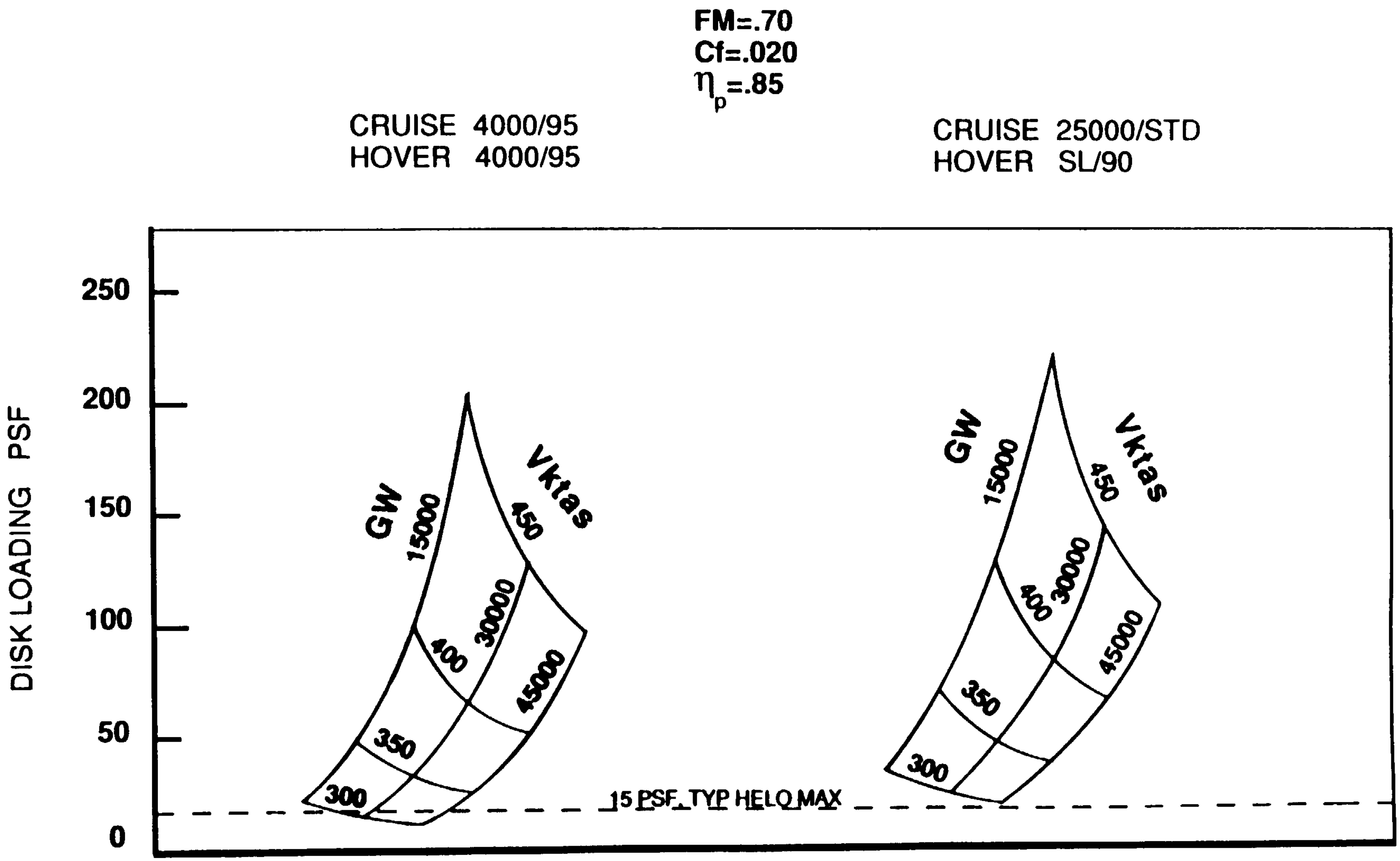

Figure A-8. Disk loading required for installed power match between cruise and hover

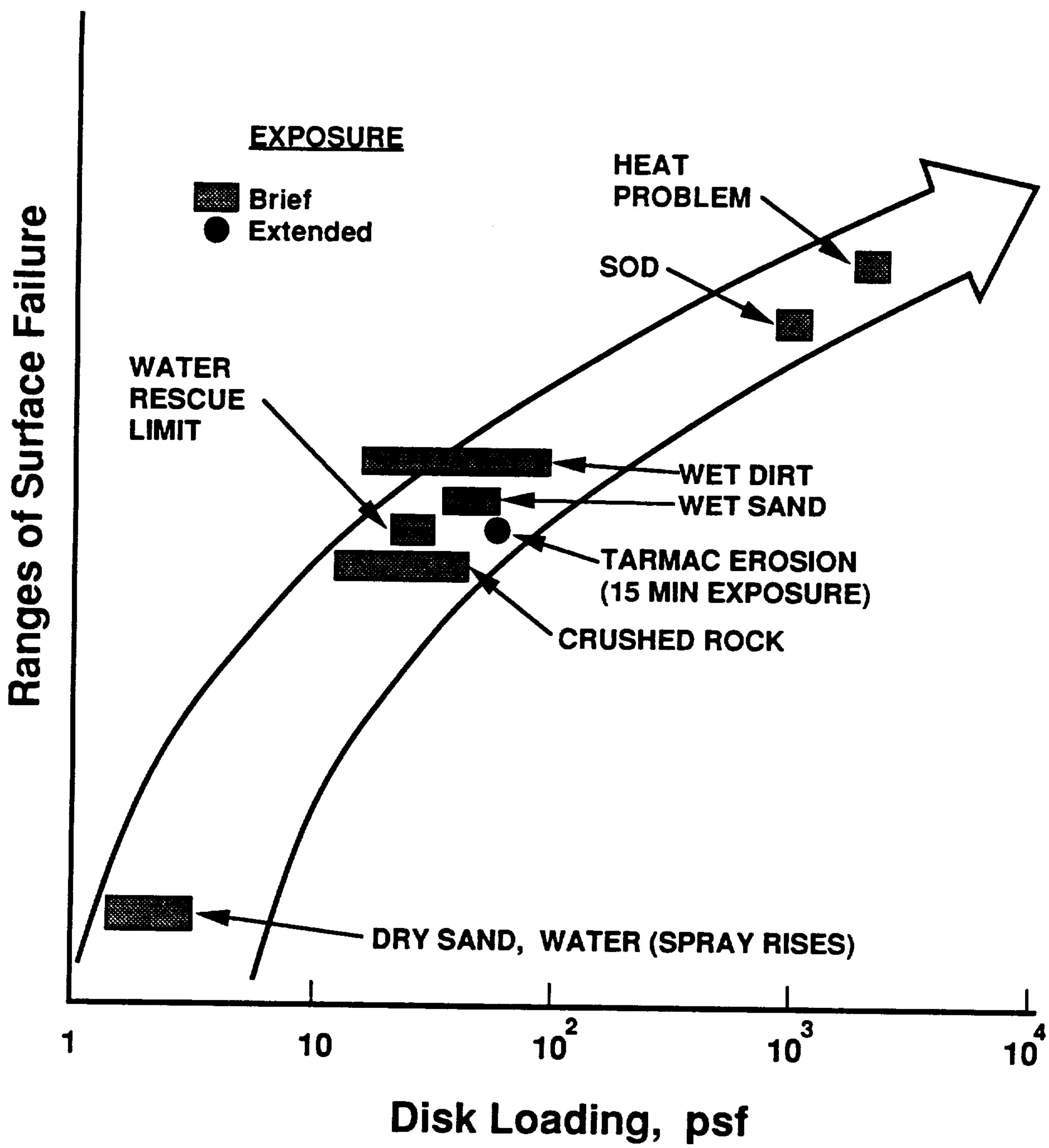

Figure A-9. Resistance of surfaces under wake dynamic presure

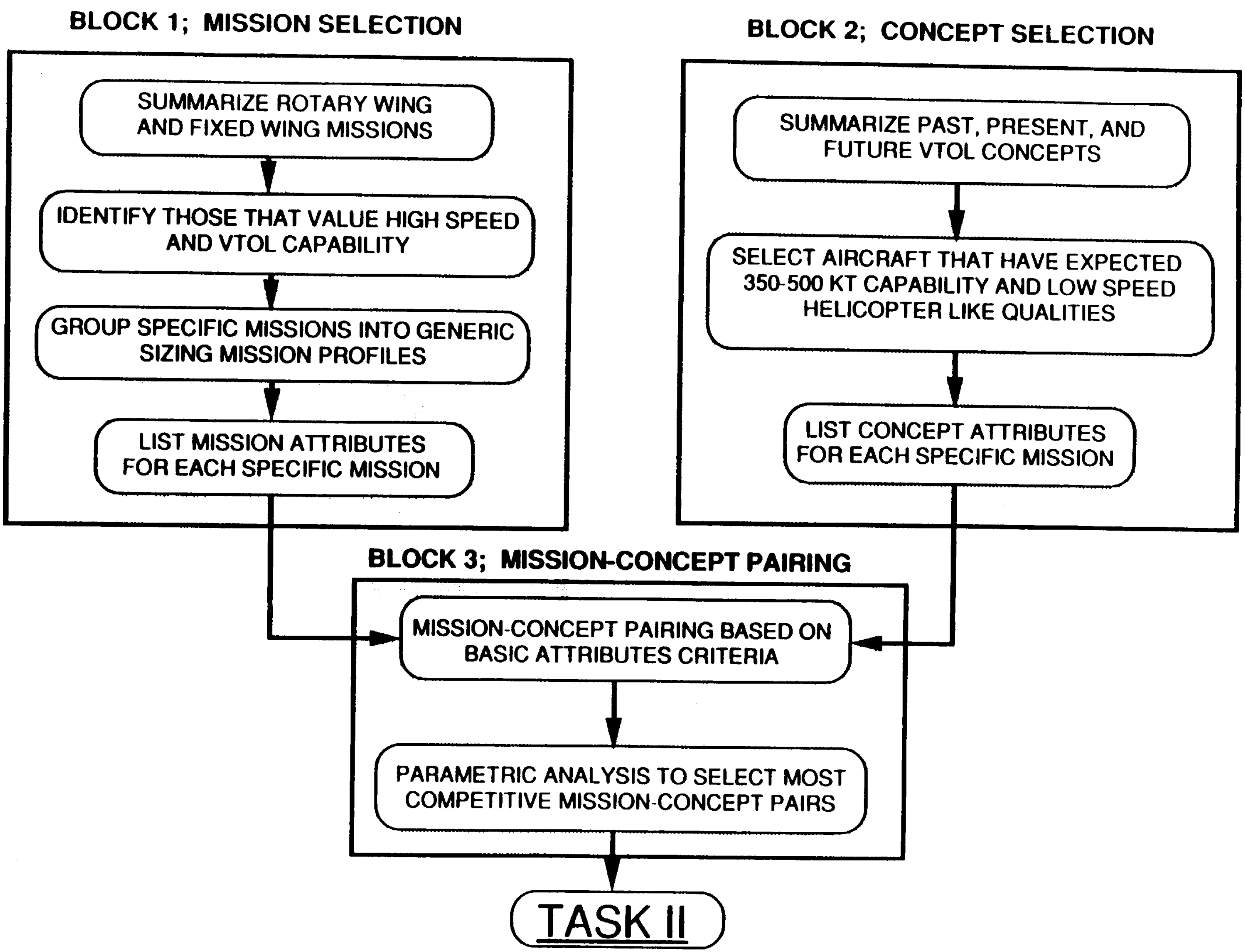

Figure A-10. Task I mission-concept pair selection process

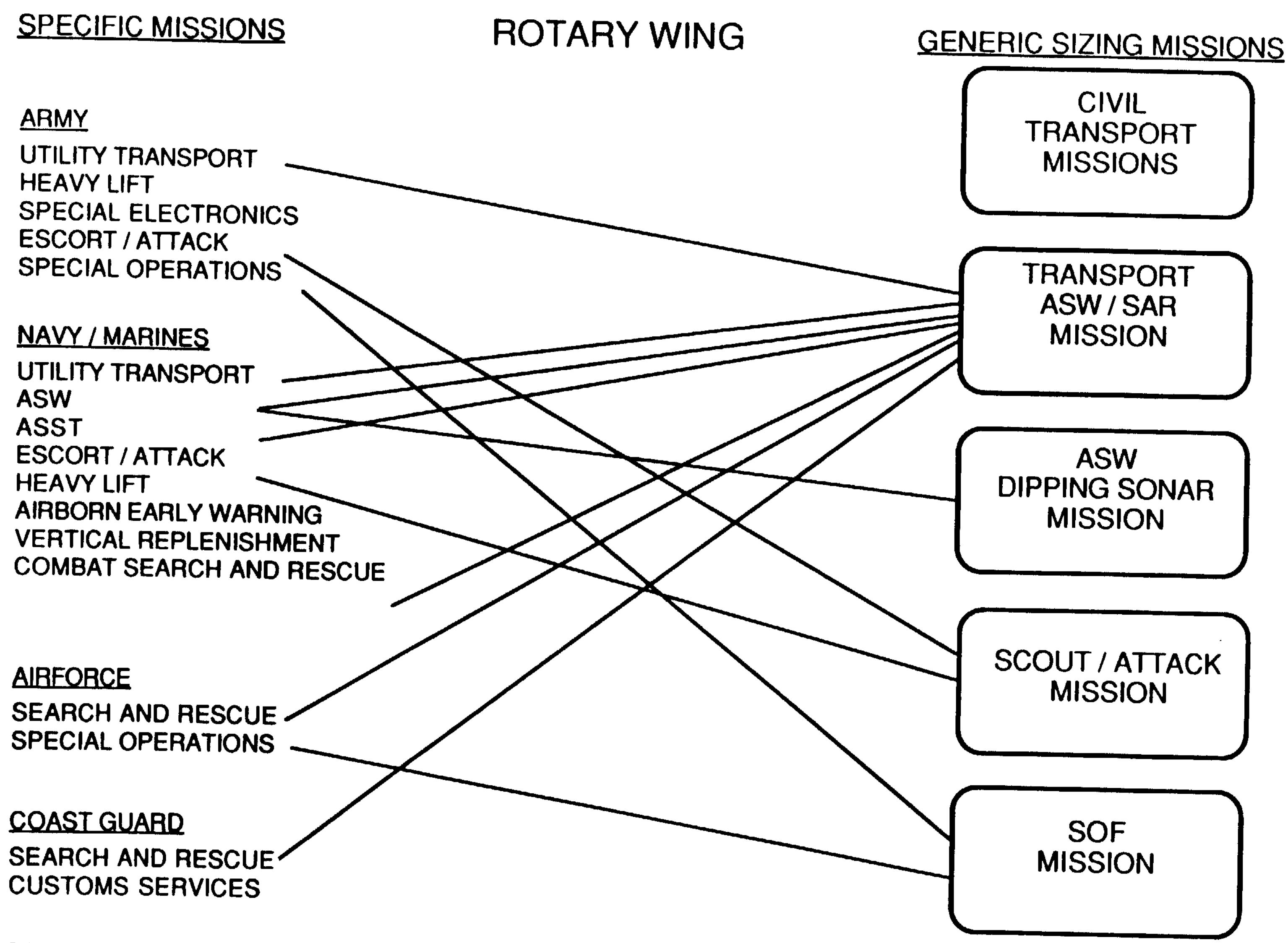

Figure A-11. Current military helicopter missions which would benefit from higher speed

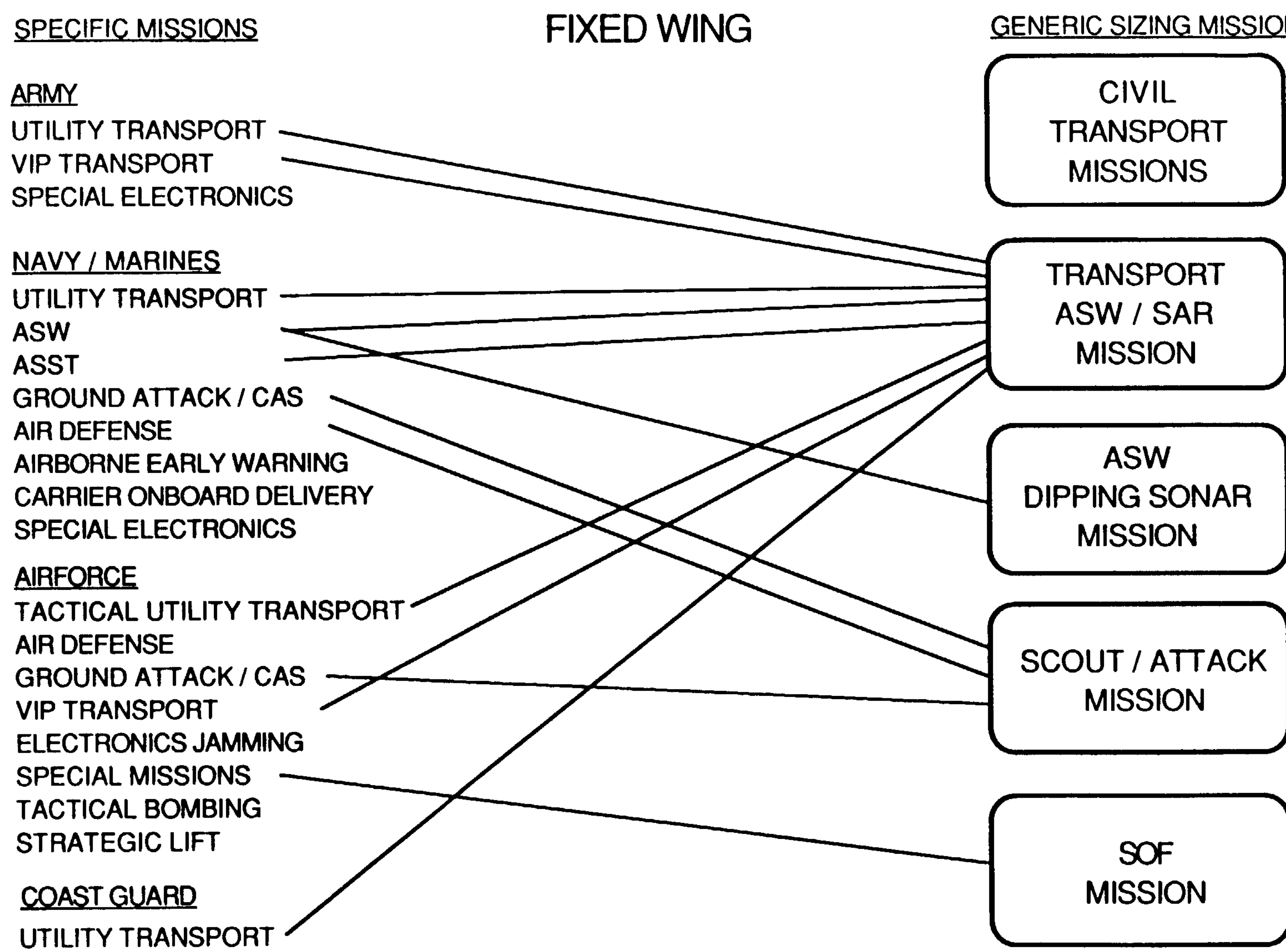

Figure A-12. Current military fixed wing missions which would benefit from VTOL

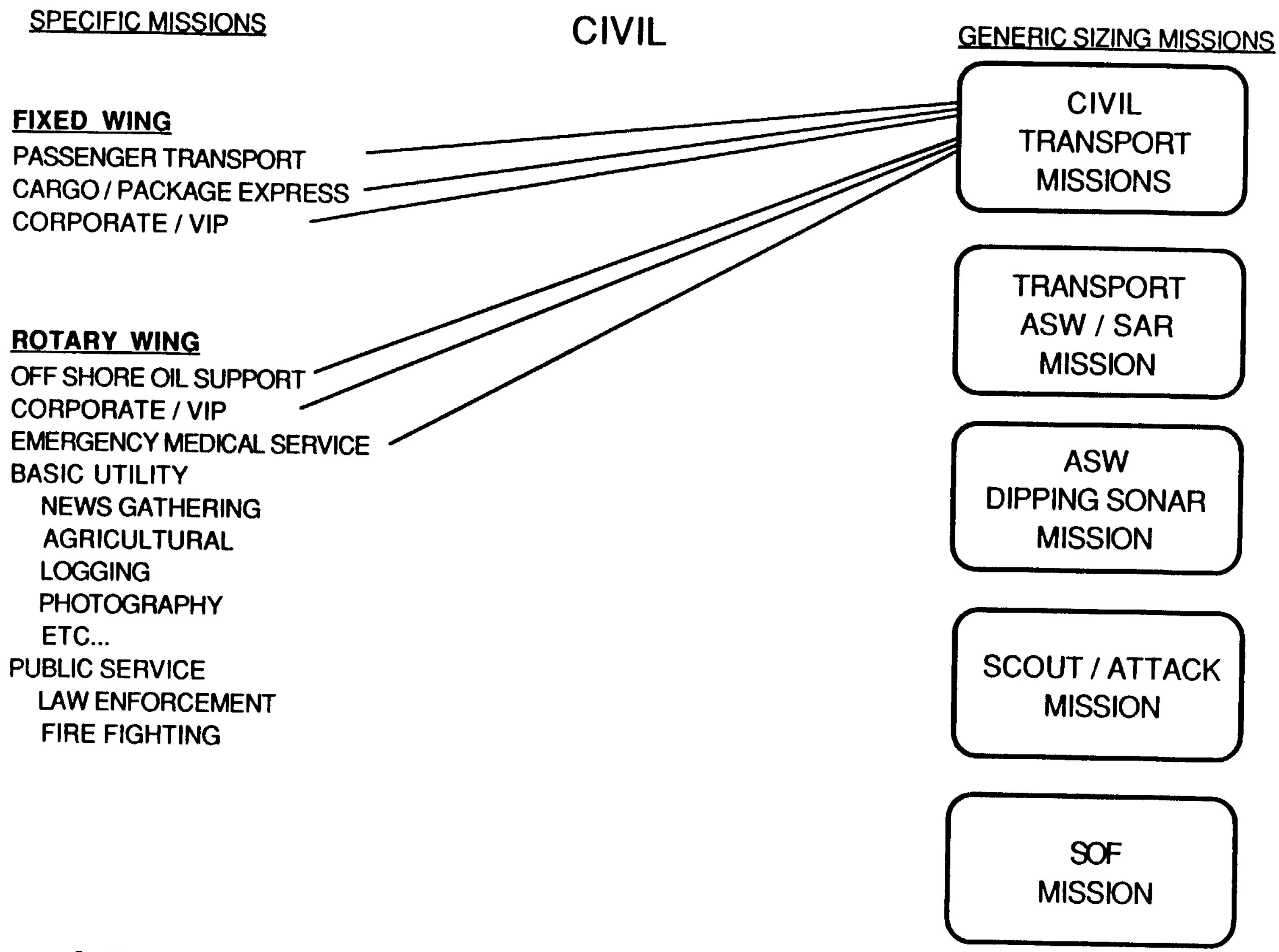

Figure A-13. Current civil missions which would benefit from both higher speed and VTOL

RATING SYSTEM
0 NON EXISTENT
1 POOR
2 GOOD
3 EXCELLENT

	COST OF OWNERSHIP (WRT HELICOPTER)	CABIN SIZE	COMFORT (NOISE + VIBRATION)	LOW EXTERNAL NOISE	MANEUVER. AND AGILITY — SPEED COND: LOW	CONV	HIGH	SURVIVABILITY AND LOW VULNERABILITY	LOW OBSERVABLES (NOISE, IR, RCS)	BENIGN DOWN WASH ENVIRONMENT	SHIP COMPATIBILITY AND SPOTTING FACTOR	EASE OF CONVERSION	OVERLOAD STOL CAPABILITY	MEASURES OF EFFECTIVENESS
UTILITY TRANSPORT														
CIVIL PASSENGER	3.0	3.0	2.0	2.5	.5	0	0	0	0	1.0	0	1.0	1.0	\$/se mi
CIVIL CARGO	2.5	3.0	1.0	2.5	.5	0	0	0	0	1.0	0	1.0	2.0	\$/ton mi
CIVIL CORPORATE	2.0	1.5	3.0	2.5	.5	0	0	0	0	1.5	0	1.5	0.5	\$/se mph
OFF SHORE OIL	2.5	2.0	2.0	1.5	.5	0	0	0	0	2.0	0	1.0	1.5	\$/se mi
EMERGENCY MEDICAL SERVICE	2.5	2.0	2.5	2.0	1	.5	0	0	0	2.0	0	1.5	0.5	\$/trip
MILITARY TRANSPORT	2.0	3.0	1.5	1.0	1.5	1	1	2.0	1.5	2.0	1.5	1.5	2.5	ton mi/hour
ASW - ASST - SAR														
NAVY ASW / ASST	2.0	1.5	1.5	0.5	1	1	1	1.0	1.5	1.5	3.0	1.5	0.5	area/hour
COMBAT SAR	2.0	2.0	1.0	0.5	1.5	1.5	1.5	2.5	2.0	2.5	2.0	1.5	1.5	reaction time
COAST GUARD SAR	2.0	2.0	1.5	0.5	1	1	1	0	0	2.5	2.0	1.5	1.0	reaction time
ASW DIPPING SONAR														
NAVY ASW	2.0	1.5	1.5	0.0	1	1	1	1.0	1.5	2.0	3.0	2.0	1.0	area/hour
SCOUT - ATTACK - ESCORT														
ARMY/USAF CAS / AIR TO AIR	1.5	0.5	1.0	1.0	3	2.5	2.5	3.0	3.0	1.0	1.0	2.0	1.5	Pk/engmt
NAVAL CAS / AIR TO AIR	1.0	0.5	1.0	0.5	3	2.5	2.5	3.0	3.0	1.0	3.0	2.0	1.5	Pk/engmt
SPECIAL OPERATION FORCES														
ARMY/USAF SPECIAL OPER.	1.0	2.0	1.5	1.0	2.5	2	1.5	2.5	3.0	3.0	1.5	2.0	2.0	ton mi/hour
NAVAL SPECIAL OPER.	1.0	2.0	1.5	1.0	2.5	2	1.5	2.5	3.0	2.0	2.5	2.0	2.0	ton mi/hour

Figure A-14. Mission attributes

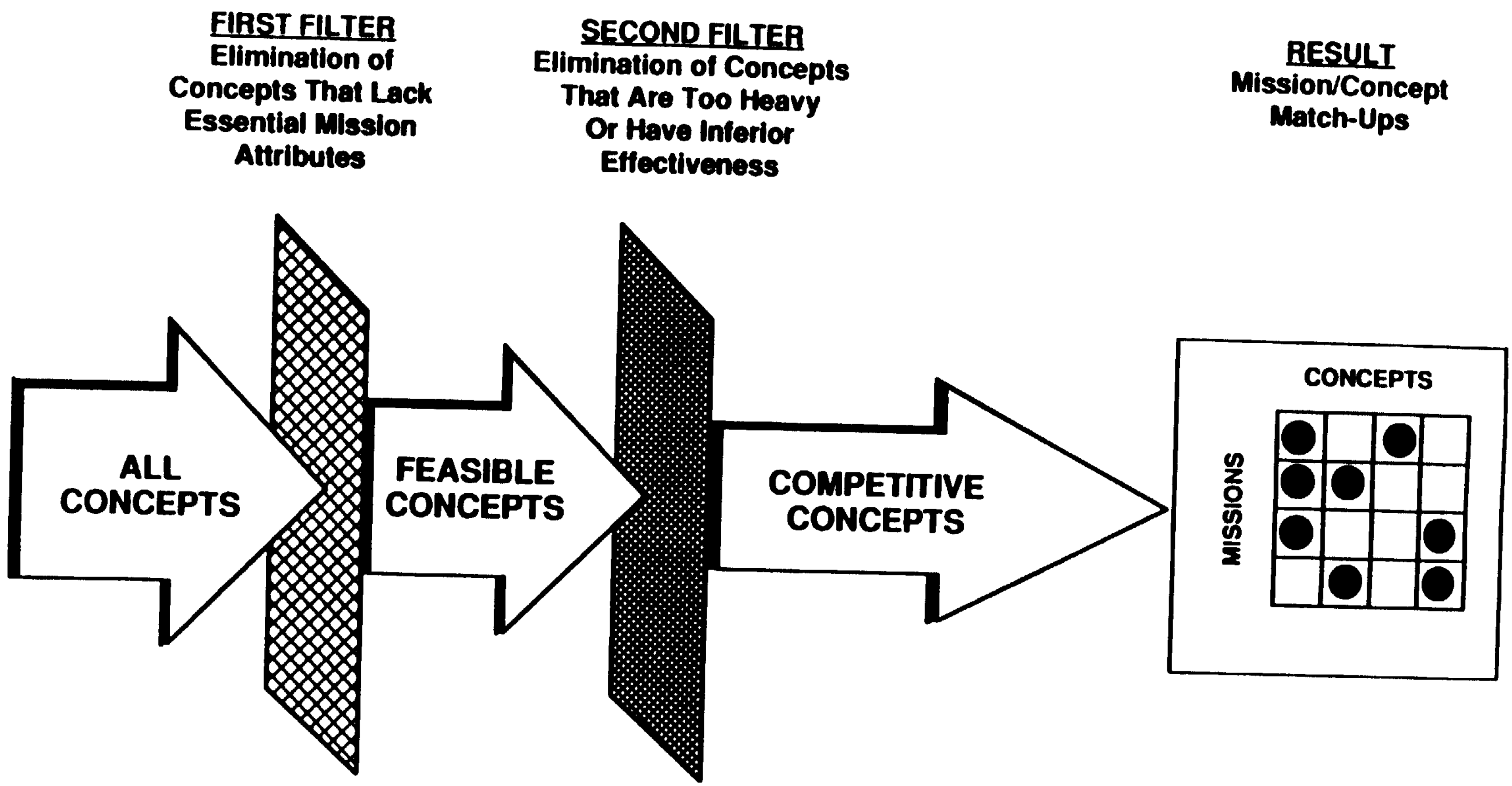

Figure A-15. Mission-concept pair selection process

BASED ON INHERENT ATTRIBUTES, THREE FAMILIES OF CONCEPTS IDENTIFIED AS CANDIDATES FOR TASK II

TILT THRUSTER

TILT ROTOR
TILT WING
TILT DUCT FAN
VARIABLE DIA. TILT ROTOR
FOLDING TILT ROTOR

DOUBLE PROPULSION
(STOPPED ROTOR)

X WING
TIP DRIVE X WING
STOPPED ROTOR
TIP DRIVE STOPPED ROTOR
STOPPED RETRACTABLE ROTOR
STOWED ROTOR

DOUBLE PROPULSION
(BURIED FAN(S))

FAN IN WING
FAN IN FUSELAGE

Figure A-16. Concept grouping into three families

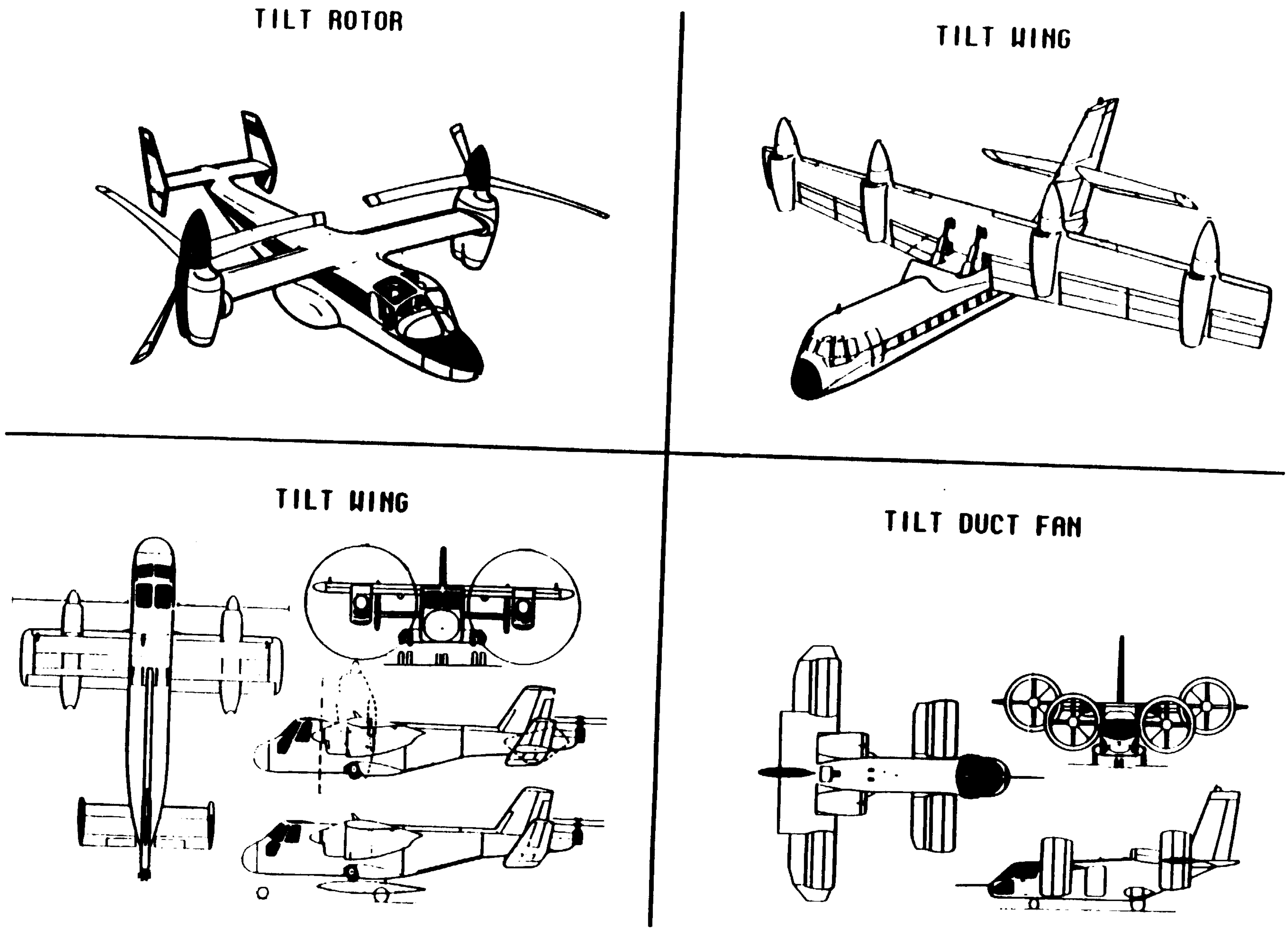

Figure A-17. Candidate high speed rotorcraft concepts

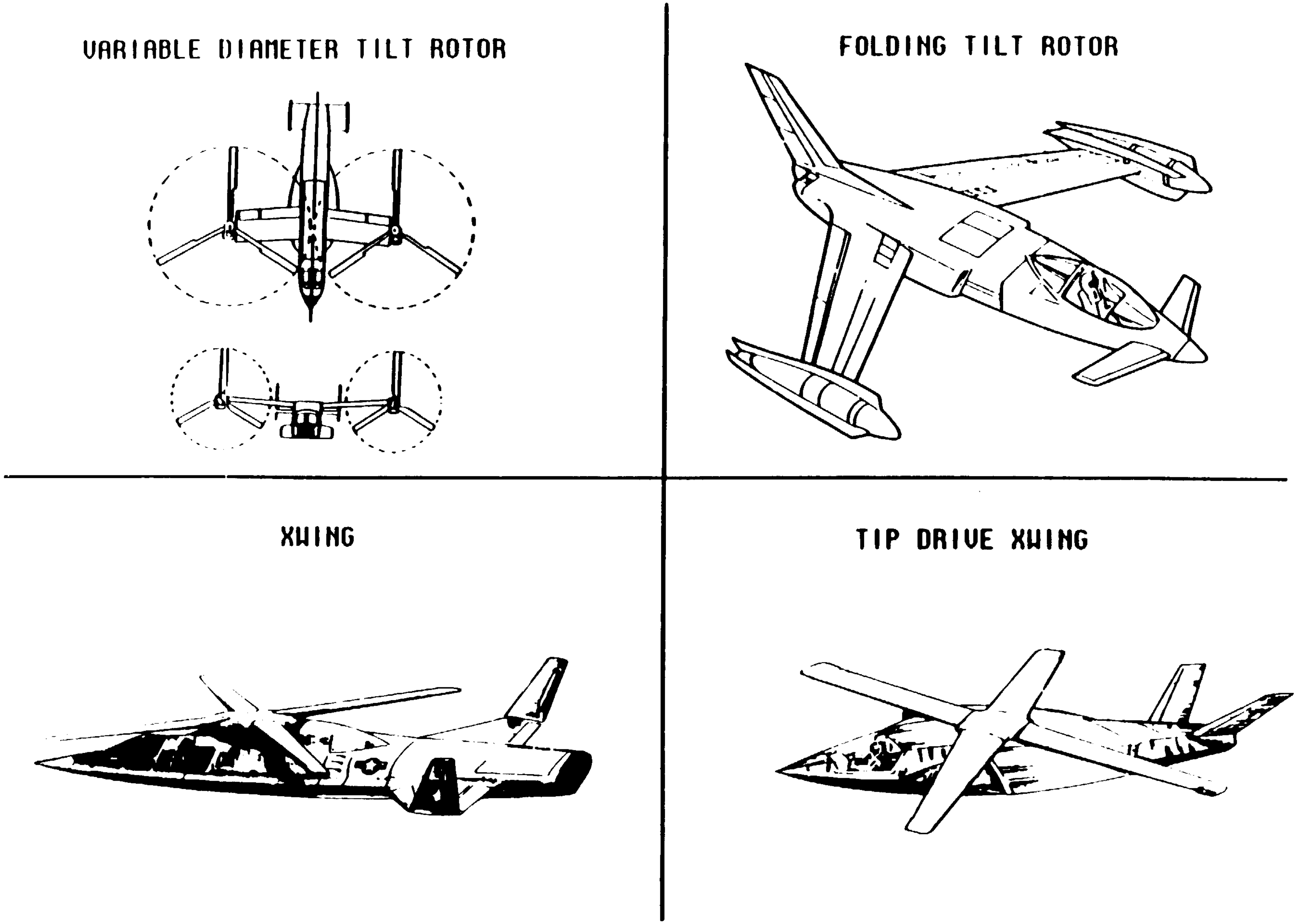

Figure A-17. continued

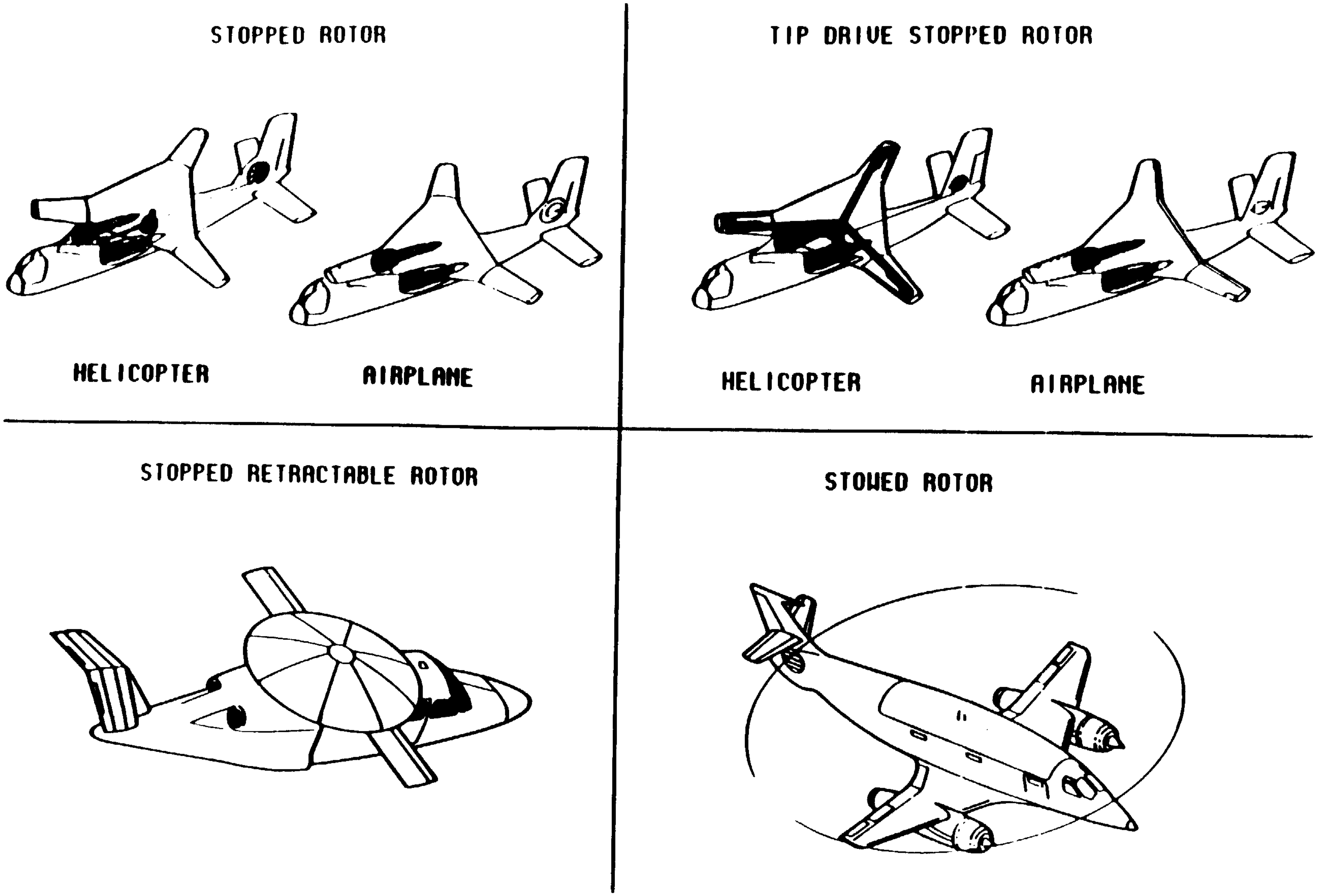

Figure A-17. continued

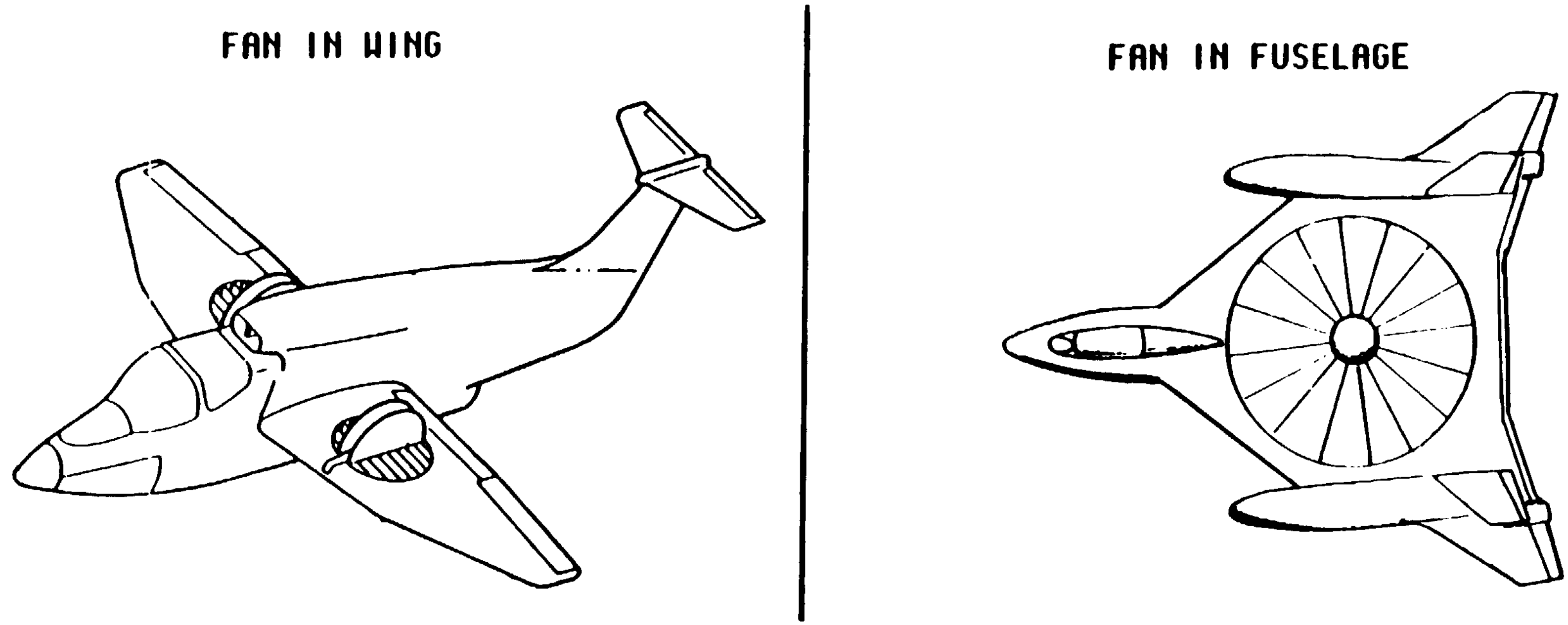

Figure A-17. continued

RATING SYSTEM
1 POOR
2 GOOD
3 EXCELLENT

{ WITH RESPECT TO A HELICOPTER OF SAME SIZE }

	Cost of Ownership	Cabin Size	Comfort (Noise + Vibration)	Low External Noise	Maneuver. and Agility — Speed Cond: Low	Conv	High	Survivability and Low Vulnerability	Average	Low Observ (Noise, IR, RCS): Noise	IR	RCS	Benign Down Wash Environment	Ship Compatibility and Spotting Factor	Ease of Conversion	Overload STOL Capability
TILT ROTOR		2.8	2.6	2.3	2	1.5	2.3	1.7	1.7	2.3	1.8	1	2	1.5	2.7	2.8
TILT WING		2.5	2.9	2.0	1.2	1.5	2.8	2.0	1.6	1.8	1.5	1.3	1	1.5	2.0	2.8
TILT DUCT FAN		2.8	2.5	1.7	1.7	1.0	2.5	1.8	1.6	2	1.3	1.5	1	1.8	2.0	2.3
VARIABLE DIAMETER TILT ROTOR		2.8	3.0	2.5	2	1.2	2.5	1.7	2.7	2.5	2	1.5	2.2	1.5	2.0	3.0
FOLDING TILT ROTOR		2.8	3.0	2.5	2	1.2	2.8	1.7	2.4	2.5	2	2.8	2	1.5	1.7	2.8
X WING		1.7	2.3	2.0	1.8	1	2.3	2.0	2.2	2	2	2.5	2	1.5	1.5	1.3
TIP DRIVE X WING		1.5	2.0	1.5	1.2	1	2.3	1.7	1.9	1.5	1.5	2.5	2	1.5	1.5	1.8
STOPPED ROTOR[1]		2.0	2.8	2.3	1.8	1	2.3	2.3	2.3	2	2.3	2.8	1.8	1.8	1.3	1.8
TIP DRIVE STOPPED ROTOR[2]		1.3	2.3	1.0	1.5	1	2.3	1.7	2.0	1.3	1.8	2.8	1.8	1.8	1.3	1.8
STOPPED-RETRACTABLE ROTOR[3]		1.7	2.7	2.5	2	1	2.3	2.3	2.2	2.3	2	2.5	2	2.0	1.0	2.3
STOWED ROTOR		1.1	3.0	2.5	2	1	2.8	2.3	2.3	2.3	2	2.8	2.2	2.0	1.0	2.3
FAN IN WING		2.0	2.2	1.8	1.5	1.5	2.8	2.3	2.1	2	1.8	2.8	1.2	1.8	2.0	1.7
SHROUDED ROTOR		1.0	2.2	1.8	2.8	1.5	2.5	2.3	2.8	2	2	2.8	1.5	2.0	1.7	1.3

1 RIGID SHAFT DRIVEN ROTOR-WING CONCEPT
2 HUGHES ROTO-WING CONCEPT
3 STROUB ROTOR CONCEPT

Figure A-18. Concept attributes

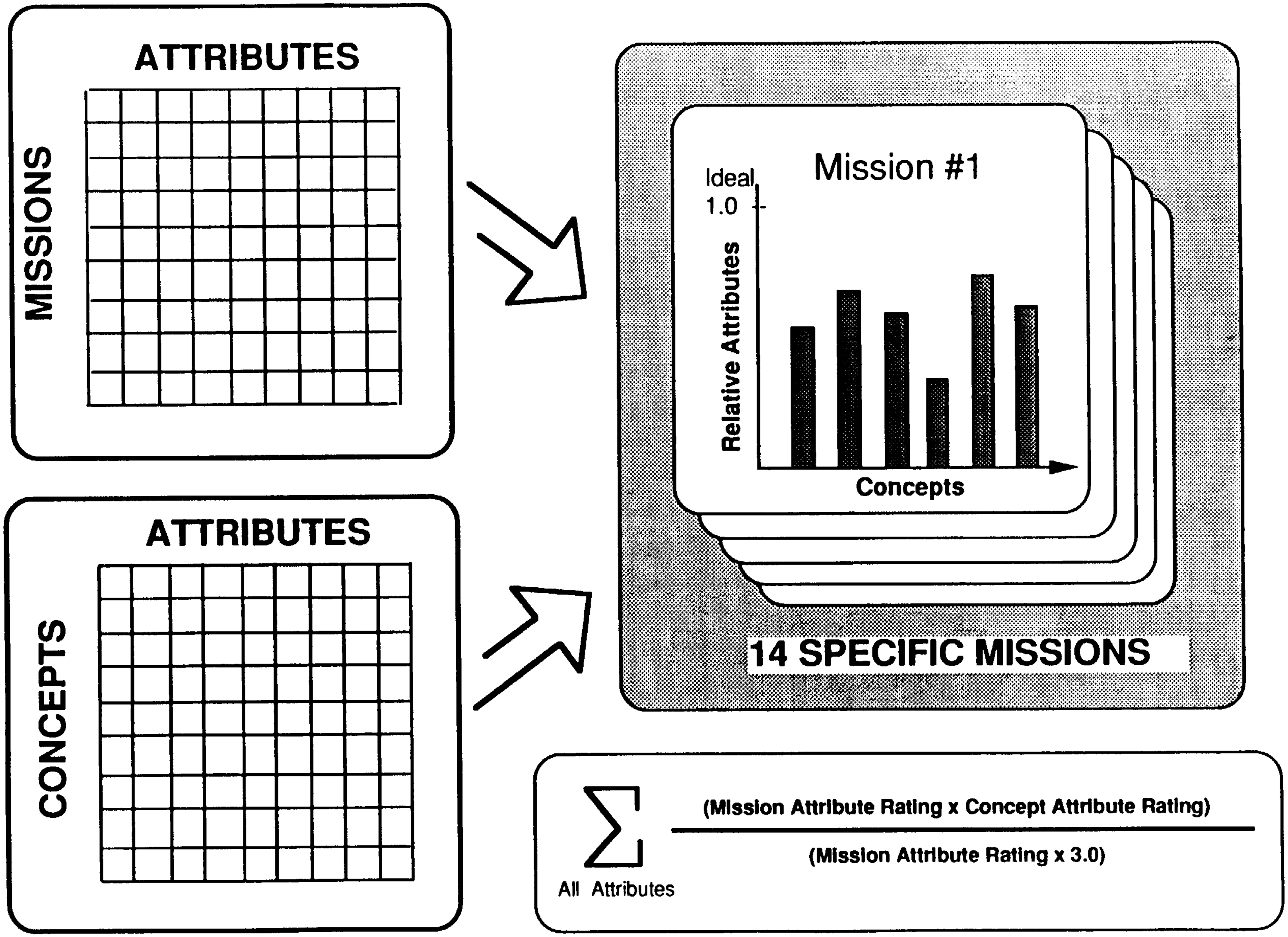

Figure A-19. Diagram of mission relative attributes rating formulation

AIRCRAFT SIZE IS A FUNCTION OF;

MISSION VARIABLES

RANGE
TIME ON STATION
HOVER TIME
SPEED FOR EACH LEG
PAYLOAD & MEP & FUL
RESERVE FUEL
AMBIENTS FOR EACH LEG

AND

CONCEPT PERF. VARIABLES

WE/GW
A/C FM
HOVER DISK LOADING
PARASITE DRAG
SPAN LOADING
PROPULSIVE EFFICIENCY
ENGINE SFC

Figure A-20. Variables affecting mission sizing

Hover Efficiency

$$\eta_{HOV} = \frac{\left(GW/100\right)}{\left(LBS/HR\right)} \quad \Rightarrow \quad \eta_{HOV} = \frac{1/100}{\left(\dfrac{SFC}{LBS_{GW}/HP}\right)}$$

Loiter Efficiency

$$\eta_{LTR} = \frac{\left(GW/100\right)}{\left(LBS/HR\right)} \quad \Rightarrow \quad \eta_{LTR} = \frac{\left(GW/100\right)}{\left(\dfrac{SFC \cdot D \cdot V_{be} \cdot 1.6878}{\eta_p \cdot 550}\right)} \text{ Airplane}$$

$$\eta_{LTR} = \frac{\left(GW/100\right)}{SFC \cdot HP_{vbe}} \text{ Helicopter}$$

Cruise Efficiency

$$\eta_{CRS} = \frac{\left(GW/100\right)}{\left(LBS/NM\right)} \quad \Rightarrow \quad \eta_{CRS} = \left(GW/100\right) \cdot \left[\frac{V_{KTS}}{\left(\dfrac{SFC \cdot D \cdot V_{KTS} \cdot 1.6878}{\eta_p \cdot 550}\right)}\right]$$

Figure A-21. Fundamental concept performance value derivations

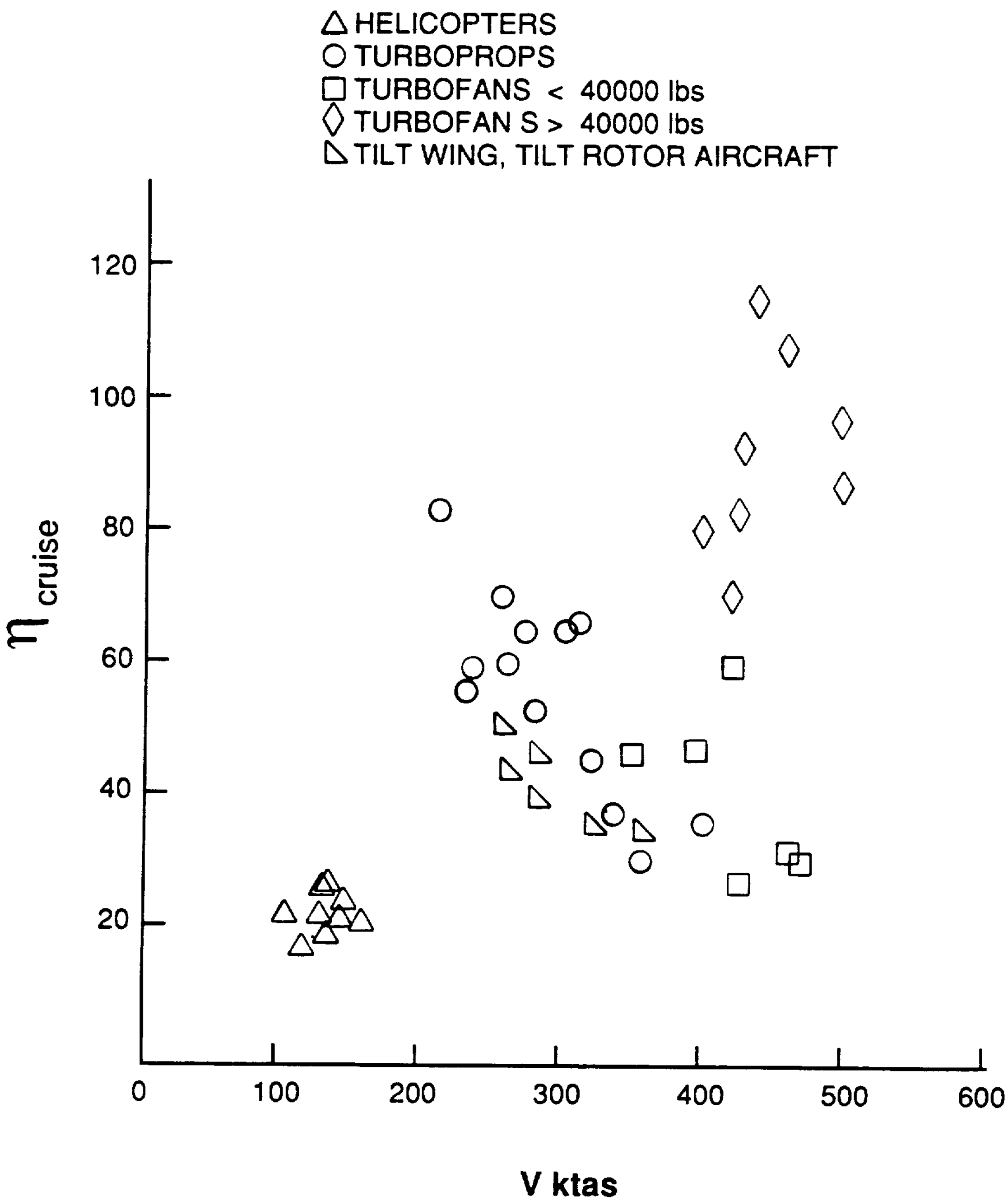

Figure A-22. Cruise efficiency for various types of aircraft

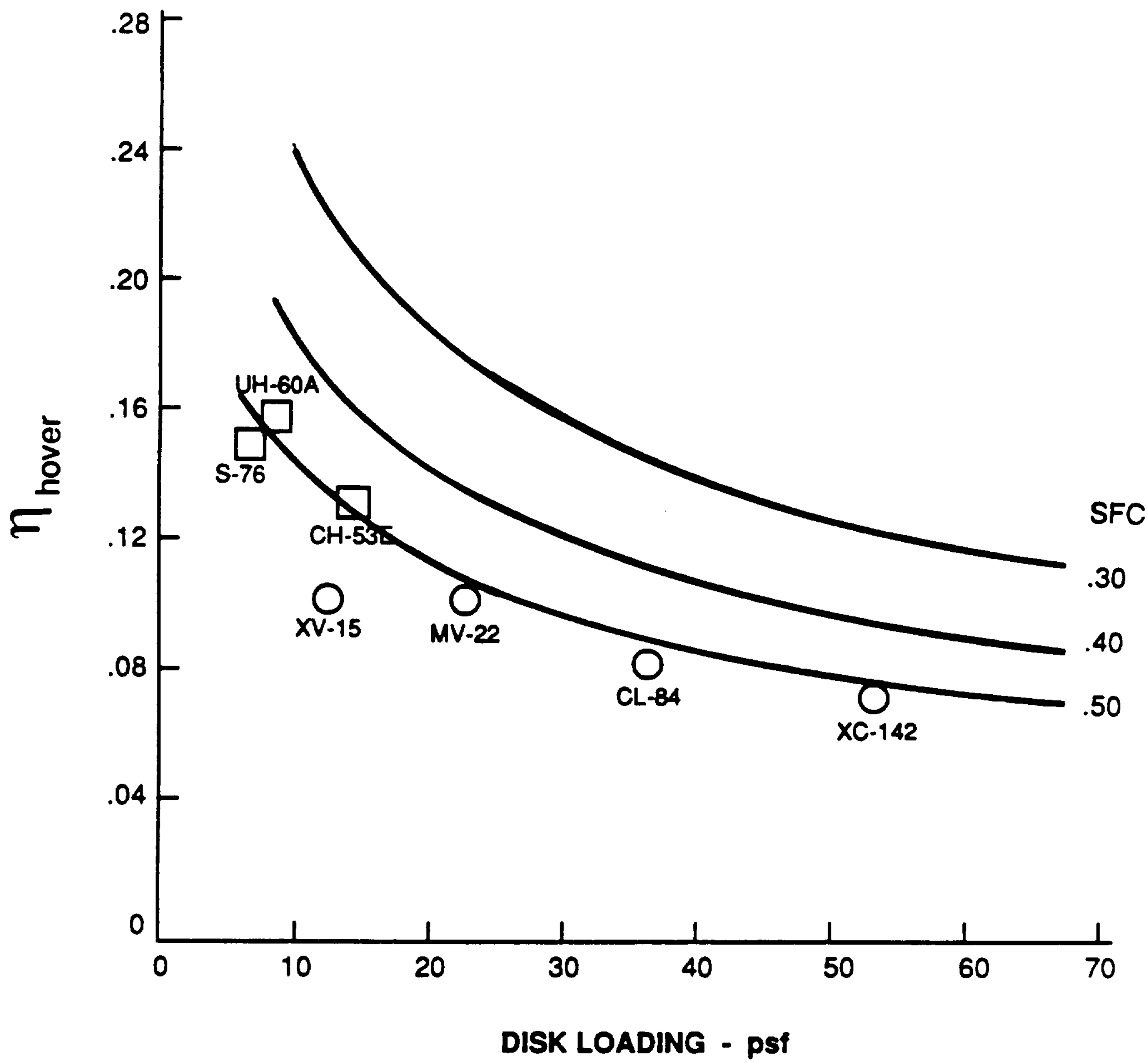

Figure A-23. Hover efficiencies vs. disk loading and SFC

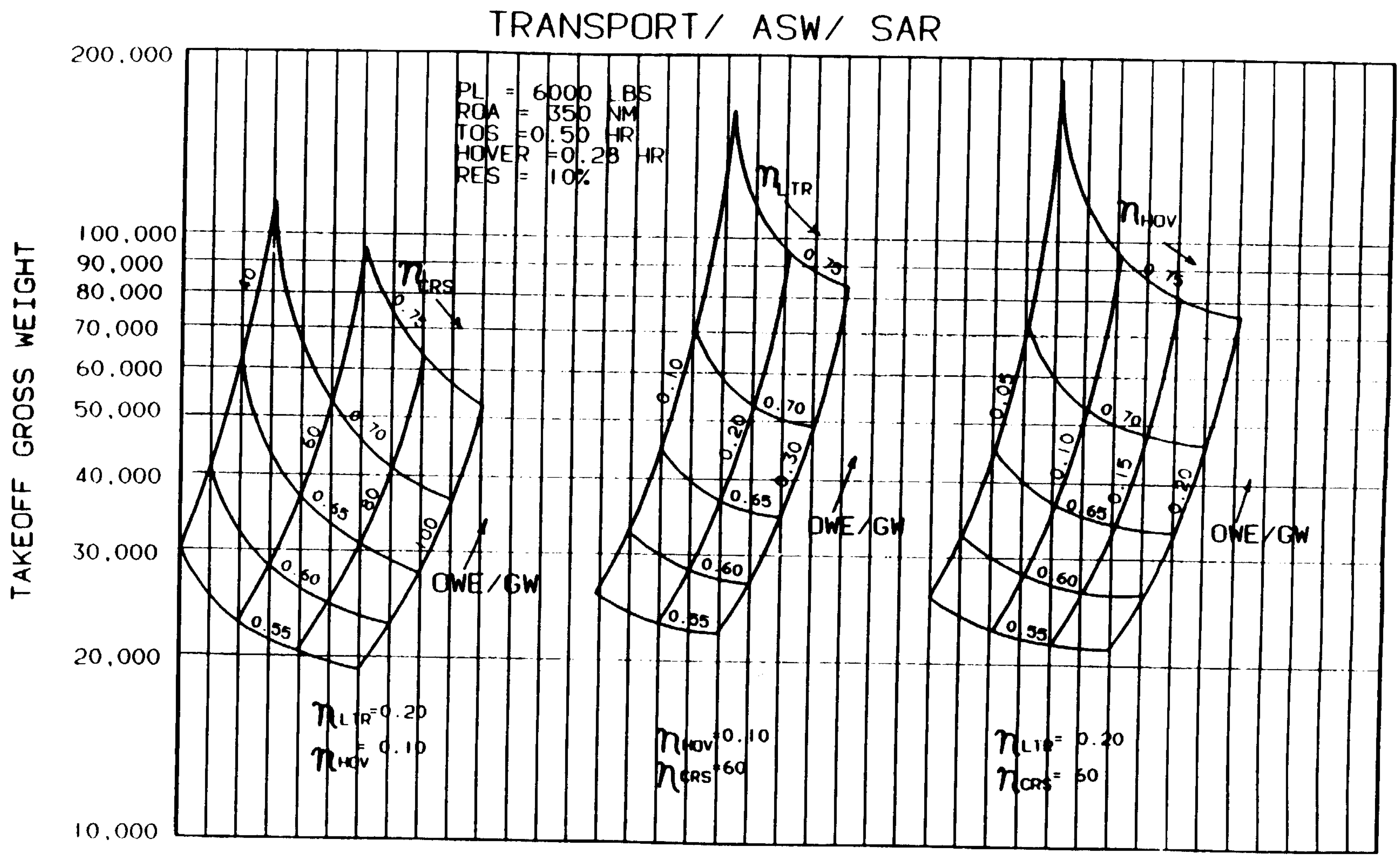

Figure A-24. Military transport mission sensitivity to fundamental performance variables

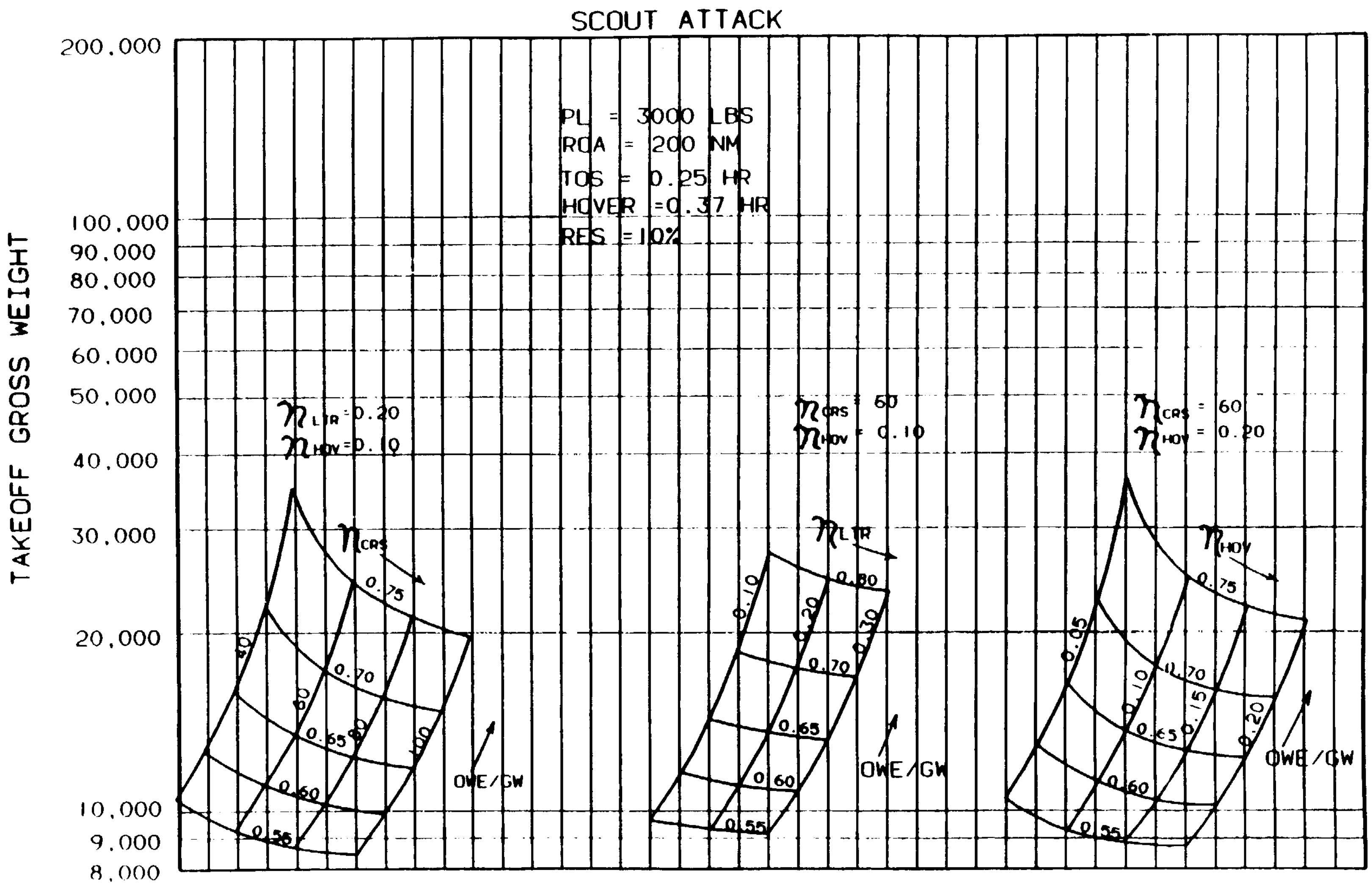

Figure A-25. Scout-attack mission sensitivity to fundamental performance variables

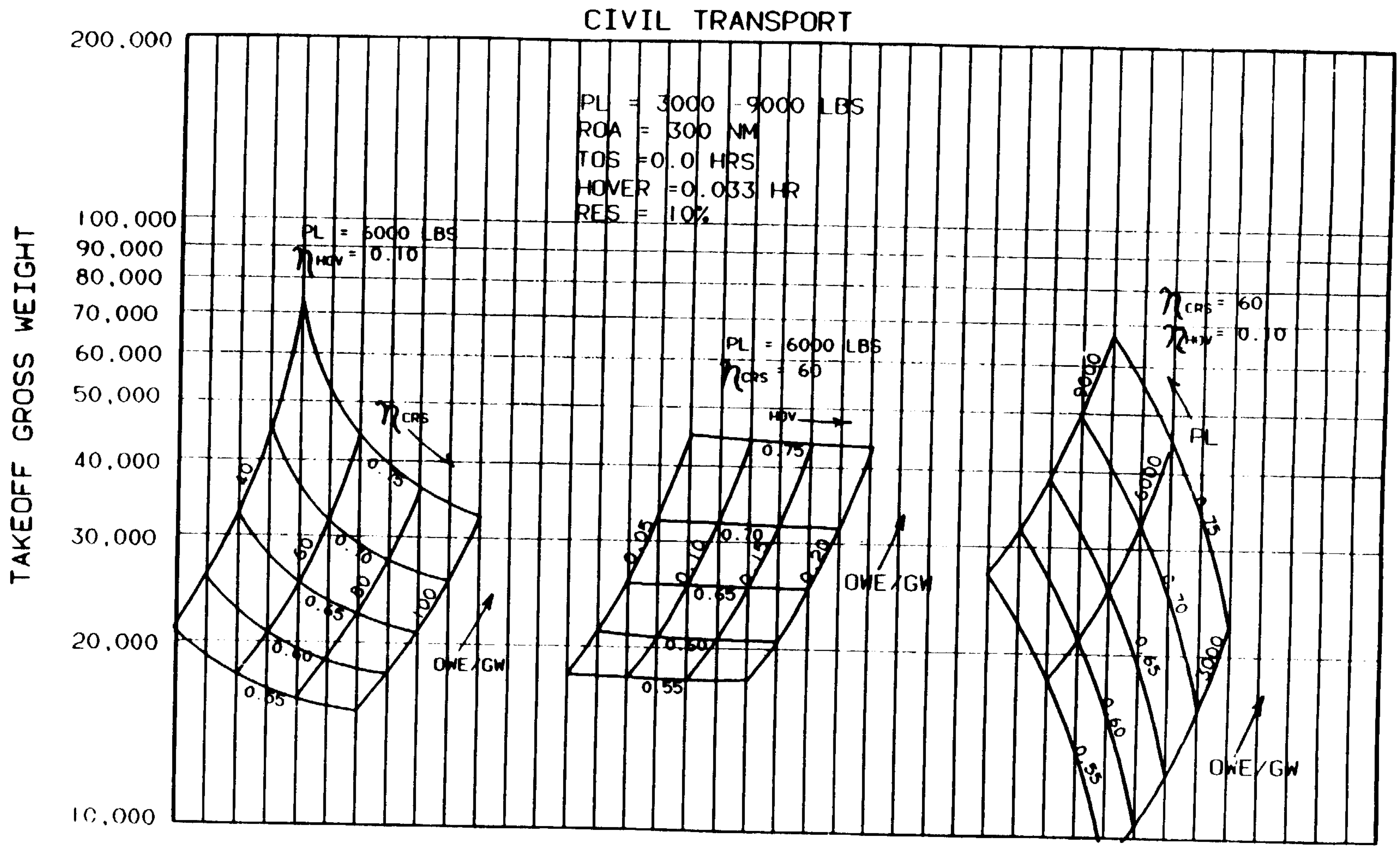

Figure A-26. Civil transport mission sensitivity to fundamental performance variables

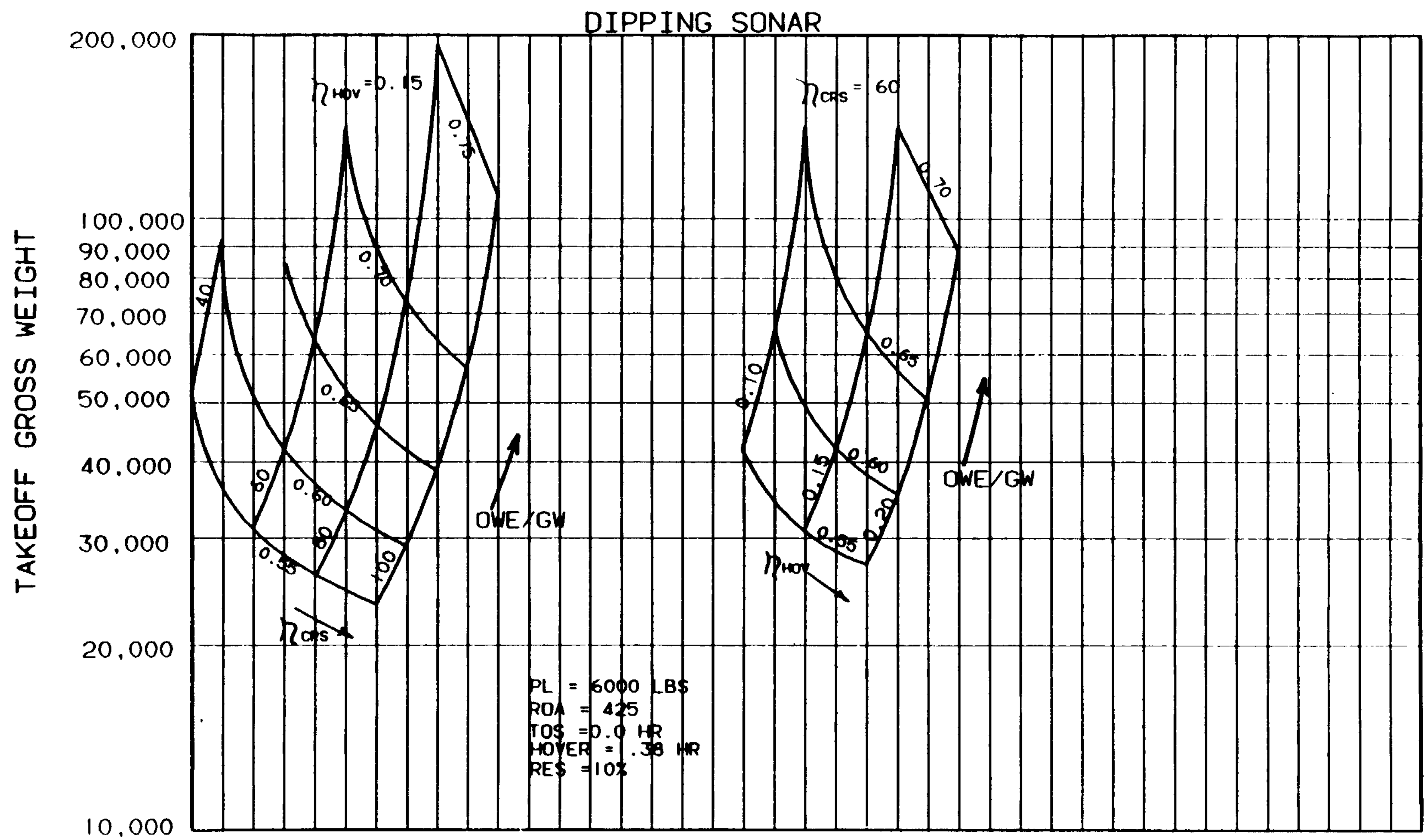

Figure A-27. Navy dipping sonar mission sensitivity to fundamental performance variables

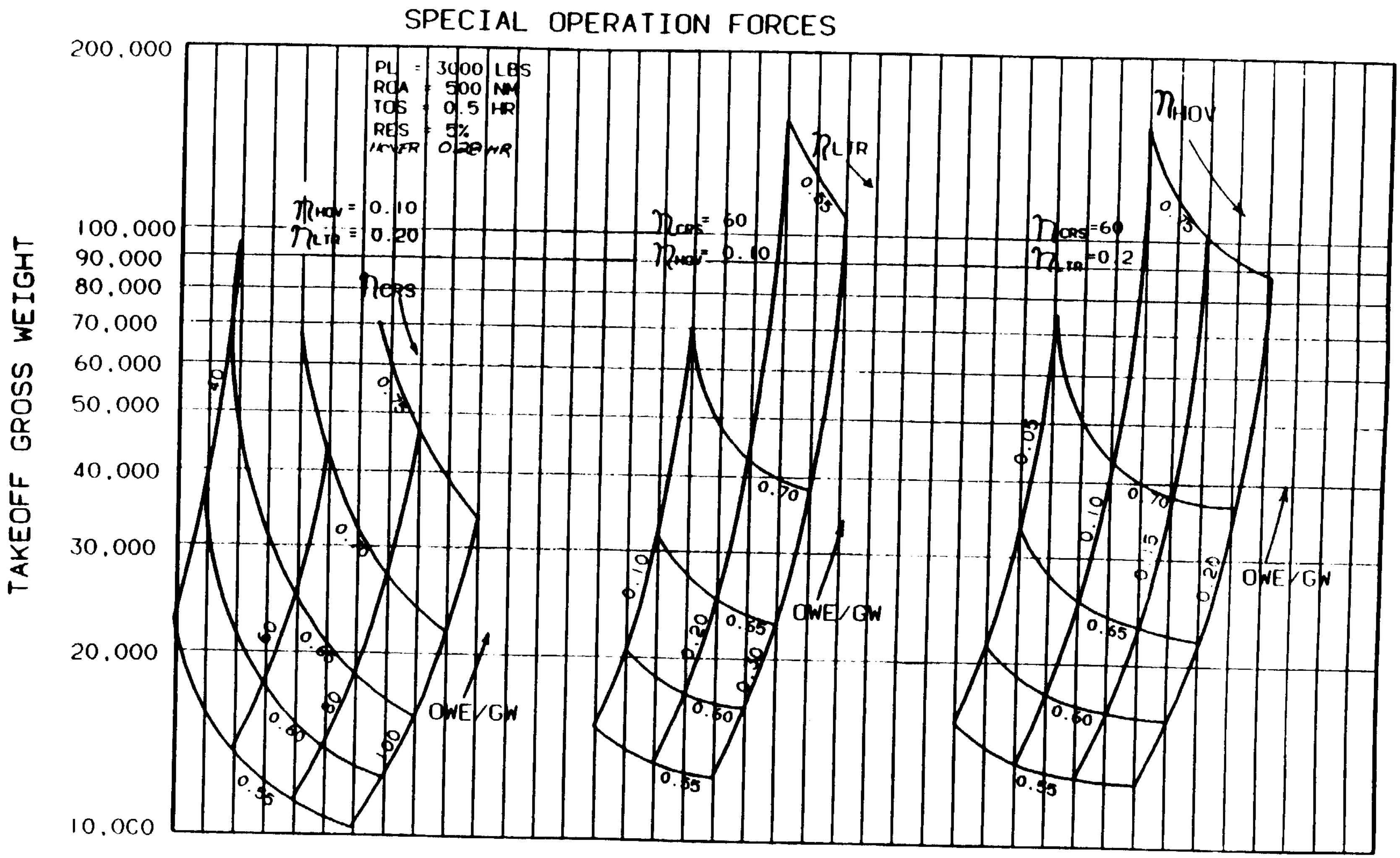

Figure A-28. Military SOF mission sensitivity to fundamental performance variables

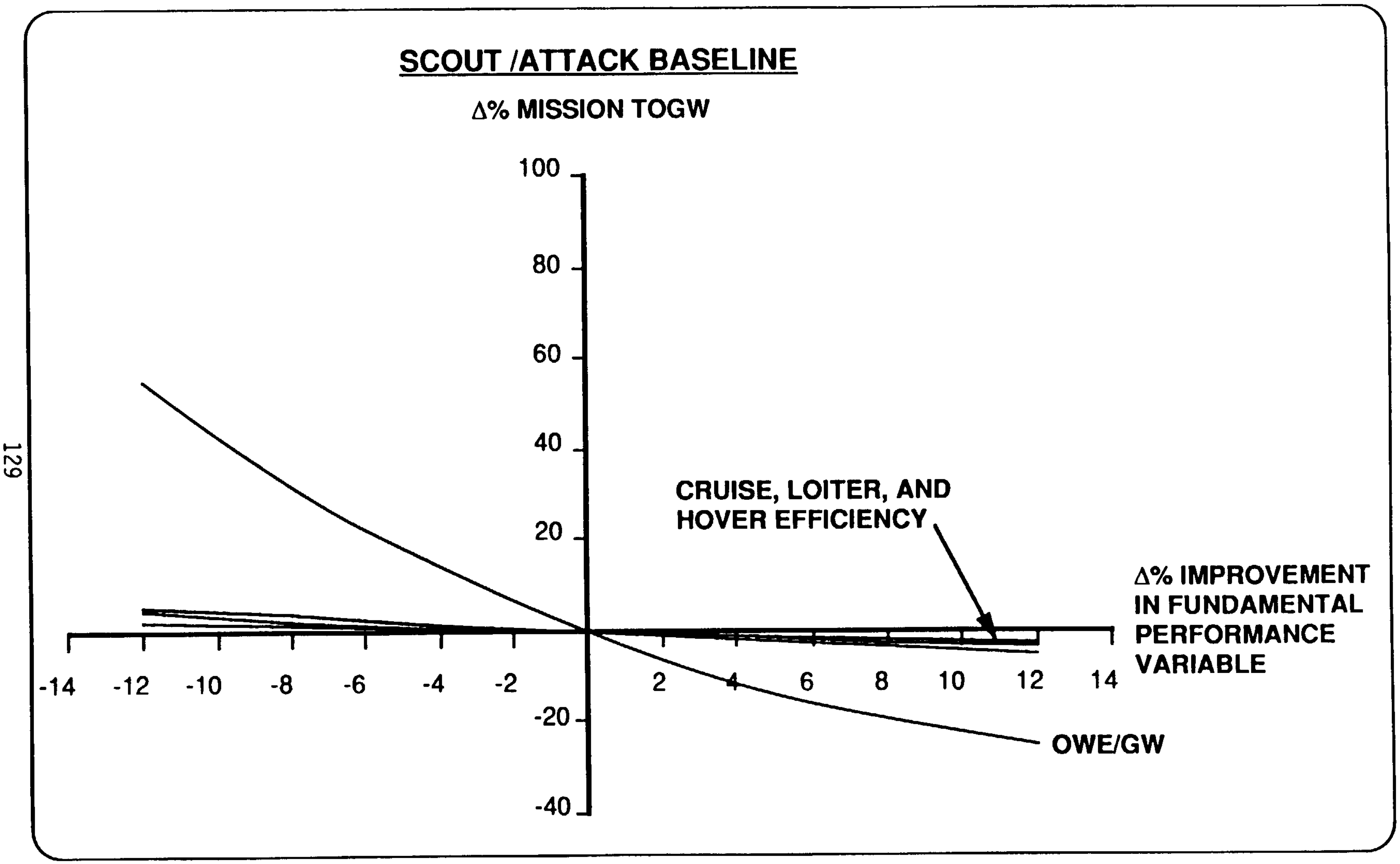

Figure A-29. Sensitivity of SCAT baseline to fundamental performance variables

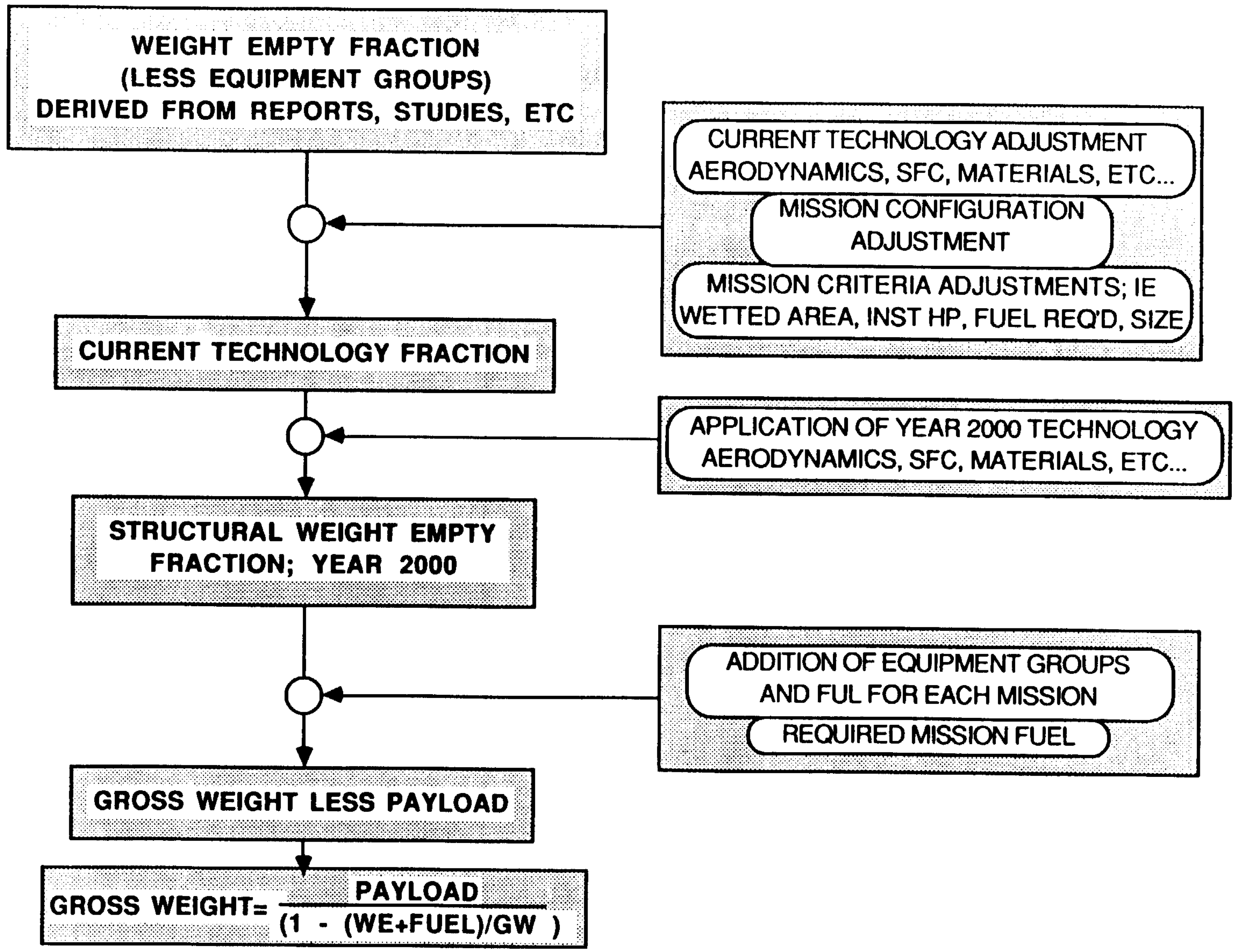

Figure A-30. Candidate concept empty weight derivation format

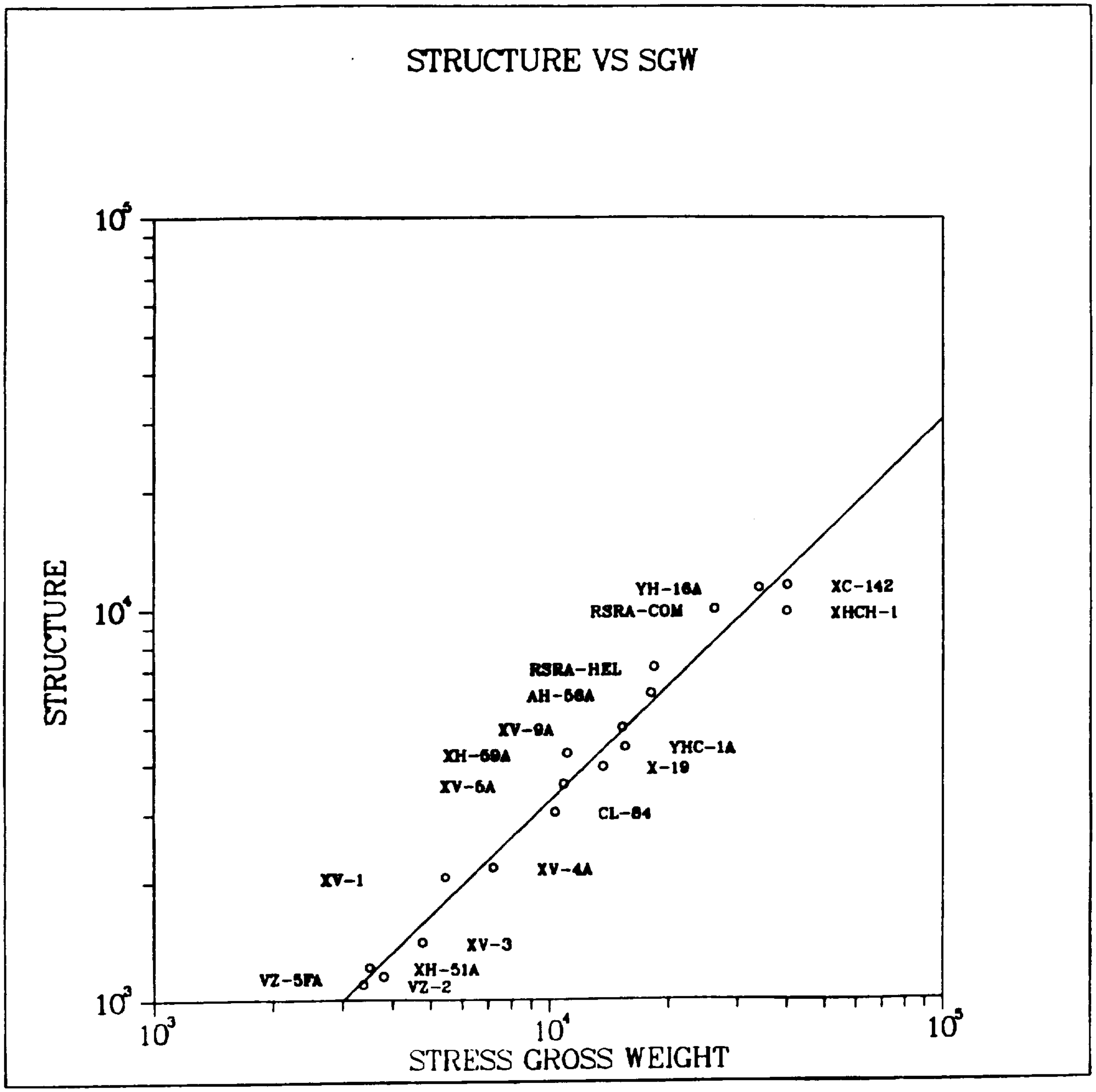

Figure A-31. Structural weight vs. stress gross weight

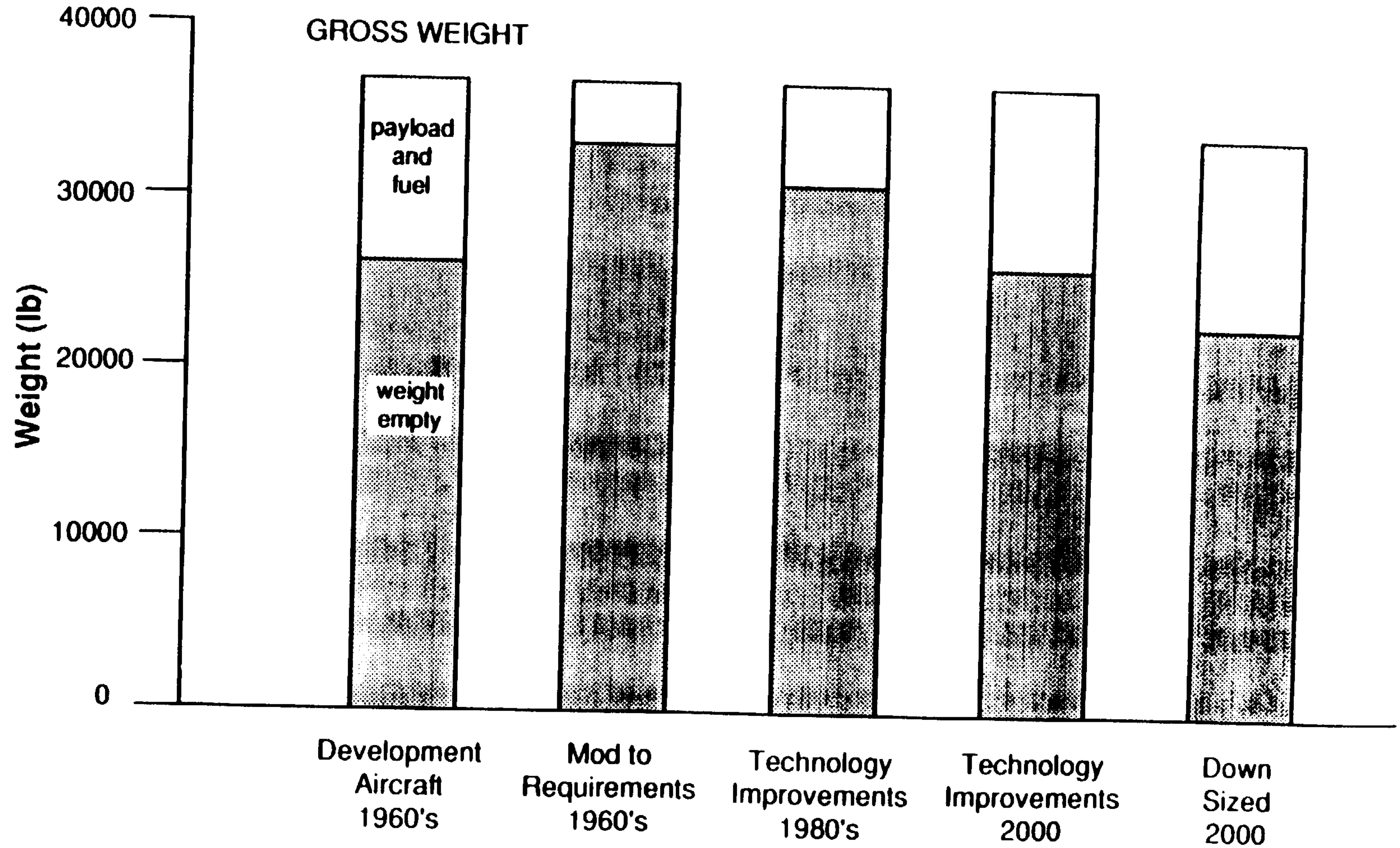

Figure A-32. Impact of technology on mission capability

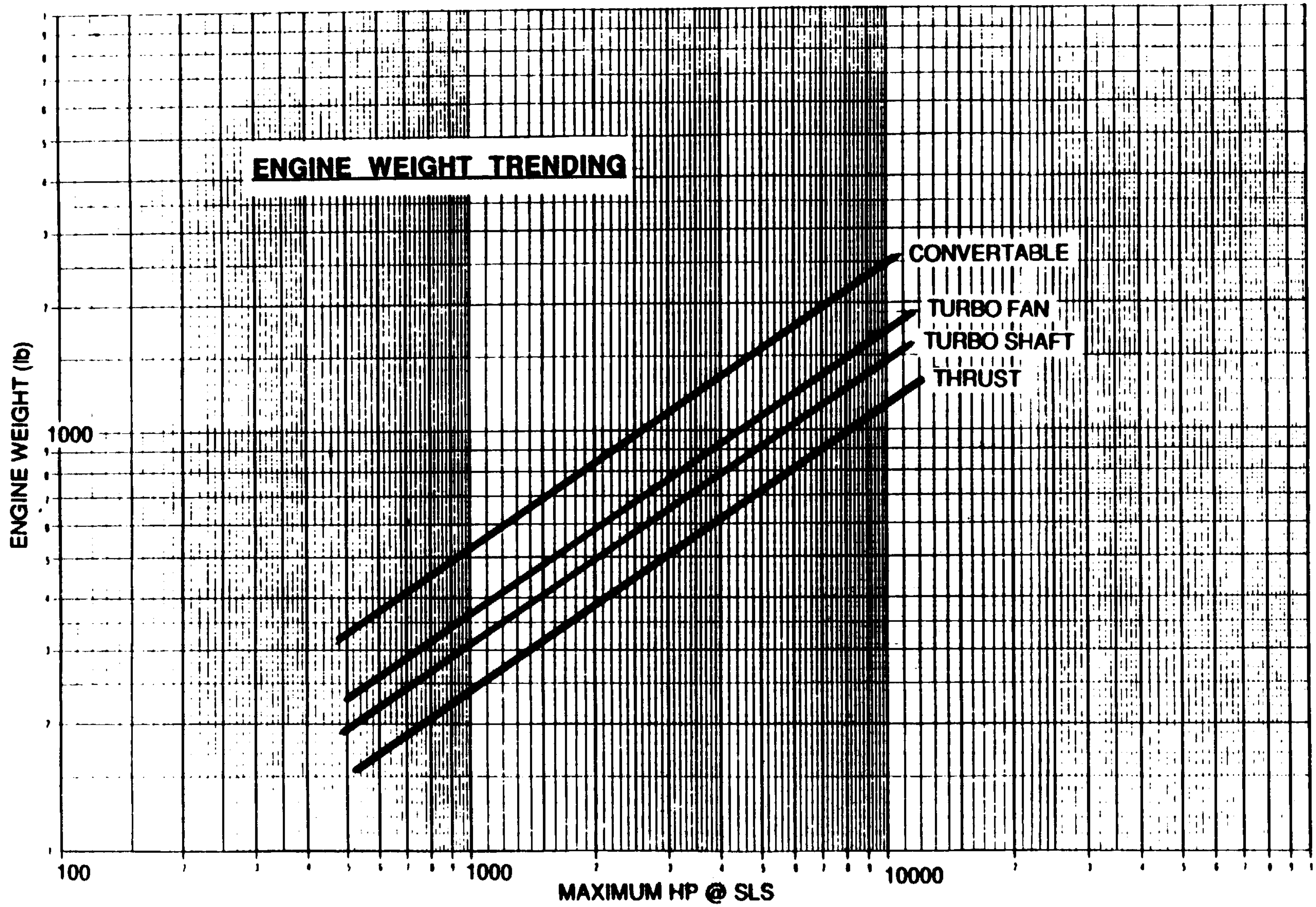

Figure A-33. Engine weight trends

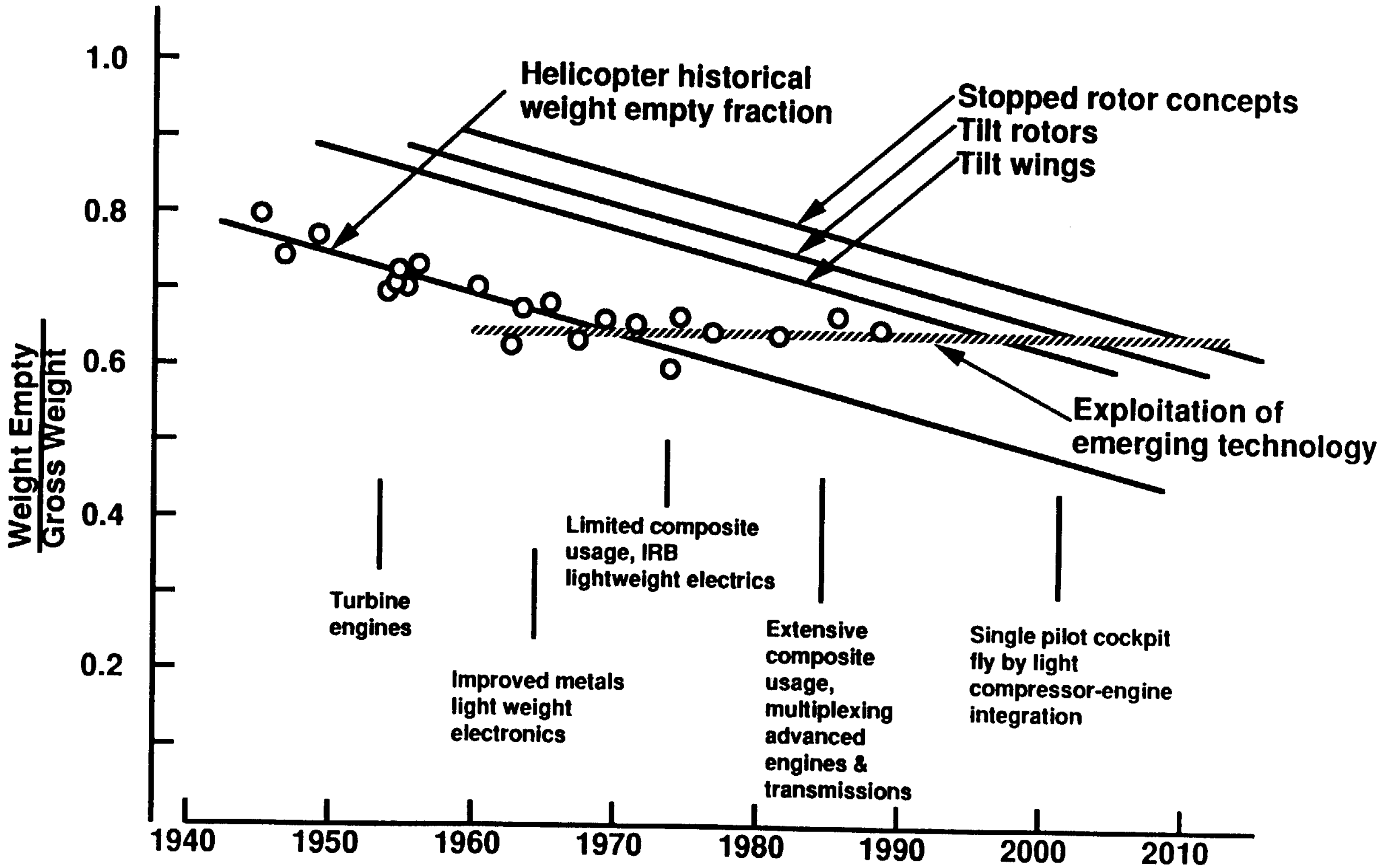

Figure A-34. Empty weight fraction vs. time and requirements

1980 TO YEAR 2000 VALUES FOR EACH PARAMETER

	DL	Dv	FM	FM	Cf	η_p	SFC	SFC	WE/GW	
	act/eff	%GW	rotor	a/c			HP	lbf	1980	2000
TILT ROTOR	20	.10-.07	.80-.81	.69-.73	.017-.016	.70-.75	.45-.35	.871		.708
TILT WING	50	0	.78-.80	.78-.80	.017-.016	.75-.80	.45-.35	.806		.655
TILT DUCT FAN	95/50	0	.80-.85	.80-.85	.030-.026	.75-.80	.45-.35	---	X	X
VARIABLE DIAMETER TILT ROTOR	15	.08-.07	.75-.77	.67-.70	.017-.016	.73-.78	.45-.35	.883		.723
FOLDING TILT ROTOR	20	.10-.07	.81-.82	.70-.74	.017-.016	---	---	.907		.760
X WING UNSUITABLE									X	X
TIP DRIVE X WING	15	.08-.06	.55-.59	.46-.51	.020-.017	---	hvr .63	.70-.55	.909	.751
STOPPED ROTOR	15	.04-.03	.53-.57	.43-.48	.026-.023	---	---	.70-.55	.920	.768
TIP DRIVE STOPPED ROTOR	15	.04-.03	.53-.57	.47-.55	.026-.018	---	hvr .63	.70-.55	.828	.686
STOPPED-RETRACTABLE ROTOR	15	.04-.03	.65-.69	.54-.59	.026-.020	---	---	.70-.55	.924	.775
STOWED ROTOR	15	.12-.10	.75-.79	.56-.61	.017-.015	---	---	.70-.55	.914	.771
FAN IN WING	95/50	.01-.005	.67-.73	.66-.73	.019-.017	---	---	.70-.55	X	X
FAN IN FUSELAGE UNSUITABLE									X	X

Figure A-35. Fundamental performance values for military transport / ASW / CSAR concepts

1980 TO YEAR 2000 VALUES FOR EACH PARAMETER

	DL	Dv	FM	FM	Cf	η_p	SFC	SFC	WE/GW	
	act/eff	%GW	rotor	a/c			HP	lbf	1980	2000
TILT ROTOR	20	.10-.07	.80-.81	.69-.73	.012-.0112	.72-.77	.45-.35	---	.759	.596
TILT WING	40	0	.78-.80	.78-.80	.017-.0112	.77-.82	.45-.35	---	.722	.584
TILT DUCT FAN								---	X	X
VARIABLE DIAMETER TILT ROTOR	20	.08-.07	.75-.77	.67-.70	.012-.0112	.75-.80	.45-.35	---	.779	.625
FOLDING TILT ROTOR	20	.10-.07	.81-.82	.70-.74	.012-.0112	---	---	.80-.62	.810	.669
X WING UNSUITABLE	15	.07-.05	.55-.59	.43-.48	.013-.0122	---	---	.80-.62	.878	.720
TIP DRIVE X WING	15	.07-.05	.55-.59	.47-.52	.013-.0122	---	hvr .63	.80-.62	.827	.669
STOPPED ROTOR	15	.03-.02	.53-.57	.44-.49	.020-.0182	---	---	.80-.62	.963	.640
TIP DRIVE STOPPED ROTOR	15	.03-.02	.53-.57	.48-.53	.020-.0132	---	hvr .63	.80-.62	.706	.564
STOPPED-RETRACTABLE ROTOR	15	.03-.02	.65-.69	.55-.60	.020-.0182	---	---	.80-.62	.790	.657
STOWED ROTOR	15	.07-.06	.75-.79	.61-.65	.011-.0102	---	---	.80-.62	.809	.676
FAN IN WING	95/50	.01-.005	.67-.73	.66-.73	.013-.011	---	--	.80-.62	1.006	.836
FAN IN FUSELAGE UNSUITABLE	95/50	.01-.005	.63-.70	.63-.70	.013-.011	---	----	.80-.62	1.036	.881

Figure A-36. Fundamental performance values for scout-attack concepts

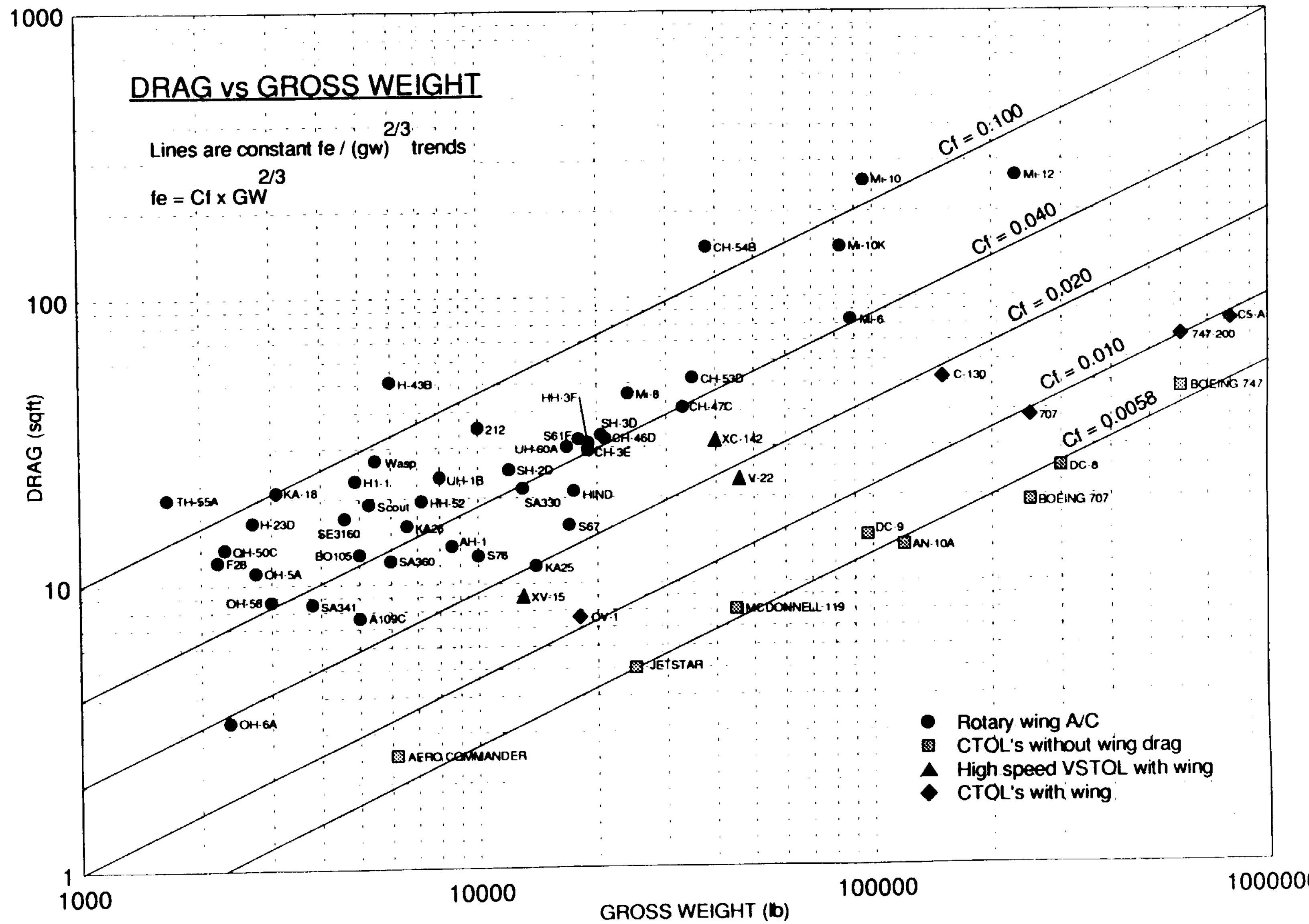

Figure A-37. Equivalent flat plate drag vs design TOGW

	STRUCTURAL WEIGHT SAVINGS (MATERIALS + ANALYSIS)	CONVERTIBLE ENGINES	WARM CYCLE ENGINE CONVERSION SYSTEMS	CIRCULATION CONTROL	PROPELLER/PROP ROTOR PROP FAN TECHNOLOGY	HIGHER HARMONIC CONTROL	CONTROL SYSTEMS (ACTIVE SYSTEMS)	NOISE REDUCTION	ROTOR HOVER AERODYNAMICS	ROTOR DYNAMIC MECHANISMS (FOLD, VD, ETC.)	IMPROVED DRAG DIVERGENCE AIRFOILS	AEROELASTIC DESIGN (DIVERGENCE)	
TILT ROTOR	✓				✓						✓	✓	
TILT WING	✓				✓						✓	✓	
TILT DUCT FAN	✓				✓					✓	✓	✓	
VARIABLE DIAMETER TILT ROTOR	✓				✓					✓	✓	✓	
FOLDING TILT ROTOR	✓	✓								✓	✓	✓	
X WING	✓	✓		✓		✓	✓		✓		✓	✓	SCAT ONLY
TIP DRIVE X WING			✓	✓		✓	✓	✓	✓		✓	✓	
STOPPED ROTOR	✓	✓				✓	✓		✓		✓	✓	
TIP DRIVE STOPPED ROTOR	✓		✓	✓		✓	✓	✓	✓		✓	✓	
STOPPED-RETRACTABLE ROTOR	✓	✓				✓	✓		✓	✓	✓	✓	
STOWED ROTOR	✓	✓				✓	✓			✓		✓	
FAN IN WING	✓		✓	✓			✓			✓	✓		
SHROUDED ROTOR	✓		✓	✓			✓			✓	✓		SCAT ONLY

* Improved SFC Assumed for All Concepts

Figure A-38. Future technology applications that are expected to produce significant performance improvements

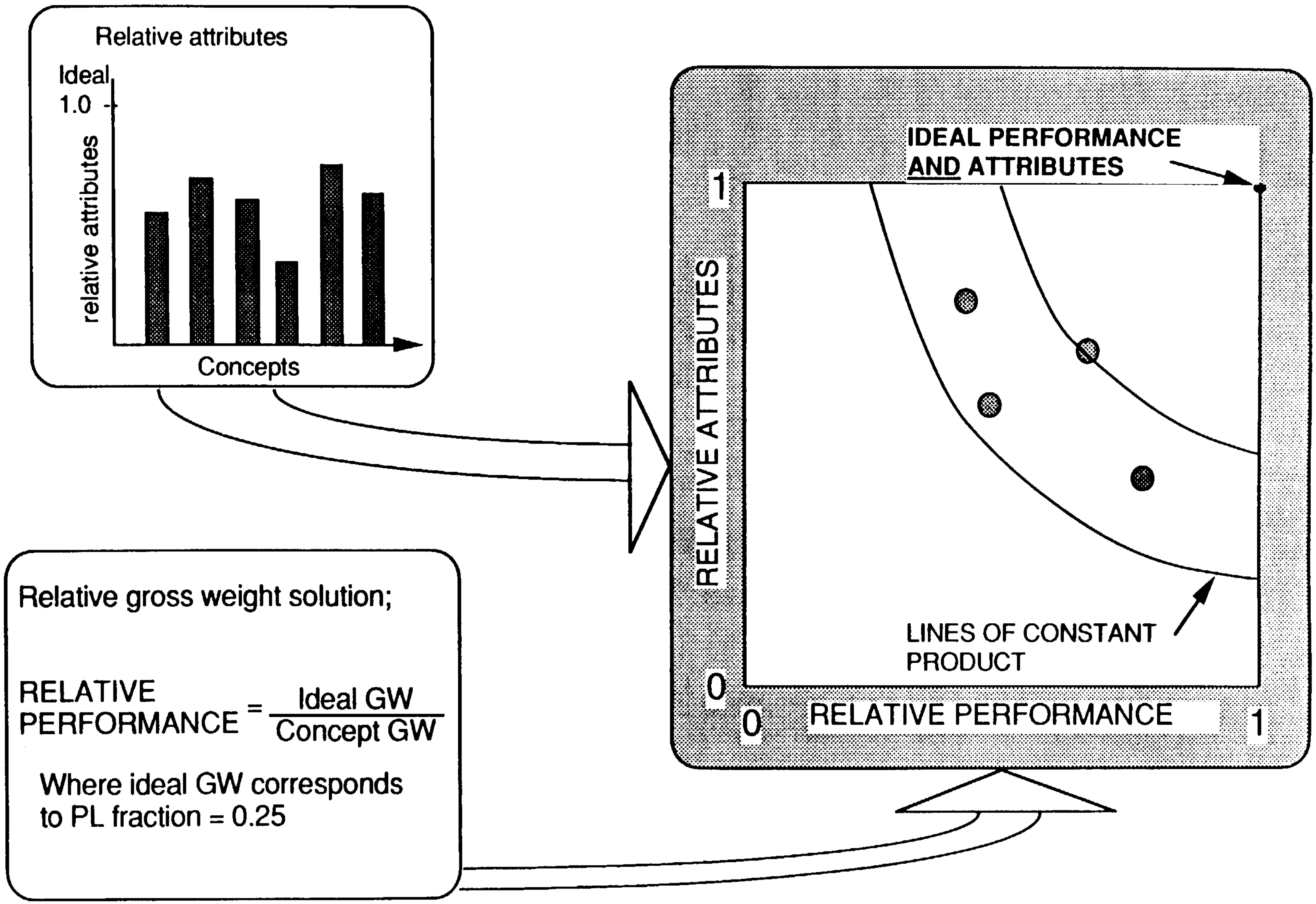

Figure A-39. Components of relative attributes vs. relative performance diagram

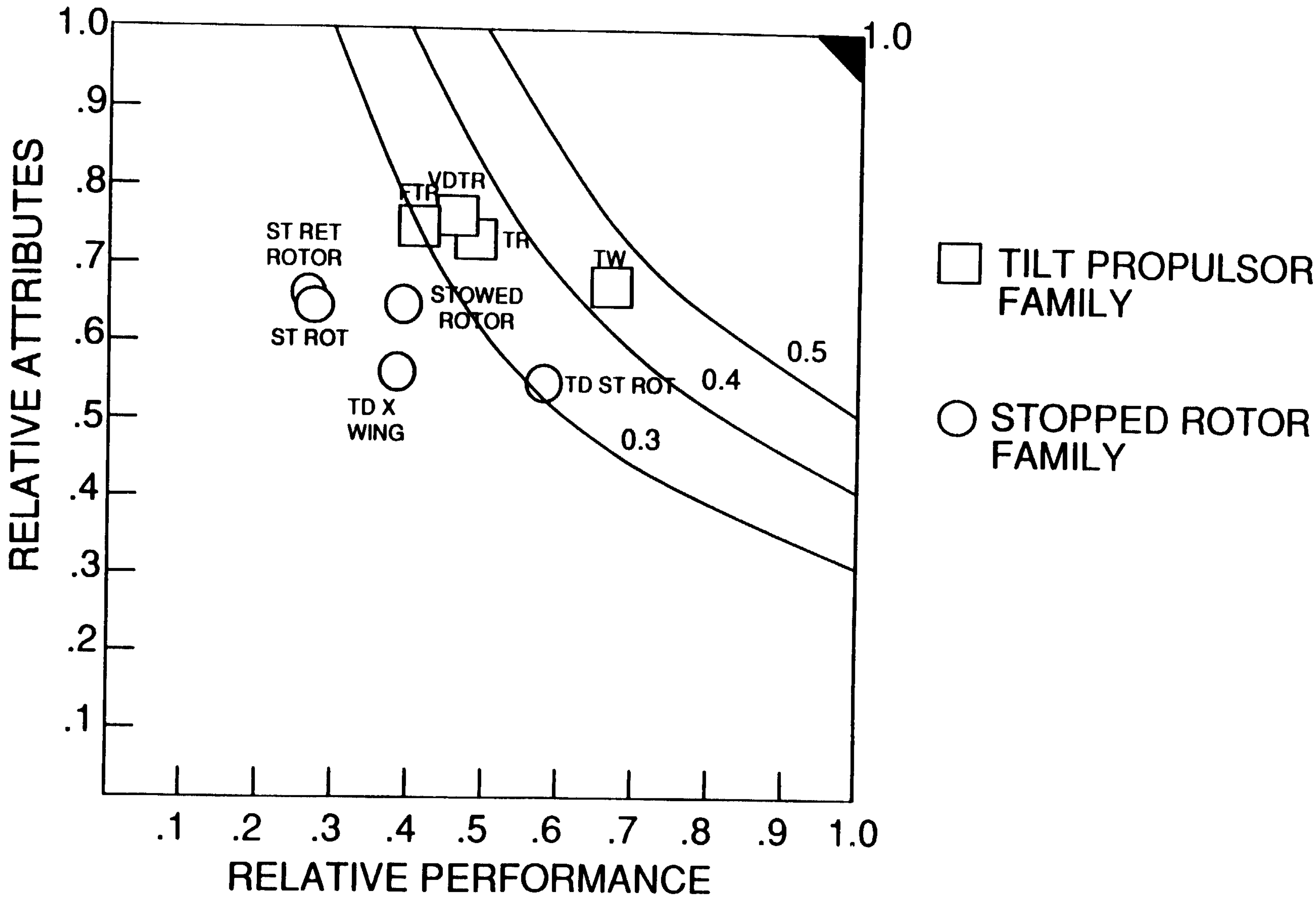

Figure A-40. Relative attributes vs. relative performance, 450kt military transport mission

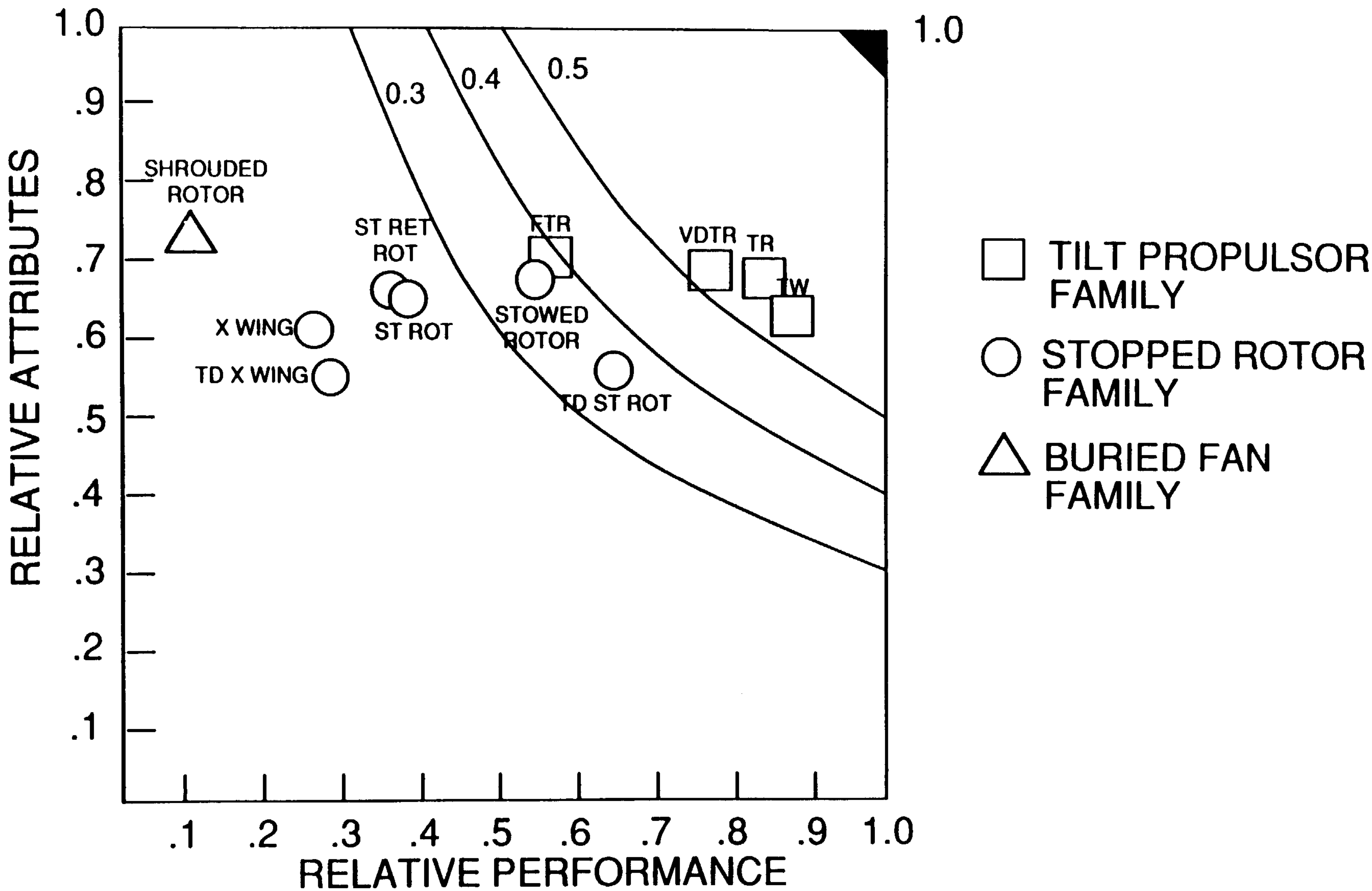

Figure A-41. Relative attributes vs. relative performance, 400 kt scout-attack mission

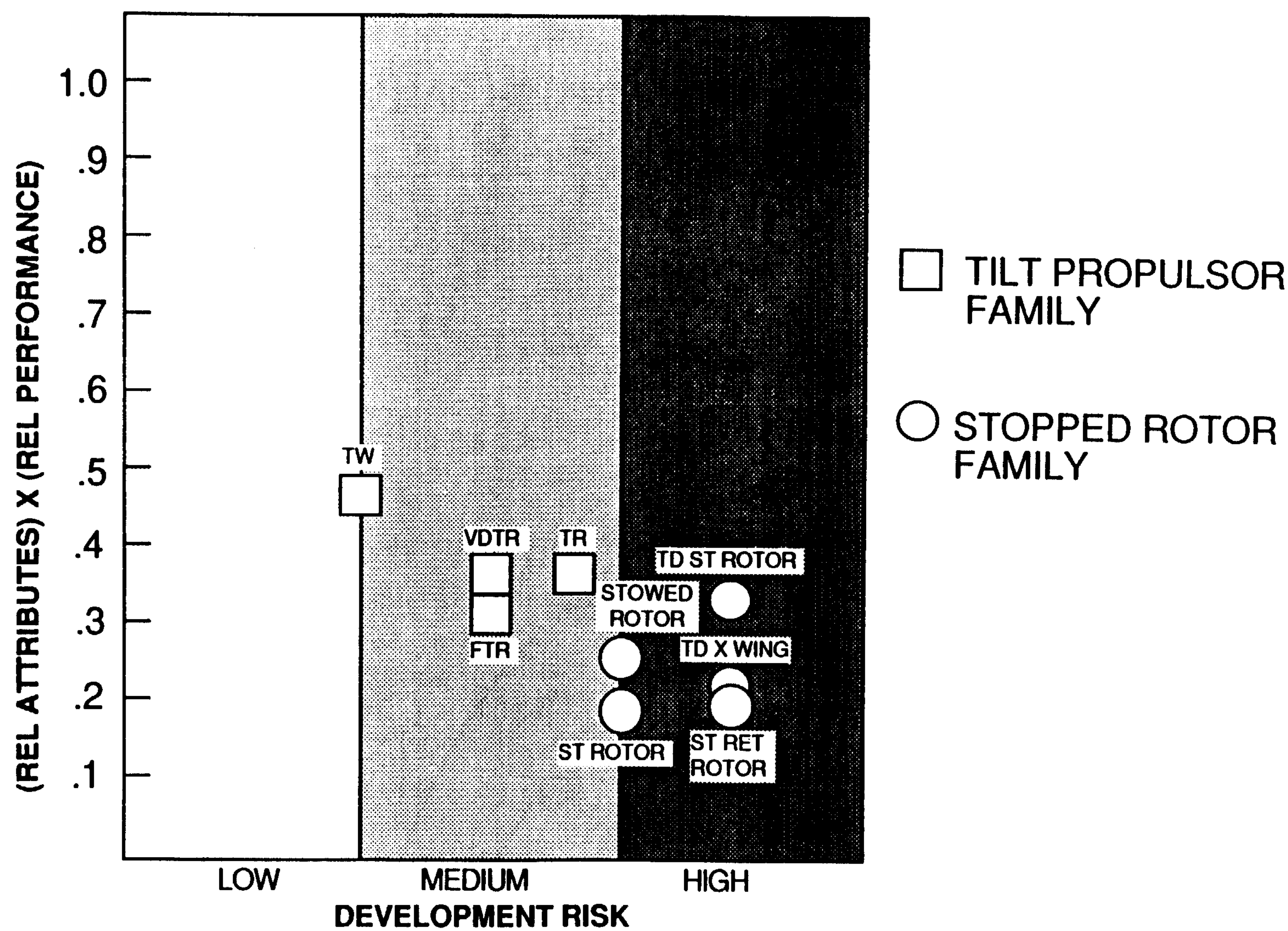

Figure A-42. Overall concept rating vs. development risk, 450 kt military transport mission

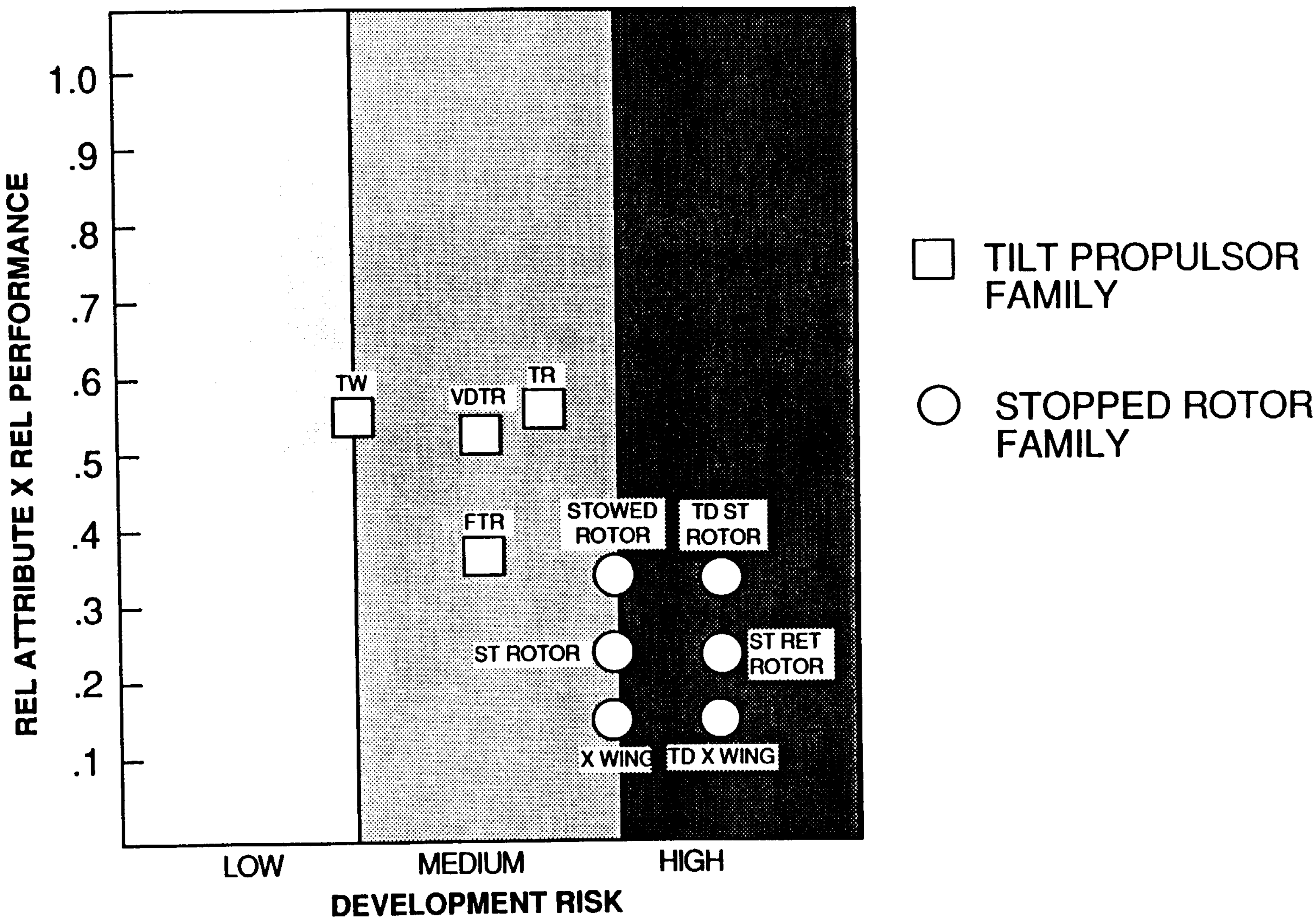

Figure A-43. Overall concept rating vs. development risk, 400 kt scout-attack mission

WEIGHT REDUCTION	MATERIALS STRUCTURAL ANALYSIS AEROELASTIC ANALYSIS
HIGH SPEED PROPROTORS	DYNAMICS CONVENTIONAL PROPROTORS WITH GREATER THAN 75% EFFICIENCY AT HELICAL TIP MACH OF .92 TO .96 VARIABLE DIAMETER PROPROTOR MECHANICS AND DYNAMICS 75% EFFICIENCY AT HELICAL MACH OF .83 TO .87 AND AT HIGH ADVANCE RATIOS
ENGINES	IMPROVED SFC, HP/GW RATIO HIGH CONTINGENCY RATINGS
DRAG REDUCTION	IMPROVED ANALYSES; CFD AND EXPERIMENTATION HIGH DRAG DIVERGENCE MACH No FOR 21 TO 23% AIRFOILS
OBSERVABLES	NEED TO IMPROVE OBSERVABLES TECHNOLOGY AND SPECIFIC APPLICATION

Figure A-44. Technology areas important to the feasability of high speed tilt wing and VDTR aircraft

WEIGHT REDUCTION	MATERIALS STRUCTURAL ANALYSIS
MECHANISMS	LIGHT WEIGHT ROTOR COVERING SYSTEM STIFF, CLOSELY SPACED ROTOR SYSTEM, ROTOR DRIVE SYSTEM
AERODYNAMICS & CONTROL	LOW SPEED INFLOW AND AUGMENTATION EFFECTS INCREASED WING AIRFOIL DIVERGENCE MACH NUMBER CIRCULATION CONTROL
ENGINES	CONVERTIBLE ENGINES IMPROVED SFC INCREASED POWER TO WEIGHT RATIO HIGH CONTINGENCY RATINGS

Figure A-45. Technological areas important to the feasability of a high speed shrouded rotor aircraft

APPENDIX B

Task II: Aircraft Performance, Characteristics, Substantiating Data, and Sensitivity Study Results

Section 1. Introduction

The main bodies of work performed in this task were:

- Design refinements of the selected mission-concept pairs
- Gross weight minimization analysis
- Aircraft performance and characteristics definition
- Gross weight sensitivity to design and mission variables

The progression of work in Task II is shown schematically in Figure B-1. Optimization was an iterative process. Applied refinements yielded increasingly better solutions, but a point of diminishing returns was reached. This is a potential pitfall in a limited study of this nature. Excessive time can be consumed trying to refine designs leaving less time for the primary aim of this task.

The sizing and performance analyses in this study were done at a conceptual level and were predicated on the projected technology levels in the year 2000. Projections were made based on historical trends augmented by application of specific technologies in related areas. Year 2000 technology is defined as that which has undergone substantial development testing and is ready for implementation into a preliminary design of a production aircraft.

The shrouded rotor concept showed the potential for very good maneuverability, agility, low observable qualities, and high speed. Due to the limited amount of data generated in Task I, however, these advantages could not be quantified and directly compared to the VDTR SCAT. The concept was carried into Task II as a contractor option and was redesigned to improve the empty weight fraction. It was changed from a shaft drive to a tip drive system similar to that used succesfully on the XV-5A.

Optimization, performance, and characteristics analyses were performed for the tilt wing and VDTR transports, and for the VDTR SCAT. These results are discussed concurrently for each aircraft in each section. This format helps to highlight the inherent differences between concepts. The shrouded rotor design is introduced and described in Section 3 but since it was subjected only to limited analysis it is discussed at the end of Appendix B in Section 5.

Section 2. Design Guidelines

The design and sizing of each of the four selected aircraft in this task followed the same set of design guidelines. This ensured that differences in overall performance was attributed to the concept and not to a difference in mission capabilities. Table B-1 lists the guidelines used for these high speed rotorcraft designs. Most of these guidelines are standards by which many military transport and SCAT Helicopters are currently designed.

A design load factor (DLF) of 3.0 is typical for a transport aircraft. A VTO DLF of 2.0 is sufficient to handle a very rapid collective pull encountered in a jump takeoff condition. High turn rates are very important for attack aircraft. This is a strong function of load factor capability. Hence a higher DLF of 4.5 has been selected for the SCAT aircraft.

There is no question that crashworthiness should be incorporated into a military transport. However, for the SCAT aircraft, which does not have a rotor above the cockpit, there is the option of ejection seats. This option was selected for the SCAT aircraft. A zero-zero ejection capability enhances the crews survival rate, and the extra weight of the ejection system is more than offset by the removal of crashworthy features in the airframe, seats and fuel system.

The engine rating structure was based on the T700 engine with a 10% increase in the IRP/MCP ratio. The 30 second rating is 125% of the IRP takeoff rating. This is 140% of MCP and is consistent with the requirements stated for the civil transport mission.

The tilt wing and VDTR concepts will have good STOL characteristics. To take advantage of this a high maximum alternate gross weight ratio of 1.4 was selected. At this value ample load factor capability is available for long range ferrying or self deployment missions.

Section 3. Tilt Wing Transport, VDTR Transport, and VDTR SCAT Mission Sizing Optimization

The first step in Task II was to resize each aircraft about their respective missions using more detailed aerodynamics and weights methodologies. Sweeps in disk loading and wing area were made to minimize mission TOGW. These analyses were made using the Sikorsky developed VTOL Trending Model (VTM) program which is particularly well suited for this application. The aircraft definition in Task II was conceptual in form. This required a sizing program that utilized only fundamental performance inputs. A Sikorsky developed sizing program called VTM (VTOL Trending Model) was used in Task II to size each aircraft for its respective mission. VTM is a traditional sizing program that is generic enough to handle any VTOL concept

Table B-1. DESIGN GUIDELINES

REQUIREMENTS	GUIDELINE	MISSION
Design load factor (DLF)	2.0 VTO 3.0 FW	XPORT
	2.0 VTO 4.5 FW	SCAT
Landing gear sink speed	10ft/s	XPORT
	10ft/s	SCAT
Crashworthiness	UH-60A Level 40ft/s	XPORT
	AH-1 level w/ejection seats	SCAT
IR suppression,	UH-60A level	XPORT
Ballistic tolerance	UH-60A level	SCAT
Vne	1.2 Vdive, 621 kts	XPORT
	1.2 Vdive, 552 kts	SCAT
Control system backup	UH-60A level	XPORT
	UH-60A level	SCAT
Engine ratings	20 min IRP = 1.12 MCP	XPORT
	2 1/2 min CRP = 1.20 MCP	and
	30 sec OEI = 1.40 MCP	SCAT
Max alternate GW	1.40 * SDGW	XPORT
	1.40 * SDGW	SCAT

concept ranging from helicopters to direct thruster types. Figure B-2 lists the performance calculations and input variables required for VTM. The number of inputs is appropriate for the limited definition of these conceptual aircraft. There are no rotor performance maps, engine performance curves, or other detailed information required. The weights analysis is done to a MILSTD-1374 Part 1 level. Weights equations developed from linear regression analysis are used. More discussion on weights analysis and technology factors is provided in Section 4.

The concepts selected from Task I were resized in Task II incorporating the design guidelines described in Section 2, the detailed mission profile, refined aerodynamic performance variables, and refined weights methodology. A summary of refined values as compared to the Task I estimates is listed in Table B-2.

Over the course of the iterative loop diagramed in Figure B-1, a detailed drag analysis was carried out for each aircraft using Reference 4. This analysis accounts for surface roughness, viscosity, interference, separation, Mach effects and a host of other smaller effects. The tilt wing parasite drag coefficient was reduced 16% to .0135 as a result of this analysis. Part of this was

Table B-2. YEAR 2000 DESIGN VARIABLES, TASK I AND REFINED TASK II VALUES

	Military Transport		Military SCAT	
Task I	TW	VDTR	VDTR	SHR
Propulsive eff.	.80	.78	.80	--
Cf	.016	.016	.0112	.0110
FMac	.80	.70	.70	.83
SFC	.35	.35	.35	.35
Lapse rate	Proportional to density ratio			
DLF	3.0	3.0	3.0	3.0
Task II	TW	VDTR	VDTR	SHR
Propulsive eff.	.77	.75	.79	--
Cf	.0135	.0121	.0131	.0128
FMac	.79	.67	.67	.70
SFC	.321	.321	.321	.70(lb/hr/lb)
Lapse rate	(-.282)% per deg F and (-2.73)% per 1000 ft			
DLF	3.0	3.0	4.5	4.5

due to detailed analysis and part from careful shaping of the nacelles, afterbody, and the lack of large sponsons. The VDTR transport drag level was reduced 24%. Careful shaping and the lack of sponsons accounted for part of this. However, a large percentage was due to relocating the engines from the wing tips to the fuselage. The reduction of skin friction, form, and interference drag at the tip more than compensated for the slight increase in surface area and form drag of the fuselage. The reduction of weight at the tip also increases the natural bending and torsional frequencies of the wing. This is beneficial from an aeroelastic standpoint and is important at high cruise speeds.

The SCAT VDTR drag increased 8% from the initial Task I value. Most of this is due to the addition of external stores interference drag. Reference 4 contains a detailed estimation method for skin friction drag. For a given temperature, altitude, and Mach number their is a particular surface roughnesses beyond which a rapid increase in skin friction drag is incurred. This critical roughness at 4,000 ft, 95 deg F is only about half that at 30,000 ft STD. In other words, at the same airspeed the aircraft at 4,000 ft 95 deg F must have a surface twice as smooth in order to have the same skin friction coefficient. Typical military finish, particularly infrared (IR) paint, is rather rough. To the touch it feels like 180 to 120 grit sandpaper. The transports in this study were assumed to have an average smooth matte paint. The SCAT aircraft were assumed to have a carefully applied paint finish with a sand grain height of about half that of typical current aircraft.

The overall propulsive efficiencies for the transport aircraft were lowered several points for both the tilt wing and VDTR. This stems from accounting for transmission, engine and fixed losses. For the SCAT VDTR the propulsive efficiency of the proprotor was reestimated two points higher, so only a one point net reduction resulted. Both drag and propulsive efficiency are important to the overall aircraft design. A more detailed discussion of each is presented in the sensitivity study and enabling technology plan sections.

The sensitivity of the designs to hover figure of merit was investigated late in Task I. The engine size and the majority of the fuel required is determined by the cruise condition. Each aircraft enjoys a high power margin in hover. It was found that mission TOGW was fairly insensitive to rotor figure of merit. Therefore, hover performance was traded for an increase in propulsive efficiency. This gives more latitude in proprotor cruise optimization and increases the probability of being able to attain the projected propulsive efficiencies.

The tilt wing aircraft FM (FMac) was only reduced by one point. Calculations were made of the net vertical drag that the wing would produce in hover. The swirl angle of a tilt wing proprotor wake is approximately 13 to 17 degrees, depending on thrust loading. At 15 degrees swirl together with the associated downwash velocity, the immersed wing area produces a negative download of approximately 5% of gross weight. This was confirmed by analytical investigation of past tilt wing aircraft performance. This negative download in effect raises FMac by recovering energy imparted into the wake. The VDTR transport and SCAT FMac were reestimated at .62 and .65 respectively. The SCAT's higher value is the result of slightly lower download and airfoils better suited for hover as opposed to high helical tip Mach operation.

According to the IHPTET stage III engine development program, SFC by the year 2003 is projected to be 40% lower than GE-T700 technology of today. This program was reviewed with both Allison Gas Turbine Division and General Electric aircraft engine company. Each indicated that achievement of this goal will require fundamental changes in engine design and materials. Based on the historical trend of engine SFC vs time this is expected to be achievable but at this time manufacturers are not exactly sure how to get there. Step II of the IHPTET program expects to achieve a 30% reduction in SFC by 1995 to 1997. This value was chosen as a more realistic value for this study. The GE T700-701C has an uninstalled SFC of .458 at maximum continuous power. A 30% reduction yields a value of .321. An SFC relationship with percent power typical of turboshaft engines was used. This is shown in Figure B-3. The GE-T700-701C representative of late 1970's technology has lapse rates of -3.1% hp/1000 ft and -.32% hp/deg F. It is expected that a year 2000 engine could do somewhat better than this. Power loss with increased altitude and temperature is more a function of physics than design, so a lot of improvement does not appear possible. Values of -2.73%

hp/1000 ft and -.282% hp/deg F were chosen as projected lapse rates for an advanced engine designed for high altitude, high speed operation. This represents a 12% improvement over the T700 engine. The engines were assumed to be designed for vertical as well as horizontal operation. Engine SFC, power available and installation losses were assumed to be unaffected during the conversion process.

The design load factor for the military transports remained at 3.0 in Task II. For the SCAT mission it was raised to 4.5 for the reasons cited in the design guideline section.

The TW transport, VDTR transport, and VDTR SCAT were all optimized for minimum gross weight. Sweeps in design variables were made for each aircraft; disk loading and wing chord-to-diameter ratio for the tilt wing, disk loading and wing aspect ratio for the VDTR transport, and disk loading, aspect ratio, and tip speed for the VDTR SCAT. The tip speeds for the tilt wing and VDTR transports were selected based on propulsive efficiency requirements. As temperature drops with increasing altitude, propulsive efficiency is reduced due to the increasing helical Mach number. Increased specific range that accompanies higher cruise altitudes compensates for this. These two trends counter each other. Sweeps in cruise altitude were made to find the optimum altitude.

The results of the tilt wing sizing for the military transport mission are plotted in Figure B-4. Minimum gross weight resulted at 118 PSF, a wing chord-to-diameter ratio of .40, and 30,000 ft cruise altitude. In Task I a disk loading of 50 PSF was identified as the maximum that could be tolerated. This is close to the knee of the curve and incurs an 8.6% gross weight penalty compared to 118 psf. The minimum chord to diameter ratio required for effective flow turning has been experimentally found to be about .43. Effective turning is necessary in order to maintain control and wing lift during transition. For this reason a slightly conservative value of .45 was selected.

The VDTR transport sizing results are shown in Figure B-5. There is little sensitivity to cruise altitude. The 25,000 ft altitude was determined to be the best overall. From an operational point of view the 15 PSF solution at an aspect ratio of 5.3 would be best in terms of downwash characteristics. From a technology risk standpoint the higher aspect ratio blades and wing at this solution are more difficult to keep dynamically stable at high forward speeds. A compromise selection of a baseline at a 20 psf disk loading and an aspect ratio of four was chosen. This results in a 5% TOGW saving, much better structural geometry, and only a moderate degradation in downwash environment.

It is important to note that the VDTR is the only tilting thruster concept for which a high speed 15 psf diskloading solution exists. The performance and characteristics of a VDTR designed at 15 psf would be very similar to the 20 psf solution selected for this study. Proprotor and wing technology are more challenging and there is a moderate TOGW penalty but this is probably acceptable if low disk loading is an overriding operational requirement.

The sizing results for the VDTR SCAT are presented in Figures B-6 and B-7. Figure B-6 shows approximately the same sensitivity to wing aspect ratio and proprotor disk loading as the VDTR transport (Figure B-5). There is a noticeable decease in TOGW with increased tip speed. Mission TOGW's were significantly higher than expected prompting a review of the VDTR SCAT design. By improving nacelle shape, inlet design, wing placement, and canopy contoures drag was reduced by about 21%. This resulted in a Cf of .131. Sweeps in disk loading and aspect ratio were remade at a hover tip speed of 800 fps and the results are shown in Figure B-7.

Helical tip Mach effects are not as much of a problem for this design and more latitude in tip speed selection is available. The upper bound of 800 FPS at a disk loading of 25 PSF and AR=3.5 was found to yield minimum gross weight. The more desirable 15 PSF solution at AR=5.3 is 16% heavier. A compromise was again made and the 20 PSF, AR=4 solution was selected. This is only 6% heavier than the optimum and much lower risk in terms of meeting aeroelastic structural requirements. It also gives more wing area for higher maneuvering G's. The airfoil design does not require any new technology application since it is operating at Mach .56. The wing does require a high design Cl max capability and this would have to be designed in using conventional airfoil optimization techniques.

The final aircraft configurations that resulted from the Task II sizing are presented in Figures B-8 to B-11. Table B-3 lists dimensions and other design characteristics. The cut-away view of each aircraft shows the placement of major components such as the transmission, engines, fuel tankage, cabin, and cockpit. All of these were sized and are drawn to scale.

A two-engine, two-proprotor configuration was selected as the most attractive tilt wing. Before the VTM sizing was begun a two engine/prop rotor solution for the same mission was parametrically found to be lighter than a four engine/prop rotor solution. The two engine design requirement of 6000-7000 horsepower a side is within currently available engine sizes. The induced drag of a four-engine/proprotor configuration is lower than a two-engine/proprotor design, however, at 450 Kts the induced drag is a small percentage of overall drag. The wing airfoil is a 16% t/c advanced super critical design with a drag divergence Mach number slightly greater than the design condition of Mach .74.

Table B-3. AIRCRAFT DIMENSIONS AND CHARACTERISTICS

	Tilt Wing XPORT	VDTR XPORT	VDTR SCAT	SHROUDED ROTOR
Design VTO TOGW lb	33512	39839	25597	25000
Max Alt TOGW lb	46900	55750	35800	30000
Weight Empty lb	22352	26972	18867	18183
Weight Empty Fraction VTO	.667	.677	.737	.727
Internal Fuel lb	4689	6397	3259	5732
Wing Span ft	51.3	40.5	37.3	28.3
Proprotor spacing ft	31.4	36.6	34.5	--
Sweep (@ C/4) deg	0.0	-25.0	-5.0	66.0
Wing Area sqft	477	335	298	572
Aspect Ratio	5.52	4.0	4.0	1.4
Design WL psf	70.3	118.9	85.8	43.7
Wing t/c	.16	.21	.21	--
Overall Length ft	63.4	60.0	42.2	45.4
Overall Height (VTO) ft	22.6	22.1	14.7	13.8
Hp or lbst Inst(SLS,MCP)	2x6205	2x6917	2x3736	2x3900
Xmsn Rating Hp	8840	9490	8340	--
Fuse Wetted Area sqft	1255	1355	545	235
Cabin LxWxH ft	6x6x20	6x6x22	--	--
Fe sqft	14.0	13.7	11.4	9.7
Vert. Tail Area sqft	90	105	53	68
Horiz. Tail Area sqft	135	77	51	--
Design DL psf	50.0	20.0	20.0	100
Tip Speed hover fps	800	725	800	800
Tip Speed cruise fps	640	471	520	0
Diameter (ext) ft	20.66	35.61	28.54	17.84
Diameter (ret) ft	--	23.15	18.55	--
Solidity (ext)	.235	.130	.147	.39
Solidity (ret)	--	.200	.226	--
Design hover Ct/sigma	.140	.147	.123	.125
AF/blade (ret)	144	163	184	--
Number of Blades	4	3	3	6
Dv/GW	-.05	.13	.11	.01

The canard configuration of the VDTR is the result of the forward sweep necessary to increase the drag divergence Mach number of the wing airfoil. The cruise Mach of .73 would require an airfoil of 17% t/c or less. This is too thin to satisfy the structural requirements of the VDTR. Therefore, a 21% t/c super critical section was used with 25 degrees of forward sweep. The engines are placed inside the fuselage for the reasons previously stated.

The VDTR SCAT has tilting transmissions and fixed engines. Fixing the engine horizontally gives a much greater available roll angle at low wheel heights and eliminates the hot gas impingement on the ground.

The shrouded rotor was designed at a disk loading of 100 psf. Due to the lack of wake contraction the far wake velocity is effectivly a 50 to 60 psf downwash. The engine exhaust flows through vectoring nozzles. These are currently in development on both the X-31 and a modified F-15 and show great promise. Their use on the shrouded rotor concept provides very good agility. Residual thrust in hover can be diverted for additional yaw control. Primary yaw control is from moveable stator vanes below the rotor. Roll and pitch control is provided by cyclic pitch on the rigid rotor. Recent Sikorsky wind tunnel tests have shown that this provides sufficient control power in hover and up to speeds where control surfaces would become effective. A circulation control trailing edge is used on the wing. This enables a relatively thick wing section which is needed for the shrouded rotor while avoiding airflow separation off the blunt trailing edge. Air for the rotor and circulation control trailing edge is fed from a combination of core and bypass air through a diverter valve. This is the same as was done on the XV-5A except that it used all core air. The rotor is covered in forward flight by a set of louvers on top and bottom.

Not enough detailed information is available on fan-in-wing concepts to develop parametric trends for the shrouded rotor. Therefore it was designed as a 25,000 lb aircraft and the empty weight was minimized. The empty weight fraction improved considerably as a result of the Task II effort, from about .88 in Task I to .73. Most of this was due to configuration changes. However, the mission was slightly shortened to only include 10 minutes of total NOE maneuvering. Unfortunately the SFC of the low bypass turbofan engine at low altitude increases fuel consumption considerably. The resulting payload was less than one third the desired value. A description of the analysis performed on this design is covered in Section 5. Although the shrouded rotor concept offers attractive potential benefits, it was judged that the technology levels required to make it viable were beyond what is likely to be available in the year 2000 time frame of this study. It was therefore eliminated from more detailed study.

The wetted area and component drag breakdowns for the aircraft are listed in Table B-4. The three view drawings were generated on a CAD computer. This enabled accurate area calculations. The component drag levels were done using the method of Reference 21. Drag was the predominant variable requiring refinement each time an optimum was found. The iteration loop was completed several times about this variable. A major reshaping was done to the VDTR SCAT during this process. Skin friction drag is the largest contributor. This is very dependent on surface finish. The surface finish for these aircraft were assumed to be that of a high speed turboprop. Technologies invested into smooth military paint, particularly infrared paint, is a good area for technology investment.

Table B-4. WETTED AREAS AND DRAG BUILD-UPS

	Wetted areas		
	Tilt wing Transport	VDTR Transport	VDTR SCAT
Fuselage	1255	1355	545
Wing	795	508	512
Sponsons	190	190	-
Nacelles	360	238	208
Horizontal tail	270	154	147
Vertical tail	180	209	147
	Equivalent flat plate area, sqft		
Fuselage	4.6	5.5	2.3
Wing	4.6	5.1	4.2
Empennage	1.4	1.0	1.4
Sponsons	0.8	0.7	-
Nacelles	2.1	0.9	2.6
External stores (*)	-	-	1.0
Miscellaneous	0.5	0.5	0.4
Total	14.0	13.7	11.9

* Specified by contract

The installation of IR suppressors was selected as a design guideline. No appreciable increase in momentum drag was assumed to be incurred in cruise. Actual suppressor design will require an innovative effort to accommodate the big differences in inflow between hover and cruise. Most likely some sort of variable geometry will be needed like that employed on the V-22. The flat plate drag of the tilt wing and VDTR's are plotted against other helicopter and fixed wing aircraft in Figure B-12.

Section 4. Aircraft Characteristics

Proprotor Design

Propulsive efficiency and weight of the proprotors have significant impact on aircraft performance. Special tailoring is required to efficiently operate in both hover and forward flight. This is an area that requires further research to enable a high speed rotorcraft in the 350- to 500-kt class.

The proprotor of the tilt wing is of a rigid design similar to those used on fixed wing aircraft. There is no cyclic control so bending moments are relatively low. This simple rotor system carries with it the reliability and operating cost benefits associated with propellers of this type.

The VDTR proprotor is more complex. This is the price of having high speed capability combined with a relatively low disk loading. There have been many variable diameter rotor schemes, and a few have been demonstrated with experimental hardware. The system that received the greatest development effort and achieved the most impressive results is the TRAC (Telescoping Rotor AirCraft) concept pioneered by Sikorsky in the late 1960's and early 1970's. Initiated with company funds, it received substantial contract support from the U.S. Army. Although highly successful in meeting essentially all program goals, interest waned when a redefinition of Army roles and missions during development activity eliminated the need for the high speed aircraft types that the rotor was intended to benefit.

A schematic arrangement of the Sikorsky telescoping blade is shown in Figure B-13. The basic retracting mechanism is a jack screw that serves as the primary tension member of the blade. Rotation of this screw imparts a linear retraction or extension motion to the nut (actually a series of nuts) and, through tension torsion straps, to the outboard half of the blade, which is the main lifting member. A torque tube which is a streamlined ellipse in cross section, provides some of the lift, encloses the jack screw, transmits blade pitch control motion to the outboard blade, and carries bending moments across the sliding joint. When the rotor diameter is reduced, typically to 65% of the hover value, the outboard blade slides over and encloses the torque tube. The outboard blade, with a full airfoil cross section, comprises slightly over half of the radius when the blade is extended. The blade planform is unusual in that the effective root cutout is very large. However, even on a conventional blade the outboard half typically produces over 90% of the total lift in hover. Tests have shown that the large root cutout in the extended position produces only a few percent loss in hover efficiency.

The means for actuating the blade jackscrew is shown in Figure B-14. The heart of the mechanism is a differential gear set contained within the rotor head. The differential consists of upper and lower bevel gears and one bevel pinion connected to each blade jackscrew through a universal joint. This joint permits precone and prelag angles or any degree of articulation that might be desired, and permits blade fold. The upper and lower bevel gears are each connected by coaxial shafts to a brake at the bottom of the transmission. Stopping the lower bevel gear with respect to the fuselage while the rotor is turning forces the pinions to roll around the bevel gear and thus turn the jackscrews and retract the blades. Braking the upper bevel gear reverses the pinion motion and extends the blades. With both brakes released, there is no relative motion and the diameter remains fixed. The basic mechanism is as simple and reliable as an automobile differential. The gears are fully engaged at all times and the blades are completely synchronized. No separate power supply is required, as the system is driven in both directions by rotation of the main shaft. The rotor diameter is under direct control of the pilot and is not influenced by aerodynamic forces or torques.

The rotor can be retracted at any nacelle position and can be retracted as the nacelles are moving. Extension and retraction time is dependent on hub geometry and the helical pitch of the jackscrew. A wind tunnel model of the TRAC system fabricated by Sikorsky could extend or retract in four seconds. Due to scaling effects the retraction time for the full scale VDTR transport and SCAT would be on the order of 10 to 15 seconds.

The transport and SCAT aircraft rotors are articulated designs. The transport was designed with a two percent equivalent hinge offset. The SCAT was estimated to require a four percent offset due to maneuverability requirements and the closer vertical proximity of the aircraft CG to the proprotor.

The scope of this study did not allow propulsive efficiency determination based on detailed proprotor design. Instead estimates of the efficiency of an advanced design had to be made. These estimates were based on available information on tilt rotor proprotors, conventional propellers, propfans, and airfoils. Designs shown herein are expected to achieve the estimated levels of efficiency.

Plots of proprotor chord, relative thickness, twist, and sweep as a function of nondimensional radius are shown in Figures B-15 to B-17. For the VDTR aircraft these values are shown for both the retracted and extended cases. Table B-5 gives a list of proprotor characteristics at the design cruise condition.

For the most part the tip speed, planform, and outboard airfoil sections are driven by forward flight. The solidity and inboard sections are driven by hover. Twist is a compromise but is biased towards forward flight because it is the installed power sizing point. The tilt wing transport solidity was sized for a design CT/sigma of .14. Tilt rotor figure of merit curves peak at this value and allows sufficient thrust margin for maneuvering. The VDTR was initially sized at this same value, however it was recognized that the design solution was sensitive to solidity changes. The design Ct/sigma accounts for vertical drag in hover. Maneuvering will most likely be done at low air speeds where the download is small and the blade loading is reduced. The V-22 design CT/sigma is approximately 5 to 10% higher than .14. For a more optimum rotor design with comparable low speed maneuvering capability to the V-22 and the tilt wing, the VDTR rotor was designed for a CT/sigma of .147. The VDTR SCAT design CT/sigma was selected to be .123. This provides more thrust margin in hover and low speed which enhances maneuverability.

There are experimental studies that show surprisingly high CT/sigma capability for proprotors. The reason for this has not been clearly established yet. It appears to have to do with wake aerodynamics yielding very high Cl capability at the inboard blade sections. If this mechanism can be identified rotors designed for higher hover blade loadings can be made with savings in rotor, hub, controls weight, and improved forward flight performance.

Proprotor propulsive efficiency drops off very quickly as the helical tip Mach number reaches the drag divergence Mach number (Mdd) of the tip section. Airfoil coefficient of drag rises exponentially as the local Mach number exceeds Mdd. When this condition occurs at a propeller tip, the sharp drag rise at the long moment arm greatly increases the torque required. Consequently the propulsive efficiency drops very quickly with incremental Mach number rise above Mdd. This is the primary reason why propellers are limited to high subsonic speeds. The Mdd of an airfoil is a function of relative thickness, chordwise location of maximum thickness, and shape. Figure B-18 was generated from references 18 and 22. Location of maximum t/c has a small effect, however, supercritical airfoil designs have superior Mach capability at the greater t/c values. The Mdd number was defined at the point where the slope of Cd vs Mach number equalled .10. Supercritical airfoils first developed about 20 years ago by Richard Whitcomb are a mature fixed wing technology.

Figure B-19 diagrams effective helical Mach number as a function of nondimensional radius for each proprotor at their respective design cruise conditions. The selected tip speeds are the result of the iterations required to arrive at a balanced design. The SCAT VDTR proprotor operates at a helical tip Mach number somewhat lower than conventional propellers and the airfoil design will not require pushing state of the art technology. The tilt wing and VDTR transport proprotor airfoils have a more difficult regime to operate in and therefore offer a more demanding technology challenge.

In order to maintain good propulsive efficiency it is necessary that the local helical Mach number not exceed the Mdd of the airfoil. By cross plotting the information from Figures B-18 and B-19, the maximum allowable thickness for each type of section can be determined for each proprotor. This information as well as the design t/c distribution for each aircraft is plotted in Figures B-20, B-21, and B-22. The significant increase in allowable t/c enabled by supercritical design is evident.

Table B-5. PROPROTOR CHARACTERISTICS AT DESIGN CONDITIONS

	Tilt wing Transport	VDTR Transport	VDTR SCAT
Cruise			
Thrust/proprotor lb	1996	2579	2670
Collective @ 75% R deg	59.5	67.3	62.0
Advance ratio J	3.73	5.07	4.08
CT (propeller notation)	.135	.214	.148
CP (propeller notation)	.622	1.37	.721
Integrated Cl avg	.20	.26	.21
Integrated Cd avg	.083	.175	.080
Propulsive Efficiency	.81	.79	.83
Hover			
Thrust/proprotor lb	15958	22569	14168
Collective @ 75% R deg	20.4	17.8	16.2
CT (helicopter notation)	.0329	.0191	.0180
CP (helicopter notation)	.0115	.00513	.00462
Cl average	.84	.88	.74
Figure of Merit	.77	.76	.78

A tilt wing proprotor needs to be fairly stiff and able to operate efficiently at helical tip Mach numbers of about .94 to .98. This necessitates a relatively low aspect ratio blade with some amount of tip sweep and airfoils with high drag divergence Mach numbers. Sweep starting at 75% radius and progressing to 20 degrees at the tip was judged to be the most that could be tolerated aeroelasticly. This combined with a 3% t/c tip airfoil at a two dimensional Mdd of .90 yields an effective tip Mdd of .97. At the 30,000 ft, ISA+15 deg C cruise point and a 20% RPM reduction, a hover tip speed of 800 fps results. This is significantly lower than the 900 to 1000 fps tip speeds used by the XC-142 and CL-84. This configuration was analyzed with Hamilton Standard forward flight propeller code H444 at the design cruise point. A propulsive efficiency of .81 appears to be achievable with this geometry and assumed airfoil characteristics. With the proprotor biased towards cruise the peak hover figure of merit is estimated to be .77. This value is about .03 less than the peak FM of the V-22.

With respect to high speed operation it is desirable to have a minimum t/c distribution for the tilt wing proprotor. Structurally it is desirable to maintain a moderate thickness in order to reduce blade weight. The tilt wing proprotor t/c distribution was selected based on airfoil Mdd capabilities about half way between conventional and supercritical designs on the inboard sections and close to the full capabilities of supercritical sections around 80% radius.
The VDTR transport proprotor achieves a 65% reduction in tip speed by virtue of diameter reduction. At 25,000 ft, ISA+15 deg C

and a hover tip speed of 725 FPS the cruise helical Mach number is .85. This is about the limit for an unswept conventional tip airfoil at about 5% t/c. A parabolic tip is employed on the outer 10% of retracted radius to reduce the effective Mach number and allow a slightly thicker section better suited for hover. This amount of sweep is small and is not expected to be structurally difficult to obtain. The sections inboard of 55% cruise radius require a 13% t/c in order to accommodate the retraction mechanism. Figure B-21 shows that this geometry requires the use of new airfoil designs as well. As for the tilt wing the VDTR proprotor airfoil Mdd capabilities are projected to be about half way between conventional and supercritical capabilities.

The VDTR SCAT proprotor airfoil sections operate at helical Mach numbers lower than the capabilities provided by conventional sections. Figure B-22 shows the ample margin available at the design dash condition.

Control System Design

Stability and control has been the Achilles heel of many high speed VTOL concepts. Developing sufficient control force in one or more axes often proved to be difficult. Variable gain and mixing of control functions were required of many concepts. Inherently poor stability often required augmentation systems as well. The resulting control systems were complex and heavy. Even though performance was demonstrated to be satisfactory in some aircraft inadequate control precluded further development. The Wright brothers success was as much due to control development as it was to performance.

Gains in stability and control technologies in the last 20 years have been revolutionary. Fly by wire (FBW) and active control enables design alternatives never before possible. The X-29 with its active controls is a prime example of a very high gain feed-back system incorporated into an inherently unstable aircraft. The V-22 also uses a FBW system. Its primary advantage is the elimination of the mechanical mixing box that is required to phase controls in and out as the nacelles are indexed. The mixing box becomes a solid- state electronic unit that is more flexible to reprogram and much smaller. The use of these kinds of systems is necessary for all of the concepts presented herein.

The tilt wing and VDTR do not require any revolutionary strides in controls technology. This is a significant strength of these concepts and was an important factor in their selection as the most attractive high speed VTOL concepts to continue with into Task II. In fixed wing forward flight conventional control surfaces are used in roll, pitch, and yaw. In hover and low speed flight the tilt wing transport would use the same control methods and laws used on previous tilt wings, differential collective for roll and differential aileron for yaw. Control mixing and phasing would be a function of wing angle. The weakest point of previous tilt wings was pitch control. The VZ-2, X-18, CL-84 and XC-142 all had an auxiliary thruster in the tail to produce aircraft pitching moment. This introduced a number of problems; increased weight, drag, complexity, probability of failure, and cost. Its elimination and replacement with a system of good authority integrated into the existing wing and rotor is very desirable. Two alternative systems have been reviewed for this purpose: monocyclic pitch control and the geared flap wing control system. Both of these have been explored to some degree in the past. In light of today's controls technology they need to be reinvestigated and viewed as important technologies which need to be researched. Sizing results showed that a savings of 3% to 7% in TOGW was achieved by eliminating a tail rotor pitch fan and replacing it with monocyclic or geared flap control system respectively.

Monocyclic as described in Reference 23 is attractive because it uses the existing proprotors and a conventional helicopter cyclic control system. However, reservations exist about its viability on a rigid tilt wing proprotor. When cyclic is applied to a rigid rotor there is very little tip path plane movement. Moment is created by a lift offset on the rotor. Accompanying this is a distortion of the inflow. As the cyclic input is increased the inflow becomes higher on the increased pitch side and lower on the low pitch side. Experimental testing done at Sikorsky has demonstrated this. At an extreme case zero inflow on the low pitch portion of the disk can be created. The power required for a given thrust also increases as cyclic is applied because of an effective disk loading increase. For an isolated rotor this is not a problem. For a coupled rotor and wing lifting system as on a tilt wing it is a problem. A significant portion of the aircraft lift is carried by the wing during transition. This is accomplished by the turning of the prop rotor wash. If this slipstream is distorted and its core is moved above and below the wing as cyclic is applied the wing lift will be affected. This introduces undesirable couplings that significantly degrades aircraft controlability.

The geared flap control system does not introduce such couplings and has other advantages as well. This control system is described in detail in Reference 7. It uses the flaps of the wing as a servo tab to create a moment and position the wing and proprotors with respect to the fuselage. Figure B-23 taken from Reference 7 diagrams the system. The wing is not rigidly connected about its pivot to the fuselage and the wing position is maintained by a feed-back system that drives the flaps. A conventional damper is used for proper wing dynamic response. A constant force spring device is used to maintain a level fuselage attitude for off CG conditions. Apart from the distinct advantages of eliminating the tail pitch control rotor it requires no additional control mechanisms because it uses the existing wing flaps.

The control system for the VDTR transport is the same as for a conventional tilt rotor. Monocyclic is used in hover for yaw and pitch control, and differential collective is used for roll. An option is to have lateral control accomplished by having full cyclic capability on the proprotors. This would allow lateral translation with little body roll which would be particularly attractive for precision hovering. Rotor controls are washed out as the nacelles reach the horizontal and the conventional fixed wing control surfaces take over in cruise. This worked well on the XV-15 and V-22. The variable diameter rotor retraction mechanism would be automatic and work independently of the controls.

The VDTR SCAT would use the same conventional tilt rotor control system, however, a maneuverability enhancement may be needed in order to meet its more demanding agility requirements. The tilt rotor inherently has very high roll inertia for the same gross weight, roughly 10 times more than a helicopter. In high speed transition and low speed fixed wing flight the control power of the ailerons is low. By retaining the cyclic proprotor capability in cruise more lateral control power can be developed. This concept is discussed by J. Drees in reference 24. This would require a new technology effort in order to establish the control laws and design implications of loads and proprotor stability.

Weights Analysis

High speed VTOL concepts have always suffered from a lower useful load fraction than a helicopter or fixed wing aircraft. For the same technology level an aircraft that can hover and also cruise at fixed wing speeds will inevitably suffer an empty weight fraction penalty compared to an aircraft that does one or the other. Increased weight and complexity is the price paid for the combined capability. To make it worthwhile mission VTOL and high speed capability must be highly valued.

The first airplanes had high empty weight fractions that enabled only the pilot and a modest amount of fuel to be carried. They were impractical machines, but through technological development payload fractions grew and the airplane progressively became more economical. Helicopters 50 years later also started with small payload capabilities and followed the same progressive path to where they are today.

The high speed VTOL concepts of the 50's and 60's also had high empty weight fractions that enabled only small payloads to be carried. Payload fractions will grow as technology is improved. This will make them more economical and eventually production machines will appear. The V-22 is the first example of this. The aircraft designed herein with projected year 2000 technology have much better useful loads than those that have flown in the past. A component weight breakdown for each aircraft is presented in Table B-6 and graphically charted in figure B-24. The fixed equipment weight was specified by the contract.

The weight trends established in Task I for these aircraft were confirmed by more detailed analysis in Task II. Task II weights analysis started with information on existing airframes. The CL-84 and XC-142 detailed weight breakdowns were used as starting points for the tilt wing. The XV-15 as well as published and estimated weights for the V-22 were used for the VDTR designs. The variable diameter rotor weights were estimated using equations in Reference 8 updated for modern materials and construction techniques.

The weights of individual major components for these aircraft were plotted on charts with the same or similar components from both fixed and rotary wing aircraft. A trend factor was derived for the component as applied to a high speed VTOL aircraft and then modified for the appropriate advancement in technology. This was done for all of the components listed in the weight breakdown in Table B-6. The weight of each component was then determined using standard linear regression analysis. Weight equations in VTM were then calibrated to the resulting weight trends.

In general the tilt wing's superior mission efficiency as compared to the VDTR is a result of the better match between hover and cruise power requirements. Figure B-24 shows that the biggest difference in component weights is a function of the size and type of proprotor. A smaller proprotor saves weight by virtue of being smaller, having a reduced gearbox size, reduced control forces, and being simpler overall. The wing structure is also relatively lighter. It is loaded edgewise in hover which is much more desirable than flatwise as in a tilt rotor. In cruise the torsional arm of the wing out to the proprotor is shorter and there is less inertia to keep stable at high speeds. Both of these facts beneficially increase the natural torsion and bending frequencies of the wing.

The VDTR transport trades mission efficiency in terms of a minimum sized aircraft for more rotorcraft-like low speed attributes. The importance of these attributes, such as ground erosion, groung personnel operation, noise and autorotation needs to be assessed by the operator. There is no doubt that rotorcraft qualities are more desirable, but the penalty is evident. The payload fraction for the tilt wing is .179, The VDTR's is .151. This is an 18.5% difference. Despite this the VDTR offers the best and possibly only reasonable solution for a 450 kt transport with relatively low disk loading and rotorcraft-like qualities.

Table B-6. COMPONENT WEIGHT BREAKDOWN (lb)

	Tilt Wing Transport	VDTR Transport	VDTR SCAT
Wing	1702	2131	2133
Rotor System	2322	3277	2262
Empennage	828	651	458
Body	3594	4034	1337
Alighting Gear	856	983	690
Engine section	810	1439	858
Engines, Installed	1952	2106	1368
Exhaust System	225	288	223
Engine Controls	59	104	62
Starting System	59	103	63
Fuel System	687	854	397
Drive System	1594	3049	2129
Flight Controls	1764	2053	1987
Fixed Equipment(*)	5900	5900	4900
	-----	-----	-----
Weight empty	22352	26972	18867
Fixed Useful load	470	470	470
Payload	6000	6000	3000
Fuel	4690	6397	3260
	-----	-----	-----
Mission TOGW	33512	39839	25597

* Specified by contract

Each aircraft's roll, pitch, and yaw inertias in helicopter and fixed wing mode are listed in Table B-7. This was done by estimating the center of gravity of each major component and calculating its contribution to the total inertia.

In hover mode the roll and pitch inertias for each aircraft increase somewhat and yaw inertia decreases slightly. This is due to the rotation of the proprotor and wing or nacelle. This causes a CG shift as well. At design GW the CL-84 shifts about 3.2% MAC, the XV-15 about 4.9% MAC. Compared to the CG excursion limitations listed in Table B-8 these are not large variations and they do not pose any difficult control problems for these aircraft. The tilt wing and VDTR's of this study are expected to have about the same or better CG excursion capability as past demonstrators. The hover CG excursion capability of the CL-84 is a bit narrow. Presumably this was due to the limited authority of the tail pitch rotor. The geared flap control system should have better capability than the CL-84. Reference 7 describes how a constant force actuator can be used with the geared flap system to bias the wing moment and give level body hover attitude for CG's off the thrust line.

Table B-7. ROLL, PITCH, AND YAW INERTIAS @ MISSION TOGW
(Slug-ft^2)

	Roll Ixx	Pitch Iyy	Yaw Izz
Tilt Wing transport			
Hover	106,240	111,020	192,245
Fixed wing mode	102,150	102,795	194,185
VDTR transport			
Hover	158,490	159,030	249,160
Fixed wing mode	150,940	147,250	253,725
VDTR SCAT			
Hover	82,700	38,300	110,730
Fixed wing mode	79,515	36,130	111,850

Table B-8. CG CAPABILITIES OF THE CL-84 AND XV-15

	CL-84 (MAC=7 ft) % MAC	XV-15 (MAC=5.25 ft) % MAC
Hover	35%-40%	24.7%-40%
Fixed wing	27%-41.5%	20%-35%

Performance Characteristics

System losses

Throughout the study losses were kept as a constant percentage of power required. For the tilt wing and VDTR aircraft the losses were broken down as follows.

Transmission	2.0%
Engine installation	1.5%
Fixed	1.5%
Total	5.0%

These values are slightly optimistic as compared to those achieved today and reflect some savings through technology gains. However, if these savings are not realized, the study conclusions will not be affected. Engine installation inevitably results in an increase in engine SFC. For this study an SFC increase of 4% over the uninstalled value was estimated.

Hover and STOL Performance

Hover performance was analyzed using momentum theory with figure of merit curves as a function of Ct/sigma. The scope of this study did not call for a detailed rotor hover analysis to be performed. Mission TOGW was found to be rather insensitive to rotor FM. The FM trend with blade loading for each rotor system is shown in Figure B-25. Proprotor berformance was biased towards cruise since this sized the propulsion system.

Weight-Altitude-Temperature plots, more commonly referred to as WAT curves, are shown for each aircraft in Figure B-26. Vertical drags were calculated by a moment of inertia method. This method was calibrated to the known download values of the XV-15 and V-22 rotor tests. Due to the large installed power required for cruise, hover performance at high density altitude is outstanding for the transports and good for the VDTR SCAT. The tilt wing even at its high disk loading is flat rated by the transmission up to 18,000 ft. At the SL/ISA+15 deg C design point the tilt wing falls only 1% short in power for OEI hover capability. This capability is better than most of todays helicopters.

The VDTR transport has a great deal of hover thrust capability. This is by virtue of having both high installed power and a moderate disk loading. Like the tilt wing it is transmission limited to very high density altitudes. It is OEI hover capable up to nearly 3000/ISA+15 deg C.

The low density altitude of the SCAT mission results in a lower power-to-weight ratio for the attack VDTR. However the hover capability is still very good compared to a typical helicopter.

Short field performance is less likely to be used for aircraft that have such high power-to-weight ratios. However, operationally this type of takeoff can be used to lift off at a gross weight higher than the HOGE limit at high density altitudes, or to perform a takeoff with no exposure to an excessively hard landing due to engine failure. In civil terms the latter is referred to as a Category A takeoff. Figure B-27 was generated for the transport aircraft and the VDTR SCAT. The calculations are based on XC-142, CL-84 and XV-15 short field takeoff flight test data. This was nondimensionalized using a method in Reference 25. Based on aircraft power-to-weight ratio and the calculated lift off speed, the takeoff roll and distance to 50 ft altitude were calculated. The tilt wing transport was assessed at 6000/ISA+15 deg C. The VDTR transport, being as overpowered as it is, was analyzed for an OEI condition at the same density altitude. The VDTR SCAT was examined for an OEI condition at SL/ISA+15 deg C.

Forward Flight Performance

The lift-drag polars for each aircraft are shown in Figure B-28. The Cl at best range speed and design cruise speed are indicated.

Power required as a function of true airspeed is shown for each aircraft at maximum and minimum gross weight in Figures B-29 to B-31. The power available and transmission limits are shown as well. The tilt wing cruise transmission limit is 80% of hover due to the 20% RPM reduction.

Turboprop engines exhibit a substantial rise in power as airspeed is increased. This is very advantageous because it reduces the size of the power plant required to meet the design condition. This trend was derived as a function of Mach number from performance information for the Allison T-406, GE-19 and other General Electric and Pratt and Whitney turboshaft engines.

Accurately calculating the power required in a semi-converted mode is very difficult and there are only a few computer codes that can do so. Sikorsky has this capability however the scope of this study did not permit them to be used. Instead a parametric approach was used based on XV-15, XC-142, and CL-84 flight test data to fill the speed range between hover and minimum fixed wing stall speed. Any errors incurred by this method affect mostly the climb rate which has substantial margin and do not affect the conclusions of this study. Using Reference 26 the tiltwing Clmax capability was estimated at 2.7 and the VDTR's at 2.5.

Rate of climb as a function of airspeed is shown in Figure B-32 for SLS and SL/ISA+15 deg C. This was done using the excess power available method with an empirical correction derived for rotary wing and fixed wing flight.

Specific range for each aircraft is given in Figure B-33 for both maximum and minimum gross weights. Each aircraft experiences a large increase in specific range with increasing altitude. As with power available, an engine SFC trend as a function of Mach number was identified for turboprop engines. This benefit percentage is nearly the same at cruise as the SFC decrement due to installation.

The tilt wing cannot meet the 450 kt requirement at ISA conditions. This is because the lower temperature increases the helical Mach number and reduces proprotor efficiency. The VDTR nearly maintains its 450 kt capability because it has more helical tip Mach margin. The VDTR transport has a higher wing loading and span loading than the tilt wing. Its performance starts to fall off at the higher gross weights and altitudes. This is part of the reason for the 5000 ft lower optimum cruise altitude. All the aircraft have best range speeds significantly lower than maximum design speed, particularly the VDTR SCAT.

The limitation of each curve segment of the airspeed-altitude envelopes in Figure B-34 are labeled. Maximum altitude was based on absolute ceiling capability. A 42,500 ft altitude limit was imposed on the tilt wing due to pressurization limitations.

The payload range performance for the transport aircraft is shown in Figure B-35 for an ISA+15 deg C degree day and best range cruise speed. The usable fuel is the same as listed in the characteristics in Table B-3.

Conversion Corridor

Adequate control during conversion has been a problem on many past high speed VTOL concepts. The tilt wing and tilt rotor have inherently good thrust margin, power margin, and control characteristics within this regime. The conversion process can be stopped at any point and reversed. This has been proven by a number of flight test aircraft. The conversion characteristics of the VDTR are nearly the same as a conventional tilt rotor. The relative power required is somewhat higher in the 60 to 80 degree nacelle angle positions because of the reduced diameter. However, the increased mass flow that creates the power bucket region at these airspeeds more than compensates for this and substantial excess power still remains. A detailed analysis of the level flight conversion corridor and associated limits was not warranted for this study. No potential pitfalls are foreseen. Conversion of the tilt wing and VDTR with the exception of a mechanism to ensure synchronized rotor retraction does not require any special technologies.

The tilt rotor conversion corridor plot of nacelle angle vs. airspeed is a familiar format for describing the conversion corridor and its limits. This is shown for the VDTR transport and SCAT aircraft in Figures B-36 and B-37 for a mid CG position. The calculation of each point on the plot was not carried out due to the limited scope of this study. This would have required use of a program such as the NASA Generic Tilt Rotor Program (GTR) that requires a large number of dimensional and characteristic inputs. Figures B-36 and B-37 were based on the conversion profiles found in published information on the XV-15 and V-22. The stall line is anchored by the calculated stall speed for the given aircraft at zero nacelle angle. The 75 degree nacelle angle defining the opposite limit is the same as for the XV-15, and represents the maximum operational slope landing limit. The outer bound, maximum speed as a function of nacelle angle is limited by structural or nose-down attitude limits. These limits are set by design. Structurally, the rotor is subjected to significant loads as vibrations build up at high helicopter-like wake skew angles. This is primarily due to blade stall resulting from high blade twist. The lines estimated for the VDTR transport and SCAT were based on a conversion corridor width similar to that of the XV-15 and V-22. Pilots report that there was no problem staying within the limits set for the XV-15. The inner dashed lines are the normal operational limits. The outer solid lines are physical limits. Below Vso the aircraft can no longer fly, above Vne the aircraft sustains structural damage.

The tilt wing conversion corridor presented in Figure B-38 is different. The wing of a tilt rotor quickly reduces download and slowly builds up lift as speed increases and the skew angle becomes shallow enough to eventually create a positive wing angle of attack. The wing of a tilt wing produces substantial aircraft lift very early in the conversion process. It supports itself on proprotor and deflected thrust throughout the conversion until full wing-borne flight is reached. This situation results in a reversed curve reflex on the nacelle angle-airspeed plot compared to a tilt rotor.

The trim line was developed for level body conversion by using geared flap data from Reference 7. The immersed wing creates a rearward thrust. This negative propulsive force is balanced with a few degrees of forward wing tilt. This is the reason for a non-vertical wing position in hover. The stall line is anchored at the fixed wing mode Vso of 88 Keas. Hover maximum nose up angle is set at the same 75 degree angle of the VDTR. No serious stall problems were encountered by tilt wing test pilots in conversion during level flight so this boundary is not expected to be a problem. However, the stall line for a geared flap controlled wing is a coupled function of both the CG offset as fuselage pitch is increased and the wing maximum Cl capability as flap deflection is changed to counter this. No information was obtained for the geared flap concept at low wing angle, low speed flight. An estimate was made and is shown on the plot. This region would be investigated during the development of the geared flap technology. The 10 degree nose down line was used as a Vmax criteria and was estimated using trim angle solutions from Reference 7 and forward flight analysis. Like the VDTR the Vne line was selected to give a reasonable margin above Vmax. Given that the conversion corridor is somewhat narrow, an automatic wing tilt system as a function of airspeed may be a good feature to incorporate. Past test aircraft and recent simulation do not indicate a strong need for such but it could be a desirable feature. Since the 1960's the advancements in automatic controls has been dramatic. Implementation of such a system would not be too difficult from a controls standpoint, would ease pilot workload and should be investigated during the development of this control system.

Structural Stability

The structural stability of the proprotor both by itself and coupled with the wing is a key enabling technology. Little analytical information and no test data concerning the required wing frequencies and proprotor design for 400-450 kt tilt wings or tilt rotors exist.

Few production turboprops exceed 400 Kts. None exceed 425 kts. Propfans are the only existing "propeller driven" propulsion systems that can reach these speeds. Their impressive performance capabilities at very high helical Mach numbers was discussed earlier. The preferred installation for propfans is attached at the back of the fuselage in a pusher configuration. The supporting stub wing is short and deep in chord with respect to the length of the nacelle. This makes for a very rigid attachment. A tilt wing and especially a tilt rotor proprotor is larger, heavier, and is at a much longer torsional and bending arm. This situation significantly reduces the inherent rigidity or natural frequency of the installation and make it more susceptible to flutter.

Maximum aircraft speeds were set by the prescribed missions. Dive speed (Vd) is typically 20% higher than maximum cruise speed and the flutter boundary is 15% beyond that. The established boundaries for these aircraft are listed in Table B-9.

Flutter boundaries are often stated in equivalent airspeed. This is because destabilizing forces are proportional to dynamic pressure. In a vacuum the flutter speed is infinite. Equivalent airspeed is true airspeed multiplied by the square root of the density ratio. In Reference 27 the XV-15's true airspeed flutter boundary of 400 Kts at sea level increases to 500 Kts at 19,000 ft. However, the equivalent airspeed decreases somewhat from 400 Keas at sea level to 371 Keas at 19000 ft. All things being equal the 400 Keas would be maintained to 19,000 ft but Mach number, virtual mass, and Lock number effects at altitude reduce yhe equivalent airspeed.

At 30,000 ft, ISA+15 deg C the tilt wing is at an equivalent airspeed about that of the XV-15's Vne even though it is at a true airspeed of 621 kts. The tilt wing's relatively smaller proprotor and shorter supporting wing structure makes its design appear to be within reach of today's technology. Development would have its hurdles but no need for active controls or significantly advanced materials are foreseen. Hub design would be the area requiring the most research. A beneficial stability by-product of the geared flap system is the ability to use a rigid propfan-like proprotor. With monocyclic control the hub would necessarily be gimbaled and would be less stable. Another tilt wing advantage is its ability to have zero or even slight aft sweep. Aft sweep develops a stabilizing wing pitch-flap

Table B-9. LIMIT SPEEDS FOR MILITARY TRANSPORTS AND SCAT

		Tilt wing Transport	VDTR Transport	VDTR SCAT
Max cruise (Vmax)	Ktas	450	450	400
Dive speed (Vd)	Ktas	540	540	480
flutter speed (Vne)	Kts	621	621	552
	Keas	369	403	497

coupling similar to a rotor delta three flapping hinge effect. Forward sweep even at small angles develops a destabilizing coupling. This is true of the XV-15 which has -6.5 degrees of forward sweep. This tilt wing advantage was recognized in Task I and was a primary reason for it being judged the lowest risk high speed rotorcraft concept.

Clearly the VDTR vehicles designed in this study require an improved state of the art in aeroelastic design, especially with a forward swept wing. This state had to be projected using information available today. The V-22 has design flutter speed boundaries similar to the XV-15. The V-22 does have a slightly different hub design that reduces unfavorable negative pitch-flap coupling. Such a hub design (as described in Reference 10) would be the basis for advanced hub design required of the VDTR.

The weight required to maintain structural stability at the design speeds is important from a sizing standpoint. Protection of the proprotor from instability is best achieved by careful design and not structural beef-up. Protection of the coupled wing-proprotor system on the other hand is generally a matter of having sufficient wing torsional and bending stiffness. Increased stiffness inevitably increases wing weight. An established method of preliminary wing sizing and weight estimation for the tilt rotor is to start with a known set of wing bending, torsion, and edgewise frequencies and then design a primary structure to meet the required stiffness. Then the primary members are weighed and an estimate is made for secondary structure weight. The determination of proper wing frequencies is a very involved calculation that requires design characteristics in far more detail than was available in this study. Fortunately, Reference 10 includes the torsional and bending frequency of a theoretical 400 kt tilt rotor SCAT design that was done in a fair amount of detail. Using these values as a starting point the wing weight trend for the VDTR SCAT was estimated.

The 25 degree forward swept wing of the VDTR transport makes it much more difficult to insure freedom from instabilities. As a conservative estimate the same SCAT frequency ratios were assumed even though the transport's Vne equivalent airspeed is less. The undesirable pitch-flap coupling was assumed to be reduced or eliminated by elastic tailoring technology developed for the X-29 research aircraft.

The X-29 has 33.7 degrees of forward sweep. The airfoil sections are supercritical and have root and tip t/c's of 6.2% and 4.9% respectively. The graphite fibers of the upper and lower wing skins are oriented in such a way that the leading edge rotates nose down as the wing flaps up and vice versa if it flaps down. The X-29 has a mixed construction wing. The structure beneath is of conventional aluminum stringer and rib construction and the skins are carbon graphite composite. The design of a forward swept wing tilt rotor will require an improved application of this technology to accommodate a much thicker wing and tip-mounted proprotor.

If it is possible to maintain variable diameter rotor stability and handle hover bending loads with a 17% thick airfoil, the wing could be designed with very little forward sweep like that of conventional tilt rotors. This is a simpler solution that would not require as much aeroelastic technology development. This gives the VDTR a distinct advantage over a conventional tilt rotor that must use forward sweep to increase the wing airfoil Mdd. The dynamic characteristics of the variable diameter rotor are not yet known but a relatively thin straight wing is a possibility due to the 35% diameter reduction capability.

Autorotation and Glide Characteristics

Power failure is one of the most critical failure modes on an aircraft. An OEI condition was addressed in the takeoff characteristics. An all-engine-out condition, albeit rare, is also a concern. A total loss of power in takeoff or climb out will most likely result in loss of the aircraft. This is true of all fixed wing aircraft. In cruise airplanes have enough altitude and can glide to a field. This is practiced by all light single engine aircraft and is also possible for large aircraft. In Florida a Boeing 767 once performed an all engine out landing when the aircraft inadvertently exhausted its fuel supply.

The glide ratio, descent rate, and power-off stall speed was calculated for each aircraft. This data is presented in Table B-10. The key to a survivable off-field landing is to land at as low a speed as possible in controlled flight. The inertia of the tilt wing proprotors is very low and autorotation is not an option. In spite of this the tilt wing has a comfortable descent rate and the slowest touchdown speed of the three designs. At 88 Keas at maximum weight a controlled landing would most likely be survivable. The VDTR transport with its higher wing loading would touch down at 118 Keas. This represents 80% more relative energy to be dissipated upon contact. This energy is dissipated in deforming the aircraft and hence makes it less survivable for the

same level of crashworthiness. The VDTR SCAT would touch down at 100 Keas, however, the crew has ejection seats as an option in this aircraft.

Autorotation is an option for the VDTR aircraft. The autorotative descent rate was calculated for each of the VDTR designs at the minimum descent speed. These values are listed in Table B-11. For comparison a UH-60A is also shown. Sikorsky uses a measure of autorotational flare capability called an autorotatioal index defines as;

Autorotational index, Ia = (Ir x OMEGA)/(DL x GW)

Ir = Rotational inertia of the rotor Slug ft^2
OMEGA = Rotor rotational velocity Rad/sec
DL = Disk loading PSF
GW = Gross weight lbs

This index is the ratio of the rotational energy stored in the rotor to the energy required to stay aloft. The index values were calculated for each aircraft and are listed in Table B-11 as well. Both VDTR designs have significantly lower (poorer) indices than the UH-60A.

Table B-10. ALL-ENGINE-OUT CHARACTERISTICS

	Vso Keas	V Best glide Keas	Glide Ratio	V min sink Keas	ROD fpm	Clmax A/C
Tilt wing Transport	88	175	11.2	140	1400	2.7
VDTR Transport	118	200	8.8	170	2185	2.5
VDTR SCAT	100	185	9.2	150	1815	2.5

Table B-11. AUTOROTATIVE INDEX AND MINIMUM RATE OF DESCENT

A/C	GW	DL	Ir	Ia	ROD min fps
UH-60A	16450	7.3	4722	19.5	2250
TW XPORT	33512	50.0	604	4.3	>6000
VDTR XPORT	39840	20.0	2263	9.4	2700
VDTR SCAT	25597	20.0	1002	12.3	3060

Hover Downwash and Noise

A principle aim of this study was to investigate high speed VTOL concepts that had a downwash environment compatible with operation over or near ground personnel. In Task II a quantification of the downwash velocity profile and perceived noise was made for each aircraft.

A distinct disk loading beyond which downwash becomes unacceptable cannot be precisely established. In terms of personnel operation it depends upon the size of the aircraft, a person's size and strength, the ground surface and what type of activity being performed. The amount of ground erosion is very dependent on surface texture. None-the-less disk loading constraints were established and explained in the Task I report.

The downwash velocity profile is a function of both disk loading and gross weight. As disk loading increases the dynamic pressure increases proportionately. For a given disk loading, as the size of the vehicle increases the flow field beneath becomes thicker. Both of these principles can be shown through momentum theory analysis. An analysis of this sort was done in reference 4. References 1, 6, and 28 provided measurements of the velocity flow field for the OH-6A, CH-34, UH-1H, OH-58A, CH-54, CH-53E, and XV-15. The method in reference 4 was used to calculate the velocity profiles for these aircraft. and reasonably good agreement was found for all aircraft. As with any kind of turbulent flow measurement a certain amount of scatter was evident in the test data. However, the mean velocity and profile derived from the analysis matches the test data well enough to make it a useful method for estimating velocity distributions.

For each study aircraft the velocity profile was calculated at maximum TOGW. The results are plotted in Figure B-39. The most severe downwash position is at a rotor height-to-diameter ratio (H/D) of 1.0 to 1.5 and a radial position of 1.2 to 1.4 times the radius. This is where each profile was calculated. At an H/D less than 1.0 the wake does not have enough distance to contract to its full velocity. At an H/D greater than 1.5 the wake begins to slow down by mixing with the stationary air and its impact on the ground is lessened. The tilt wing, due to its small diameter, is at an H/D of .98 with the wheels on the ground. At a wheel height of 10 ft the H/D is 1.47. Tabulated on the figure is the force and moment created by each flow field on a man assumed to have an evenly distributed equivalent flat plate drag of 9 sqft. This value was found in Reference 18. Without knowledge of what to expect from the selected designs an overturning moment of 225 ft-lbs and force of 75 lbs was established in Task I for loose surface operations. The overturning moment of 225 ft-lbs was not exceeded by any of the aircraft. Both the tilt wing and VDTR did exceed the 75 lb force limit. The tilt wing transport even though it is smaller generated more force than the VDTR transport. The moment generated by the tilt wing was less because the flow field is more shallow. The VDTR SCAT even though it has the same disk loading generates a substantially lower force and moment than the VDTR transport. This is a good illustration of the gross weight effect.

This momentum method was derived for a single rotor system. The wake interaction of a two-rotor system distorts this profile in the nose and tail region of a tilt rotor. Reference 1 gives a comprehensive set of survey results for the XV-15. It was found that the wakes meet each other under the aircraft and are forced outward at the nose and tail positions. The flow field profile at these positions becomes nearly wall-like. The velocity of this fairly constant profile is about one and a half times the induced velocity at the rotor. This factor was used to estimate the velocity distribution for the tilt wing and VDTR aircraft at the nose and tail positions. The results are also plotted in Figure B-39. Since the VDTR aircraft have side position flow field depths greater than the XV-15, it is expected that their constant velocity distributions will be deeper than the six feet found for the XV-15. The tilt wing has a shallow but high velocity field. This may not build up to six feet in depth. Unfortunately no nose or tail position flow field measurement data was found. The tilt wing nose and tail profiles were estimated as having the same constant profile up to six feet of depth.

The positions at which the body force and moment calculations were made are very close to the aircraft. The contract required that the most severe position be analyzed. This is aproximatelt at 1.4 radii. This position for the VDTR transport is only 3.6 ft outside of the rotor disk. It is even closer for the others. The only time a person would be expected to approach this close is when moving under the aircraft to attach an external load. Otherwise personnel would most likely be anywhere from 50 to 75 ft away. At these distances the forces would be appreciably less. Reference 5 discusses the rapid dissipation of downwash velocity experimentally observed for higher disk loading aircraft beyond about 50 ft. References 1 and 6 show similar results for the XV-15 and CH-53E.

External load missions are a poor use of a high speed rotorcraft. The high speed capability is wasted because external cargos cannot be normally transported faster than normal helicopter speeds. Helicopters are superior for this mission due to both low disk loading and precision hovering control.

Surface failure is not affected by gross weight. It is only a function of the dynamic pressure in the wake. Figure B-40 taken from Reference 3 is a good summary of what breaks loose when. It is by no means definite but provides a good indication of relative regions. The tilt wing transport is at a disk loading where it will have to take care when operating in loose surface environments. The XC-142 was flown in desert environments, however, only very short hover durations were performed.

Helicopters often encounter visual obscuration in snow, sand, and water environments. Helicopter pilots have learned to cope with this by implementing takeoff and landing procedures that minimize the time spent in a high power condition close to the ground. Takeoffs are performed with a collective pull into a moderate vertical climb with no hover after lift off. Landings are performed by initiating little or no flair. These procedures are frequently practiced by the Army. The excellent landing gear load capability of the UH-60A enables pilots to terminate touchdowns with little flare without fear of bending the aircraft. Tilt wing and VDTR aircraft designed with high landing load capability will also enable these swift landings that minimize surface effects.

Visual obscuration is also a function of configuration. Helicopters recirculate snow, sand, and water directly on to the top of the windscreen. The cockpit of a tilt wing or tilt rotor aircraft is not beneath the wake. The dual wake circulation pattern of tilt wings, tilt rotors, and VDTR's will produce obscuration characteristics different from helicopters. As to whether or not these high speed rotorcraft are better or worse needs to be investigated both analytically and experimentally.

High speed rotorcraft performance is very sensitive to disk loading. The higher the speed requirement, the higher the optimum disk loading since the installed power required for high speed can produce the same hover thrust with a smaller rotor. The ill effects of high disk loading must be understood in all contexts in order to design an aircraft appropriate for the user. It is recommended that research be done in the area of wake impingement and recirculation. This is not a technology development per se but a research effort to better understand high disk loading implications.

The noise signatures for the tilt wing and VDTR aircraft were parametrically calculated for a 100 ft hover at a 500 ft sideline position. A detailed noise analysis is very computer intensive and time consuming. Consequently a parametric model sensitive to primary aircraft design parameters was used. These parameters include gross weight, number of blades, engine power level, and tip speed as well as the blade planform, twist, sweep, and t/c distribution. Ground reflection is also accounted for. The calculations were done for the aircraft hovering over a hard surface. For this study the model used XV-15 test data as a base. To get an indication of the model's accuracy XC-142 A-weighted noise levels were calculated and compared to test data taken by Sikorsky in 1967. The error was only 1 dbA.

An A-weighted sound presure level (measured in terms of dBA) weights the frequencies that the human ear can perceive and is a good measure of annoyance and susceptibility to hearing damage. An A-weighted sound level estimate was made for each aircraft and is listed in Table B-12. For comparison the estimated value for the XC-142 is also shown. A maximum daily exposure level was calculated for each aircraft at the 500 ft sideline position. By OSHA standards this is the maximum amount of time one can be exposed before hearing damage occurs.

Although the tilt wing has a relatively high 800 fps tip speed the combination of lower TOGW, tip sweep, and thin tip results in sound levels slightly lower than the VDTR transport which is at 725 fps tip speed with little tip sweep and somewhat thicker tip sections. The VDTR SCAT runs at 800 fps tip speed. The result is a higher sound level than the transports despite its lower weight.

Table B-12. HOVER A-WEIGHTED SOUND LEVEL ESTIMATES (dBA)

(SLS)	Tilt wing Transport	VDTR Transport	VDTR SCAT	XC-142
500′ sideline position at 100′ hover, dbA	87.8	88.1	93.8	94.0
Maximum daily exposure hrs	10.9	10.4	4.7	4.4

Noise detectability is a very important issue for SCAT aircraft. To the human ear the XC-142 was considered a rather noisy aircraft and the SCAT is nearly as noisy. The combination of high tip speed and straight 8% t/c tips are the key drivers. Both VDTR aircraft have similar rotor geometries. If the tip speed of the SCAT were brought down to the 725 fps tip speed of the transport and given swept tips the noise level would result a couple dBA lower than the VDTR transport. Tip speed reduction incurs a weight penalty sensitivity identified back in Figure B-40. It is expected that in order to meet future requirements this would be a necessary trade.

Maneuverability

Turn rate is a direct function of load factor capability. It is generally limited by either stall, excess power available, or structural limitations. Velocity-load factor diagrams, commonly referred to as V-Nz diagrams are shown for the tilt wing and VDTR aircraft in Figures B-41, B-42, and B-43. The outer boundary is the design structural limit. Superimposed are the wing and rotor stall limits as well as the sustained load factor capability. The transports are shown at sea level standard and the SCAT at 4000 ft, 95 deg F. Information on proprotor stall characteristics at high skew angles was not found during the course of this study. In addition, the calculation of rotor-wing lift sharing commonly done with more sophisticated programs is beyond the scope of the study. For these reasons the rotor stall limit in transition is not shown. Is is recommended that further maneuverability studies focus on this regime.

The tilt wing transport has a greater fixed wing sustained Nz capability than the VDTR transport. This is due to the lower span loading and wing loading of the tilt wing. However neither can sustain the structural limit of 3 G's in a turn. In hover each transport becomes power limited before it reaches rotor stall which was defined as a Ct/sigma of .20. This allows for gust margin and some future growth in the aircraft. Both of these limits are below the hover structural design limit of 2 G's. The VDTR SCAT also reaches its sustained load factor capability before the structural limit. Load factor capability in excess of the sustained limit is attainable in transient maneuvers. Generally an aircraft can easily pull 50% or more transient G's than its sustained capability, so this margin is not excessive.

Another important maneuverability parameter is roll control. In hover and low speed flight differential collective pitch control provides very high control power. Ample roll rates are easily attainable. In wing borne flight roll control power diminishes with decreasing air speed. Initial roll acceleration and terminal rate were calculated for each aircraft at their respective stall speeds and up to 400 Keas. The results are listed in Table B-13. A maximum aileron deflection of +-25 degrees was used at all speeds. At the higher speeds this amount of deflection is not necessary and would not be used due to the high hinge moments generated. Roll acceleration was calculated by using aileron aerodynamic data from Reference 26 to find the wing rolling moment capability and the resulting acceleration at the maximum TOGW fixed wing roll inertia value. Roll rate was estimated using the same aerodynamic data and roll damping information from Reference 29 and correlated to XV-15 roll data in Reference 30. The roll acceleration for the tilt wing transport is comparable to typical fixed wing aircraft and is significantly better than both VDTR aircraft. This is due to the larger wing and lower inertia. The VDTR aircraft have higher maximum roll rates due to the lower roll damping inherent in their short span, low aspect ratio wings.

The roll acceleration of the VDTR transport is only about a third that of the tilt wing transport. This may give the aircraft a sluggish feeling and possibly a tendency to overshoot its commanded position. A detailed handling qualities analysis beyond the scope of this study would be necessary to ascertain whether handling qualities improvements are warranted in this design. A good handling SCAT aircraft should have high roll acceleration

Table B-13. INITIAL ROLL ACCELERATION AND TERMINAL ROLL RATE

Initial Roll Acceleration (Deg/sec^2)

V keas	Tilt wing Transport	VDTR Transport	VDTR SCAT
88 (Vso TW XPORT)	46.9	-	-
100 (Vso VDTR SCAT)	60.5	-	37.7
118 (Vso VDTR XPORT)	84.2	27.5	52.5
200	242.0	78.9	150.9
300	544.5	177.6	339.4
400	968.1	315.6	603.5

Maximum Roll Rate (Deg/sec)

V keas	Tilt wing Transport	VDTR Transport	VDTR SCAT
88 (Vso TW XPORT)	34.3	-	-
100 (Vso VDTR SCAT)	39.1	-	90.8
118 (Vso VDTR XPORT)	46.1	100.0	107.1
200	78.1	169.5	181.5
300	117.2	254.2	272.3
400	156.2	339.0	363.1

and rate throughout its combat speed range. An air to air fighter should have a roll rate on the order of 150 to 180 degrees per second. The VDTR does not reach these values in fixed wing mode until near 200 Keas. Considering that combat may be done at lower airspeeds the SCAT's low roll rate capability at low speed may be a handicap. At speeds within the conversion envelope the nacelles should be kept at the highest acceptable nacelle angle for a given speed. This enables powerful differential proprotor lift to be used for roll control. High nacelle angles can be maintained up to surprisingly high speeds. The XV-15 can be flown up to 100 Kts at nacelle angles at or near 90 degrees. A set of control laws different from that of a transport is needed for the SCAT. A fly by wire control system is a very good application for an adaptable control system that changes control laws as a function of a number of flight state variables.

Characteristically the yaw control of previous tilt wing aircraft has been adequate but weak. The yaw acceleration and maximum rate was estimated for the tilt wing transport. The results are listed in Table B-14 for four loading conditions.

All of the tilt wing's fuel is located in the wing and most of it is in the outer panels. This significantly increases the yaw inertia. The moment created by the deflected ailerons is a function of gross weight. Maximum yaw rate is limited for the

Table B-14. TILT WING YAW ACCELERATION AND MAXIMUM RATE

Condition	GW lbs	Acceleration Deg/sec^2	Max rate Deg/sec
Minimum TOGW	23000	30.6	32.7
Half fuel, 6000 lb PL	31167	35.2	38.1
Full fuel, no PL	27512	28.8	35.8
Full fuel, 6000 lb PL	33512	34.2	39.5

same physical reasons as roll rate. As an initial estimate, yaw rate was calculated in the same manner as maximum roll rate using the
same aerodynamic characteristics of the ailerons and wing roll damping. The downwash velocity was assumed to be at 75% of the final value in the contracted wake.

The yaw acceleration values are good even at low gross weight and full fuel. They are better than the XV-15 with a SCAS off maximum yaw acceleration of 17.5 Deg/sec^2. The MIL-H-8501 requirement is 27.2 Deg/sec^2.

Maximum yaw rate is lowest at minimum TOGW. This value of 32.7 deg/sec is acceptable but a rate of 40 to 45 degrees per second may be more desireable for a tiltwing designed for other missions. Aerodynamically, not much more force can be obtained from the ailerons. One possible way to increase yaw rate is to install a reaction control system in the wing tips fed by engine bleed air. The AV-8A and AV-8B are controlled in this manner in hover about each axis. This system adds complexity and weight but appears to be the easiest method of obtaining additional control power.

Cost and Manufacturability

The materials and structures assumed for the study designs are of a somewhat more advanced state than the composite technologies in use today. No fundamental tooling changes within the aerospace industry are assumed to be needed to manufacture the aircraft. There are a number of advantages and disadvantages associated with composite construction. The weight savings is a major benefit and very important to these types of vehicles. However it is presently still more costly to produce per pound than conventional metal structures. Mass production techniques for composite parts are still being developed. Production of uniform parts is difficult for a variety of reasons. The scrap rate of composite parts is higher than for aluminum structures.

An estimation of each aircraft's production cost was made based on a dollars-per-pound ($/lb) of empty weight basis. The results are approximate and serve mostly to highlight the differences in cost per major component group. These rates were derived from the PRICE cost estimating computer modeling program. The 1989 dollar amounts in Table B-15 include labor, materials, engines, equipment, sustaining engineering and average profit. They do not include amortization of development costs.

The biggest difference between the tilt wing and the VDTR is the proprotor system. The complexity of the tilt wing proprotor was assumed to be 75% that of a conventional tilt rotor proprotor. This is due to the relative simplicity of the rigid tilt wing proprotor compared to a gimbaled, cyclically controlled system.

The VDTR proprotors were assumed to be 50% more complex than a conventional tilt rotor proprotor. The drive system and wing of the VDTR transport were assumed to be 10% more expensive with respect to the tilt wing. The manufacture of the forward swept wing requires a more complicated orientation of fibers in order to reduce the disadvantageous flap-torsional coupling. The drive system has a combining box in the fuselage and drives shafts located in the wing out to tilting transmissions on the tips.

Despite the much more complicated rotor system the production cost of the VDTR transport is only 11% higher than the tilt wing. The differences in proprotor costs is overshadowed by the engine and fixed equipment costs. The average dollars per pound are slightly higher for the tilt wing. The VDTR SCAT was the most costly per pound. This is primarily due to the high power-to-weight ratio and expensive electronics.

The V-22 prototypes have nearly all-composite wing and fuselage. They were constructed by hand with little automation. The production aircraft will be constructed in a more automated way. Its unit production cost is estimated to be between $35 and $40 million. The guaranteed empty weight as of late August 1990 was 31955 lbs. At $37.5 million this equates to $1174/lb, which is close to the averages in Table B-15.

Construction cost can be very sensitive to certain low RCS qualities. The B-2 is held to very tight tolerances in order to maintain proper surface contours. This entails very sophisticated automated design and manufacturing techniques. Special coatings and materials also increase the cost dramatically. For the VDTR SCAT a trade of cost vs low observable qualities would be needed to find the most cost effective ballance.

Section 5. Sensitivity Study Results

The sensitivity of the designs to fundamental mission and design variables was determined to help establish which technologies have the greatest potential payoff.

TABLE B-15. HIGH SPEED ROTORCRAFT PRODUCTION COST ESTIMATES

TILT WING TRANSPORT

		lbs	$/lb	$/COMPONENT
WING		1702	450	765900
ROTOR SYSTEM		2322	248	575856
TAIL		828	225	186300
BODY		3594	450	1617300
LANDING GEAR		856	208	178048
ENGINE SECTION		810	325	263250
ENGINE INST		1952	1836	3583872
EXAUST		225	200	45000
ENG CONTROLS		59	431	25429
STARTING SYSTEM		59	325	19175
FUEL SYSTEM		687	450	309150
DRIVE SYSTEM		1594	290	462260
FLIGHT CONTROLS		1764	431	760284
MISSION EQUIPMENT		5900	3000	17700000
		--------		--------
EMPTY WEIGHT		22352		26491824
FUL		470.00		
PAYLOAD	INT	6000.00		
	EXT	0.00	AVERAGE	
FUEL		4690.00	$/lb EW	
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TOGW		33512.00	1185.21	

VDTR TRANSPORT

		lbs	$/lb	$/COMPONENT
WING		2131	495	1054845
ROTOR SYSTEM		3277	496	1625392
TAIL		651	225	146475
BODY		4034	450	1815300
LANDING GEAR		983	208	204464
ENGINE SECTION		1439	325	467675
ENGINE INST		2106	1836	3866616
EXAUST		288	200	57600
ENG CONTROLS		104	431	44824
STARTING SYSTEM		104	325	33800
FUEL SYSTEM		854	450	384300
DRIVE SYSTEM		3049	363	1106787
FLIGHT CONTROLS		2052	431	884412
MISSION EQUIPMENT		5900	3000	17700000
		--------		--------
EMPTY WEIGHT		26972		29392490
FUL		470.00		
PAYLOAD	INT	6000.00		
	EXT	0.00	AVERAGE	
FUEL		6397.00	$/lb EW	
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TOGW		39839.00	1089.74	

TABLE B-15. CONTINUED

VDTR SCAT

	lbs	$/lb	$/COMPONENT
WING	2133	450	959850
ROTOR SYSTEM	2262	496	1121952
TAIL	458	225	103050
BODY	1337	450	601650
LANDING GEAR	690	208	143520
ENGINE SECTION	858	325	278850
ENGINE INST	1368	1836	2511648
EXAUST	223	200	44600
ENG CONTROLS	62	431	26722
STARTING SYSTEM	62	325	20150
FUEL SYSTEM	397	450	178650
DRIVE SYSTEM	2129	290	617410
FLIGHT CONTROLS	1988	431	856828
MISSION EQUIPMENT	4900	4000	19600000
	------		--------
EMPTY WEIGHT	18867		27064880
FUL	470.00		
PAYLOAD INT	2000.00		
EXT	1000.00	AVERAGE	
FUEL	3260.00	$/lb EW	
-------	--------	--------	
TOGW	25597.00	1434.51	

The sensitivity of each design was expressed as a percentage change in TOGW vs. percentage change in each variable. Figure B-44 shows these sensitivities for the military transport aircraft and the VDTR SCAT. By normalizing to a percentage of TOGW, differences in the relative sensitivity of each transport can be directly compared. Overall both transports had very similar sensitivities. The VDTR was slightly more sensitive to all parameters except increased hover time. This is attributed to the lower fuel flow as a result of the lower disk loading. The VDTR's increased sensitivity to all other parameters is mainly due to the larger growth factor associated with the higher empty weight and fuel fraction.

The variation of +-50% hover time had only about a +-2.0% to +-2.5% change for each aircraft. The design hover time was only 15 minutes for each mission. A +-50% change in this value does not make much difference in the total mission time of 154 to 159 minutes for the transports and 107 minutes for the SCAT. An additional point was run for each aircraft. The hover time was tripled to 45 minutes. This raised the TOGW of the tilt wing by 10%, the VDTR by 7.9%, and the VDTR SCAT by 8.7%. Even for this large increase in hover time the increase on TOGW is still surprisingly small.

A +-20% change in maneuverability was accomplished by changing the rotor solidity which affects rotor thrust capability and the design load factor. The VDTR proved to be a bit more sensitive than the tilt wing because the proprotor is a greater percentage of the vehicle weight.

Aircraft L/D, engine HP/lb, and SFC had about the same sensitivity. Aircraft L/D was a bit more sensitive because it affected propulsion sizing.

Since the variable diameter proprotor is a new device and parametric trends do not exist, its predicted weight is subject to more variability. For this reason an additional sensitivity to rotor weight technology was examined. A +-20% change in the weight of the variable diameter rotor makes about a +-3% change in TOGW for the transport and +-2.5% for the SCAT.

Propulsive efficiency had a noticeable effect on sizing and is the most sensitive of the performance parameters. It is also less linear than L/D with percentage gain or loss. The rate of aircraft size reduction with increasing efficiency is about the same as for L/D. However, with decreasing efficiency TOGW begins to grow at a slow exponential rate. It is interesting that an ideal propulsive efficiency of 100% represents about a 25% increase for each aircraft and results in less than a 10% gross weight saving.

The most sensitive parameter is weight technology. This was found early in the study. The significant proportion of time invested in the weight estimation of these vehicles was justified. Small differences in empty weight magnify the final sizing solution. For these aircraft the percentage growth in TOGW is approximately 50% greater than percentage growth in empty weight.

All of these sensitivities were done with the fixed equipment at the contract specified weight. Table B-15 shows that by percentage this is a major portion of the empty weight.

Table B-15. FIXED EQUIPMENT AS A PERCENTAGE OF EMPTY WEIGHT

	Fixed Equipment lb	% of WE
Tilt Wing Transport	5900	26.4%
VDTR Transport	5900	21.9%
VDTR SCAT	4900	26.0%

An estimation was made of the fixed equipment weight for each aircraft at its final design solution. It was found that the VDTR transport and SCAT values of 5900 and 4900 lb respectively are appropriate. The tilt wing fixed equipment was estimated to be slightly lower than 5900 lb. This does not make a major difference but it is expected that the tilt wing could be 200 to 300 lbs lighter.

A study of historical trends indicates that approximately 45% of the specified fixed weight would vary with gross weight. If this portion is assumed to trend in proportion to gross weight the sensitivities would increase in slope by 15%. This amplifies the importance of all the technologies.

The selected baseline aircraft were not designed to any particular noise requirement. The results of the hover A-weighted noise estimates were a fall-out. The tilt wing at its 800 fps tip speed was quieter than expected. Tip sweep, t/c, twist, and blade number can be tailored to reduce noise. The tilt wing blade geometry is favorable to lowered noise. Not a lot more reduction may be possible from tweaking these variables alone. Tip speed is a very powerful driver of noise. A tip speed reduction from 800 to about 750 fps is estimated to be required For a 5 dBA reduction. This results in a TOGW of 34443 lbs, 2.8% more than the baseline. The VDTR transport and SCAT have moderately thick tip airfoils. The transport has a relatively minor portion of the outboard blade swept. It is expected that airfoil and blade geometry could be modified to reduce noise by 5 dBA for each aircraft with little performance or weight impact.

Speed Sensitivity

The selection of a design speed requirement is often dependent upon operational considerations. But it must also be chosen within the limits of practical design. For example, it is desirable to make fighters very fast. The top speed of most supersonic fighters is Mach 2.2 to 2.5. However, at higher speeds surface temperature increases, propulsion effects and other factors necessitate substantially larger, more complex aircraft incorporating unconventional materials such as titanium and carbon-carbon matrix. There are aircraft such as the SR-71 that operate at higher Mach numbers but they are very sophisticated and expensive. Therefore an operational maximum of about Mach 2.5 or so has fallen out of the physics of the situation.

The speed sensitivity results shown in Figure B-45 indicate a similar 'wall' at around 500 Kts for the tilt wing and VDTR concepts. Sizing was performed about the design mission with the maximum speed segment changed accordingly. Propulsive efficiency, engine ram effect, and dynamic pressure effect were all accounted for as a function of speed. Propulsive efficiency as a function of speed plotted in Figure 19 was used. Up to about 400 kts TOGW rises at a moderate rate with speed. Beyond 400 kts TOGW begins to rise rapidly. Even at a constant propulsive efficiency the aircraft will grow in size as higher speed capability is designed in. In general, about half the incremental rise above the flat region is due to increased engine size and fuel volume to overcome the increased drag. The rest is due to the increased engine size and fuel due to diminishing propulsive efficiency. The design points more or less fall on the knee of these curves. This is because the knee of each proprotor propulsive efficiency curve is at the design speed.

Speed vs. aircraft size is an important trade typically considered in aircraft preliminary design. One measure of the combination of speed and weight is productivity. This can be defined in a number of ways. In general it relates speed, payload, and either TOGW, empty weight, or cost. Figure B-46 plots each aircraft's productivity as a function of speed where productivity is defined as:

$$\text{Productivity} = \frac{\text{Payload (lbs)} \times \text{Speed (Kts)}}{\text{Empty Weight (lbs)}}$$

The speed used in the productivity equation is different for different missions. If an outbound dash is most important, the maximum cruise speed is used. Using this definition the design point falls slightly beyond the peak achievable productivity. To take advantage of reduced size and maintain 99% of the productivity based on maximum speed each aircraft should be designed for about 25 kts less speed.

For overall mission productivity block speed is commonly used, which is mission distance divided by total mission time. The second set of dotted lines on Figure B-46 were made using this definition. For this productivity the 99% point can be attained at about 50 kts less than the design speed.

For the technology levels assumed in this study and based on productivity, the most appropriate speed range of future tilt wing and VDTR designs appears to be between 350 kts and 425 kts.

Design Sensitivity to Observables Treatment

The observable qualities of an aircraft are usually broken down into infrared (IR), acoustic, and radar cross section (RCS) signatures. Through these physical radiations or reflective qualities sensors detect motion, position, and size. The goal is to reduce these as much as possible to minimize the detectability of the aircraft.

The IR signature is dominated by the engine exhaust. Suppressors were included in all the designs. Depending on detail design, removal of the IR suppressors on the transports would save from 150 to 250 lbs and 75 to 150 lbs on the SCAT. In general, helicopter suppressors cause 1% to 2% in power loss due to back pressure. This is very design dependent and can be more or less dependent on the design and suppression goals.

Acoustic detectability is measured both in the human perception range and in frequency ranges used by electronic detection equipment. For military aircraft electronic detection range is usually more important. No calculations were made regarding these levels. In general design that reduce aural detection reduce electronic detection also. The acoustic signature is very sensitive to tip speed and less so to blade planform and airfoil design. Engine noise is also significant and is a function of power level and exhaust treatment.

The VDTR transport design is at a relatively low tip speed. Any lower and the proprotor cruise advance ratio would increase to the point where significant losses may begin to occur. Any further noise reduction would most likely come from blade planform and airfoil design. This would incur little weight gain as long as FM and propulsive efficiency could be maintained, but these detail design trades have not been done.

The tilt wing proprotor has very streamlined blade tips. Any significant noise reduction would need to come from tip speed reduction. A reduction from 800 to 750 fps increased TOGW by 2.8%.

The noise detectability of the VDTR SCAT could be reduced further for little weight gain by incorporating a thinner tip and a slight amount of sweep. More reduction could be gained by reducing tip speed. The weight sensitivity of this trade is evident in Figure B-6. Given the same tip speed and similar blade geometry the VDTR SCAT could be as quiet or slightly quieter than the VDTR transport.

Aircraft RCS reduction is a complicated task. Generally shaping, coating, and masking are the primary methods of RCS reduction. The signature of rotating hardware is particularly difficult to reduce. These aircraft all have relatively large proprotors. They pose problems both in terms of their own return and reflections they may induce from other parts of the aircraft. This would be the primary subject of effort on these types of designs

Shaping has a most dramatic effect on overall design. This is evident on the YF-117, B-2 and to a lesser degree on the YF-22 and YF-23 aircraft. Shaping almost inevitably increases fuselage surface area. This increases weight and drag. In the case of the YF-117, which supposedly has shaping a generation older than the

B-2, very large form drag increases can result as well. The performance for all of the study aircraft is fairly drag sensitive. No effort was made to incorporate shaping in these designs. Shaping will therefore have a noticeable negative impact on performance and sizing.

Section 6. Shrouded Rotor Design

The shrouded rotor configuration analyzed in Task I was a co-axial shaft driven concept. The poor payload performance of this aircraft was due to a very high empty weight fraction, about .88 for the SCAT mission. Much of this was due to the rotor covering and large wing area. The aircraft was also found to be overpowered in hover. Early in Task II a single impulse tip driven rotor system was investigated for this concept. A beneficial trade of decreased transmission efficiency for decreased weight was expected. Tip drive systems are known for their simplicity and generally lighter overall weight. General Electric Aircraft Engine group was consulted and very helpful in the design and performance evaluation of the tip drive system.

The observable characteristics of this aircraft are inherently very good. There is no tail rotor and the single main rotor is enclosed within the shroud which acts like a noise and radar barrier. In cruise the highly swept delta planform combined with small cockpit and blended design lends itself very well to low RCS. Treatment of the IR returns in cruise can be handled the same as fixed wing aircraft returns are handled, but hover will require new design solutions.

The roll inertia of the shrouded rotor design is only about 44% that of the VDTR SCAT. Combined with the large control power provided by the rigid rotor the low speed agility characteristics are expected to be very good. In fixed wing mode the circulation control system can create large Cl values. Differential blowing on the upper and lower surfaces gives high 'aileron' power. Roll acceleration is estimated at over three times that of the VDTR SCAT at the same equivalent airspeed. Roll rate in fixed wing mode is greater too. Analysis shows a roll rate in excess of 200 degrees/second at the conversion speed of 100 kts.

High sustained load factor capability has historically been shown to be critical to a fighter's combat effectiveness. The shrouded rotor does not have inherently good load factor capability. Figure B-47 shows thrust available and thrust required at load factors of 1.0,1.5 and 2.0. The maximum sustained capability was found to be only 1.7. The very low aspect ratio wing creates a great deal of induced drag. The span efficiency of a delta wing is poor, on the order of 50% compared to 80% to 85% for more conventional wings. The F-15 and F-18 which are very good maneuvering aircraft have wing aspect ratios of about four, nearly three times greater than the shrouded rotor. The dramatic rise in shrouded rotor thrust required as lift increases quickly eats up the available thrust margin. The delta wing planform is, at the moment, the only practical shape for enclosing the rotor. Any other shape would result in excessive wetted area and weight. Increased power is a possible solution, however, from the weights analysis any significant increase in power will yield zero payload. Typically todays fighters have thrust to weight ratios of .80 to 1.0 depending on the mission load-out. The shrouded rotor only needs a thrust to weight ratio of .35 due to the magnification the rotor yields.

The shrouded rotor power required curve has an unusual shape (see Figure B-47). The low speed hump is due to a washing out of the shroud augmentation effect. Shrouded fans show this effect, however, the cyclic pitch input on the rotor required to counter body pitch-up amplifies the augmentation washout. This aerodynamic phenomena has been observed in Sikorsky wind tunnel tests. The critical engine sizing point is not hover but the speed range of 25 to 45 kts. The engine for this design was sized at the 30 kt point and oversized to give some excess power for maneuvering. The resulting maximum speed is a very respectable 460 kts.

The low payload fraction and depressed load factor capability of the shrouded rotor are serious impediments to a successful design. No inherent 'show stoppers' of this sort were found for the tilt wing or VDTR so the shrouded rotor cannot be considered at the same level of development. Fundamental aerodynamic analysis needs to be completed before the design and construction of a shrouded rotor can be considered viable. One aspect the shrouded rotor has going for it is that it is a rather unexplored concept. Room exists for the application of related technologies and innovation. Basic research into circulation control on delta wings and the rotor-shroud interaction itself may well turn up unforeseen opportunities. This kind of work could not be performed under this contract. At this point it was decided to terminate any further analysis on this concept and to direct remaining analysis efforts on the other concepts. The sizing and analysis efforts performed on the shrouded rotor are valuable because they outline the fundamental advantages and disadvantages of the concept.

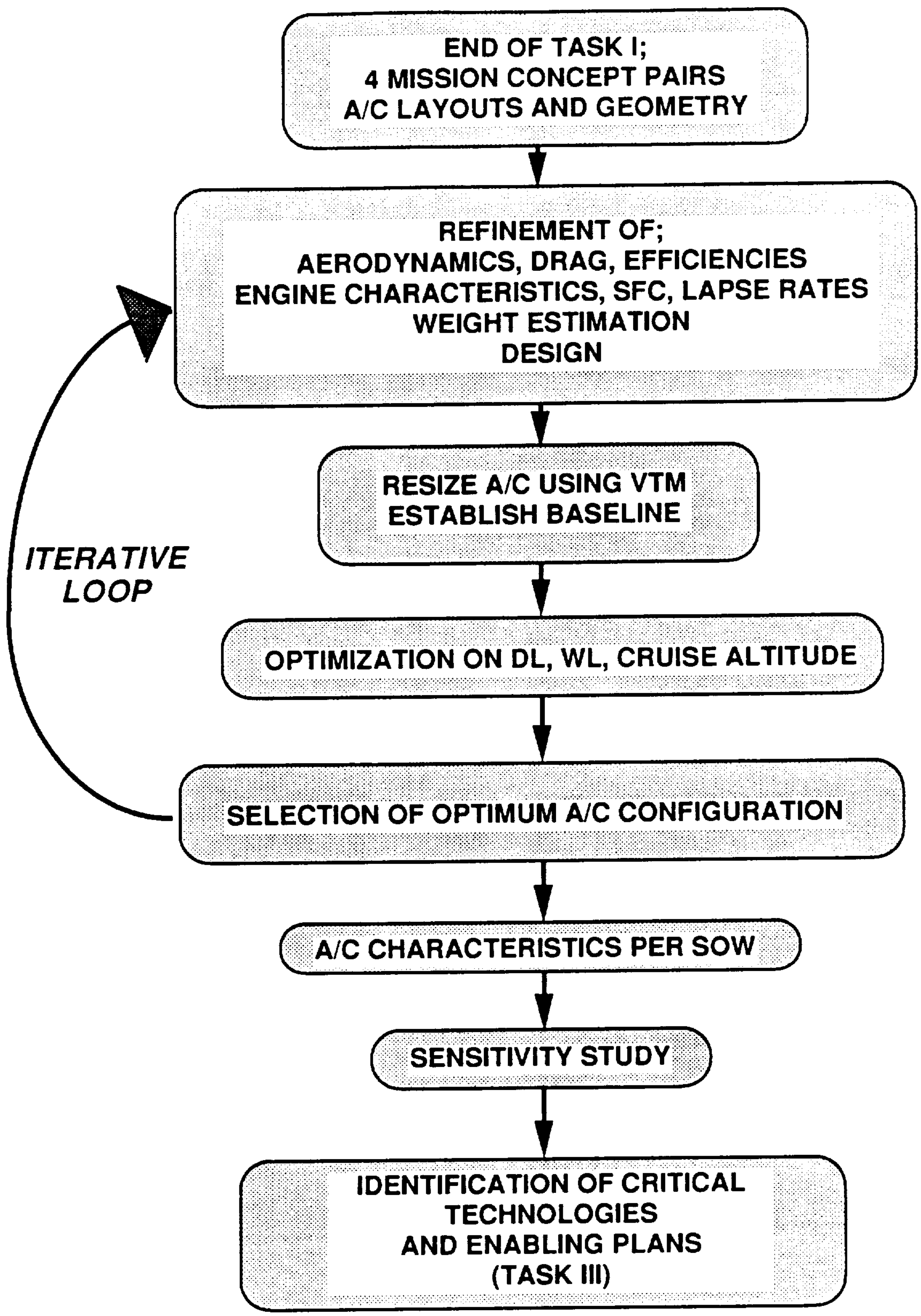


Figure B-1. Task II progression of work

HOVER

$$\text{REQUIRED ENGINE SHAFT POWER} = \frac{GW}{550\ FM}\left(\frac{DL}{2\rho}\right)^{1/2}\left(\frac{T}{GW}\right)^{3/2}(1-X_1)$$

$$\text{REQUIRED ENGINE NET STATIC THRUST} = GW\left(\frac{T}{GW}\right)X_1 \qquad \text{(LB)}$$

WHERE:

- GW = GROSS WEIGHT, LB
- T/GW = REQUIRED THRUST TO WEIGHT RATIO
- DL = DISK LOADING, PSF
- ρ = AIR DENSITY, SLUGS/CUFT
- FM = SYSTEM FIGURE OF MERIT
- X_1 = FRACTION OF LIFT PROVIDED BY THRUST ENGINES

FORWARD FLIGHT

$$\text{REQUIRED PROPULSIVE FORCE} = PF = \frac{2\,(SPL)^2}{\pi\rho V^2} + \frac{Cf\,(GW)^{2/3}\rho V^2}{2} \qquad \text{(LB)}$$

$$\text{REQUIRED ENGINE SHAFT POWER} = \frac{PF}{\eta_p} \times \frac{V\,(1-X_2)}{550}$$

$$\text{REQUIRED ENGINE NET THRUST} = PF \times X_2 \qquad \text{(LB)}$$

WHERE :

- SPL = SPAN LOADING, LB/FT
- V = AIRSPEED, FT/SEC
- Cf = DRAG COEFFICIENT, $f/GW^{2/3}$
- f = PARASITE AREA, FT^2
- η_p = POWER EFFICIENCY (ACCOUNTS FOR ROTOR PROFILE POWER)
- X2 = FRACTION OF PROPULSIVE FORCE PROVIDED BY THRUST ENGINES

Figure B-2. Performance calculations and input variables

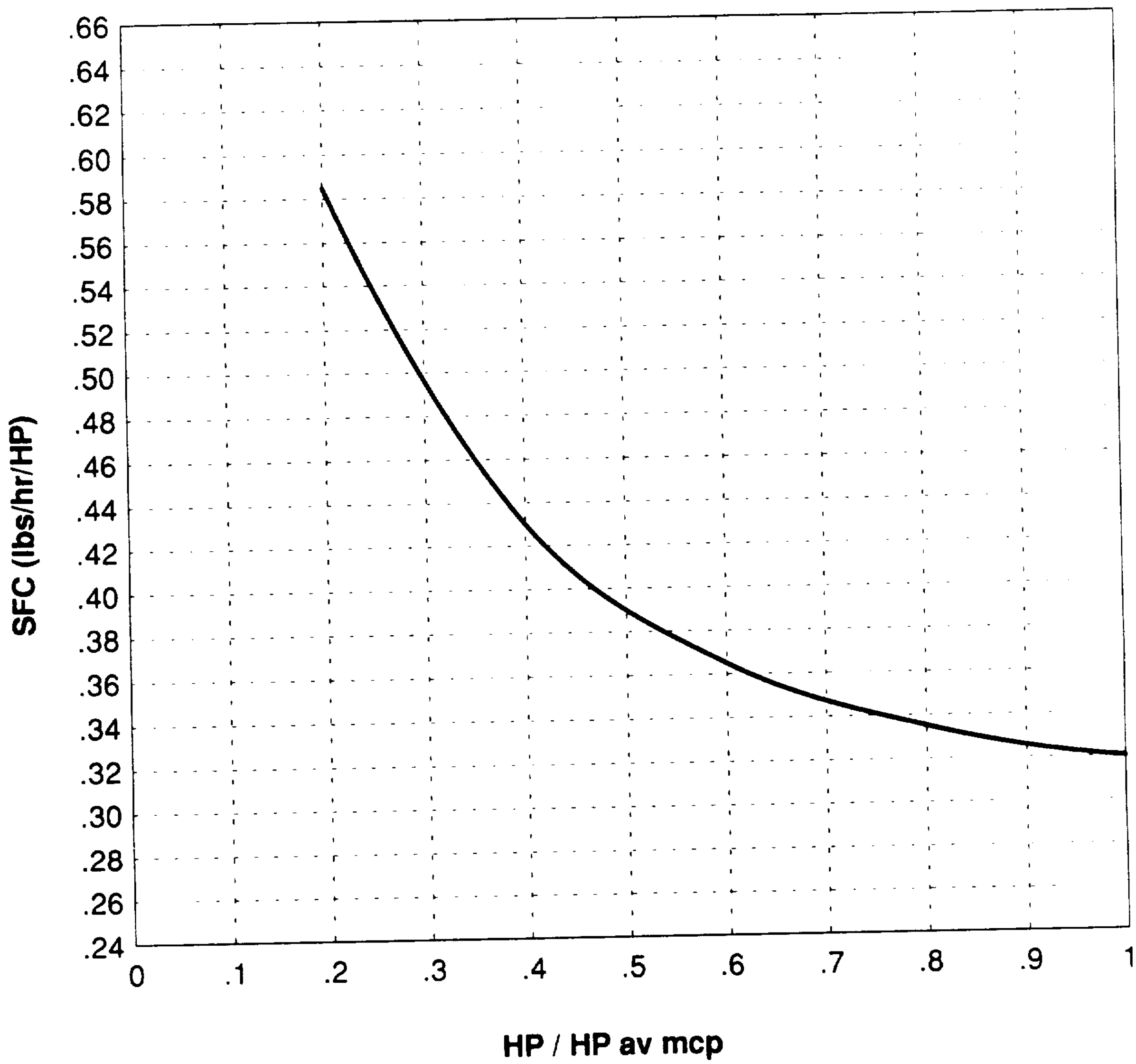


Figure B-3. Static SFC vs percent HP available

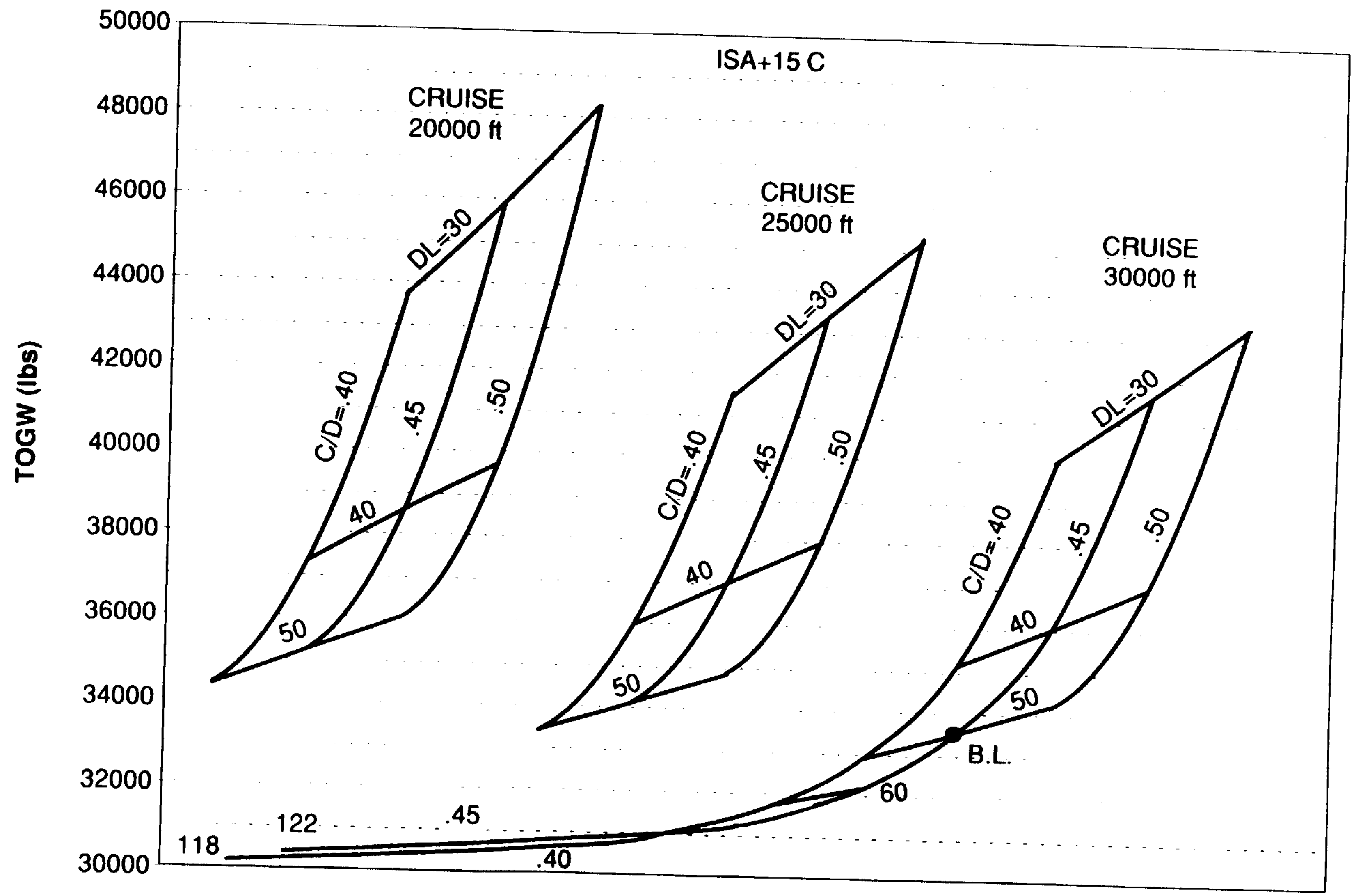


Figure B-4. Tilt wing transport optimization

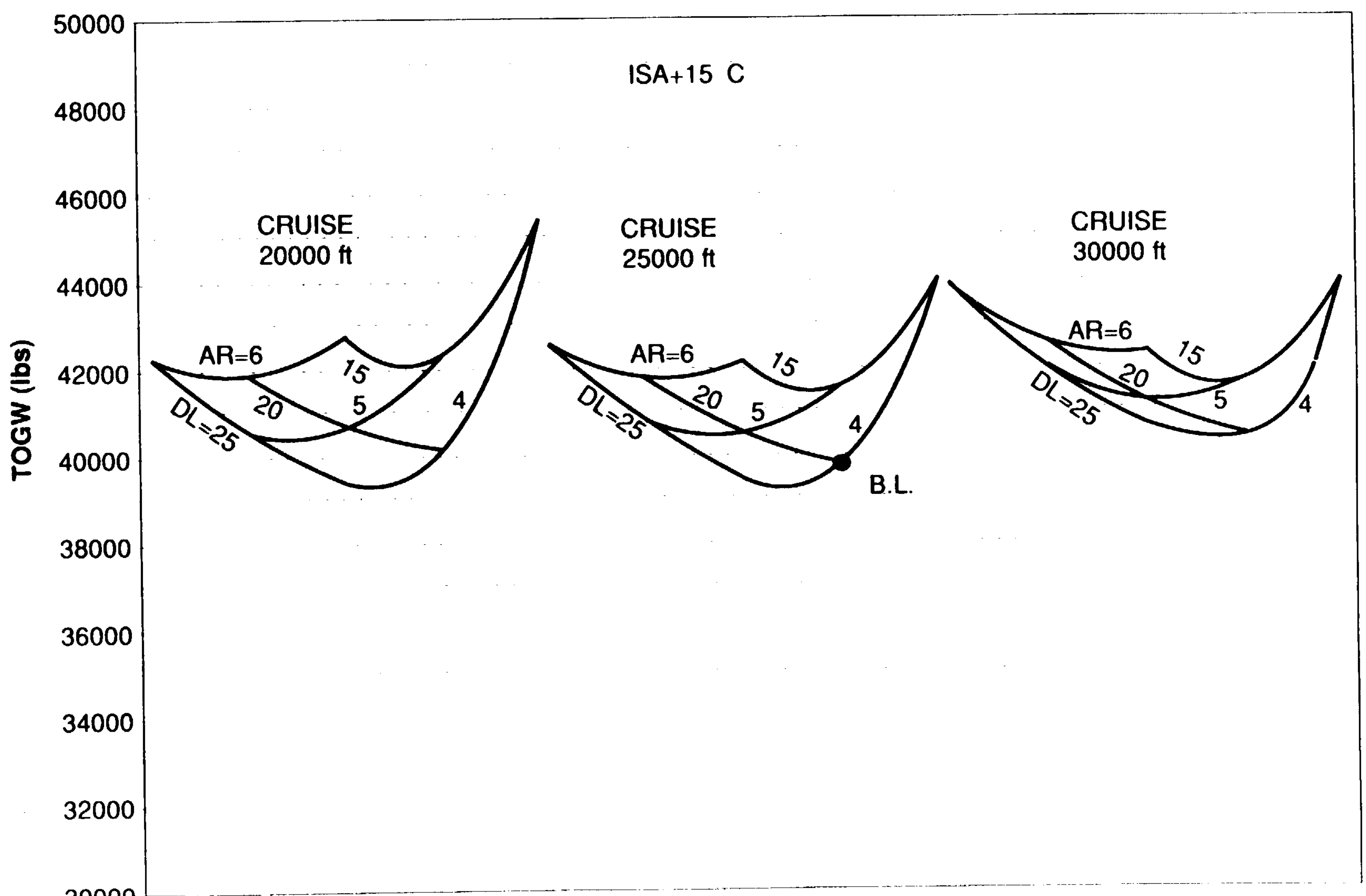


Figure B-5. VDTR transport optimization

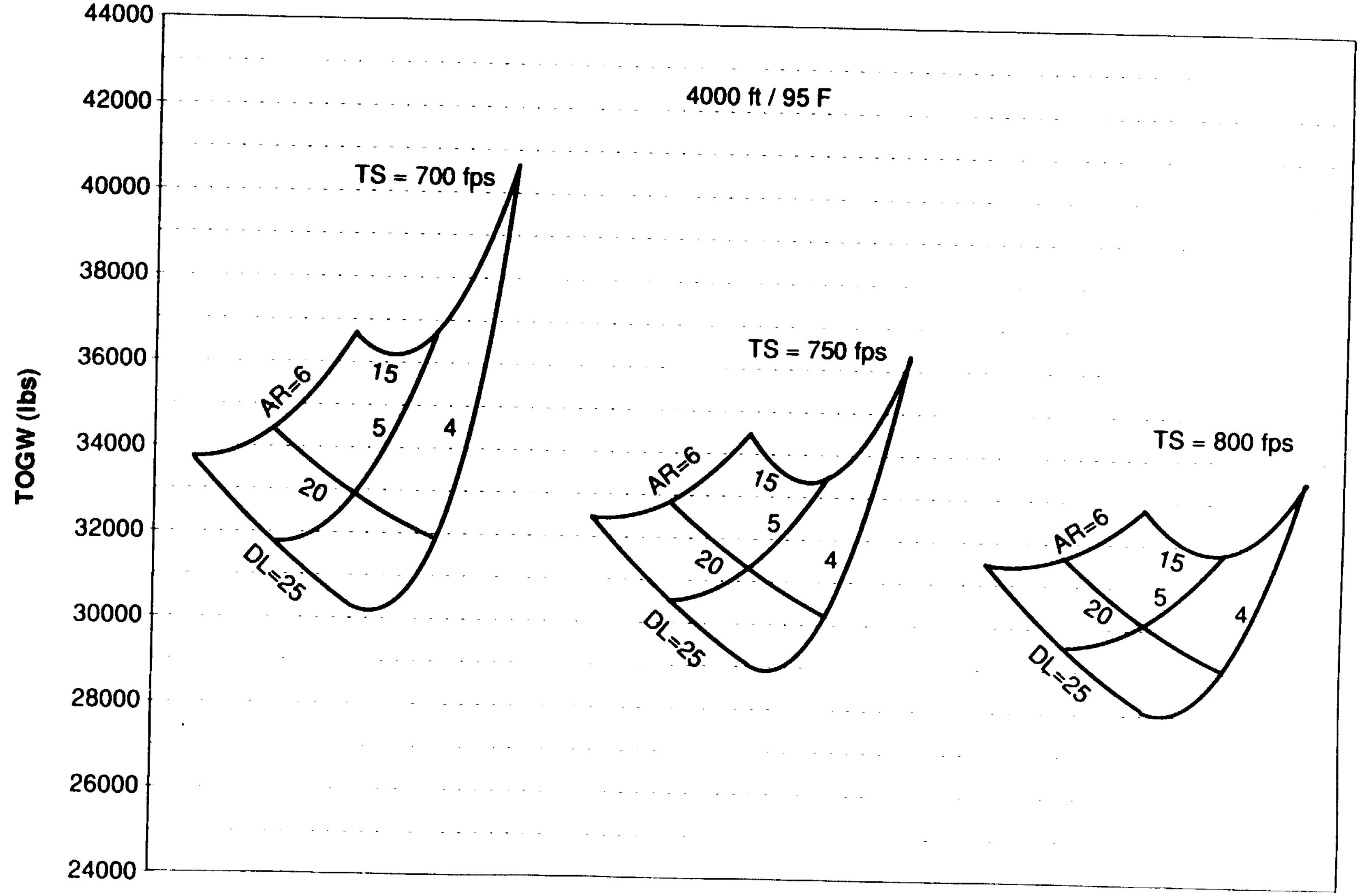


Figure B-6. VDTR SCAT optimization

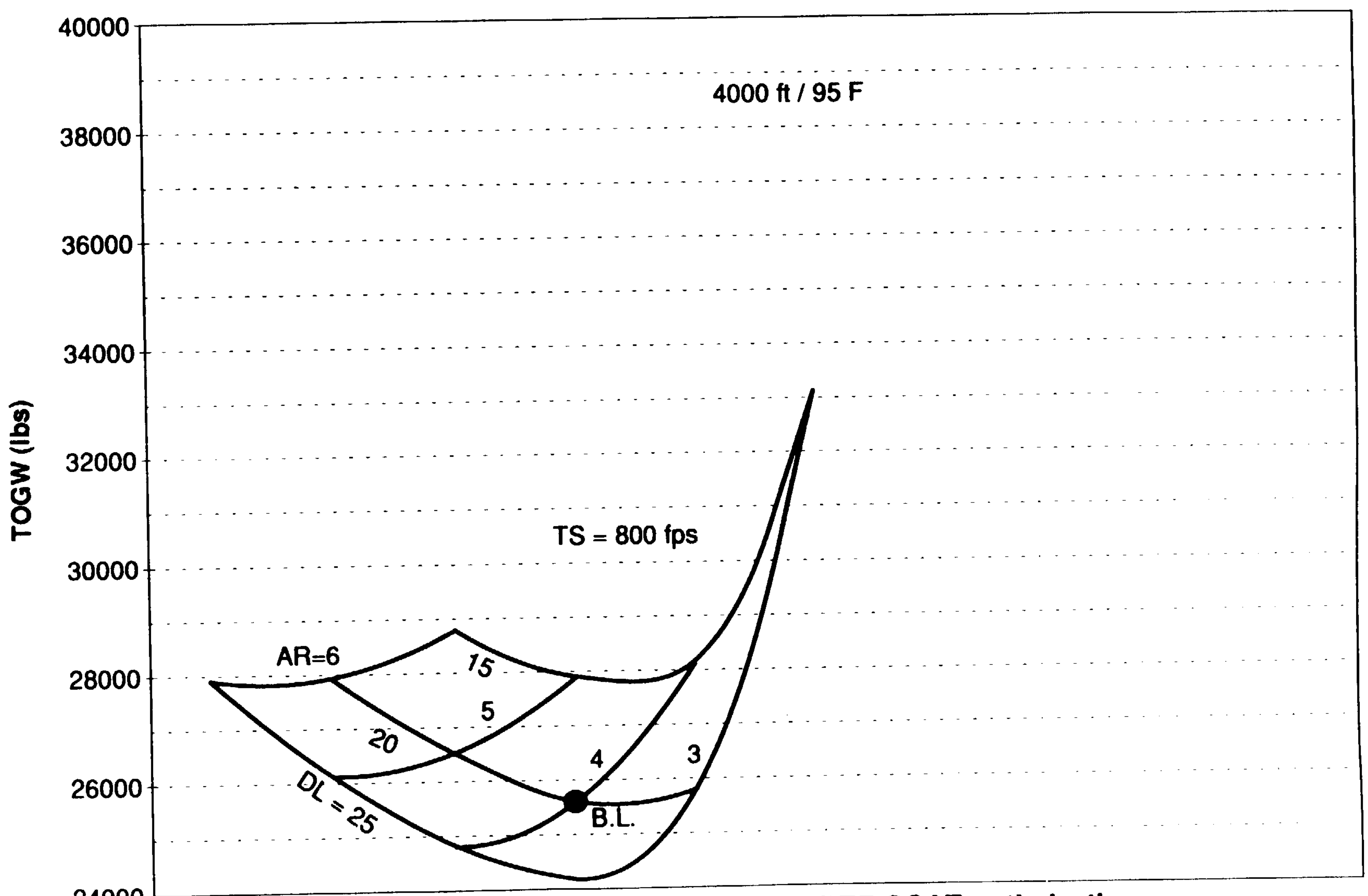


Figure B-7. Redesigned VDTR SCAT optimization

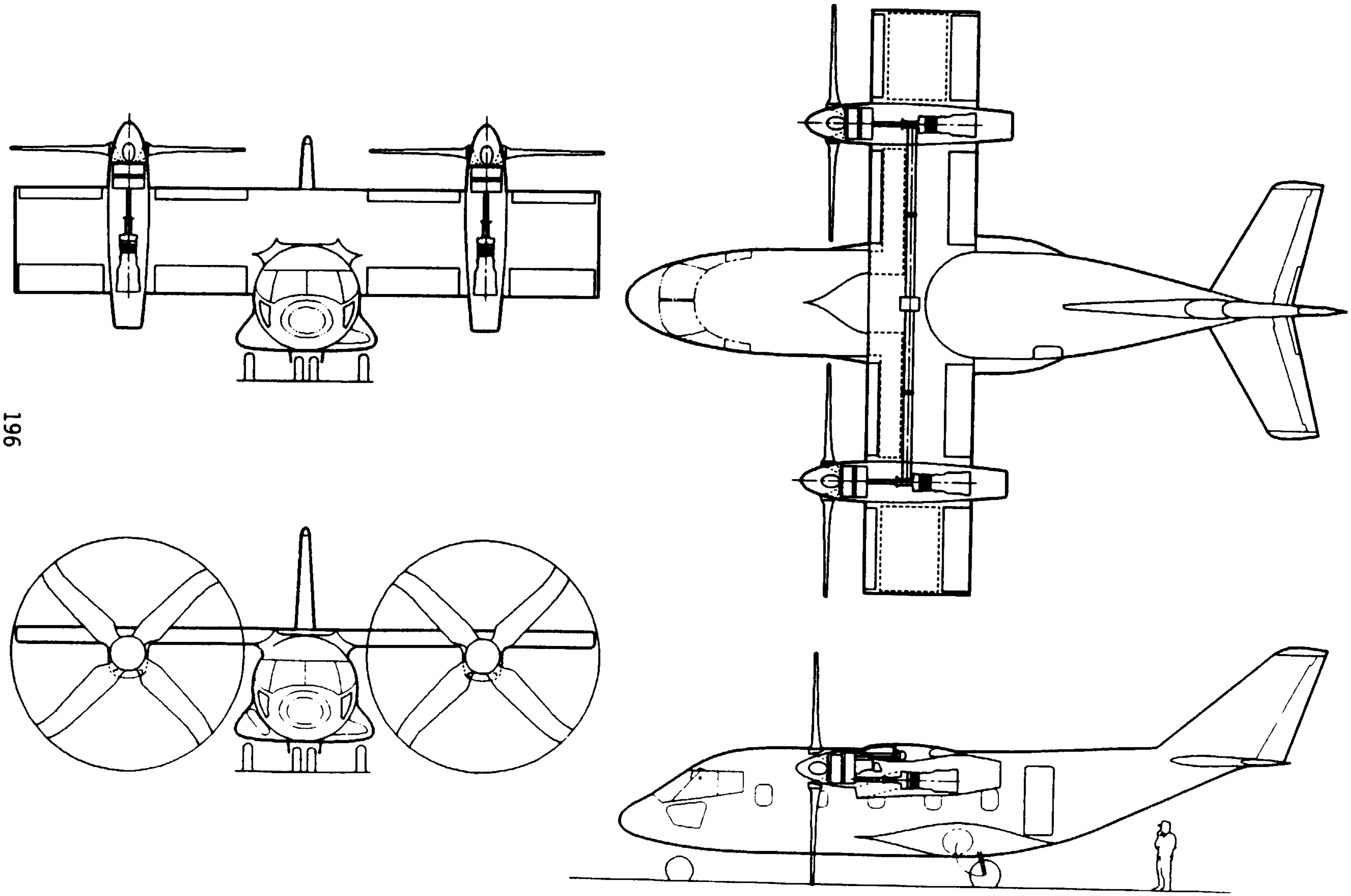


Figure B-8. Tilt wing transport configuration and internal views

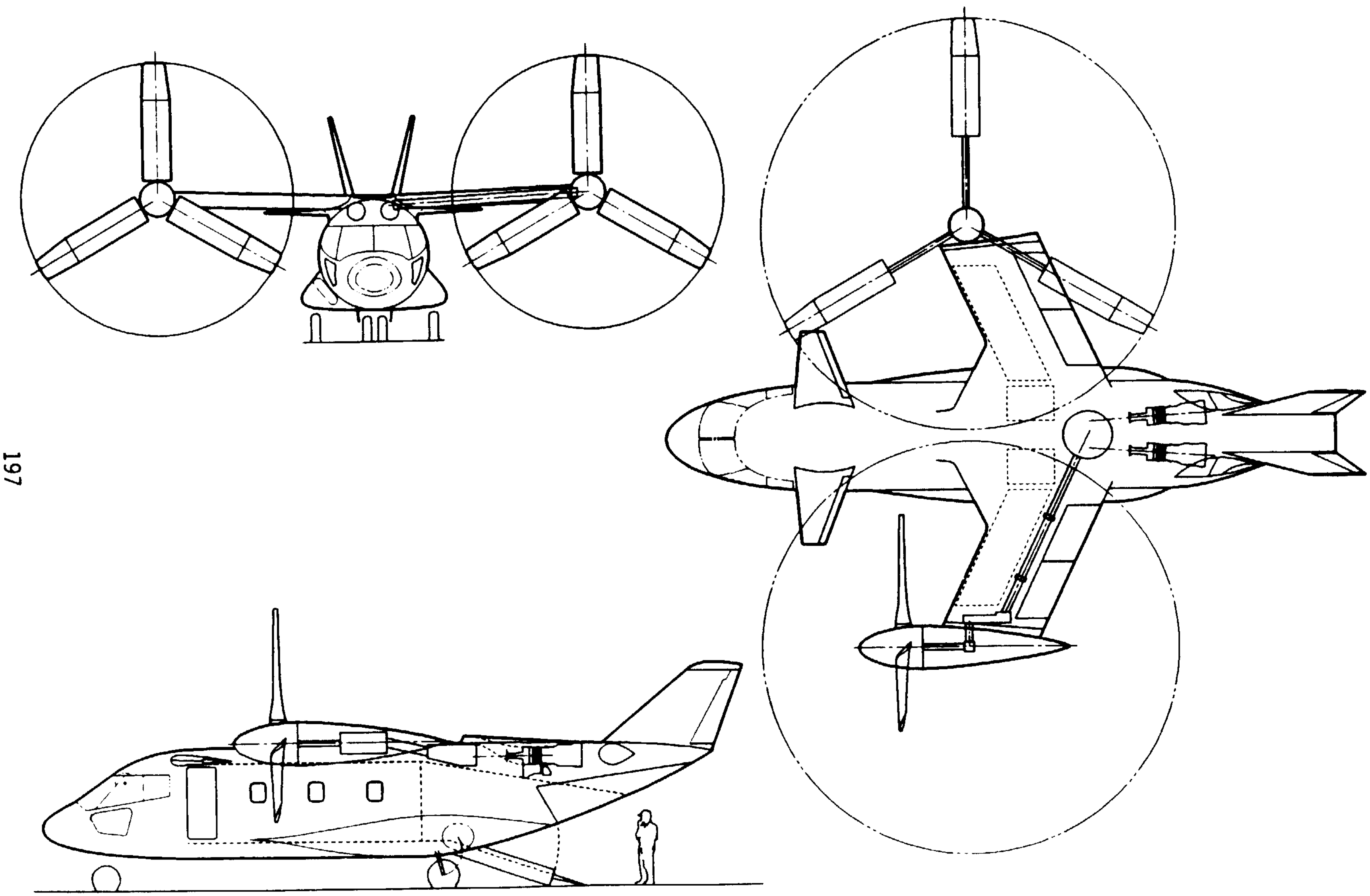


Figure B-9. VDTR transport configuration and internal views

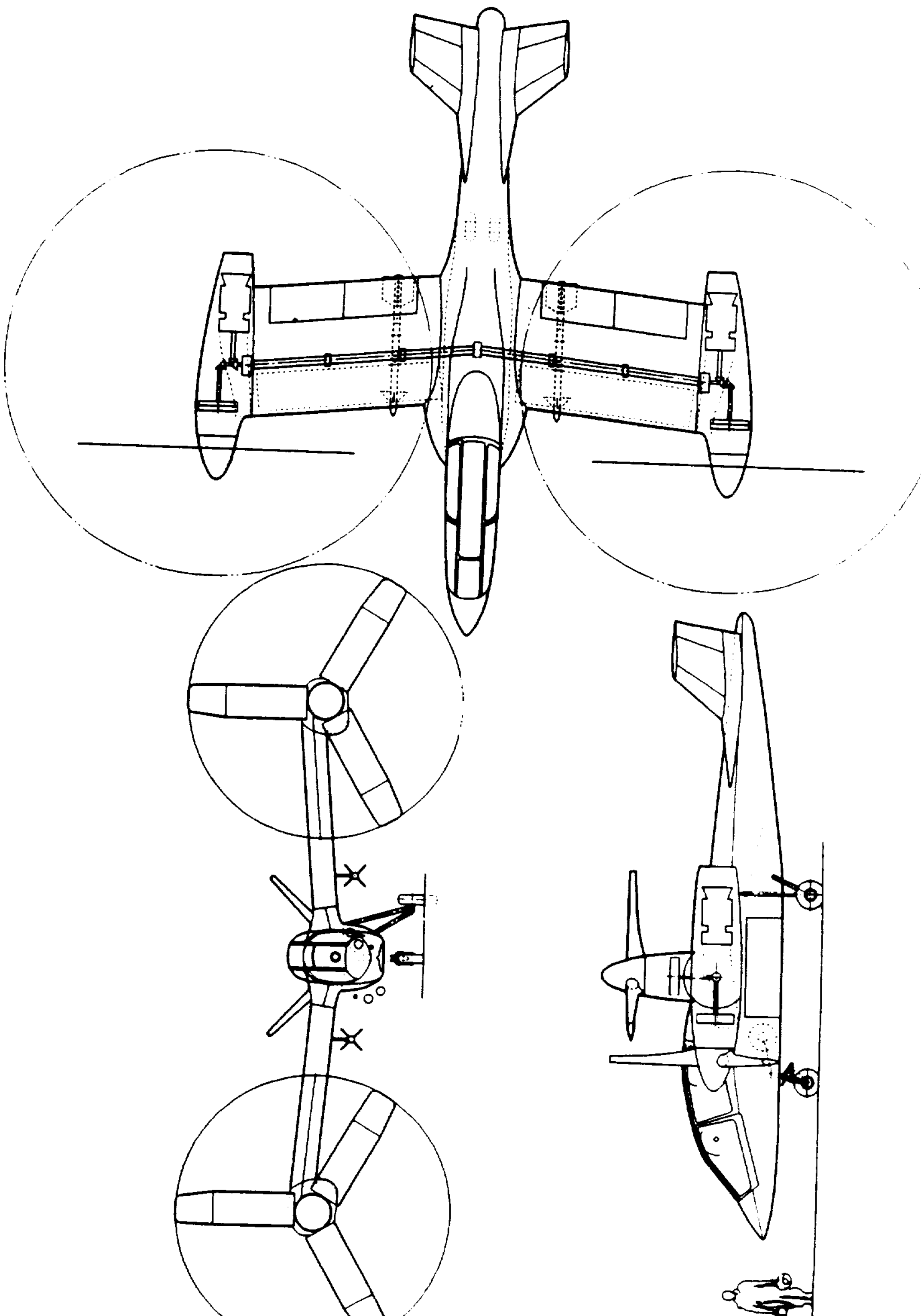


Figure B-10. VDTR SCAT configuration and internal views

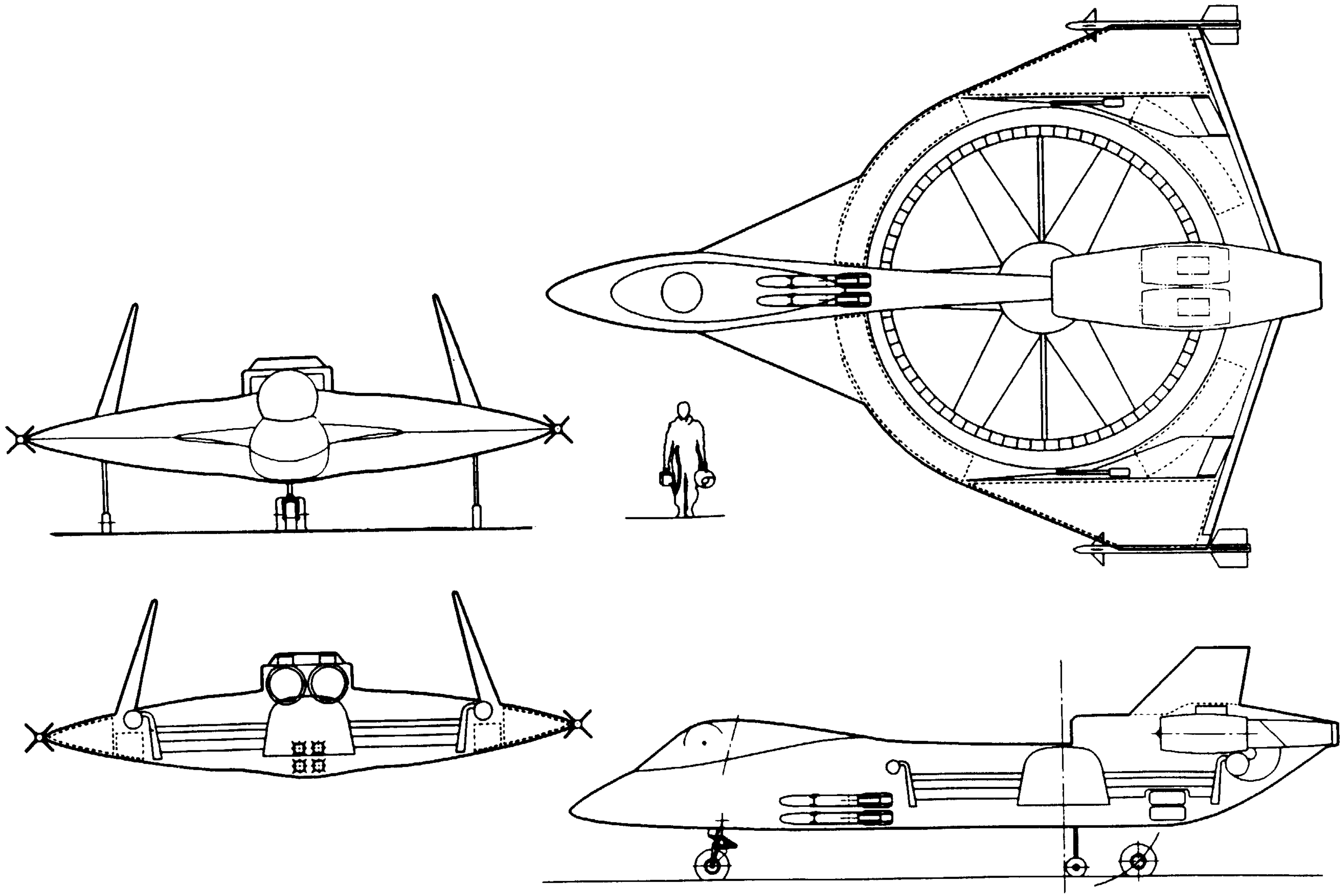


Figure B-11. Shrouded rotor SCAT configuration and internal views

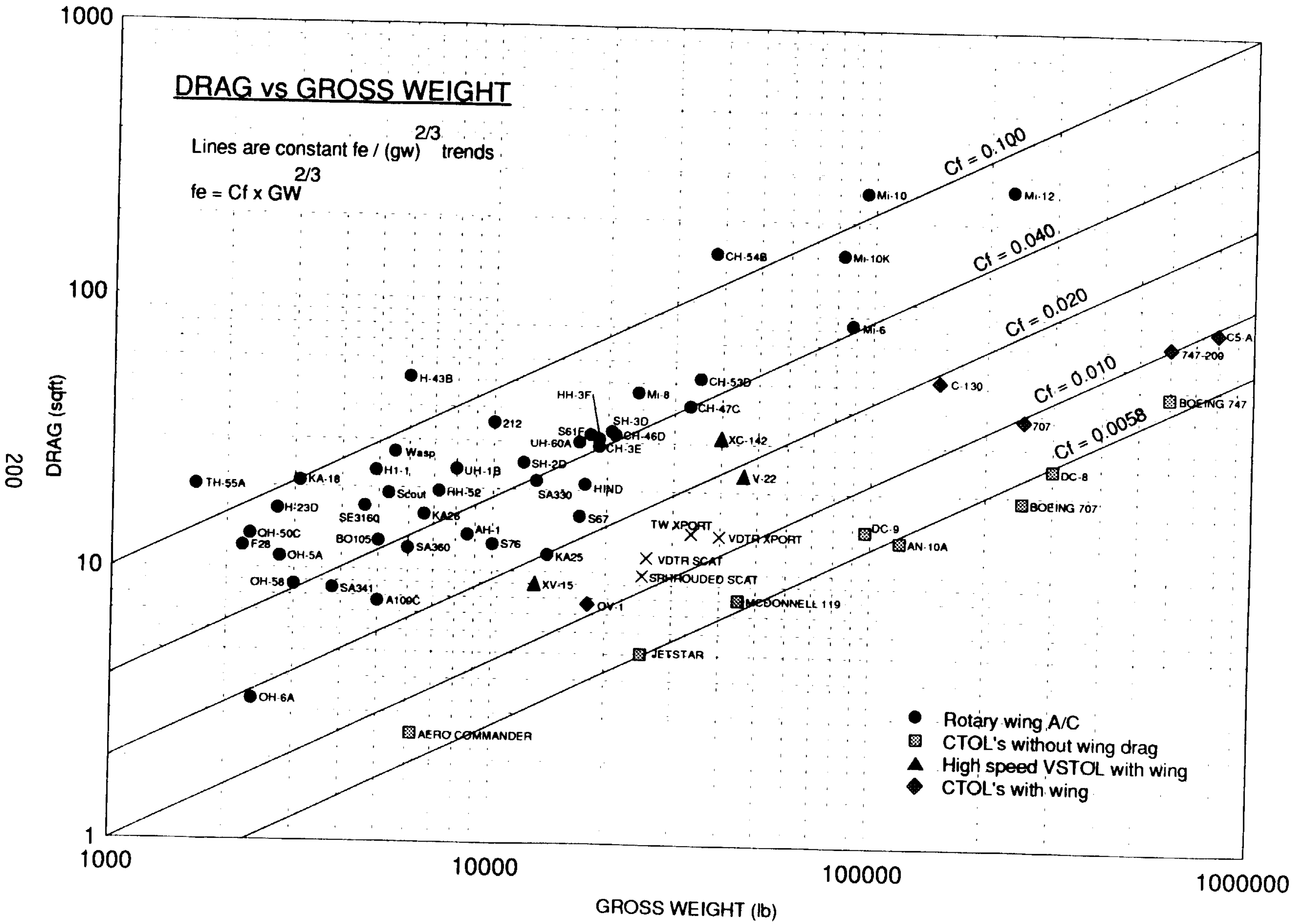


Figure B-12. High speed rotorcraft drag comparison

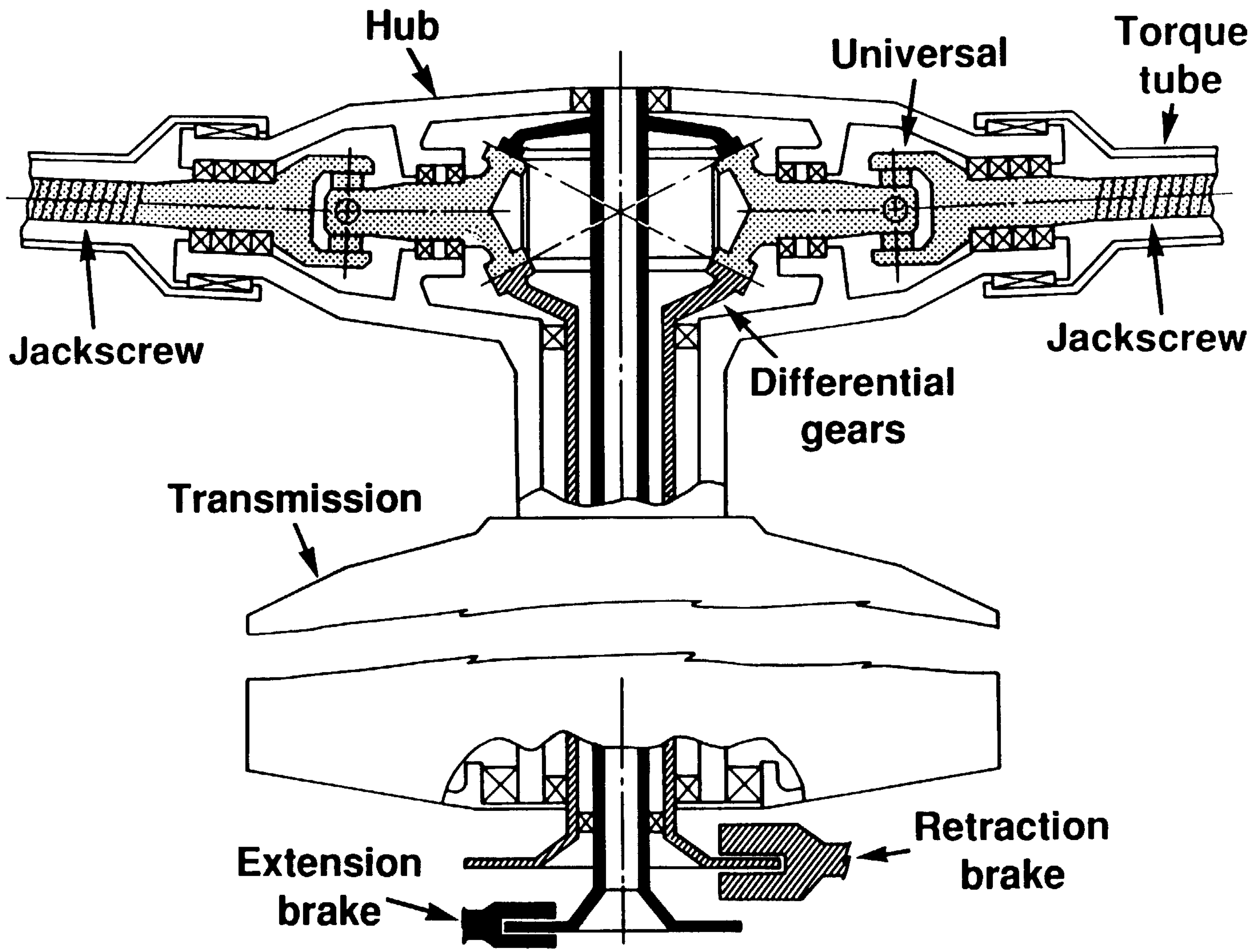


Figure B-13. Schematic of variable diameter hub mechanism

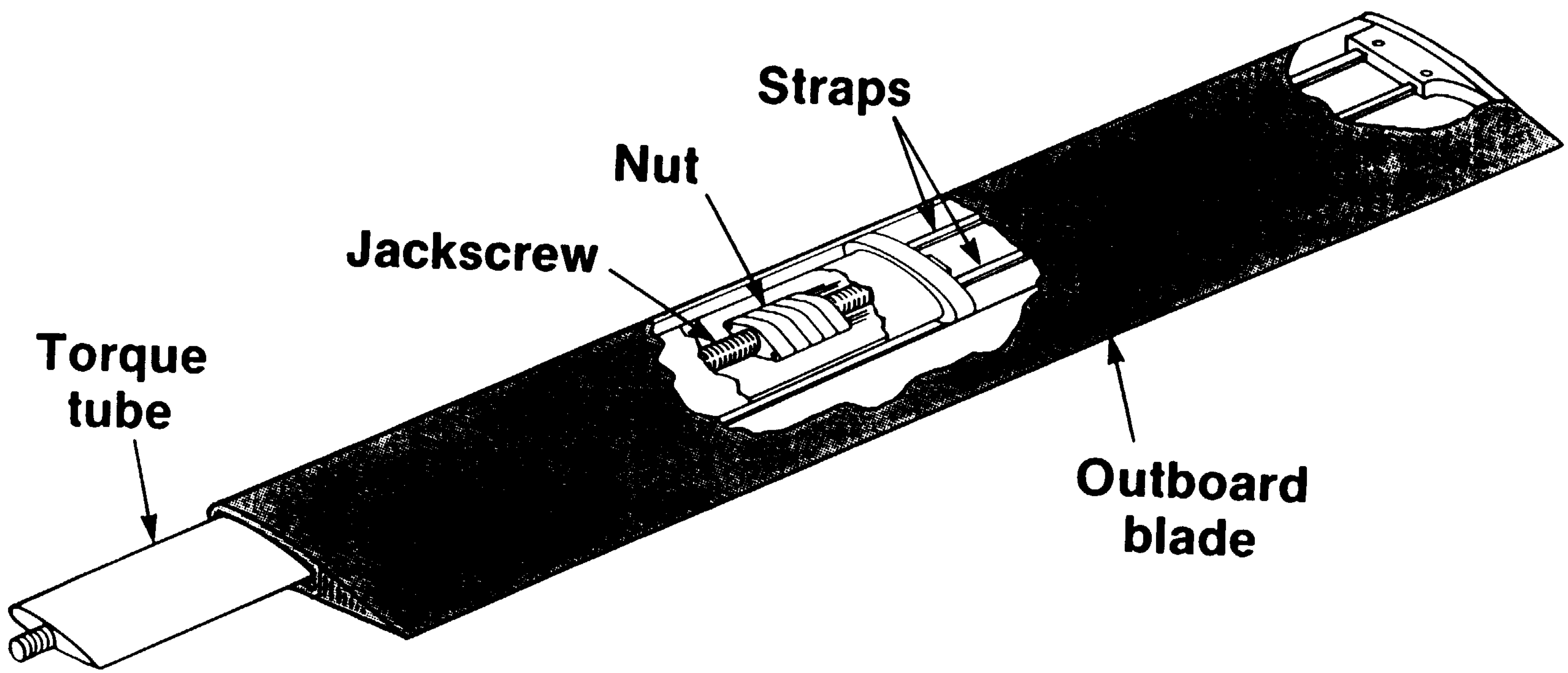


Figure B-14. Schematic of variable diameter blade mechanism

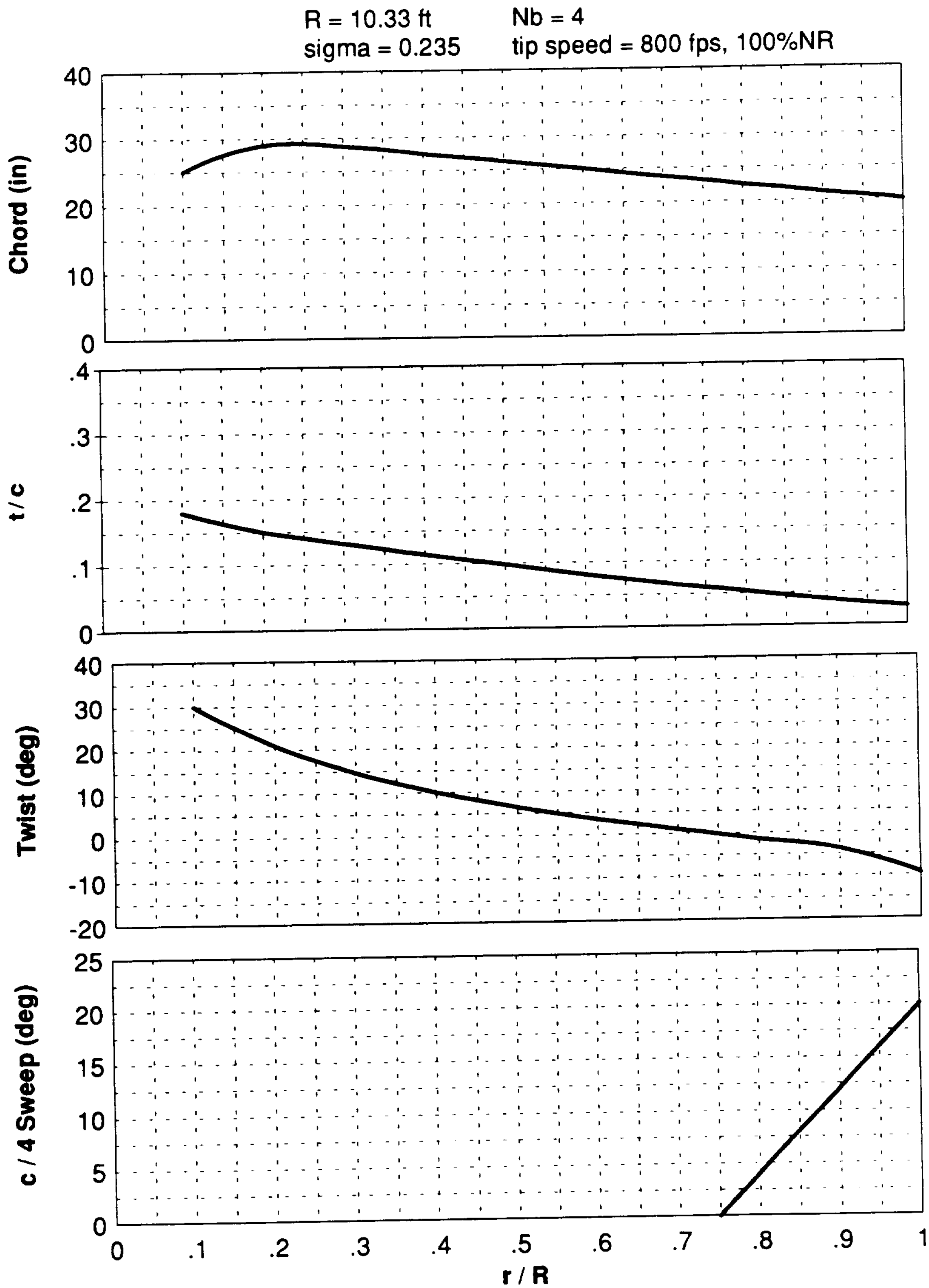


Figure B-15. Tiltwing transport proprotor geometry

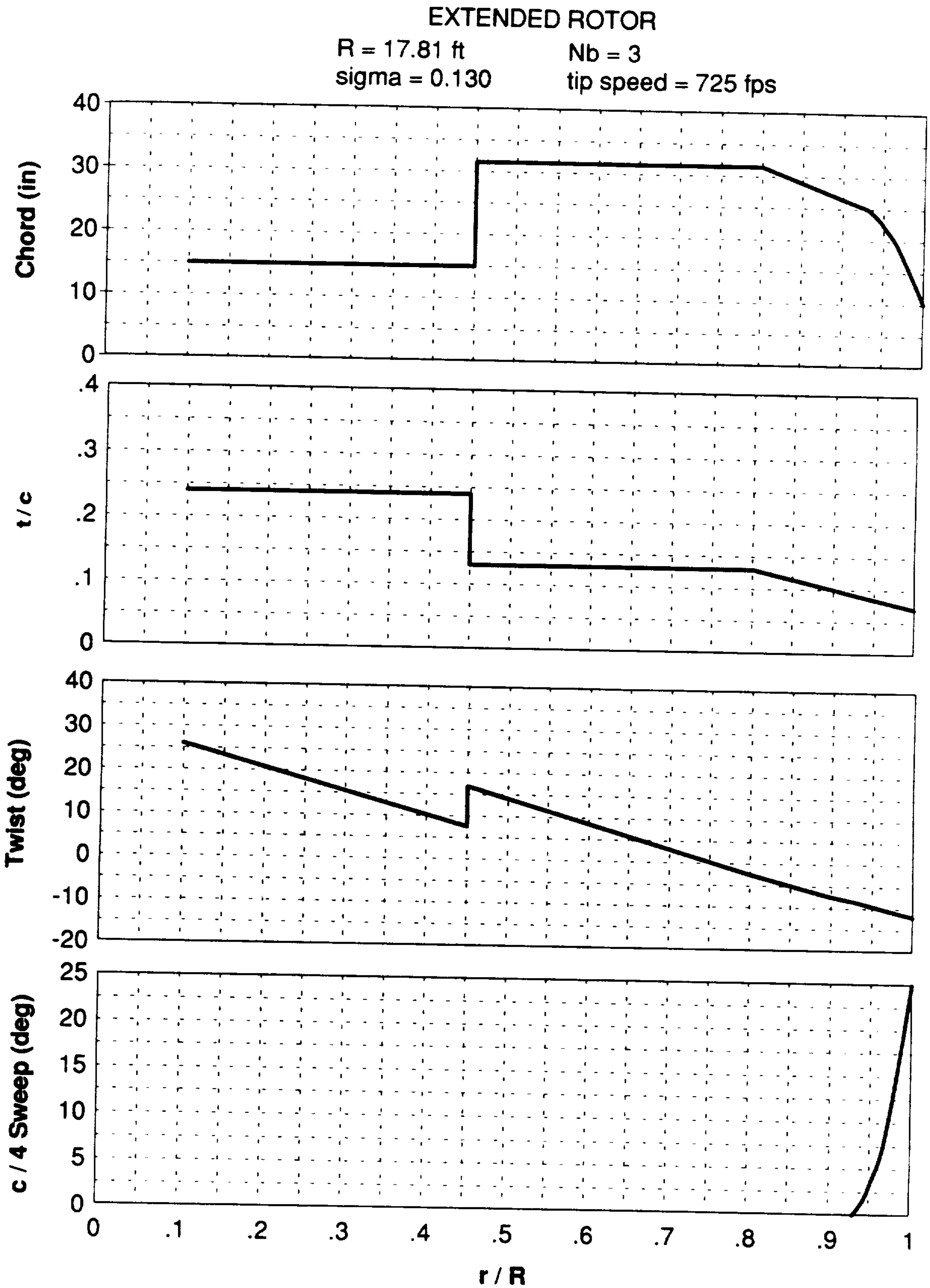


Figure B-16. VDTR transport proprotor geometry

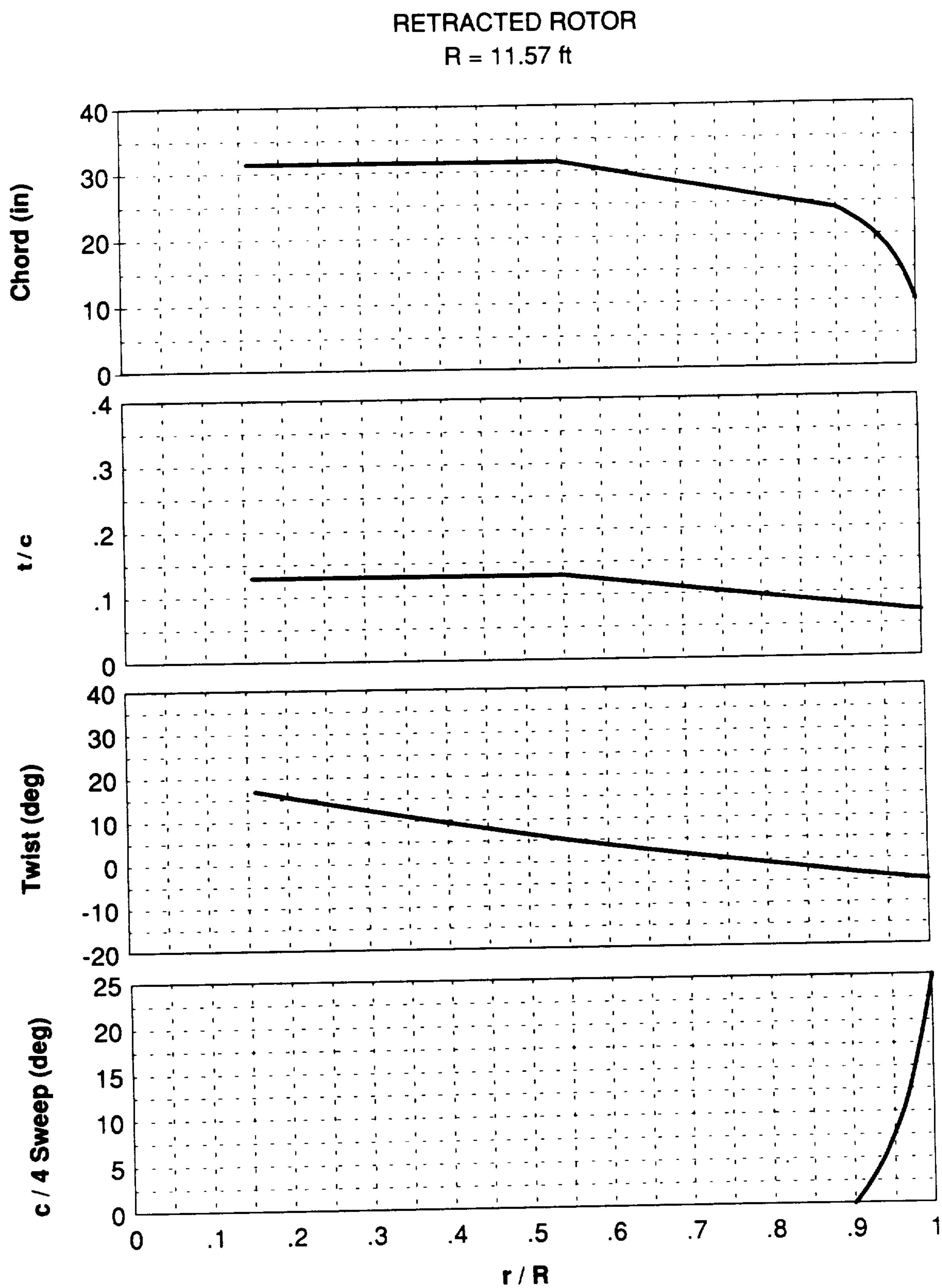


Figure B-16. VDTR transport proprotor geometry (continued)

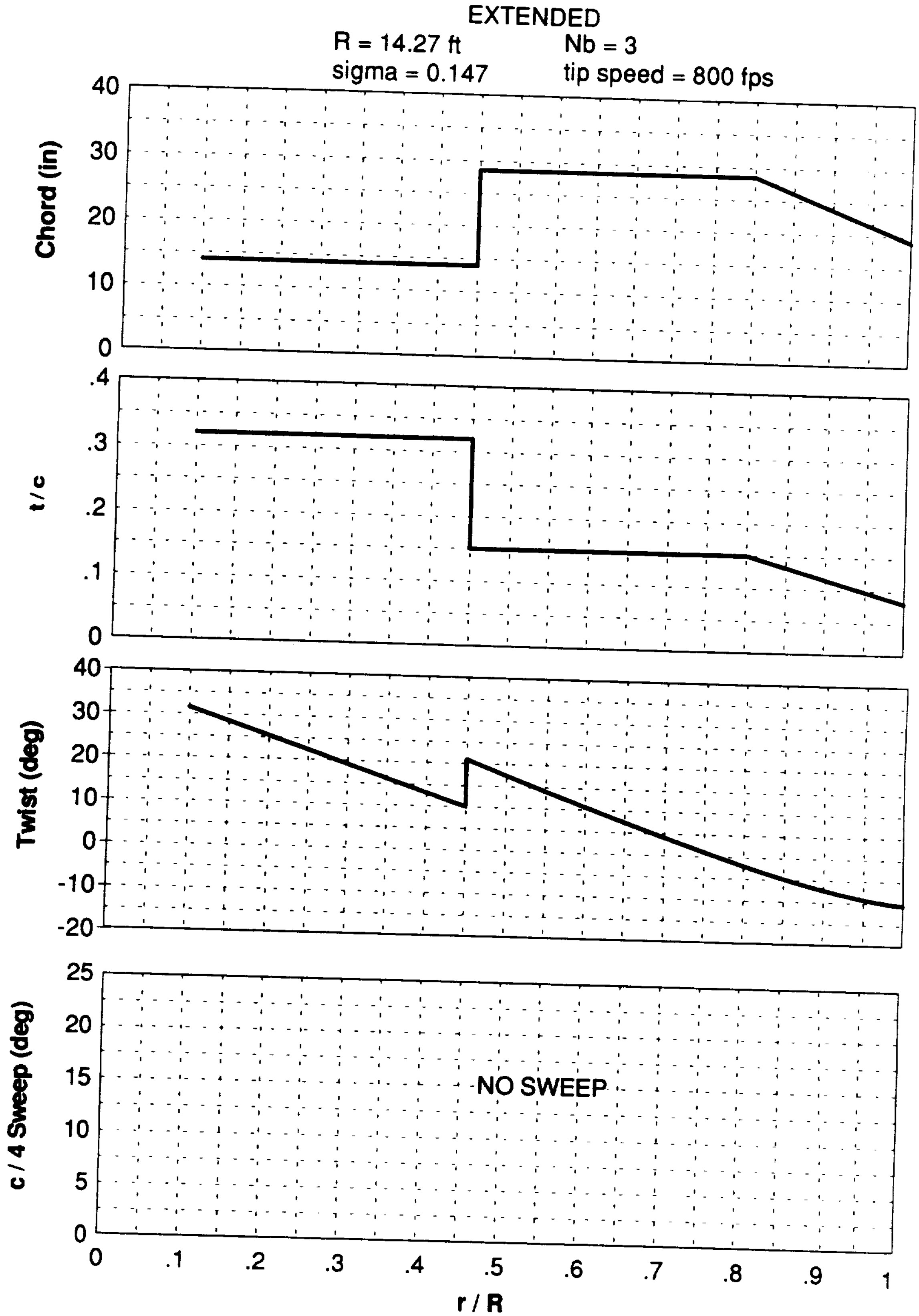


Figure B-17. VDTR SCAT proprotor geometry

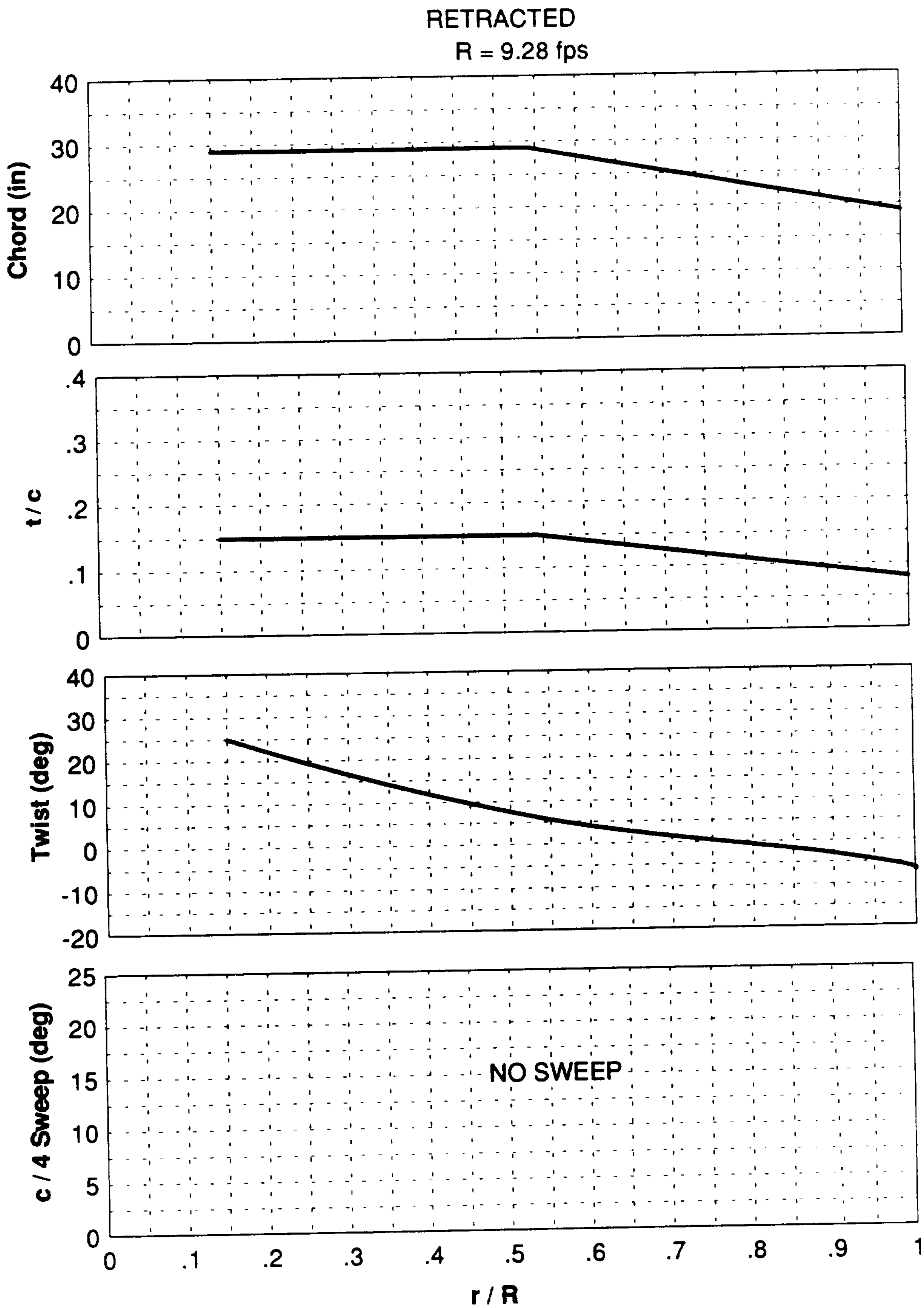


Figure B-17. VDTR SCAT proprotor geometry (continued)

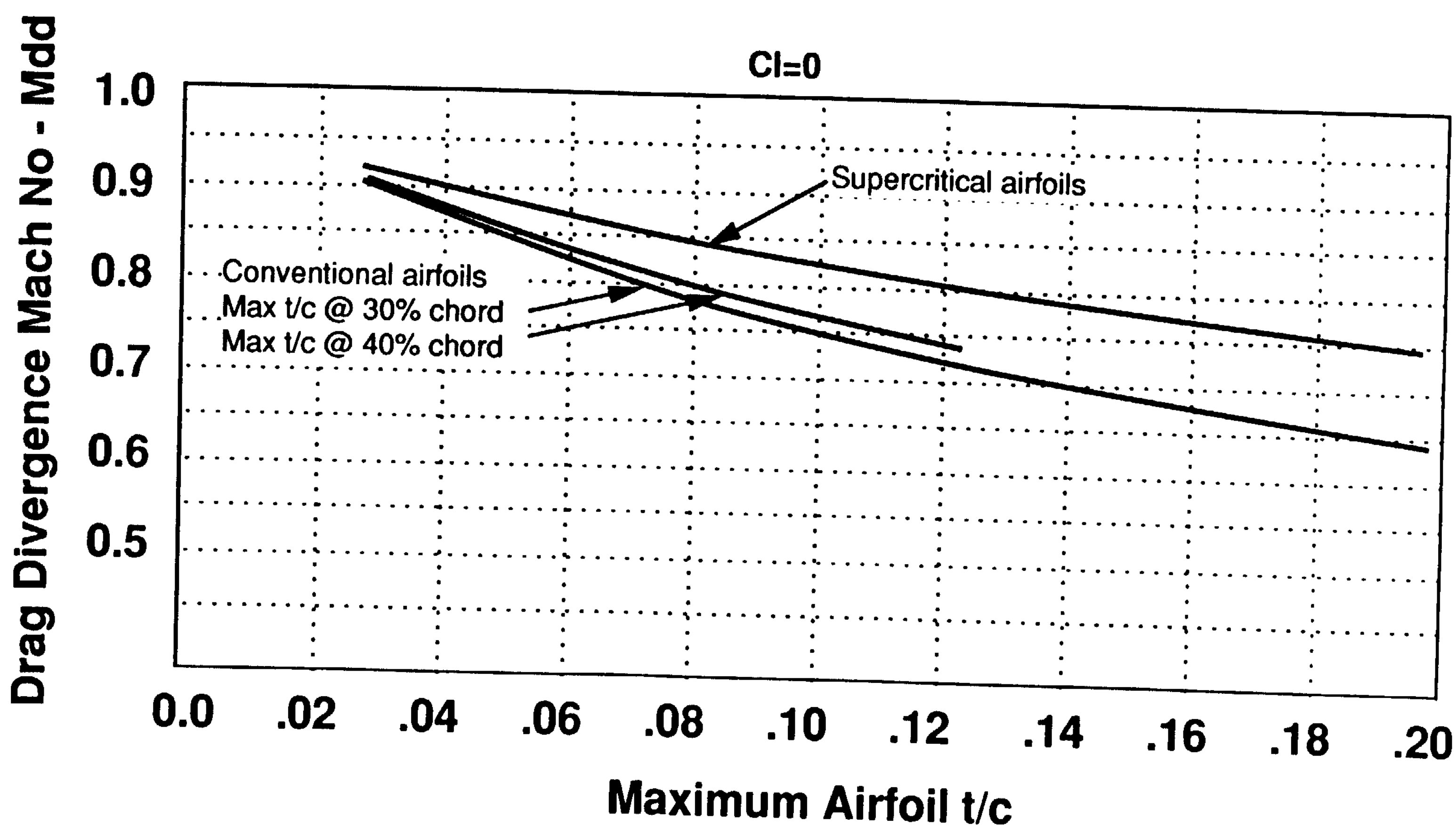


Figure B-18. Drag divergence Mach No. vs. airfoil type and t/c

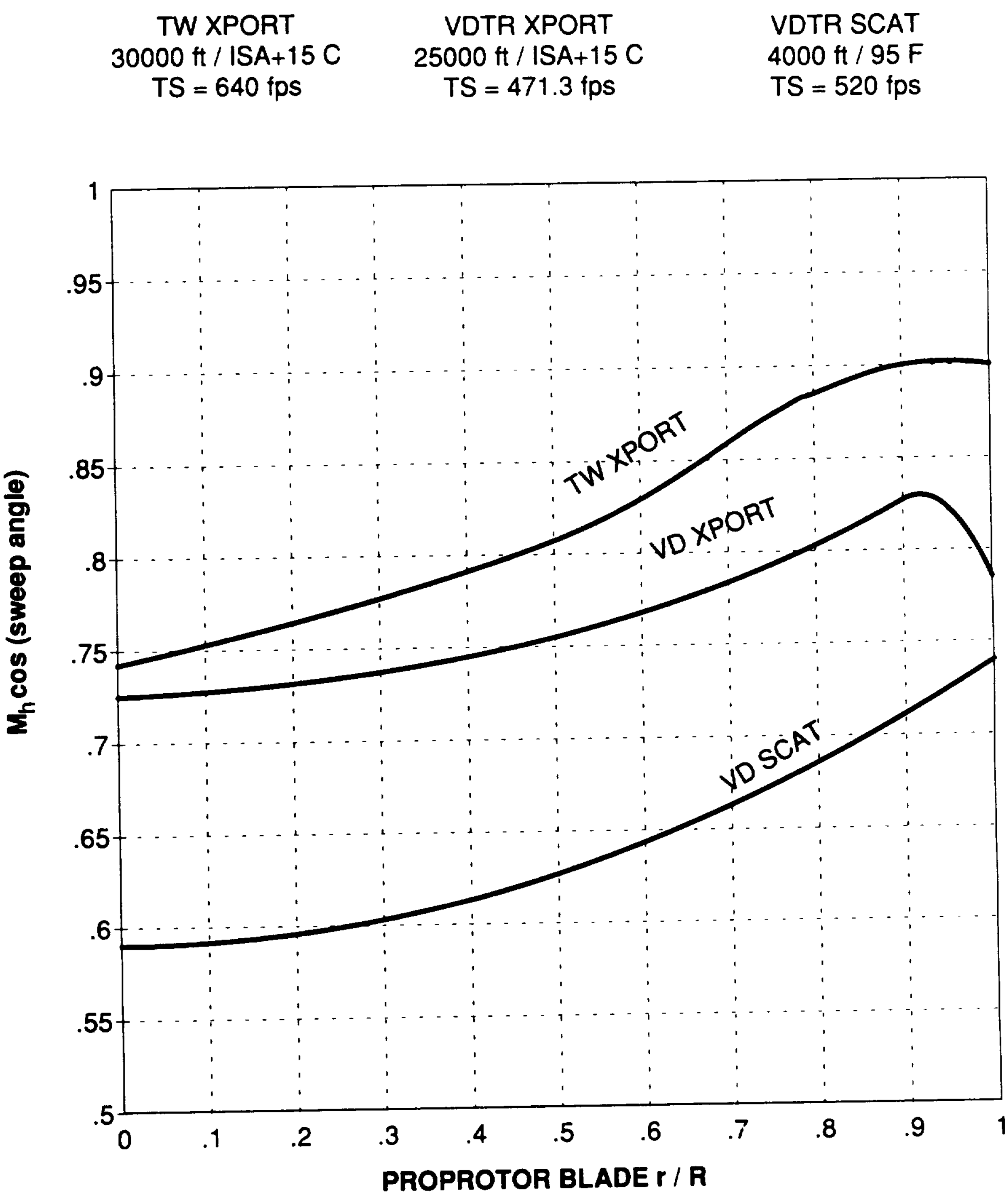


Figure B-19. Effective Mach number vs proprotor r / R at design cruise conditions

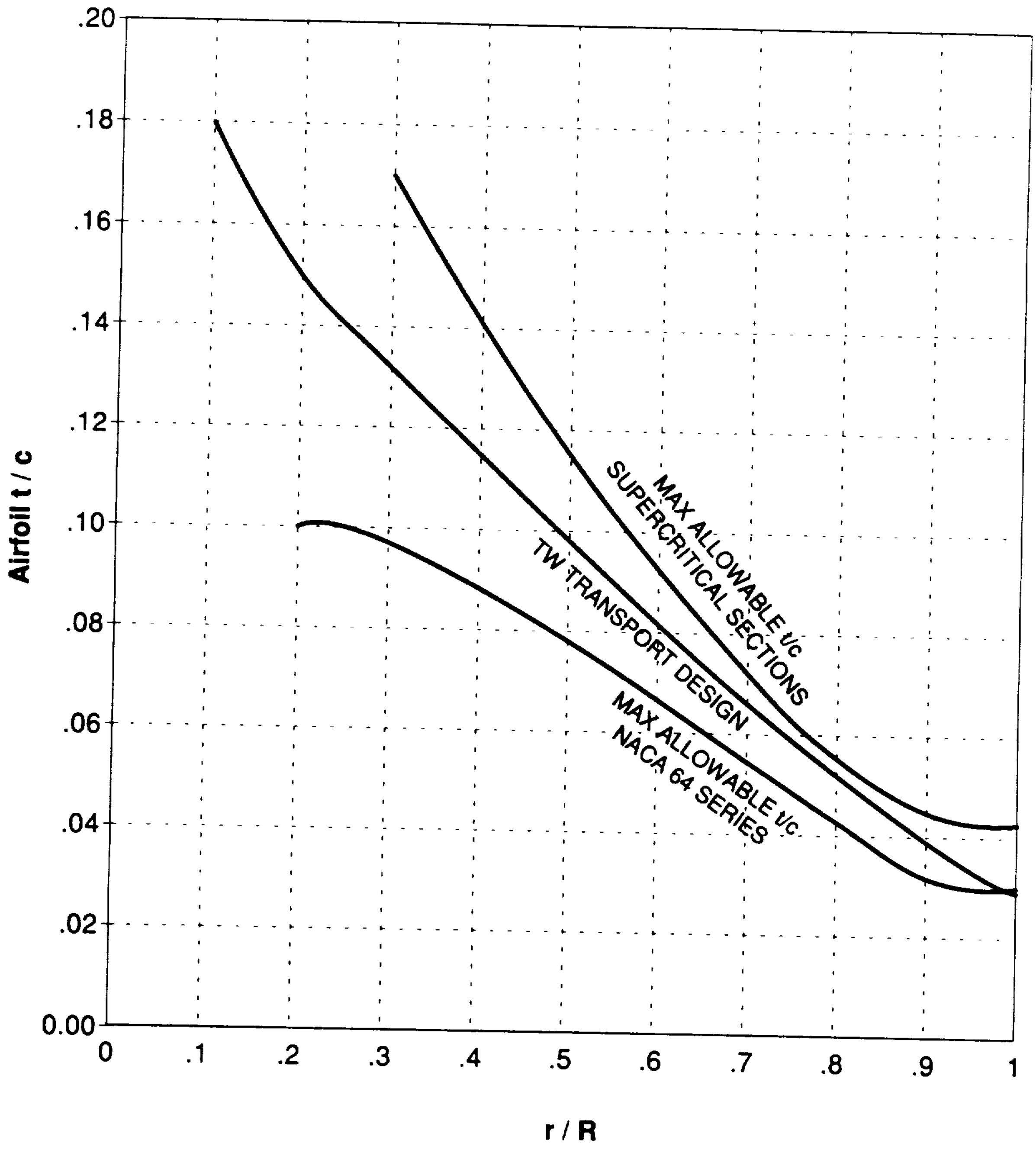


Figure B-20. Tilt wing transport blade thickness distribution with respect to maximum allowable for 64 series and supercritical profiles

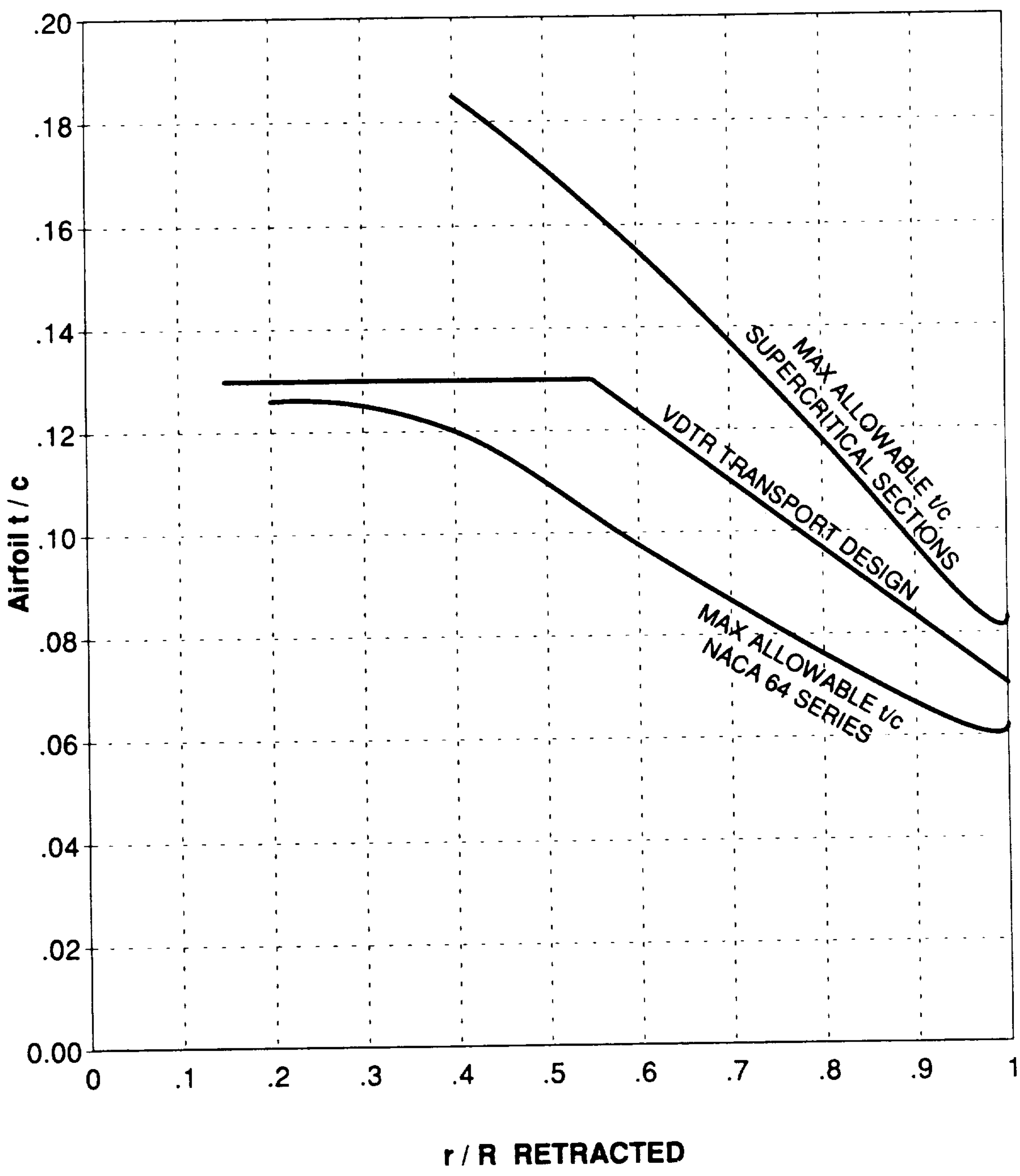


Figure B-21. VDTR transport blade thickness distribution with respect to maximum allowable for 64 series and supercritical profiles

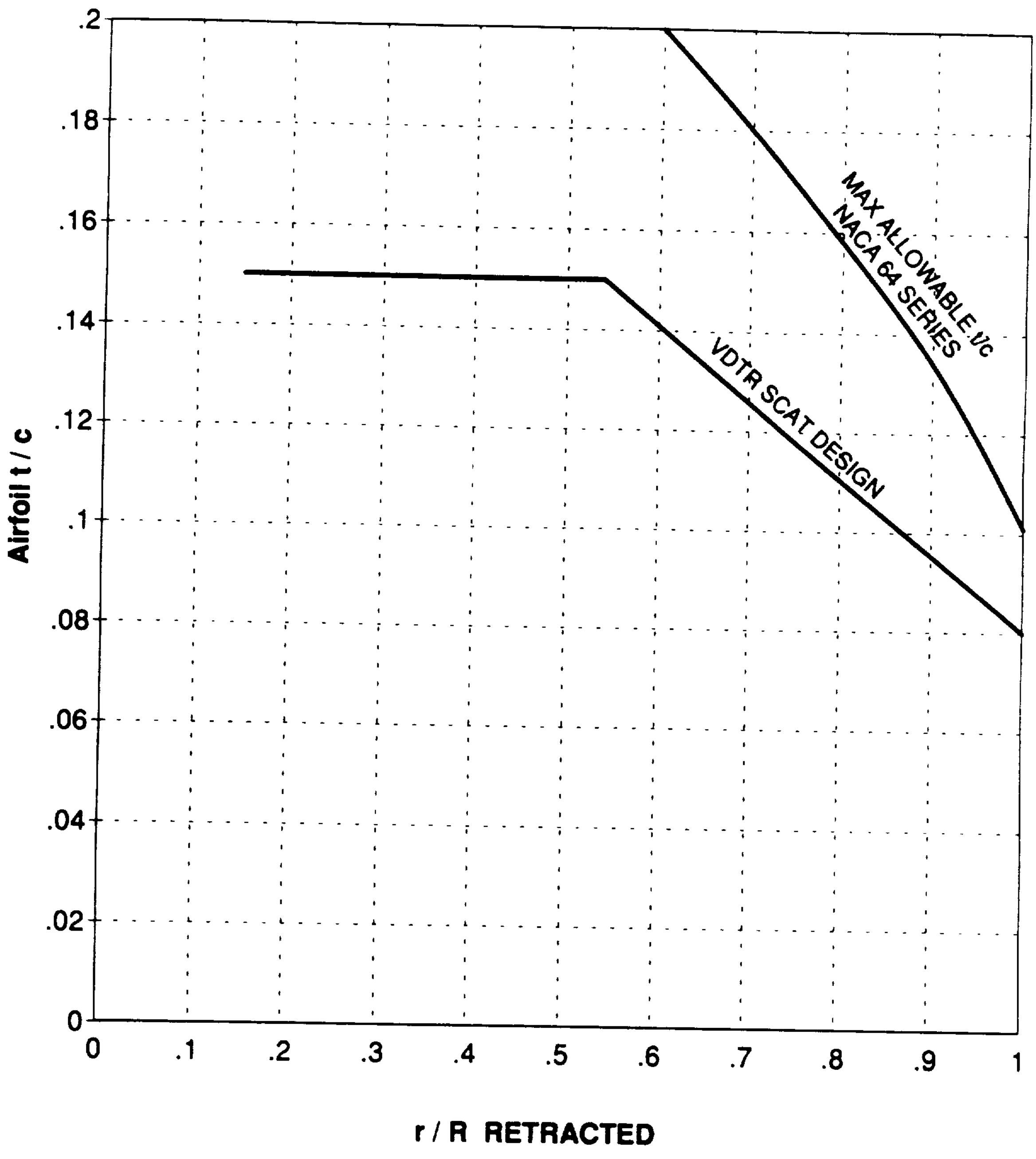


Figure B-22. VDTR SCAT blade thickness distribution with respect to maximum allowable for 64 series and supercritical profiles

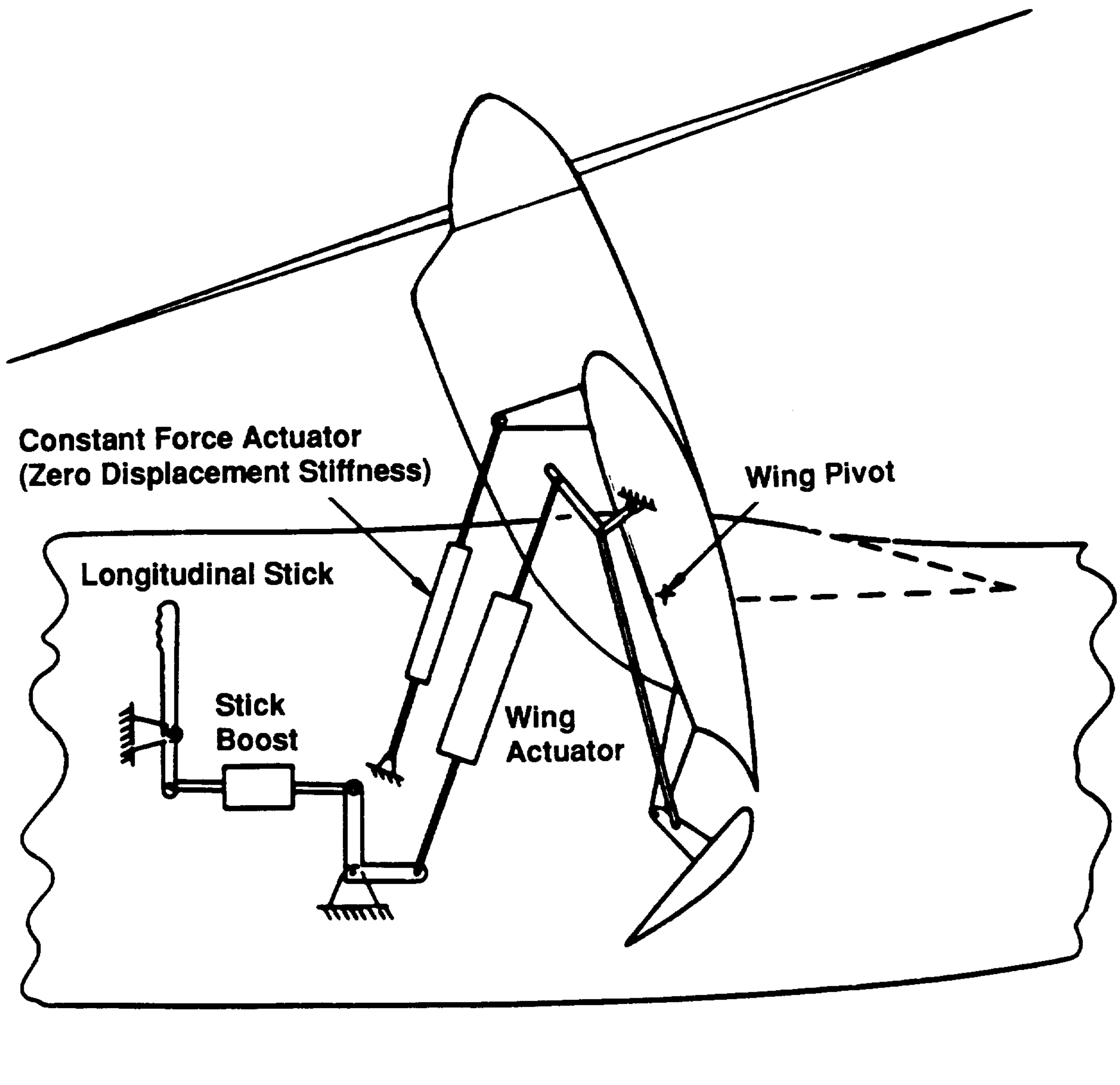


Figure B-23. Schematic of geared flap control system

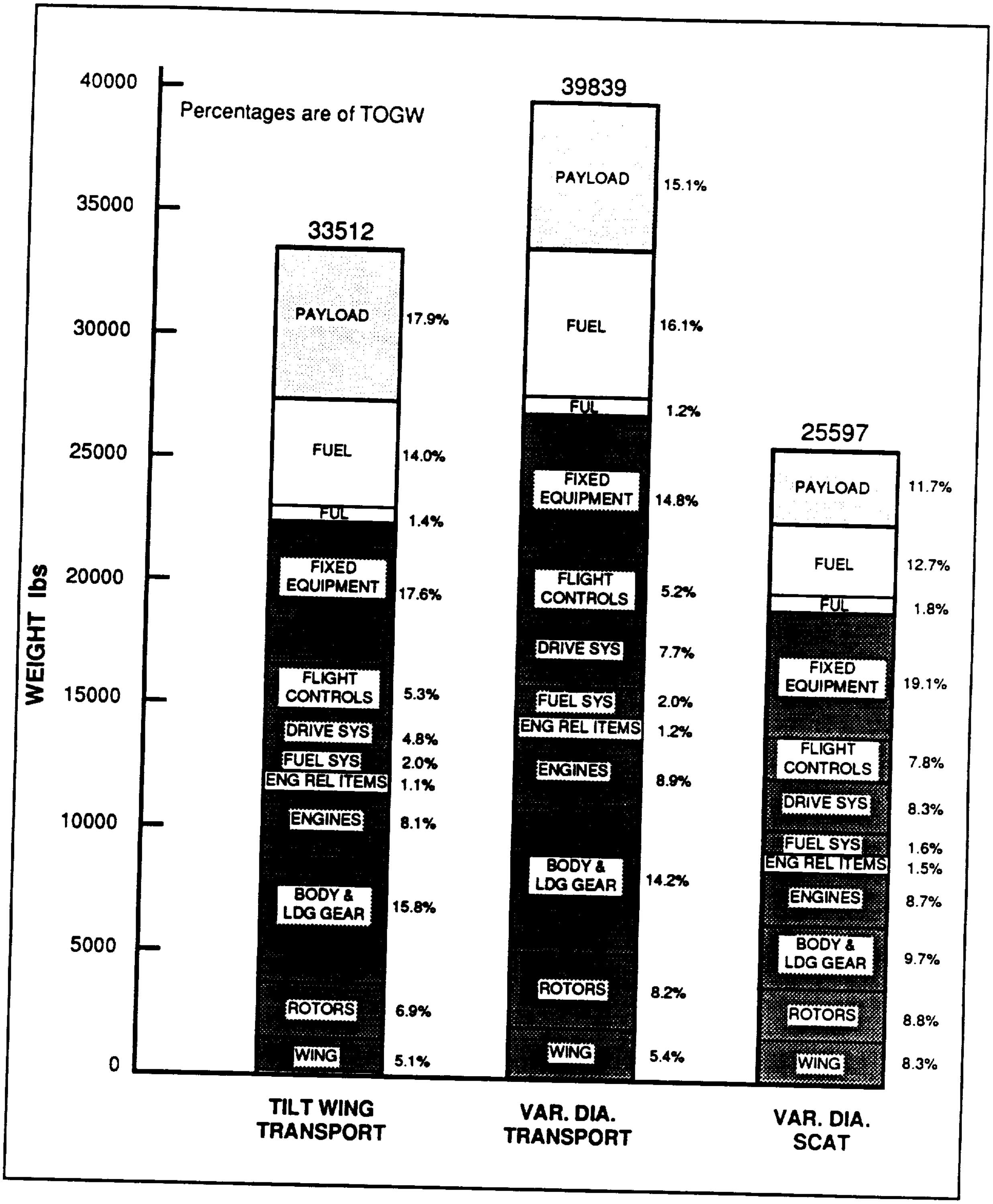


Figure B-24. Weight build up for tilt wing and VDTR transports and VDTR SCAT

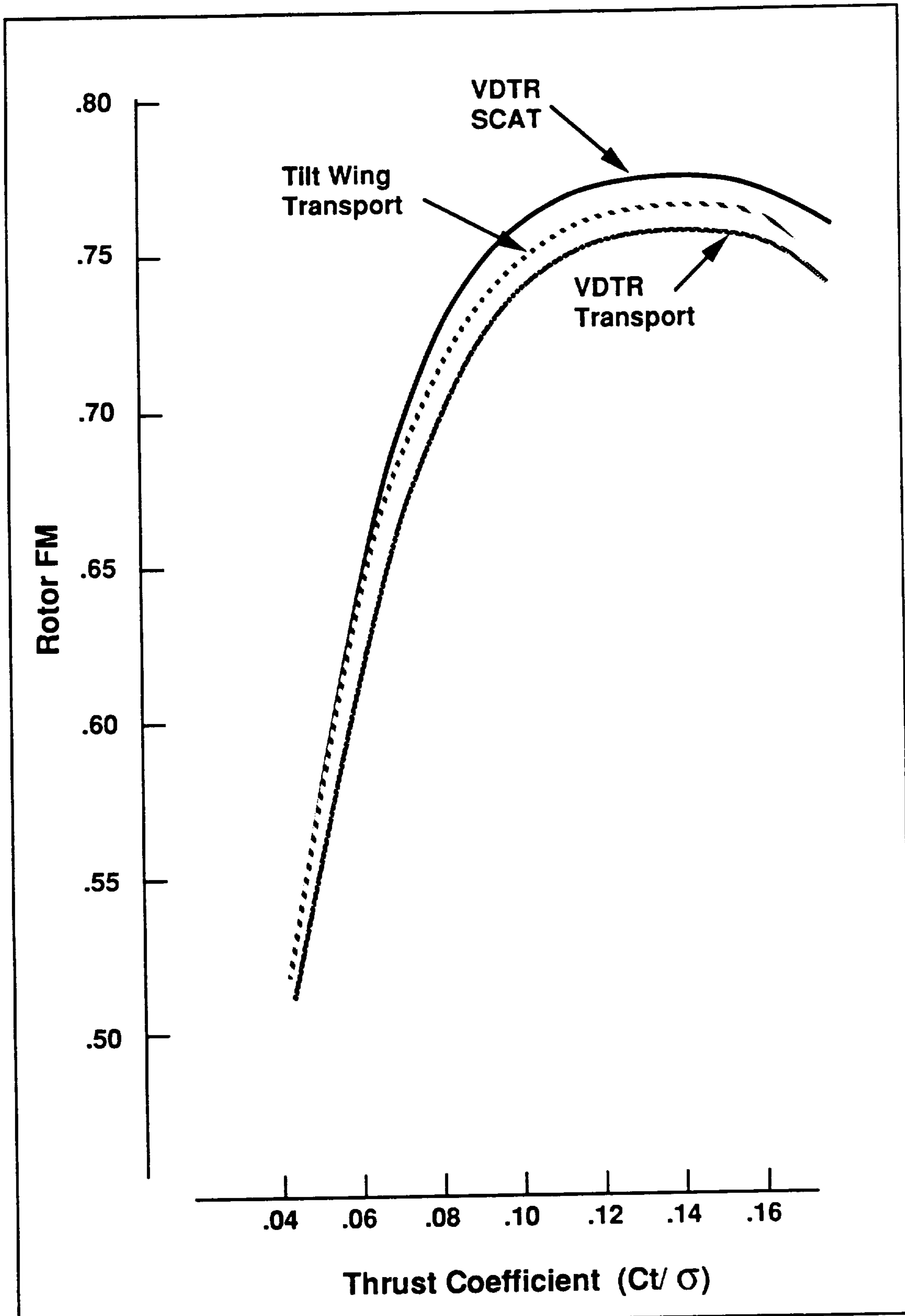


Figure B-25. Estimated proprotor hover performance

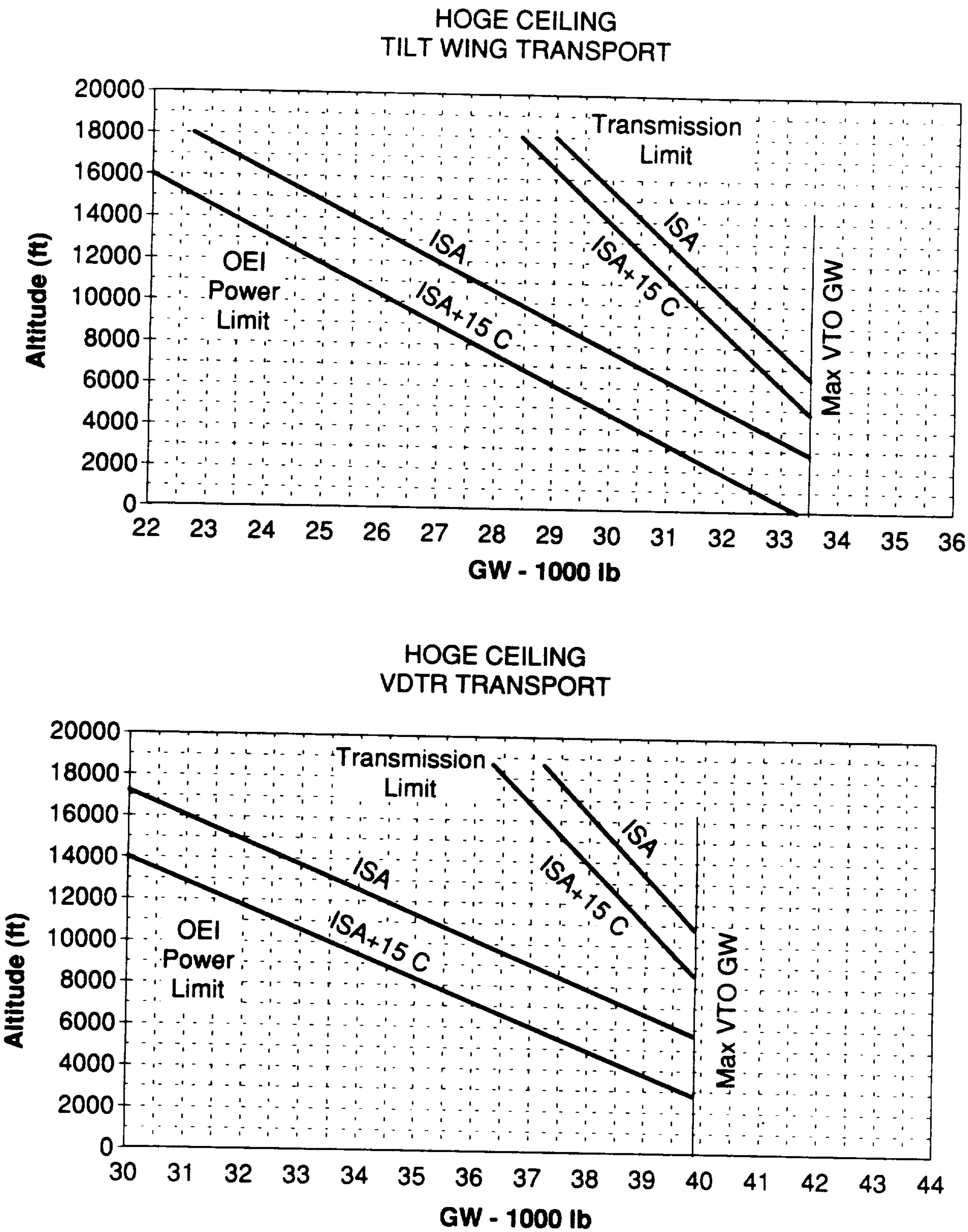


Figure B-26. Hover ceiling performance

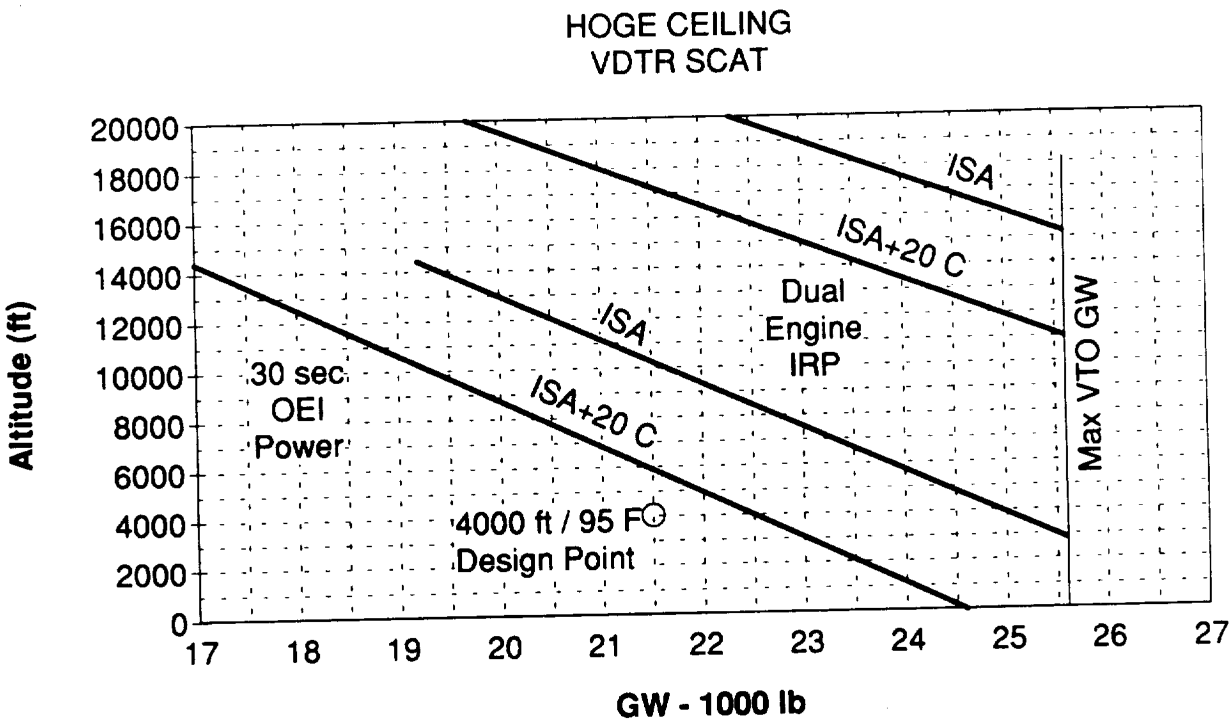


Figure B-26. Hover ceiling performance (continued)

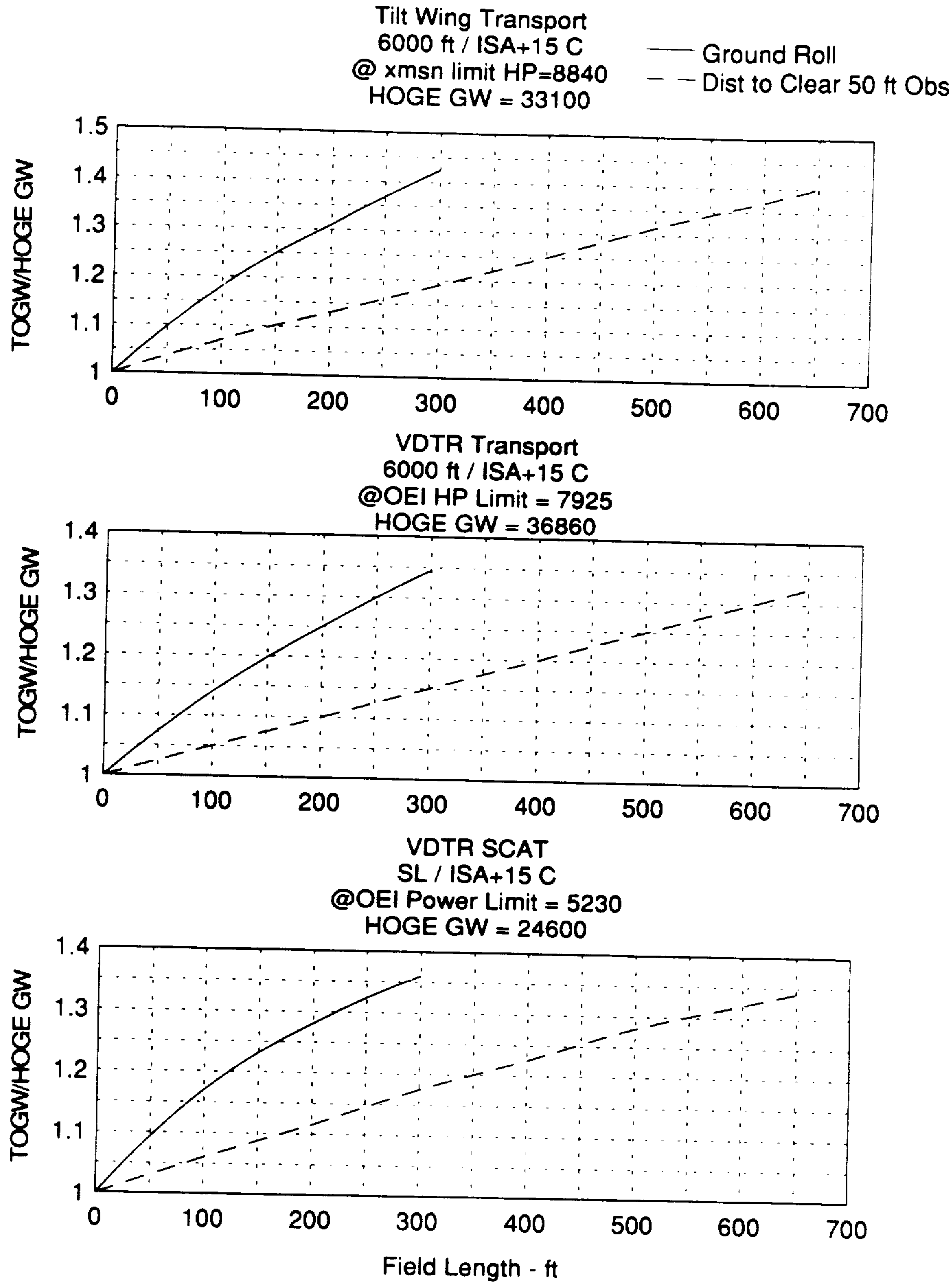
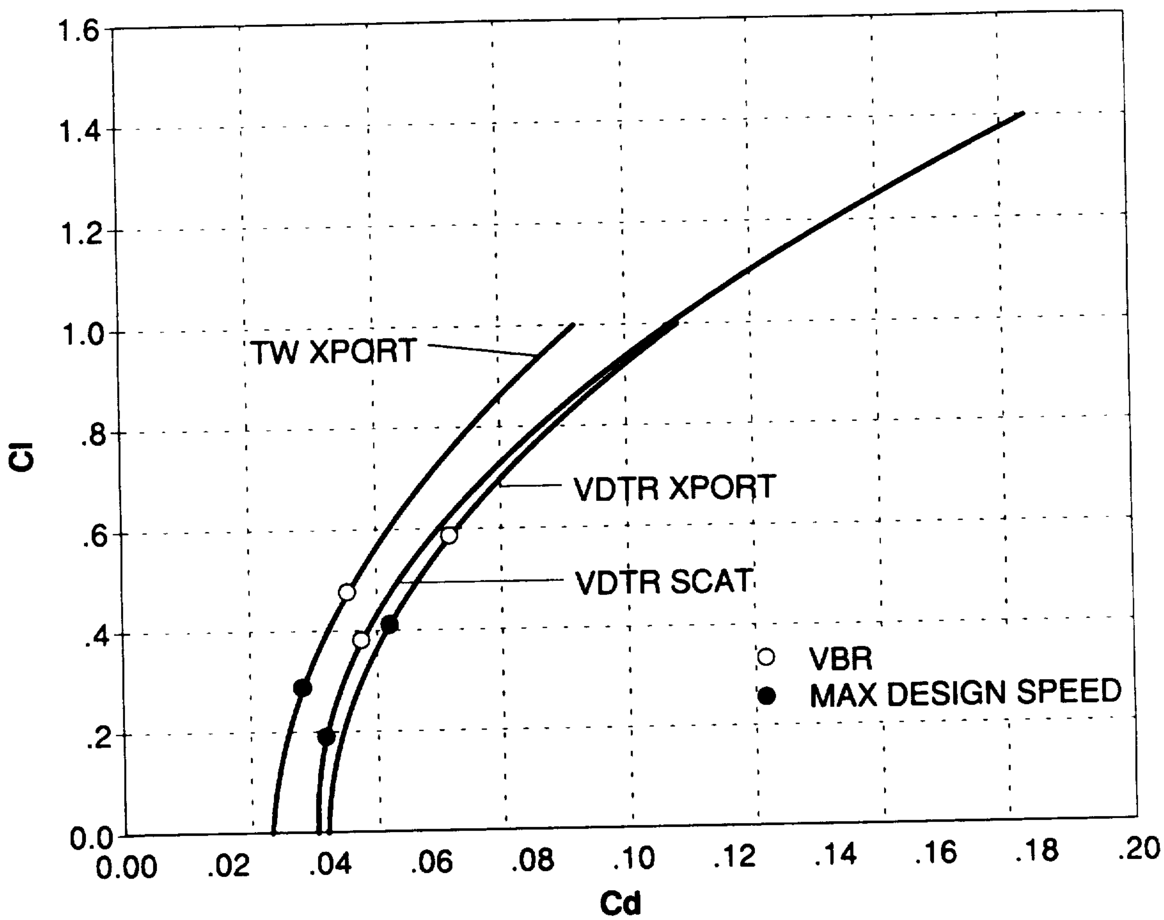


Figure B-27. STOL performance



Cd BASED ON WING AREA

	Sw sqft	Max Design Speed - kt
TILT WING XPORT	477	450
VDTR XPORT	335	450
VDTR SCAT	298	400

Figure B-28. Aircraft Cl vs Cd polar

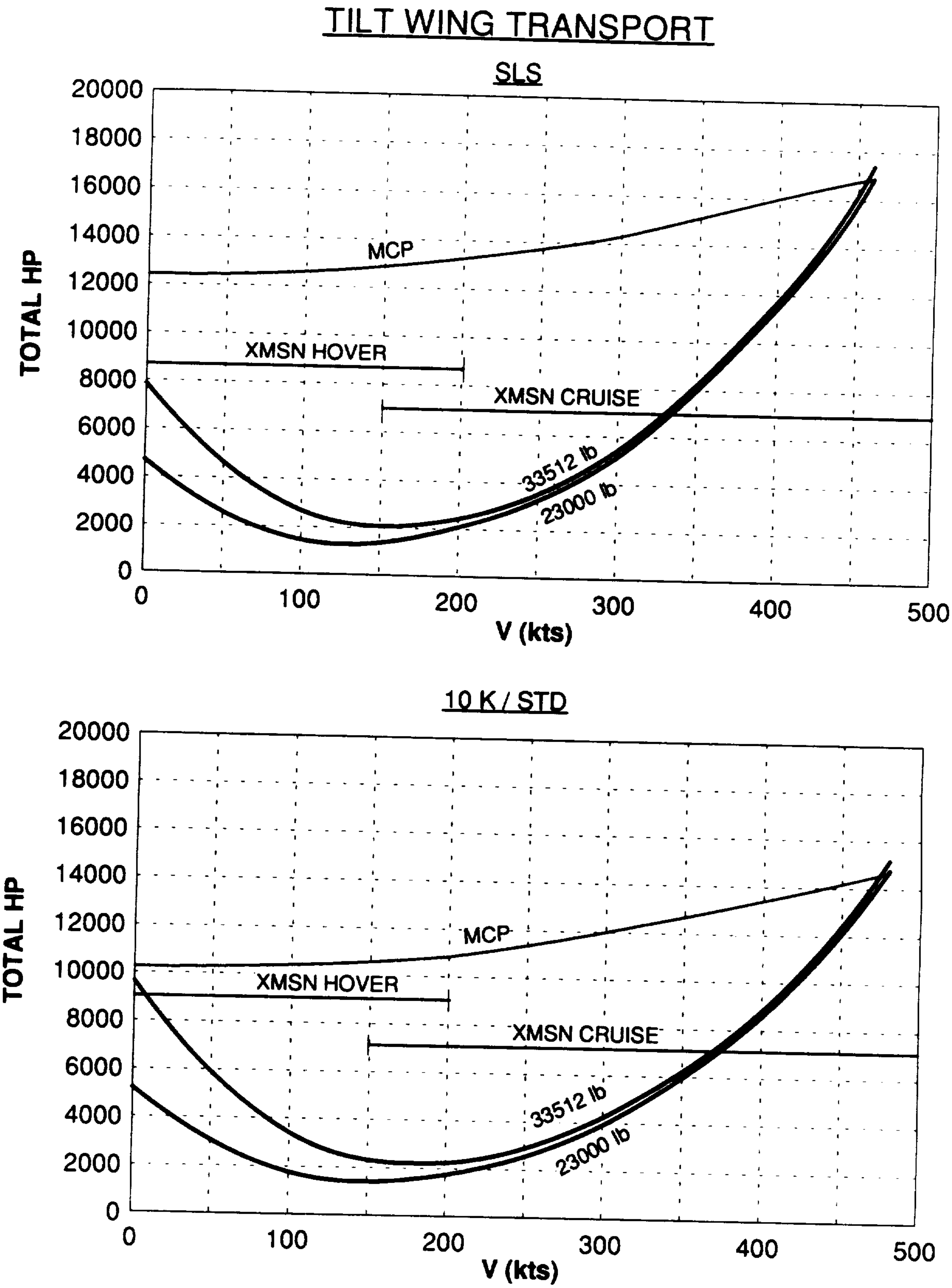
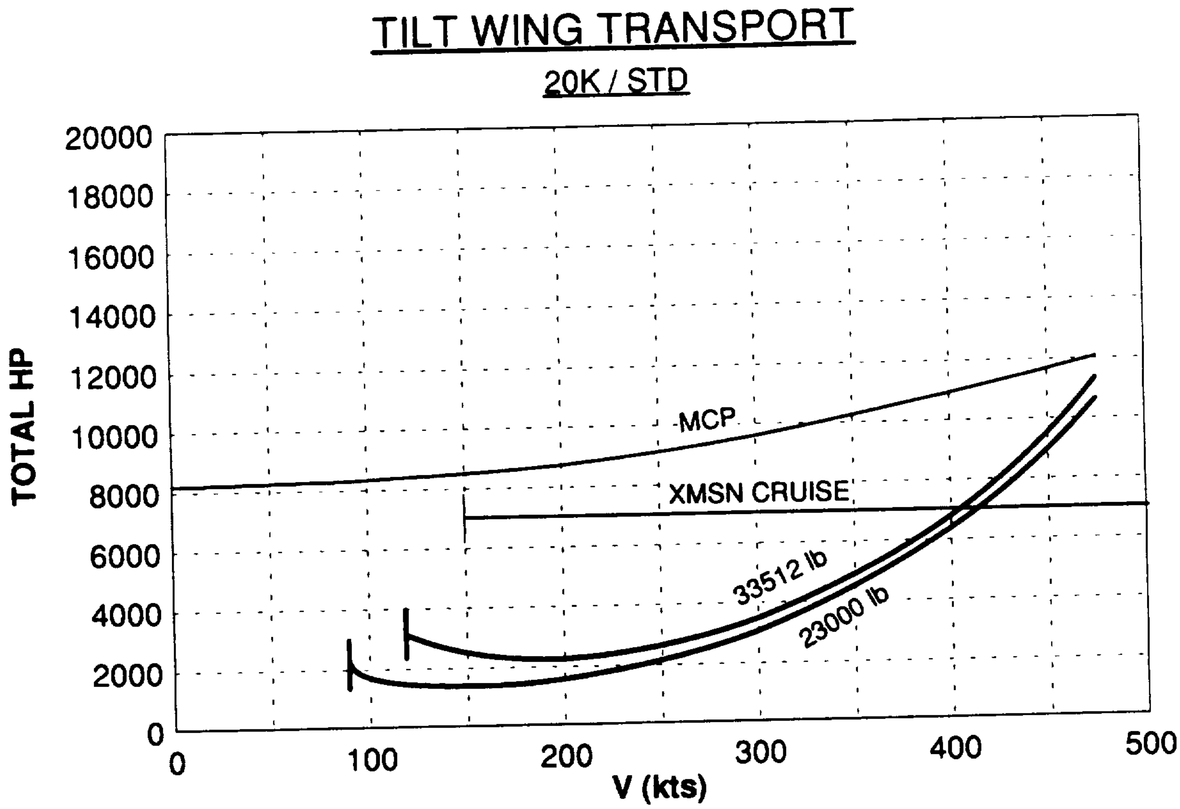


Figure B-29. TW transport power required vs airspeed



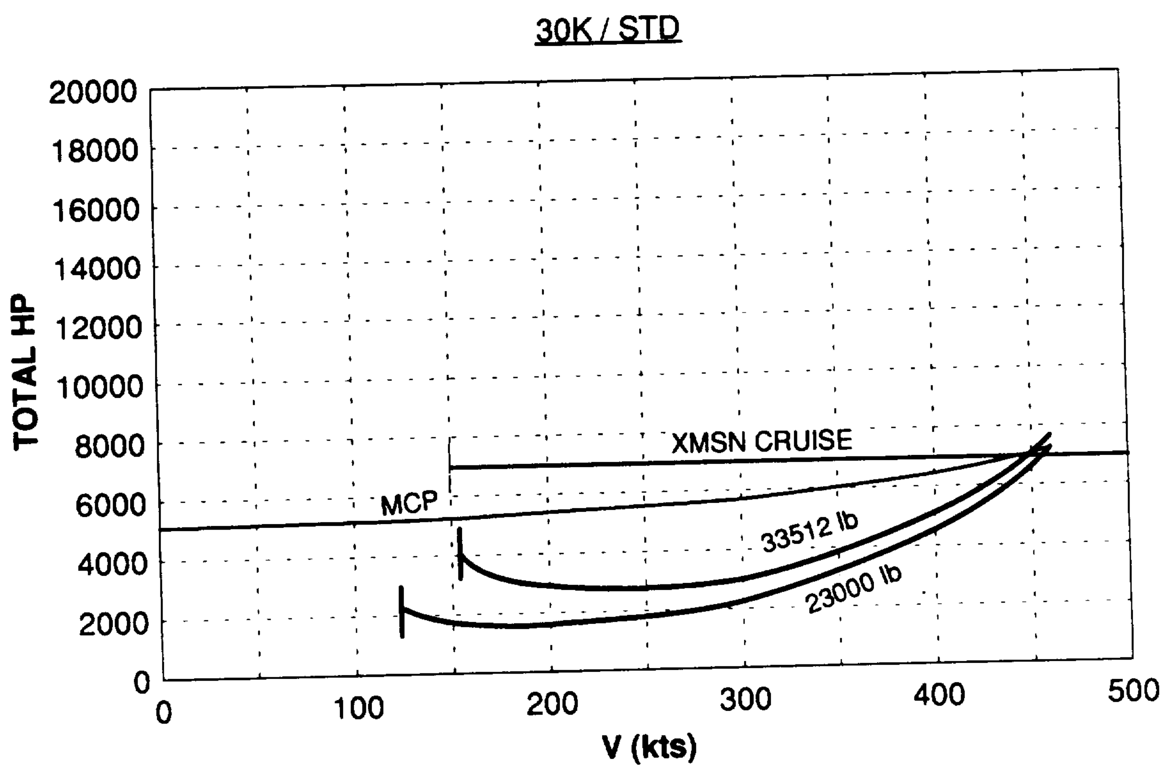


Figure B-29. TW transport power required vs airspeed (continued)

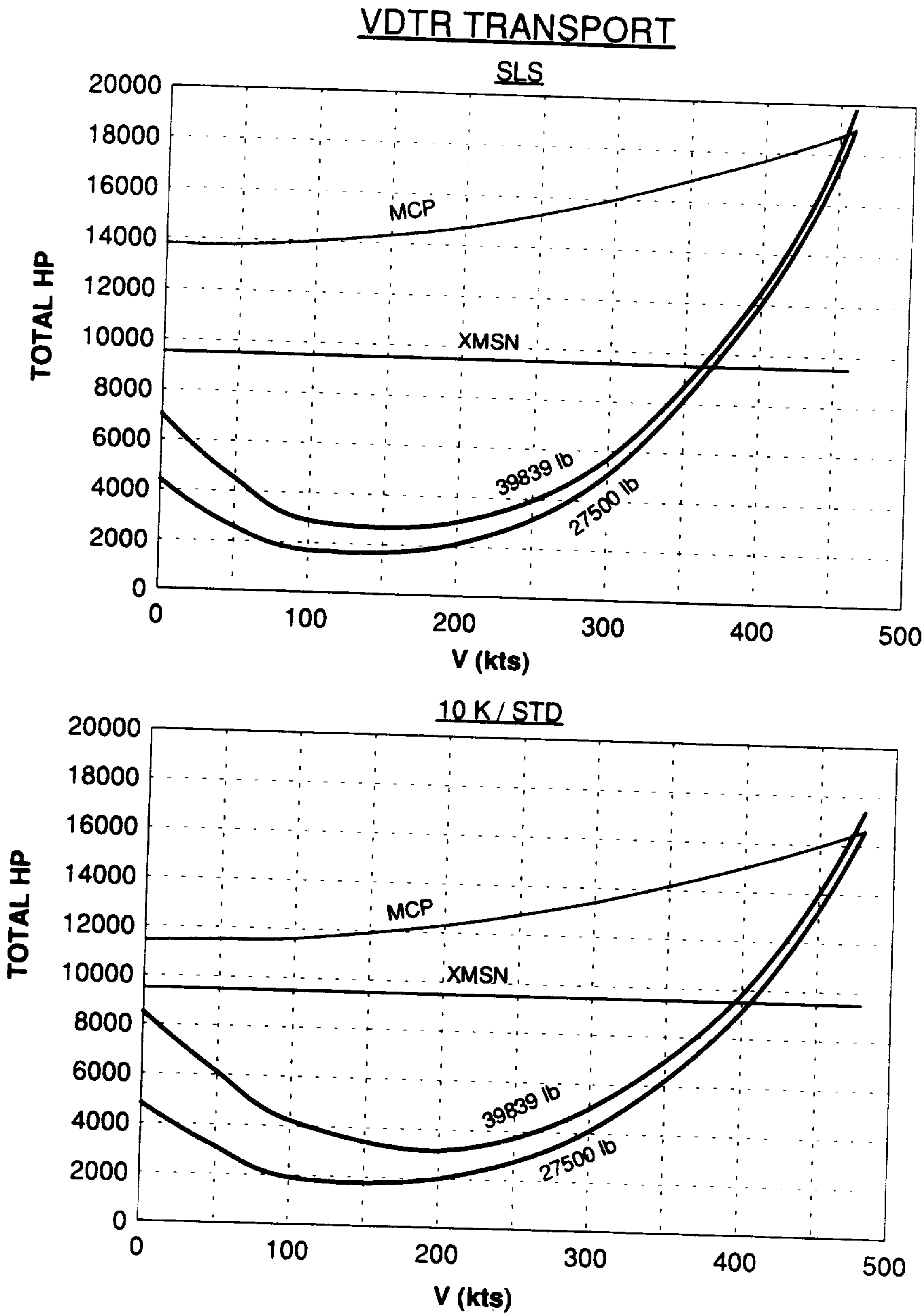


Figure B-30. VDTR transport power required vs airspeed

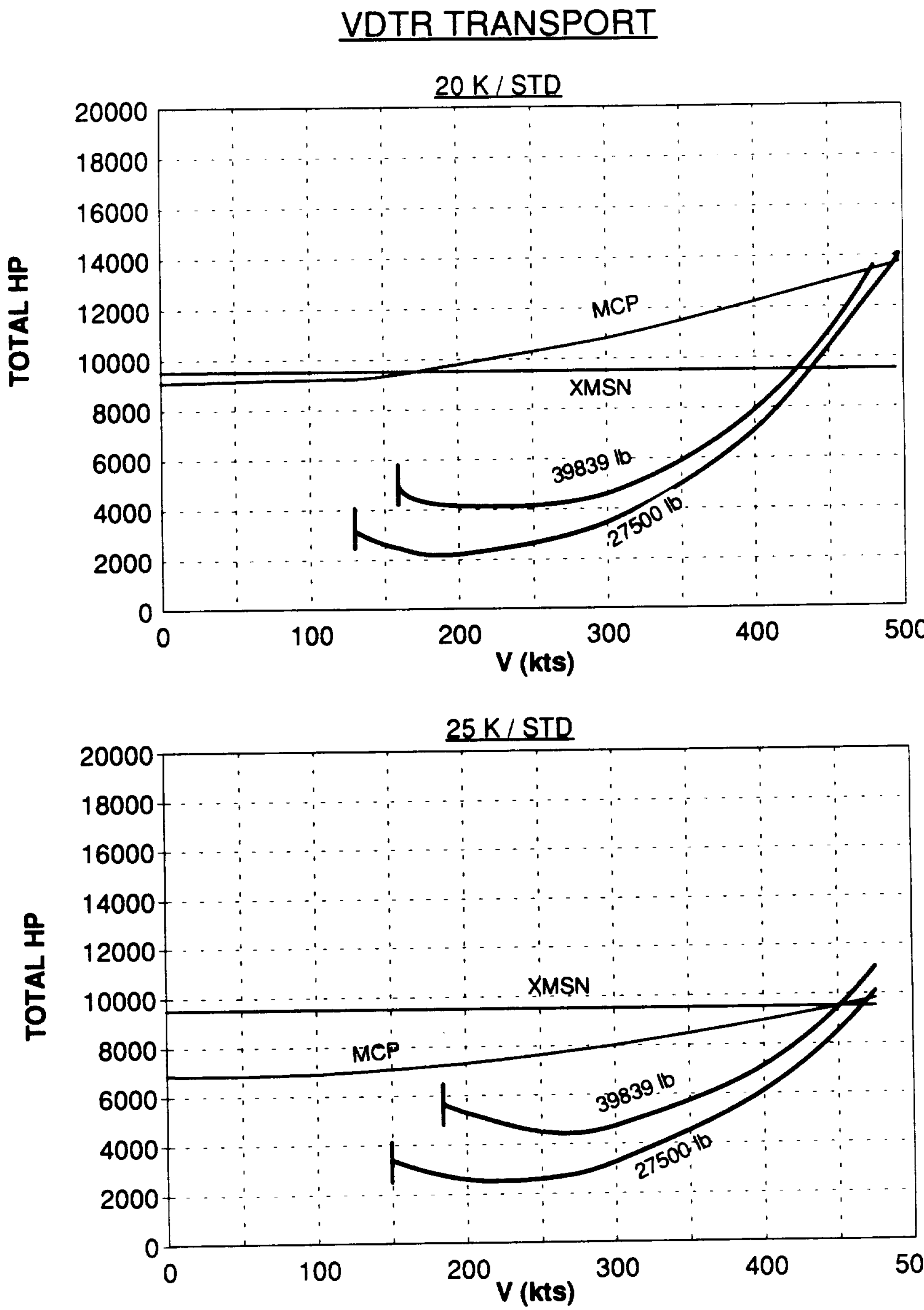


Figure B-30. VDTR transport power required vs airspeed (continued)

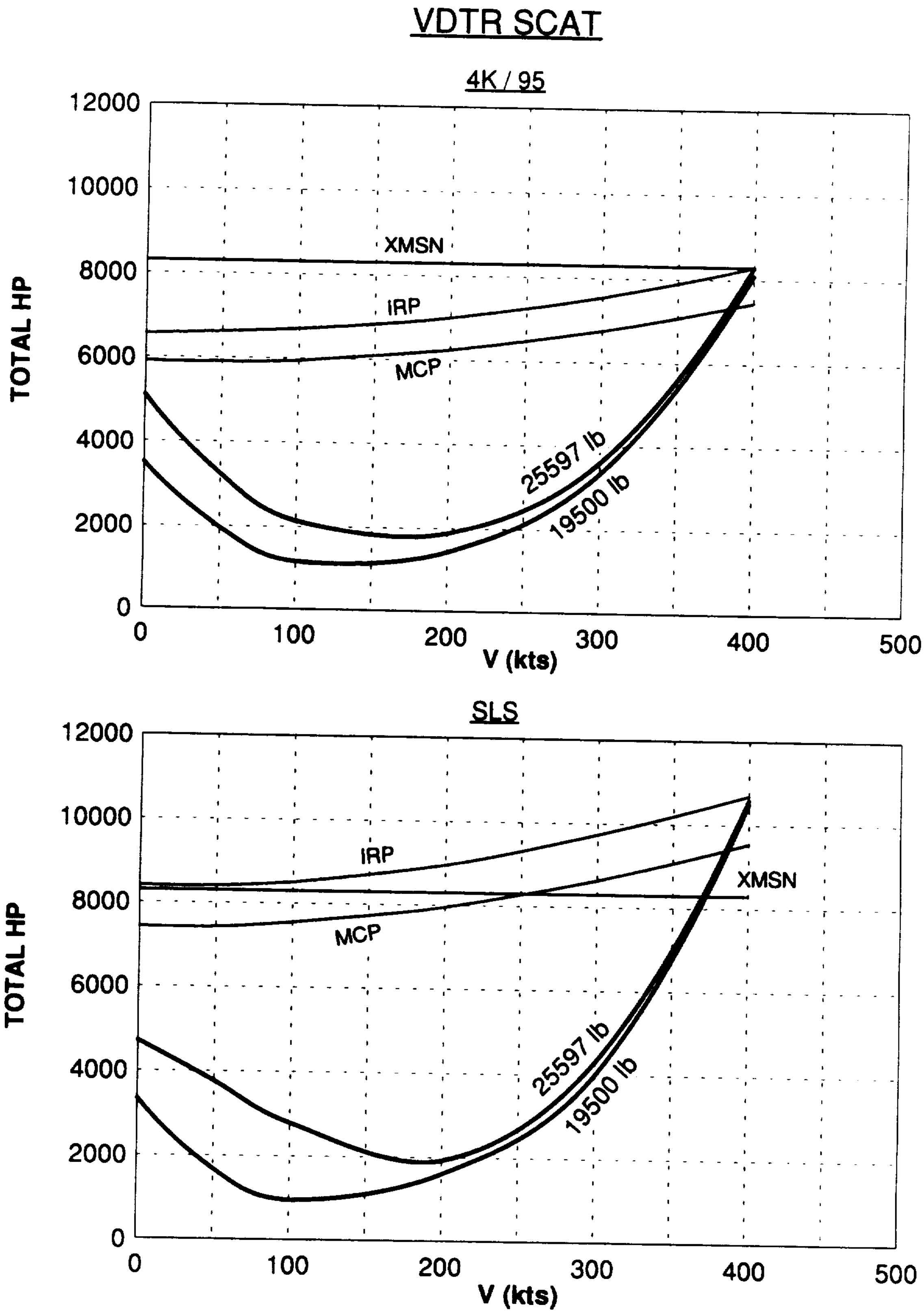


Figure B-31. VDTR SCAT power required vs airspeed

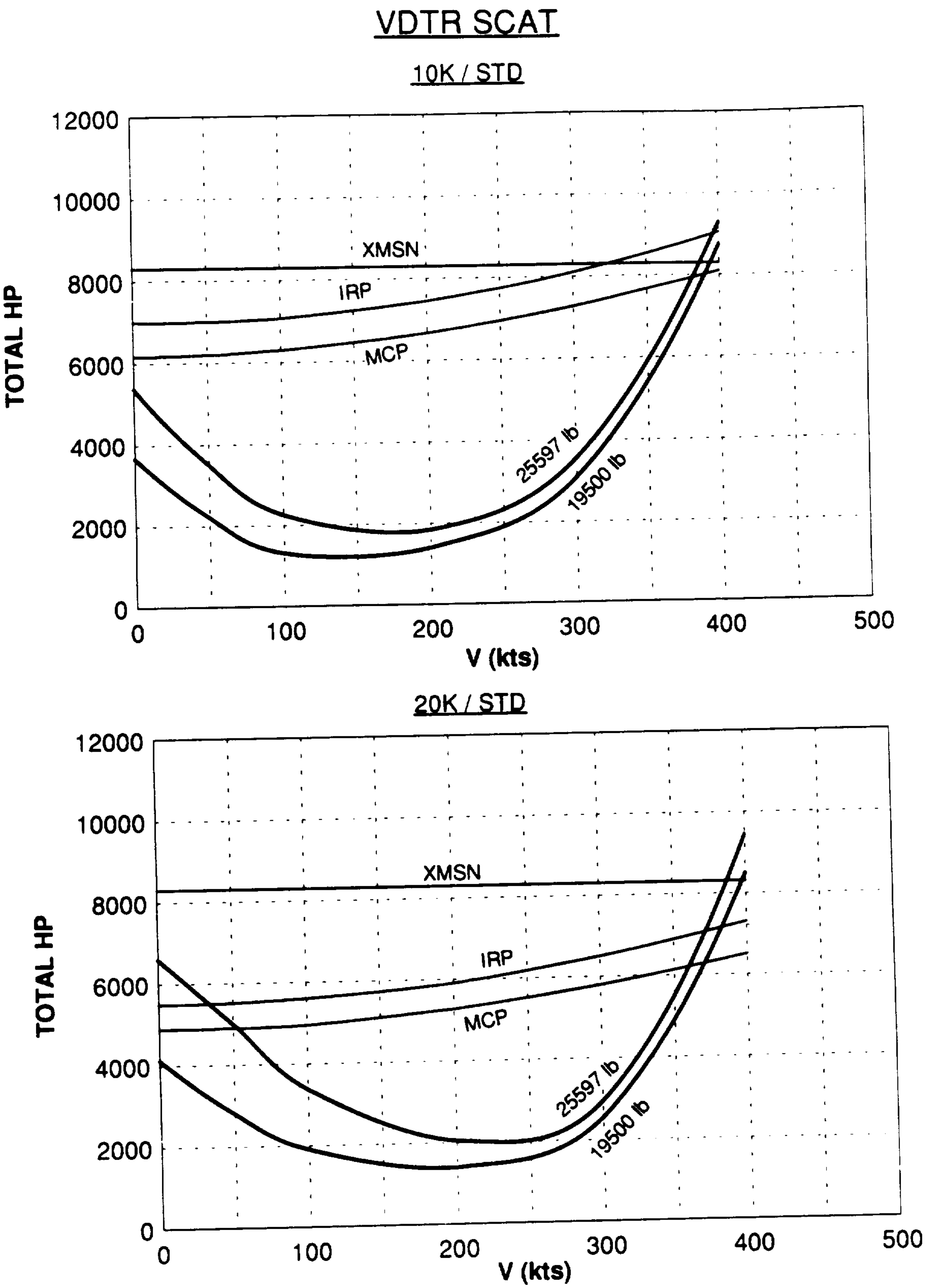
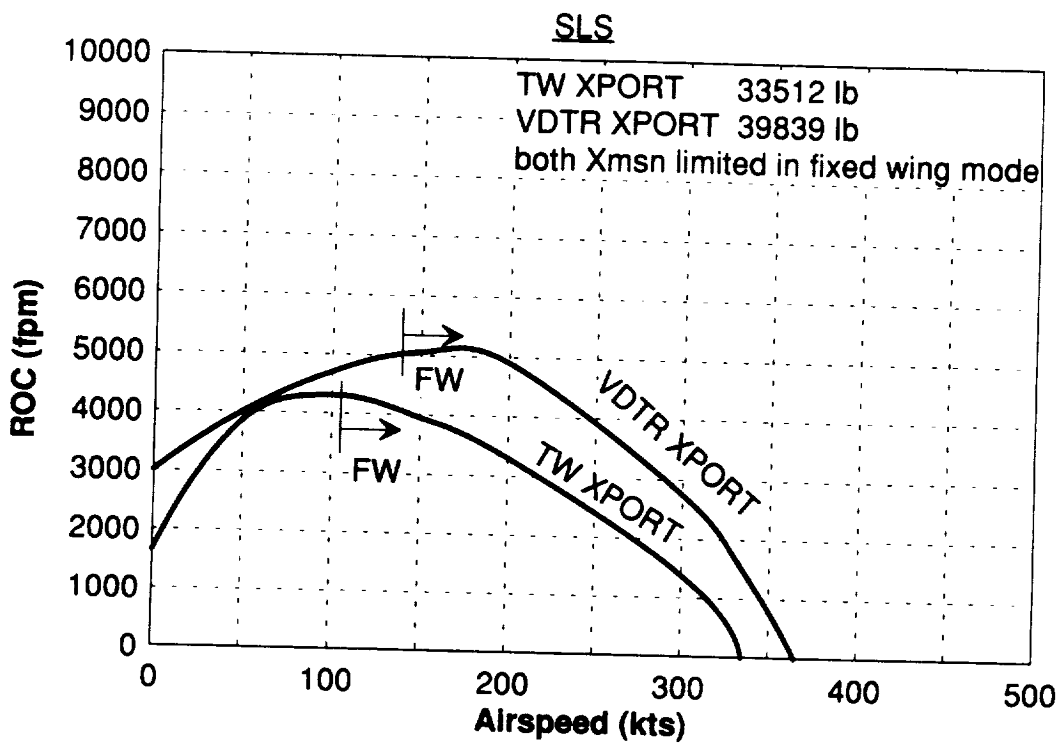


Figure B-31. VDTR SCAT power required vs airspeed (continued)

MILITARY TRANSPORTS



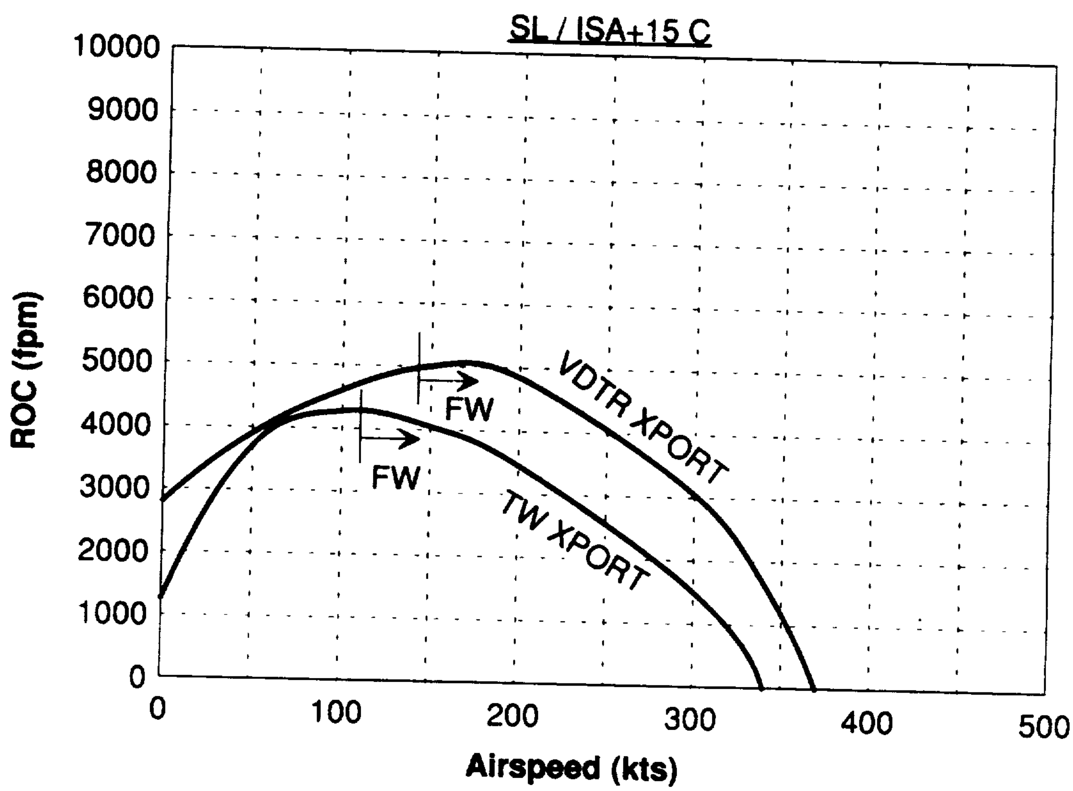


Figure B-32. Rate of climb vs airspeed

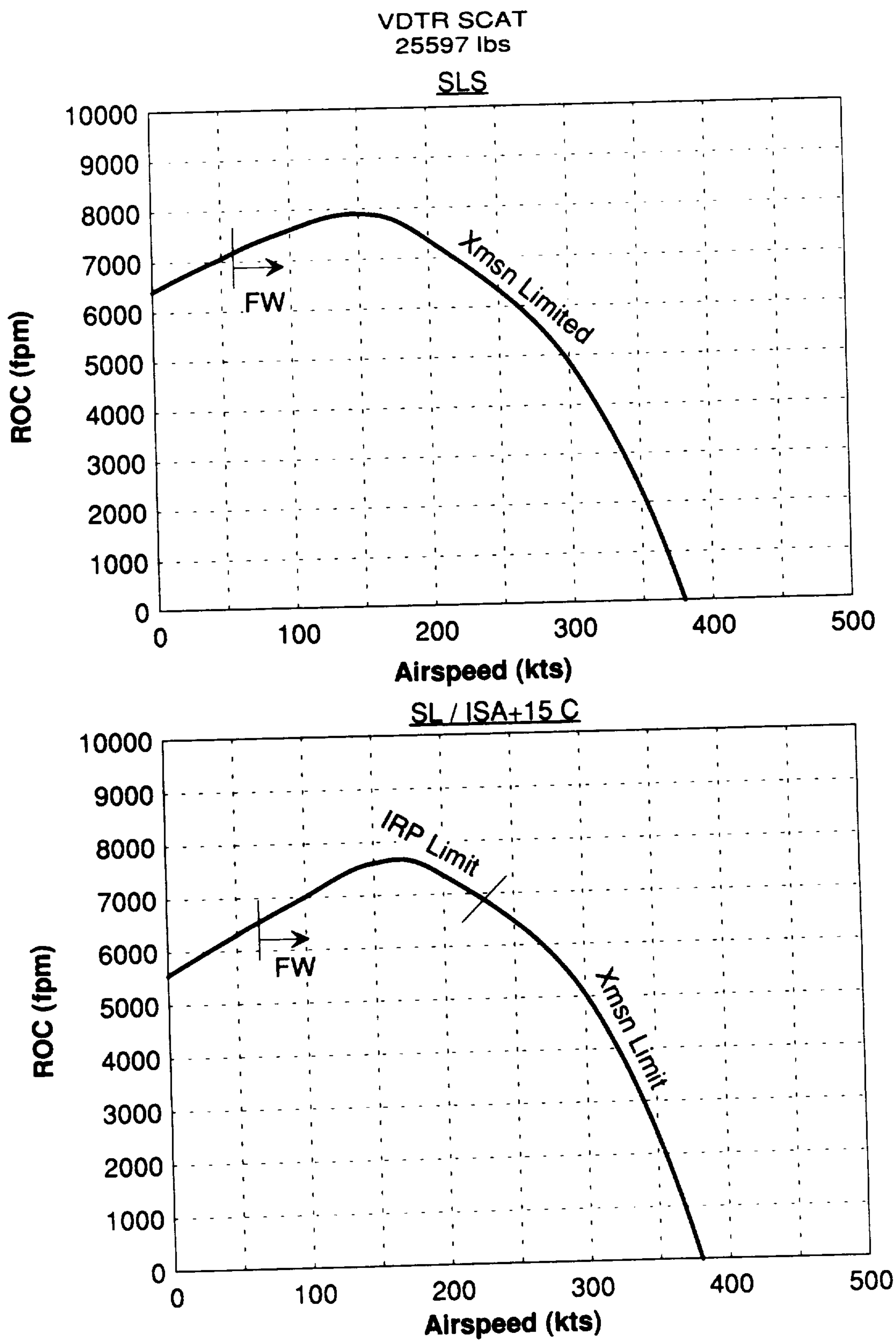


Figure B-32. Rate of climb vs airspeed (continued)

TILT WING TRANSPORT

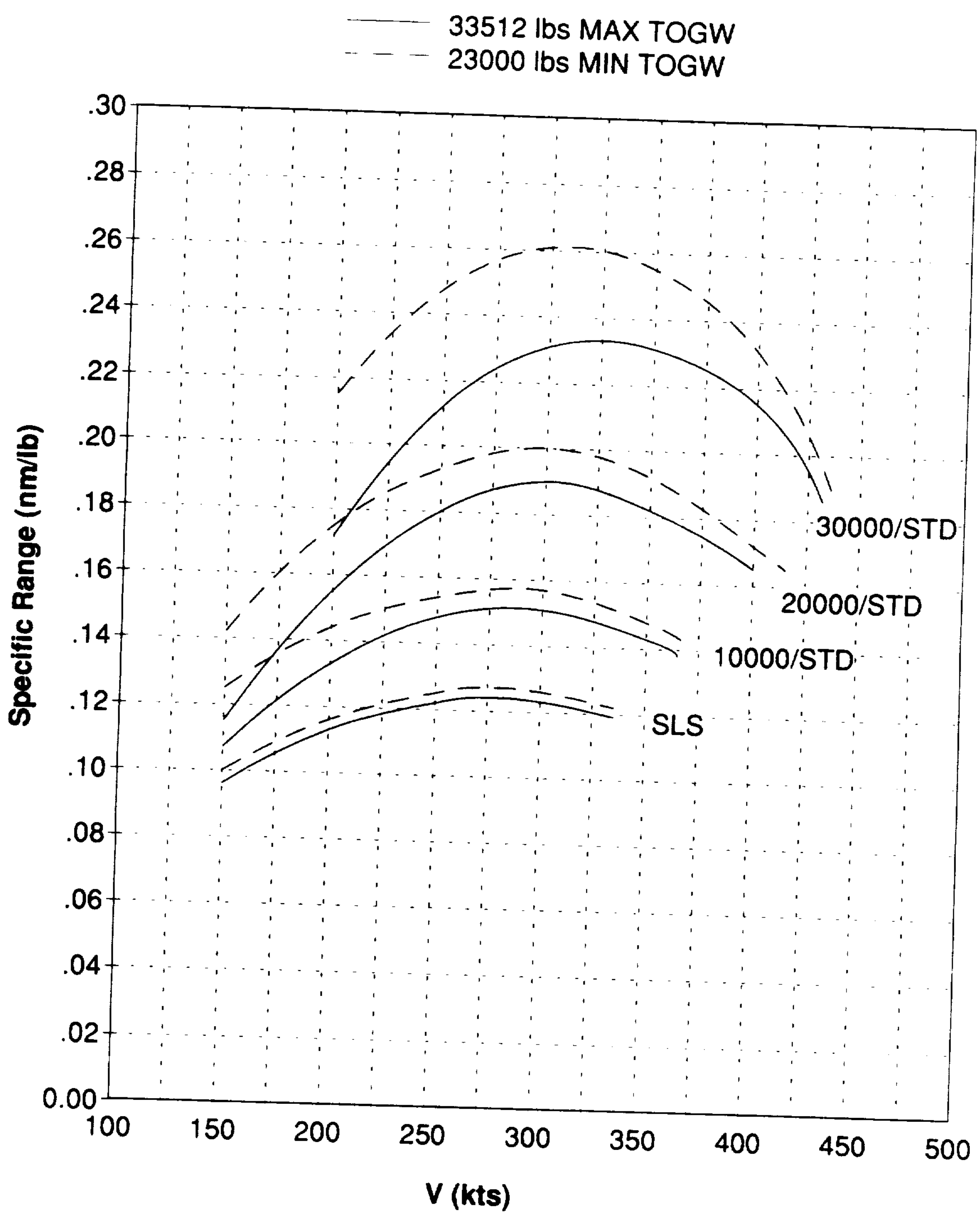


Figure B-33. Specific range vs airspeed

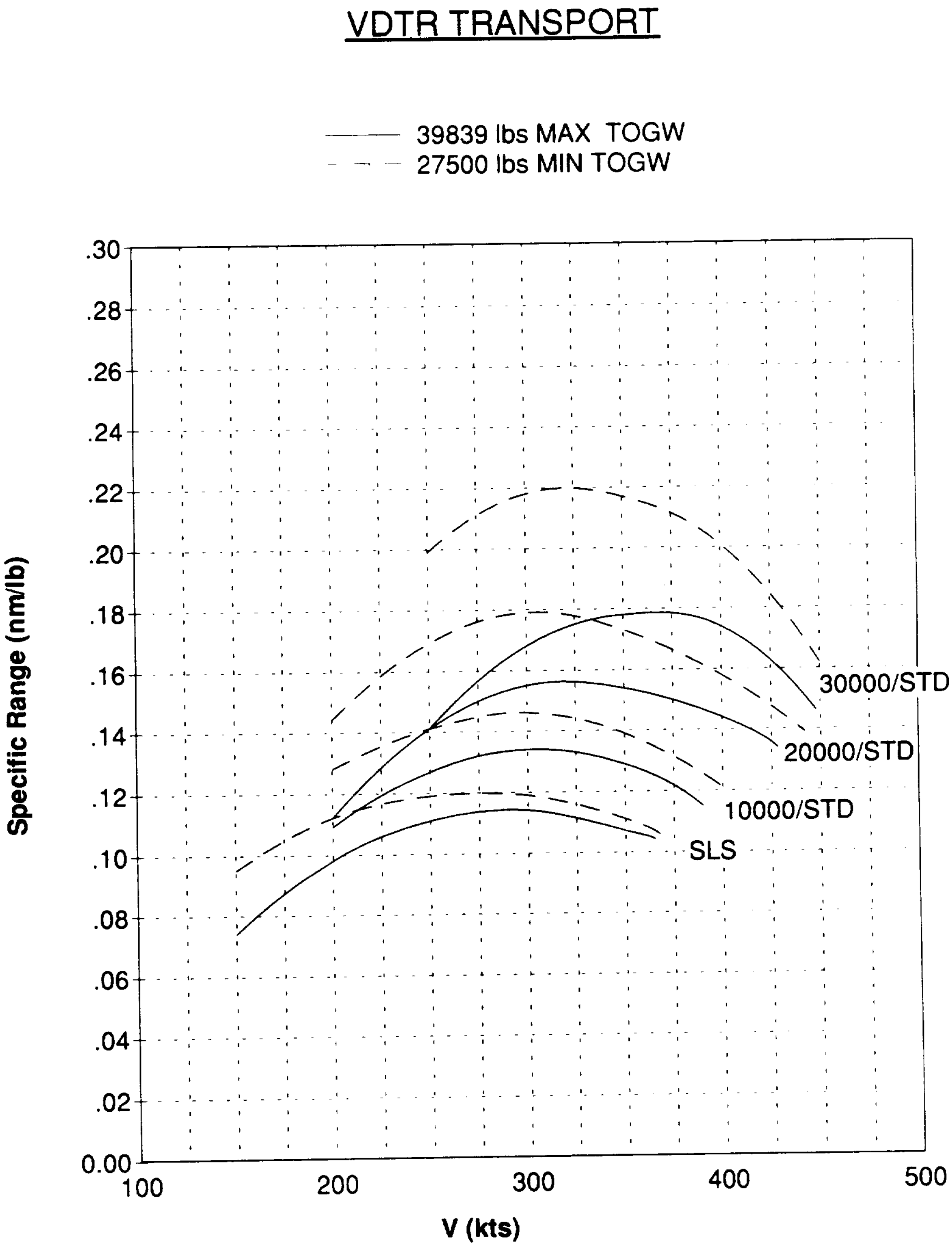


Figure B-33. Specific range vs airspeed (continued)

VDTR SCAT

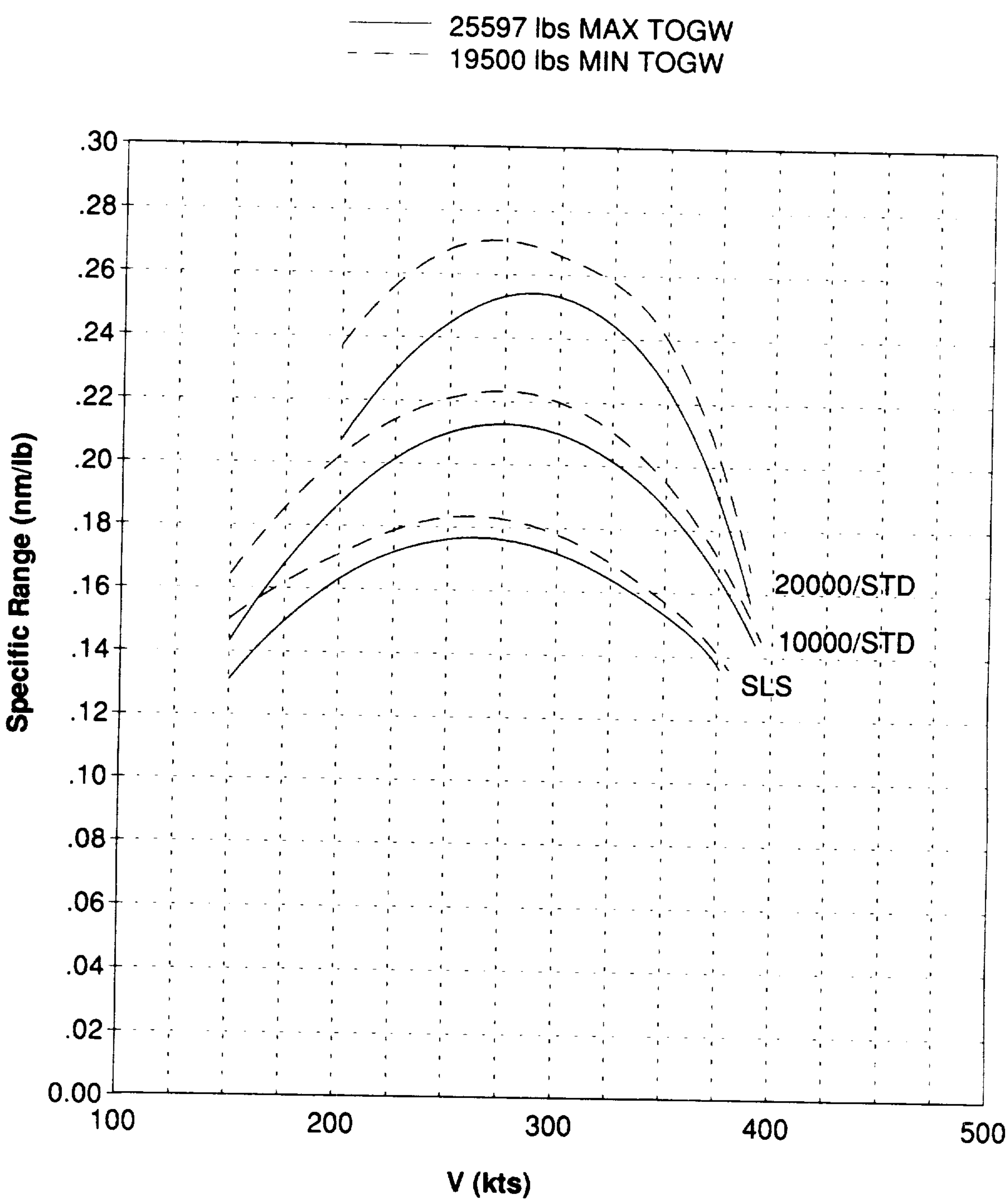


Figure B-33. Specific range vs airspeed (continued)

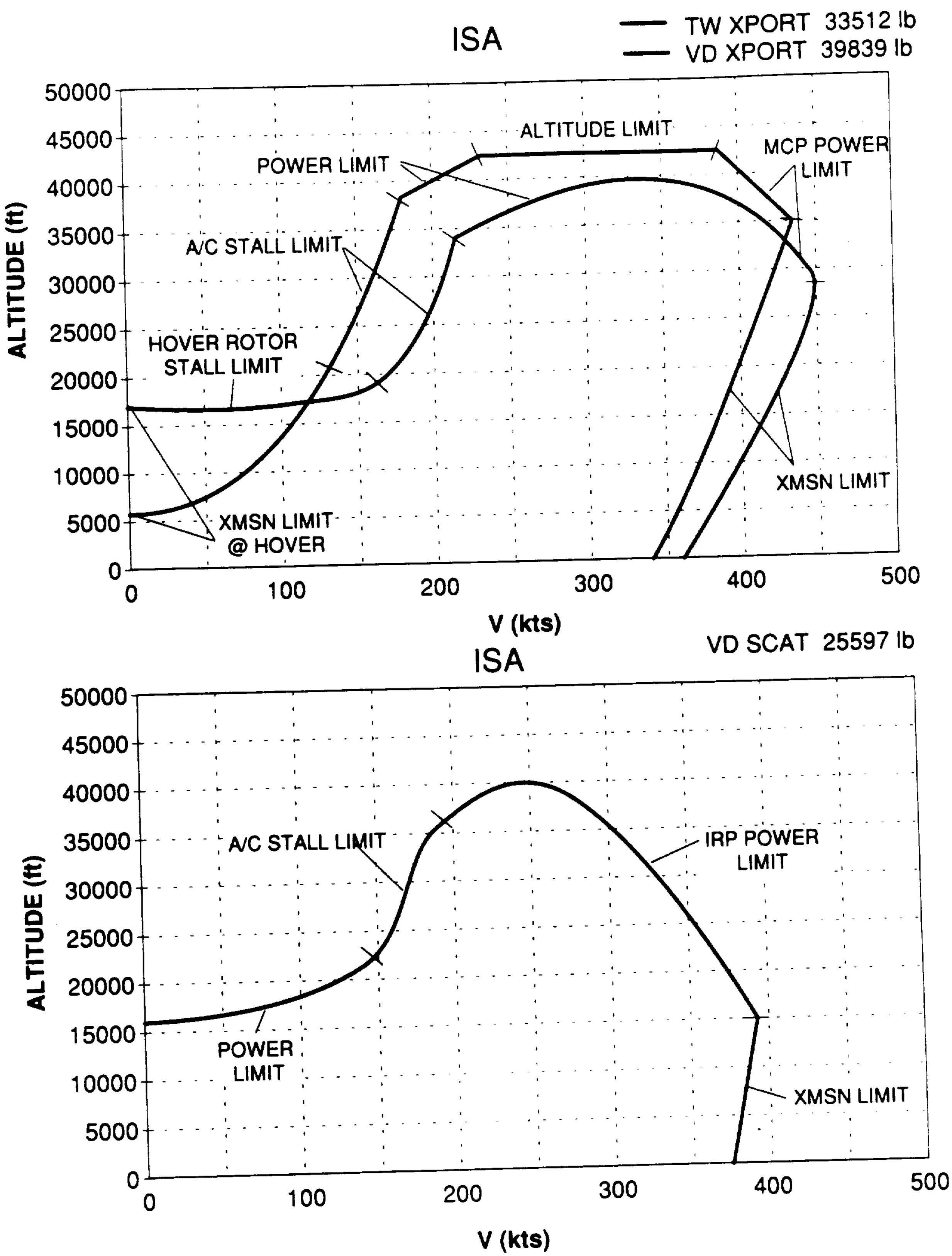


Figure B-34. Airspeed vs altitude

HOGE T/O
CRUISE Vbr,
30 MINUTE RESERVE

	TOGW	Cruise Conditions
Tilt Wing Transport	33512	30000 ft ISA+15 C
VDTR Transport	39839	25000 ft ISA+15 C
VDTR SCAT	25597	4000 ft, 95 F

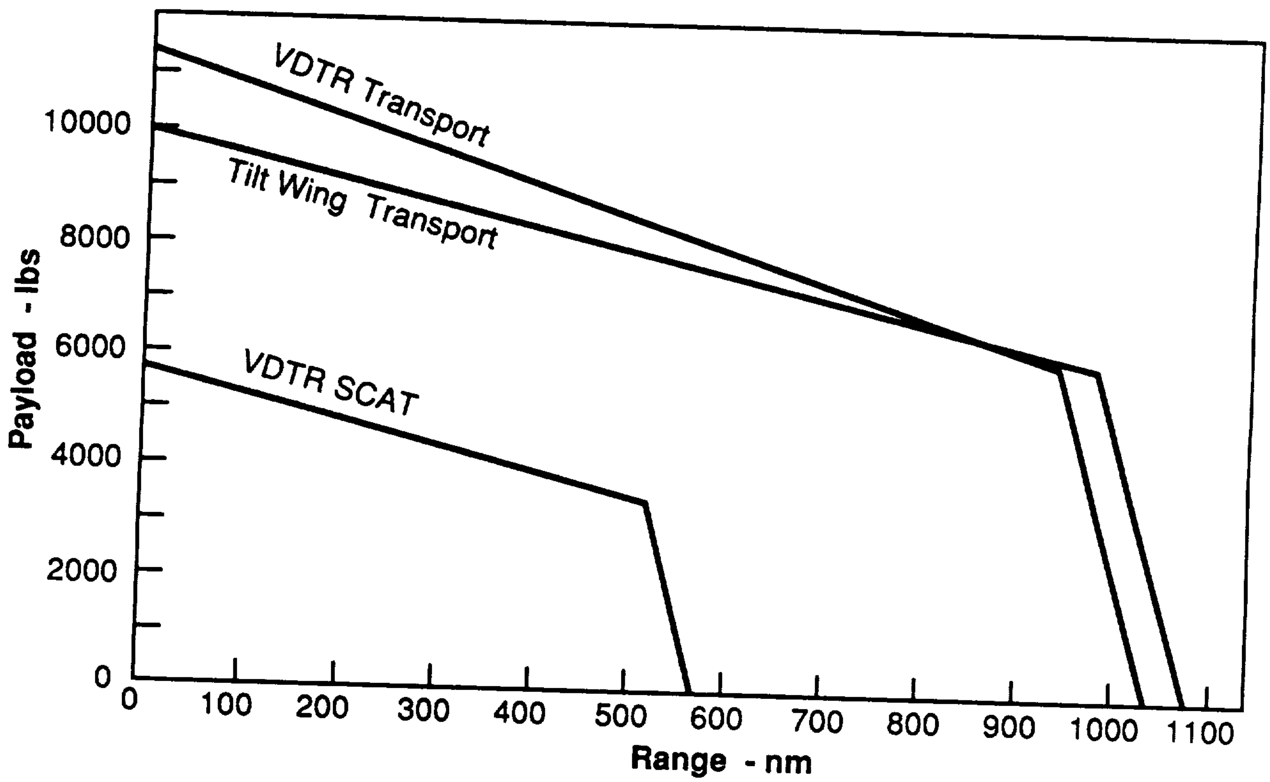


Figure B-35. Payload-range performance

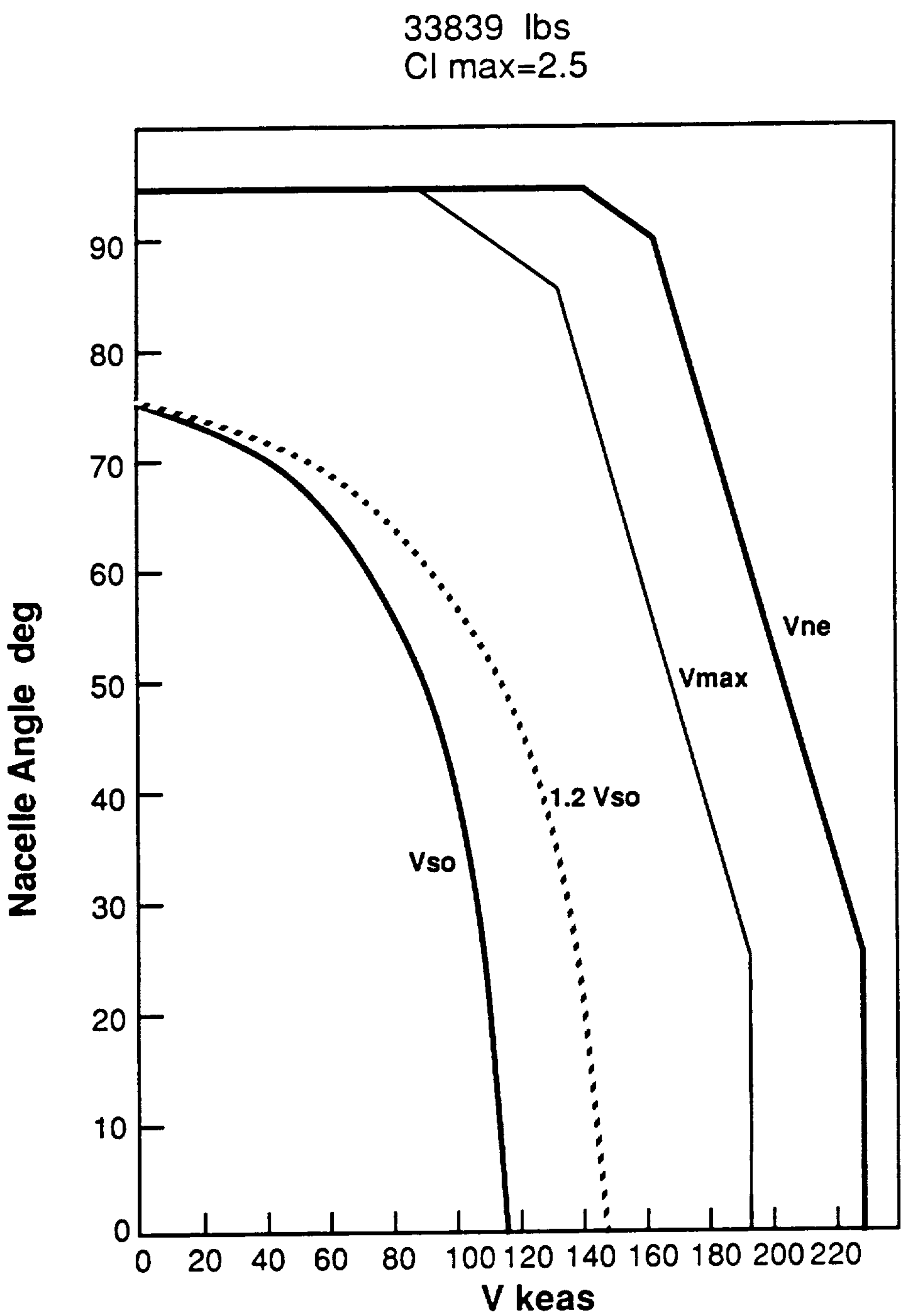


Figure B-36. VDTR transport conversion corridor

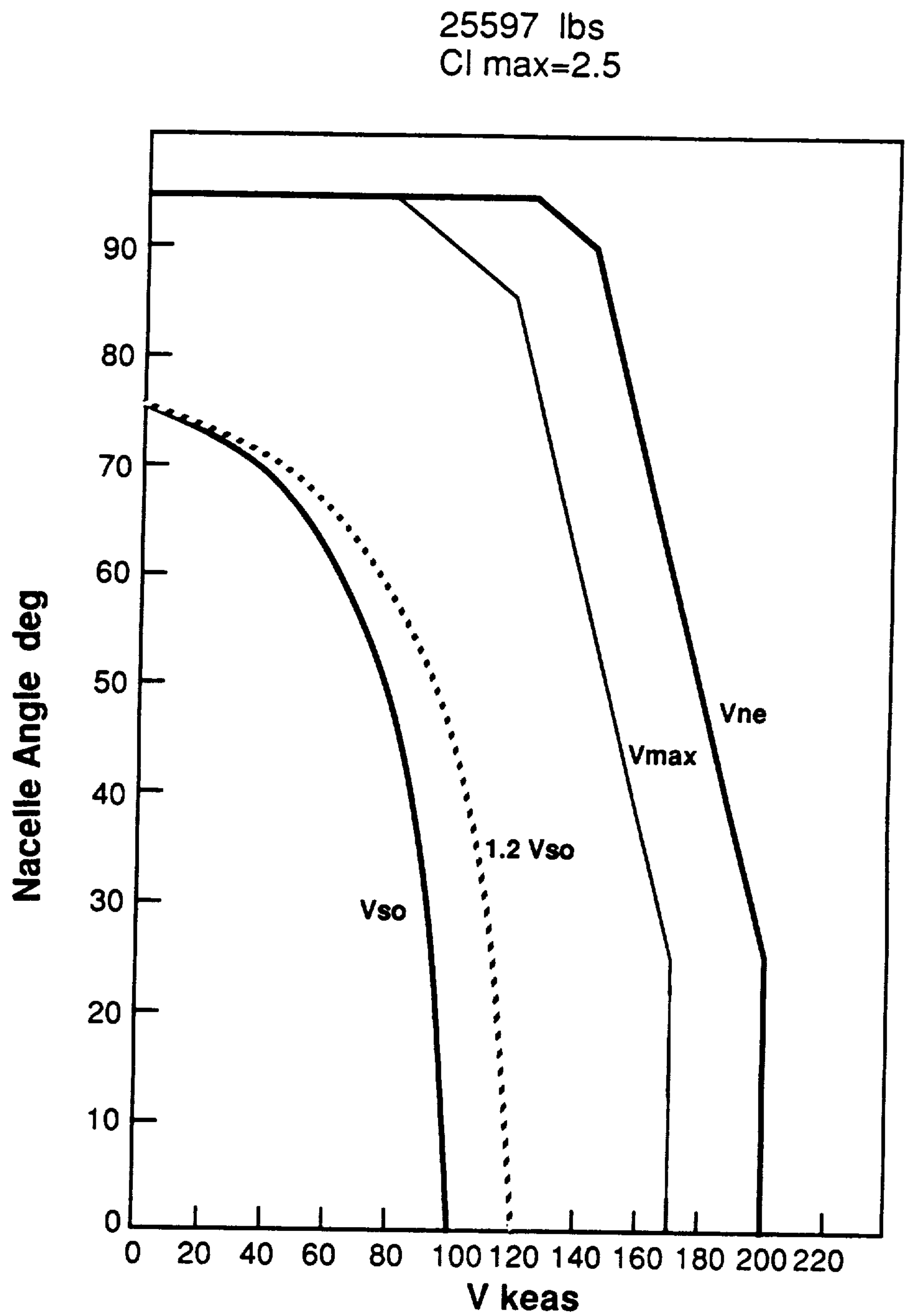


Figure B-37. VDTR SCAT conversion corridor

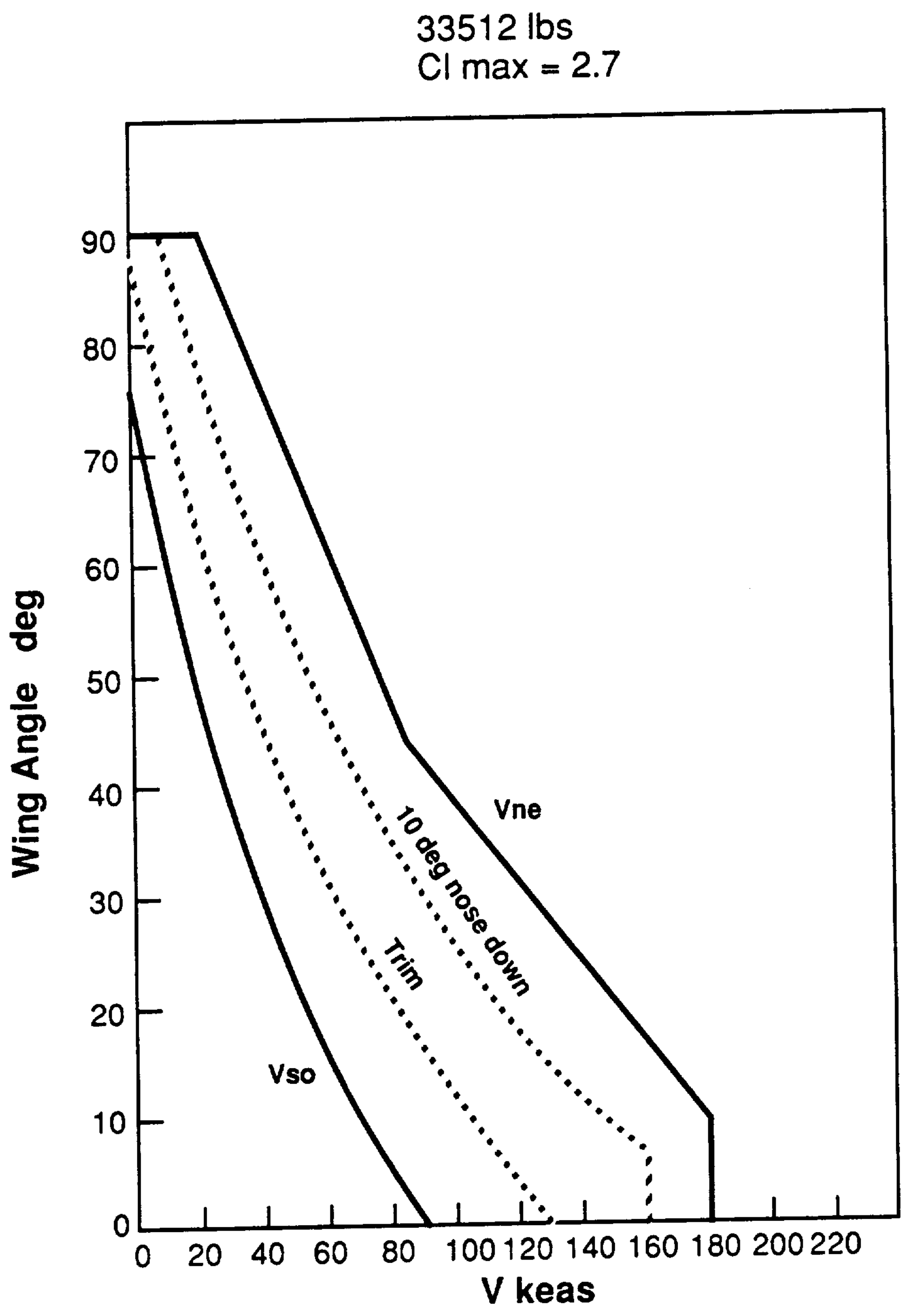
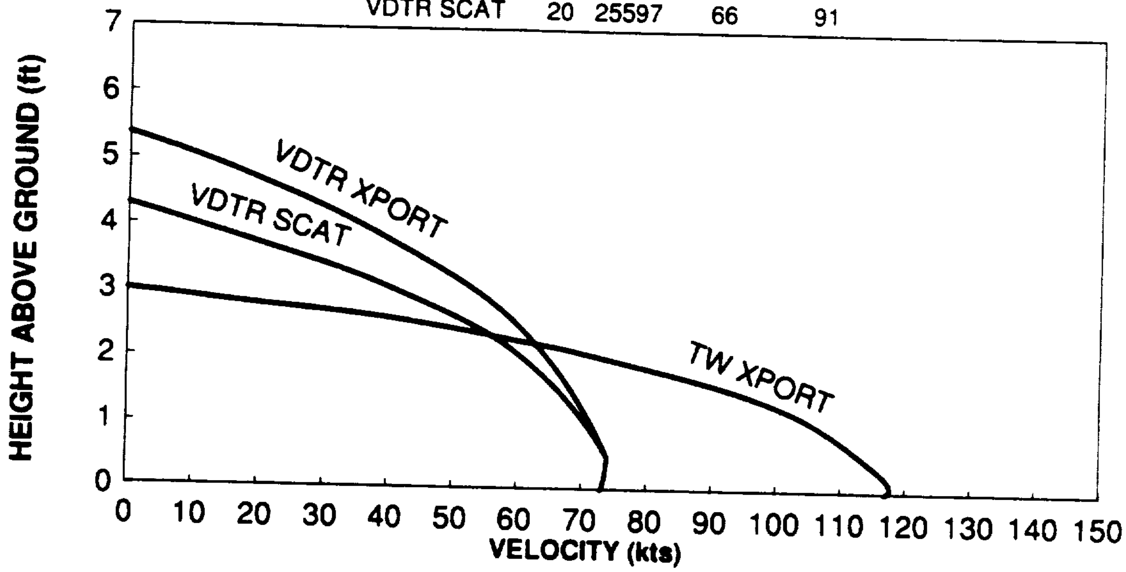


Figure B-38. Tilt wing conversion corridor

SIDE POSITIONS

AIRCRAFT	DL (psf)	GW (lbs)	FORCE (lbs)	MOMENT (ft-lbs)
TW XPORT	50	33512	119	120
VDTR XPORT	20	39839	82	142
VDTR SCAT	20	25597	66	91



NOSE AND TAIL POSITIONS (+/- 20)

AIRCRAFT	FORCE (lbs)	MOMENT (ft-lbs)
TW XPORT	119	120
VDTR XPORT	82	142
VDTR SCAT	66	91

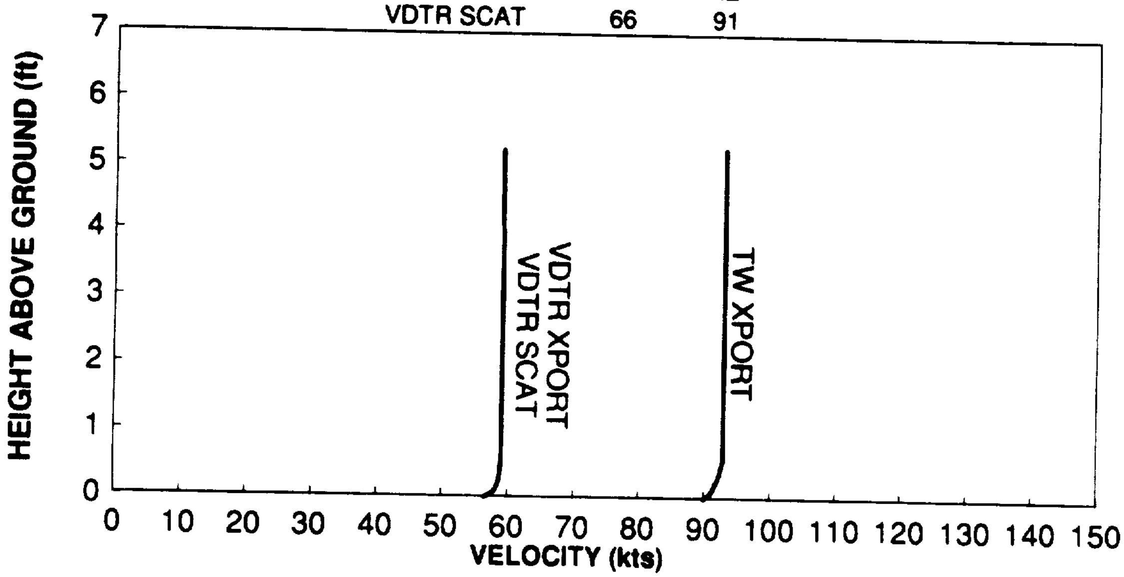


Figure B-39. Downwash velocity vs height above ground

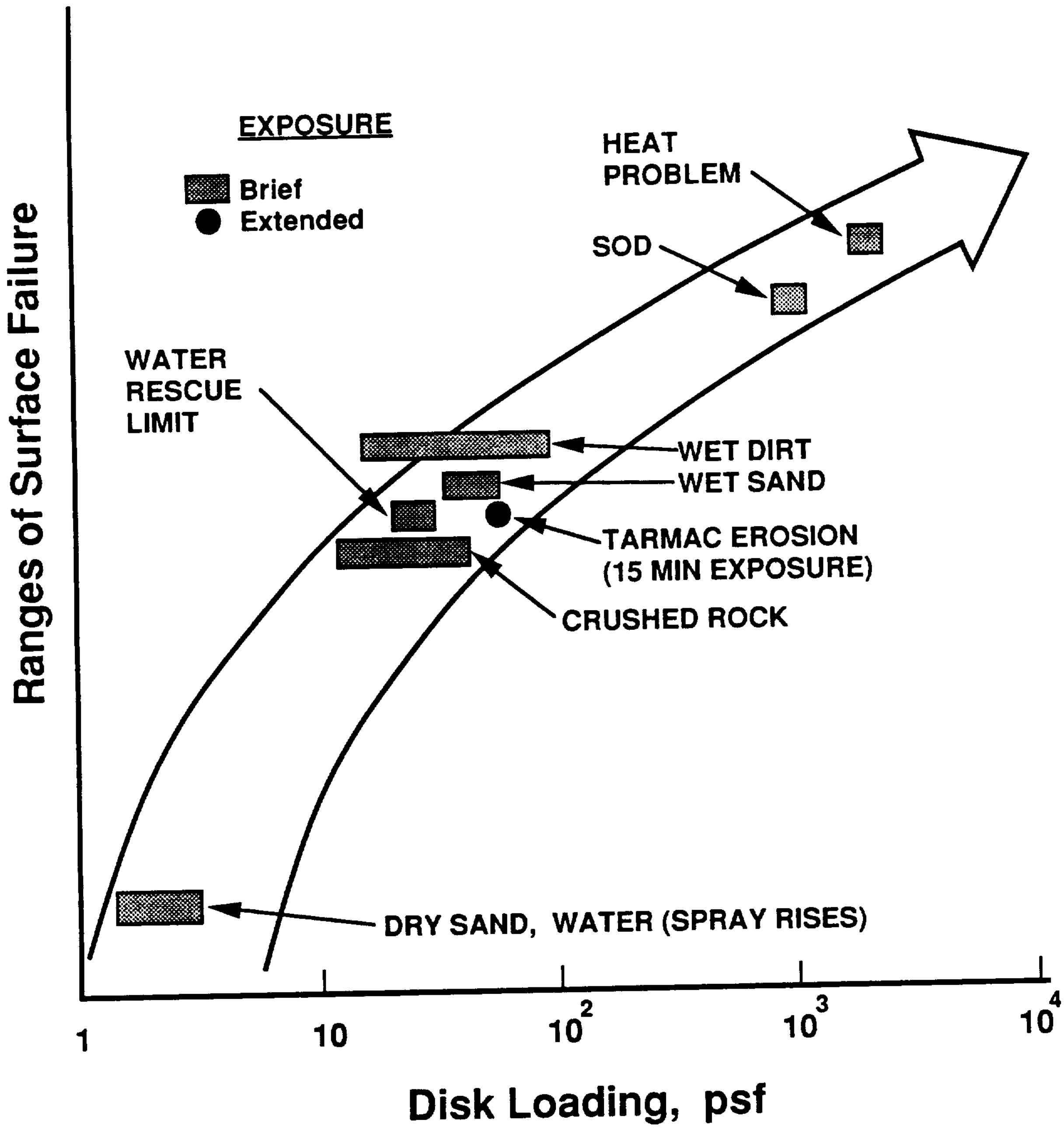


Figure B-40. Resistance of surfaces under wake dynamic presure

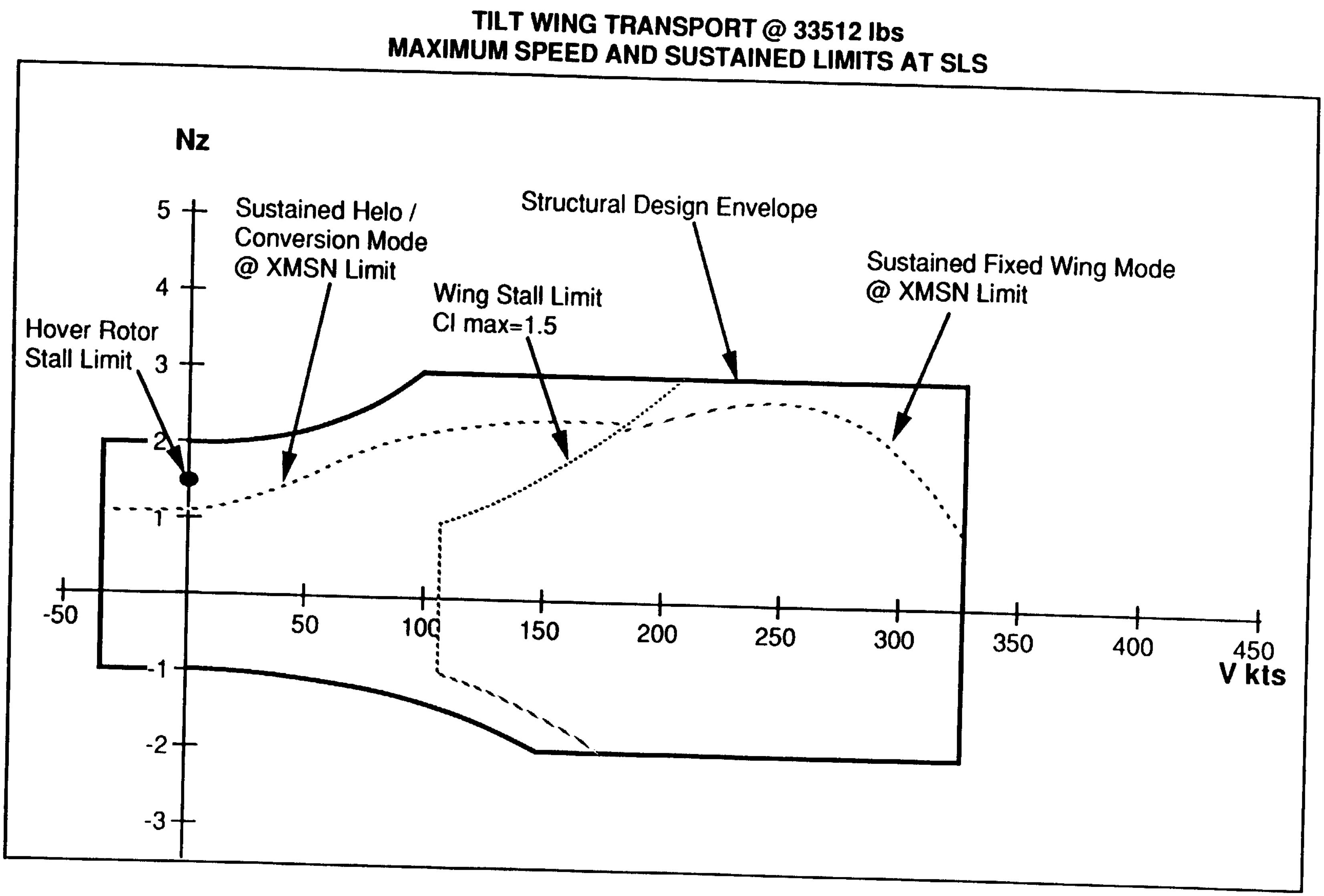


Figure B-41. Velocity-load factor diagrams

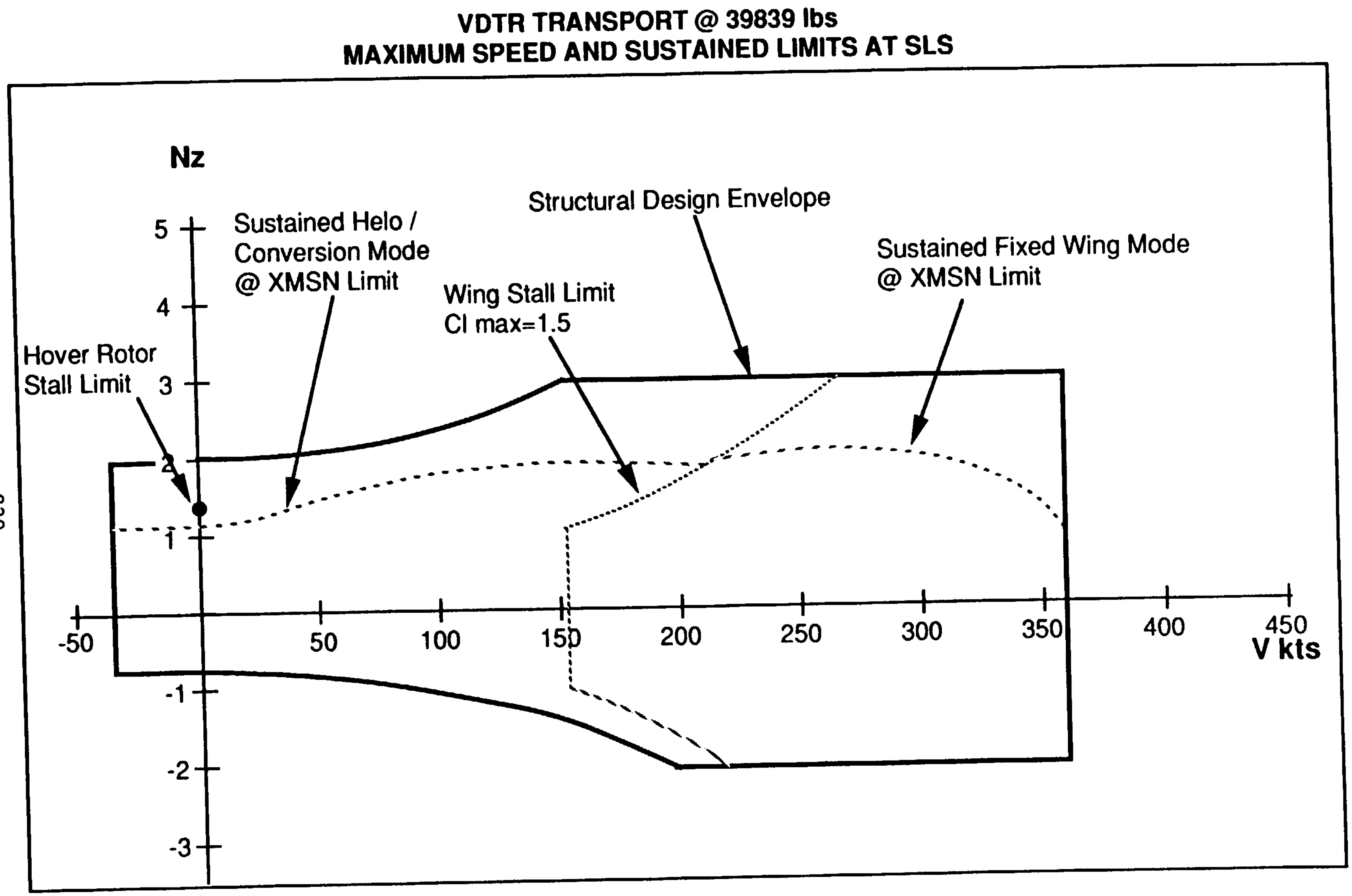


Figure B-42. Velocity-load factor diagrams (continued)

VDTR SCAT @ 25597 lbs
MAXIMUM SPEED AND SUSTAINED LIMITS AT 4000' / 95 F

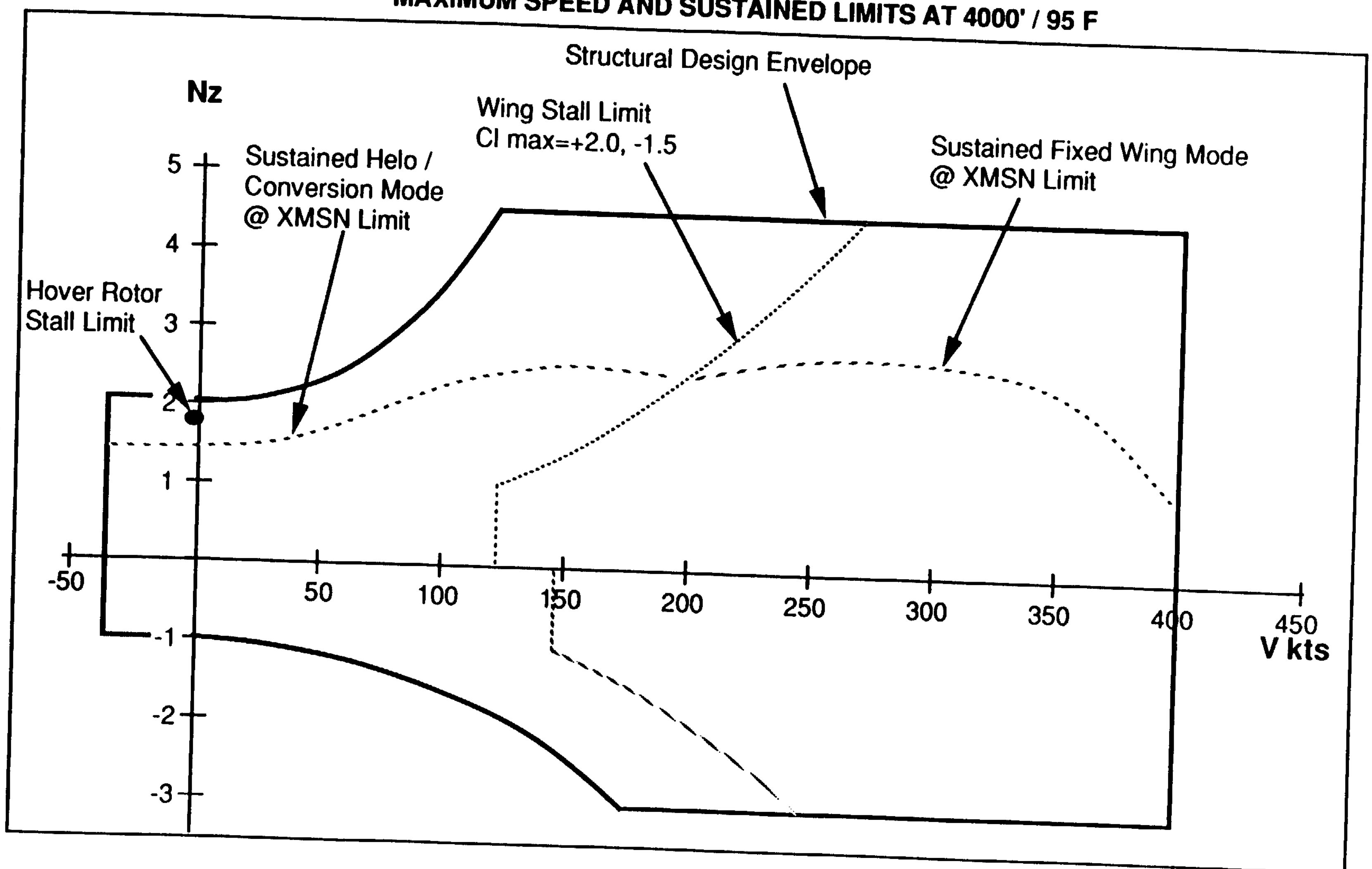


Figure B-43. Velocity -load factor diagrams (continued)

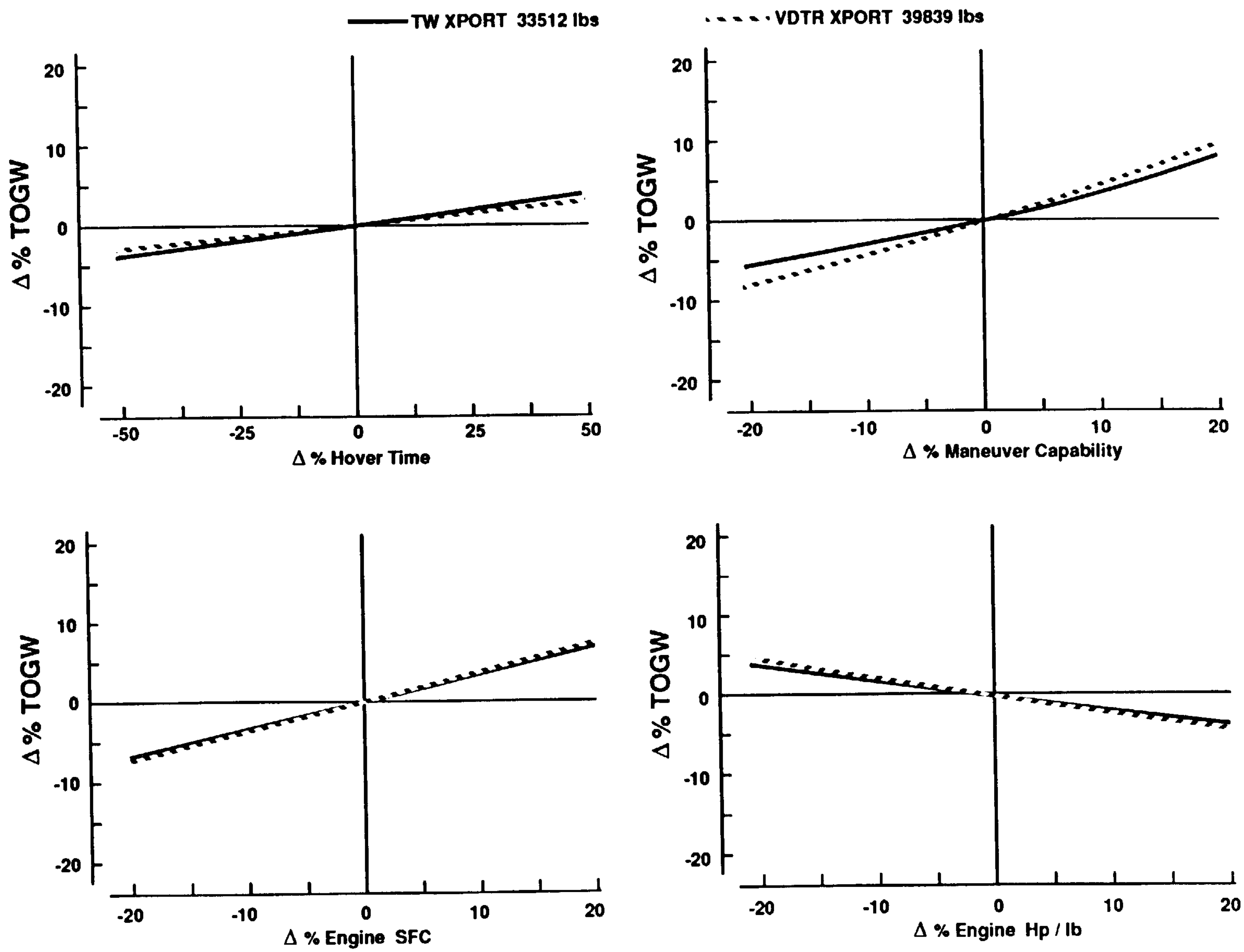


Figure B-44. Mission TOGW sensitivity to mission and performance variables

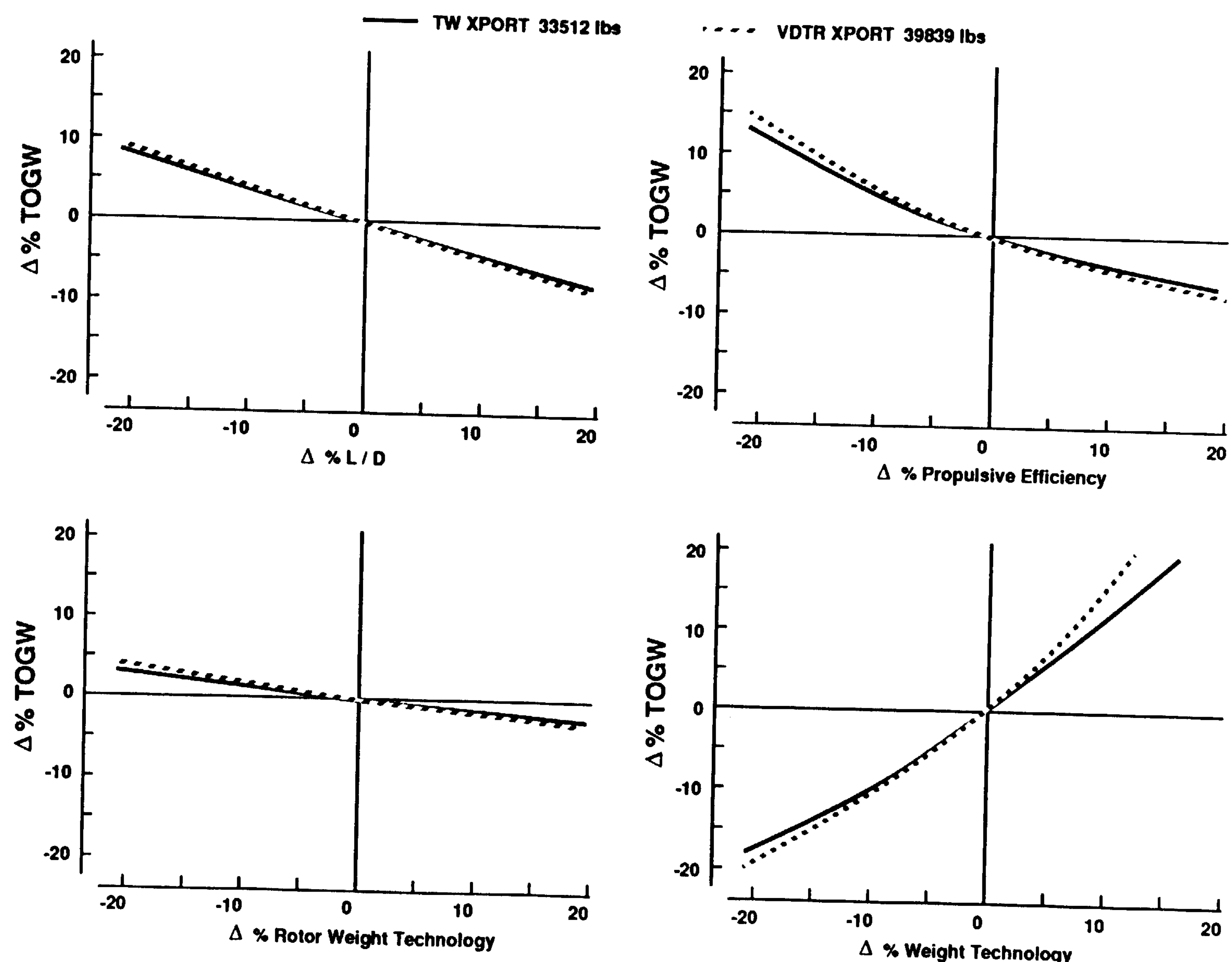


Figure B-44. Mission TOGW sensitivity to mission and performance variables (continued)

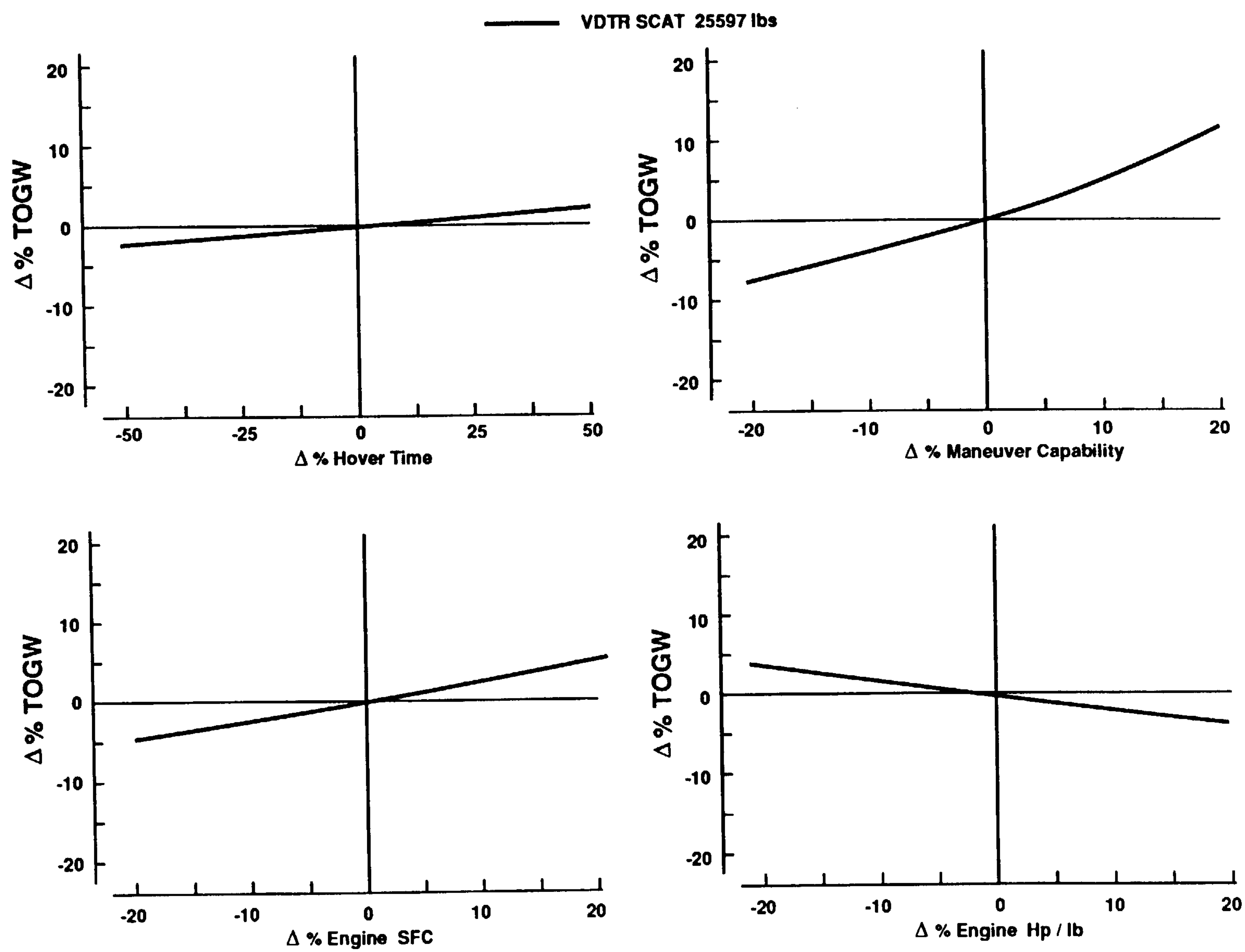


Figure B-44. Mission TOGW sensitivity to mission and performance variables (continued)

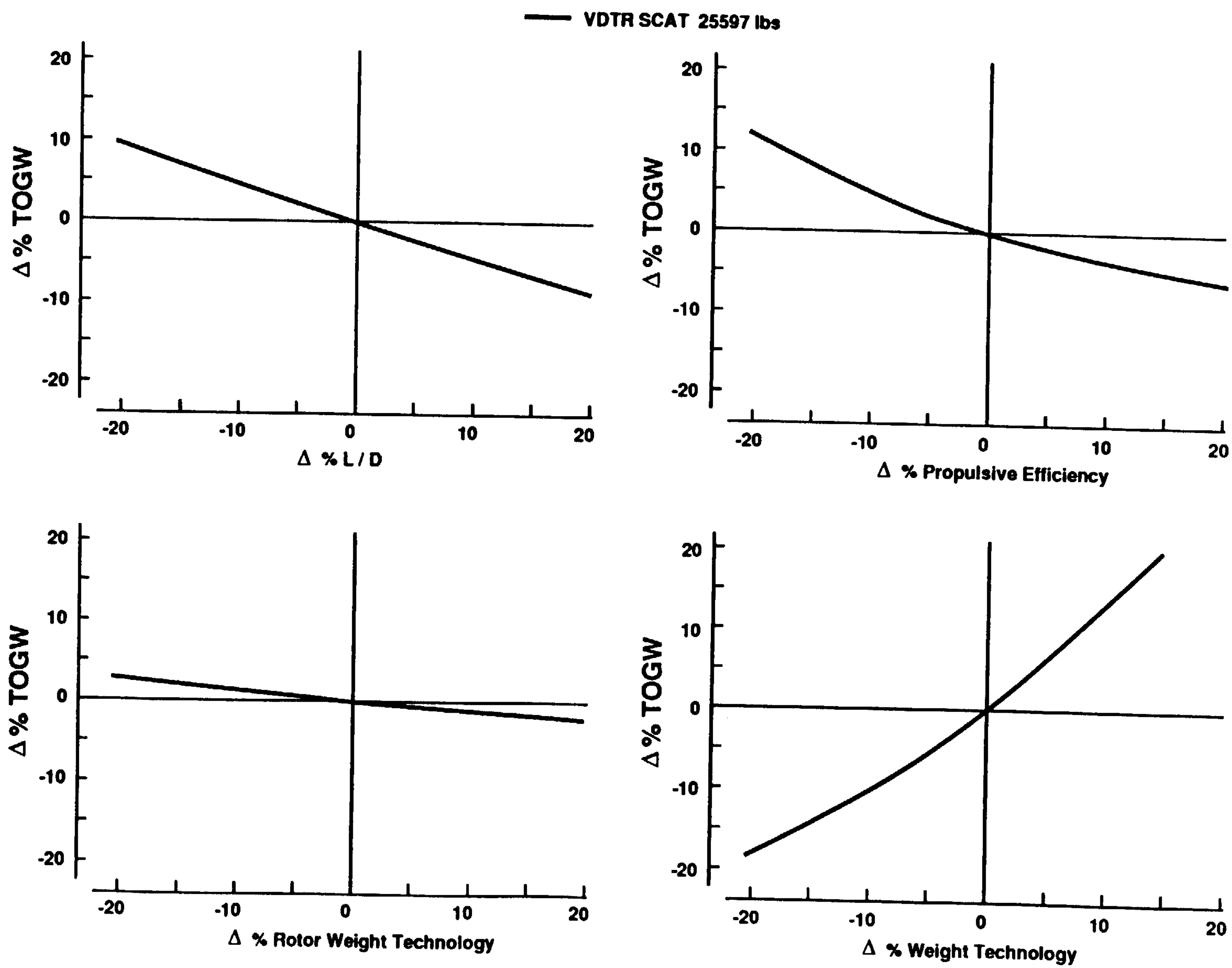


Figure B-44. Mission TOGW sensitivity to mission and performance variables (concluded)

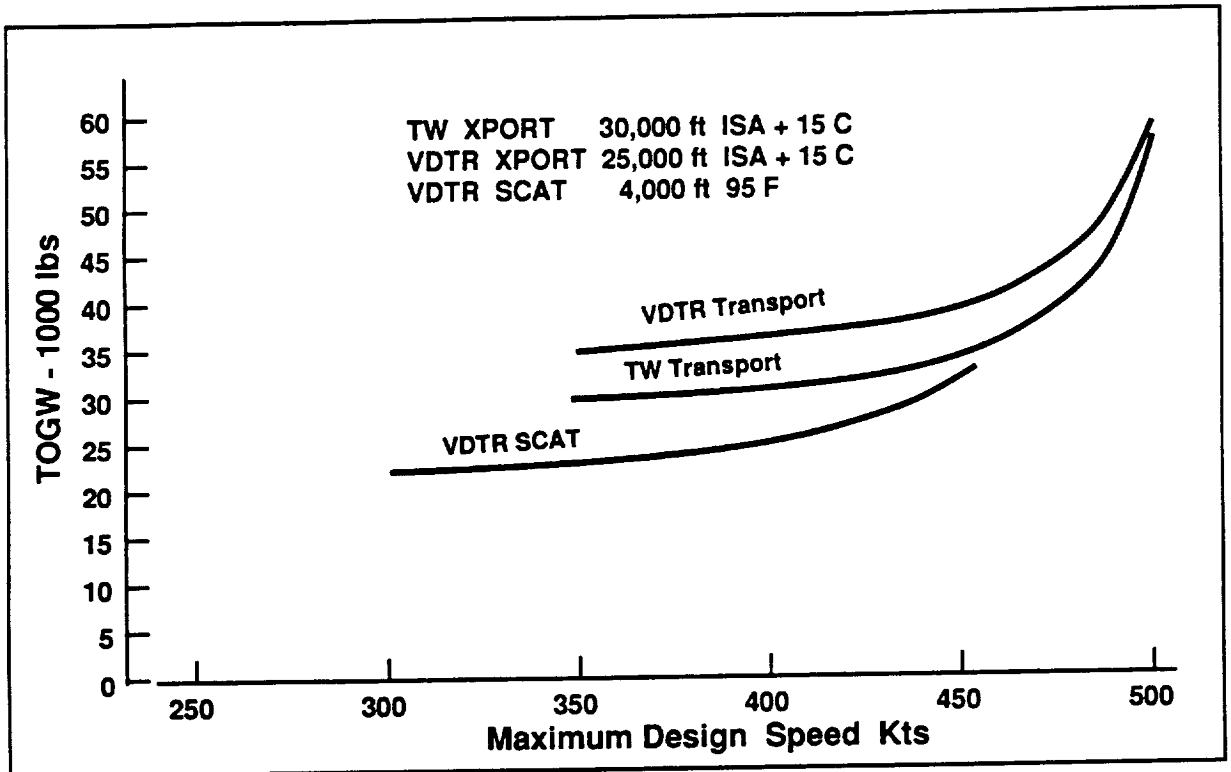


Figure B-45. Mission TOGW vs. maximum design speed

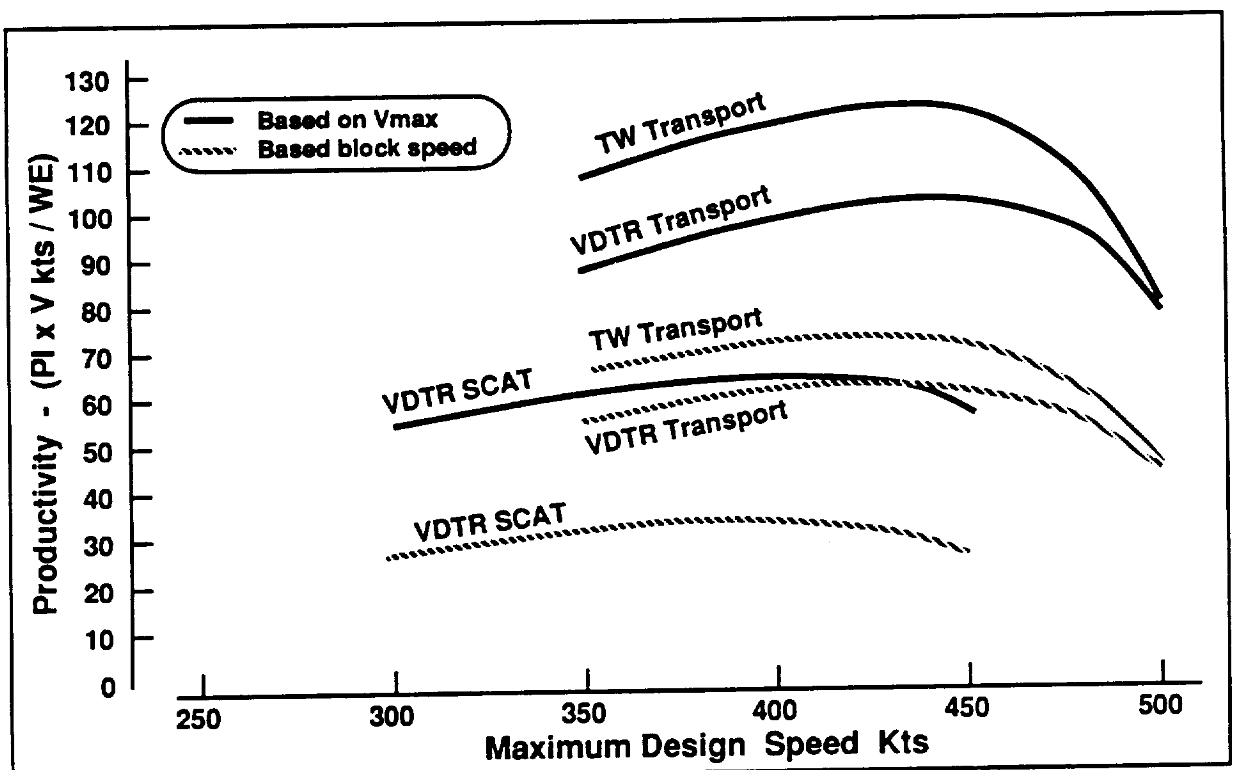


Figure B-46. Productivity vs. maximum design speed

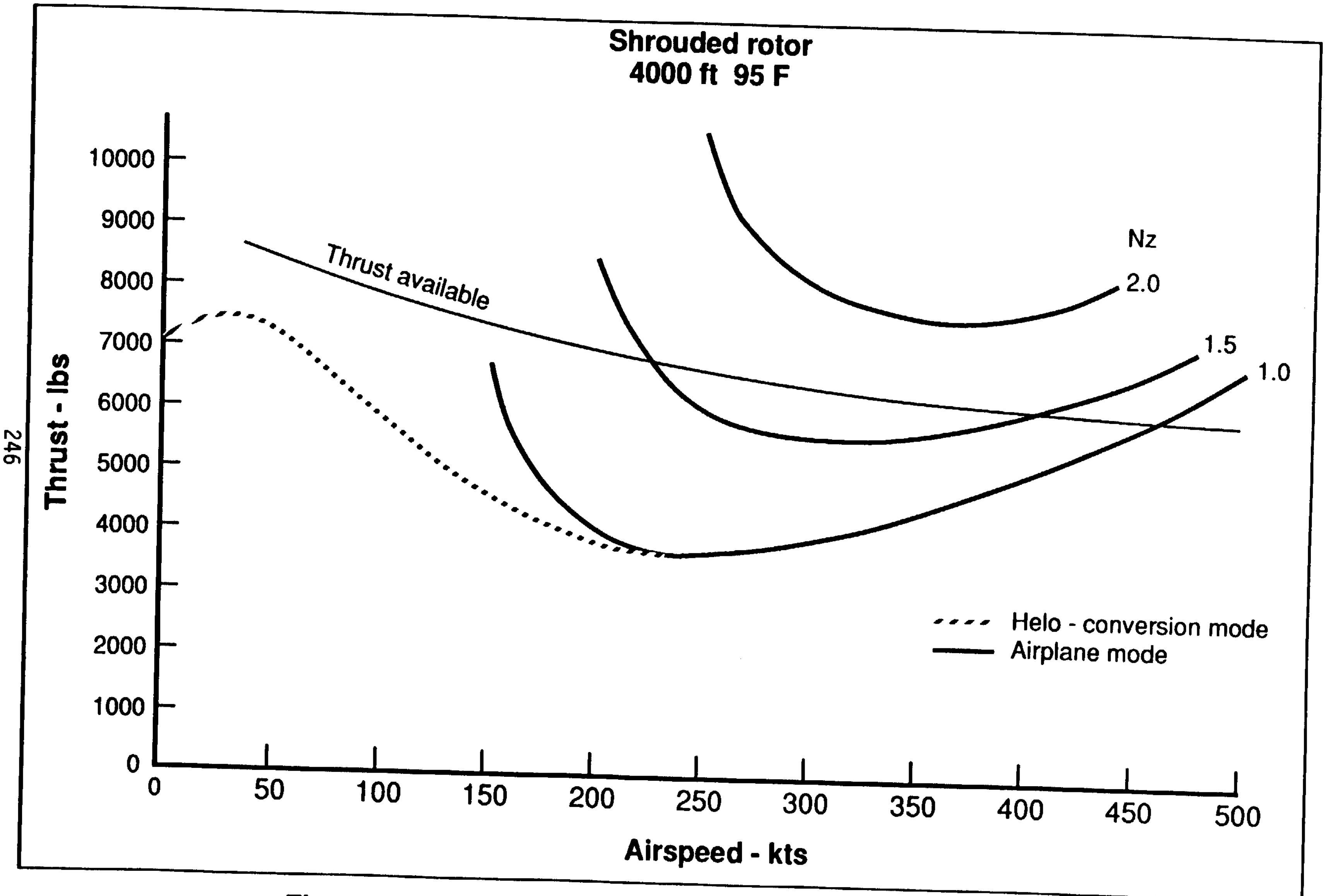


Figure B-47. Shrouded rotor thrust required vs. airspeed

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13. ABSTRACT *(Maximum 200 words)*

An analytical study was conducted to identify rotorcraft concepts best capable of combining a cruise speed of 350 to 450 knots with helicopter-like low speed attributes, and to define the technology advancements needed to make them viable for full scale development by the year 2000. A systematic approach was used to compare the relative attributes and mission gross weights for a wide range of concepts, resulting in a downselect to the most promising concept/mission pairs. For transport missions, tilt-wing and variable diameter tilt-rotor (VDTR) concepts were found to be superior. For a military scout/attack role, the VDTR was best, although a shrouded rotor concept could provide a highly agile, low observable alternative if its weight empty fraction could be reduced. A design speed of 375 to 425 knots was found to be the maximum desirable for transport missions, with higher speed producing rapidly diminishing benefits in productivity. The key technologies that require advancement to make the tilt-wing and VDTR concepts viable are in the areas of wing and proprotor aerodynamics, efficient structural design, flight controls, refinement of the geared flap pitch control system, expansion of the speed/descent envelope, and the structural and aerodynamic trade-offs of wing thickness and forward sweep. For the shrouded rotor, weight reduction is essential, particularly with respect to the mechanism for covering the rotor in cruise.

14. SUBJECT TERMS
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