AD

USAAMRDL TECHNICAL REPORT 71-23

ADVANCED ANTITORQUE CONCEPTS STUDY

By

Arthur W. Grumm

Groves E. Herrick

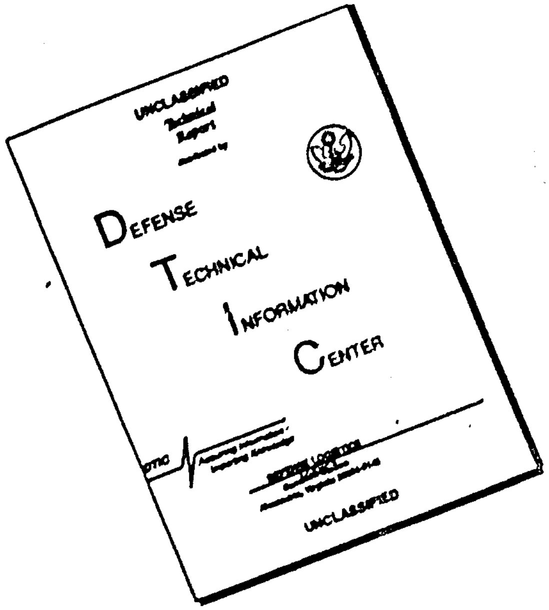
July 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-70-C-0049
SIKORSKY AIRCRAFT
DIVISION OF UNITED AIRCRAFT CORPORATION
STRATFORD, CONNECTICUT

167

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Sikorsky Aircraft Division of United Aircraft Corporation Stratford, Connecticut	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

ADVANCED ANTITORQUE CONCEPTS STUDY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Arthur W. Grumm
Groves E. Herrick

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1971	160	25

8a. CONTRACT OR GRANT NO. DAAJ02-70-C-0049 b. PROJECT NO. c. Task 1F162204AA4405 d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAMRDL Technical Report 71-23 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) SER - 50697

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Eustis Directorate U.S. Army Air Mobility R&D Laboratory Fort Eustis, Virginia

13. ABSTRACT

This report summarizes a study of possible alternatives to the tail rotor on single-rotor shaft-driven helicopters. The objective was to select concepts that show improvements over the tail rotor in high-speed dynamics, vulnerability, reliability and maintainability, safety, and at a lower priority level, acoustic detectability, and erosion and foreign object damage. These characteristics were to be obtained without incurring unacceptable penalties in aircraft weight, performance, or cost. The stability and control criteria of MIL-H-8501A were imposed throughout.

Of the 32 antitorque concepts initially evaluated, only 2 were found to offer significant improvements over the tail rotor in all characteristics specified for this study. The most promising is the fan-in-fin, which uses a high-disc-loading shrouded prop-fan mounted in the tail fin, similar to the installation on the Sud SA.341 light helicopter. The fan-in-tailcone concept employs a similar thruster mounted within the fuselage end of the tail cone, with the fan airflow ducted through the tail cone to exhaust nozzles beneath the tail fin. The fan-in-fin concept has the lower risk and the smaller aircraft performance penalty, approximately 9 percent higher gross weight than the tail rotor. The fan-in-tailcone concept offers somewhat more improvement in the areas of safety, vulnerability, and foreign object damage, at roughly twice the performance penalty.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

DISCLAIMERS

DISPOSITION INSTRUCTIONS

Unclassified

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Helicopters						
Antitorque						
Advanced Antitorque Concepts						
Tail Rotor						
Propfan						
Directional Control						

Unclassified

Security Classification

DEPARTMENT OF THE ARMY
U. S. ARMY AIR MOBILITY RESEARCH & DEVELOPMENT LABORATORY
EUSTIS DIRECTORATE
FORT EUSTIS, VIRGINIA 23604

This report has been reviewed by the U. S. Army Air Mobility Research and Development Laboratory, and is considered to be technically sound. The report is published for the exchange of information and the stimulation of ideas. The program was conducted under the technical management of Mr. Frederick A. Raitch of the Aeromechanics Division of this Directorate.

Task 1F162204AA4405
Contract DAAJ02-70-C-0049
USAAMRDL Technical Report 71-23
July 1971

ADVANCED ANTITORQUE CONCEPTS STUDY

Final Report

Sikorsky Engineering Report 50697

By

Arthur W. Grumm
Groves E. Herrick

Prepared by

Sikorsky Aircraft
Division of United Aircraft Corporation
Stratford, Connecticut

for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

This report summarizes a study of possible alternatives to the tail rotor on single-rotor shaft-driven helicopters. The objective was to select concepts that show improvements over the tail rotor in high-speed dynamics, vulnerability, reliability and maintainability, safety, and at a lower priority level, acoustic detectability, and erosion and foreign object damage. These characteristics were to be obtained without incurring unacceptable penalties in aircraft weight, performance, or cost. The stability and control criteria of MIL-H-8501A were imposed throughout.

Of the 32 antitorque concepts initially evaluated, only 2 were found to offer significant improvements over the tail rotor in all characteristics specified for this study. The most promising is the fan-in-fin, which uses a high-disc-loading shrouded prop-fan mounted in the tail fin, similar to the installation on the Sud SA.341 light helicopter. The fan-in-tailcone concept employs a similar thruster mounted within the fuselage end of the tail cone, with the fan airflow ducted through the tail cone to exhaust nozzles beneath the tail fin. The fan-in-fin concept has the lower risk and the smaller aircraft performance penalty, approximately 9 percent higher gross weight than the tail rotor. The fan-in-tailcone concept offers somewhat more improvement in the areas of safety, vulnerability, and foreign object damage, at roughly twice the performance penalty.

Although significant improvements are achieved by both alternative concepts for the antitorque system alone, they represent only small improvements for the total aircraft in the areas of interest.

Despite the improvements obtainable with the two alternative systems, the conventional tail rotor remains an attractive compromise because of the increased aircraft weight and cost of the prop-fan configurations. However, these penalties in weight and cost would be reduced significantly for certain applications, such as compound helicopters, when the power installed is defined by a cruise or dash requirement.

Uncertainties remain in estimates of aircraft handling qualities and performance. For the fan-in-fin, these lie in fan thrust/power and overall drag characteristics in forward flight, and particularly in the effects of possible fan shroud lip separation. These uncertainties must be eliminated before this concept can be realistically applied to future Army aircraft. A flight test program to obtain comprehensive performance and aircraft handling qualities data for the fan-in-fin concept is required. It is recommended that the Army fund such a program on an aircraft in the 10,000- to 15,000-pound gross weight range, to represent the weight range of utility transport helicopters and potential high-speed light compounds.

FOREWORD

This document was prepared for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, by Sikorsky Aircraft, a Division of United Aircraft Corporation, under Contract DAAJ02-70-C-0049 (Task 1F162204AA4405), June 1970 through January 1971.

Hamilton Standard, a Division of United Aircraft Corporation, provided prop-fan data upon which portions of this study were based.

Major technical contributions were made by the following Sikorsky employees:

Mr. William E. Bausch	-	Acoustics
Mr. Robert J. Flemming	-	Performance
Mr. Everett F. Fournier	-	Reliability/Maintainability
Mr. Walter H. Gerdes	-	Handling Qualities
Mr. Neville F. K. Kefford	-	Helicopter Design Model
Mr. Bernard G. Richitelli	-	Configuration Design
Mr. David K. Unsworth	-	Mass Properties
Mr. Charles H. Zimmerman	-	Sikorsky Consultant

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

Figure		Page
45	Design Gross Weight Versus Blockage Factor	80
46	Design Gross Weight Versus Design Technology	80
47	Design Gross Weight Versus Control Ramp Time	81
48	Fan-in-Fin Concept	99
49	Fan-in-Tailcone Concept	100
50	Linear Fan Concept	102
51	Squirrel-Cage Rotor Concept	103
52	Main-Rotor Downwash Deflection Concepts	106
53	Accelerated Flywheel Concept	111
54	Turbine-in-Tail Concept.	113
55	Chemical Rocket Concept	115
56	Main-Engine Airflow Deflection - Bifurcated Nozzle Concept	118
57	Main-Engine Airflow Deflection - Compressor Bleed Air Concept	120
58	Piasecki Ringtail Concept.	122
59	Coaxial Speed Brake Concept	127
60	Typical Experimental Downwash Velocity Distribution, Sea Level, 95°F, HOGE.	131
61	Thruster Power Loading Versus Effective Disc Loading . . .	133
62	Schematic Flow Diagram, General Helicopter Design Model .	139
63	Weight Statement Printout	140
64	Main Rotor C_T/σ Trade-off Printout	141
65	Mission Analysis Printout	142

LIST OF TABLES

LIST OF SYMBOLS

a	slope of lift curve
a_s	speed of sound, feet/second
AFCS	automatic flight control system
A_4/A_2	ratio of shroud area at exit to thruster disc area
AGW	alternate gross weight, pounds
AGWf	alternate gross weight factor
API	armor-piercing incendiary
b	number of thruster blades
B	tip loss factor
c	chord, feet (rotor: blade chord; prop-fan: aft shroud chord)
C_D	drag coefficient
C_{FA}	flyaway cost, dollars
C_L	lift coefficient
C_O	10-year operating cost, dollars
C_{OM}	10-year overhaul and maintenance costs, dollars
C_P	power coefficient
$C_{Q, D}$	rotor torque coefficient arising from profile drag
C_T	thrust coefficient
C/D	aft shroud chord/thruster diameter
d	thruster diameter, feet
DGW	design gross weight, pounds
DL	thruster disc loading, pounds/foot squared
E	aircraft efficiency = PL V_{cr}/LCC, pound-knots/dollars
FM	effective figure of merit (= 1.0 for ideal unshrouded rotor)
FM_{gen}	generalized figure of merit (= 1.0 for ideal thruster)

FM_{max}	maximum effective figure of merit
FOD	foreign object damage
GW	gross weight, pounds
HP_{HR}	power applied to main rotor, horsepower
IFR	instrument flight rules
IGE	in ground effect
K	ratio of downstream area of flow through thruster, to thruster disc area
LCC	10-year life cycle cost, dollars
L_{TR}	perpendicular distance between center of tail rotor and axis of main rotor shaft, feet
M	Mach number
$\dot{m}$	mass flow rate, slugs/second
MMH/FH	maintenance man-hours per flight hour
MRP	military rated power level, horsepower
MTBF	mean time between failures, hours
n	rotor speed, revolutions per second
N_f	antitorque yaw moment of tail thruster, foot-pounds
N_r	antitorque yaw moment of vertical tail, foot-pounds
N_R	rotor speed, percent of design value
N_{req}	yaw moment due to yaw rate, foot-pounds
NRP	normal rated power level, horsepower
OAT	outside air temperature, °C
OGE	out of ground effect
p	total pressure in duct, pounds/foot squared
P	installed engine power, horsepower
PCTPR	portion of available engine power applied to antitorque device, percent

PL	design payload, pounds
PNL	perceived noise level, PNdB
PR	ratio of total pressure across thruster (≥ 1.0)
q	dynamic pressure in duct, pounds/foot squared
Q	draft torque applied to main rotor, foot-pounds
Q'	torque applied to fuselage by antitorque device , foot-pounds
R	main rotor radius, feet
RPM_{MR}	main rotor speed, revolutions per minute
SFC	engine specific fuel consumption, pounds per hour/horsepower
SHP	shaft horsepower
T	temperature, °F
T_{TR}	net thrust of antitorque device, pounds
TAF	total activity factor
TOGW	takeoff gross weight, pounds
v_o	mean induced velocity through thruster, feet/second
V_{BR}	aircraft velocity for best range
V_{cr}	cruise velocity, knots
VFR	visual flight rules
VROC	vertical rate of climb
W	aircraft empty weight, pounds
α	blade incidence angle, radians
γ	ratio of specific heats
δ	ratio of pressure at altitude to pressure at sea level at standard conditions
δ_b	blade sectional drag coefficient
δ_{ped}	pedal deflection, percent of full excursion
δ_r	rudder deflection, degrees

η	duct efficiency
θ	ratio of temperature at altitude to temperature at sea level
$\theta_{.75}$	blade pitch angle at 75 percent radius station, radians
μ	rotor advance ratio
ρ	density, slugs/cubic foot
σ	solidity = $bc/\pi R$
$\ddot{\Psi}$	yaw acceleration, radians/second squared
Ω	rotor speed, radians/second

INTRODUCTION

ANTITORQUE SYSTEM REQUIREMENTS

The antitorque system of a conventional single-rotor shaft-driven helicopter performs four basic functions: antitorque, side-wind torque compensation, yaw control, and yaw damping and directional stability.

Antitorque

The torque supplied by the helicopter powerplant to rotate the lifting rotor leads to an equal and opposite reaction torque on the helicopter fuselage. The reaction torque tends to rotate the fuselage opposite sense to the direction of the rotor. To prevent this rotation, a compensating torque equal and opposite to the reaction torque must be supplied to the fuselage. Tail rotor thrust, acting at some moment arm distance from the aircraft main rotor hub, supplies this compensating torque. For the conventional single-rotor shaft-driven helicopter, this torque may be written

$$Q = \frac{HP_{MR}\ 33000}{2\pi\ RPM_{MR}}$$

where Q = torque required - foot-pounds

HP_{MR} = horsepower applied to main rotor at hub

RPM_{MR} = main rotor speed - revolutions per minute

The compensating torque Q' is supplied on a conventional helicopter by side thrust from the tail rotor, as

$$Q' = T_{TR}\ L_{TR}$$

where T_{TR} = tail rotor thrust - pounds

L_{TR} = perpendicular distance from aircraft main rotor hub to center of tail rotor - feet

Alternative types of helicopters, such as coaxial, tandem, or multirotor shaft-driven configurations, cancel the net torque applied to the fuselage by counterrotation of the main rotors, use of differential blade pitch control, or tilting rotor-shaft axes. Configurations employing reaction-driven rotors eliminate the antitorque requirement by isolating the fuselage from the rotor/drive system.

Side-Wind Torque Compensation

Yaw control must be sufficient to allow steady sideward flight at 35 knots in either direction, and to allow steady hover in a 35-knot side wind from either direction, as specified in MIL-H-8501A[1].

Yaw Directional Control

Yaw control must be sufficient to provide adequate directional control in either direction, in both hover and forward flight in still air. MIL-H-8501A, the applicable military stability and control requirement, specifies a yawing rotation of 12.4 degrees after 1 second of maximum control pedal deflection as "adequate" for the 15,000-pound base-line aircraft defined for this study. In the presence of a 35-knot side wind, this requirement is reduced to 4.13 degrees.

In autorotation, with all engines and control augmentation systems assumed to be inoperative, sufficient control must be available for coordinated turns in either direction at all forward speeds between zero and the maximum speed of the helicopter. Transition from power to autorotative flight must be smooth and controllable.

In both powered and autorotative flight, angular acceleration in the desired direction must begin within 0.2 second of pedal deflection.

Yaw Damping and Directional Stability

The antitorque/yaw control system, in concert with fuselage aerodynamic surfaces and stability augmentation, must produce a yaw angular velocity damping as specified by MIL-H-8501A.

Further, it is required that aircraft of the type evaluated in this study possess positive, directional stability with the controls fixed in both powered and autorotative flight at all forward speeds above 50 knots. The capability to maintain steady sideslip angles in forward flight is also required.

THE TAIL ROTOR AS AN ANTITORQUE DEVICE

The conventional tail rotor, or its logical developments, appears to be the best overall compromise system for meeting these requirements on conventional shaft-driven single-rotor helicopters. It is attractive in terms of weight and power, which become increasingly important as prescribed mission endurance times increase.

In certain areas, however, the conventional tail rotor is less than satisfactory. The tail rotor system is relatively complex. It requires one or two right-angle gearboxes and relatively long high-speed shafting. Unsatisfactory reliability and maintainability characteristics are a possibility in a combat zone.

In small helicopters particularly, the relatively large, fully exposed tail rotor blades have been susceptible to ground impact and foreign object damage, especially in jungle-like combat zones. The rotor can also represent a hazard to disembarking troops, due to the relative invisibility of the whirling blades. This is less of a factor on medium and large helicopters, because of the higher placement of the tail rotor.

The tail rotor, as commonly employed, represents one of the primary sources of noise on a conventional military helicopter. Because the tail rotor radiates a significant portion of its acoustic energy in a fore and aft direction, it is more readily detectable along its flight path than a device that radiates sideward primarily.

Highly desirable, therefore, is definition of systems that can overcome such shortcomings without unacceptable weight, power, or handling quality penalties.

STUDY OBJECTIVES

The advanced antitorque concepts study was undertaken to select, and conduct a preliminary design study of, a replacement for the tail rotor on a conventional single-main-rotor shaft-driven helicopter. This replacement must show improvement over a conventional tail rotor in the following areas:

1. Dynamic stability at high aircraft speed
2. Vulnerability to small-arms fire
3. Vulnerability to terrain contact damage
4. System reliability
5. System maintainability
6. Safety of ground personnel

and improvement is desired in the following areas:

7. Acoustic detectability
8. Sensitivity to erosion and foreign object damage (FOD)

The study consisted of five tasks.

Task 1 - Survey of a wide variety of possible tail rotor replacement system concepts, including definition, evaluation, and rating of the suitability of each for use on a squad carrier-size conventional single-main-rotor shaft-driven helicopter.

Task 2 - In-depth evaluation of the concepts that best fulfilled the objectives of the study.

Task 3 - Preliminary design study incorporating the best alternative concepts in an H-34 helicopter.

Task 4 - Development of preliminary planning information on design, fabrication, installation, and ground and flight test of the aircraft defined during Task 3. The results of this task have been submitted under separate cover and are not included in this report.

Task 5 - Comparison of the alternative concepts carried through Task 3 as they would be applied best to a totally new aircraft.

TASK 1. SURVEY OF ANTITORQUE CONCEPTS

The concepts examined represent the complete spectrum of possible tail rotor replacement solutions. The examination was directed not only toward discovery of potentially attractive concepts but also toward delineation of the shortcomings or failures in less attractive concepts and toward providing a framework for evaluating additional concepts that may be suggested in the future.

CONCEPTS EVALUATED

Nine categories of concepts were evaluated:

1. Tail rotors: conventional (base line) and advanced
2. Passive thrusters (systems requiring an external power source): ducted propellers, prop-fans or fans of various types mounted either at the base-line tail rotor station or in the fuselage with the efflux ducted through the tail cone and exited through controllable nozzles
3. Deflection of rotor downwash flow: tail cones and rudders incorporating squirrel-cage fans, jet-flap airfoils, circulation-controlled airfoils with tangential blowing, Flettner rotors, Thwaites-flap airfoils, and conventionally flapped cambered airfoils
4. Inertial solutions: accelerated flywheels, precessed gyroscopes
5. Active thrusters (auxiliary engines): rockets (both chemical and exotic), acoustic radiators, turbojets, turbofans, or pulsejets, mounted either at the base-line tail rotor station or in the fuselage with the efflux ducted through the tail cone and exited through controllable nozzles
6. Deflection of main engine flow: exhaust deflection, compressor bleed, use of convertible turboshaft/fan engines, etc.
7. Pseudo-compound solutions: deflected thrust from thrusting propeller, turbojet or turbofan, cyclic pitch on thrusting propeller, differential thrust on stub-wing mounted propellers, turbojets, or turbofans
8. Pseudo-coaxial main rotor solutions: coaxial speed brakes
9. Combined concepts

BASE-LINE AIRCRAFT DESCRIPTION

A base-line aircraft was defined for preliminary analysis of the control requirements of the various antitorque systems. Figure 1 is the general arrangement drawing for this aircraft, a typical next-generation single-rotor shaft-driven light-utility transport helicopter. This base line serves as a starting point for all the comparisons and optimizations presented in this Task. Table I lists the design parameters and mission criteria that define the aircraft in sufficient depth for this purpose.

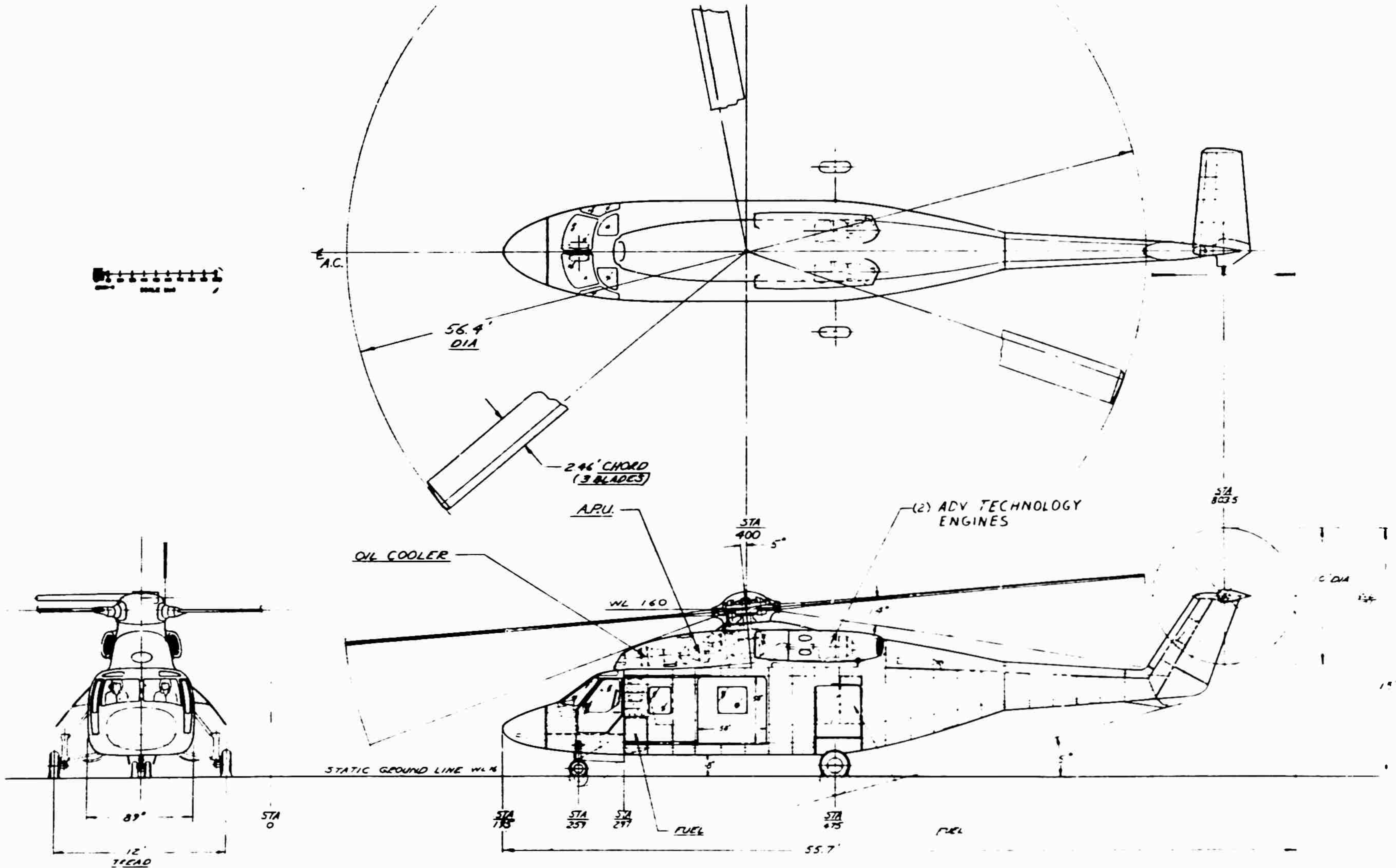


Figure 1. General Arrangement - Base-Line Aircraft.

TABLE I. BASE-LINE AIRCRAFT PARAMETERS	
Design Gross Weight - lb	15,000
Limit Vertical Load Factor at DGW	3.0
Alternate Gross Weight - lb	18,000
Limit Vertical Load Factor at AGW	2.5
Disc Loading ($DGW/\pi R^2$) - psf	6
Main Rotor Tip Speed - fps	700
Main Rotor Radius - ft	28.2
Yawing Moment of Inertia - slug-ft^2	
at DGW	38,000
at AGW	39,000
Critical Hover Condition - HOGE at 95% MRP, 500 fpm VROC	
Temperature - $^{\circ}$F	95
Altitude - ft	4,000
Main Rotor Power Required at the Critical Hover Condition	1,660
Power Losses in Hover - %	17
Tail Rotor	8
Drive System	3
Accessories	2
EAPS	2
IRS	2
Shaft Horsepower Required at the Critical Hover Condition	2,000
Drive System Design Horsepower	
(125% of critical hover power required)	2,500
Maximum Main Rotor Power	2,075
Installed Mil Power	2,275
4000 ft, 95°F	2,275
Sea Level Standard Day	2,966

CONTROL REQUIREMENTS

Tail rotor thrust requirements for the base-line aircraft were determined based on MIL-H-8501A. Table II lists the critical thrust requirements for forward and aft aircraft center-of-gravity conditions.

TABLE II. BASE-LINE AIRCRAFT THRUST REQUIREMENTS

MIL-H-8501A CONDITION	C.G. LOCATION	Thrust Required - Lb			
		Anti-torque	Yaw Accel.	35 kt Side Wind	Total
Para. 3.3.5	Fwd (sta 391)	1370	852	-	2222
	Aft (sta 409)	1370	870	-	2240
Para. 3.3.6	Fwd (sta 391)	1370	284	342	1996
	Aft (sta 409)	1370	290	294	1954

Maximum thrust requirement is 2240 pounds based on criteria outlined in paragraph 3.3.5 of MIL-H-8501A. This provides the capability of attaining a yaw displacement of $330/\sqrt[3]{AGW + 1000}$ degrees after 1 second while hovering in still air at the maximum overload gross weight. This is based on maximum main rotor horsepower, a gearbox limit for the base-line aircraft.

Maximum steady-state thrust requirement is 1712 pounds based on criteria in paragraph 3.3.6 of MIL-H-8501A. This provides the capability of attaining a yaw displacement of $110/\sqrt[3]{AGW + 1000}$ degrees after one second while hovering in a 35-knot side wind at the maximum overload gross weight and maximum main rotor horsepower.

The required angular accelerations are 0.732 radian per second squared while hovering in still air and 0.244 radian per second squared while hovering in a 35-knot side wind.

The damping requirement of 1.137 foot-pounds per radian per second is assumed to be met with the use of AFCS augmentation. Aircraft inherent damping with tail surface sizing criteria similar to Sikorsky's past practice is one-fourth to one-third of the requirement of paragraph 3.6.1.1 of MIL-H-8501A.

These thrust requirements defined for the base-line aircraft were used for sizing the antitorque concepts. Although basic aircraft parameters (inertia, damping, and side-wind moment) differ, use of constant thrust does not significantly affect determination of whether a concept has enough merit to be carried into more detailed analysis.

SUMMARY OF ANTITORQUE CONCEPTS SURVEY

Only four groups of concepts are considered to be acceptable as substitutes for a conventional tail rotor without incurring highly undesirable weight, performance, cost, or risk penalties. Of these four, only two offer significant improvements in the goal areas specified in this study. They are the "fan-in-fin" and the "fan-in-tailcone" concepts, which were selected for evaluation in greater depth. The four feasible groups of concepts are discussed briefly in this section. The details and a description of the rating criteria used are given in Appendix I.

Advanced Tail Rotors

Advanced tail rotor concepts represent refinements of the conventional tail rotor, such as increased number of blades, cambered blades, or jet-flapped or boundary-layer controlled blades. Individual concepts may offer substantial improvements in performance, weight, size, detectability, reliability, or vulnerability, but no single concept offers significant improvement in all these areas. Improvement in ground personnel safety is slight, because of the retention of exposed moving blades. Advanced tail rotor concepts offer considerable promise in several types of advanced helicopters, but no single concept offers an outstanding advance toward the particular goals of this study.

Fan-in-Fin (Fans Mounted in Tail Fin)

Fan-in-fin concepts replace the conventional tail rotor with either a ducted fan or a prop-fan, a device conceptually midway between a propeller and a ducted fan. (See Appendix IV). A shaft drive is generally employed, although a gas-driven version was examined. No engine exhaust or auxiliary engine solutions are included in this category. Power consumption of these concepts is generally higher than for the tail rotor, but weight is similar. Improvements in detectability, reliability, maintainability, safety, and foreign object damage are anticipated, with no significant penalties in stability and control.

By far the most promising of these systems is the prop-fan configuration. The prop-fan is superior to the ducted fan in terms of power required and technical risk levels. A French version of the prop-fan fan-in-fin is in service on the Sud SA.341. The fan-in-fin configuration has been selected for a more detailed evaluation.

Fan-in-Tailcone (Fans Mounted in Tail Cone, Exhausting At Tail Fin)

Fan-in-tailcone concepts use thrusters similar to those of the previous category, but mounted in the forward portion of the tail cone, with the fan axis fore and aft instead of side-to-side. The exhaust flow is ducted through the tail cone and exits through deflecting nozzles beneath the tail fin. These approaches tend to be heavier and require more power than either the conventional tail rotor or the fan-in-fin concept, but they offer further improvements in detectability, safety, high-speed dynamics, vulnerability, and foreign object damage categories.

The prop-fan approach appears to be superior to the ducted fan, particularly in regard to power, noise, and technical risk. The relatively high disc loading required of the prop-fan in this arrangement increases the technical risk of the system over that of the previous category, but the resulting risk is acceptable. This approach has also been selected for more detailed evaluation.

Pseudo-Compound Solutions

Pseudo-compound solutions provide antitorque and directional control thrust by using devices commonly employed to produce forward thrust. Of the wide variety of concepts examined, two appear to be practicable. The Sikorsky ROTOPROP$_{TM}$ is a propeller that swivels from a conventional tail rotor configuration at low forward speeds to a pusher-prop configuration at high speeds. The Piasecki Ringtail is a ducted pusher-prop with controllable deflector vanes to provide antitorque and directional control. The ROTOPROP requires less power than the Ringtail but represents a greater technical risk and a significantly greater safety hazard. A ducted ROTORPROP arrangement reduces this hazard, but at a further penalty in weight and risk. By the mid 1970's, a promising solution will be available that uses a compound turboshaft/turbofan engine in the fuselage and exhausts through deflector vanes in the tail fin. Currently, the risk is excessive.

No pseudo-compounds represent viable alternatives to the conventional tail rotor as specified for this study, because of the large difference in control, structure, and mission requirements between compound helicopters and pure helicopters. These effects result in a significant weight and cost penalty in converting a conventional helicopter into a compound. The factors that must be considered in evaluating alternative conversions of this type are beyond the scope of this preliminary comparison.

CONCEPT DEFINITION

Both of the concepts selected for further analysis (fan-in-fin and fan-in-tailcone) use a 12-bladed highly twisted prop-fan with a total activity factor of 2200. Figure 2 shows the prop-fan geometry used in the analysis of the fan-in-fin concept.

The fan-in-tailcone concept uses the same type of prop-fan, but axially driven, with flow straighteners positioned on the downstream side. Access to the prop-fan is a primary concern in design of the fan-in-tailcone. The two approaches considered were (1) to fold the tail pylon, as in the H-34, exposing the prop-fan, and (2) to gain access through a structural hatch in the tail cone. A more detailed study would be required to evaluate fully this structural and maintainability trade-off.

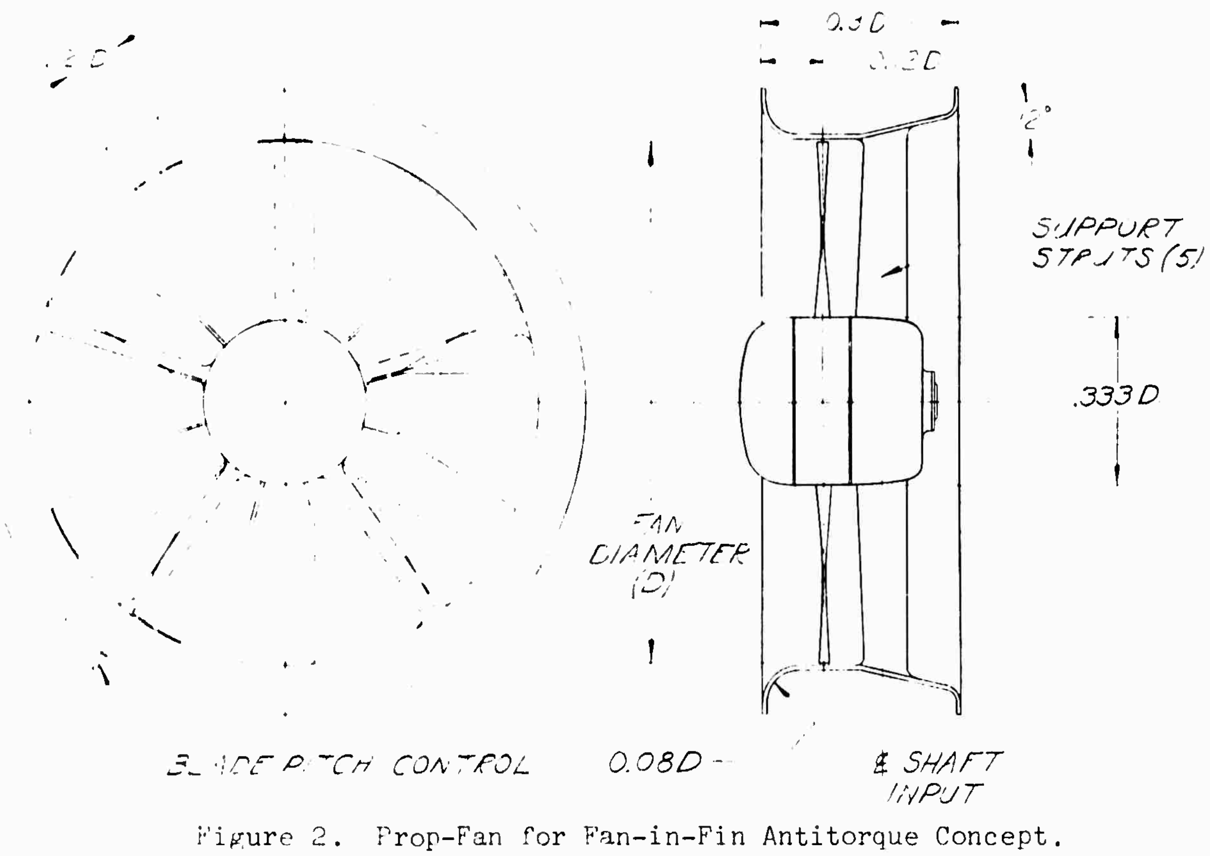


Figure 2. Prop-Fan for Fan-in-Fin Antitorque Concept.

General arrangement drawings of aircraft using these concepts are shown in Figures 3 and 4. The intent has been to make the aircraft as similar as possible to the base-line aircraft with tail rotor (Figure 1). Advanced technology engines, scaled to the exact aircraft requirements, are used for these designs. The engine size and performance characteristics approximate those of the Pratt and Whitney ST-9 and the General Electric GE-12.

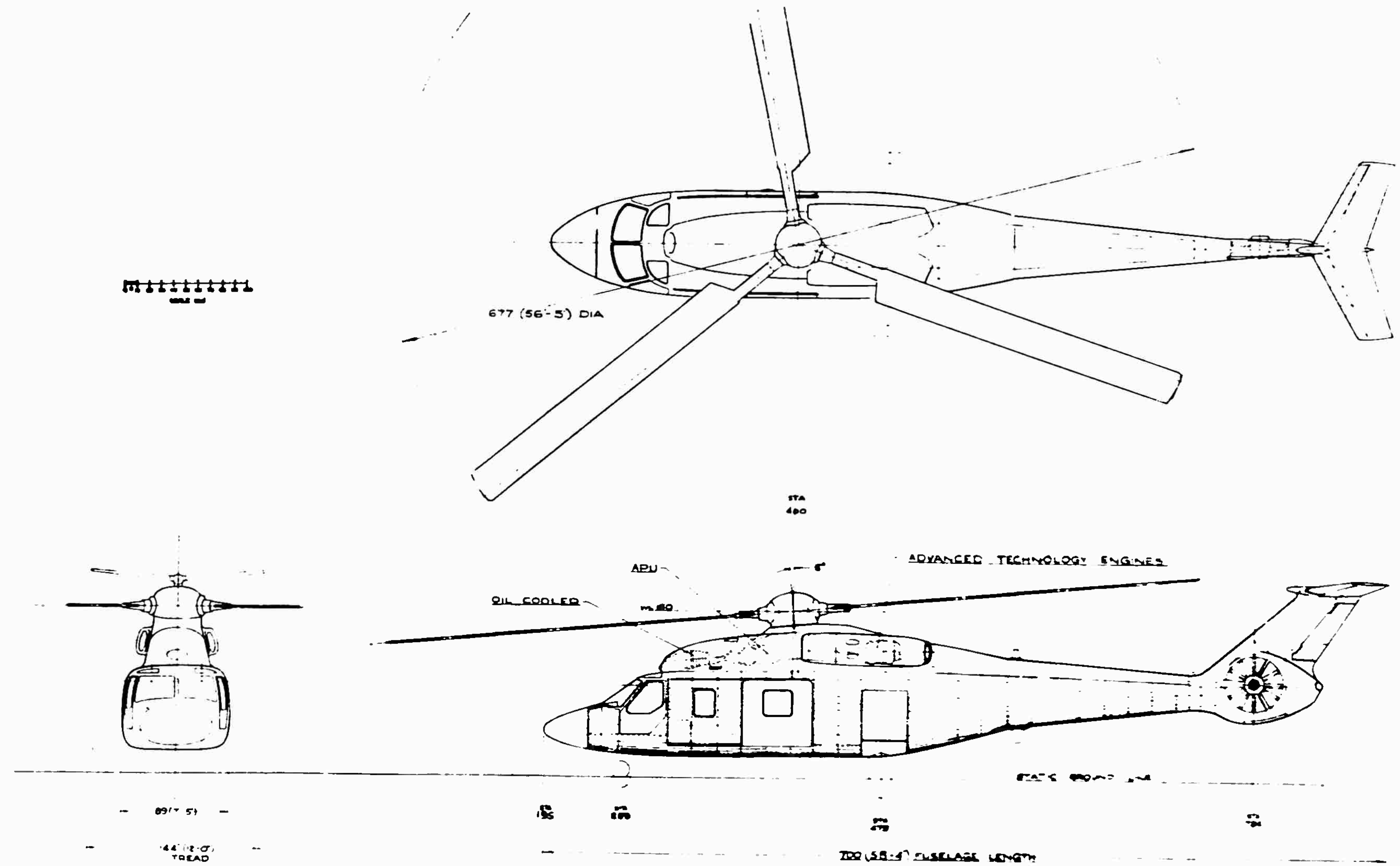


Figure 3. General Arrangement - Fan-In-Fin Configuration.

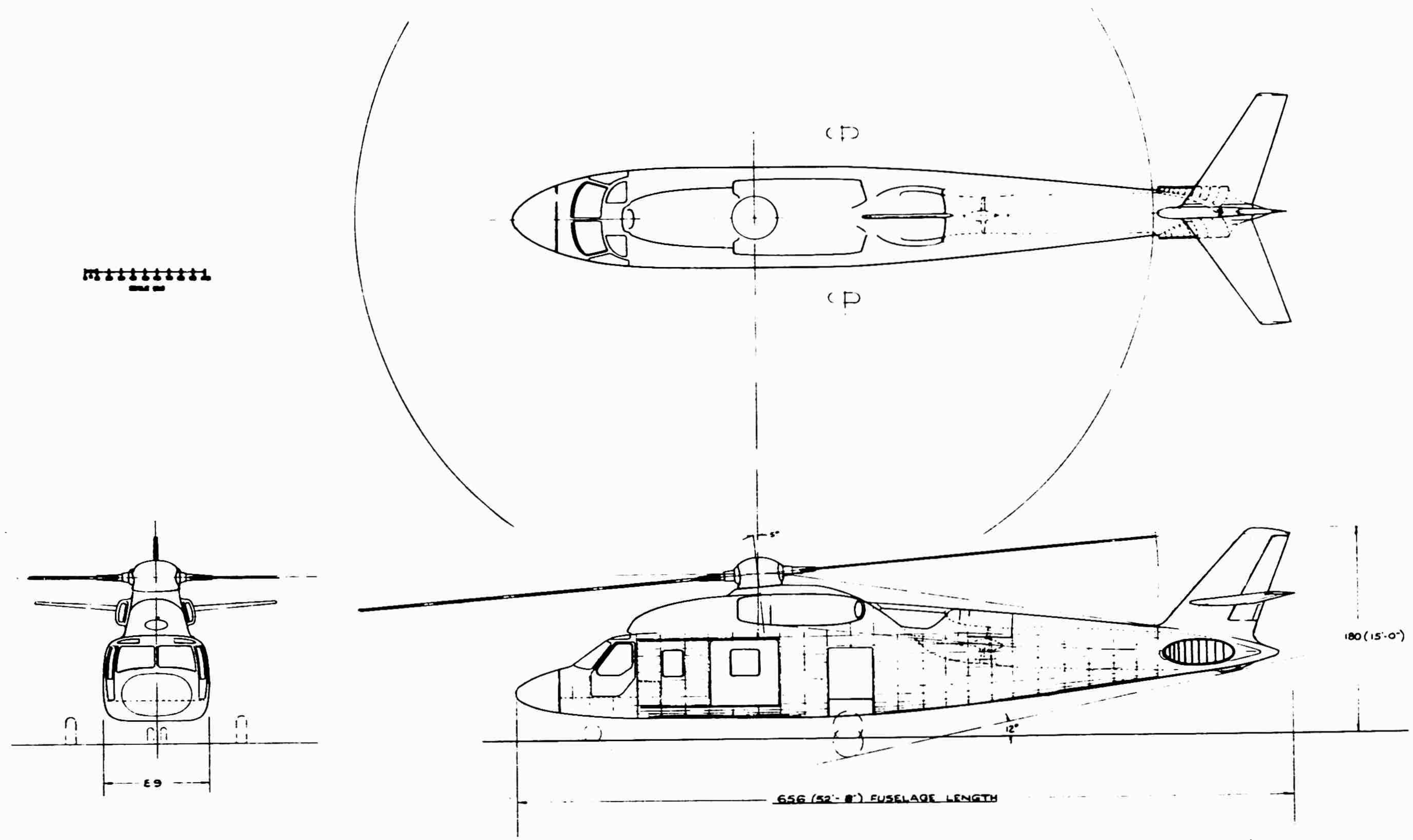


Figure 4. General Arrangement - Fan-In-Tailcone Configuration.

AIRCRAFT SIZING AND EVALUATION CRITERIA

A Sikorsky Aircraft design model (Appendix V) was modified to optimize the basic aircraft parameters for the antitorque devices selected for detailed study. The basic parameters are main rotor disc loading, main rotor C_T/σ, and percentage of available power allowed the antitorque device. These parameters must be optimized if a fair comparison of the alternative systems is desired.

The optimization parameter used in this study is an aircraft efficiency defined as

$$E = \frac{PL\ V_{cr}}{LCC}$$

where E = aircraft efficiency - pounds-knots/dollar

PL = design payload - pounds

V_{cr} = cruise speed at normal rated power - knots

LCC = aircraft 10-year life cycle cost - dollars

The aircraft efficiency parameter is considered to be a valid measure of aircraft performance potential. All the trade-off studies performed were based on aircraft with the required payload of 2640 pounds. The use of cruise speed at normal rated power is significant. It takes advantage of the speed potential not used in the study mission, which is an endurance mission rather than a range mission. This benefits concepts that have high hover antitorque power requirements that are reduced in forward flight.

Aircraft 10-year life cycle cost used in this study is based on the following parametric equations, derived from Army[2] data:

$$LCC = C_{FA} + C_o$$

$$C_{FA} = 19.71\ (W\ P)^{0.6} + 30{,}000$$

$$C_o = 15{,}820\ (W\ P)^{0.3}$$

where C_{FA} = total flyaway cost, including 30,000 for avionics - dollars

C_o = 10-year operating cost - dollars

W = aircraft empty weight - pounds

P = installed engine power - horsepower

The 10-year operating cost assumes an average use of 480 hours per year. These relationships represent a simplified cost model that can be used for rapid evaluation of alternative design features. They should not be used to estimate absolute life cycle cost for a particular aircraft.

MISSION DESCRIPTION

The aircraft mission profile and requirements used in this study are relatively demanding but reasonable for the next generation of squad carrier utility transport. The effects of the mission profile on the antitorque selection process are discussed in Task 5. The mission is defined as follows:

Altitude - feet	4000
Temperature - ^oF	95
Hover OGE at DGW, 95 percent Mil Power with 500 feet per minute VROC	
Mission Profile (3-hour mission)	
Warm-up	3 min @ NRP
Takeoff	1 min @ MRP
Cruise outbound	70 min @ 150 knots
Dash	15 min @ MRP
Hover	20 min OGE
Cruise inbound	70 min @ 150 knots
Approach and land	1 min @ NRP
Reserves	20 min @ 150 knots
Payload	11 troops @ 240 pounds each
Crew	3 @ 200 pounds each

PERFORMANCE METHODS

Hover

Main-rotor and tail-rotor hover-power-required information for the Task 2 aircraft was calculated using the figure-of-merit ratic method [3].

This method uses a correction term to account for the differences between hover test data and the maximum figure of merit, including profile drag on an ideal rotor.

The maximum figure of merit is calculated from

$$FM_{MAX} = \frac{C_T^{3/2}}{\left(\frac{C_T^{3/2}}{B\sqrt{2}} + \frac{\sigma \delta_b}{8} \right) \sqrt{2}}$$

where B = tip loss (=0.97)

$\delta_b = .0087 - .0215\alpha + .4\alpha^2$

$\alpha = 6\ (C_T/\sigma)\ (1/a)$

a = slope of the lift curve (=5.73)

The factor, $\sqrt{2}$, represents the contraction of the flow downstream from an unshrouded rotor.

The figure of merit for isolated rotors has been measured and compared with the maximum figure of merit. After the effects of twist and cutout are removed (these are the only isolated effects now used to correct base data), the ratio of actual figure of merit to maximum figure of merit is computed. The method, depending heavily on test data, should be used for conventional rotors only.

Forward Flight

Forward flight performance was calculated using a semiempirical nondimensional performance method. An energy method is the base, and corrections are made to this "ideal rotor" for tip losses, profile drag, vertical drag, parasite drag, compressibility, blade stall, and blade interference effects. The effects of Reynolds number and skewed flow are also taken into consideration.

A continuous set of equations is used for hover, level forward flight, and climb. The empirical relations used were developed from S-55 (UH-19), S-56 (CH-37), and S-58 (CH-34) flight; whirlstand testing ; and NASA Ames wind tunnel data. As other data became available (S-61, S-62, S-64 (CH-54A & CH-54B), and S-65), they were checked against the method and found to be in excellent agreement. Although not a rigorous analytic procedure, the approach offers the best present method for overall performance prediction.

Shrouded Prop-Fan Performance

The performance of prop-fan systems was calculated using a digital computer program based primarily on Hamilton Standard wind tunnel data. Some of the Hamilton Standard data were acquired from three- and four-bladed shrouded propeller tests in the 18-foot low-speed test section (Mach numbers less than 0.2) and the 8-foot high speed test section (Mach numbers between 0.2 and 0.5) of the United Aircraft Research Laboratories subsonic wind tunnel facility. Shroud and propeller configuration were varied in these tests, including propeller position in the shroud, propeller planform, tip clearance, number of blades, shroud length, shape and exit area ratio, and lip shape. Also studied were the effects of inlet and exit guide vanes.

Recently, a shrouded prop-fan similar in design to the configurations chosen for antitorque was tested in the 8-foot section in the UARL subsonic wind tunnel. Only one basic model configuration was tested in this test, and the test did not include any static cases. Static thrust and power were derived from nonstatic test data from the relationships of Appendix

III of HSIR 2836[4]. Figure 5 shows these results in terms of $C_{T_{net}}/C_P$ versus C_P.

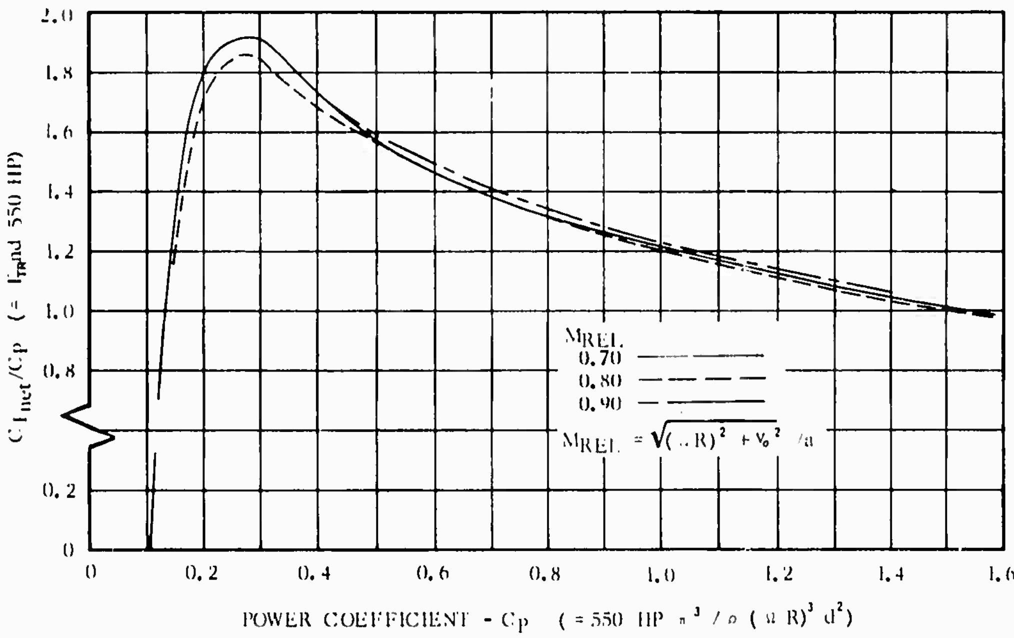


Figure 5. Nondimensional Prop-Fan Performance - Static, TAF = 2200.

The effect of swirl recovery vanes was determined, using a linear extension of the thrust increase for vanes at Mach numbers from 0.2 to 0.5. This extrapolation, which is slightly conservative, is shown in Figure 6.

The effect of duct length on net thrust for short ducts was applied to the prop-fan data, using a correction on exit area ratio [5, 6]. This correction is shown in Figure 7. Prop shroud length eliminates contraction and aids diffusion, so shroud length effect can be included in the area ratio correction described below.

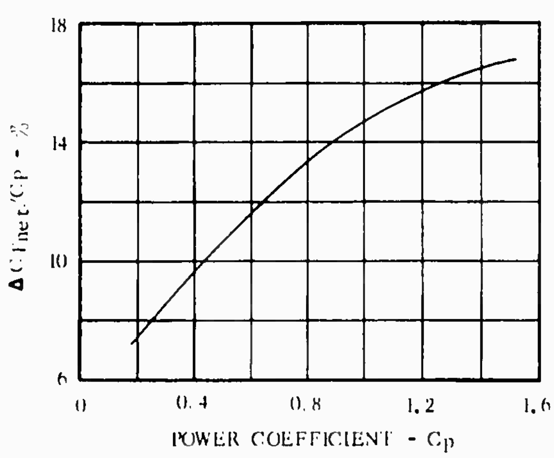


Figure 6. Effect of Prop-Fan Swirl Recovery Vanes on Performance - TAF = 2200.

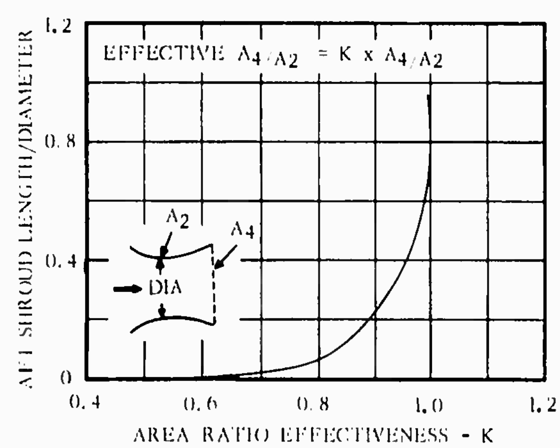


Figure 7. Effect of Prop-Fan Shroud Length on Performance.

Since thrust is proportional to the cube root of the area contraction ratio of the stream tube downstream of the propeller, the area of the shroud exit is proportional to the thrust. The thrust values from the prop-fan test were for a near optimum shroud exit area ratio of 1.3, and the thrust correction for the area was made from this base.

Hamilton Standard data and NACA TN 4126[6] show that a lip radius of approximately 8 percent of the propeller diameter is required to retard separation. This value was used exclusively in this study, and the shroud length in front of the fan was assumed as not contributing to the shroud length for the area ratio correction.

The effect of change in total activity factor (TAF) from a base total activity factor of 2200 is small, as shown in Figure 8. The operating regime of the Task 2 prop-fan for the fan-in-tailcone configuration is such that a TAF of 2400 shows a 0.5-percent gain in thrust above a TAF of 2200 for the maximum control requirements, while a TAF of 1800 shows a 0.7-percent gain over a TAF of 2200. A TAF of 2200 provides the best overall performance for antitorque application. For the fan-in-fin configuration, a TAF of 2200 is optimum for maximum control. A TAF of 1700 shows a 1.5-percent gain over a TAF of 2200 for the steady condition. A total activity factor for this configuration of about 1900 would reduce the zero thrust profile power, but for normal hover, the potential gain is small.

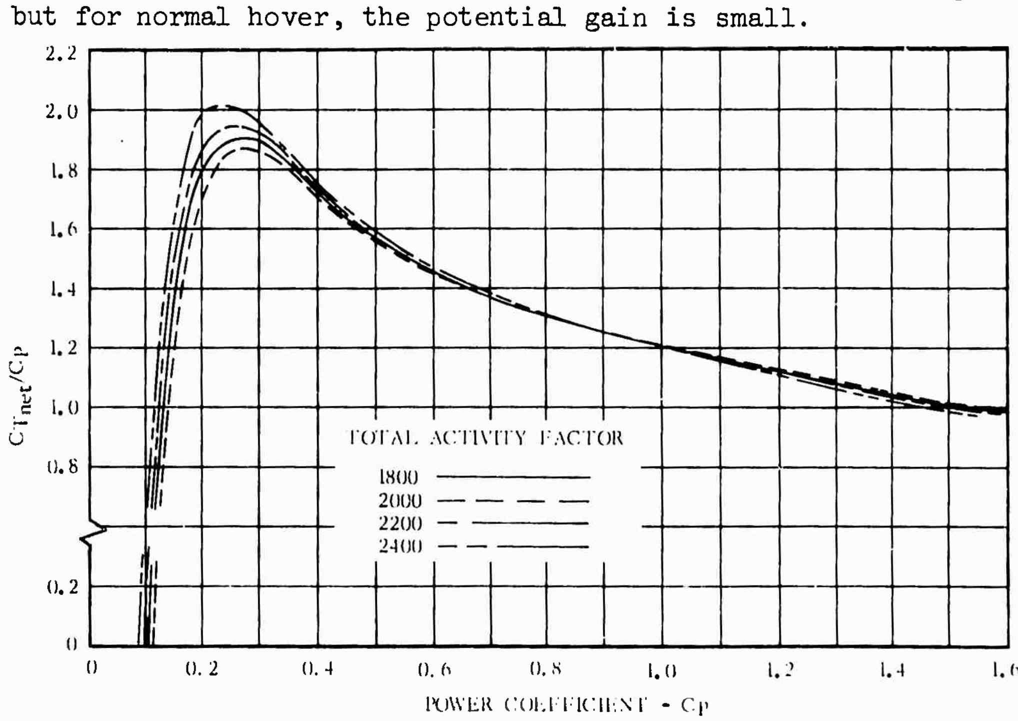


Figure 8. Effect of Prop-Fan Activity Factor on Performance - Relative Mach No. = 0.8.

In order to maintain blade clearance so that reverse thrust is possible, the fan blades must be tapered near the root to allow negative blade angles. Final design is for a blade with a blade chord/fan diameter equal to 0.121, tapering to 0.084 at the root. This will allow a spacing of 0.3 inch between each blade near the root for a 4-foot-diameter system. The blade is rectangular in planform for the outboard 52.5 percent of the radius. Hub diameter was selected to be one-third of the fan diameter to allow adequate space for gearboxes and the blade pitch control mechanism.

Nominal blockage, interference, and other losses associated with installation of a tail rotor or a prop-fan in a helicopter were calculated. The tail rotor is subject to a 5-percent loss based on thrust due to inflow interference of the tail rotor pylon. The fan-in-fin installation deliminates this loss, since it is buried in the tail fin, but it has other compensating losses of 5.5 percent. These include drive shaft and control line blockage and suction drag, equivalent to rear body form drag, of the airflow on the aft corners of the center body and the fan exit rim. The fan-in-tailcone has losses of approximately 17 percent due to duct friction, flow turning, and shaft drag.

Fan-In-Tailcone Duct Losses

Fan-in-tailcone duct flow inefficiencies arising from skin friction and turning losses were estimated for a typical Task 2 aircraft configuration. The resulting overall duct efficiency was converted to an effective prop-fan blockage percentage that was assumed to be constant over the size range ofsimilarly configured vehicles investigated. A separate analysis was made for the S-58T flight vehicle proposed in Task 3.

The losses associated with individual duct components (inlet, turns, straight sections, deflector valve and exhaust nozzle) were estimated as fractions of the local dynamic pressure (q) from previously published results [7, 8] for general geometric forms and from Sikorsky Propulsion Group experience.

Effective blockage is determined by estimating a representative dynamic pressure at each of the duct components corresponding to the required net thrust with zero duct losses. The pressure drop (Δ p) arising from each individual component is then determined. The previously computed prop-fan pressure ratio corresponding to zero duct losses is then altered by these incremental pressures. Effective duct blockage is defined as the ratio of thrust obtained if duct losses are neglected, to the thrust actually produced, and is obtained as a simple function of the prop-fan pressure ratios with and without duct losses:

$$\text{Blockage Factor} = \frac{\left[PR^{(\gamma-1)/\gamma}-1\right]_{\text{with losses}}}{\left[PR^{(\gamma-1)/\gamma}-1\right]_{\text{without losses}}}$$

For the typical case chosen to evaluate this blockage, a duct area of 7.07 square feet and a required thrust of 2238 pounds were taken at an altitude temperature condition of SL 95°F. The loss breakdown for this condition is given in Table III.

TABLE III. FAN-IN-TAILCONE DUCTING LOSSES			
Component	$\Delta p/q$	q (psf)	Δp (psf)
Inlet (including drive shaft)	0.05	138	6.9
12° Turn	0.031	225	7.0
Straight Duct (14 feet)	0.0036/foot	170.4	8.52
Deflector Valve	0.0	170.4	0.0
90° Turn (9 turning vanes)	0.04	170.4	6.81

The no-loss pressure ratio was computed to be 1.083. With losses, the value was approximately 1.097, leading to an effective blockage value of 1.168.

CONCEPT COMPARISONS

Mission Performance

Table IV gives the design parameters for aircraft using the three antitorque concepts under comparison. These aircraft represent near-optimum solutions in terms of main rotor disc loading, main rotor blade loading, and antitorque device sizing. These optimizations, along with other design criteria sensitivity studies, are discussed in more detail under Task 5.

Stability and Control (Hover and Low-Speed Flight)

This section discusses the stability and control requirements of tail-rotor helicopters. It also presents possible problem areas for the fan-in-fin and fan-in-tailcone antitorque devices, and how they compare with the tail rotor.

Even though tail rotors have been used for many years as antitorque devices for shaft-driven single-rotor helicopters, improvement is still needed in certain aspects of handling quality. In many cases, trade-offs have to be considered that would lessen the undesirable characteristics of the tail rotor without creating new problems.

For example, there is the question of handling characteristics when the tail rotor drive becomes inoperative. In this emergency, the pilot must react rapidly. In most helicopters, he must take immediate action to enter autorotation, where no antitorque requirement exists.

Although loss of antitorque capability is very serious in hover or at low speeds, it need not be at moderate to high forward speeds. With proper sizing of the vertical tail, the helicopter can continue in forward flight. Tests of flight boundaries without a tail rotor have been conducted on the

TABLE IV. AIRCRAFT DESIGN PARAMETERS AND CRITERIA

Antitorque Concept	Tail Rotor	Fan-in-Fin	Fan-in-Tailcone
Design Gross Weight - lb	15,103	16,474	17,483
Aircraft Efficiency - lb kn/$	0.1388	0.1293	0.1213
Alternate Gross Weight - lb	18,124	19,769	20,980
Disc Loading - psf	6.0	6.0	6.0
Main Rotor Diameter - ft	56.6	59.1	60.9
Number of Main Rotor Blades	4	5	5
Main Rotor Blade Chord - ft	1.825	1.649	1.734
Main Rotor Solidity Ratio	0.0821	0.0888	0.0906
Main Rotor Tip Speed - fps	700	700	700
Main Rotor Blade Loading (C_T/σ)	0.080	0.0725	0.074
Tail Device Tip Speed - fps	700	800	950
Tail Device Diameter - ft	10.6	4.60	3.43
Tail Rotor Max. Blade Loading (C_T/σ)	0.12	-	-
Tail [illegible]de Chord - ft	0.660	-	-
Tail Rotor Solidity Ratio	0.198	-	-
Prop-Fan Total Activity Factor	-	2200	2200
Number of Tail Device Blades	5	12	12
Max. Tail Device Thrust Required - lb	2180	2475	2767
Max. Tail Device Power Required - HP	534	924	1343
Power Available at AGW Condition - HP	2359	2953	3483
Installed Shaft Horsepower	2835	3549	4186
Drive System Design Horsepower	2359	2953	3483
Empty Weight - lb	9582	10,455	11,141
Mission Fuel - lb	2232	2717	3028
Design Payload - lb	2640	2640	2640
System Efficiency in Hover			
at DGW	0.852	0.806	0.791
at AGW	0.837	0.728	0.655
System Efficiency in Cruise			
at DGW	0.921	0.869	0.877
Parasite Drag - ft^2	13.4	14.2	16.9
Vertical Drag - % GW	3.0	3.0	3.0

Sikorsky S-58. Results indicated that the aircraft could maintain adequate static stability even in climb at speeds between 40 and 80 knots. Addition of a rudder could give the aircraft adequate maneuver control with the primary antitorque device inoperative.

The tail rotor also is highly sensitive to gusts, since its thrust to angle-of-attack derivative is relatively high. Keeping the tail rotor size down helps this situation. Sensitivity can also be reduced by appropriate sensing of gusts and application of corrective control through feedback.

In the interest of ground clearance and personnel safety, tail rotors are usually placed above the aircraft center of gravity, but this creates both rolling and yawing moments after pedal displacements. If too pronounced, this type of coupling can degrade aircraft handling qualities. Control coupling of lateral cyclic to pedal input can minimize this problem, but pilot opinion must be considered, since automatic control coupling limits the lateral control available to the pilot.

Roll attitude during hover is another characteristic of single-rotor helicopters that is directly related to the height of the tail rotor above the center of gravity. Most single-rotor helicopters hover with the left wheel low. The nonlevel attitude is caused by the fact that the lateral cyclic applied in hover to counteract tail rotor thrust also creates a head moment. To balance both lateral force and rolling moment, a force contribution from the aircraft weight results in a small roll angle. For any given helicopter, the roll angle required depends on the vertical placement of the tail rotor. As the tail rotor moves higher, less roll angle is necessary. Alternatively, application of lateral shaft tilt to the main rotor relieves this problem. However, the high placement aggravates the coupling characteristic, and the lateral shaft tilt creates other attitude considerations in low-speed approaches. A compromise must be reached that considers all these factors.

The fan-in-fin characteristically has a nonlinear thrust to pedal displacement derivative with an almost flat slope at the zero thrust level. The fan-in-fin should be designed to carry some load on the fan at high speed to avoid this null area, but the null must be traversed in going into autorotation.

Information from Sud Aviation indicates that a hydraulic servo-control is necessary in the Fenestron gearbox since control loads in hover are high. These loads result from designing the fan blades to give low control loads in high-speed flight. The fan-in-fin prop-fan, therefore, will require hydraulic boost for control.

Because the fan-in-fin and fan-in-tailcone will be at about the same height as the aircraft center of gravity,the coupling of roll to yaw previously mentioned for the tail rotor will be less severe. This, however, will aggravate the hover trim attitude of the aircraft, due to the additional lateral cyclic required. Again, a compromise must be considered.

Helicopters fitted with either of the fan configurations will be more stable in the event of loss of antitorque power than will the tail rotor configuration, since the vertical tails will be designed larger. This sizing will provide the adequate static directional stability that the tail rotor provides in a conventional helicopter, yet the larger vertical fins will reduce the lateral maneuverability of these aircraft compared with the tail rotor version. To maintain a comparable value with the tail rotor, rudders are incorporated in these designs.

The fan-in-tailcone has problems that will be unique to this concept. The first will be a delay in response time due to losses in the ducting, creating serious problems in meeting MIL-H-8501A response criteria. Another problem will be the nonlinear control response in autorotation due to the thrust deflector valve used in this design.

In summary, neither fan configuration offers an improvement over the tail rotor in regard to stability and control. The device with the highest unknown factor appears to be the fan-in-tailcone device.

High Speed Dynamics

Characteristics of the tail rotor at high forward speed are well known. The fan-in-fin and fan-in-tailcone are expected to perform better than the tail rotor in this flight regime. As tail rotor helicopters are presently designed, the tail rotor must provide high levels of thrust for antitorque control at high speeds, and the rotor approaches stall as speed is increased. During maneuvers, particularly nose left, high blade stress levels can be encountered due to stall. One solution is to increase the vertical fin area or improve the vertical fin airfoil section so the tail rotor unloads in forward flight. A larger tail would reduce directional maneuverability somewhat unless a rudder were added, but this would complicate the control system. A compromise must be arrived at, therefore, depending on helicopter mission requirements.

Tail shake is sometimes encountered when the main rotor downwash impinges on the tail rotor during high-speed flight. Helicopter trim attitude can usually be controlled so that the tail rotor is not in the main rotor wake, but the tail rotor can traverse this flow during certain maneuvers. This often results in high transient vibrations.

Because the prop-fan is operating in a shroud for the fan-in-fin configuration, this device should be less affected by main rotor wake than the tail rotor. This same shroud, however, is subject to forward lip stall in forward flight, causing high blade stresses and increased vibration. Lip stall detracts from fan-in-fin performance if the fan is operating at high loadings. Therefore, the fan is unloaded in high-speed flight by the relatively large vertical tail surface required for stability.

The fan-in-tailcone appears to be the best of the three designs in regard to high-speed dynamics, since the generation of thrust is relatively independent of ambient flow conditions.

Reliability and Maintainability

Based on a helicopter of approximately 12,000 pounds empty weight, baseline reliability/maintainability values for the conventional tail rotor system were derived from a 68,457-flight-hour sample of H-53 data. The data were reported by the U.S. Navy Maintenance and Materiel Management (3M) data collection system. Using these values as a point of departure, similar values were calculated for the fan-in-fin and fan-in-tailcone antitorque systems. Adjustments were made in the data to account for basic system differences, such as reduction in number of major components, size and weight of components, improved accessibility, and reduction of failures caused by stress, fatigue, foreign object damage, or maintenance errors. The calculated value for each of the two advanced antitorque systems was then extrapolated to establish: (1) best-case value, (2) median value, and (3) worst-case value. Table V presents the ranges of reliability and corrective maintenance values established.

TABLE V. COMPARISON OF ANTITORQUE SYSTEM R/M VALUES

Antitorque Subsystem	Conventional Tail Rotor	Fan-in-Fin			Fan-in-Tailcone		
		Worst	Median	Best	Worst	Median	Best
Mean Time Between Failures - hr	35	36	47	54	39	48	57
Mean Time Between Maint. Actions - hr	23	35	38	41	38	42	46
Maint. Man-Hours Per Flt-Hr	0.161	0.173	0.145	0.118	0.129	0.117	0.105
Maint. Down-Hours Per Flt-Hr	0.069	0.070	0.055	0.041	0.065	0.057	0.049

Analysis of the values indicates that each of the advanced antitorque systems has the potential for significant reliability and maintainability improvement relative to the conventional tail rotor system. Both alternative systems require fewer major components and afford easy access for maintenance. The blades are less vulnerable to foreign object damage and are not subject to wear encountered on conventional flap-hinged tail rotors. The potential hazard to ground personnel from exposed blades is minimized. Stresses applied to the blades and transmission system are not as severe as in a conventional system, since these components are subjected to high loads only during hover.

The fan-in-tailcone configuration poses problems with respect to fan assembly access that will require careful attention during detail design if the full potential of this concept for maintainability improvement is to be realized. A hinged tailcone arrangement has been suggested for rapid access to the fan assembly, and the values presented in Tables V and VI assume that this is the case.

The values presented in Table VI are those predicted for a vehicle of approximately 12,000 pounds empty weight and represent the nonbiased, or median, value calculated for eacn advanced antitorque concept at the organizational and direct support levels of maintenance.

TABLE VI. ESTIMATED ANTITORQUE SYSTEM RELIABILITY AND MAINTAINABILITY

	Conventional Tail Rotor	Fan-in-Fin	Fan-in-Tailcone
<u>Reliability</u>			
Mean Time Between Failures			
Total - hr	35	47	48
Downing - hr	389	521	529
Aborting - hr	1770	2370	2405
<u>Maintainability</u>			
Corrective Maintenance			
Mean Time Between Maintenance Actions - hr	23	38	42
Maintenance Man-Hours Per Flight-Hour	0.161	0.145	0.117
Down-Hours Per Flight-Hour	0.069	0.055	0.057
Preventive Maintenance			
Man-Hours Per Flight-Hour	0.099	0.061	0.069
Down-Hours Per Flight-Hour	0.008	0.004	0.005
Total			
Maintenance Man-Hours Per Flight-Hour	0.260	0.206	0.186
Down-Hours Per Flight-Hour	0.077	0.059	0.062

Safety

Army accident records, representing 4,788,670 flight-hours, from September 1968 to September 1969, were analyzed. Representative figures were obtained for the frequency of accidents due to strikes by tail rotor blades, with each occurrence classified with respect to damage in four categories (strike, major, minor, or incident). A summary of these accidents is given in Table VII.

TABLE VII. ARMY HELICOPTER ACCIDENTS DUE TO TAIL ROTORS

Aircraft Type	Accident Category				
	Strike	Major	Minor	Incident	Total
UH-1	8	34	5	100(5)	147(5)
OH-23	-	7(1)	1	20(1)	28(2)
OH-6	-	2	-	27(4)	29(4)
OH-13	-	4	1	15	20
TH-55	-	1	-	25	26
TOTAL	8	48(1)	7	187(10)	250(11)

The numbers in parentheses are accidents that involve personnel hit by tail rotors.

Care was taken in extracting the initial data to eliminate instances of collisions with the tail boom as opposed to the tail rotor blades, since this type of accident is applicable to all three configurations. In general, tail boom strikes outnumber blade strikes by approximately two to one. In addition, the data of Table VII do not include accidents involving objects blown or sucked into the tail rotors. This type of accident is possible for both the fan-in-fin and fan-in-tailcone configurations, although with the fan-in-tailcone inlet under the main rotor, the probability should be reduced considerably.

Accidents involving personnel should be reduced greatly with either device. One would not expect ground personnel to run into the fan-in-fin, which is shielded by a shroud that is visible even during operation. However, the suction field present near the inlet would be a hazard. Covering the inlet with a screen or grill may reduce this hazard, but potential clogging and icing problems would have to be considered. The fan-in-tailcone configuration will eliminate the possibility of personnel being sucked into the prop-fan. While high-velocity exhaust flow would still be a hazard, the danger would not be as great because personnel would be blown away from the aircraft.

Accidents involving terrain/thruster contact would be eliminated almost completely with either configuration, as both shield the thruster with structure. The danger of pushing the structure into the thruster exists for what would be called a tail boom strike for a helicopter with a tail rotor. With good design practice, this danger should not be significantly greater than the danger of damaging the tail rotor drive and control system during a tail boom accident.

Vulnerability

The relative vulnerability of aircraft using tail rotor, fan-in-fin, or fan-in-tailcone antitorque concepts to a 7.62mm and 12.7mm API threat was estimated, assuming Sikorsky S-61 helicopter vulnerable areas [9] to be representative of the base-line tail rotor value.

Each of the three alternative designs includes a vertical tail fin adequate to provide antitorque control at forward speeds greater than approximately 50 knots. Thus, the tail thruster (in either of the three concepts) and its associated drive system contribute to "K" kill vulnerable areas only in hover and forward speeds below 50 knots. The reduction in total aircraft "K" kill vulnerability due to the use of fan-in-fin on fan-in-tailcone concepts is less than 1 percent, for both 7.62mm and 12.7mm API threat levels.

Antitorque system "A" kill vulnerable areas include shafting, gearboxes, and rotor (or prop-fan) blades. Both new concepts reduce the required shafting and the number of gearboxes. Loss of a single blade from the 12-bladed prop-fan used in both new concepts is judged to be significantly less likely to result in loss of the entire system than would be the loss of a blade from a typical 4-bladed tail rotor.

For aircraft in the 15,000-pound gross weight range, tail rotors and tail drive systems are relatively invulnerable to 7.62mm. The reduction in "A" kill vulnerable areas to this threat is estimated to be approximately 3 percent for both the fan-in-fin and the fan-in-tailcone configurations. For the 12.7mm API threat, however, the additional simplification and compactness of the new antitorque systems is much more effective. The reduction of aircraft "A" kill vulnerable areas to this threat is predicted to be 19 percent for the fan-in-fin and 26 percent for the fan-in-tailcone.

Vulnerability to terrain contact damage has been discussed in the previous subsection.

Aural Detectability and Annoyance

Separate noise analyses were made of near-optimum solution aircraft employing tail rotor, fan-in-fin and fan-in-tailcone concepts. In each analysis, the aircraft were assumed to be hovering at an altitude of 50 feet over sparse jungle terrain. Standard values [10] for terrain attenuation and atmospheric absorption coefficients were used. Techniques appropriate to each concept were employed to predict both noise intensity and frequency content.

Tail rotor noise estimates, including separate broadband and discrete frequency (rotational noise) components, are based on measured data scaled to account for effects of radius, tip speed, number of blades, blade area, and thrust.[11, 12]

Estimates of fan-in-fin noise levels were based on a preliminary prop-fan noise estimating procedure developed by the Hamilton Standard Division of United Aircraft Corporation and known to correlate well with measured noise octave band spectrum shape data from model tests. Sikorsky and Hamilton Standard engineers predict such prop-fan model tests to show a 3 PNdB optimism compared to a similar prop-fan installed in an aircraft, arising from neglecting thruster wake interaction with the supporting structure associated with the installed fan. Therefore, perceived noise levels predicted by the preliminary method were increased by 3 PNdB to predict the noise level of the installed fan-in-fin configuration. No references have been published to officially document the prop-fan noise estimating procedure as of January 1, 1971.

Estimates of fan-in-tailcone noise include contributions from downstream supports, flow straightening vanes, inlet flow turbulence, and the fan. The similarity of the fan-in-tailcone configuration to that of an axial compressor permits direct application of the compressor noise analysis techniques.[13]

This method considers the system geometry, fan tip speed, number of blades and vanes, air mass flow, and applied power to calculate system noise. Correlation of predicted noise levels with a limited number of noise measurements of operating compressors has verified the usefulness of this approach.

The basic conclusions arising from these analyses are: (1) both of the proposed concepts offer a significant reduction in detection range compared to the tail rotor, but (2) for aircraft optimized for maximum productivity per life cycle dollar (as defined under "Aircraft Sizing and Evaluation Criteria"), both concepts represent a greater acoustic annoyance, in terms of perceived noise level, than does the tail rotor. These results are summarized in Table VIII. It is seen that the detection range of the tail rotor is roughly twice that of the alternative concepts, while tail rotor perceived noise level is between 6 and 9 dB less than that of the alternatives. The calculated detection ranges are estimates suitable for ranking the relative detectability of the concepts and not for assigning absolute distances. Detectability in comparison with the tail rotor is improved because of the shift of acoustic energy from the relatively low-frequency pure tones associated with the tail rotor to higher frequency components between 1 kHz and 4 kHz for which terrain attenuation and atmospheric absorption have more effect.

This frequency shift, while reducing detectability, concentrates the acoustic signature of the fan-in-fin into a more annoying region, significantly increasing the predicted perceived noise level.

In the fan-in-tailcone configuration, noise from the downstream supports controls the acoustic signature in the mid-frequencies and above, while jet noise from the exit nozzle dominates the low frequencies. Noise from the fan is negligible compared to that from the interaction between the fan wake and its supporting structure and associated flow straighteners. This interaction produces high discrete frequency noise levels, which dominate any broadband noise produced and lead to the high annoyance levels shown in Table VIII.

TABLE VIII. QUANTITATIVE ACOUSTIC COMPARISON

	Tail Rotor	Fan-in-Fin*	Fan-in-Tailcone**
PNL @ 500 Feet - PNdB	87	96	93
Detection Range - ft	6700	3000	3700
Antitorque Power - hp	185	500	565
Diameter - ft	13	4	3
No. Blades	5	12	12
Tip Speed - fps	700	950	950

* Includes allowance for acoustic penalties of downstream stator close to rotor, and short shroud.

**PNL and detectability for bare duct.

Because noise reduction was not specified as one of the prime objectives of this study, solution aircraft parameters were selected on the basis of overall system efficiency rather than acoustic characteristics.

A brief study of the effects on noise signature of alternative fan and tail parameters indicated that more emphasis on noise reduction could lead to significant improvement in this area without excessive degradation in aircraft efficiency. In particular, efficiency optimization resulted in prop-fan solution disc loading and tip speed significantly higher than would be desirable from an acoustic standpoint. In addition, the proximity of fan support members to the fan blades, optimized from weight and fan efficiency considerations, is costly in terms of interference noise.

Of the two new concepts, the fan-in-tailcone possesses the greater potential for acoustic improvement over the tail rotor. This reflects the relative ease with which the structure downstream from the prop-fan can be acoustically treated. It is estimated that the PNL from this source could be reduced between 5 and 10 PNdB through alteration of the support strut axial displacement and geometry to separate the fan and struts by at least two fan blade chord lengths, and by lining the exit turning vanes with acoustically absorbent material. Treating the turning vanes was determined to be preferable to treating the duct wall itself, both from weight and acoustic considerations, but no detailed formulation of an overall system efficiency trade-off was attempted.

An examination of the effects of prop-fan tip speed on both aircraft noise and efficiency is described under "Antitorque Tip Speed Sensitivity" in Task 5. This examination suggests that a reduction in tip speed is effective in reducing perceived noise level in both concepts. Only a marginal reduction in detectability range was noted. Tip speed reduction has a slightly more limited application in the fan-in-tailcone configuration because of the rapid increase in DGW with decreasing tip speed below roughly 750 feet per second.

Geometric constraints on the fan-in-fin configuration, especially limits on overall duct length, severely restrict the acoustic improvement available through rearrangement of the fan supports. Acoustic lining of the duct and placement of the supports at least two blade chord lengths downstream from the fan are predicted to reduce the PNL by up to 5 PNdB. Again, the resulting penalties in aircraft weight, performance,and cost were not evaluated. It is likely, however, that rearrangement of supports would impose greater penalties on the fan-in-fin than on the fan-in-tailcone.

Foreign Object Damage

The fan-in-fin configuration may be more susceptible than a tail rotor to foreign object damage, because the device is located no higher above the ground than the tail rotor and would suck in larger objects due to its higher disc loading. The fan-in-tailcone configuration represents an improvement over the tail rotor because the air to the prop-fan passes through the center of the main rotor disc, eliminating the hazard from heavy objects that would not be recirculated. Both concepts could operate in similar erosion environments. The fan-in-fin configuration is considered to be better in this area because lower prop-fan tip speeds are feasible.

SELECTION OF BEST CONCEPT

Cost Study

Both the fan-in-fin and fan-in-tailcone meet the objectives of this study by offering improvements in all the areas specified by the contract statement of work. An attempt has been made to cost these improvements. The analysis, of course, is highly dependent on the ground rules assumed.

Table IX shows the estimated correction to the basic life cycle cost estimate due to the aircraft characteristics that vary from the conventional tail rotor. The total saving due to these differences is about 1 percent of the life-cycle cost estimate, which is based on aircraft installed power and empty weight. This saving may fall within the accuracy of the aircraft life cycle cost trend, so the only conclusion drawn from these data is that, for the ground rules of this study, a tail rotor is still the least expensive antitorque system for the aircraft design requirements and mission specified for this study.

TABLE IX. EFFECTS OF OPERATIONAL CHARACTERISTICS ON LIFE-CYCLE COST			
Operational Characteristics	Antitorque Concept		
	Tail Rotor	Fan-in-Fin	Fan-in-Tailcone
Basic Life-Cycle Cost (LCC), Weight & HP Only - $	3,286,828	3,667,556	3,978,018
Basic LCC Ratio	1.000	1.116	1.210
Reliability Saving - $	-	265	359
Maintainability Saving - $	-	12,673	17,695
Vulnerability Saving - $	-	4,320	3,687
Safety Saving - $	-	8,006	8,842
Adjusted Life-Cycle Cost - $	3,286,828	3,642,292	3,947,435
Adjusted LCC Ratio	1.000	1.108	1.201

The approach used to estimate the cost adjustments shown in Table IX are briefly outlined below.

Reliability

The mean times between failures (MTBF) in hours resulting in a mission abort for the three configurations are estimated as:

Conventional Tail Rotor	1770
Fan-in-Fin	2370
Fan-in-Tailcone	2405

Applying these figures to an assumed average mission length of 3 hours, mission abort rates are computed, leading to the following relative probabilities of successful mission completion:

Conventional Tail Rotor	0.99831
Fan-in-Fin	0.99868
Fan-in-Tailcone	0.99875

For 100% mission completion, the respective fleet sizes would be increased by the reciprocal of these probabilities. The resulting fleet size ratios for the two fan configurations are subtracted from the ratio for the tail rotor to obtain relative savings ratios. The latter are applied to the basic flyaway costs for the two configurations to obtain relative savings in dollars.

Maintainability

The relative maintenance man-hours per flight-hour for the three anti-torque systems are estimated as:

Conventional Tail Rotor	0.260
Fan-in-Fin	0.206
Fan-in-Tailcone	0.186

A representative MMH/FH figure for the complete base-line (tail rotor) aircraft based on UTTAS design studies is 9.0. The relative saving in man-hours is computed as the difference in the tail system maintenance man-hours quoted above as a proportion of the total aircraft man-hours, giving the following savings:

Fan-in-Fin	0.667%
Fan-in-Tailcone	0.823%

These percentages are applied to the total lifetime cost for overhaul and maintenance, which is estimated by means of the following equation:

$$C_{OM} = (\ W\ P)^{0.4158}$$

where C_{OM} = life overhaul and maintenance cost - dollars
W = aircraft weight empty - pounds
P = installed engine power - horsepower

Vulnerability

The relative "A" kill vulnerable areas in square feet are estimated as follows for the three configurations:

	7.62 mm API	12.7 mm API
Conventional Tail Rotor	2.11	7.75
Fan-in-Fin	2.04	6.27
Fan-in-Tailcone	2.04	5.73

Two cases were examined, representing "A" kill probabilities when making a 150-knot pass at 200 feet altitude over 7.62 mm and 12.7 mm API threats. The relative probability of survival is estimated using a standard survivability computer model containing a representative distribution of weapons.

The reciprocal of the relative survival probabilities is used as a scaling factor applied to flyaway cost. It is then normalized to the base-line case (tail rotor) by subtraction, as described previously in the reliability discussion. The relative savings in dollars are shown in Table IX.

Detectability

The effects of detectability differences were analyzed using the survivability model above. Differences in aural detection ranges were taken into account by scaling the area over which firing took place, hence the number of weapons engaged at any time. This scaling method is considered valid since, in the majority of areas where natural cover is provided for ground troops, aural detection significantly precedes visual detection. This analysis showed detectability reduction to be potentially the most significant improvement offered by the advanced antitorque concepts. The magnitude of this improvement, however, is strongly dependent on the threat assumed.

Because of this dependence and the lack of a specifically defined threat, cost savings due to reduced detectability are not included in Table IX. Typical savings, computed for the particular threat assumed in the survivability analysis, are summarized below.

Concept	Detectable Range ft	Delta Cost $
Conventional Tail Rotor	6700	-
Fan-in-Fin	3000	-53,276
Fan-in-Tailcone	3700	-46,705

The detection ranges above assume aircraft parameters optimized for overall system efficiency, and are therefore conservative, as discussed under "Aural Detectability and Annoyance", earlier in this task.

Comparison of these results with Table IX indicates that reduced detectability can lead to roughly twice the cost savings arising from reliability, maintainability, vulnerability, and safety improvements combined. This suggests that an in-depth analysis of detectability savings is desirable. No foreseeable threat, however, seems likely to significantly alter the basic conclusion that both new concepts are more expensive than the tail rotor in terms of life cycle cost, due to the large cost penalties of aircraft power and weight increases associated with these concepts.

Safety

Safety includes relative costs resulting from:

1. Collisions between the tail rotor blades and the terrain or fixed objects.

2. Damage caused by personnel colliding with the tail rotor.

Using the accident data previously supplied, mean times between occurrences of a given category of damage were estimated. The times are derived from published total flight-hour statistics for the aircraft types considered.

Damage Category	Estimated Average Repair Cost - $	Mean Time Between Occurrences - hr
Strike	Total aircraft cost	597,333
Major	37,500	99,556
Minor	7,500	682,667
Incident	1,500	25,554

Relative probability of occurrence was obtained by relating the above times between occurrences to a 3-hour mission duration, with the reciprocal of the probability again used as a scaling factor on flyaway cost. In addition, the average repair cost per aircraft life was computed as a dollar increment in operating cost. In this instance, the total costs computed were considered as savings for both fan configurations when compared with the conventional tail rotor.

The cost of injuries to personnel is not included in this assessment.

Final Selection for Task 3

The fan-in-fin is considered to be the best, most cost effective, lowest risk alternative to a conventional tail rotor system for a helicopter sized to the mission requirement defined for this study. This concept provides improvements in all characteristics required by the contract statement of work at a reasonable increase in aircraft size and cost. Although this concept has been developed to the point where technical risk is low, comprehensive flight testing will be required to accurately assess the performance and stability and control characteristics of a helicopter sized for future squad carrier utility transport use.

The fan-in-tailcone offers additional improvements in safety, vulnerability, and foreign object damage, but an additional penalty in aircraft size and cost. Although this concept was flown with moderate success in the 1940's, the technical risk is higher than for the fan-in-fin, specifically in the areas of ducting losses, stability and control, and possible inlet drag problems.

Preliminary sizing of prop-fans for the fan-in-fin and fan-in-tailcone concepts installed in the S-58T for Task 3 indicates that a single prop-fan can demonstrate both concepts. At this time, the cost of the prop-fan unit appears to be a significant portion of any future flight test hardware cost. With minimal compromise to a fan-in-fin design, therefore the fan-in-tailcone design could also be demonstrated at a significant cost saving over that of two independent demonstrator aircraft.

TASK 3. PRELIMINARY DESIGN STUDY

The candidate aircraft for conversion to the fan-in-fin and the fan-in-tailcone antitorque systems is a U. S. Army H-34 helicopter.

S-58T DESCRIPTION

The Sikorsky S-58T is a turbinized H-34 helicopter powered by the United Aircraft of Canada T400-CP-400 Twin Pac engine system. Use of a turbinized H-34 for flight tests of advanced antitorque concepts is desirable for two reasons: first, additional installed power is required to use the maximum gross weight capability of the H-34 airframe and dynamic systems due to the high power requirements of the two prop-fan antitorque concepts; second, for operational usage, the rudder pedals may have to be coupled to the engine controls to presense an antitorque system power requirement. On current helicopters, the transient power requirement of a tail rotor in a maneuver is initially satisfied by extracting power from the main rotor. This results in a slight decrease in rotor rpm, and the aircraft tends to settle until the engine responds to provide the additional power. Because power requirements of the prop-fan configurations are larger than those of a tail rotor, the aircraft may tend to settle excessively unless the engine can presense the power requirements. Although this coupling is not being proposed in the preliminary planning for a flight test program, determination of a coupling requirement would be desirable. As future designs will use turbine engines, the test vehicle should also use turbine engines to account for the difference in engine control and response characteristics of reciprocating and turbine engines.

FAN-IN-FIN MODIFICATION

A preliminary design layout drawing of the H-34 tail section modified to accept the 3.5-foot-diameter prop-fan selected is given in Figure 9. The existing H-34 tailcone and tail pylon structure forms the basic structural members to which the prop-fan and the enlarged vertical fin are mounted. Local beef-up and modifications to existing structures are required to support the prop-fan and to provide access for the power train and controls. The tail drive system modifications include a new increased face width tail takeoff section, and a new tail drive shaft. An existing SH-3 drive shaft will carry the significantly higher power levels of the prop-fan.

FAN-IN-TAILCONE MODIFICATION

Figure 10 shows the preliminary design layout of the fan-in-tailcone modification, which involves complete redesign of the H-34 airframe aft of Station 246. The H-34 tail landing gear is retained, and the prop-fan and beefed-up main gearbox tail takeoff section from the fan-in-fin configuration is used. A new angle gearbox and further modifications to the fan-in-fin tail drive shaft are needed to adapt the prop-fan to the previously modified H-34 tail takeoff section. Flow straightener vanes are located directly aft of the prop-fan, which is refaired to reduce the hub drag. Turning vanes at the tail exhaust nozzles reduce turning losses. In addition, a deflector valve diverts the flow to obtain the reverse thrust

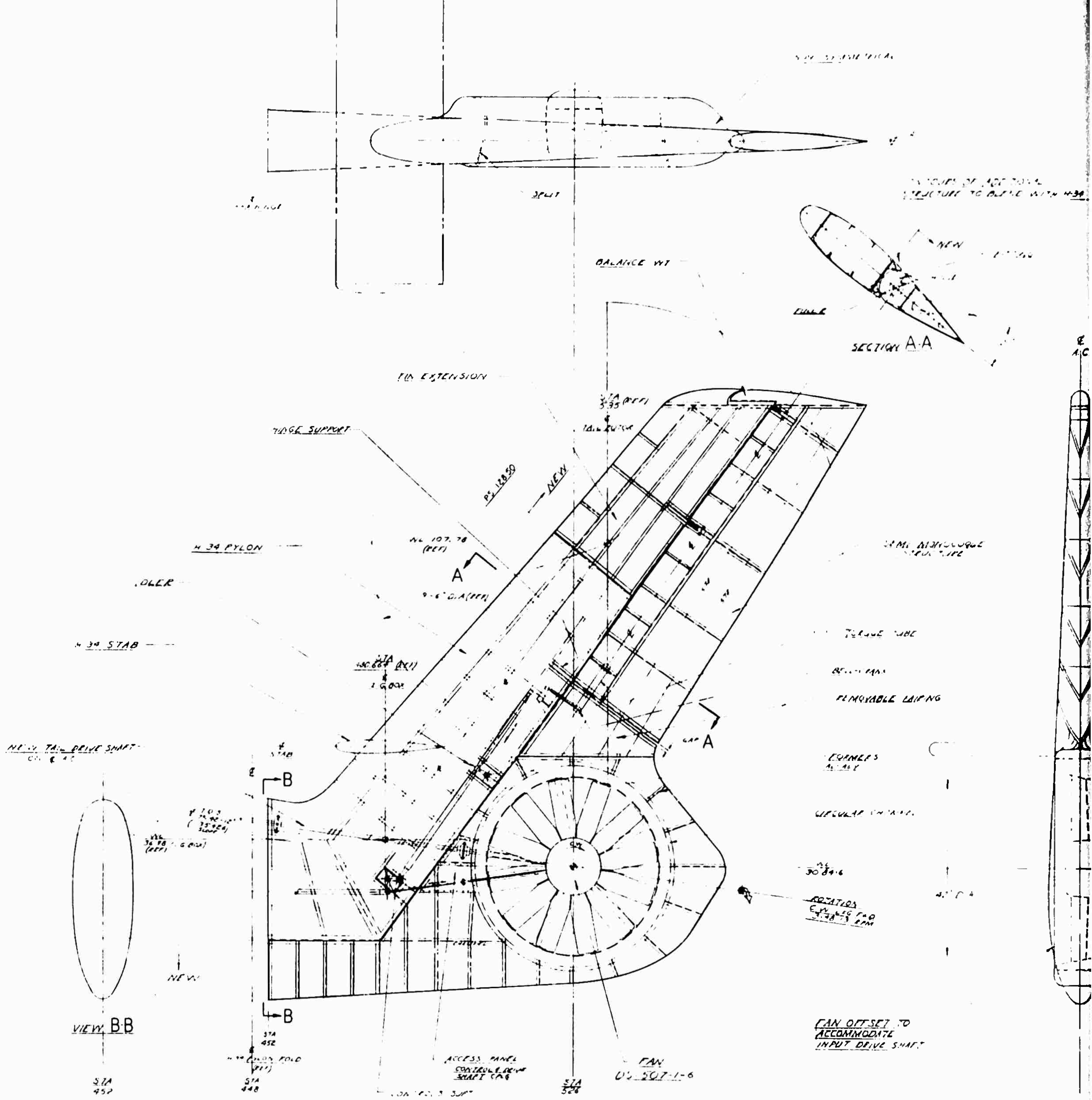
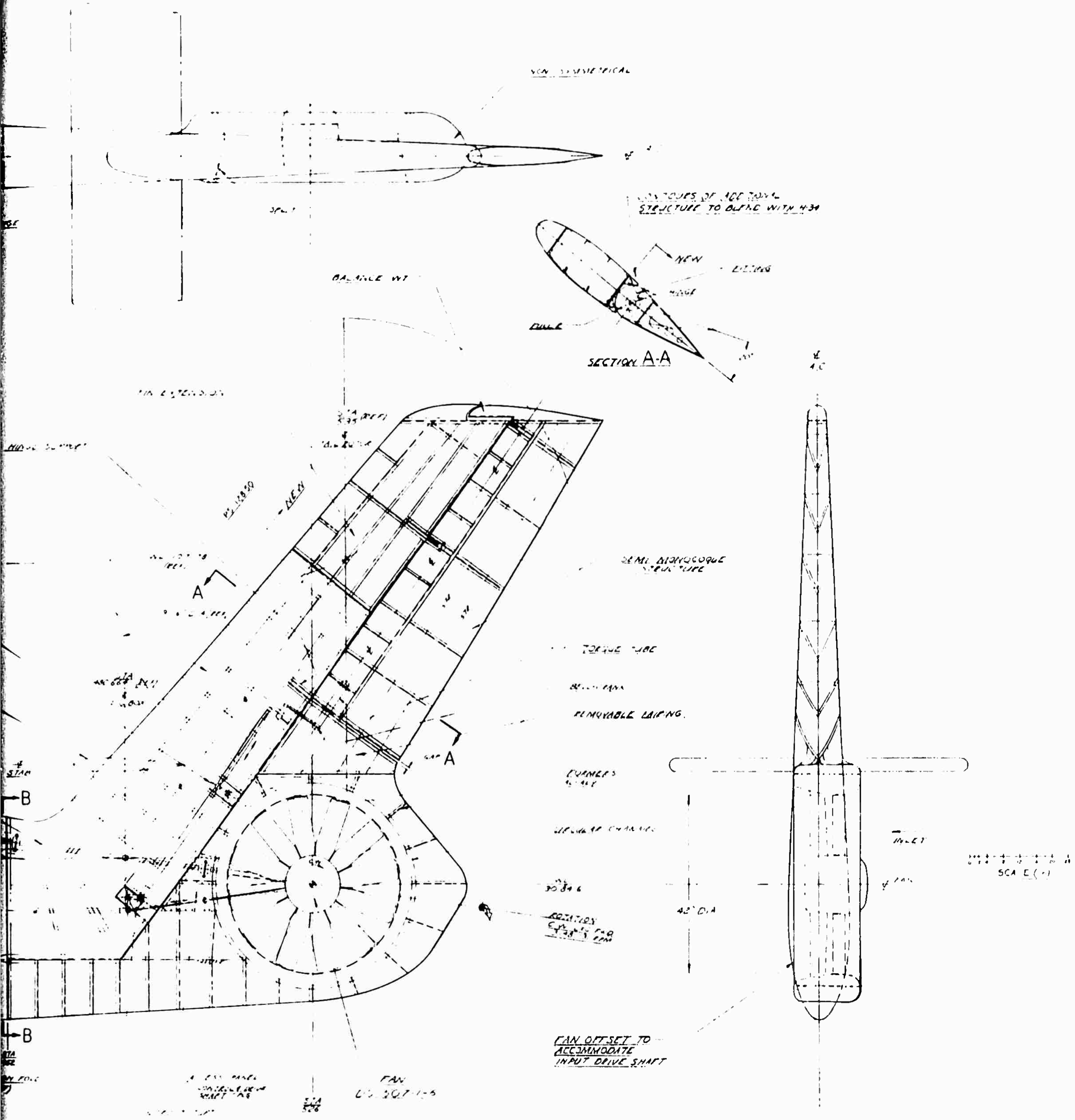


Figure 9. Design Layout - S-58T Fan-in-Fin Modification.



n Layout - [illegible]-58T Fan-in-Fin Modification.

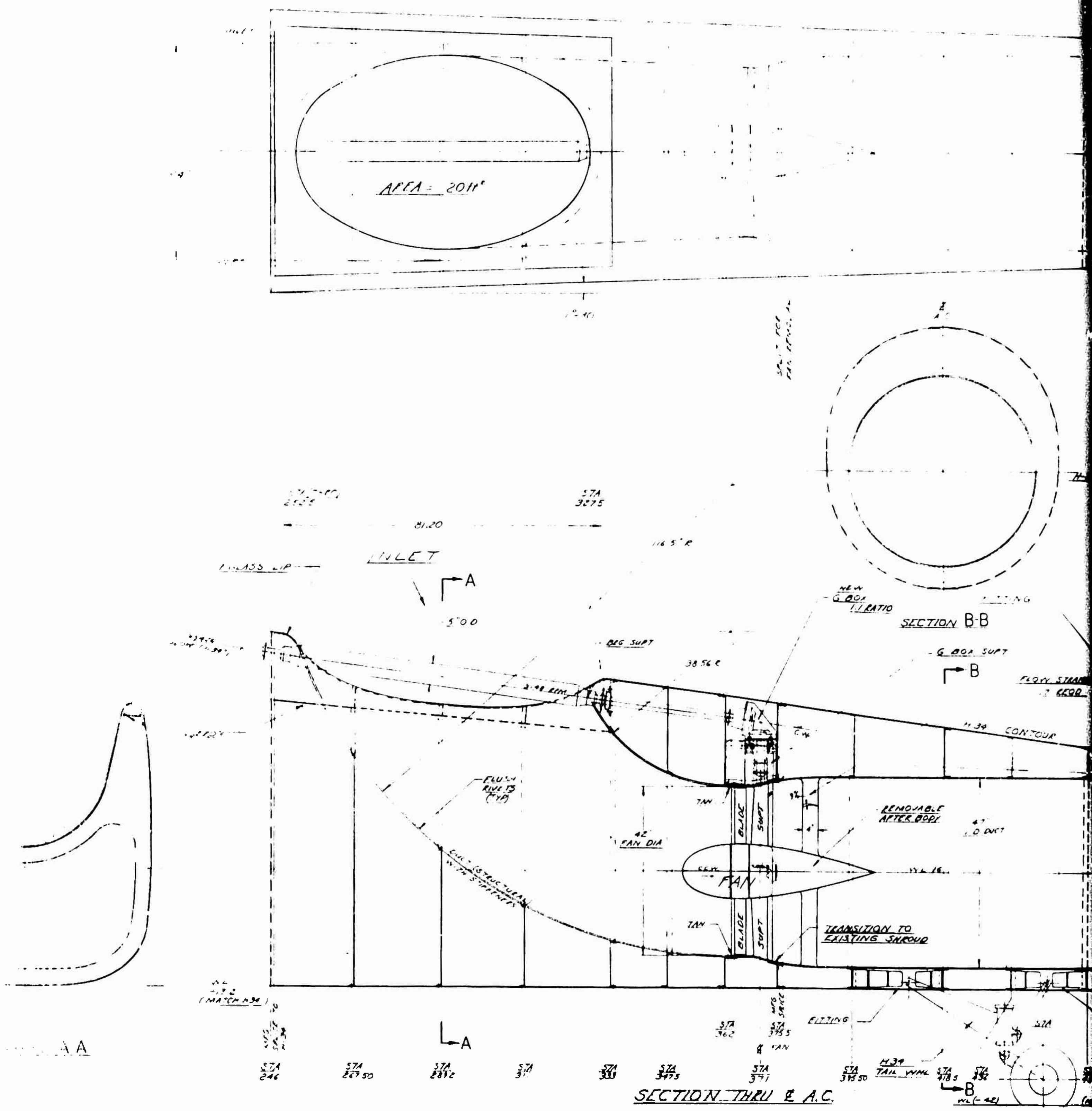
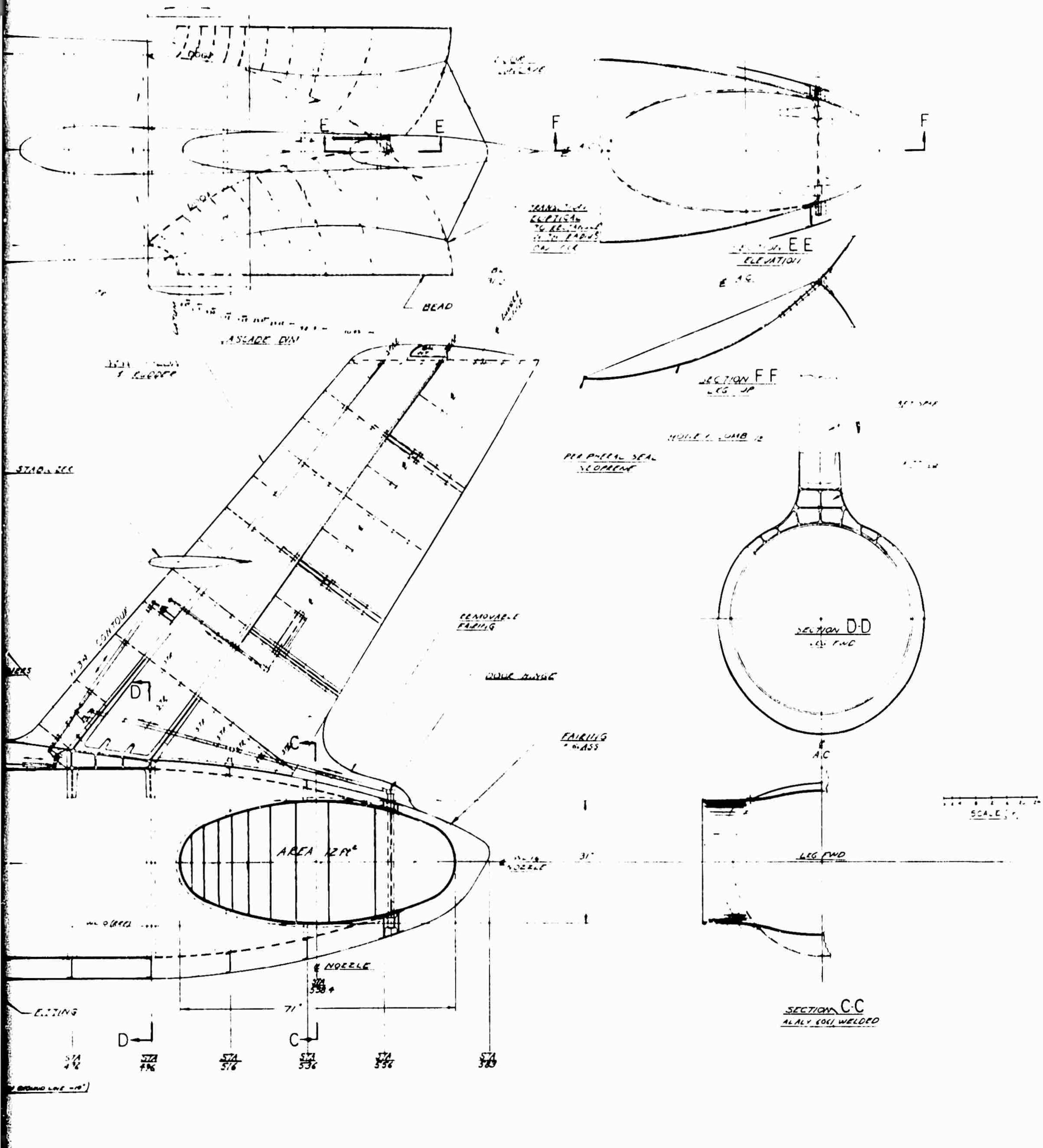


Figure 10. Design Layout - S-58T Fan-in-Tailcone Modification.



E
E
F
F
SECTION E E
ELEVATION
BEAD
CASCADE DWN
SECTION F F
PERIPHERAL SEAL
NEOPRENE
REMOVABLE
FAIRING
DOOR HINGE
SECTION D·D
FAIRING
D
C
AREA 12 FT²
NOZZLE
LEG FWD
71"
D
C
STA 476
STA 496
STA 516
STA 536
STA 556
STA 583
SECTION C-C
ALLOY CAST WELDED

B

required during autorotation and rapid maneuvers.

ANTITORQUE SYSTEM CONTROL

Fan-in-Fin Control

The criteria used in determining the coupling of the rudder and the fan-in-fin pitch-to-pedal displacement are based on the requirements that (1) the prop-fan provides full antitorque and lateral control in hovering flight, and (2) the rudder assumes this function in high speed flight, when the prop-fan is unloaded.

Data for the effectiveness of a prop-fan in forward flight were unavailable. Therefore, a relation between prop-fan effectiveness, defined as $dC_T/d\,\theta_{.75}$, and aircraft forward speed was assumed from two known relations: (1) prop-fan effectiveness in hover, estimated by Hamilton Standard, Division of United Aircraft Corporation, to be 0.044; and (2) a theoretical trend, checked against flight test, of tail rotor effectiveness over a range of forward speeds. The trend of prop-fan effectiveness versus forward speed was assumed to be identical in shape to that of the tail rotor, but to lie below the tail rotor trend by a constant delta defined by the respective hover effectiveness values.

Linkage of the fan pitch to pedal displacement was based on the maximum and minimum levels of fan thrust required in hover, as specified in MIL-H-8501A. The maximum thrust requirement was hovering at overload gross weight with 35 knots side wind from the right and obtaining the acceleration levels specified for a full control displacement. The maximum negative level was determined at the same condition but with the wind and tail acceleration directions from and to the left, respectively. The maximum negative level is usually determined by the amount of control required in autorotation. Since this aircraft has a rudder, the autorotative condition was not critical in the design of the prop-fan linkage. The maximum positive and negative thrust requirements in hover were converted to blade pitch angle, $\theta_{.75}$, and corrected for the effect of side wind on the blade pitch. The results are shown in Figure 11. A pedal displacement limit of ±3.25 inches was chosen since this is the current level of displacement for the S-58T and has proved to be acceptable to pilots.

After the coupling of fan pitch to pedal displacement was obtained, the required amount of rudder deflection was determined for the aircraft at overload gross weight at 120 knots. Prop-fan thrust levels should be kept as low as possible in forward flight to keep blade stresses down in trim and during maneuvers. A nominal thrust level of 200 pounds was selected, since 200 pounds is available for approximately 15 horsepower in addition to profile power. This level of thrust requires a given amount of pedal displacement and fixes the rudder deflection for trim to this displacement. Knowing the pedal displacement, the prop-fan and rudder effectiveness, and the main rotor torque that must be overcome, the slope of rudder deflection to pedal displacement is given by

$$\frac{\partial \delta_r}{\partial \delta_{ped}} = \left[N_{req} - \left(\frac{\partial N_f}{\partial \delta_{ped}}\right)(\delta_{ped} - 27.5)\right] \Bigg/ \left[\left(\frac{\partial N_r}{\partial \delta_{ped}}\right)(\delta_{ped} - 27.5)\right]$$

where δ_r = rudder deflection, degrees

δ_{ped} = pedal deflection, percent

N_{req} = yawing moment due to yaw rate, foot-pounds

N_f = antitorque yawing moment of prop-fan, foot-pounds

N_r = antitorque yawing moment of vertical tail, foot-pounds

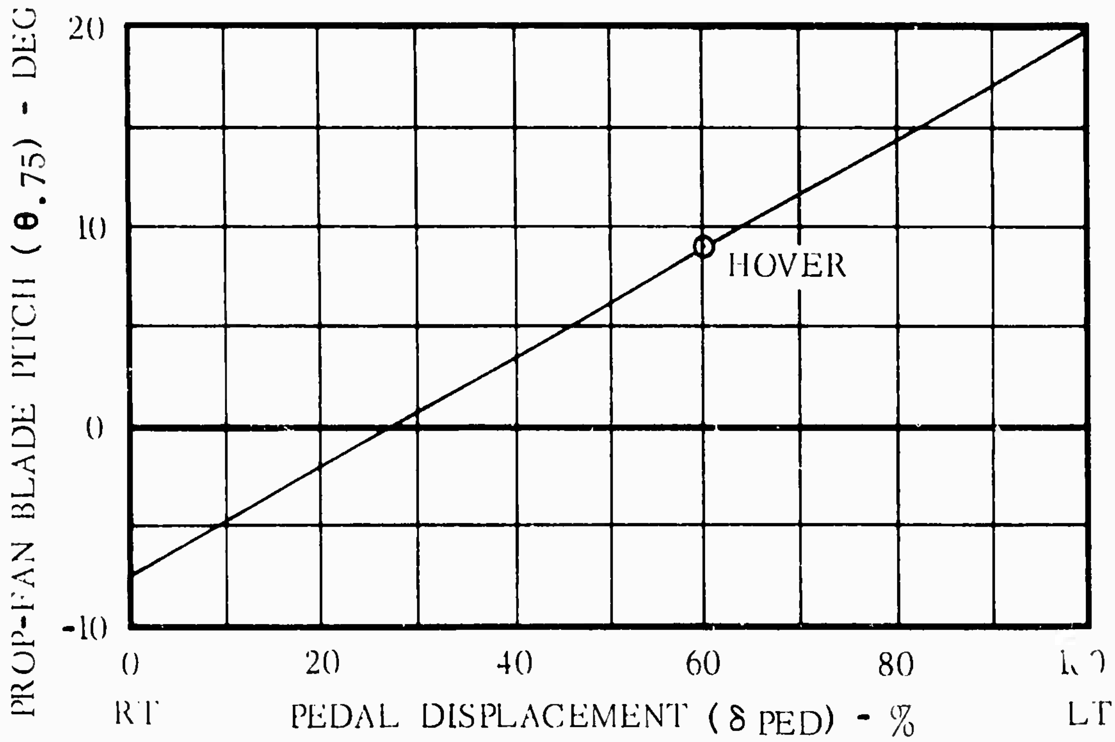


Figure 11. Fan Blade Pitch to Pedal Displacement Coupling.

From this information, Figure 12 was constructed to show the coupling of the rudder to the pedal position.

After the control coupling was determined, the variation of pedal displacement with speed was checked to determine whether the linear linkages resulted in a smooth curve within the control range limits. For this analysis, coupling of directional control to collective was not constant. The above equation was used where δ_{ped} was the unknown parameter.

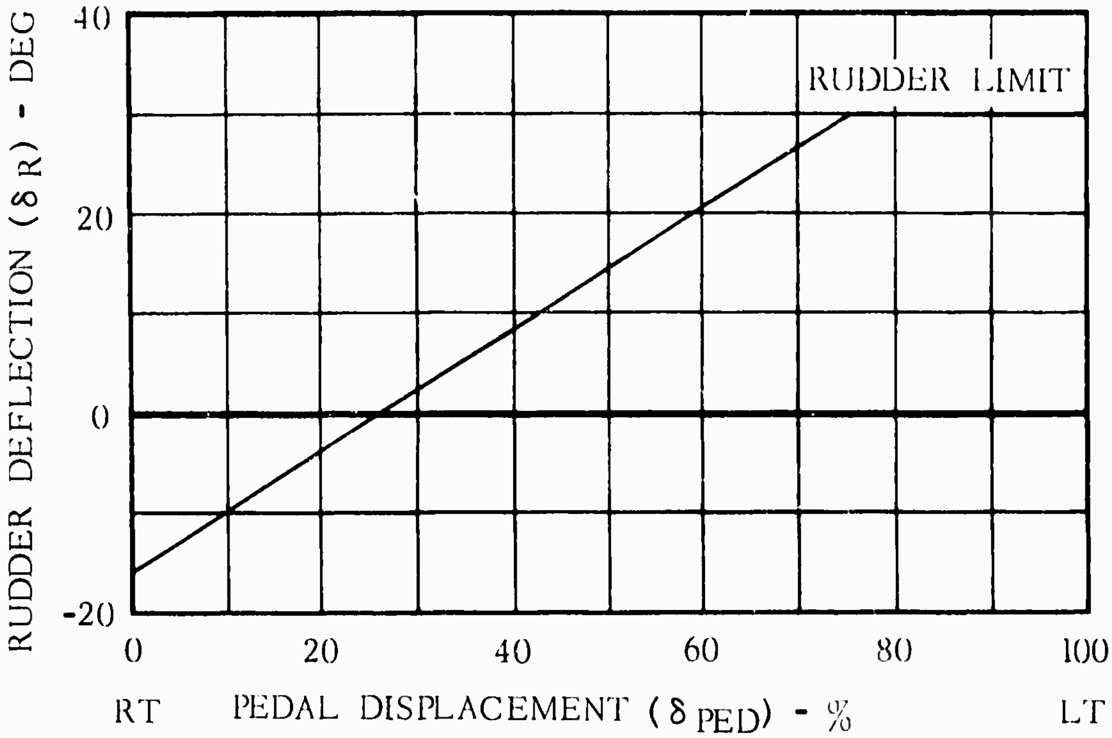


Figure 12. Rudder Deflection to Pedal Displacement Coupling.

Figure 13 shows the resulting pedal travel, which is satisfactory. The actual coupling for the fan-in-fin will be defined as a function of tail rotor pitch and velocity during the basic data phase of the design. This coupling is expected to be representative of the final value.

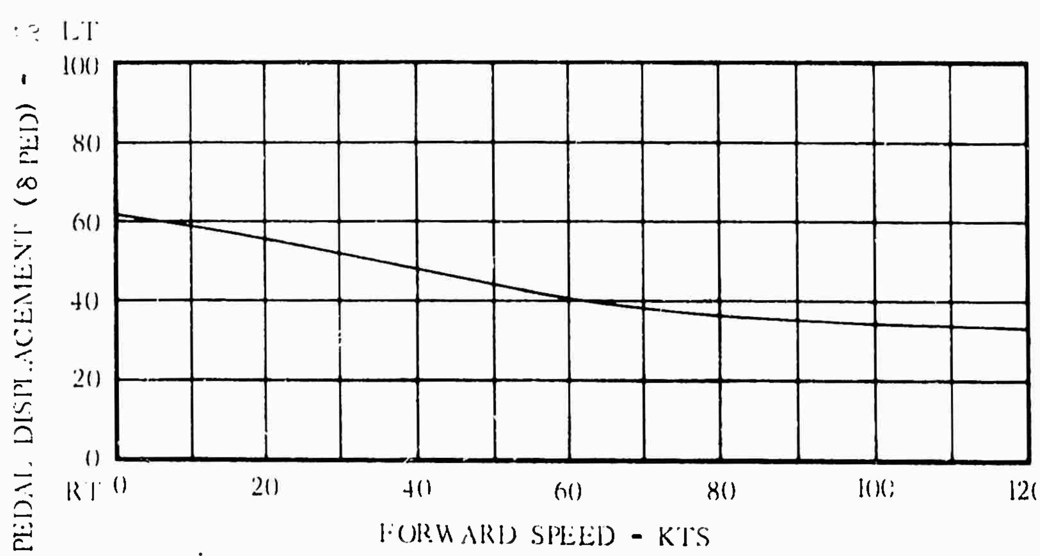


Figure 13. Pedal Requirements for Level Trim Forward Flight.

Fan-in-Tailcone Control

Various approaches were considered for controlling the fan-in-tailcone thrust output. Before the best control system can be selected, more detailed information is needed concerning prop-fan performance, internal flow problems, and thrust output lags for prop-fan blade pitch and thrust deflection valve changes. This information would be generated during the basic data phase of a hardware development program.

Figure 14 shows possible control system approaches based on using the prop-fan and the internal thrust deflector valve for control over various ranges of thrust. The figure assumes that thrust output varies linearly with fan blade pitch and that thrust is zero when blade $\theta_{.75}$ is zero. Sketches on each diagram indicate the associated deflector valve door position and a qualitative representation of the resulting exhaust nozzle flow.

Maximum positive and negative thrust requirements were established for hover in a 35-knot side wind at the acceleration level specified in MIL-H-8501A. As in the fan-in-fin study, the maximum thrust was required when the wind was from the right side with a nose-left acceleration. The maximum negative thrust was defined when the wind was from the left with a nose-right acceleration. Maximum positive and negative values are represented in Figure 14 as levels A and B, respectively.

Figure 14a depicts the manner in which the antitorque force is controlled in the blade pitch and deflector system. Thrust levels are controlled by fan blade pitch, $\theta_{.75}$ between the thrust levels A and C, and by the action of the thrust deflector valve between levels C and the estimated maximum negative thrust level, B. The prop-fan thrust is constant for net thrust requirements less than those required at C. A potential disadvantage is that this minimum prop-fan thrust defines the dynamic pressure environment in which the thrust deflector door must operate as well as the minimum net thrust used in high-speed trim. The net thrust level at point C is approximately 500 pounds, which corresponds to a 50-horsepower requirement. This will be offset partially by reduced vertical fin induced drag. However, the velocity in the duct, about 150 feet per second, may be high for the type of deflector valve proposed for the design.

Figure 14b shows a system that would eliminate the above noted objections. This system has the fan pitch controlling thrust continuously. The deflector valve is actuated only at zero $\theta_{.75}$. The door then swings rapidly over to exhaust the air out the right side of the exhaust nozzle. As more right pedal is applied, prop-fan pitch begins to increase, increasing negative thrust. An obvious problem is around the zero thrust point, where nonlinearities in thrust response to pedal displacement may be difficult to eliminate.

Another approach that uses the prop-fan pitch for antitorque control throughout the normal flight regime is shown in Figure 14c. Antitorque thrust is controlled by prop-fan blade pitch for all moderate and high-speed normal flight conditions for thrust levels from A to D. At low speeds or in autorotation, the path is A-C-B. The selection of whether the

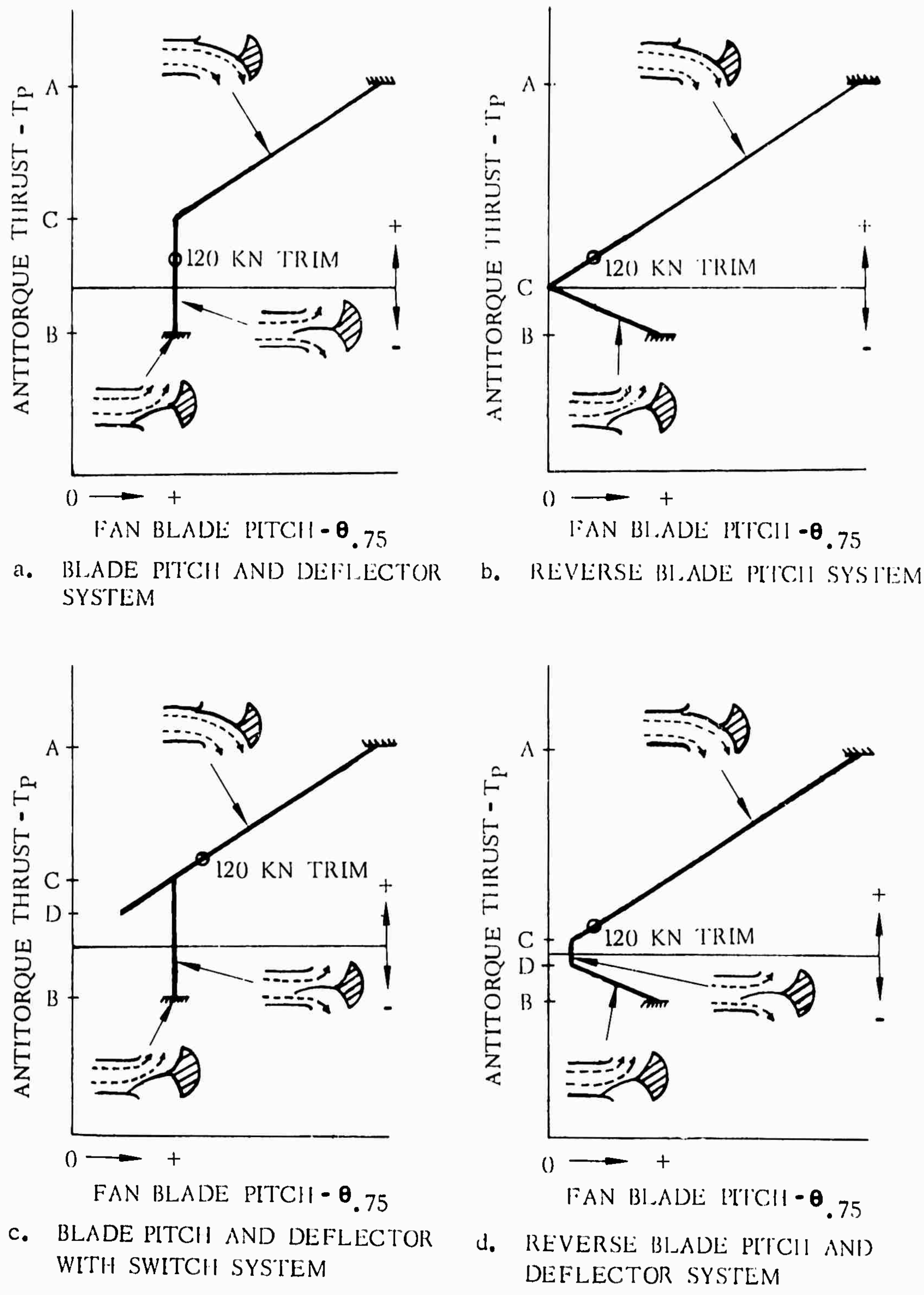


Figure 14. Alternative Control Concepts for Fan-in-Tailcone.

pedal controls the thrust along path A-C-D or A-C-B would be determined by a switch that is activated above approximately 35 knots, or is activated by the bottoming of collective during autorotative entry. During autorotation, the thrust levels of C and B will be large enough that adequate yaw control is provided without going past level C. This criterion avoids possible nonlinear effects when transitioning from curve A-C to C-B. Control of the switch during autorotation will be irreversible, so that raising the collective off the bottom position after entry will not deactivate the switch. This particular control can be deactivated by the speed control switch or a special pilot switch. It is desirable that the 120-knot trim condition lie between points C and A in this approach. This may necessitate reducing the camber of the vertical fin to increase the required net antitorque thrust for trim above the nominal 200 pounds assumed for the other approaches.

The last proposed system is shown in Figure 14d. This system combines the systems shown in Figures 14a and 14b. Blade pitch controls antitorque thrust for levels A to C; the deflector controls it from C to D; and blade pitch takes over again from D to B, but with a prop-fan pitch-to pedal displacement derivative of the opposite sign. This system will reduce the problems associated with the uncombined systems, but control system complexity may be excessive.

Before a control system can be selected, more detailed information is needed about duct losses and internal flow problems with the deflector valve partially deflected. From current information, the system shown in Figure 14c is favored. After the control system is chosen, the rudder coupling can be selected through a process similar to that used for the fan-in-fin concept.

STABILITY ANALYSIS

One primary stability and control objective was to size the vertical tail for the fan-in-fin and fan-in-tailcone configurations so that each configuration would have adequate handling qualities. The design philosophy was to maintain the lateral static stability characteristics of the tail rotor S-58T, which exceed MIL-H-8501A requirements. This similarity provides a clear basis for comparison between the characteristics of the tail rotor and the other antitorque devices.

Static and dynamic analyses were performed to size the vertical tail. The static stability analysis provided various combinations of tail size and AFCS authority that would satisfy static criteria. The dynamic analysis was used for final sizing the tail, but the selection was influenced by static stability requirements.

Static Stability

In determining the tail size for the fan-in-fin and fan-in tailcone configurations of the S-58T, sufficient area was added to the vertical tail for given levels of AFCS authority to provide the same total static stability as the S-58T tail rotor. Assumptions had to be made concerning contributions to static stability provided by the fan-in-fin and fan-in-tailcone. Investigation of ducted fans shows that their contribution to static stability is a function of aircraft speed similar to the conventional tail rotor. At approximately 120 knots, the effective tail surface area of the prop fan is approximately one-third the disc area.[14] At lower speeds, prop-fan effectiveness increases similar to that of a tail rotor. For this analysis, effective tail surface is considered to be that which falls above an extension of the tail-cone line. Since approximately one-third of the prop-fan area extends into this effective tail surface, it was considered to be effective as surface area, with no further contribution to static stability considered for the prop-fan. For the fan-in-tailcone, the area of the exhaust lies outside of the defined effective area, and the exhaust area is assumed to have no effect on the static stability.

Figure 15 shows a limiting combination of AFCS authority and additional tail area above that currently on the S-58T, which provides the same static stability as that of the tail rotor.

In this design, rudder deflection and fan blade pitch are coupled. In determining the AFCS authority limits, it was assumed that rudder effectiveness remained constant. The AFCS authority was selected to provide the same levels of yawing moment as that of a tail rotor when the aircraft has been yawed to the angle at which the vertical tail stalls. Beyond this point, linearity no longer holds. The 65-knot airspeed used in this calculation is a reasonable minimum steady forward flight speed. Speeds greater than this would require less tail area, and lower speeds are assumed to be transitionary. The effect of varying the tail surface aspect ratio is also shown in Figure 15. This information was used with the dynamic response analysis of the aircraft in selecting vertical tail aspect ratio and size.

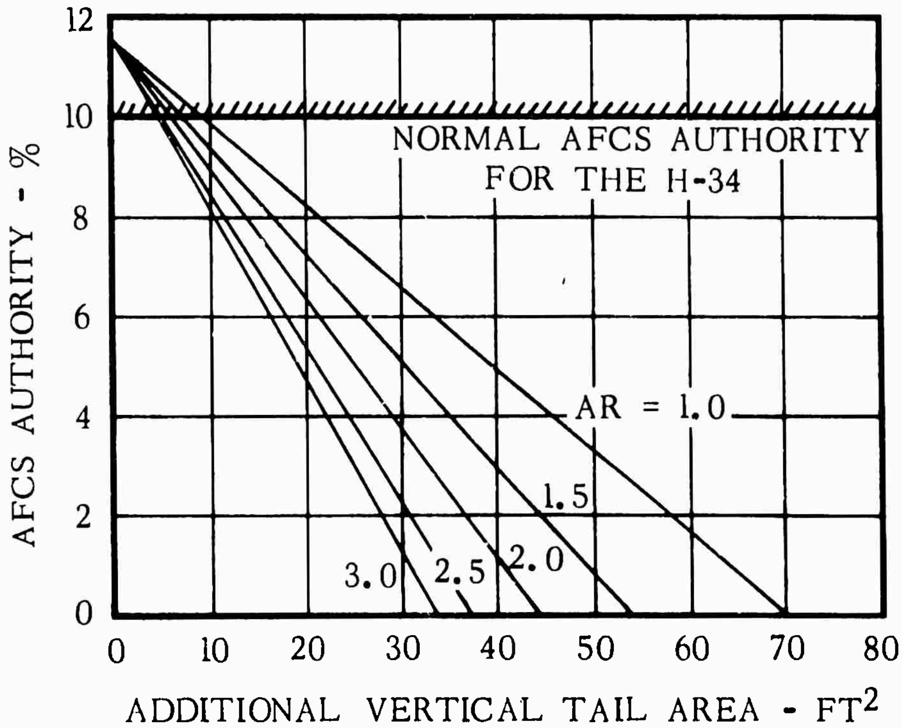


Figure 15. Additional Vertical Tail Areas Versus AFCS Authority for S-58T Without Tail Rotor.

Dynamic Stability

A dynamic stability analysis sized the vertical fin to meet the MIL-H-8501A VFR requirements without use of AFCS. A speed of 90 knots was selected, which is somewhat below normal cruise speed. The dynamic equations of motion considered only the lateral direction degrees of freedom, considered independent of the longitudinal, following common practice in helicopter design.

Figure 16 shows the periodic roots used to size the vertical fin area. The aperiodic roots for all cases were negative and therefore stable. As they made no direct contribution to the analysis, they are not shown in Figure 16. An aspect ratio of 2.0 for the vertical tail was assumed nominal. An area increase of 17 square feet would give the aircraft neutral stability, which is the VFR limit defined in MIL-H-8501A. The IFR requirements can be obtained by proper selection of gains for the AFCS, but that is beyond the scope of this study. It is seen from Figure 15 that 17 square feet of additional tail area is a reasonable solution from the static stability analysis with an AFCS authority requirement of ±7 percent.

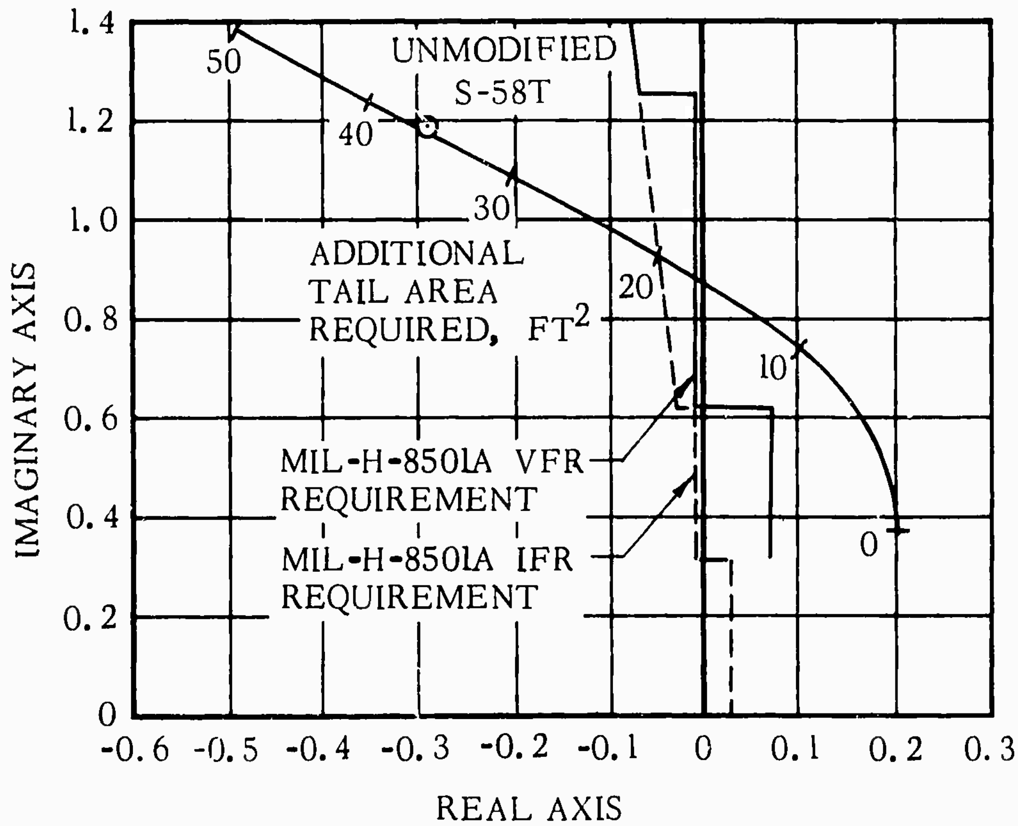


Figure 16. Vertical Tail Surface Area Required - S-58T With Fan-in-Fin or Fan-in-Tailcone Modification.

AIRCRAFT PERFORMANCE DATA

S-58T hover and forward flight performance characteristics are consistent with flight test information on the H-34A aircraft, adjusted to reflect the improved mechanical efficiency and increased power available provided from the T400-CP-400 turbine installation. The H-34A Flight Manual Performance Substantiation Report[15], approved by the U.S. Air Force, is used as the basis for the S-58T power required throughout the flight envelope presented.

UACL T400-CP-400 Engine Performance

Installed engine performance of the UACL T400-CP-400 engine in the S-58T is presented in Figures 17 and 18. The engine is installed in the original Wright R-1820 engine compartment, lengthened to accommodate the new engine. Engine losses for the inlet and exhaust ducts and engine accessory power are included in these curves. The engine data presented are for zero bleed air consumption. Hover data are for zero wind. Experience in out-of-ground-effect hover at the presented airspeeds indicates no reingestion effects.

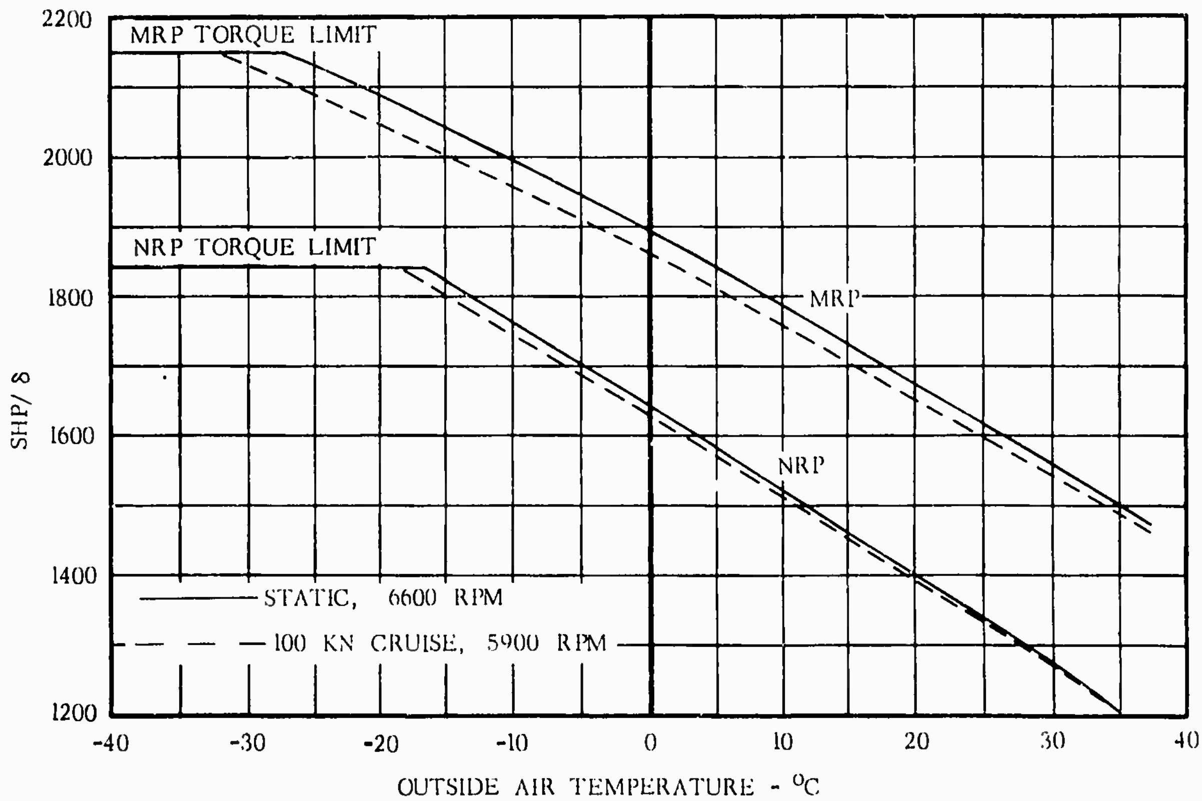


Figure 17. Horsepower Over Pressure Ratio Versus Ambient Temperature.

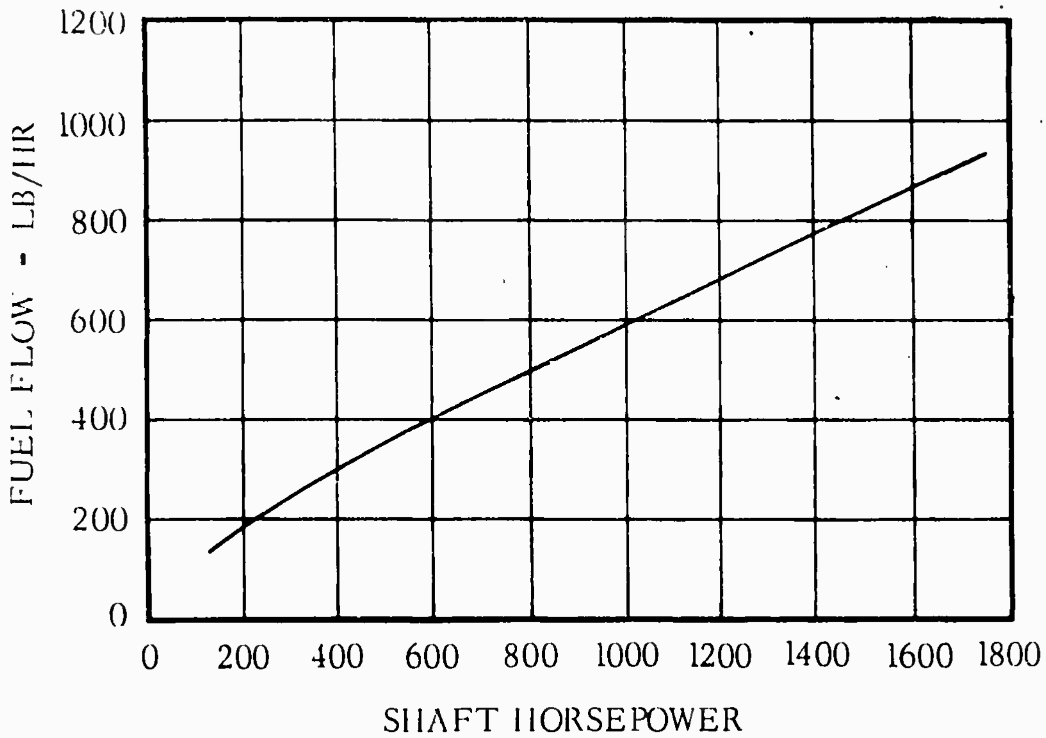


Figure 18. Installed Engine Fuel Flow (T400-CP-400) Versus Shaft Horsepower.

Aircraft Power Required

Power for the S-58T is provided by a UACL T400-CP-400 Twin Pac$_{TM}$ turboshaft engine installation. This powerplant consists of two UACL PT6 engines driving a single combining gearbox forward of the engines. This gearbox drives the helicopter main transmission through an angle gearbox aft of the engines.

Engine power available is defined as the power available at the output of the combining gearbox. Power required as used in all performance discussion is defined as: main rotor power + antitorque power + transmission losses and accessory power requirements that occur beyond the output from this gearbox. The difference in accessory power plus transmission losses between the H-34A and the S-58T due to design changes amounts to a 51.55 - SHP reduction at a main rotor tip speed of 647 feet per second. The hover and forward flight power required is thus determined by deducting 51.55 SHP from the relevant flight test substantiated power required by the H-34A[15]. At a main rotor hover tip speed of 727 feet per second, this reduction is approximately 51 SHP.

Table X lists the power-required breakdown for the H-34A and S-58T when hovering at sea level and 95° F, at a main rotor tip speed of 647 feet per second.

TABLE X. H-34A/S-58T POWER REQUIRED COMPARISON		
ITEM	H-34A	S-58T
Main Rotor Power	1020.0	1020.0
Tail Rotor Power	97.0	97.0
Angle Gearbox Loss	-	17.85
Main Gearbox Loss	19.79	19.79
Tail & Inter. Gearbox Loss	2.41	2.41
Accessories	19.00	39.60
Cooling Fan	77.00	
Starting Generators	13.00	Included in Engine Losses
TOTAL	1248.20	1196.65

Antitorque Thrust Requirements

Table XI shows the thrust levels required by MIL-H-8501A for the fan-in-fin and fan-in-tailcone antitorque concepts installed on an S-58T.

TABLE XI. ANTITORQUE THRUST REQUIREMENTS FOR MODIFIED S-58T

MIL-H-8501A Condition	C.G. Location	Antitorque Thrust (lb)	Control Thrust (lb)	35-Kn Side Wind Thrust (lb)	Total Thrust (lb)
Fan-in-Fin					
Para. 3.3.5	Forward	745	455	-	1200
	Aft	745	495	-	1240
Para. 3.3.6	Forward	568	152	739	1459
	Aft	568	165	620	1253
Fan-in-Tailcone					
Para. 3.3.5	Forward	754	462	-	1216
	Aft	754	504	-	1258
Para. 3.3.6	Forward	574	154	813	1541
	Aft	574	168	750	1483

In both cases, maximum thrust is required in a 35-knot side wind with a forward center of gravity. These values are based on the S-58T alternate gross weight of 13,300 pounds and sea level standard conditions. The aircraft mass moment of inertia values about the vertical axis at this gross weight are 21,426 and 22,515 $lb-ft-sec^2$ for the forward and aft center of gravity conditions, respectively.

Antitorque System Efficiency

Efficiency of the fan-in-tailcone configuration was determined by the method described in Task 2. Estimated losses from each basic component are given in Table XII.

TABLE XII. S-58T FAN-IN-TAILCONE DUCTING LOSSES

Component	$\Delta p/q$	q(psf)	Δp(psf)
Inlet	0.035	25.2	0.882
Shaft	0.015	25.2	0.378
45° Turn (No Turning Vanes)	0.062	90	5.58
Straight Duct	0.032	66.5	2.13
Thrust Deflection Valve	0.005	66.5	0.33
90° Turn (9 Turning Vanes)	0.060	66.5	4.00

The thrust deflector valve was assumed to contribute only 0.005q loss in its normal positive thrust position, although significant loss is predicted in the negative thrust position. Total pressure loss upstream from the fan is predicted to be 6.15 pounds; downstream, the prediction is 4.8 pounds. In zero-loss duct flow, the required prop-fan pressure ratio to provide the required 1541 pounds side force at SLS is 1.0317. Including the duct losses, the required pressure ratio is approximately 1.038, leading to a system efficiency of 0.83 or an effective blockage factor of 1.20. These values are based on a duct area of 12 square feet and a jet exhaust angle of 10 degrees from the lateral axis.

The fan-in-fin efficiency of .947 estimated during Task 2 was also used for the S-58T configuration.

S-58T Prop-Fan Performance

Figure 19 shows two representative thrust levels for the S-58T fan-in-fin. For this aircraft, the MIL-H-8501A control plus side wind requirement becomes the more critical. This is due to the large fuselage area aft of the rotor that creates large aerodynamic moments. New aircraft designed for turbine engines would have more area in front of the rotor to partially balance this moment. Figure 15 shows the trade-offs between size and tip speed for high-and low-thrust requirements. After consideration of aircraft configuration, noise, and performance, a 12-bladed 3.5-foot-diameter prop-fan with a hover tip speed of 800 feet per second and a total activity factor of 2200 was selected for both the fan-in-fin and fan-in-tailcone. Aircraft configuration and thrust requirements make it possible to use the same prop-fan for both configurations.

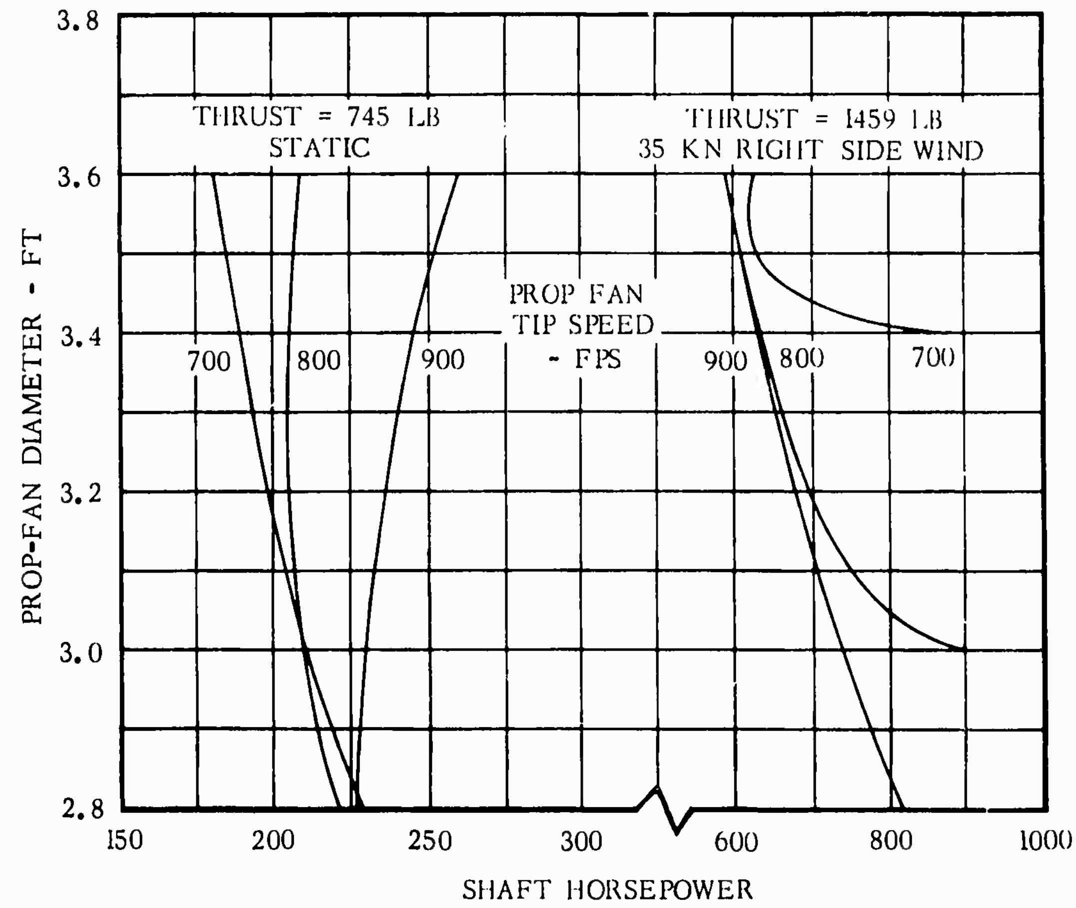


Figure 19. Prop-Fan Diameter Versus Shaft Horsepower - Fan-in-Fin.

Figure 20 shows the power-required curves for 3.5-foot-diameter prop-fan systems on a sea level standard day. Because of the matched sizes and recovery vanes and a relatively efficient duct on the fan-in-tailcone, the latter system consumes approximately the same power as the fan-in-fin. Figure 21 illustrates the effects of altitude and temperature on prop-fan performance.

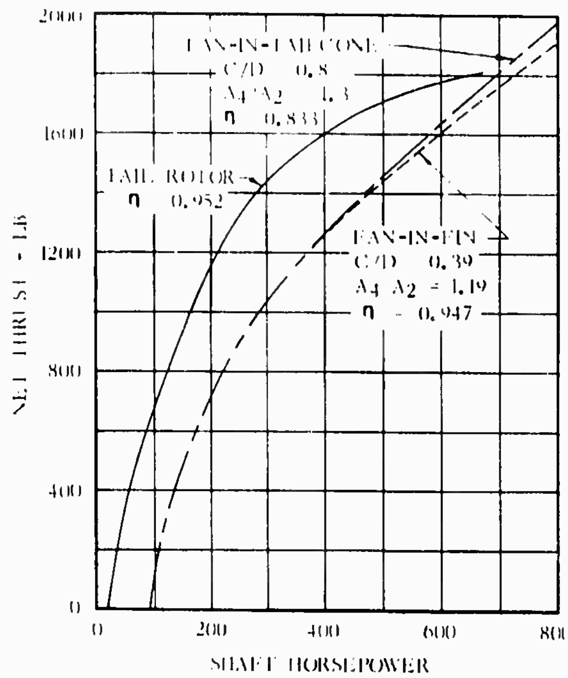


Figure 20. Antitorque Device Net Thrust Versus Shaft Horsepower, Sea Level Standard.

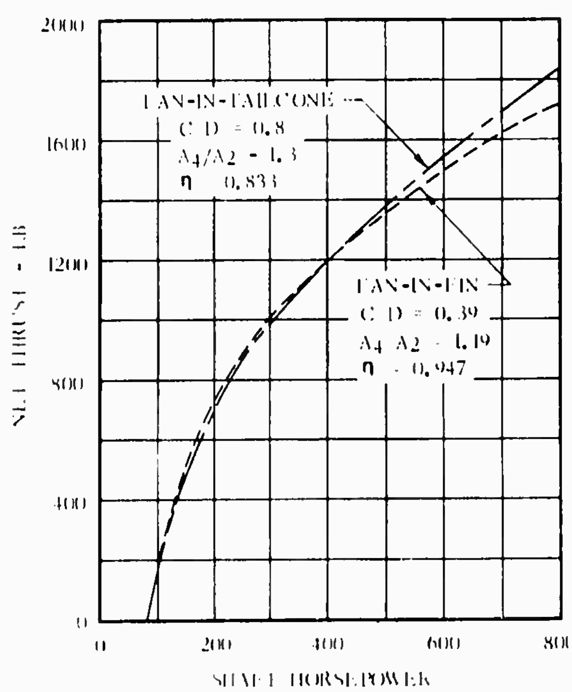


Figure 21. Antitorque Device Net Thrust Versus Shaft Horsepower, 4000 Ft, 95°F.

Hover Performance

The minor fuselage nose modification required to accept the turbine powerplant does not affect the aircraft vertical drag characteristics. Therefore, the power required to hover was derived directly from H-34A flight manual test information and revised to update the accessory and power train losses associated with the new powerplant system.

Figure 22 provides the nondimensional hover characteristics for out-of-ground effect (OGE) operations. Substantiated flight manual performance[15] at 221 rotor rpm establishes the basic C_P - C_T range shown by the curve equivalent to $N_R/\sqrt{\theta}$ = 88%. Since sufficient test data at operating conditions where Mach number effects begin to become evident are not available to establish the trend, the figure-of-merit ratio method previously discussed is used to determine the compressibility losses for the higher N_R conditions. This method is an empirical hover procedure based on isolated rotor whirl stand data. It consists of establishing the degree to which the theoretical maximum figure of merit is achieved for a specified C_T/σ , solidity, and tip Mach number.

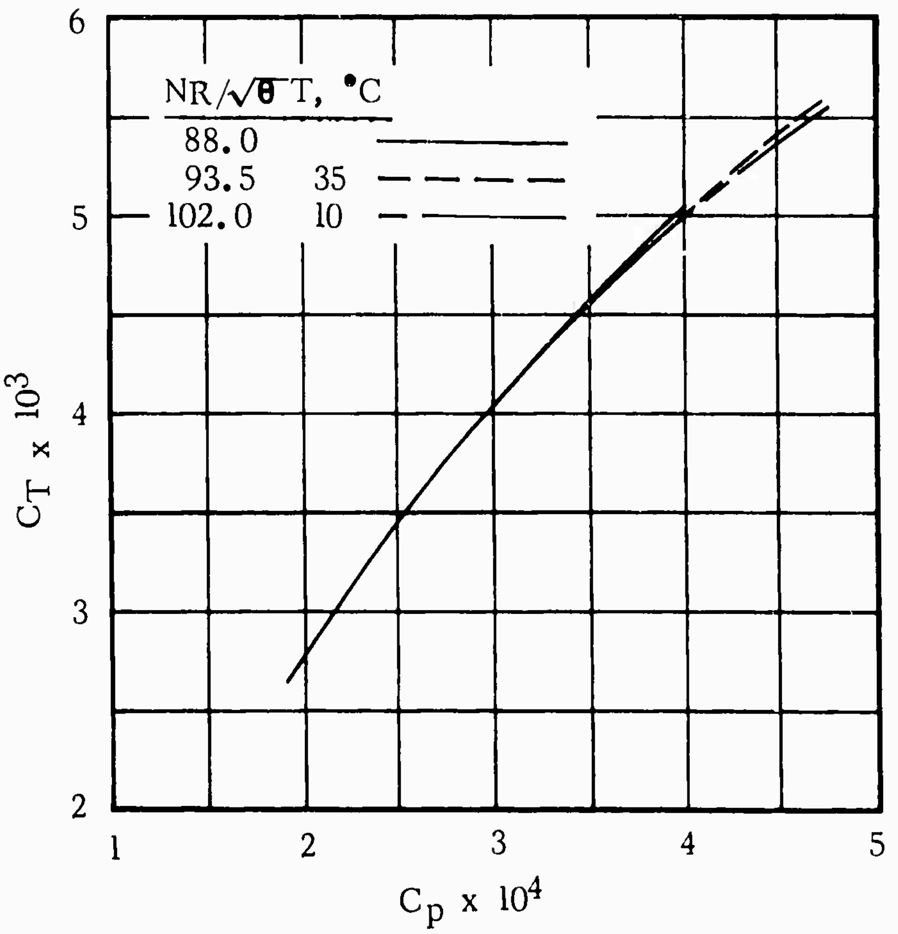


Figure 22. Nondimensional S-58T Hover Performance, OGE.

Gross weight versus shaft horsepower curves for sea level standard and 4000 feet, 95° F hover conditions are shown in Figures 23 and 24. Fan-in-fin and fan-in-tailcone curves are included in these figures. Hover ceilings for the same aircraft at standard day conditions are given in Figure 25.

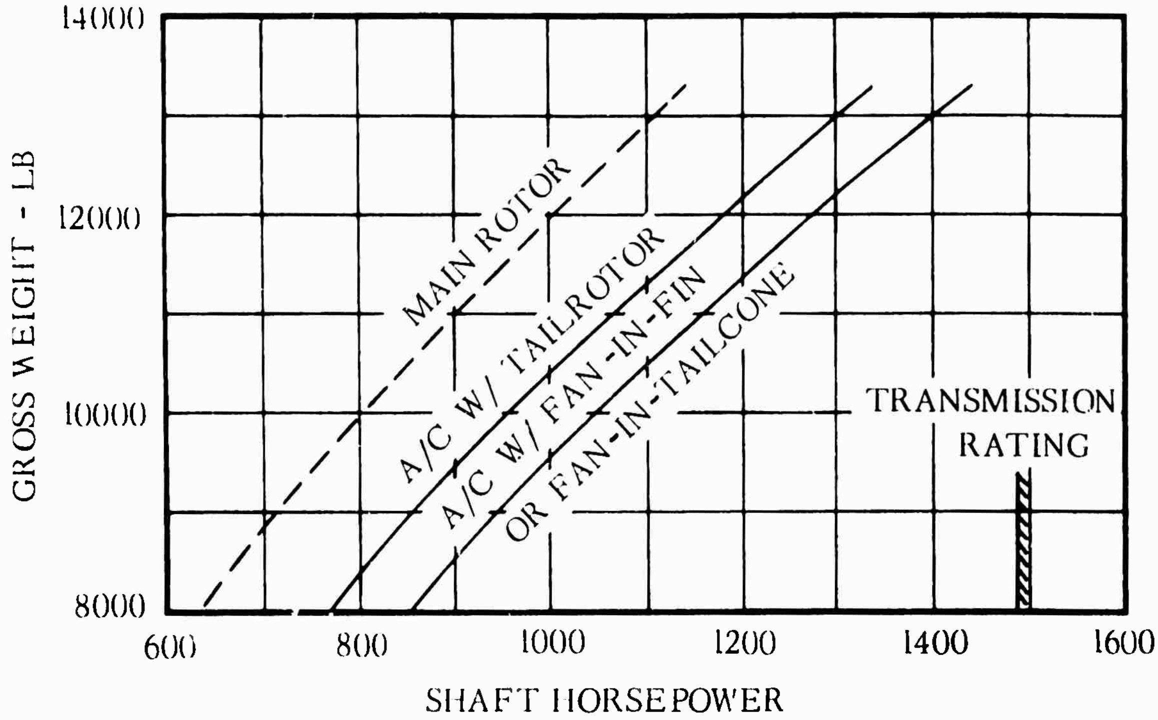


Figure 23. Gross Weight Versus Shaft Horsepower, Sea Level Standard.

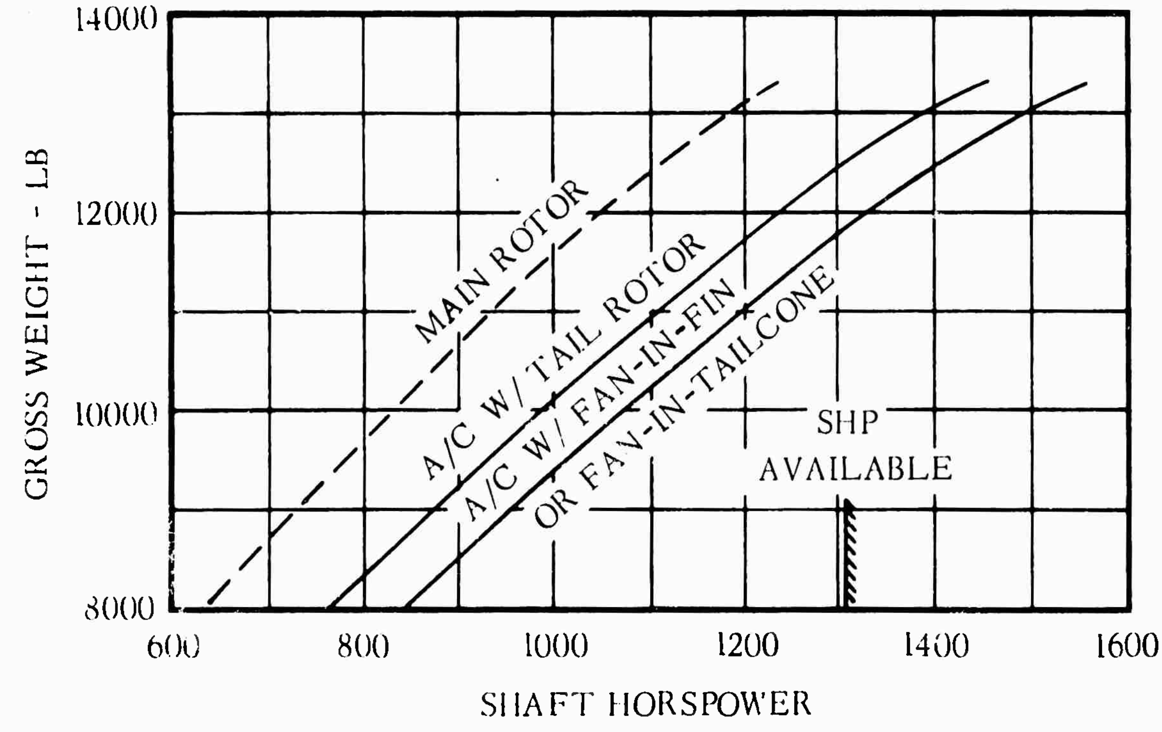


Figure 24. Gross Weight Versus Shaft Horsepower, 4000 Ft, 95°F.

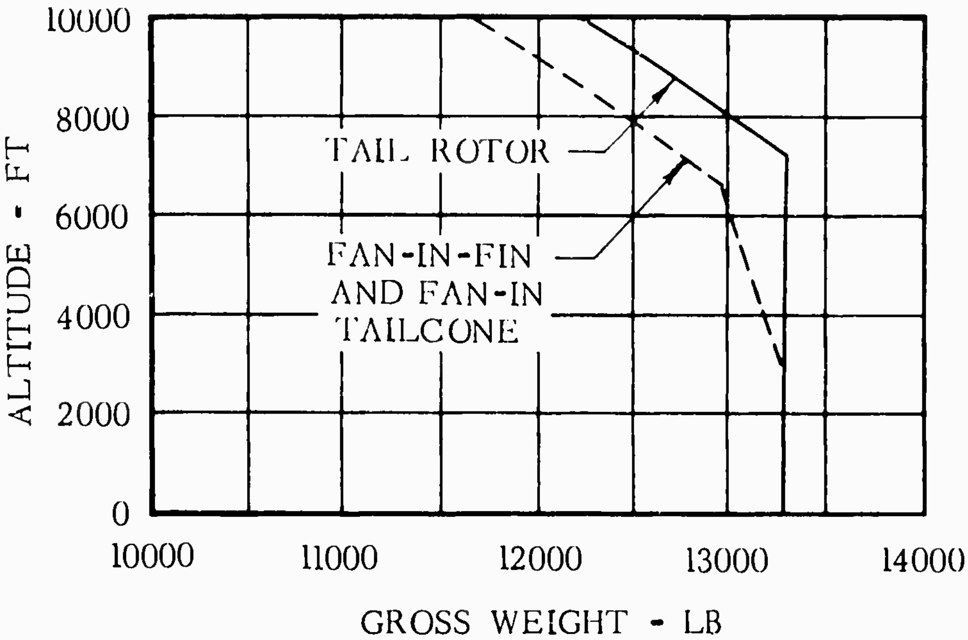


Figure 25. Hover Ceiling Versus Gross Weight, Standard Day.

Forward Flight Performance

The H-34A forward flight test data[15] establish the power-required characteristics. These characteristics are presented nondimensionally in Figure 26 for a 95° F temperature condition.

The performance presented includes the efficiency changes that result from the turbine powerplant installation, but excludes the parasite drag saving that results from the fuselage nose modification. S-58T parasite drag is estimated to be 2 square feet less than that of the H-34A. The breakdown of the parasite drag change derived from the configuration alteration, relative to the H-34A, is given in Table XIII.

TABLE XIII. S-58T PARASITE DRAG DERIVATION, RELATIVE TO H-34A

Component	S-58T With Tail Rotor	S-58T Fan-in-Fin	S-58T Fan-in-Tailcone
Fuselage	+0.5	+0.5	+0.7
Engine Inlet	+0.25	+0.25	+0.25
Momentum Drag	-2.75	-2.75	-2.75
Vertical Tail	0.0	+1.0	+0.5
Tail Rotor/Fan	0.0	-0.2	-0.7
TOTAL	-2.0	-1.2	-2.0

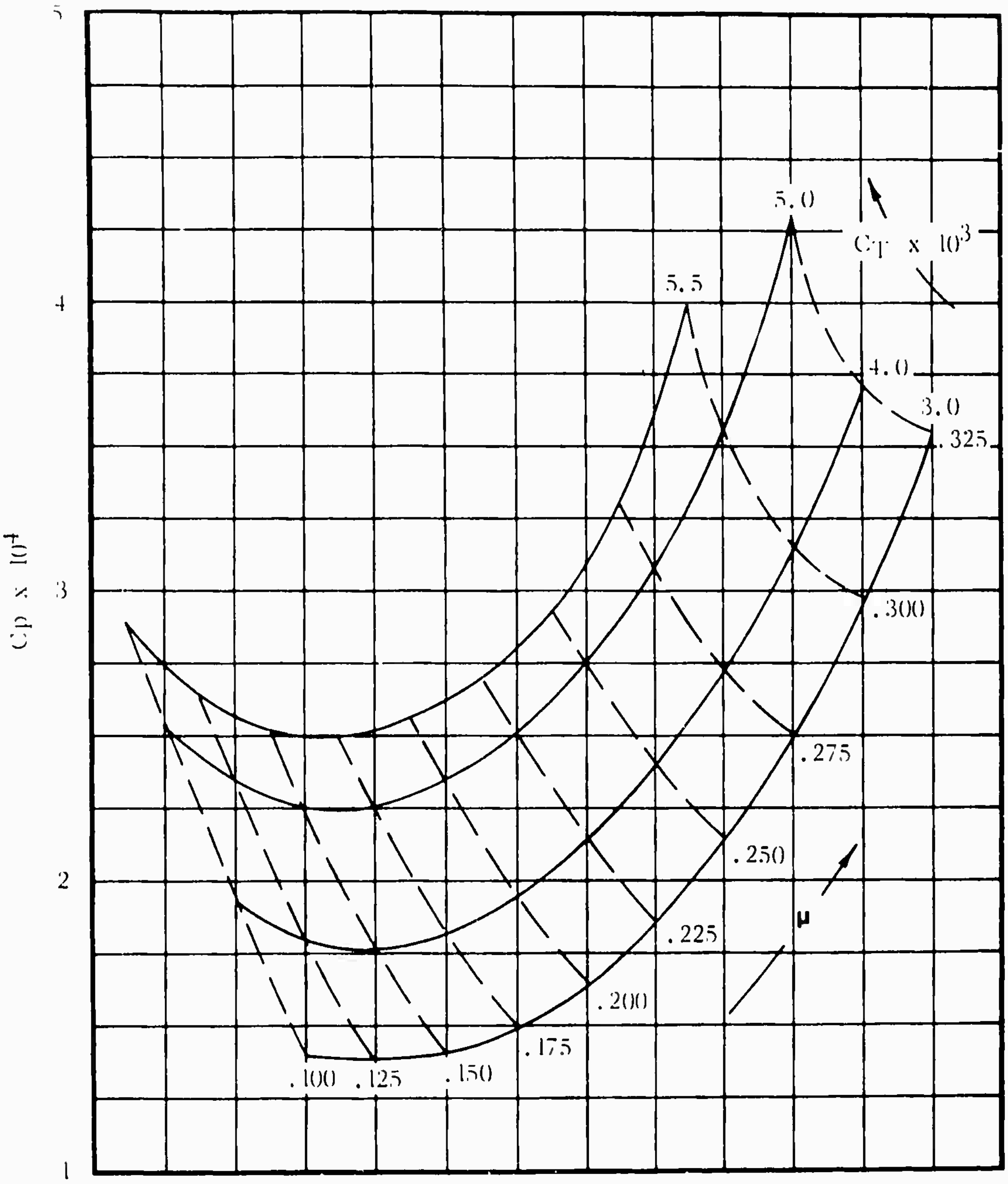


Figure 26. S-58T Forward Flight Performance, 95°F.

The forward flight characteristics are presented in Figure 27, showing aircraft flight restrictions. Engine power ratings and recommended maximum cruise speeds are indicated.

Figure 28 shows the current S-58T maximum recommended cruise speeds. The criterion for these speeds was established during H-34A testing and was defined as the forward cg roughness speed, less 10 knots. While the current limits are hig' enough to provide the necessary data to evaluate performance of the prop-fan systems, expansion of this flight envelope will permit the aircraft to enter a flight regime where the prop-fan-equipped aircraft can demonstrate less power demand than the current-tail-rotor-equipped aircraft, as shown in Figure 27.

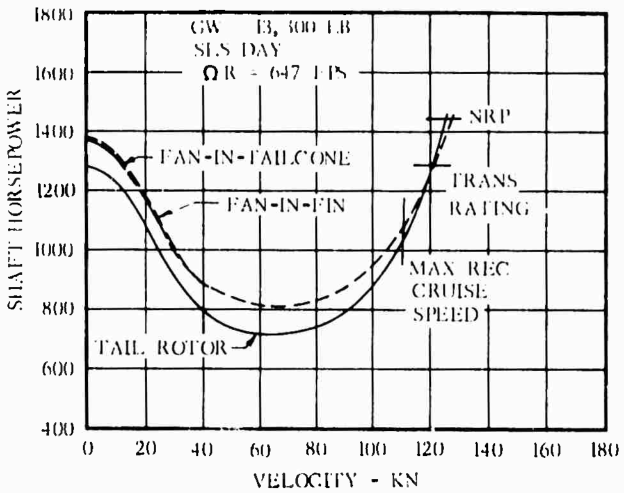


Figure 27. S-58T Shaft Horsepower Versus Velocity, Sea Level Standard.

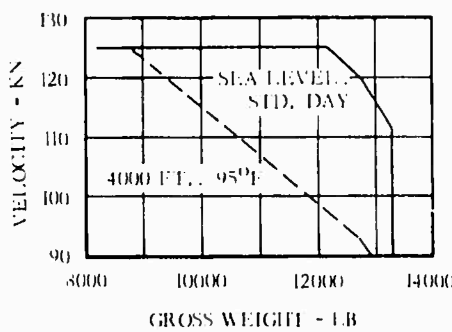


Figure 28. S-58T Maximum Recommended Cruise Speeds.

Cambering the S-58T vertical tail fin to unload the tail rotor will shift the point of equal power required to a higher airspeed. Reducing the gross weight also decreases the tail rotor disc loading so that the tail rotor power loading is increased. Therefore, the prop-fan configurations require slightly more power than the tail rotor up to approximately 125 knots. At speeds greater than 125 knots, the prop-fan will be superior to the tail rotor. Further study is necessary to evaluate prop-fans in this environment and adequately determine the thrust-power relationship.

Specific range characteristics are presented in Figures 29 and 30 for a sea level standard day cruise condition based on UACL T400-CP-400 Twin Pac powerplant specification SFC increased by 5 percent. A payload-range curve for a sea level standard day is shown in Figure 31.

Antitorque System Comparison

To obtain the hover and forward flight curves of Figures 23, 24, and 27, the main rotor power was found by subtracting the S-58T accessory and tail rotor power from the total power required. The antitorque requirements can be determined from this main rotor power. The antitorque and accessory power added to the main rotor power gives the prop-fan aircraft total power requirements.

In forward flight, the rudder and tail surfaces unload the prop-fan to a minimum value of approximately 200 pounds of thrust.

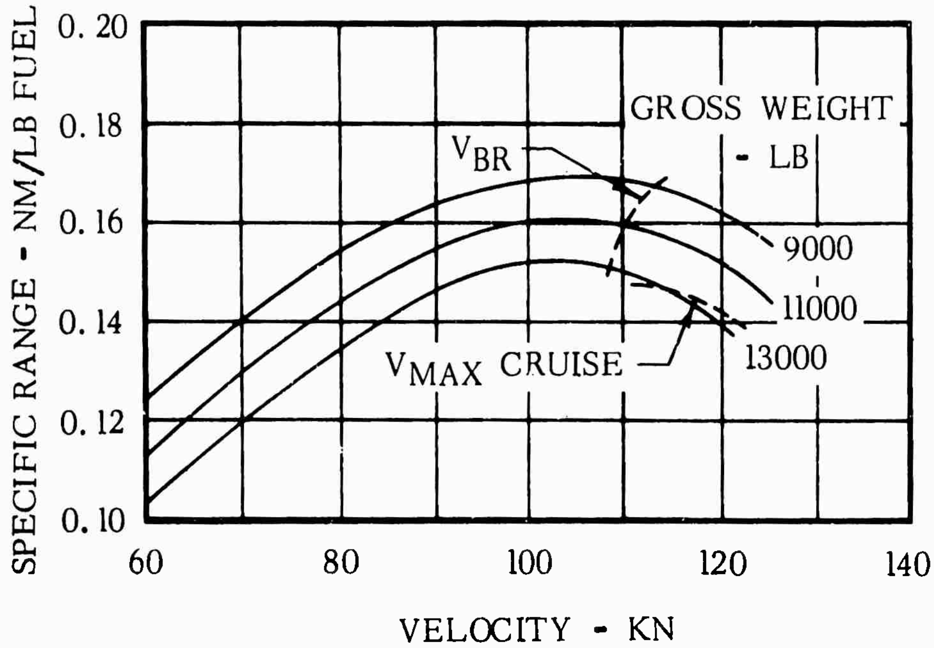


Figure 29. Specific Range Versus Speed - Tail Rotor, Sea Level Standard.

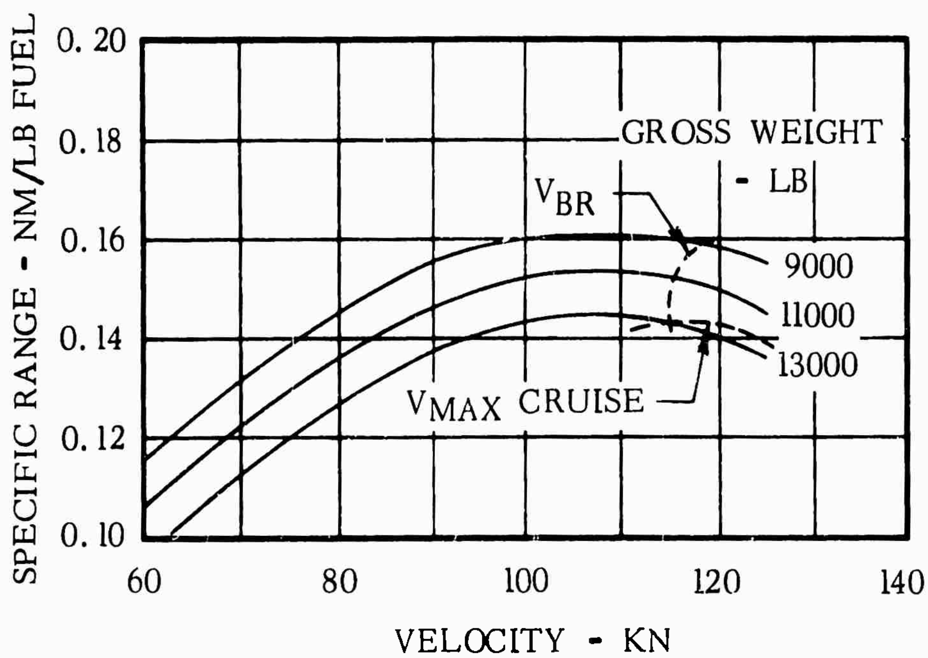


Figure 30. Specific Range Versus Speed - Fan-in-Fin or Fan-in-Tailcone, Sea Level Standard.

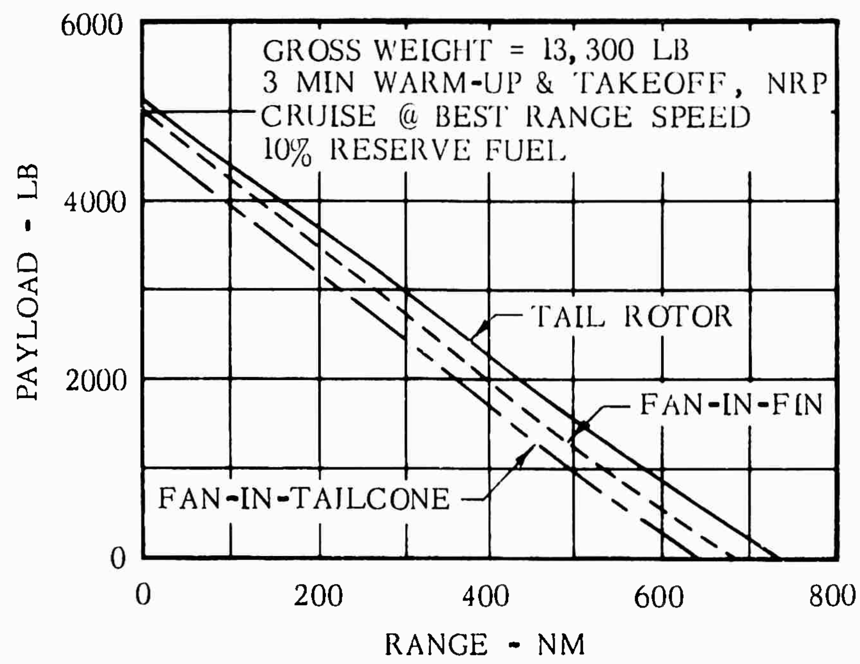


Figure 31. Payload Versus Range, Sea Level Standard.

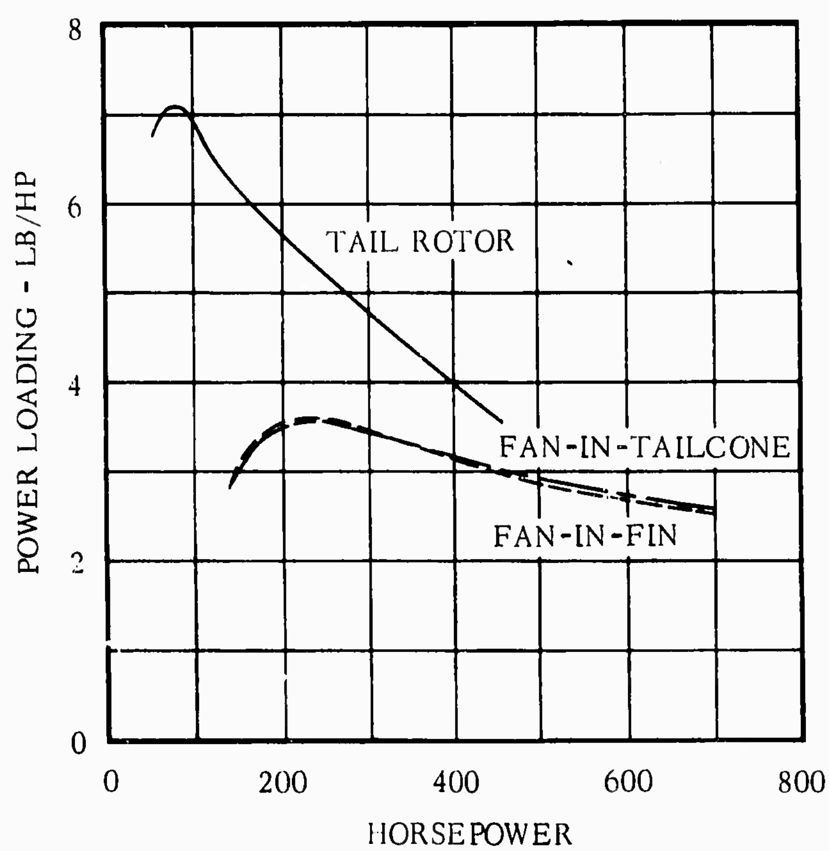


Figure 32. Antitorque System Power Loading Versus Shaft Horsepower, Sea Level Standard.

The effective figure of merit of this prop-fan is much higher than that of the tail rotor, but due to the decrease in radius of a practical prop-fan, the power loading is less, as shown in Figure 32. At low powers, the tail rotor has twice the power loading of the prop-fan systems. This is due to the relatively high profile power required by the prop-fan.

Power loading and effective figure of merit for each configuration for zero wind hover and for a 35-knot side wind with yaw control at 13,300 pounds gross weight at sea level are given in Table XIV.

TABLE XIV. S-58T ANTITORQUE DEVICE POWER LOADING AND FIGURE OF MERIT

Flight Condition	Tail Rotor		Fan-in-Fin		Fan-in-Tailcone	
	Figure of Merit	Power Loading	Figure of Merit	Power Loading	Figure of Merit	Power Loading
Steady Zero Wind Hover	.57	6.8	.82	3.6	.81	3 5
35-Kn Right Side Wind, $\ddot{\psi}$ = 0.232	.47	4.2	.91	2.4	.91	3.0

Figure 32 shows the tail rotor power loading decreasing at a much more rapid rate than for prop-fans. This is due to the more linear thrust-power curve of the prop-fan, as compared to the S-58T tail rotor shown in Figure 20. The tail rotor thrust-power curve has been included in Figure 32 to show this effect.

WEIGHT AND BALANCE

The H-34A base-line empty weight of 7848 pounds[16] has been updated to include transmission oil in order to conform with MIL-STD-451 format, and an arbitrary 100-pound allowance for in-service weight growth since 1959. The revised H-34A empty weight is 7998 pounds.

Conversion of the H-34A to an S-58T reduces empty weight by 362 pounds, resulting in an S-58T empty weight of 7636 pounds. The weight deltas for the turbine conversion, detailed in Table XV, are based on actual weights.

Conversion of the S-58 to the fan-in-fin antitorque concept is established in Table XVI. The estimated empty weight increase over the S-58T with the conventional tail rotor is 117 pounds, resulting in an empty weight of 7753 pounds. The prop-fan weight estimates are based upon Hamilton Standard statistical trends for prop-fans. The gearbox weight is based upon Sikorsky statistical trends for angle gearboxes. The remaining weight changes are estimated from preliminary design drawings.

Conversion of the S-58T to the fan-in-tailcone antitorque concept is shown in Table XVII. The prop-fan gearbox is retained from the fan-in-fin test program. Weight deltas are estimated from preliminary design drawings. The estimated empty weight increase over the S-58T with the conventional tail rotor is 395 pounds, resulting in an empty weight of 8031 pounds.

Table XVIII compares the group weight statements of the unmodified S-58T and the two modified aircraft.

The weight estimates for the antitorque studies were determined on the assumptions that this would be a one-of-a-kind test program and that, if either concept were chosen for a production program, weight reductions could be anticipated in the prop-fan and gearbox.

An aircraft empty weight balance check shows no significant problems.

TABLE XV. WEIGHT DERIVATION - H-34A to S-58T

Group	Weight Removed (lb)	Weight Added (lb)
Top Structure, Engine Compartment	13	61
Nose Doors	46	83
Engine Section	147	-
Engine Mounts	-	71
Firewalls	-	96
Electrical Compartment Structure	-	16
Engine	1403	673
Engine Accessories	88	-
Engine Air Induction System	-	65
Engine Exhaust System	-	21
Engine Lube System	95	81
Engine Controls	26	21
Engine Cooling System	93	-
Engine Starting System	32	10
Engine Clutch System and Controls	83	-
Fuel System Modifications	-	15
Angle Gearbox	-	341
Support, Angle Gearbox	-	14
Drive Shaft	-	37
Instruments	11	34
Hydraulic Utility Pump	-	5
Electrical Generators	58	70
Electrical Inverters	50	37
Electrical Motor	-	11
Electrical Battery and Container	90	62
Electrical Wiring Changes	-	20
Fire Detection and Extinguishing System	9	38
TOTAL	2244	1882
NET WEIGHT EMPTY CHANGE		-362

TABLE XVI. WEIGHT DERIVATION - FAN-IN-FIN INSTALLATION ON S-58T			
Group	Weight Removed (lb)	Weight Added (lb)	Net Weight Change (lb)
Vertical Pylon	(111)	(113)	+2
Beams and Stiffeners	59	51	
Covers	39	32	
Fairings	13	5	
Additional Area	-	22	
Rudder Fitting Beef-Up	-	3	
Tail Rotor	(100)	-	-100
Tail Rotor Blades	23		
Tail Rotor Hub	14		
Integral Controls	26		
Sleeve and Spindle	33		
Misc. Hardware	4		
Prop-Fan	-	(114)	+114
Prop-Fan and Integral Gearbox		114	
Rudder	-	(51)	+51
Beams and Stiffeners		20	
Covers		12	
Hinge and Torque Tube		5	
Fittings		4	
Balance Weights		10	
Body Group	-	(100)	+100
Prop-Fan Covers and Stiffeners		41	
Strap and Ring		10	
Prop-Fan Structural Shroud		49	
Flight Controls	(9)	(10)	+1
Bellcranks and Idlers	5	4	
Control Rods	3	4	
Supports	1	2	
Drive System	(149)	(97)	-52
Intermediate Gearbox	29	-	
Tail Gearbox	46	-	
Drive Shafting	73	87	
Misc. Hardware	1	-	
Tail Takeoff Beef-Up	-	10	
Electrical System	(4)	(5)	+1
Anticollision Light	3	3	
Misc. Clips and Wiring	1	2	
TOTAL	373	490	+117

TABLE XVII. WEIGHT DERIVATION - FAN-IN-TAILCONE INSTALLATION ON S-58T			
Group	Weight Removed (lb)	Weight Added (lb)	Net Weight Change (lb)
Vertical Pylon	(111)	(86)	-25
Beams and Stiffeners	59	48	
Covers	39	30	
Fairings	13	5	
Rudder Fitting Beef-Up	-	3	
Tail Rotor	(100)	-	-100
Tail Rotor Blade	23		
Tail Rotor Hub	14		
Integral Controls	26		
Sleeve and Spindle	33		
Misc. Hardware	4		
Antitorque System	-	(292)	+292
Prop-Fan and Integral Gearbox		114	
Duct Installation		98	
Cascade Assy		52	
Diverter Valve Instl		18	
Inlet Assy		10	
Rudder	-	(51)	+51
Beams and Stiffeners		20	
Covers		12	
Hinge and Torque Tube		5	
Fittings		4	
Balance Weights		10	
Body Group	(209)	(411)	+202
Covers	69	155	
Stringers and Stiffeners	48	75	
Frames	43	67	
Fittings and Fold Mechanism	29	17	
Protective Coating	8	10	
Misc Hardware and Attachments	12	20	
Fairings	-	8	
Prop-Fan Removable Structure	-	5	
Flow Straighteners	-	2	
Prop-Fan Structural Shroud	-	49	
Prop-Fan Support Hardware	-	3	
Flight Controls	(43)	(53)	+10
Cables, Rod and Bellcranks	19	13	
Supports	5	4	
Servo	10	14	
Servo Supports	-	3	
Hydraulic System	5	12	
Misc Hardware	3	7	

TABLE XVII - Continued			
Group	Weight Removed (lb)	Weight Added (lb)	Net Weight Change (lb)
Drive System	(149)	(112)	-37
Intermediate Gearbox	29	44	
Tail Gearbox	46	-	
Drive Shafting	73	58	
Misc Hardware	1	-	
Tail Takeoff Beef-Up	-	10	
Electrical System	(4)	(5)	+1
Anticollision Light	3	3	
Misc Clips and Wiring	1	2	
TOTAL	616	1010	+394

TABLE XVIII. GROUP WEIGHT STATEMENT COMPARISON

Group	S-58T With Tail Rotor	S-58T With Fan-in-Fin	S-58T With Fan-in-Tailcone
Rotor Group	1314	1314	1314
Tail Group	118	147	325
Body Group	1383	1485	1560
Alighting Gear	475	475	475
Flight Controls	352	353	363
Engine Section	170	170	170
Propulsion Group	2568	2572	2587
Instruments	139	139	139
Hydraulics	117	117	117
Electrical System	319	320	320
Electronics Group	281	281	281
Furnishings	174	174	174
Air Cond and Anti-Ice	72	72	72
Aux Gear Group	34	34	34
In-Service Weight Growth	100	100	100
WEIGHT EMPTY	7636	7753	8031

RELIABILITY AND MAINTAINABILITY

A preliminary reliability and maintainability design study was conducted to compare the present S-58T helicopter with an S58T using a fan-in-fin or fan-in-tailcone antitorque system. The data source for this study consisted of a 33,000-flight-hour sample of SH-34J pilot-reported mission aborts recorded by Sikorsky service representatives and a 27,650-flight-hour sample of six months of fleet-wide UH-34D operation in 1968, as documented by the U.S. Navy Maintenance and Materiel Management (3M) data collection system. The values cited in Table XIX reflect predicted total air-vehicle reliability and maintainability values after deletion of non-applicable rates, maintenance man-hours, and down-hours from the base-line data. Predictions were calculated for the overall air vehicle and for each antitorque system at the organizational and direct support (intermediate) levels of maintenance.

The subsystem analysis performed during Task 2 indicated that significant reliability and maintainability improvements are possible within the antitorque system of a 12,000-pound empty weight vehicle using either of the two advanced concepts. The same relative improvement is displayed in the S-58T study within the antitorque subsystem of an 8000-pound empty weight vehicle. An improvement is also seen for the overall aircraft.

The degree of improvement becomes less significant when measured in terms of impact on total air vehicle reliability and maintainability, since the conventional antitorque system is responsible for only 6.3 percent of the total air vehicle failure rate, 5.2 percent of the maintenance man-hours and 4.4 percent of total air vehicle down-time. Consequently, the degree of overall air vehicle reliability and maintainability improvement possible through implementation of advanced antitorque concepts is somewhat limited. Table XIX predictions are mature aircraft values and are not applicable to prototype systems or air vehicles.

BALLISTIC VULNERABILITY

The modified S-58T design was developed in terms of a flight test vehicle for a noncombat environment. Thus, ballistic vulnerability was not a prime design consideration, and no provision was included for protective armor. All trade-offs involving cost or ease of conversion versus considerations of ballistic vulnerability favored the former.

In particular, the S-58T fan-in-tailcone design employs an intermediate gearbox between main transmission and prop-fan. Addition of this gearbox, not required for the new design of Tasks 2 and 5, significantly increases the ballistic vulnerability of the modification relative to the new design, while allowing use of the unmodified S-58T gearbox.

Once this additional gearbox and the absence of protective armor are accounted for, the general points of the ballistic vulnerability discussion of Task 2 designs are applicable to the modified S-58T designs.

TABLE XIX. R/M COMPARISON OF CONVENTIONAL S-58T to S-58T WITH FAN-IN-FIN AND FAN-IN-TAILCONE

Antitorque Subsystem	S-58T with Tail Rotor	S-58T with Fan-in-Fin	S-58T with Fan-in-Tail-cone
Subsystem Reliability, Mean Time Between Failures			
Total- hours	34	54	52
Downing- hours	409	644	622
Aborting- hours	1705	2685	2590
Subsystem Maintainability, Organizational and Direct Support Levels			
Corrective Maintenance			
Maintenance Man-Hours Per Flight Hour	0.139	0.105	0.103
Down-Hours Per Flight Hour	0.060	0.048	0.052
Preventive Maintenance			
Maintenance Man-Hours Per Flight Hour	0.100	0.049	0.059
Down-Hours Per Flight Hour	0.008	0.003	0.010
Total Preventive and Corrections			
Maintenance Man-Hours Per Flight Hour	0.239	0.154	0.162
Down-Hours Per Flight Hour	0.068	0.051	0.062
Total Air Vehicle Reliability, MTBF			
Total- hours	2.19	2.25	2.25
Downing- hours	25	27	27
Aborting- hours	136	140	140
Total Air Vehicle Maintainability, Organizational and Direct Support Levels			
Maintenance Man-Hours Per Flight Hour	4.58	4.49	4.50
Down-Hours Per Flight Hour	1.55	1.53	1.54

SAFETY

Basic sources of tail thruster-associated hazard to either flight or ground personnel include:

1. Contact between thruster blades and the ground while aircraft is airborne.
2. Contact between thruster blades and personnel adjacent to the thruster.
3. Contact between thruster blades and personnel sucked toward the thruster.
4. Effects of the high-intensity thruster exhaust flow on nearby personnel
5. Hazard to ground maintenance personnel.

Recent U.S. Army data indicate that the sources listed above are roughly in the order of relative probability of an accident.

As discussed in Task 2, both the fan-in-fin and the fan-in-tailcone configurations can be expected to show a significantly reduced probability of accidents arising from source 1 above, due to the increased shielding of the dynamic components from actual ground contact. For the S-58T, however, the conventional tail rotor configuration is already protected from this source of hazard by the tail wheel landing gear configuration.

This landing gear layout is even more effective in reducing the probability of source 2 accidents in the existing tail rotor configuration. Throughout the range of the probable vehicle orientations, the tail rotor blades remain at least 7 feet from the ground. In contrast, all of the vehicles included in the accident breakdown in Table VII (in Task 2) can readily be maneuvered in IGE hover so that the tail rotor blades are within 3 feet of the ground, greatly increasing the probability of tail rotor - ground personnel strikes. On this basis, the fan-in-fin configuration of the S-58T is potentially more hazardous than the existing configuration, as the prop fan blades can extend to within 33 inches of the ground, accessible to ground personnel even though protected with a shroud. The fan-in-tailcone S-58T will offer effectively zero probability of hazard from this source, as the dynamic components are completely shielded from ground personnel so long as all access panels are in place.

Accidents from sources 3 and 4 were not included in the data of Table VII. During this study, several semiempirical attempts were made to evaluate the extent of personnel hazard associated with thruster inflow and exhaust flow. None were judged to adequately predict the hazard, primarily due to inadequate induced flow data over the wide range of thruster disc loadings and environmental configurations required.

Several pertinent points about sources 3 and 4 can be noted. The greatest potential personnel hazard can be expected to arise from source 3. The effect of the exhaust flow on personnel will be to force them away from the thruster and perhaps to cause them to fall. The effect of the inlet will be to draw them nearer the thruster blades, the strength of the attracting force increasing rapidly as distance to the fan decreases. In the particular case of the fan-in-tailcone configuration, placement of the relatively large airflow inlet on the upper surface of the tailcone, out of reach of ground personnel, effectively eliminates this hazard, making the exhaust flow the greater potential hazard.

For a given axial distance from the thruster, assuming either a tail rotor or a fan-in-fin configuration, the induced inflow velocity is roughly proportional to the velocity induced through the thruster, which is in turn proportional to

$$K \sqrt{\text{thruster disc loading}} \equiv K\sqrt{DL}$$

where K is an empirical constant (defined in Appendix III). The value of K varies from 0.5 for a conventional rotor to near 1.0 for a ducted or shrouded thruster. The induced flow produces an aerodynamic force on personnel passing across the extended thruster axis proportional to (K^2) times DL. Prop-fan dimensions selected for the fan-in-fin S-58T yield an induced velocity at the thruster roughly 3.5 times that of the existing tail rotor, and an induced aerodynamic pressure on an object in the induced inlet flow roughly 10 times as high as for the tail rotor.

The potential hazard of an induced flow depends on the induced pressure and on the height at which it acts. Thus, partly due to the high tail rotor placement on the S-58T the fan-in-fin configuration can be expected to represent a greater hazard than the current S-58T tail rotor. The pressure at a given axial distance is of the order of 10 times greater, and the inlet flow will be centered about chest-high on nearby personnel rather that at roughly 11 feet above the ground.

If a specific value of induced inflow velocity is assumed to represent the critical value above which significant hazard results, the higher disc loadings of the fan-in-fin imply a larger hazardous region around the prop-fan than is currently found around tail rotor machines. A brief search during this study uncovered no published data either on the value or existence of such a critical value, or on the three-dimensional distribution of induced velocity in the neighborhood of a thrusting prop-fan. Such information could be generated through relatively simple experiments on isolated rotors and prop-fans, or could be obtained as part of the ground test program of the fan-in-fin test aircraft.

The fan-in-fin S-58T configuration is predicted to have a marginally more hazardous exhaust flow than either the prop-fan in tailcone or the tail rotor because of the greater dynamic pressure of the exhaust. Examination of the three-view drawings of the fan-in-fin and fan-in-tailcone concepts, Figures 9 and 10 respectively,shows that although both employ the same prop-fan, the larger exhaust area of the latter leads to a reduced exhaust velocity for a given thrust level. As noted above, none of the concepts presents a serious exhaust flow hazard.

Hazards to maintenance personnel, source 5, are related in basically mechanical systems to accessibility and weight of individual components. On this basis, the S-58T fan-in-fin configuration is predicted to represent a reduced hazard compared to the tail rotor, because of its lower and more accessible mounting. The fan-in-tailcone configuration represents an increased potential maintenance hazard, because the relatively heavy tail cone must be removed to perform major operations on the prop-fan. In view of the projected operational environment of this test vehicle and of the cost penalties in providing simpler field maintenance capability for the aircraft, the relatively poor maintainability characteristics of the S-58T fan-in-tailcone configuration were felt to be justified.

In conclusion, the fan-in-tailcone appears to be the least hazardous of the proposed S-58T configurations, followed very closely by the existing tail rotor and then by the prop fan-in-fin. It is emphasized that a major contribution to the high personnel-safety rating of the S-58T tail rotor arises not from an inherent superiority of this concept over the fan-in-fin but from the particular alighting gear configuration of the S-58T. If one of the newer Army aircraft in Table VII had been selected for modification in place of the S-58T, the tail rotor concept would have represented a far greater hazard to personnel than either of the alternative concepts.

Acoustic Detectability and Annoyance

The procedures used to evaluate acoustic characteristics of promising concepts in Task 2 also were used during the preliminary design study. Figure 33 shows a predicted octave band spectrum for each concept during steady hover. All acoustic comparisons are based on the hover condition for maximum confidence in the predicted noise levels. As the aircraft gains forward speed, the inflow for both fan-in-fin and the tail rotor becomes more turbulent, producing more noise. In addition, radiation patterns of the noise change with forward speed. Fan-in-tailcone noise may be less sensitive to forward speed effects since the fan is fairly well protected from nonuniformities of inflow.

The spectra of Figure 33 result in detection ranges of 4200 feet for the tail rotor, 2800 feet for the fan-in-fin, and 2900 feet for the fan-in-tailcone. These ranges assume a helicopter hovering at an altitude of 50 feet over sparse jungle terrain. Noise from the antitorque devices only is considered in these detection estimates; noise from other rotors and engines is neglected. The tail rotor is detected at large distances because most of its acoustic output is low-frequency pure tones which are not affected significantly by terrain attenuation and atmospheric (molecular) absorption. Detection ranges for the other concepts are smaller because the noise is characterized by higher frequency components that diminish rapidly with distance because of terrain attenuation and atmospheric absorption.

In terms of acoustic annoyance, the perceived noise level at 500 feet from the tail rotor is 83 PNdB. For the fan-in-fin, the corresponding value is 86 PNdB; for the fan-in-tailcone, 90 PNdB.

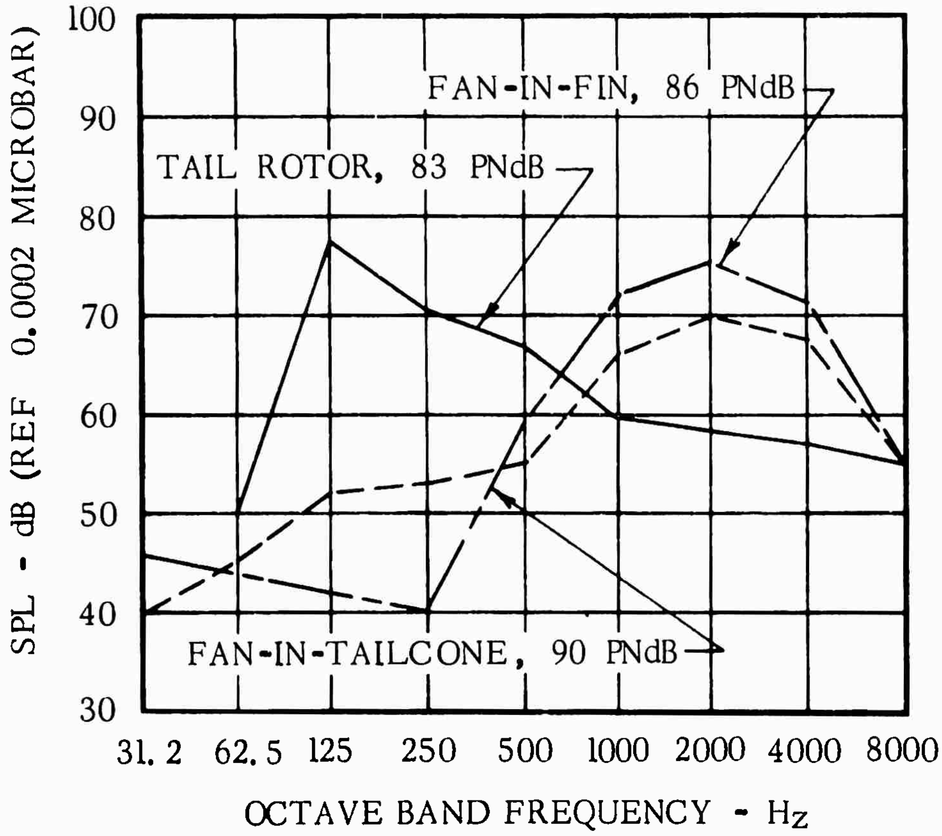


Figure 33. Octave Band Levels at 500 Ft - Steady Hover.

The use of the same prop-fan assembly in both the fan-in-fin and the fan-in-tailcone configurations eliminates the possibility of reduced fan-in-tailcone PNdB levels through altered prop-fan support geometry. It is anticipated that acoustic lining of the duct wall or of the exit turning vanes could significantly reduce fan-in-tailcone annoyance, but only at a cost penalty unjustifiable for the basic flight test program proposed.

TASK 5. NEW AIRCRAFT DESIGN STUDIES

SUMMARY

The objective of Task 5 was to evaluate and compare the fan-in-fin and fan-in-tailcone antitorque concepts as they would be applied to an entirely new light utility transport helicopter using the mission defined in Task 2. Because the design model was used during Task 2, the concepts were evaluated on the basis of new aircraft design. Emphasis was placed on the specific design optimizations and design and mission sensitivities that will influence design of a light utility helicopter using one of the three concepts being compared. None of the studies justifies a reversal in the selection of the fan-in-fin concept over that of the fan-in-tailcone on a performance basis.

AIRCRAFT DESIGN TRENDS

Alternate Gross Weight Design Requirement

The overload capability of existing transport helicopters has been consistently used and increased to satisfy new operational requirements and is considered to be a primary design requirement in new aircraft design. The proposed design criterion for sizing the installed power for the conventional tail rotor was out-of-ground-effect (OGE) hover with 500 feet per minute vertical rate of climb with 95 percent of military power at 4000 feet, 95°F. This results in an overload gross weight OGE hover capability, at sea level, 95°F, of approximately 1.2 times the design gross weight.

From Figure 34, we see that as the alternate gross weight factor (AGWf) is increased from 1.0, the design gross weight increases slowly until a point is reached where the overload requirement begins to dictate the installed power level. The curve slope now increases because of the greater impact on design gross weight of installed power increases (see Figure 35). The small increases in design gross weight with AGWf near 1.0 are due to increases in tail rotor/fan size alone. The point at which the slope breaks occurs at a lower value of AGWf as we move from tail rotor, to fan-in-fin, to fan-in-tailcone due to the increasing fraction of installed power required by the antitorque device as disc loading increases. As aircraft weight increases, the antitorque thrust requirement increases, and so the engine power required increases, but at a faster rate for a high-disc-loading device. Thus the available power, as defined by design gross weight hover considerations, will be reached at a lower AFWf as thruster disc loading increases.

The engine sizing throughout the study has been based on the most demanding of the following conditions so that the aircraft comparisons are based on equal overload capability.

1. Hover OGE at design gross weight, 4000 ft, 95°F, 500 fpm VROC, 95% of military power.

2. Hover OGE at overload gross weight (1.2 times design gross weight), sea level, 95°F, no VROC, 100% of military power with adequate power to meet MIL-H-8501A requirements.

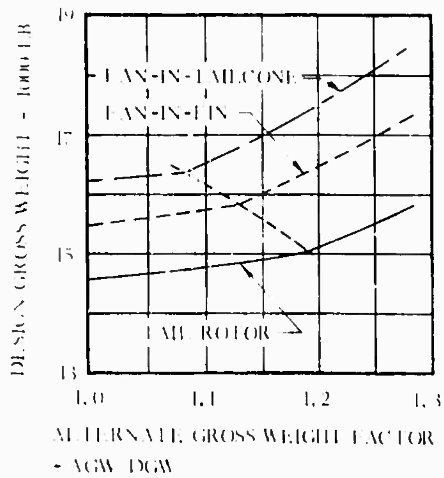


Figure 34. Design Gross Weight Versus Alternate Gross Weight Factor.

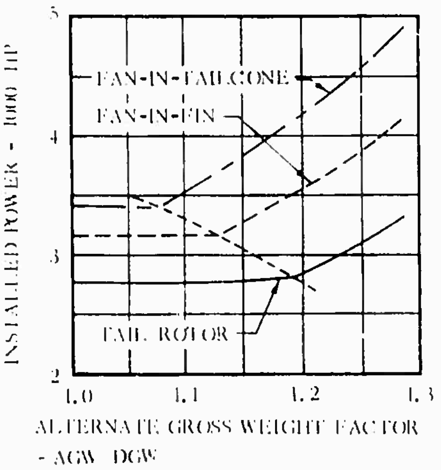


Figure 35. Installed Power Versus Alternate Gross Weight Factor.

Main Rotor Blade Loading (C_T/σ) Optimization

The helicopter main rotor blade loading (C_T/σ) is a primary design parameter in the optimization on design gross weight or aircraft mission efficiency. Figure 36 compares the two alternate concepts and the tail rotor.

All three configurations are near their minimum weight points at a C_T/σ of 0.09. However, aircraft efficiency is dropping rapidly from the optimum C_T/σ value of 0.07 to 0.08. This difference in optimization is due primarily to the cruise speed term in the aircraft efficiency parameter. For example, cruise speed for the tail rotor configuration is almost constant for C_T/σ values less than 0.08, due to installed power limitations. For C_T/σ values greater than 0.08, cruise speed drops rapidly due to rotor blade stall. Optimum aircraft efficiency then maximizes near the C_T/σ value where cruise speed is at the intersection of the normal rated power limit and the blade stall limit.

A change in engine sizing criteria such that the engines are always sized to provide power to achieve rotor blade stall speed was initially believed to result in higher aircraft efficiencies. When this was evaluated, the weight and cost penalty was so great that the additional speed capability did not increase aircraft efficiency. In fact, a reduction in aircraft efficiency occurs for C_T/σ values less than the optimums shown in Figure 36.

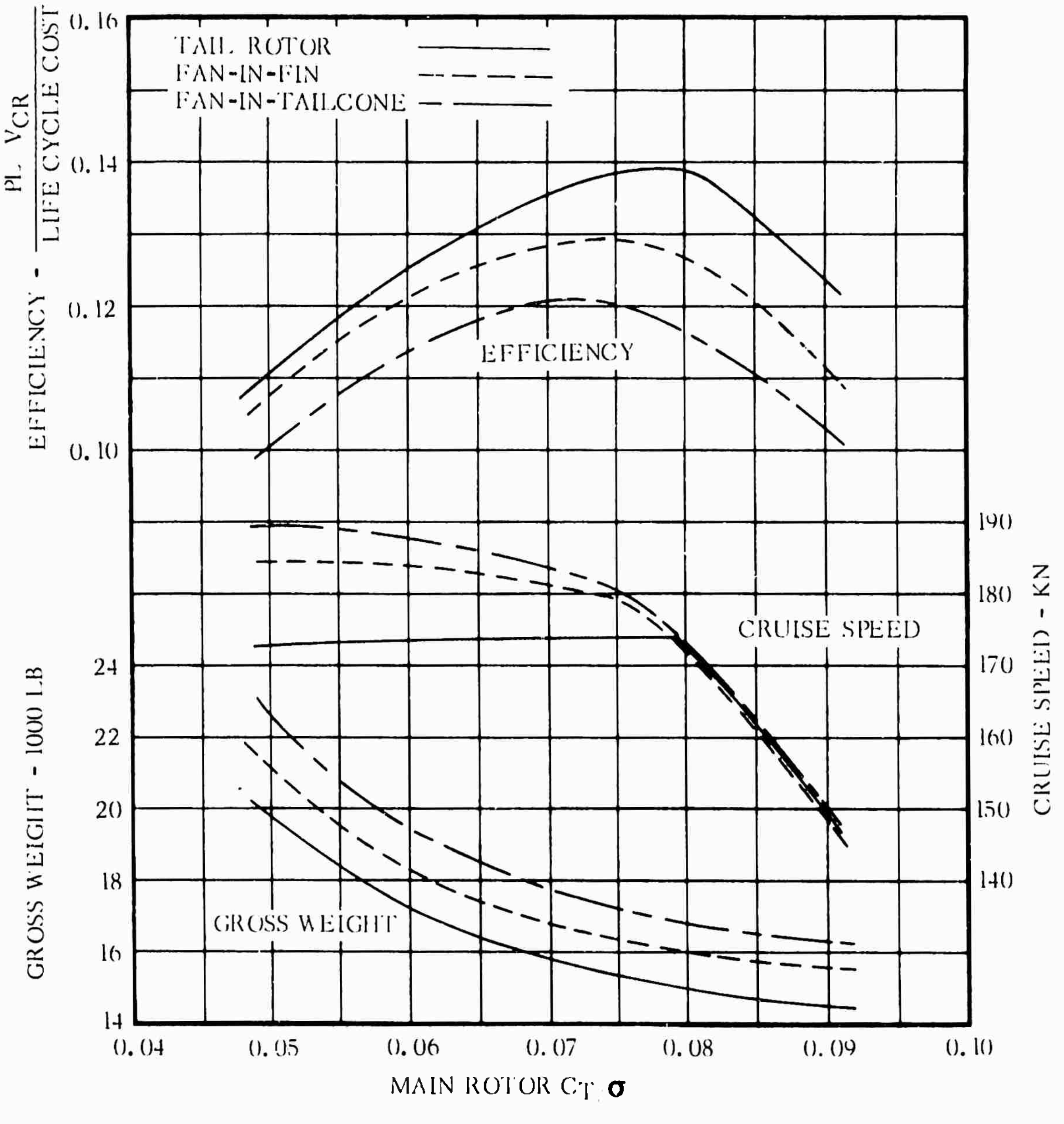


Figure 36. Main Rotor Blade Loading (C_T/σ) Optimization Trends.

If optimizations are performed using minimum gross weight as the criterion, the mission required cruise speed of 150 knots would become a limit at a C_T/σ of approximately 0.09. This criterion would not take full advantage of the forward propulsive capability of the main rotor and is considered to be unrealistic for a new helicopter design. Use of the gross weight does not give credit for speed potential for aircraft that have high installed power due to the use of a high disc-loading antitorque device. The use of an aircraft efficiency parameter that accounts for productivity is considered to be the best method for quantitative comparison. Near-optimum

C_T/σ values of 0.08, 0.074, and 0.0725 were selected for the tail rotor, fan-in-fin, and fan-in-tailcone configurations, respectively.

Main Rotor Disc Loading and Antitorque Power Optimization

Main rotor disc loading and power fraction allocated to the antitorque device also affect gross weight and aircraft efficiency. Figures 37, 38, and 39 show these curves for the three configurations. A disc loading of 6.0 is seen to be near optimum for all three devices and was used throughout the study.

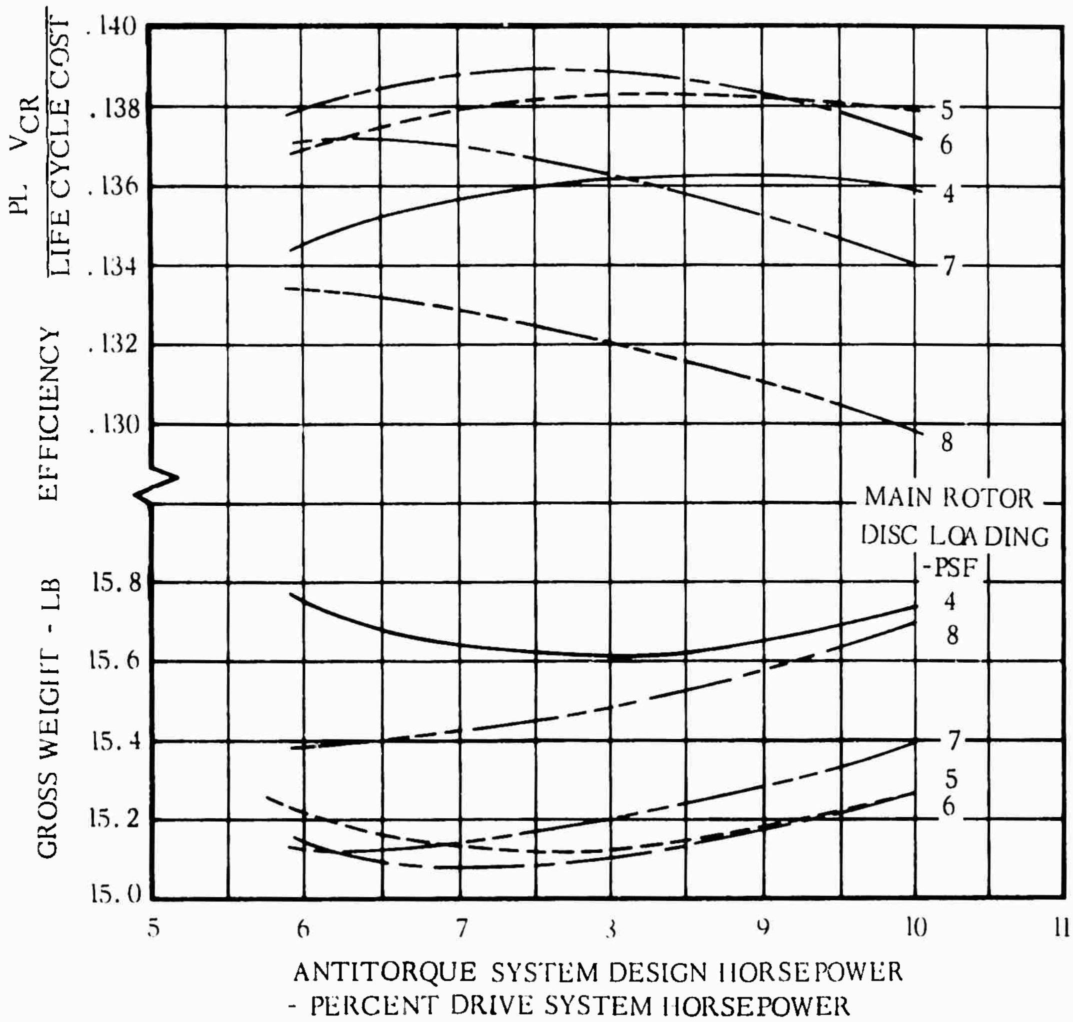


Figure 37. Main Rotor Disc Loading and Antitorque Power Optimization - Tail Rotor.

Antitorque system design horsepower is defined as the power required by the antitorque device to provide the critical thrust required by MIL-H-8501A less the power that can be extracted from the main rotor for the transient portion of the required thrust. Power available from the main rotor is defined as the power that can be diverted from the engines plus that which can be extracted from main rotor momentum such that main rotor RPM does not decay more than 2 percent over a 1-second period. The antitorque system design power is expressed as a percentage of the total power available at the alternate gross weight design condition. The near-optimum percentages selected for the tail rotor, fan-in-fin, and fan-in-tailcone are 8, 20, and 28, respectively, at the selected disc loading of 6.0.

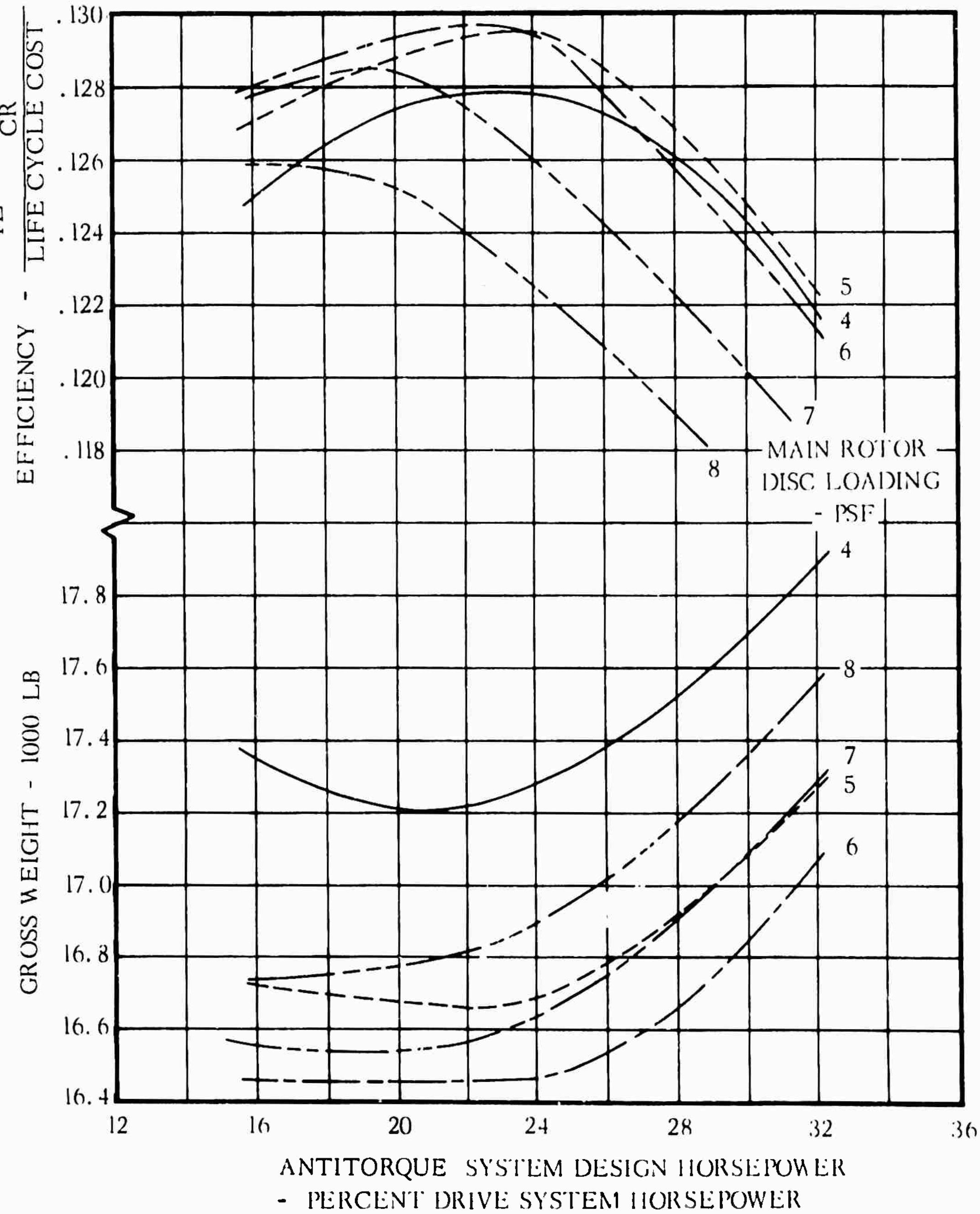


Figure 38. Main Rotor Disc Loading and Antitorque Power Optimization - Fan-in-Fin.

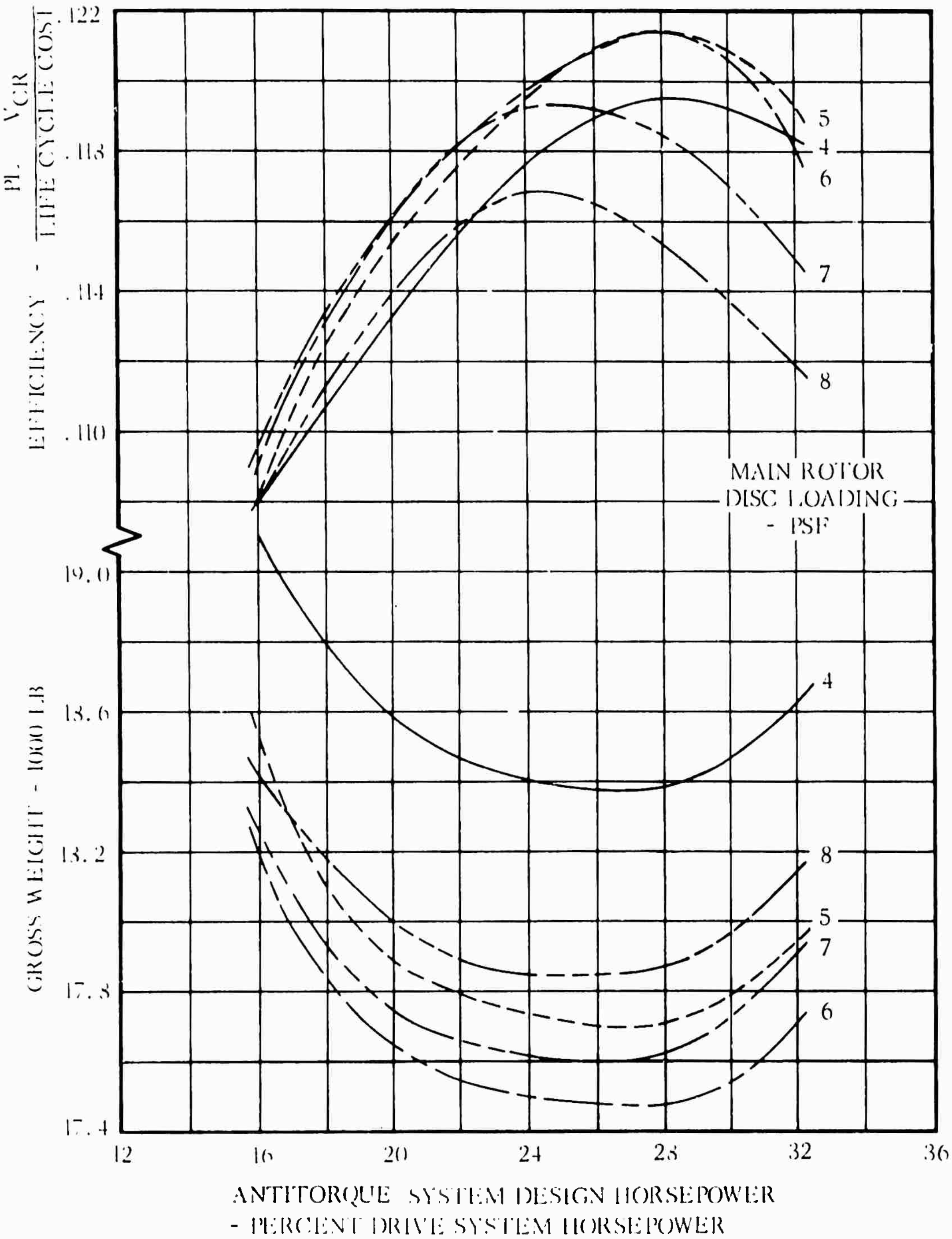


Figure 39. Main Rotor Disc Loading and Antitorque Power Optimization - Fan-in-Tailcone.

Mission Sensitivity

The mission selected for this study is a relatively difficult utility tactical transport mission. Figure 40 shows the change in gross weight as the mission is reduced. Mission segments requiring the most power were eliminated first. Dash and hover segments are most often omitted from this type of mission, as this results in a significant reduction in gross weight - 1000 to 1500 pounds for the three concepts shown. However, the primary concern here is whether the mission could reverse the selection of the fan-in-fin concept over that of the fan-in-tailcone. Figure 40 shows that the fan-in-tailcone is 16 percent heavier than the fan-in-fin for the full mission and that this is reduced to 13 percent as the dash and hover segments are eliminated. When the cruise segments and reserves are also eliminated, the fan-in-tailcone is still 7 percent heavier. Thus it is concluded that selection of the best concept is not greatly influenced by a reasonable variation of mission requirements.

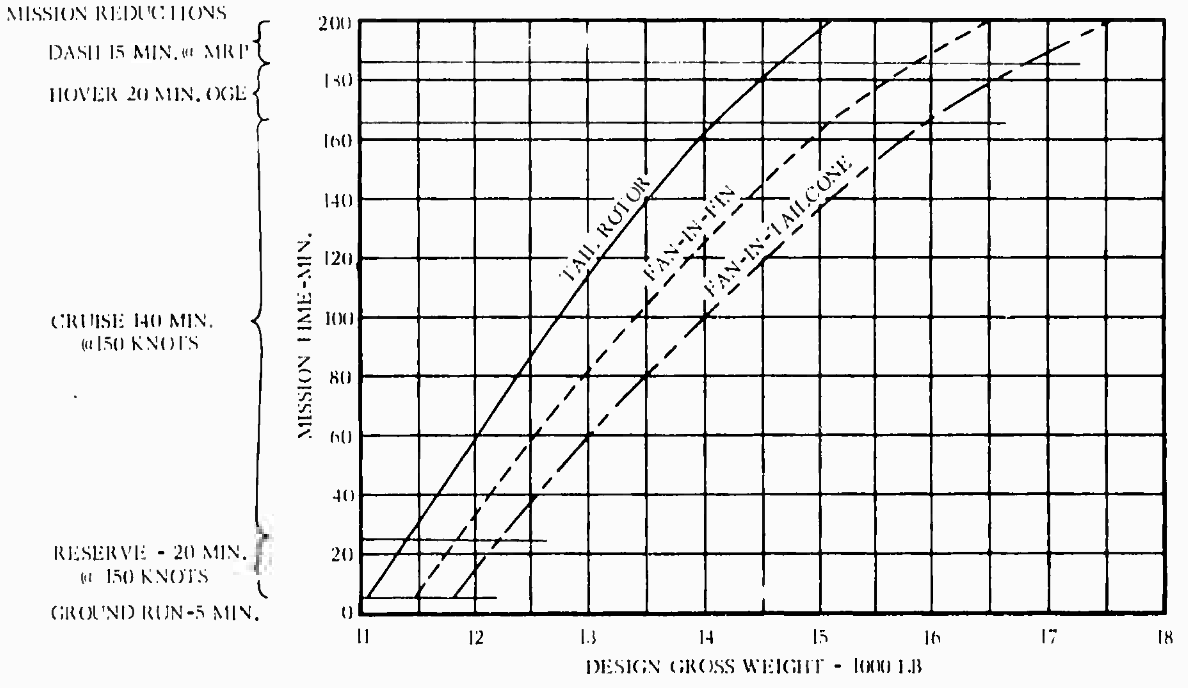


Figure 40. Design Gross Weight Versus Mission Segment, 4000 Ft, 95°F.

Antitorque System Tip Speed Sensitivity

Optimum tip speeds for the antitorque systems were selected on the basis of performance and acoustic trends. Figures 41 and 42 show the effect of tip speed on aircraft gross weight and on prop-fan or rotor diameter. These figures show the fan-in-tailcone to be the most sensitive to tip speed variation.

Figures 43 and 44 show the acoustic trends for the three configurations. Detection factor is the ratio of the calculated detection range to the base-line tail rotor detection range. The tail rotor base-line detection range is 4700 feet with a 10.6-foot-diameter tail rotor operating at 700 feet per second. The abrupt increase in detection factor of the tail rotor occurs between 700 and 800 feet per second because the acoustic energy shifts down in frequency due to the shift from 5 to 4 blades as required from blade aspect ratio considerations. In general, low frequency noise results in large detection ranges.

Further acoustic improvements can be made by varying other parameters, such as number of blades or blade loading, or through use of acoustically absorbent materials.

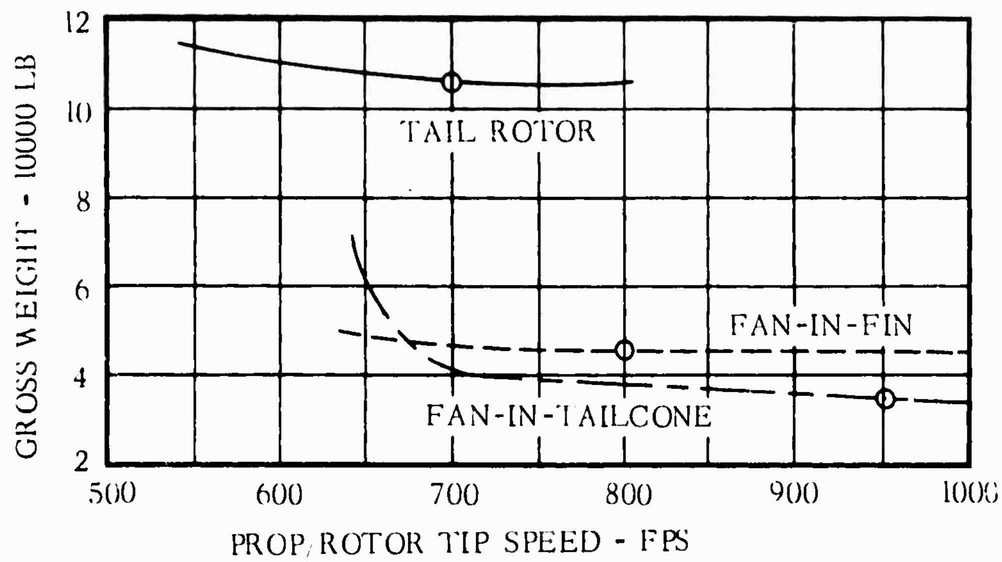


Figure 41. Design Gross Weight Versus Prop-Fan/Rotor Tip Speed.

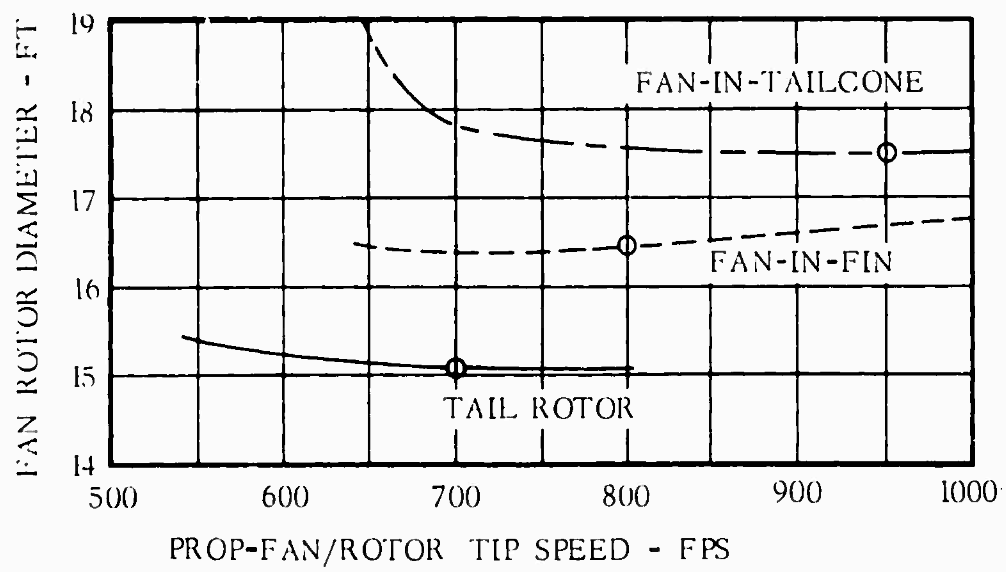


Figure 42. Prop-Fan/Rotor Diameter Versus Tip Speed.

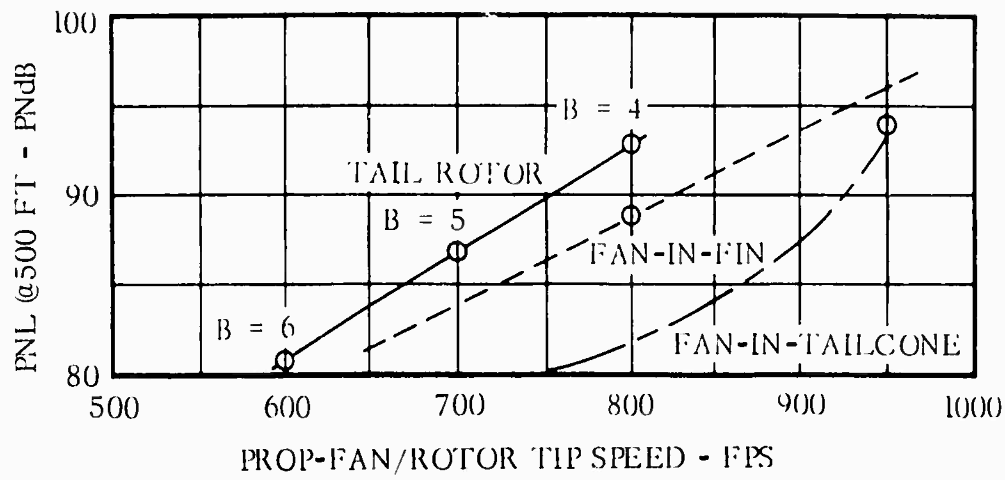


Figure 43. Perceived Noise Level Versus Prop-Fan/Rotor Tip Speed.

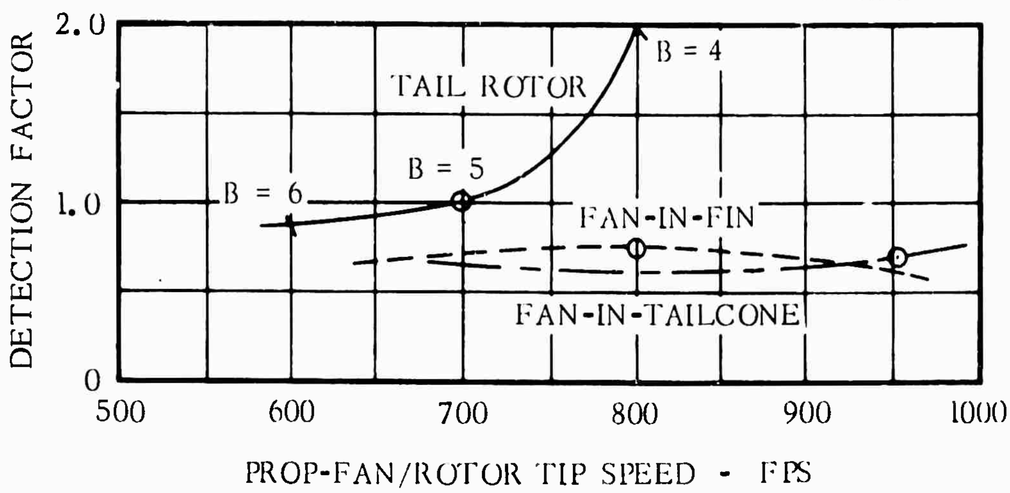


Figure 44. Detection Factor Versus Prop-Fan/Rotor Tip Speed.

Antitorque System Blockage Sensitivity

Losses in antitorque system thrust due to interference of tail surfaces, support struts, drive shafting, and control rods as well as turning and ducting losses have been accounted for as blockage. A blockage factor is defined as the thrust available if these losses were not present divided by the design thrust requirement. Because the three systems being compared are obviously quite different, the question arises as to the effect of the blockage estimate on selection of the best concept. Figure 45 shows that the possible error in the estimate would not reverse the selection of the fan-in-fin concept over that of the fan-in-tailcone. The optimum antitorque system power fraction increases with increasing blockage. The trends in Figure 45 were derived assuming this optimum fraction throughout.

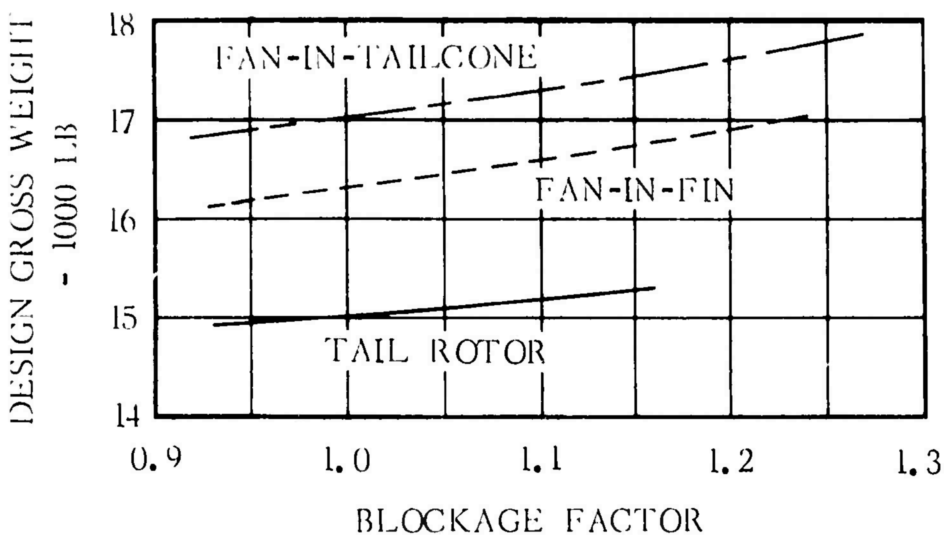


Figure 45. Design Gross Weight Versus Blockage Factor.

Weight Technology Sensitivity

Design technology trends were derived for the aircraft using the three antitorque concepts. Figure 46 shows the effect of technology level on design gross weight for 1972 to 1985 design technology.

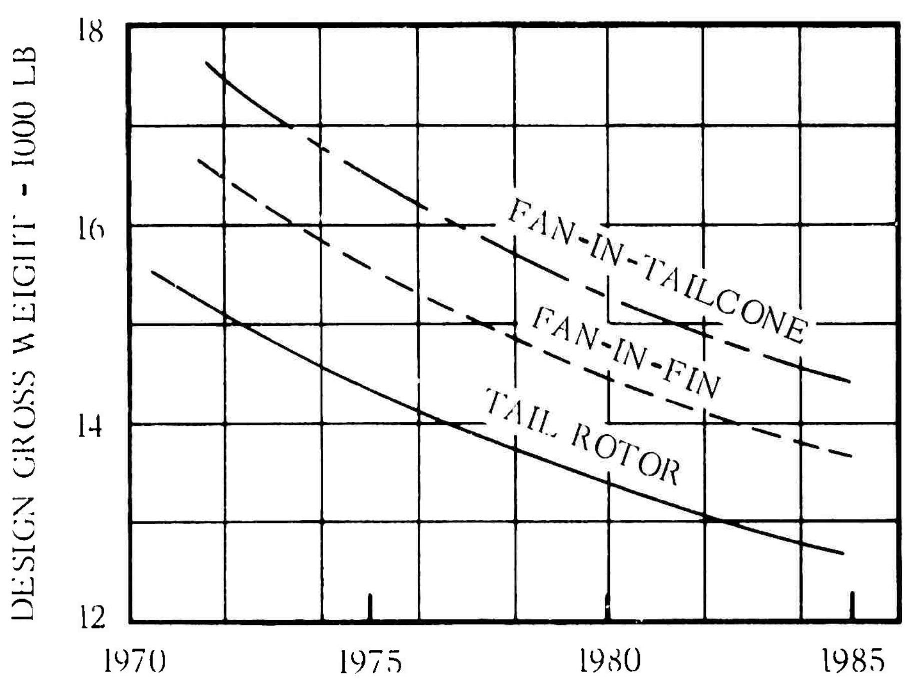


Figure 46. Design Gross Weight Versus Design Technology.

Empty weight savings are included in this analysis, but engine fuel consumption reduction is not. This analysis does not include weight increases due to more stringent design requirements and increased fixed equipment requirements that will exist during this time frame. The design technology is seen to have very little effect on selection of the best antitorque concept.

Control Ramp Time Sensitivity

Calculation of the maximum antitorque system thrust depends on an estimated system lag due to pilot reaction, control system lag and, in the case of the fan-in-tailcone concept, the air transport time in the duct. To account for this lag, it is assumed that the thrust increases linearly from zero to the maximum thrust level during the ramp time. The longer the ramp time, the higher the maximum thrust level must be to achieve a given angular displacement in 1 second. Sikorsky uses a ramp time of 0.2 second for a normal tail rotor design. Values of 0.25 and 0.40 second were used for the fan-in-fin and fan-in-tailcone concepts to account for the anticipated reduction in response. Figure 47 was developed to show the sensitivity of this parameter. Both prop-fan concepts are more sensitive than the tail rotor, but the ramp time penalty given to the prop-fan concepts does not significantly affect aircraft design or concept selection.

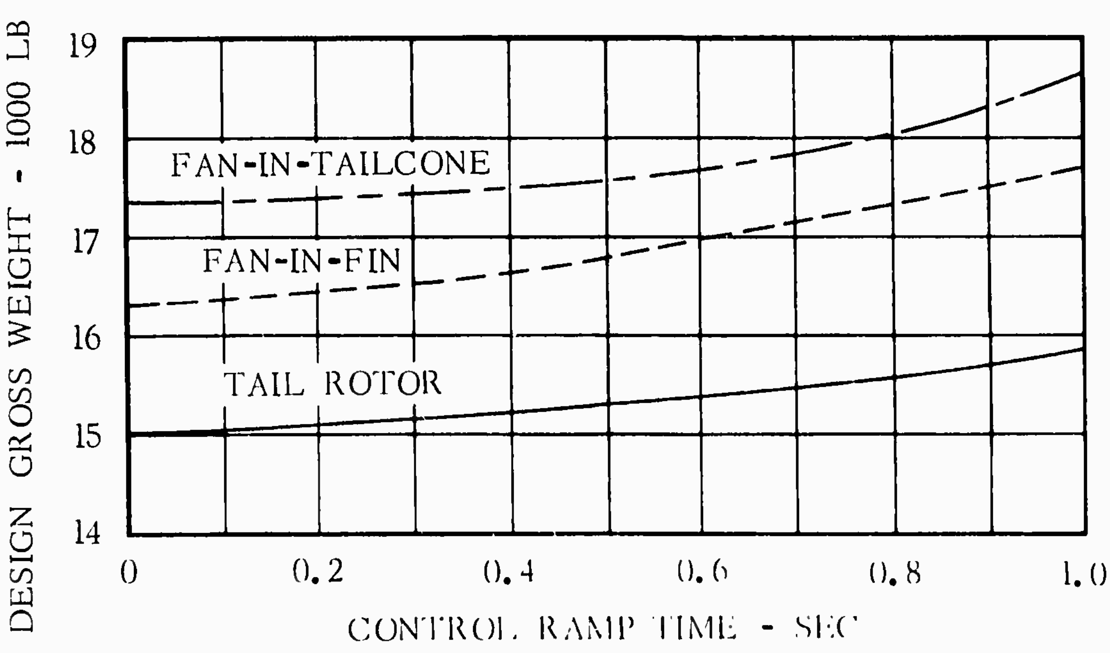


Figure 47. Design Gross Weight Versus Control Ramp Time.

CONCLUSIONS

The fan-in-fin antitorque concept is considered to be the best, most cost effective, lowest risk alternative to a conventional tail rotor system for a helicopter sized to the mission requirement defined for this study. This concept provides improvements in all the characteristics required by the contract statement of work at a reasonable increase in aircraft size and cost.

The fan-in-tailcone concept offers additional improvements in the areas of safety, vulnerability and foreign object damage with an additional penalty in aircraft size and cost. Although this concept was flown in the 1940's, the technical risk is higher than for the fan-in-fin, specifically in the areas of ducting losses, stability and control, and possible inlet drag problems.

Both the fan-in-fin and the fan-in-tailcone concepts will be less susceptible to high-speed instabilities than the tail rotor. This is attributable to the hingeless construction of the prop-fan and the fact that it is unloaded in forward flight by the relatively large vertical tail surface required for stability.

Antitorque system reliability is improved by approximately 35 percent for both the prop-fan concepts when compared to a conventional tail rotor. This results in an improvement in aircraft reliability of about 3 percent.

Antitorque system maintenance man-hours are reduced by 21 and 29 percent for the fan-in-fin and fan-in-tailcone concepts respectively. Corresponding reductions in down-hours per flight hour are 23 and 20 percent. The resulting improvement in overall aircraft maintainability is approximately 2 percent.

Accidents involving personnel should be greatly reduced with either device. The probability of ground personnel injury due to contact with the fan-in-fin is reduced because the prop-fan is shielded by a shroud, visible even during operation. However, the suction field present near the inlet would be a hazard. The fan-in-tailcone configuration will eliminate the possibility of personnel contact with the prop-fan.

The reduction in aircraft "A" kill vulnerable areas to a 7.62 mm API threat is estimated to be approximately 3 percent for both the fan-in-fin and the fan-in-tailcone configurations. Corresponding reductions for a 12.7 mm API threat are 19 and 26 percent. Accidents involving terrain/thruster contact would be eliminated almost completely with either configuration, as both shield the thruster with structure.

Both the fan-in-fin and the fan-in-tailcone concepts offer a significant reduction in aural detection range compared to the tail rotor, but both represent a greater acoustic annoyance, in terms of perceived noise level, than does the tail rotor.

For the gross weight and speed range examined in this study, the tail rotor has been shown to be the superior antitorque system when compared on a weight or cost basis. However, the cost evaluation did not account for the potential savings in life associated with the operation of the aircraft due to the improvements in safety and improved probability of mission completion, or for the potential savings in life and material in military units being supported by these more reliable, less vulnerable aircraft. It is considered beyond the scope of this contract to attempt an objective comparison of the fan-in-fin and fan-in-tailcone concepts with the tail rotor including these factors.

The penalties in aircraft weight and cost for the prop-fan antitorque concepts can be reduced significantly for certain applications, such as compound helicopters, specifically when the installed power is defined by a cruise or dash requirement and not the hover requirement, as was the case in this study. The excess power available in hover could then be used for the antitorque function.

Both the fan-in-fin and fan-in-tailcone concepts have been flight demonstrated, but not in the 15,000-pound gross weight range required for squad carrier helicopters. Therefore, comprehensive flight testing is required to accurately assess the performance and handling characteristics.

LITERATURE CITED

1. HELICOPTER FLYING AND GROUND HANDLING QUALITIES, GENERAL REQUIREMENTS FOR, MIL-H-8501A, Amendment 1, Department of Defense, 3 April 1962.

2. UNITED STATES ARMY AVIATION PLANNING MANUAL, FM 101-20, Headquarters Department of the Army, August 1968.

3. Olson, John R., FIGURE OF MERIT RATIO (FMR) METHOD FOR ROTOR/HOVER PERFORMANCE PREDICTION, Sikorsky Aircraft, SYM-A-12, Sikorsky Aircraft Stratford, Connecticut, 8 April 1968.

4. Black, Donald M., SHROUDED PROPELLER TEST PROGRAM DATA ANALYSIS, Hamilton Standard, HSER 4348, Vol. 1, Hamilton Standard, Windsor Locks, Connecticut, May 1967.

5. Black, Donald M., TWELVE BLADE AXIAL FLOW FAN AND DUCTED PROPELLER TEST SUMMARY OF EXPERIMENTAL DATA AND DATA ANALYSIS, Hamilton Standard, HSER 2836, Hamilton Standard, Windsor Locks, Connecticut, July 1969.

6. Taylor, Robert T., EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF SOME SHROUD DESIGN VARIABLES ON THE STATIC THRUST CHARACTERISTICS OF A SMALL-SCALE SHROUDED PROPELLER SUBMERGED IN A WING, NACA TN 4126, Langley Aeronautical Laboratory, Langley Field, Virginia, January 1958.

7. Sogin, Harold H., A DESIGN MANUAL FOR THERMAL ANTI-ICING SYSTEMS, Illinois Institute of Technology, WADC TR-54-313, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, December 1954.

8. SAE AEROSPACE APPLIED THERMODYNAMICS MANUAL, Section Ia, ed. Gregg, G.E., 2nd Edition, New York, Society of Automotive Engineers, October 1969, pp. 6-14.

9. Fansler, J. D., and Knapp, F. J., SURVIVABILITY/VULNERABILITY STUDY (U), Sikorsky Aircraft, SER-611420, Sikorsky Aircraft, Stratford, Connecticut, March 21, 1969 (SECRET)

10. Leowy, R. G., HELICOPTER AURAL DETECTION IN TACTICAL SITUATIONS, PART II, Institute for Defense Analysis, IDA Research Paper P-25, Institute for Defense Analysis, Alexandria, Virginia, May 1963, AD 409535.

11. Schlegel, R. G., King, R. J., and Mull, H. R. , HELICOPTER ROTOR NOISE GENERATION AND PROPAGATION, Sikorsky Aircraft ; USAAVLABS Technical Report 66-4, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, October 1966, AD 645884.

12. King, R. J., and Schlegel, R. G., PREDICTION METHODS AND TRENDS FOR HELICOPTER ROTOR NOISE, Proc. Third Annual CAL/AVLABS Symposium, 18-20 June 1969, Buffalo, New York.

13. Ollerhead, J.B., and Munch, C.L., AN APPLICATION OF THEORY TO AXIAL COMPRESSOR NOISE, Wyle Laboratories, NASA Contractor Report 1519, National Aeronautics and Space Administration, Washington, D. C., April 1970.

14. Ham, N., and Moser, H., INVESTIGATION OF A DUCTED FAN IN LIFTING FLIGHTS, Journal of American Helicopter Society, Vol. 3, No. 3, July 1958, pp. 17-29.

15. Kepchar, J., FLIGHT MANUAL PERFORMANCE SUBSTANTIATION - H-34A HELICOPTER, Sikorsky Aircraft, SER-58114, Sikorsky Aircraft,Stratford, Connecticut, 31 December 1957.

16. Matthies, F. B., ACTUAL WEIGHT AND BALANCE REPORT - LAST AIRCRAFT Sikorsky Aircraft, SER-58207, Sikorsky Aircraft, Stratford, Connecticut, 13 January 1959.

17. Schlegel, R. G., HUSH FINAL REPORT - QUIET HELICOPTER PROGRAM (U), Sikorsky Aircraft, SER-611478, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, January 1970, (C).

18. Lewis, Richard B., JET FLAP ROTOR RESEARCH, Proceedings of V/STOL Technology and Planning Conference, Las Vegas, Nevada, September 1969.

19. Robinson, Frank, INCREASING TAIL ROTOR THRUST AND COMMENTS ON OTHER YAW CONTROL DEVICES, Journal of the American Helicopter Society, Vol. 15, No. 4, October 1970, pp. 46-52.

20. Pullin, C. G., HELICOPTER RESEARCH AND DEVELOPMENT, Bulletin of the Helicopter Society of Great Britain, March 1947, pp. 21-36.

21. Shapiro, J. S., SOME TECHNICAL ASPECTS OF W.9 DEVELOPMENT, Journal of the Helicopter Society of Great Britain, Vol. 2, No. 1, 1948, pp. 19-39.

22. Liptrot, R. N., A HISTORICAL VIEW OF HELICOPTER DEVELOPMENT, Bulletin of the Helicopter Society of Great Britain, March 1947, pp. 4-20.

23. Unsigned article, VARIABLE PITCH FAN DESIGNED FOR LOW-NOISE STOL AIRCRAFT, Aviation Week & Space Technology, Vol. 92, No. 11, 14 September 1970, p.66.

24. Flemming, R. J., SMALL SCALE MODEL ROTOR WAKE SURVEY, Sikorsky Aircraft, SYTR-A-12, Sikorsky Aircraft, Stratford, Connecticut, May 1969.

25. Gessow, Alfred, and Myers, Garry C. Jr., AERODYNAMICS OF THE HELICOPTER, New York, The MacMillan Company, 1952, p.53.

APPENDIX I

SURVEY OF ANTITORQUE CONCEPTS

Appendix I summarizes a qualitative survey of concepts representing potential alternatives to the tail rotor of conventional shaft-driven single-main-rotor helicopters. A 15,000-pound gross weight, 1970-technology utility helicopter was assumed as a base line. A wide variety of alternatives, promising and unpromising, were examined to provide a broad basis for selection of the best concepts and for qualitative evaluation of additional concepts which may be suggested from other sources. The basic criterion employed in eliminating concepts from consideration was the requirement that each concept be capable of producing either a force or a moment in an antitorque application. The magnitude of the available force or moment, or of the associated penalties, was not considered in the selection procedure, but was included in the evaluation of the concepts.

The first three sections of the appendix describe, respectively, the objectives and applicable evaluation criteria of the survey, general results, and general conclusions. The fourth section, representing the main body of the appendix, describes each concept and a qualitative evaluation of its potential in this application. The fifth section briefly discusses alternative helicopter applications for which certain of the concepts examined may be worth reevaluating.

Thirty-two concepts were examined. For convenience, these concepts may be divided into nine categories:

1. Tail rotors: conventional (base line) and advanced
2. Passive thrusters (systems requiring an external power source): ducted propellers, prop-fans, or fans of various types mounted either at the base-line tail-rotor station or in the fuselage with the efflux ducted through the tail cone and exited through controllable nozzles
3. Main-rotor downwash deflectors: tail cones and/or rudders incorporating conventional flapped cambered airfoils, squirrel-cage fans, jet-flap airfoils, Thwaites-flap airfoils, circulation-controlled airfoils with tangential blowing, or Flettner rotors
4. Inertial solutions: accelerated flywheels, precessed gyroscopes
5. Active thrusters (auxiliary engines): turbojets or turbofans, pulsejets, rockets (both chemical and exotic) or acoustic radiators, mounted either at the base-line tail-rotor station or in the fuselage with the efflux ducted through the tail cone and exited through controllable nozzles
6. Main engine flow deflectors: power turbine exhaust deflection, use of convertible turboshaft/fan engines, or compressor bleed
7. Pseudo-compound solutions: deflected thrust from thrusting shrouded propeller, Sikorsky ROTOPROP variable-direction propeller, cyclic pitch on thrusting propeller, differential thrust on

stub-wing mounted propellers, turbojets or turbofans.

8. Pseudo-coaxial main rotor solutions: coaxial speed brakes
9. Combined concepts

SURVEY OBJECTIVES

Each Task 1 concept was evaluated on the basis of its capability to meet MIL-H-8501A low speed control moment requirements for the base-line aircraft and on the determination of the associated penalties in:

1. Mission fuel
2. Structure and powerplant weight
3. Stability and control characteristics
4. Development risk

Concepts were then rated according to their potential for improvement over current conventional tail rotors in six areas:

1. Antitorque/yaw control system dynamic stability at high flight speeds
2. Vulnerability to small-arms fire
3. Vulnerability to terrain contact damage
4. System reliability
5. System maintainability
6. Safety of ground personnel

and, at a lower priority:

7. Detectability
8. Sensitivity to erosion and foreign object damage

The four preliminary penalty evaluation categories were evaluated on the basis of performance requirements, and no aircraft growth factor corrections were imposed. Thus, an installed power penalty was calculated, assuming the base-line critical flight condition and the base-line maximum required control force or the equivalent control moment. The structural and powerplant weight estimates include the weight of the increased powerplant required to supply this moment and the increased control and fuel system weights, but make no correction for the main rotor power required to lift this increased weight or the larger required control moment arising from the increased aircraft inertia. Similarly, the mission fuel is based on the base-line aircraft weight and inertia parameters. It does not reflect the influence of increased aircraft weight, drag, or inertia.

The eight categories in which improvement over the tail rotor is specifically required or desired were rated under the same set of assumptions. In general, because of the qualitative nature of the Task 1 evaluation, the estimated relative potential of the alternative concepts is not altered by this analysis simplification.

The evaluation of the potential of each concept in the above areas was based on criteria summarzied below:

- Mission Fuel
  1. Mission elements and duration
  2. Installed power requirements
  3. SFC values of required powerplants at mission power levels
- Powerplant and Structural Weight
  1. Type and power rating of required powerplant
  2. Requirements for ducts, values, shafting, gearboxes, controls, thruster units, support structure, fuel system, etc.
  3. Weight penalties due to balance requirements
- Stability and Control Characteristics
  1. Capability of meeting MIL-H-8501A control moment requirements
  2. Capability of smooth transition to autorotation, and adequate control in autorotation
- Development Risk
  1. Extent to which concept as a whole has been proved
  2. Extent to which individual components have been proved
  3. Applicability of current manufacturing, assembly, and testing techniques
- High-Speed Dynamics
  1. Anticipated maximum helicopter speeds
  2. Possibility of aerodynamic instabilities, including flutter and instabilities in valves and internal ducting; possibility of blade stall
  3. Possibility of non-aerodynamic instabilities (shaft whirl, etc.)
  4. Possibility of large (probably flapping) excursions that might impinge on structure

- Ballistic Vulnerability (Small Arms)
  1. Area of critical components (based on likely threat direction)
  2. Robustness of critical components
  3. Vulnerability of individual systems to small-arms projectile impact

- Terrain Contact Vulnerability
  1. Vulnerability of critical components to light ground contact
  2. Probability of system ground contact in operational environment (a function of overall aircraft configuration)

- Reliability
  1. Number and complexity of critical components
  2. Fail-safe capability
  3. Reliability of individual components or subsystems
  4. Magnitude and duration of vibration and stresses

- Maintainability
  1. Maintenance hours and down-time predicted for basic concept
  2. Penalties due to component inaccessibility, weight, and size
  3. Requirements for special maintenance facilities or techniques

- Ground Personnel Safety
  1. Exposure of moving parts (particularly to disembarking troops)
  2. Velocity, temperature, etc., of thruster inlet and exhaust flows
  3. Weight and accessibility of components (hazard to maintenance personnel)
  4. Height of required operating platform
  5. Fire hazard in crash situations

- Detectability
  1. Perceived noise level (PNdB) } primary considerations
  2. Degree of uniqueness of audio signature } primary considerations
  3. IR radiation
  4. Aircraft size, etc. (visual detectability)

- Erosion and Foreign Object Damage
  1. Thrust air inlet velocity and filtering capability
  2. Proximity of thruster air inlet to ground
  3. Tip speed and construction of exposed blades

GENERAL RESULTS

Table XX summarizes the relative merit of each concept examined in each of the areas of comparison. Ratings in the table are defined on a scale ranging in descending order of desirability or promise, as:

EXCELLENT

VERY GOOD

GOOD

FAIR

POOR

UNACCEPTABLE

Only four groups of concepts can be substituted for the conventional tail rotor without incurring highly undesirable effects for the base-line aircraft and mission. The potentially acceptable classes of alternatives are:

1. Advanced tail rotors
2. Prop-fans or fans mounted in the tail fin
3. Prop-fans or fans mounted in the tail cone, exhausting at the tail fin
4. Pseudo-compound solutions

Advanced Tail Rotors

Individual concepts involving refinement of the conventional tail rotor may offer substantial improvements in one or more of the areas of performance: weight, size, detectability, reliability, or vulnerability. None offers significant improvements in all areas. Improvement in ground personnel safety must be rated marginal, due to retention of exposed moving blades. Such concepts offer considerable promise in several types of advanced helicopters. For the particular goals of this study, no single concept offers an outstanding advance.

Fan-in-Fin (Prop-Fans or Ducted Fans Mounted in Tail Fin)

A ducted prop-fan or a ducted fan can be used in a shaft-driven or gas-driven system as a direct replacement for the tail rotor. No engine exhaust or auxiliary engine solutions are included in this category. Power consumption of these concepts is generally higher than for the tail rotor, while weight is similar. Improvements in detectability, reliability, maintainability, safety, and foreign object damage are anticipated without significant penalties in stability and control. The most promising of these systems is the ducted prop-fan configuration. It is superior to the ducted fan in nearly all of the above areas and has acceptably low power required and technical risk levels. A French version of this concept, the Fenestron, is in service on the Sud SA.341. The prop-fan concept has been analyzed in greater detail in the main body of this report.

Fan-in-Tailcone (Prop-Fans or Ducted Fans Mounted in Tail Cone, Exhausting at Tail Fin)

Other feasible concepts use thrusters similar to those of the previous group but mounted in the forward portion of the tail cone, with the fan axis fore and aft instead of side-to-side. The fan exhaust flow, perhaps augmented by the main engine exhaust flow, is ducted through the tail cone and exits through deflecting nozzles beneath the tail fin. These approaches generally are heavier and require more power than either the conventional tail rotor or the prop-fan fan-in-fin concept. They offer further improvement in detectability, safety, high-speed dynamics, vulnerability, and foreign-object-damage protection. As in the previous group, the prop-fan approach appears superior to the ducted fan, particularly from power, noise, and technical risk considerations. The relatively high disc loading required of the prop-fan in this arrangement increases the technical risk of the system over that of the previous category, but the resulting risk is acceptable. This approach is also analyzed in the main report.

Pseudo-Compound Solutions

Pseudo-compound concepts employ devices commonly used to produce forward thrust to provide antitorque and directional control moments. Of the wide variety of such concepts examined, two appear practicable: the Sikorsky ROTOPROP$_{TM}$ - propeller that swivels from conventional tail rotor configuration at low forward speeds to a pusher-prop configuration at high speeds, and the Piasecki Ringtail, a ducted pusher-prop with controllable deflector vanes to provide antitorque and direction control. The ROTOPROP requires less power than the Ringtail but represents a greater technical risk and significantly greater safety hazard. A ducted ROTOPROP arrangement would reduce this hazard, but at further penalty in weight and technical risk. By the mid 1970's, a solution using a compound turboshaft/turbofan engine within the fuselage and exhausting through deflector vanes in the tail fin may be feasible. Currently, the technical risk of this solution is excessive.

No pseudo-compound solution represents a viable alternative to the conventional tail rotor as specified for this study, because of the large difference in control, structure, and mission requirements between compound helicopters and pure helicopters. These effects impose a large weight and cost penalty in converting a conventional helicopter into a compound. The factors that must be considered in evaluating the merits of alternative conversions of this type are beyond the scope of this preliminary comparison.

GENERAL CONCLUSIONS

Two concepts, the prop-fan fan-in-fin and the prop-fan fan-in-tailcone, appear most promising under the guidelines imposed for this task. Each concept is predicted to be superior to the tail rotor in each of the eight areas of required or desired improvement. Associated penalties in aircraft performance, weight, and cost are predicted to be acceptable for utility aircraft.

The two concepts will be referred to in comparisons throughout this appendix. For simplicity,they will be denoted "fan-in-fin" and "fan-in-tailcone" respectively, with the use of a prop-fan type thruster always implied.

DESCRIPTION AND EVALUATION OF INDIVIDUAL CONCEPTS

This section describes and discusses the 32 concepts examined in Task 1.

Conventional Tail Rotor

The conventional tail-rotor concept is employed for anti-torque and directional control on all operational single-main-rotor U.S. military helicopters. The rotor typically includes from two to six symmetrical-section blades, articulated in flapping and pitch. The rotor is mounted at the aft end of the tail cone, commonly on a vertical pylon so that the tail-rotor disc lies just outside that of the main rotor. The tail rotor is shaft driven from the main gearbox via two intermediate gearboxes, one at the base of the pylon and the second at the rotor hub.

This concept has been selected for the vast majority of single-rotor shaft-driven helicopters because it meets stability and control requirements with relatively low weight and low power requirements. It also provides inherent damping of aircraft yaw motion to a greater degree than most alternatives.

The basic drawbacks of this concept lie in just those areas emphasized in this study. Under certain conditions, some tail rotors are susceptible to dynamic instabilities in high-speed flight, although the critical forward speed can be increased significantly by proper design. The exposed rotor blades are vulnerable, particularly to terrain contact and foreign object damage. Experience has shown that the tail rotor requires a relatively high proportion of the maintenance requirements of the helicopter. Noise levels are high, particularly in the fore and aft direction, making the tail rotor a dominant component in regard to detectability. Finally, the exposed blades, which are relatively invisible at full rpm, represent a hazard to ground personnel, particularly in combat.

Advanced Tail Rotor

A number of advanced tail rotor concepts were examined. Although improvements are obtainable in each area specified under "Survey Objectives", it does not appear possible to make the required improvement in all areas simultaneously.

Improvements in reliability, maintainability, weight, and performance may be expected in advanced conventional rotors due to refinements in hub, gearbox, and rotor blade design and fabrication techniques.

Although maintenance personnel safety can be expected to increase as maintainability and component weight improve, exposed rotor blades remain a potential hazard to ground personnel and remain susceptible to foreign object and ground impact damage. Application of a shield and a protective screen around the tail rotor will improve these categories at the cost of substantially reduced performance, increased weight, increased drag, and increased noise.

TABLE XX. PRELIMI

	CONCEPT	HIGH SPEED DYNAMICS	VULNERABILITY		RELIABILITY	MAINTAINABILITY	SAFETY PERSO
			BALLISTIC	TERRAIN CONTACT			
TAIL ROTORS	Conventional tail rotor	Good (Possible flapping problems)	Fair	Poor to fair	Fair	Fair	Poor to
TAIL ROTORS	Advanced tail rotor	Good	Fair	Poor to fair	Fair to good	Fair to good	Poor to
PASSIVE THRUSTERS	Prop-fan in tail fin (Shaft-drive)	Good to very good	Good	Good	Good	Good	Good
PASSIVE THRUSTERS	Prop-fan in tail fin (Gas tip-drive)	Good to very good	Fair to good (Tip turbine is vulnerable)	Good	Good	Good	Fair to
PASSIVE THRUSTERS	Prop-fan in tail cone	Very good	Good to very good	Good to very good	Good to very good	Fair to good	Good
PASSIVE THRUSTERS	Linear fan in tail fin	Good (Potential inlet separation)	Poor	Good to very good	Fair	Poor to fair	Good
PASSIVE THRUSTERS	Squirrel-cage fan in tail fin (Cyclic pitch)	Unacceptable	Poor	Poor	Poor	Poor	Poor
PASSIVE THRUSTERS	Ducted fan in tailfin	Good (Potential inlet separation)	Fair	Good	Good	Fair to good	Fair to (High exhau
MAIN ROTOR DOWNWASH DEFLECTION	Flapped conventional airfoils	Poor (Airfoil buffeting likely)	Good	Poor to fair (Flaps are near ground)	Very good	Good	Good very
MAIN ROTOR DOWNWASH DEFLECTION	Squirrel-cage rotors collective pitch	Unacceptable (Blade stall)	Unacceptable to poor	Unacceptable (Exposed blades)	Poor	Poor (Several separate rotors)	Unacce to
MAIN ROTOR DOWNWASH DEFLECTION	Jet flaps	Poor (Airfoil buffeting likely)	Fair to good	Fair to good	Fair	Fair to good	Go
MAIN ROTOR DOWNWASH DEFLECTION	Thwaites flaps	Fair to good (High drag)	Fair	Fair	Poor (Suction areas clog)	Poor (Suction areas need monitoring)	Good very
MAIN ROTOR DOWNWASH DEFLECTION	Circulation control via tangential blowing	Fair to good (High drag)	Fair to good	Good	Fair to good (fixed fan pitch)	Fair (Several simple systems)	Good very
MAIN ROTOR DOWNWASH DEFLECTION	Flettner rotors	Fair (High drag)	Poor to fair	Fair	Poor	Poor	Fa (Rotati ders e
INERTIA SYSTEMS	Accelerated flywheel	Very good	Good to very good	Very good	Good	Good	Go
INERTIA SYSTEMS	Precessed gyroscope	←	Aircraft employing this concept are unflyable				

TABLE XX. PRELIMINARY QUALITATIVE COMPARISON OF ALTERNATIVE ANTITORQUE CONCEPTS

Y	MAINTAINABILITY	SAFETY OF PERSONNEL	DETECTABILITY	EROSION & F.O.D.	WEIGHT			STABILITY & CONTROL
					MISSION FUEL	STRUCTURE & POWERPLANT	OVERALL SYSTEM	
	Fair	Poor to fair	Fair	Poor	Good	Good	Good	Good to very good (Inherent yaw damping)
od	Fair to good	Poor to fair	Fair to good	Poor to fair	Good	Good	Good	Good to very good (Inherent yaw damping)
	Good	Good	Good	Fair	Good	Good	Good	Good to very good (Reduced yaw damping)
	Good	Fair to good	Fair	Fair	Fair to good	Fair	Fair	Poor (No autorotational control)
	Fair to good	Good	Good	Good (Inlets placed high)	Fair to good	Good	Good	Good (Twice ramptime of tailrotor)
	Poor to fair	Good	Fair to good	Fair (One inlet near ground)	Fair to good	Fair	Fair	Fair to good (High control lag)
	Poor	Poor	Poor (Squirrel Screech)	Unacceptable to poor	Good	Poor	Poor	Fair to good (Suspect at high speeds)
	Fair to good	Fair to good (High speed exhaust)	Poor (High disc loading → noise)	Poor (High inlet velocity)	Fair	Fair to good	Fair ('Poor' with noise suppression)	Good
d	Good	Good to very good	Very good to excellent	Good to very good (flap hinges protected)	Very good	Poor (8-10 airfoils required)	Poor	Unacceptable to poor (No autorotative control)
	Poor (Several separate rotors)	Unacceptable to poor	Poor (Squirrel screech)	Unacceptable (low mounted fully exposed rotor)	Fair to good	Poor (High structural weight)	Unacceptable	Poor (Poor autorotation control)
	Fair to good	Good	Good to very good	Good (High blower inlet position)	Fair	Poor to fair	Poor to fair	Poor (Poor autorotation control)
eas	Poor (Suction areas need monitoring)	Good to very good	Very good	Unacceptable to poor (Suction areas clog)	Good	Poor to fair	Poor	Poor (Poor autorotation control)
od n	Fair (Several simple systems)	Good to very good	Very good	Good	Good	Poor to fair	Poor to fair	Poor (Poor autorotation control)
	Poor	Fair (Rotating cylinders exposed)	Good (Mechanical noise)	Fair	Good	Unacceptable to poor	Unacceptable	Unacceptable (Very slow control response)
	Good	Good	Fair to good (High engine noise)	Depends on main engine placement & inlet system	Unacceptable	Unacceptable (Very high power for antitorque)	Unacceptable	Unacceptable (High moment coupling)
			———→		Poor	Unacceptable (Heavy gyro)	Unacceptable	Unacceptable

EIGHT		STABILITY & CONTROL	DEVELOPMENT RISK	COMMENTS
RUCTURE & WERPLANT	OVERALL SYSTEM			
Good	Good	Good to very good (Inherent yaw damping)	Excellent (developed)	Base-line concept.
Good	Good	Good to very good (Inherent yaw damping)	Very good (current technology)	Improvement over base line in areas outside those of main interest in this study.
Good	Good	Good to very good (Reduced yaw damping)	Good (Concept flying on SUD 341	Potential inlet flow problems at high speed.
Fair	Fair	Poor (No autorotational control)	Good (Adapt Ryan XV-5A system)	Potential inlet flow problems at high speed. Requires special control to regulate prop-fan RPM.
Good	Good	Good (Twice ramptime of tailrotor)	Good (1970-73 technology)	Rating strongly influenced by details of nozzle configuration. Requires yaw damper.
Fair	Fair	Fair to good (High control lag)	Fair (Fan undeveloped)	Current linear fans heavy, inefficient, fixed pitch. Requires rotatable shroud.
Poor	Poor	Fair to good (Suspect at high speeds)	Unacceptable to poor (Structural problems)	Complex, high vibration level, exposed dynamic system. Structurally impractical.
ir to good	Fair ('Poor' with noise suppression)	Good	Fair (Thrust reversal difficult)	Similar but inferior to "prop-fan in tail fin". High disc loading complicates blade pitch reversal.
Poor 8-10 air- ls required)	Poor	Unacceptable to poor (No autorotative control)	Very good (Current technology)	Very poor in autorotation. Erratic in ground effect. Max speed limited by drag.
Poor igh struc- al weight)	Unacceptable	Poor (Poor autorotation control)	Poor to fair	Several rotors required. Max speed cut by drag. Poor autorotative control. High-speed control suspect.
r to fair	Poor to fair	Poor (Poor autorotation control)	Fair to good	Several airfoils required. Max speed cut by drag. Poor autorotative control.
or to fair	Poor	Poor (Poor autorotation control)	Poor to fair	Several airfoils required. Max speed cut by drag. Poor autorotative control.
r to fair	Poor to fair	Poor (Poor autorotation control)	Fair to good (Fixed fan pitch)	Several airfoils required. Max speed cut by drag. Poor autorotative control.
acceptable to poor	Unacceptable	Unacceptable (Very slow control response)	Poor	Several "rotors" required. Max speed cut by drag. Poor autorotative control.
acceptable high power antitorque)	Unacceptable	Unacceptable (High moment coupling)	Good	No autorotation control. High control moment coupling.
acceptable eavy gyro)	Unacceptable	Unacceptable	No basis for valid estimate	Aircraft completely unflyable. No control on ground.

	[illegible]	HIGH SPEED DYNAMICS	VULNERABILITY		RELIABILITY	MAI
			BALLISTIC	TERRAIN CONTACT		
[illegible]	Turbine in tail	Good	Poor	Fair	Poor	
	[illegible]jet in tail	Fair	Poor to fair	Fair to good	Poor to fair	Poo (In ter
	[illegible] in tail	Good	Fair	Fair to good	Good to very good	Una
	[illegible] rocket in tail	No basis for valid estimate	Poor	No basis for valid estimate	No basis for valid estimate	Una
	[illegible] radiator in tail	No basis for valid estimate	Good to very good	No basis for valid estimate	No basis for valid estimate	Unac t
ENGINE FLOW DEFLECTION	Deflected engine power-turbine flow	Good (Possible buffeting of deflectors)	Fair	Good	Good	(O
	Convertible turboshaft fan engine	Very good	Poor (Complex engine)	Good	Fair to good	
	Engine compressor bleed air	Very good	Poor to good (Large engine)	Good to very good	Good	Fai (O
[illegible]	Piasecki ring-tail	Good to very good	Good	Good	Good to very good	
	Sikorsky rotor-prop	Good to very goood	Good	Good	Good	
	Cyclic control on thruster prop	Good to very good	Fair to good	Poor (Blades near ground)	Fair to good	Fair
	Differential thrust on thruster props	Very good	Poor to fair	Poor	Fair	Poor
	Differential thrust on turbojets/turbofans	Very good	Poor	Fair to good	Poor (auxiliary engines required)	
[illegible]	Coaxial speed brakes	Poor (Paddle-main rotor interaction)	Fair	Very good (High mount)	Poor	
[illegible]	Prop-fan in tail cone plus circulation control & tangential blowing	Good to very good	Good	Good to very good	Good	
	Prop-fan in tail cone plus main engine exhaust flow	Very good	Good to very good	Good to very good	Good to very good	

TABLE XX. Continued

AINTAINABILITY	SAFETY OF PERSONNEL	DETECTABILITY	EROSION & F.O.D.	WEIGHT			STABILITY & CONTROL	DEVELOPM
				MISSION FUEL	STRUCTURE & POWERPLANT	OVERALL SYSTEM		
Poor	Poor	Unacceptable to poor (Noise & IR radiation)	Unacceptable to poor	Poor	Poor	Poor	Unacceptable to poor	Po (Engine ment re
Poor to fair (Inlet shut- ter critical)	Poor	Unacceptable (Noise & IR radiation)	Poor	Fair (If throttling capability developed)	Fair to good (Need [illegible] for OEI control)	Fair to good Unacceptable if noise suppressed	Unacceptable (Non-throttlable)	P (Cont ro
Unacceptable	Unacceptable	Unacceptable (Noise & IR radiation)	Excellent (none)	Unacceptable	Fair (Large fuel tanks required)	Unacceptable (Fuel balance problems)	Poor (Imprecise control)	F (Thrott control
Unacceptable	Unacceptable	Unacceptable	Excellent (none)	Very good (Specific impulse very high)	Unacceptable (Thrust/weight very low)	Unacceptable	No basis for valid estimate	Unacce
Unacceptable to poor	Unacceptable (Excessive sound level)	Unacceptable (Sound level → 250 PNdB)	No basis for valid estimate	No basis for valid estimate	Unacceptable (High electrical power)	Unacceptable	No basis for valid estimate	Unacce
Fair (Oversized engine)	Fair to good (High energy exhaust)	Poor to fair	Depends on main engine placement & inlet system	Poor	Unacceptable to poor	Unacceptable to poor	Poor to fair (See "comments")	Po (Require signed
Fair	Fair to good (High energy exhaust)	Fair to good (Depends on fan loading)	Depends on main engine placement & inlet system	Poor to fair	Fair to good	Fair	Unacceptable to poor (No control in autorotation)	Fa (1975 techn
Fair to good (Oversized engine)	Fair to good	Fair-good (Noise of oversized engines)	Depends on main engine placement & inlet system	Unacceptable	Unacceptable	Unacceptable	Poor (No autorotation control)	Fa (Requir signed
Good	Good (Prop partially shielded)	Poor in hover, good in forward flight	Fair to good	Fair to good	Fair	Fair (Balance problem)	Fair to good (See "comments")	Very (Curren nol
Good	Fair (Smaller than tail rotor)	Poor to fair	Fair (Robust blade construction)	Fair to good	Fair	Fair	Good (Requires "q" sensor)	Go (Basic flight
Fair to good	Poor (Blades pass near ground)	Poor to fair	Fair (Robust blades)	Poor to fair	Poor (High power required)	Poor	Fair to good	Fair t
Poor to fair	Poor (Blades pass near ground)	Poor (Much worse than tail rotor)	Poor (Blades pass near ground)	Fair	Poor to fair (High structural weight)	Fair	Good (Requires development of controls)	Go (Specia requ
Poor	Poor (High energy inlet & exhaust flows)	Unacceptable to poor	Poor to fair	Poor	Poor (4 engines required for CEI control)	Poor	Unacceptable (Very slow response in hover)	Fair t
Poor	Fair (Hazardous maintenance)	Poor (Paddle-rotor interaction)	Good	Poor to fair	Poor	Poor	Unacceptable (See "comments")	Fai (Control tem req
Fair	Good	Good to very good	Fair to good (Jet slot erodes)	Good	Fair to good	Fair to good	Good (Slow response time)	Fair t
Fair	Good	Good	Good	Fair to good	Good	Good	Good (Slow response time)	Go

	WEIGHT			STABILITY & CONTROL	DEVELOPMENT RISK	COMMENTS
MISSION FUEL	STRUCTURE & POWERPLANT	OVERALL SYSTEM				
Poor	Poor	Poor	Unacceptable to poor	Poor (Engine development required)	No autorotative control. Slow engine response doubles required thrust.
(If throttling capability developed)	Fair to good (Need … for OEI control)	Fair to good (Unacceptable if noise suppressed)	Unacceptable (Non-throttlable)	Poor (Control system problems)	No autorotative control. Can operate only near maximum thrust.
…cceptable	Fair (Large fuel tanks required)	Unacceptable (Fuel balance problems)	Poor (Imprecise control)	Fair (Throttling & control problems)	No autorotative control (by MIL-H-8501A definition of autorotation).
…ery good …ific impulse …ry high)	Unacceptable (Thrust weight very low)	Unacceptable	No basis for valid estimate	Unacceptable	Exhaust may be fatal.
…basis for …id estimate	Unacceptable (High electrical power)	Unacceptable	No basis for valid estimate	Unacceptable	Acoustic radiation levels may be fatal. Vibration levels require new structural technology.
Poor	Unacceptable to poor	Unacceptable to poor	Poor to fair (See "comments")	Poor (Requires redesigned engine)	No autorotative control. Oversized engine required. Control response depends on engine power setting.
…r to fair	Fair to good	Fair	Unacceptable to poor (No control in autorotation)	Fair (1975-1980 technology)	No autorotative control. Slow engine response increases required thrust. Requires yaw damper.
…cceptable	Unacceptable	Unacceptable	Poor (No autorotation control)	Fair (Requires redesigned engine)	No autorotative control. Slow engine response increases required thrust. High engine weight.
…r to good	Fair	Fair (Balance problem)	Fair to good (See "comments")	Very good (Current technology)	Aft weight concentration. Poor control in reverse flight. Increases sink rate in autorotation.
…r to good	Fair	Fair	Good (Requires "q" sensor)	Good (Basic concept flight tested)	Requires a "q" - sensing system. Increases sink rate in autorotation.
…r to fair	Poor (High power required)	Poor	Fair to good	Fair to good	Ineffective without application of a net thrust.
Fair	Poor to fair (High structural weight)	Fair	Good (Requires development of controls)	Good (Special props required)	Blades designed for reverse thrust efficiency rather than high forward speed efficiency.
Poor	Poor (4 engines required for OEI control)	Poor	Unacceptable (Very slow response in hover)	Fair to good	No autorotative control. Inefficiency of thrust reversers increases required installed thrust.
…r to fair	Poor	Poor	Unacceptable (See "comments")	Fair (Control system required)	No autorotative control. Very high autorotative descent.
Good	Fair to good	Fair to good	Good (Slow response time)	Fair to good	No significant improvement over "prop-fan in tail cone" alone. Control may be erratic in violent maneuvers.
…r to good	Good	Good	Good (Slow response time)	Good	Small improvement over "prop-fan in tail cone" alone.

HUSH Rotor - Experimental results show trends toward significantly reduced tail rotor system noise levels as the number of blades increases or as blade tip speed is reduced.[17] The HUSH tail rotor system combines these alterations, reducing experimentally observed noise by approximately 30 dB on a 10-bladed rotor compared to a conventional tail rotor of roughly equivalent performance. For this experimental prototype, tail rotor noise was essentially invisible in the background noise from the main engine, transmission, and rotor systems, which had also been treated to reduce noise. The HUSH tail rotor weighs more and requires more power than the conventional system of equal performance. It can be expected to require slightly more maintenance. A marginal improvement in personnel safety can be anticipated from the higher visibility of the rotating tail rotor compared to a conventional system.

High-Performance Conventional Rotor - This approach uses cambered blades in place of the symmetrical section blades on a conventional tail rotor. Flight tests conducted by Hughes Tool Company indicate significant increases in maneuverability for a given disc area, with acceptable penalties in power and weight.[18] Pitch link loads were found to increase by roughly 20 percent. No high-speed dynamic instabilities were reported.

Further performance improvement can be anticipated by increasing the tail-rotor blade tip speed, at the cost of increased weight and noise; or by increasing tail-rotor solidity, at the cost of increased weight.

None of these configurations shows a direct improvement in reliability or maintainability. Safety of maintenance personnel would be slightly improved by the smaller, potentially lighter components.

Rotor With No Flapping Hinge - Removal of the flapping hinge from a conventional tail rotor is attractive for reliability and maintainability, but only for hover and low-speed forward flight. In high-speed forward flight, high vibratory blade and hub stresses are produced unless automatic cyclic pitch control can be introduced.

The penalties associated with introduction of cyclic pitch control are predicted to outweigh the reliability/maintainability gain arising from removal of the flapping hinge, resulting in a system inferior to the conventional tail rotor for this application.

Jet Flap Rotor - Theoretical predictions regarding the performance of small, relatively simple jet flap rotors have not been borne out in practice. Results published by Lockheed[19] for a 4-bladed, 6-foot-diameter pure jet-flapped rotor indicated that the thrust from the rotor was approximately equal to the jet thrust alone; that is, the rotor was no more effective than a single air jet having the same area as the sum of the blade blowing slot areas.

The sum of the slot area on the Lockheed model was less than 1/10 percent of the rotor disc area. To compute the effective power loading of the jet flap rotor, we must assume an effective thruster disc loading more than 1000 times as great as the true rotor disc loading. For this disc loading ratio, Appendix III shows that the jet flap required horsepower per pound of thrust will be on the order of 20 times that required by a conventional tail rotor of the same area and thrust. Increasing the thrust efficiency of the jet by a factor of four reduces the power required ratio to the order of 10, which is still unacceptable.

Use of the jet flap to increase the blade lift coefficient on an otherwise conventional tail rotor will result in a significantly less reliable, less easily maintainable system. No worthwhile improvement will be realized in safety or noise-induced detectability, and there will be a substantial increase in installed power required, compared with the conventional tail rotor.

A tip-driven jet-flapped tail rotor will lie midway between the shaft drive and the pure jet flap in required power, and will offer no worthwhile improvement over either alternative.

The most promising aspect of the various jet flap approaches is possible elimination of the blade pitching hinges, although the extra complication of the ducting system outweighs this gain, at least for tail rotors on small or medium helicopters.

Boundary Layer Control Rotor - This approach involves use of an auxiliary system to augment the lifting conditions on the blades of a shaft-driven tail rotor. Such a system could involve mechanical slots or slats, or suction or blowing. Although aerodynamic performance could be improved, reliability, maintainability, weight, and vulnerability penalties would be imposed. Overall, this approach does not represent a worthwhile improvement over the conventional system in the areas specified in this study.

An extreme case of boundary layer control is circulation control by tangential blowing, which is discussed later in this appendix in connection with main rotor downwash deflection. Here, 20 to 40 percent thick elliptical-section blades are used, the lift being controlled by varying the intensity of a thin, relatively low intensity airjet blown tangentially downstream from a slot near the 50-percent chord position. Blade geometric pitch is fixed. Such rotors operate at a hovering figure of merit roughly 35 to 50 percent that of a conventional rotor and thus require between 2 and 3 times the power of a conventional rotor. Improvements in overall reliability and safety are slight. Maintenance is significantly more difficult because of the relative inaccessibility of the hub ducting system.

Fan-in-Fin (Shaft-Driven Prop-Fan)

The prop-fan fan-in-fin concept is currently operational on the Sud SA.341 utility helicopter. A shrouded prop-fan, thrusting horizontally sideward, is mounted low in a relatively large vertical fin as shown in Figure 48. The prop-fan in this study was assumed to have 12 hingeless blades. The shroud depth was taken, subject to further refinement in Task 2, to be between 20 and 30 percent of the prop-fan diameter. The fan is shaft driven from the main gearbox via a single right-angle tail gearbox in the prop-fan hub. The horizontal stabilizer is assumed mounted on top of the vertical fin, forming a conventional T-tail. Collective pitch range allows a thrust range from -35 percent through +100 percent of the maximum value.

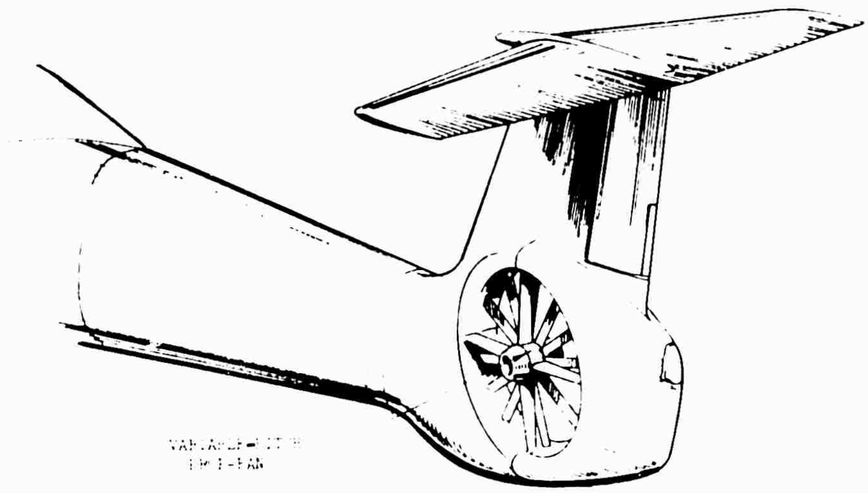


Figure 48. Fan-in-Fin Concept.

Placing two such fans in a V-tail configuration was judged to impose penalties in power, weight, and maintainability relative to the single-fan approach. System reliability and vulnerability were improved because of the redundancy of the thrusters. It was concluded that the penalties outweighed the advantages for small helicopters.

Preliminary analysis of the single shaft-driven prop-fan configuration at a fixed aircraft DGW of 15,000 pounds predicts a prop-fan maximum power consumption roughly 60 percent higher than for the optimum conventional tail rotor, and requires an increase in installed power of roughly 15 percent. No penalties are predicted in weight or stability and control compared to the tail rotor. The system will be less detectable acoustically because of the fore and aft shielding effects of the shroud, and because the sound radiation is biased toward higher frequencies, which tend to be more readily absorbed in the atmosphere. The system is predicted to show improvements over the tail rotor in reliability, maintainability, ground personnel safety, vulnerability, and susceptibility to erosion and foreign object damage, primarily due to the overall system simplification and the presence of the shroud.

Fan-in-Fin (Tip-Driven Prop-Fan)

The tip-driven prop-fan fan-in-fin concept employs a Fenestron-type prop-fan as above, but in place of the gearbox and shafting drive system, a tip turbine in a scroll around the prop-fan is used.

Because of the relatively large disc area and low disc loading of the optimum prop-fan for this application, this concept probably represents the highest efficiency engine exhaust deflection type antitorque and direction control system examined. The weakness of this approach, characteristic of deflected engine exhaust concepts, lies in the large volume of high-energy engine exhaust required. This cannot be provided by a turboshaft engine of normal size, so an auxiliary turbojet or turbofan engine of approximately 1000 pounds static thrust is required to drive the fan.

Because an auxiliary engine is required, fuel weight, maintainability, and reliability penalties are imposed over the conventional shaft-driven prop-fan for this application. An additional major drawback is that directional control is not available in autorotative flight.

This approach is thus inferior overall to the shaft-driven fan-in-fin approach.

Fan-in-Tailcone (Buried Prop-Fan)

The prop-fan fan-in-tailcone concept employs one or more variable blade-pitch prop-fans mounted in the upstream end of the tail cone. The tail cone ducts the prop-fan flow to a set of turning vanes placed at the station occupied by the prop-fan in the concept described immediately above. Many turning vane/nozzle configurations are possible, including configurations with only one moving part. Prop-fan flow is ducted from an inlet near the main rotor pylon, positioned to minimize hazard to personnel and the possibility of foreign object ingestion. All moving parts are protected until access panels are removed. One configuration employing this concept is shown in Figure 49.

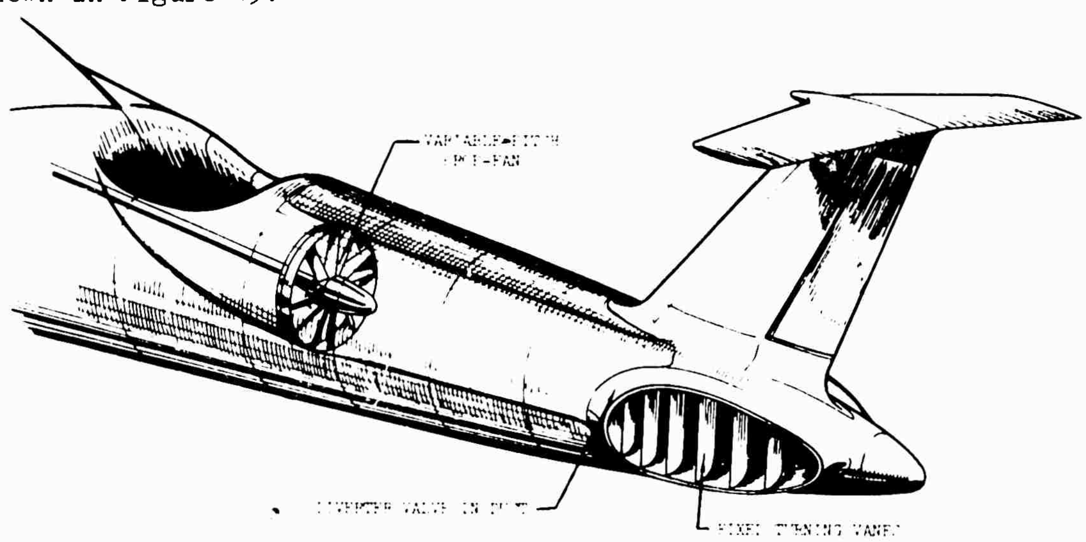


Figure 49. Fan-in-Tailcone Concept.

Task 1 analysis predicted a prop-fan maximum power consumption roughly 125 percent higher than for the conventional tail rotor on the base-line aircraft. The penalty in installed power is approximately 30 percent over the base line. Initial predictions indicate that weight penalties, if any, are small.

Significant improvement over the tail-rotor concept is predicted in several areas. In regard to acoustic detectability, potential improvement is predicted over the fan-in-fin and the conventional tail rotor due to absence of significant pure-tone components, low turbulent jet-noise levels, and acoustic shielding effect of the nozzle. Improved ground personnel safety and reduced probability of foreign object damage will result from the high fan inlet, relatively low inlet flow velocity, and shielding of all moving parts, as long as access panels are in place. Blade erosion damage will be reduced for the same reason, but improvement over the tail rotor will be partially offset by the increased tip speeds at which the prop-fan operates. The concealed placement of the prop-fan, and its unloaded operation at high forward speeds, for which a conventional vertical stabilizer and rudder are employed, will eliminate the high-speed dynamics problems associated with certain tail-rotor designs.

Improved reliability and maintainability are predicted as a result of reduced system complexity relative to the base line, and the reduced weight of nonstructural subsystems. Evaluation of the degree of improvement in these areas depends strongly on system layout solutions.

Placing the primary dynamic subsystems in the fuselage portion of the tail cone rather than at the aft end will significantly reduce terrain contact vulnerability to levels below that of either the tail rotor or the fan-in-fin. Reduced vulnerability to ballistic impact is anticipated from the shielded position of the primary dynamic components and the elimination of all angle gearboxes. Further reduction of overall system vulnerability is possible through use of two prop-fans instead of one, but at the cost of increased system weight and reduced maintainability.

A conceptually identical device was flight tested over a two-year period in the mid-1940's on the British Cierva W.9 single-rotor shaft-driven helicopter.[20,21] Stability and control were reported as satisfactory, although control response was unacceptably sluggish by modern standards. Reliability, maintainability, and safety were significantly improved, although power penalties were high. No recent application has been made of the concept, although major subsystems - particularly the prop-fan - have been tested successfully over the anticipated operating profile. The technical risk is judged to be good.

Linear Fan

The linear fan proposed in this concept is much longer but otherwise similar to the conventional centrifugal blowers produced by several manufacturers. In such blowers, the fan blades rotate about an axis parallel to the blades like blades on a paddle wheel or the barrels on a Vulcan machine gun. The blades are encased in a cylindrical scroll, and a lengthwise gap in the scroll serves as an exhaust nozzle. Air inlets to the fan are in the ends of the cylinder, as sketched in Figure 50.

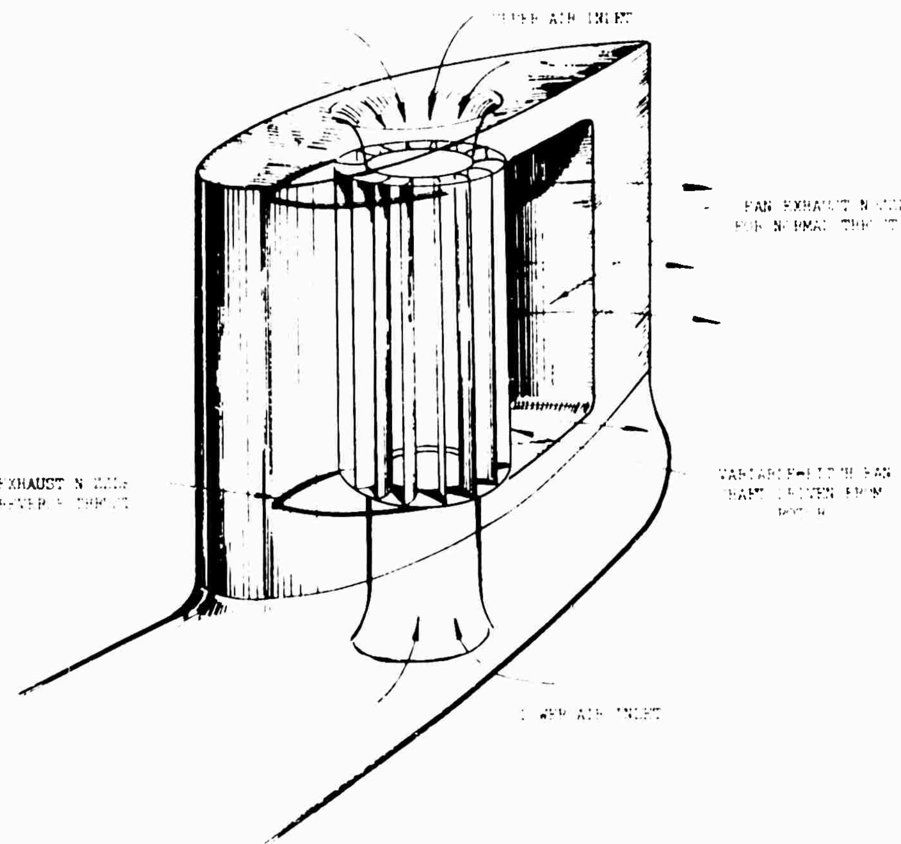


Figure 50. Linear Fan Concept.

Fans of this type suffer from a relatively low maximum pressure ratio, so relatively large air volume flows are needed to produce a given thrust. They also lack a straightforward method of producing reverse thrust. Further, current designs for such fans are not suitable for producing thrusts of precisely controlled magnitude, as required for this application.

Placing the fan along the full length of the helicopter tail cone was judged to be unpromising. The relatively short average moment arm and the inherently high airflow requirements of such fans combined to produce such a large airflow requirement that extremely complex air inlets were required at several stations along the length of the fan. This leads to unacceptable penalties in weight and maintainability.

Placing the fan vertically at the aft end of the tail cone was found to be preferable. This configuration employs a near-vertical shaft-driven linear fan, providing thrust magnitude control by varying fan blade collective pitch, and thrust direction control by rotating the fan shroud to move the exit slot to the desired orientation.

For the base-line aircraft, a fan 8 feet high and 3 feet in diameter was required, the large diameter being required to accomoodate the predicted airflow. The complexity, including controls for both slot orientation and blade pitch, was judged to be slightly higher than for a conventional tail rotor. Penalties are predicted in weight, control response, and maintainability compared to a conventional rotor. Improvements are anticipated in detectability and safety.

Current fans of this type demonstrate relatively low aerodynamic efficiencies. Assuming that the current value can be doubled, the power requirements of this concept would still be greater than for the fan-in-fin.

It is our conclusion that the technical risks and numerous penalties of this system make it less attractive for this application than either the fan-in-fin or fan-in-tailcone concepts.

Squirrel-Cage Rotor (Cyclic Pitch)

The squirrel-cage rotor is similar to the linear fan except that the scroll-casing around the linear fan has been eliminated, as sketched in Figure 51. In this case, the side force is generated as the lift force on the individual fan blades, typically eight in number. To provide a controllable force in the desired direction, the pitch of each blade is assumed to be varied in magnitude cyclically around the azimuth. The direction of the force is assumed to be controlled by the orientation of the cyclic pitch vector.

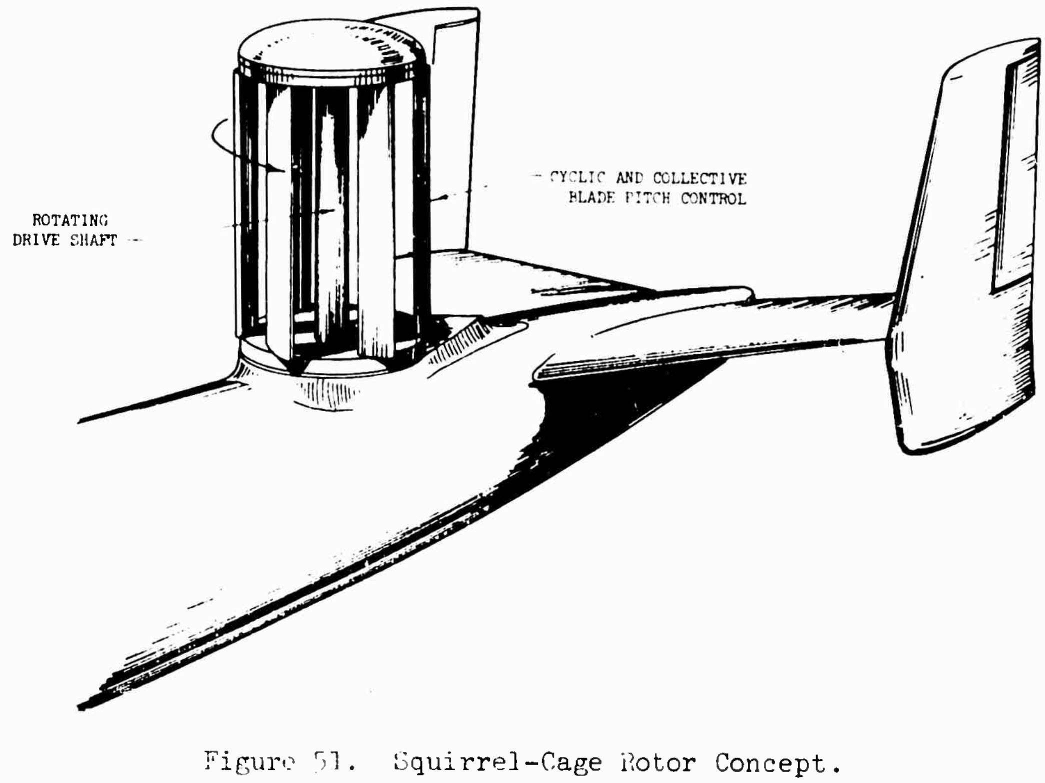


Figure 51. Squirrel-Cage Rotor Concept.

Detailed aerodynamic analysis - beyond the scope of this task - requires consideration of the inflow through the rotor and the unsteady aerodynamics of the rapidly oscillating flow about the individual blades. Initial analysis predicts a potential improvement in efficiency due to the fact that the full length of each blade travels at the specified tip speed. However, the efficiency will be substantially degraded due to the high-frequency and relatively high amplitude oscillations of the blades.

To minimize such losses, large radius and reduced tip speed are required. The former characteristic leads to weight, safety, and FOD penalties, the latter, to size and weight penalties.

Very low levels of reliability are predicted due to the high frequency aerodynamic and dynamic loads imposed by the cyclic pitch system. The exposed blades reduce reliability further because of foreign object damage and the effects of weather. They also represent a substantial hazard to ground personnel.

Maintainability is also predicted to be low because of the limited working area and requirements for special maintenance techniques and equipment.

Noise detectability cannot be predicted with certainty, but no improvement is anticipated over the conventional tail rotor. Blades of the squirrel-cage rotor may interact with downwash from other blades. The resulting intense "squirrel-screech" noise signature would make this concept inferior to the tail rotor in regard to noise detectability.

Dynamic problems are likely to occur in high-speed flight, assuming that full rotor rpm must be maintained to provide antitorque and directional control in case of a sudden change of flight speed. A cyclic pitch variation of roughly $\pm 90^\circ$ would be required to prevent stalling of the blades in this case. With a conventional tail rotor, it is necessary only to reduce collective pitch. It is unlikely that such a high cyclic pitch range could be incorporated without weight increase in an already heavy system.

Squirrel-cage, or paddle-wheel, rotors - including varieties combining collective and cyclic pitch variations - have been built for several applications, but have had little success. Application of such rotors to helicopter directional control were proposed seriously as recently as 1947.[20] A prototype helicopter using a "Maineau paddle wheel" lifting rotor was built in France.[22] Many similar devices failed, mainly due to dynamic and structural problems. This concept is inferior to the conventional tail rotor in several respects and offers no significant superiority.

Ducted Fan-in-Fin

The ducted fan-in-fin is identical to the shaft-driven prop-fan fan-in-fin except that thruster solidity, tip speed, and disc loading are increased substantially. The high disc loading permits significant thruster diameter reduction, but leads to increased power requirements (see Appendix III) and to more critical inflow problems in forward flight. Acoustic detection range will be significantly greater than for the prop-fan fan-in-fin concept, and perhaps greater than a conventional tail rotor. Weight will be higher than for the equivalent prop-fan.

Inlet and exhaust velocities will be higher than on a prop-fan, increasing risk of foreign object damage and hazard to ground personnel, although the hazard is significantly less than that of the conventional tail rotor.

Most high-solidity fans require overlap of the individual blades, so it is impossible to obtain both positive and negative thrust, thus eliminating the required autorotational control capability for this application. Such a fan with continuously variable positive-negative pitch capability was recently developed by Dowty-Rotol in England,[23] but this concept still must be considered a technical risk, particularly compared with the Fenestron prop-fan already in service in France.

The ducted fan concept appears to offer no significant advantage over the prop-fan, and is inferior in power, detectability, reliability/maintainability, and cost.

Main Rotor Downwash Deflectors

The main rotor downwash deflector group of concepts produces antitorque and yaw control forces as the side force on any one of various high-lift airfoil configurations placed horizontally within the rotor downwash flow. As described briefly in Appendix II, the useful downwash in hover is restricted to points less than about 85 percent of the rotor radius from the rotor hub. But a moment about the helicopter center of gravity is required, rather than just a side force. Further, the center of gravity may be assumed to lie near the rotor axis. Thus, deflectors placed below the inboard portion of the rotor are relatively ineffective. For these reasons and for structural considerations, it is impractical to deflect downwash outside of a region extending between roughly 40% and 85% of the main rotor radius in hover. In forward flight, however, the downwash is skewed aft from its hover distribution, so aft-mounted deflectors can profitably extend beyond the 85% radius point in this case. In most cases, a vertical fin capable of producing high lift coefficients is more effective in forward flight than an extension of a high-lift horizontal deflector surface.

Downwash deflectors examined included conventional high lift cambered airfoils with trailing-edge flaps for control, and the general category of circulation control devices, including jet flap, Thwaites flap, tangential blowing, and Flettner rotor concepts, each of which is described below.

Each of these systems requires a horizontal surface for hover control and a vertical surface for control in forward flight, when rotor downwash has a significant horizontal component. Sketches of alternative approaches are presented in Figure 52.

Because each of the downwash deflectors examined is sensitive to downwash flow velocity and/or direction, control effectiveness will be altered in violent maneuvers, sideward flight, autorotation at low forward speed, and flight in ground effect.

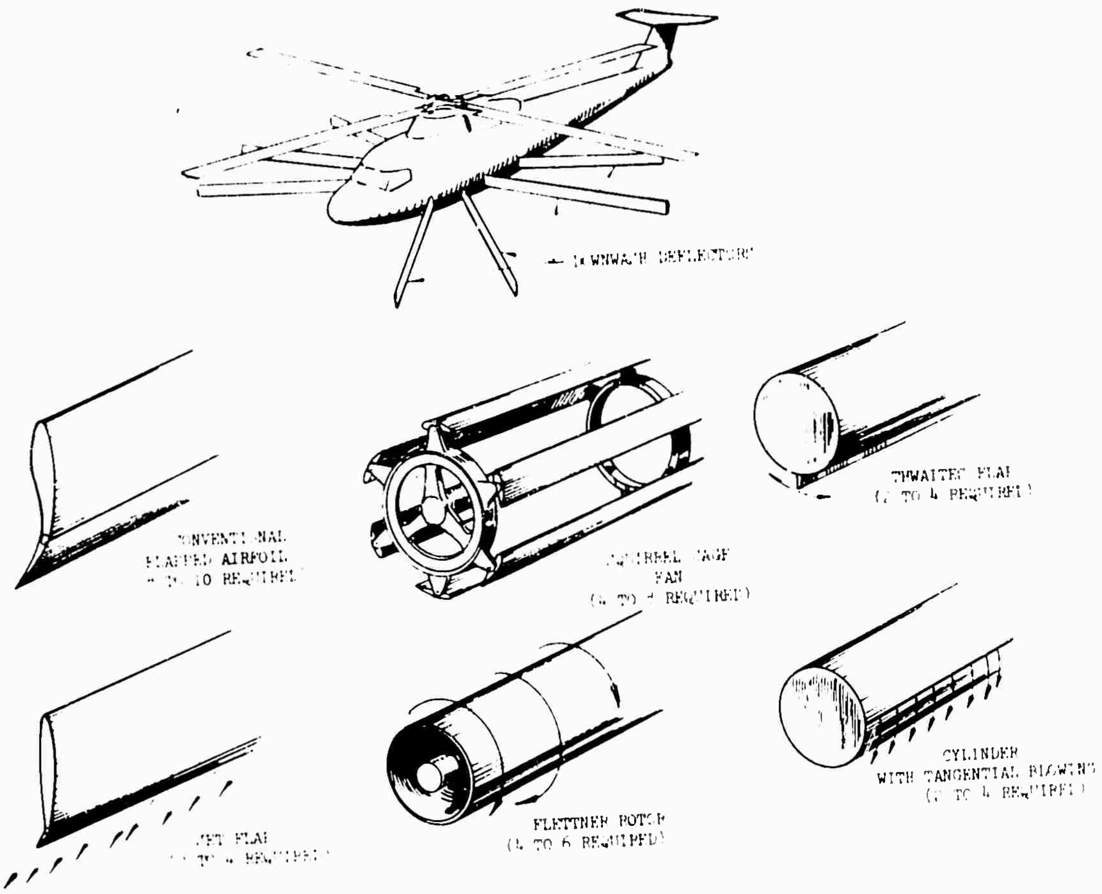


Figure 52. Main-Rotor Downwash Deflection Concepts.

Effective control in ground effect is particularly suspect. Early Dublhoff reaction-drive helicopters employing conventional high-lift airfoil tail-cone surfaces to provide directional control showed highly erratic control response near the ground. The phenomenon was confirmed by British wind tunnel tests.[20] A similar unsteady flow was noted in ground effect hover tests of the stabilator system of the Sikorsky S-67.

The performance of the circulation control devices in similar circumstances is not known, although the reduction in velocity over the airfoils will certainly reduce control effectiveness. Until specifically applicable tests are made, such concepts must remain highly suspect in this flight regime.

Aircraft using one of these concepts require a relatively large vertical stabilizer and rudder to provide control at forward speeds above roughly 25 knots.

In principle, each of the concepts to be discussed in this subsection can be used to deflect not only the main rotor downwash but also the flow from propellers, fans, or turbine engines. In practice, only the conventional airfoil approach appears to be feasible for such applications because of the penalties in reliability and maintainability imposed by additional ducting or mechanical linkage requirements of circulation control concepts.

Conventional Flapped Airfoil

In this configuration, the conventional helicopter tail cone is replaced by one or more cambered airfoils with trailing edge flaps. Such airfoils generally extend radially outward from the helicopter fuselage, with the airfoil chords vertical. The span of such airfoils is limited by the extent of the rotor downwash, and the airfoil chord is restricted by main rotor blade droop and by terrain impact constraints, including flare requirements. These considerations lead to a maximum chord for an untapered airfoil of roughly 4.5 feet, although this value can be increased by raising the main rotor.

For the base-line aircraft, airfoil span and chord constraints restrict airfoil area to roughly 55 ft^2 per airfoil, and airfoil aspect ratio to less than 3. This cuts airfoil efficiency and limits the maximum lift coefficient to roughly 2. Assuming a main rotor disc loading of 6 and the rotor downwash distribution of Figure 60, at least nine such airfoils are required. This neglects the adverse effects of the increased flat plate area in side winds and the interactions between individual airfoils. Inclusion of such effects could significantly increase the required number. A single such airfoil in place of the tail cone plus the required vertical and horizontal stabilizers are estimated to weigh more than the conventional tail cone, pylon, and tail rotor system. The eight additional airfoils required plus the associated complex control system greatly increase this weight penalty. A sketch of a possible nine-airfoil configuration is shown in Figure 52.

The forward flight drag of such airfoils, particularly those mounted at right angles to the flight direction, limits maximum aircraft forward speed to approximately 35 to 50 knots.

Squirrel-Cage Rotor (Collective Pitch)

The collective pitch squirrel-cage rotor is similar to the cyclic pitch squirrel-cage rotor discussed earlier, except that only collective pitch control is required. This approach is less complex than the former and can be expected to demonstrate higher reliability and maintainability. It can provide lift, however, only when placed in an external airflow, lift being developed due to the difference in velocity incident on blades on opposite sides of the squirrel-cage.

The preferred configuration involves a number of squirrel-cage rotors extending radially from the helicopter fuselage for use in hover and a vertically mounted rudder and vertical stabilizer. A sketch of an individual squirrel-cage is shown in Figure 52.

This concept suffers from a combination of the drawbacks associated with downwash deflectors (induced pitching moments, control characteristics dependent on main rotor loading, etc.) and those associated with squirrel-cage rotors. Among the latter are squirrel-screech noise signature, relatively high complexity, and poor high-speed dynamics.

High speed dynamics is an area of particular weakness. This concept has no blade cyclic pitch control and will experience blade stall in moderate to high-speed forward flight. The result is severely restricted high-speed performance of the aircraft and increased system structural weight penalty.

Safety of ground personnel will be poor because of the large number of whirling blades in several areas around the aircraft.

Jet Flap

The jet flap approach replaces the conventional airfoil above with a thin elliptical-section airfoil employing a high intensity full-span thin air jet exhausting from the trailing (bottom) edge. The direction and intensity of the jet are adjustable by the pilot.

Jet flap airfoils can produce lifts 4 to 8 times higher than a conventional airfoil of the same size, but effective drag is 15 to 65 times higher. While two jet-flapped tail booms can provide the yaw moment produced by the 8 to 10 conventional airfoils above, the induced pitching moment can be excessively large, often exceeding the yaw moment produced.

As the hinged main rotor on the base-line aircraft may not be capable of overcoming this pitching moment, other jet-flap airfoil concepts were examined. Considering aircraft stability, drag, weight, pilot visibility, and maximum acceptable induced pitching moment, the most promising jet-flap airfoil solution employs airfoil pairs extending radially from the aft sides of the fuselage. One airfoil on each side of the aircraft balances the induced roll moment. The design angle of sweepback of such airfoils is chosen as a compromise between reduced maximum forward speed as sweep is reduced, and increased undesirable pitching moment at low speed as sweep is increased. The final configuration will reduce aircraft maximum forward speed (unless the airfoils are assumed folded in forward flight) and significantly increase aircraft effective vertical drag in hover. A four-airfoil solution is preferable, similar to the vehicle sketched in Figure 52, but without the two forward airfoil pairs.

The thin ellipses used with the jet flap are structurally inefficient, and a significant structural weight penalty must be accepted to account for external stiffening, probably in the form of guy-wires.

Thwaites Flap

The Thwaites flap concept employs fixed circular cylinders in place of the thin ellipses of the jet flap. Lift is obtained by applying high-velocity suction through much of the cylinder surface and adjusting the position of a very small full-span flap around the periphery of the rear surface of the cylinder, as shown in Figure 52. A typical flap chord is about 2 percent of the 3-foot-diameter cylinder.

The limited maximum lift coefficient and induced pitching moment problems are similar to those found with the other circulation control approaches, and similar design and performance penalties are imposed. Required power is relatively low, a significant improvement over the jet flap. Control response times are predicted to be comparable to the tail rotor, as only the small flap need be moved to change lift from maximum positive to maximum negative. Although the fixed circular cylinders are structurally more efficient than the thin elliptical cylinders of the jet flap, the resulting system is somewhat heavier than the jet-flap system and significantly heavier than the tail-rotor system due to the large number of cylinders required.

The primary operational drawback of this system lies in the susceptability of the suction areas to clogging. By this criterion alone, the Thwaites flap concept is unacceptable for operation in any dusty or salty environment. At the least, special maintenance would be required for the suction areas.

Circulation Control by Tangential Blowing

The circulation control by tangential blowing concept employs either circular or thick elliptical cylinders. Elliptical sections of 30 to 40 percent thickness appear to be a good compromise between conflicting aerodynamic and structural requirements. Sectional lift coefficients of 25 or more are obtainable by ejecting air tangentially into the boundary layer along the side of the cylinder. The magnitude of the side force is controlled by pressure applied to the blowing slot. The sign of this force is controlled by choice of blowing slot. In principle, both functions can be performed by a single valve inside the cylinder. Side force of up to 25 times jet thrust is obtainable, an amplification factor roughly ten times greater than that obtainable from a jet-flap system. Thus, the power required to produce a given lift is significantly lower than for a jet flap. Through use of thicker cylinders with the tangential blowing concept, structural weight is reduced below that of the jet flap.

Induced drag is of the same order of magnitude as for the jet flap, so corresponding multicylinder solutions are required. Such configurations lead to weight and forward flight performance penalties compared with the tail rotor.

Because of the low fan power required to generate the required maximum slot flow, simple constant-pitch, constant-rpm fans are preferred for this purpose. Such fans yield significant improvements in reliability, maintainability, and technical risk in exchange for marginally lower overall helicopter efficiency.

This concept is superior to alternative circulation control approaches in that the moment produced is only weakly dependent on the magnitude of the downwash velocity, over a wide range of velocities. Thus, control effectiveness is less erratic than in some other approaches, particularly during violent maneuvers. Yet, a strong dependence on flow direction remains, leading to variations in control effectiveness with sideward flight velocity.

Tangential blowing appears to be the most promising of the circulation control concepts examined, in regard to weight, power, reliability, and vulnerability. (Some possible military aircraft types for which this concept could be applicable are suggested in the final section of this appendix.)

Flettner Rotor

The Flettner rotor concept obtains lift on a circular cylindrical tube rotating about its axis, the lift coefficient being controlled by the speed of rotation. Use of large end plates mounted on the ends of the tube perpendicular to the tube axis permits lift coefficients in excess of 10 to be obtained.

The most effective configuration employs rotating cylinders with a diameter of roughly 3 feet in place of the jet-flapped airfoils discussed above, as shown in Figure 52. The effect of the rotating horizontal cylinders decreases rapidly with forward speed because of the altered strength and direction of the downwash. A separate rudder and vertical stabilizer are required for directional control above approximately 25 knots. The rudder could employ a Flettner rotor mounted vertically, but the insensitivity of the rotor to changes in incident airflow direction requires a conventional stabilizer.

This concept induces the same undesirable pitching moments as does the jet flap, so a multicylinder solution is required. Although system power requirements are small in steady flight, the weight and complexity - including provision for variable rpm of the rotating cylinders - are judged to be prohibitive.

Because control moment variations are obtainable only through variation of cylinder rpm, control response is predicted to be poor. The slow response will be particularly unacceptable in autorotation, which requires rapidly variable, though small control forces. To alter control moment from positive to negative, for example, the rotation of the cylinder must be braked to a stop and then accelerated in the opposite direction. This operation will require a time delay of about 5-20 seconds, or 100 times the desired value. Unacceptably high power will be required during the acceleration phase, unless heavy rotor generator and battery systems are employed.

Regardless of design decisions, this concept will suffer substantial weight, reliability, and handling quality penalties compared with other circulation control systems.

Accelerated Flywheel

The accelerated flywheel concept employs a large, axially symmetric, rotating flywheel mounted within the helicopter fuselage on a vertical axis, as sketched in Figure 53. Directional control moments are applied to the fuselage by accelerating or decelerating the flywheel, the effective torque on the fuselage being equal and opposite to that applied to the flywheel. (A motor on the flywheel shaft supplies the acceleration force; a brake on the flywheel supplies the deceleration force.) Because of this equality, the location of the flywheel within the fuselage is immaterial so far as control effectiveness or power is concerned, and could be chosen from balance, maintainability, or structural considerations.

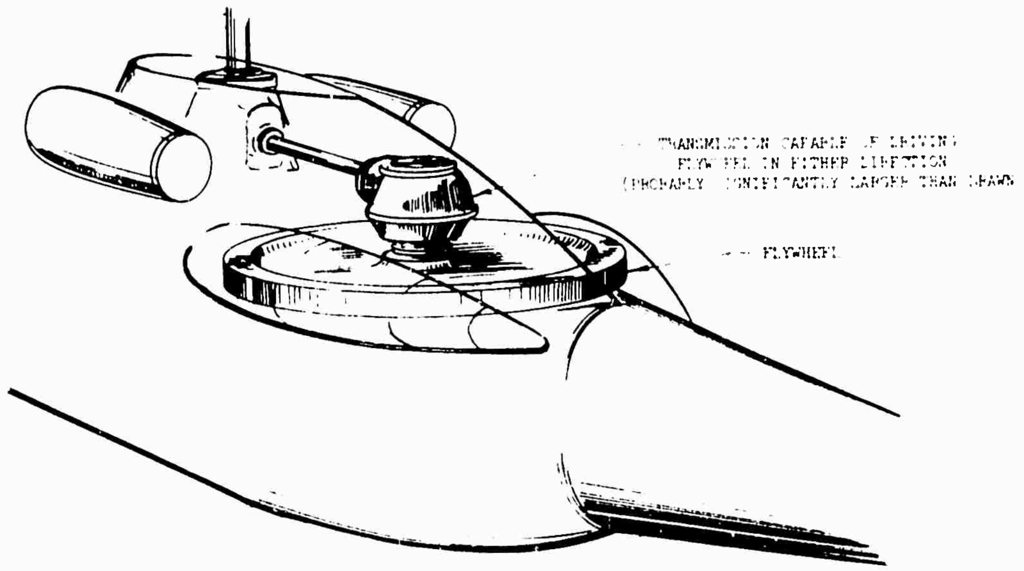


Figure 53. Accelerated Flywheel Concept.

This concept must be rated unacceptable because of excessive power requirements. We note that applied power is equal to applied torque times flywheel angular velocity, and that continuous antitorque requirements are best satisfied by speeding up the flywheel. (To provide antitorque by slowing down the flywheel would eventually stop the flywheel and force a control reversal.) The flywheel speed increases at a rate equal to the applied torque divided by the flywheel moment of inertia. Thus, required antitorque system power will increase with the square of time. The power required can be reduced by employing a flywheel of larger moment of inertia.

There is no practical weight-inertia compromise. For example, a flanged flywheel, 5 feet in diameter and weighing over 5000 pounds, would require over 30,000 horsepower to be applied after only 10 seconds of hover.

In addition, the high angular velocity and inertia of the flywheel will produce a large gyroscopic moment that will introduce unacceptably large cross-coupling of pitch, roll, and yaw motions, and make the aircraft unacceptable because of poor handling qualities.

Precessed Gyroscope

Although the precessed gyroscope antitorque concept has been proposed by inventors, it is entirely unsuitable for this application. In the preferred implementation of such a concept, a relatively large flywheel (for example, a diameter of about 6 feet and a thickness averaging 3 inches) rotates about a horizontal lateral axis within the aircraft fuselage at about 10,000 rpm. This axis is assumed to be rotatable about the fuselage longitudinal axis. Such an orientation produces a yaw moment on the fuselage when the gyro axis is forced to precess about the longitudinal (roll) axis of the aircraft. This precession is assumed to be produced by applying shaft torque about this axis to the gyro shaft.

An aircraft employing this antitorque device would be completely uncontrollable, because the axis of the precessing gyroscope varies in orientation relative to the aircraft. When the axis is aligned with the aircraft lateral axis, rotating the gyro axis about the aircraft longitudinal axis produces the desired yaw moment perpendicular to both the longitudinal and lateral axes. In the next instant, however, the orientation of the gyro axis has changed because the gyro is being rotated about the aircraft, and the resulting moment vector has components about the pitch axis as well as yaw. After the gyro has precessed through 90 degrees, the resulting moment will be pure pitch, and there will be no moment to counteract the torque of the main rotor.

To provide continuous antitorque moments, the aircraft must be rolled at exactly the same rate as the gyro precesses, clearly an unacceptable requirement.

This concept is thus unsuitable for this application.

Active Thrusters - General

Concepts requiring auxiliary engines to provide antitorque thrust, and which do not meet pseudo-compound requirements, can be defined as "active thrusters". Concepts in this category are characterized by high fuel, detectability, maintainability, and handling qualities penalties relative to the tail rotor.

Turbine-in-Tail

The turbine-in-tail concept employs a turbojet, turbofan, or turboprop engine in place of the conventional tail rotor. Two general configurations were examined. The first, with engine axis fore and aft, uses thrust deflectors to provide sideward thrust. For the turboprop, a right-angle gearbox and reversible blade pitch are employed in place of the thrust deflector. The second assumes the engine axis side-to-side and uses either thrust reversers or multiple engines to provide directional control moment port and starboard.

The first configuration (Figure 54) is preferable, though both have inherent limitations. Actuation of efficient high angle thrust deflectors is unacceptably slow, in addition to slow response time. The response time for the actuation of reverse thrust in the second configuration is significantly higher than for the already extremely sluggish simpler deflector system. To reduce these high response delays in the second configuration, a multi-engine system could be employed with a smaller thruster - directed opposite to the main antitorque and directional control thruster - to provide control in low main rotor power, high maneuver situations. This approach imposes very large penalties in weight, reliability, and cost. Reingestion of exhaust gases into engine inlets is a possible serious hazard.

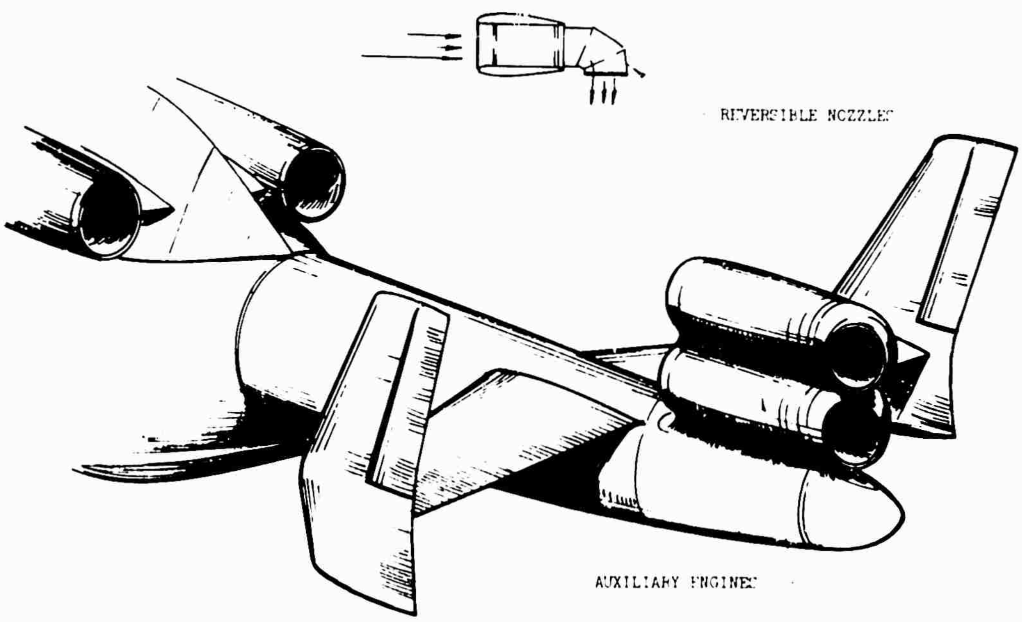


Figure 54. Turbine-in-Tail Concept.

The second configuration can also be expected to suffer from the fact that the engine air inlet flow must pass through a right angle. In forward flight, this will almost certainly lead to substantial losses and possible compressor stall.

Either configuration will incur weight, balance, and control response penalties compared with a conventional tail rotor. In addition to powerplant and structural weight penalties, mission fuel consumed in antitorque and directional control can be expected to increase by a factor of 7 to 8, increasing total mission fuel by roughly 60 percent.

Pulsejet-in-Fin

The pulsejet-in-fin concept employs engines similar to those employed in the German V-1 buzz-bomb in World War II. These engines are characterized by low weight, simplicity, high fuel consumption, and an extremely loud buzzing noise. In contrast to the equally simple ramjet, pulsejets can operate at zero forward speed and so can be employed at helicopter flight speeds. It is difficult or impossible, however, to throttle significantly from full thrust without causing the engine to stall, making the concept completely unsuitable for the precise control application required.

Chemical Rocket

The chemical rocket concept (Figure 55) consists of conventional rocket engines in place of the tail rotor. Although the dry weight of such engines is low, the noise and fuel required are prohibitive. Balance is also a problem. In helicopter design, fuel tanks are commonly distributed evenly about the center of gravity so that trim will not be altered as fuel is consumed. As a result, solid-fuel rockets may not be feasible, because the fuel is placed near the tail of the helicopter. Liquid-fuel rockets can reduce the balance problem, but require significantly more complex engines and fuel systems.

The high-temperature high-speed exhaust flow will be a significant hazard for ground personnel. A potential fire hazard is associated with this exhaust and, in case of a crash, with the very large quantity of fuel carried.

Finally, difficulties in varying the thrust of a rocket over a large number of cycles with acceptable reliability must be overcome. At least four rocket engines per aircraft are required because of the requirement for adequate control in the event of failure of a single engine and because of the difficulty of providing ±90 degree deflection of the high-temperature exhaust flow. A configuration employing four rockets directed to port and two to starboard appears to be the least impractical solution.

As with all auxiliary engine concepts, there is no autorotational control capability, since the MIL-H-8501A autorotation stability and control requirement specifies that all engines be inoperative.

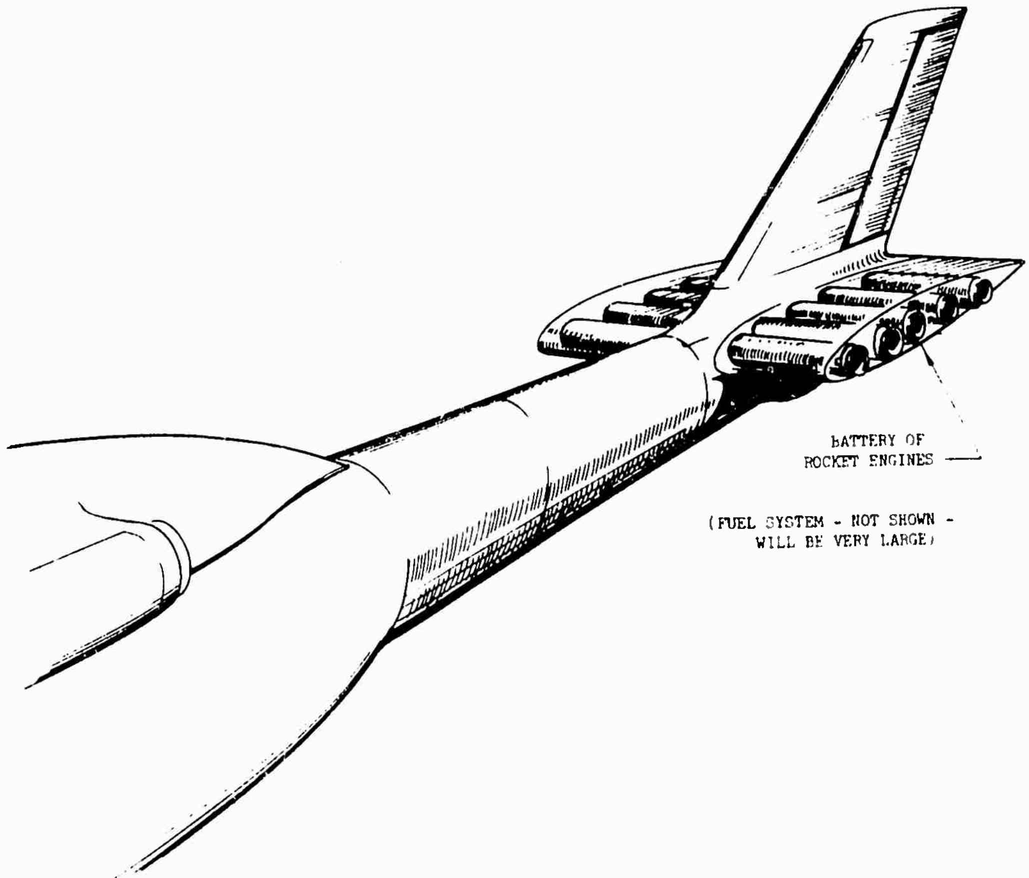


Figure 55. Chemical Rocket Concept.

The chemical rocket offers no advantages over other concepts. A possible application for solid-fuel rockets as an emergency yaw control system is discussed in the final section of this appendix.

"Exotic" Momentum Radiators

The basis of each of the concepts examined in this appendix is Newton's Second Law: For every action, there is an equal and opposite reaction. In the various concepts using rotors, propellers, prop-fans, ducted fans, or chemical rockets, the relation to this law is readily apparent: pushing a mass per unit time, $\dot{m}$ (often air), at velocity V, results in a thrust in the opposite direction equal to $\dot{m}$ times V. This is equally valid, though less obvious, in the case of concepts involving flywheels, gyroscopes, or coaxial speed brakes.

This also holds true for devices classified as "exotic" momentum radiators. Such devices are often characterized by a potentially dangerous exhaust flow and by high values of specific impulse (ratio of thrust to fuel flow rate), but by low values of thrust to weight ratio. Thus, though it consumes relatively little fuel in producing a given thrust, the weight of the dry thrusting device itself may be prohibitively large.

Such radiators are entirely unsuitable for helicopter antitorque and yaw control. Detailed analyses of each of the several types are not warranted, so only two representative types will be considered.

1. Exotic Rockets

Exotic rockets include a wide variety of space propulsion engines, among them electric propulsion engines (arc plasma engines, magnetoplasma engines, and ion rockets), photon rockets, solar rockets, and nuclear rockets. Each of these requires only a small propellant weight compared with a chemical rocket. The large weight requirements for electrical or magnetic energy sources lead to extremely low thrust-to-weight ratios. The result is an overall antitorque and yaw control system weight of the order of 10 to 6,000,000 times that of a chemical rocket. In turn, a chemical rocket is approximately 10 times heavier than a conventional tail rotor system.

Considering the potential hazard of the high-velocity efflux from such engines (velocities range from up to 15,000 - 30,000 ft/sec for the nuclear rocket, through 1,000,000 ft/sec for the ion rocket, to the speed of light for the photon rocket), such devices are unacceptable for this and similar applications.

2. Acoustic Radiators

The acoustic radiator concept is similar in principle to that of a conventional loudspeaker. High-intensity pressure waves, directed in one direction, travel outward at the speed of sound; in reaction to this momentum transfer, an equal and opposite thrust is generated on the radiator. The problem, of course, is the noise level. To provide the required maximum side force from a 200-ft^2 radiating surface, the required noise intensity almost certainly would be fatal to nearby personnel, as well as damaging to the structure of the vehicle itself.

Keeping the noise level within reasonable limits by increasing the radiator area imposes an unacceptably high structural weight penalty. The electrical power system for either of the above configurations will also be extremely large and heavy.

Application of suitable helicopter weight growth factors yields vehicle weights so high as to prohibit flight with a conventional helicopter employing this concept.

Similar arguments can be made against systems, such as lasers, which radiate light rather than sound.

Main Engine Exhaust Deflectors - General

Main-engine exhaust deflection concepts are similar in principle to the turbine-in-tail concepts discussed earlier. Instead of obtaining thrust from engines auxiliary to the main powerplant of the helicopter, the residual exhaust thrust from the main powerplant system is used.

The deflection system can vary in complexity from an unshrouded rudder placed downstream from the unaltered exhaust duct of an engine, to systems of bifurcated nozzles connected directly to the engine through a network of ducts, to gas-driven prop-fans.

Two fundamental weaknesses of such approaches, whether they employ the actual turbine exhaust or bleed air from the compressor, are readily perceived: (1) the low air mass flow rate of current helicopter turboshaft engines, and (2) the fact that no control forces are available in autorotation. To overcome the first weakness, weight, maintainability, and fuel penalties must be imposed; the second weakness cannot be directly overcome.

Deflection of Main-Engine Power Turbine Exhaust

No concept involving deflection of the main-engine power-turbine exhaust flow appears attractive as an alternative to the tail rotor on a conventional helicopter with current-technology turboshaft engines. The basic drawback is the low residual exhaust thrust of current-technology turboshaft engines - typically on the order of 1/10 pound of static thrust per output shaft horsepower. For advanced-technology turboshaft engines, this ratio drops to nearly 0.05:1, representing approximately 125 pounds of static thrust at 4000 ft, 95°F for the engines in the base-line aircraft. Assuming loss-free ducting to a nozzle in the position of the conventional tail-rotor, this represents only about 5 percent of the maximum required for antitorque and directional control. Employing the exhaust flow to tip-drive a prop-fan increases the resulting thrust, but weight and maintainability penalties negate this improvement.

Main engine exhaust deflection concepts are not practicable for this application unless significantly higher exhaust thrusts are available. This implies a requirement for greatly oversized turboshaft engines or for a turboshaft engine incorporating either a bypass fan or an oversized gas generator system to augment the exhaust flow. Thus, special engines must be developed to make a practicable deflected main-engine exhaust antitorque system. The only difference in principle between such a system and an auxiliary engine approach is that here the so-called auxiliary engine is an integral part of the main engine.

Two basic duct system concepts are available with such approaches: a straight duct to an adjustable nozzle placed near the conventional tail rotor location, and a bifurcated nozzle system.

In the latter system, the combined engine efflux (from whatever source) is split at a Y-junction, each branch of which leads to one side of the aircraft. At the outlet of each branch is another Y-junction, one branch of which exhausts forward and the other aft. Thus, there are now four exhaust nozzles, as sketched in Figure 56.

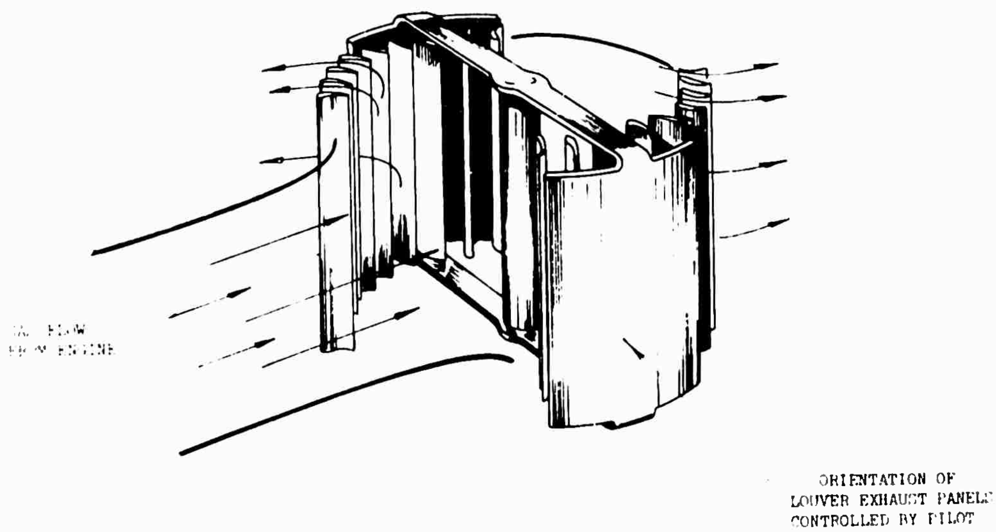


Figure 56. Main-Engine Airflow Deflection - Bifurcated Nozzle Concept.

Antitorque and directional control are obtained from this ducting system by controlling the position of a set of louver doors (Figure 56). If no control is required, the exhaust flow can be distributed equally through all four nozzles, resulting in zero net thrust and zero net moment. Alternatively, half the flow can be ducted through the forward-facing nozzle on one side and half through the aft-facing nozzle on the other side, resulting in zero net thrust, but a net moment equal to engine thrust times the lateral offset distance between the nozzles and the aircraft centerline. Intermediate louver settings, controllable by the pilot, produce intermediate results.

Although the bifurcated duct system eliminates the net side force produced by the efflux from the simple single-straight-duct approach, it is less attractive overall. Particular problems occur in the areas of high-speed dynamics, maintainability, and weight. Duct losses are substantially higher for the bifurcated system than for the straight duct. Even neglecting these losses, a thruster lateral offset equal to the distance between the main rotor shaft and the equivalent straight-duct nozzle is required to reduce the power required for the bifurcated system to that of the straight duct in the tail-cone approach. In practice, the bifurcated nozzle pairs must be mounted on two pylons, each the length of the single tail cone of the alternative system. Because a tail cone will be required to support a yaw-damping vertical stabilizer and rudder in any case, the pylons represent a large weight penalty. In high-speed forward flight, the drag on the large-diameter pylon-ducts will cut helicopter maximum speed significantly, increase fuel requirements, and introduce a buffeting problem.

Therefore, for this application the bifurcated nozzle system can be eliminated as unpromising. The alternative approach of combining the exhaust flows into a single straight duct in the tail cone employs a nozzle system similar to that of the fan-in-tailcone concept of Figure 49. This approach is inferior to the fan-in-tailcone because of lack of autorotative control capability and because of excessive power requirements, which are predicted to increase installed power requirements by between 100 and 200 percent.

Convertible Turboshaft/Fan Engine

The convertible turboshaft/fan engine can supply power both as shaft horsepower and as thrust from a high disc-loading gas-driven turbofan ($1000 \leq DL \leq 3000$ psf) within the engine. The power sharing is regulated by a valve under control of the pilot. For this application, the two such engines are assumed to replace the base-line engines, with the exhaust flow from the turbofan and gas generator ducted through the tail cone, as in the fan-in-tailcone concept.

Such convertible engines are most useful in compound helicopters, which require maximum shaft power and maximum thrust at different times. For the antitorque/directional control application, in which maximum main rotor shaft power and maximum antitorque control are required simultaneously, significant installed power penalties exist.

Because of the high effective fan disc loading of projected convertible shaft fan engine designs, the power required to generate a given fan thrust may be five times that required with a conventional tail rotor or a prop-fan solution. Special engine designs employing fan disc loadings equivalent to those used in the fan-in-tailcone concept, and including a variable-pitch fan, would reduce the power penalty significantly. Thruster redundancy gives the twin low disc-loading convertible engine concept an improvement in reliability and vulnerability over the fan-in-tailcone, with a small penalty in power and large penalties in maintainability and cost.

Control response will be below that of the fan-in-tailcone concept, unless a system is incorporated to provide transient power from the main rotor to the engine fan. Unfortunately, such a system mechanically connects the turboshaft and turbofan portions of the engine through the main rotor gearbox, thereby negating the convertibility of the engine. Without such an interconnection, directional control in autorotation could not be provided.

An improvement in detectability and fuel requirements, and a small improvement in aircraft weight can be obtained with the conventional high disc-loading engine by replacing the simple tail-cone-mounted deflector nozzles with a tip-driven prop-fan as in the fan-in-fin. Total installed power for this approach is roughly 35 percent higher than for the base-line tail rotor configuration, or 5 to 10 percent higher than for the shaft-driven fan-in-fin. Penalties relative to the simpler convertible engine/deflector nozzle approach are predicted in reliability, maintainability, vulnerability, high-speed dynamics, and ground personnel safety.

Engine Compressor Bleed Air

The compressor bleed air concept achieves antitorque and yaw control forces by ducting high-pressure air from the main engine compressor stages through a duct to a nozzle at the aft end of the tail cone (Figure 57). In principle, this is a relatively simple system. Current engines already have a provision for bleeding off a percentage of the compressor flow.

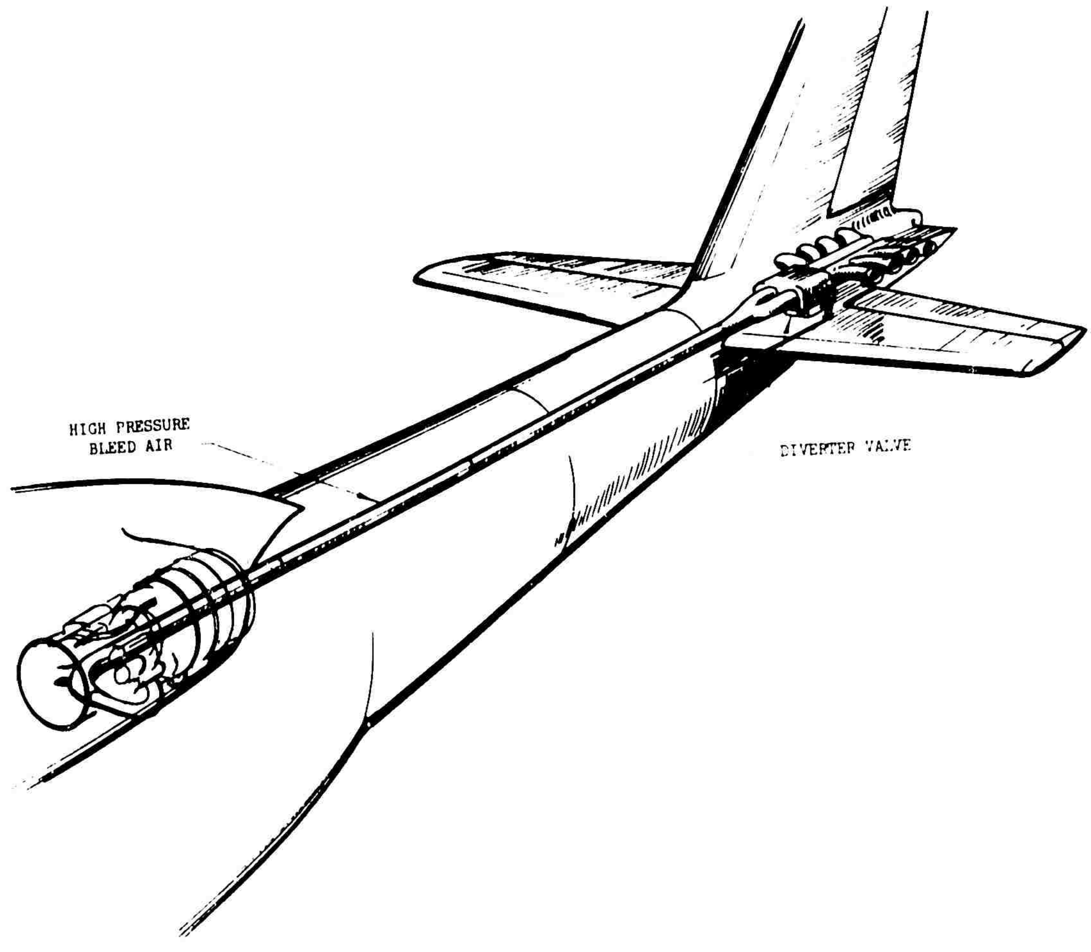


Figure 57. Main Engine Airflow Deflection - Compressor Bleed Air Concept.

For the application of interest, however, special engine designs are required. Assuming bleed air at 8.5 atmospheres (at 4000 ft, 95°F) and making standard turbulent pipe flow assumptions for the duct flow, a requirement exists for roughly 33.5 lb/sec of bleed airflow to provide maximum antitorque and yaw control. For a typical engine, a maximum of only 6 percent of total compressor airflow is available for compressor bleed. For the ST-9 engine assumed for the base-line aircraft, maximum bleed airflow will thus be roughly 0.5 lb/sec per engine. Thus, the required bleed flow is roughly 30 times that available from the installed base-line two-engine power plant.

This concept requires an engine with a greatly oversized compressor stage. This is equivalent to a turbofan engine with a very high pressure ratio fan of 8.5 compared to a typical large turbofan fan pressure ratio of roughly 2.0 at a moderate bypass ratio. Alternatively, the additional compressor may be considered as separate from the engine and as requiring additional shaft horsepower from the turboshaft engines. A flow of 33.5 lb/sec at 8.5 atmospheres will require roughly 6000 shaft horsepower at 4000 ft, 95°F, or roughly 15 times the power required by the optimized conventional tail rotor.

If the high pressure-ratio turbofan engine were employed, it would not be possible to provide yaw control by this concept in autorotation. By employing a separate shaft-driven compressor that could be driven in autorotation by the main rotor shaft, this difficulty could be overcome. Without a complex inlet-flow regulation system, however, power requirements imposed by a large pedal deflection in autorotation could lead to an unacceptable increase in autorotative descent rate.

Although for this application this concept appears to be unsuitable from power and powerplant weight considerations, it may have merit where lower maximum control moments are required and where larger basic engine airflow values are present. A potential example of such an application is discussed under "Potential Alternative Applications", the final section of this appendix.

Pseudo-Compound Solutions - General

Most solutions suitable for low-speed directional control of single shaft-driven main-rotor compound helicopters can be used on pure helicopters. In exchange for the capability of providing a choice of sideward or fore-and-aft thrust components, however, penalties will be imposed in system weight and/or power requirements. Similar penalties are associated with such concepts as the turbine-in-fin or high disc-loading convertible turboshaft/fan engine concepts, which are compatible with compound aircraft requirements.

Although such pseudo-compound concepts are feasible for a pure helicopter, they represent compromise solutions inferior to the tail rotor, fan-in-fin or fan-in-tailcone solutions. Several examples are discussed in the next five subsections.

Piasecki Ringtail

The Ringtail concept is employed on the Piasecki 16H-1C Pathfinder compound research helicopter. Antitorque and yaw control are obtained by employing large rudder vanes within the duct of a ducted propeller mounted on the helicopter tail cone. The propeller has variable-pitch blades with a reverse thrust capability. In forward flight, the rudder vanes are oriented parallel to the flight direction, and the propeller acts as a simple thruster. A typical thruster layout is sketched in Figure 58.

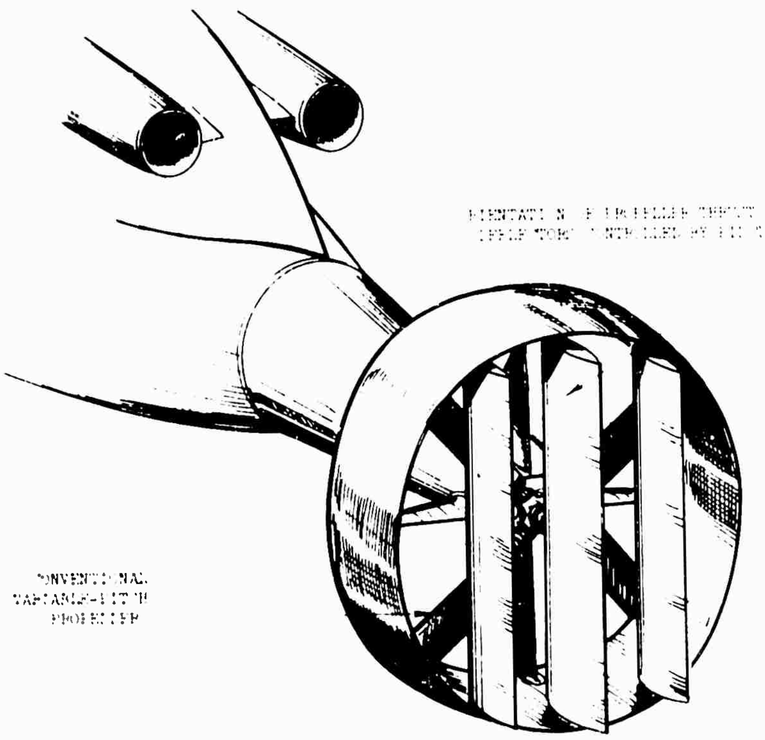


Figure 58. Piasecki Ringtail Concept.

Because the rudder vanes can turn the ducted prop flow through a maximum of roughly 60 degrees, total propeller thrust must be at least 15-20 percent higher than for the tail rotor or fan-in-fin thruster configurations. In addition to the antitorque and directional control forces produced, a forward thrust roughly equal to 60 percent of the desired side force is produced, which must be counteracted by cyclic control on the main rotor. Including the beneficial effects of the shrouded propeller, the power required is comparable to that required for the fan-in-fin and ROTOPROP concepts. A weight penalty is predicted for the Ringtail compared with either of these concepts.

The rudder vane arrangement makes it unlikely that the control requirements can be met for rearward flight.

Noise radiation is predicted to be more detectable than that of the conventional tail rotor, particularly in hover. In forward flight, the more uniform inflow of the Ringtail will improve its detectability relative to the tail rotor and fan-in-fin systems.

Reliability, maintainability, and personnel safety are predicted to be superior to the conventional tail rotor and, except for personnel safety, are equal or superior to the fan-in-tailcone or fan-in-fin concepts.

This is a potentially practical system for compound helicopter applications but is inferior to several alternatives for application to pure helicopters.

Use of jet-flap turning vanes in place of the conventional airfoil vanes does not offer significant improvement. A mechanical linkage to each vane is still required, with the additional weight and complication of ducting and valve systems. This approach appears worthy of consideration in any evaluation of possible antitorque systems for compound helicopters.

Sikorsky ROTOPROP$_{TM}$

The Sikorsky ROTOPROP was originally designed to perform a similar function to that of the Piasecki Ringtail. The ROTOPROP is a shaft-driven variable-pitch propeller mounted in the conventional tail rotor position. The conventional pylon is replaced by a large vertical fin and rudder.

In hover, the ROTOPROP acts as a conventional tail rotor. As forward flight speed increases, the propeller assembly progressively rotates about a vertical axis until, at a specified forward speed, the propeller is in a pure thruster position. Antitorque and yaw control are then supplied by the vertical fin and rudder.

Because of the lower power loading typical of a propeller, the power required for the ROTOPROP will be roughly 65% higher than for an equivalent tail rotor. A weight penalty results from provision of a gearbox incorporating the prop-mode conversion capability. Reducing the disc loading to that of a tail rotor is unattractive; although the power penalty is eliminated, weight and vulnerability increase.

Improvements are predicted over the conventional tail rotor in reliability, maintainability, resistance to foreign object damage, and ground impact damage. This is due primarily to the reduced disc area and greater ruggedness of a propeller relative to a typical tail rotor.

Under the guidelines imposed for this study, the concept is concluded to be inferior to the fan-in-tailcone and fan-in-fin concepts in regard to noise, ground personnel safety, and susceptibility to FOD. The ROTOPROP may be slightly superior to the conventional tail rotor in ground personnel safety because of its smaller disc area. The high speed dynamics problems associated with the hingeless bladed tail rotor are avoided by converting to the pusher mode in high-speed flight.

The power benefits obtained by placing a shroud around the propeller are judged to be offset by the associated weight and maintainability penalties.

Cyclic Control on Thrusting Propeller or Rotor

The cylic control on a thrusting propeller concept involves a shaft-driven propeller or rotor, mounted as a pure thruster at the aft end of the tail cone, but with both cyclic and collective pitch controls. Antitorque and yaw control moments are supplied via the cyclic pitch,but collective pitch is used only for forward flight thrust control. A control system similar to that employed on conventional helicopter main rotors would be applicable.

This concept suffers in weight and power compared to a conventional tail rotor, without providing improvements in personnel safety, reliability, maintainability, vulnerability, or susceptibility to foreign object damage.

If conventional airfoil propeller blades are employed, very large diameter propellers are required, because of the maximum blade lift coefficient constraints and because the effective moment arm is significantly less than one-half the propeller diameter. For conventional blades ($C_{L_{max}} \sim 2$), propeller diameters between 18 and 25 feet are required, making this configuration impractical. For jet-flap blades ($C_{L_{max}} \sim 10$), the minimum allowable propeller diameter is 10 feet. For elliptical section blades with tangential blowing ($C_{L_{max}} \sim 20$), an 8-foot-diameter propeller is possible.

Theoretically, such propellers cannot produce the required moment couple without producing a net thrust as well because of recirculation effects on the net inflow of air to the propeller. Although this net thrust would have to be counteracted by the main rotor, the main rotor thrust penalty is less than required to compensate for the side force on a tail rotor, fan-in-fin, or similar thrusters.

Power requirements are high for the propeller itself. For the conventional propeller, the power required is roughly twice the total installed power of the base-line helicopter system. Jet-flap and tangential blowing propeller systems are significantly less efficient.

In addition to power penalties, these approaches rate below the conventional tail rotor in detectability, weight, personnel safety with conventional blades, vulnerability to terrain impact damage, foreign object damage susceptibility, and technical risk.

This approach is significantly inferior to a number of other concepts for pure and compound helicopter applications.

Differential Thrust on Thrusting Props or Prop-Fans

Antitorque and directional control moments can be produced by a thrust differential between two propellers or shrouded prop-fans. Each of these thrusters would be mounted on a stub wing extending from the fuselage beneath the main rotor. The layout is similar to that of a conventional midwing twin engine propeller-driven aircraft. The thrusters are assumed to be shaft driven from the main gearbox. (Driving each with a separate pylon engine without cross shafting would result in loss of control in the event of engine failure.) Antitorque and yaw control are provided by adjusting the differential collective pitch on the propellers or prop-fans.

Use of this approach on a noncompound helicopter results in weight and power penalties. The weight penalty arises from the attempt to minimize the power penalty by having a large thruster-offset from the fuselage and by reducing the disc loading on the thruster. For each offset distance, however, maximum thruster diameter is limited by the requirements that the thruster not strike a main rotor blade at its maximum negative flapping angle, and that it not strike the ground in the event of failure of the alighting gear on landing. These constraints reduce the maximum allowable thruster diameter as offset distance increases.

The ability of shrouds to increase thrust on a propeller without increasing required power is discussed in Appendix III. Because of size restrictions in this application, and because of personnel safety and ground impact vulnerability improvements, shrouded propellers or low disc-loading prop-fans are preferable to unshrouded propellers.

Diameter constraints lead to a minimum installed antitorque plus directional control power of roughly 35% of total installed power or roughly three times the power applied to the optimum conventional tail rotor, at an offset distance of approximately 25 feet.

Penalties are also incurred over the conventional tail rotor in weight, maintainability, ballistic vulnerability, and noise detectability,particularly in the fore and aft direction. The concept requires the power of the fan-in-tailcone approach, but leads to greater penalties in weight, maintainability, vulnerability, personnel safety, and detectability.

An alternative approach is that of the Gyrodyne, which employs a single stub-wing-mounted forward thrusting propeller in place of the tail-mounted tail rotor. The Gyrodyne eliminates the high-speed forward-flight limitations of the tail rotor. For this application, the Gyrodyne approach imposes a power penalty above the true differential thrust approach because of the greater impact of thruster size constraints. Lateral balance and high-speed control considerations favor the use of an additional stub wing opposite to that on which the thruster is mounted, but the associated weight penalty will partially offset any benefits obtained.

Differential Thrust on Turbojets or Turbofans

The differential thrust on turbojets or turbofans concept is identical with that of differential thrust on thrusting props except that the propellers are replaced by either auxiliary turbojet or turbofan engines. As a result, the control in autorotation available in the propeller concept, with shaft power provided by the windmilling rotor, is lost. To provide full one-engine-inoperative control capability, at least four auxiliary engines would be required.

Turbojets or turbofans are superior to shaft-driven thrusters in this application in regard to terrain impact damage and ground personnel safety. Both attributes result from the smaller size of the engines compared to a propeller or prop-fan and the associated greater ground clearance. Substantial penalties in weight, fuel, reliability, maintainability, detectability, and cost outweigh these two benefits.

Pseudo-Coaxial Solutions

The torque that must be supplied to a lifting rotor arises solely from the profile and lift-induced drag acting on the blades of the rotor. A true coaxial helicopter requires little or no main rotor torque compensation because of cancellation of the resultant net torque applied to the two contrarotating main-rotor systems. A possible way of applying this principle to a conventional single-rotor shaft-driven configuration involves placing a nonlifting high-drag rotor beneath the existing main rotor, and rotating it in the opposite direction. The high-drag lower rotor blades can take the form of pairs of speed brakes that can be deflected about a full-span hinge in the blade leading edge. In the fully open position, these blades, or brakes, form a nearly flat surface perpendicular to the incident airflow and produce high drag. Fully closed, they form a thin low-lift airfoil parallel to the incident airflow and produce low drag. Intermediate deflections produce intermediate drag values.

Thus, through a programmed permutation of brake deflections, the pilot can vary the drag torque on the lower rotor to compensate for changes in main (lifting) rotor torque and to provide control moments to the fuselage. A possible configuration of such a system is sketched in Figure 59.

The weaknesses of this concept in a number of areas make it unattractive compared to the fan-in-tailcone or fan-in-fin. System weight (including a special coaxial gearbox, brakes, control system, fuel, and powerplant) and the incremental installed power will be excessive. To reduce power to produce a given torque, brake-rotor rpm must be reduced, requiring an increase in brake area and weight. A typical solution for the base-line aircraft more than doubles the total required installed horsepower and imposes an empty-weight penalty of roughly 20 percent.

Stability and control characteristics are unsatisfactory. Control can be varied only relatively slowly, and the paddles produce torque only opposite to that of the main rotor. Thus, in autorotation, directional control forces will be available in one direction only. In addition, the drag of

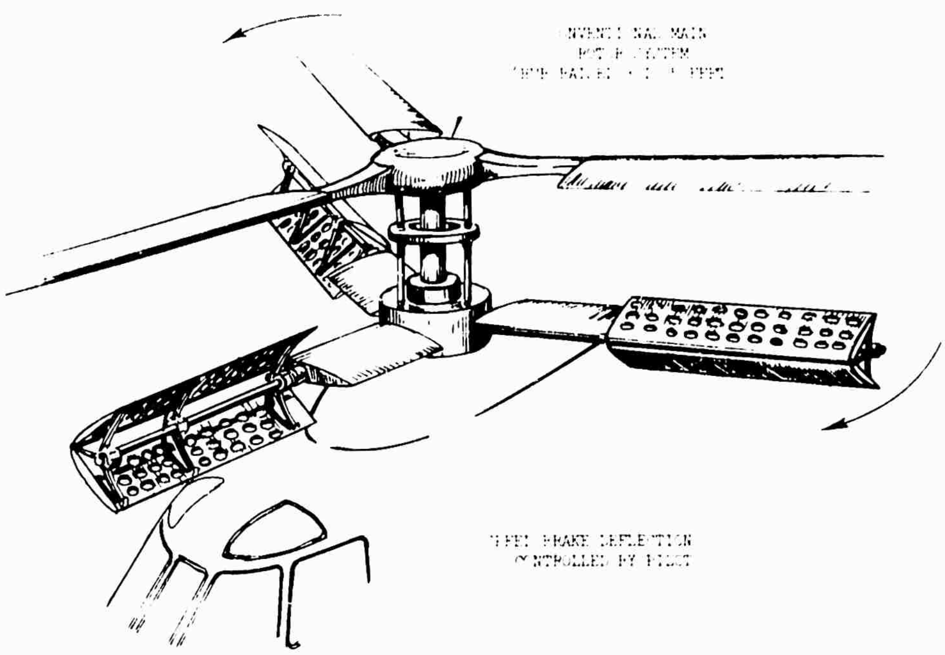


Figure 59. Coaxial Speed Brake Concept.

the undeflected brakes will reduce aircraft autorotational performance. Control characteristics will be strongly and nonlinearly dependent on forward flight speed, with a pulsing yawing moment likely.

Forward flight dynamic characteristics are predicted to be inferior to the base line. The high drag on deflected brakes can reduce vehicle cruise speed and increase forward-flight fuel consumption, unless the brakes are progressively phased out of the directional control loop and replaced by rudder control as forward speed increases.

Reliability is predicted to be poor because of the complexity and high stresses in the system. Maintainability is poor due to inaccessibility of the brakes from the ground and the small associated working area.

In all flight regimes in which the brakes are deflected, a characteristic noise signature is likely to arise from interaction of the brakes with the downwash flow from the main rotor blades.

Combined Concepts

The large majority of concepts studied revealed inherent inadequacies that cannot be eliminated readily in combination with other concepts. A combination of a fan-in-tailcone and main rotor downwash deflection using circulation control by tangential blowing was examined, because of the increased promise of the latter concept as its moment requirements are reduced. This approach may yield marginal improvements in regard to installed power and noise detectability. However, predicted penalties in weight, control system complexity, and maintainability in particular make this appro ch unattractive relative to the pure fan-in-tailcone. Technical risk must be rated high, at least until the performance of the tangential blowing concept in ground effect is examined further.

A combination of the fan-in-tailcone and deflected main-engine flow concepts was also considered. This approach, first employed on the Cierva W.9 research helicopter,[19, 20] introduces the engine power turbine exhaust flow into the duct just downstream of the prop-fan. Advantages over the conventional fan-in-tailcone are predicted in reduced infrared radiation of the engine exhaust and increased system efficiency by augmenting the fan exhaust thrust by approximately 5 percent. In opposition to these gains are penalties in weight and maintainability due to the additional ducting around the prop-fan. Counteracting the effects of the relatively high temperature exhaust flow on the nozzle system in cases of combined high engine power and low fan power, as in high-speed forward flight, may lead to further weight penalties. The advantages of this approach over that of the simpler fan-in-tailcone are judged to be small.

POTENTIAL ALTERNATIVE APPLICATIONS

Several concepts found unpromising for the requirement specified for this study were concluded to have promise for alternative applications. Two of these applications, described below, merit further analysis before a valid conclusion can be reached on these concepts.

Emergency Antitorque Systems

In the event of tail-rotor failure in high-speed forward flight, a single-rotor shaft-driven helicopter can continue in flight so long as the aerodynamic force on the tail cone and fin is sufficient to overcome rotor torque. But landing without a tail rotor, or failure of a tail rotor in low-speed forward flight, may well be catastrophic. An inexpensive, reliable, lightweight emergency directional control system is required, capable of providing at least 15 seconds of directional control.

Throttlable solid-fuel rockets appear promising. A lower risk system could employ batteries of small constant-thrust rockets with variable control moment being obtained by firing or extinguishing individual rockets. Such a system capable of providing full directional control (but no anti-torque control) for 20 seconds would weigh roughly 200 pounds installed.

Directional Control of Aircraft With Torqueless Rotor Systems

Aircraft equipped with reaction-drive rotors or coaxial shaft-driven rotors do not require antitorque moments. Such vehicles are typically more compact than conventional helicopters of the same gross weight, and may require maximum control moments as low as 35% of those on conventional helicopters of similar weight.

Any directional control concept applicable to conventional single-rotor shaft-driven helicopters can be employed on torqueless rotor machines. In addition, some otherwise unacceptable concepts can be attractive for these less-demanding configurations.

The pseudo-coaxial antitorque and yaw control concept is unacceptable for shaft-driven single-rotor helicopters. This is primarily because of large penalties in weight and power inherent in employing a large, high-drag, zero-lift rotor. In a true coaxial configuration, however, both rotors produce lift. The weight of the two is only slightly greater than that of the equivalent single main rotor and potentially less than the single main rotor plus tail rotor system currently employed. In such a configuration, directional control in hover and low forward speeds is provided by varying the lift share between the two rotors, thereby unbalancing the opposing torques applied to the rotors. In principle, this unbalancing can be produced either by introducing a differential in blade collective pitch between the two rotors or, alternatively, by introducing a differential in blade tip speed between the two rotors. In practice, the former alternative is the most promising when considering control and drive system complexity.

The stability and control characteristics of such systems in forward flight are highly dependent on rotor system flapping stiffness. Although this topic is beyond the scope of this study, it is worthwhile to consider it briefly. Interactions occur between yaw and roll moments on coaxial vehicles employing semirigid or so-called rigid rotor systems. This problem is overcome by phasing out the differential collective yaw controls in favor of conventional rudders as forward speed increases. This is the system currently proposed for the Sikorsky advancing blade concept (ABC) rigid coaxial rotor configurations.

In addition to this concept, which is restricted to shaft-driven coaxial rotor vehicles, many other previously eliminated concepts are potentially applicable.

Rotor downwash deflection employing circulation control by tangential blowing, for example, was eliminated for conventional helicopters because of the large induced pitching moment. Compressor bleed flow was eliminated for conventional helicopters because the large airflows required could not be supplied by acceptably small engines. A similar criticism was made of deflected engine exhaust concepts.

The circulation control approach would be best suited for highly compact torqueless rotor vehicles with high downwash velocities (high disc loading on the main rotor or rotors). An example of such a vehicle is the Sikorsky Armored Aerial Personnel Carrier (AAPC) concept, which has relatively low inertia per pound of gross weight because its heavy armor plate steel fuselage is concentrated near the cg. This vehicle uses an ABC rotor with a disc loading of 8.0 in the production version. Although induced pitching moment would still be a significant fraction of the desired yaw moment, the very high roll and pitch control power of the ABC rotor system could compensate for this effect.

Compressor bleed and deflected engine exhaust directional control concepts are most attractive for low inertia-to-weight ratio aircraft having relatively inefficient rotor or transmission systems (requiring high installed power in relation to the directional control moments required). These criteria are met by typical reaction-drive rotor aircraft. Most reaction-drive aircraft built or proposed, including the Army XV-9A, use either compressor bleed or deflected engine exhaust for low-speed directional control. Even on these vehicles, however, it appears that such systems cannot produce control to full military standards without special oversized engines.

APPENDIX II
EXPERIMENTAL DOWNWASH RESULTS

The capability of main rotor downwash deflection systems to provide adequate antitorque and directional control moments depends on the momentum distribution in the downwash. In hover, this distribution, although uniform circumferentially, tends to be nonuniform along any radial coordinate. A typical disc loading 6.0 downwash distribution 0.316 radii beneath the rotor disc, extrapolated from tests of a 7-bladed, 3.95-foot-diameter model rotor,[24] is shown in Figure 60. In this plot, the induced downwash is normalized with respect to the uniform downwash velocity at the rotor disc:

$$v_o = \sqrt{\frac{DL}{2\rho}} \quad \text{ft/sec}$$

as predicted from momentum theory, where DL = disc loading, and ρ = atmospheric density in slugs per cubic foot. The downwash velocity varies from roughly 25% of the predicted value near the rotor hub to roughly twice predicted at 0.8 rotor radii, outboard of which the induced velocity falls rapidly toward zero.

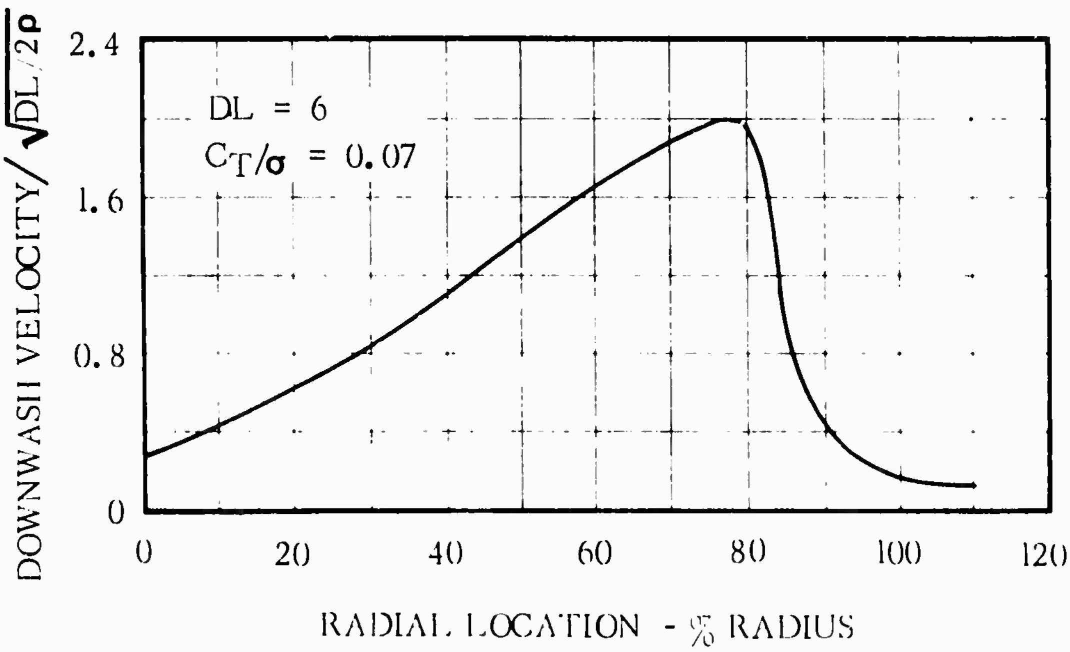


Figure 60. Typical Experimental Downwash Velocity Distribution, Sea Level, 95°F, HOGE.

APPENDIX III
THRUSTER POWER LOADING VERSUS DISC LOADING

The standard[25] relation between rotor disc loading (DL) in pounds per square foot of disc area, power loading (TPL) in pounds per horsepower, and figure of merit (FM) is

$$TPL = 34\ FM/\sqrt{DL}$$

where the constant refers to 4000-foot, 95°F conditions. This relation is theoretically applicable only to unshrouded conventional rotors, as it is based on a power comparison with an ideal rotor. This relation, and that for FM_{max} in Task 2, includes the tacit assumption that the flow through the thruster eventually contracts to one-half the thruster disc area far downstream, as on an unshrouded rotor. For shrouded thrusters, for which the static pressure of the exit flow is nearly atmospheric, little or no contraction occurs. Figure 7 (in Task 2) shows that K, the ratio of downstream flow area to thruster disc area, increases from 0.5 for unshrouded thrusters to nearly 1.0 for shroud lengths of 80 percent of thruster diameter. Values of effective figure of merit equalling $\sqrt{2}$ are attainable for an ideal shrouded thruster.

An alternative relation for DL, TPL, and figure of merit, which compares the power requirements of a given thruster with that of the "ideal" of the same type, can be written

$$TPL = 34\ FM_{gen} / \sqrt{DL/2K}$$

which reduces to the classical relation for K = 0.5. The general figure of merit, FM_{gen}, calculated from this relation cannot exceed unity, as the effect of the shroud or duct is kept separate from the basic thruster figure of merit. The effective figure of merit is related to the general value by the simple relation

$$FM = FM_{gen} \sqrt{2K}$$

Figure 61 presents a plot of the resulting disc loading versus power loading trend for a range of values of FM_{gen}. Such curves are most useful in evaluating claims for various thruster concepts which may have highly inflated thrust-to-power ratios, leading to impossibly high values of figure of merit.

Appendix IV contains a brief survey of values of effective figure of merit typical of rotors, propellers, prop-fans, and ducted fans.

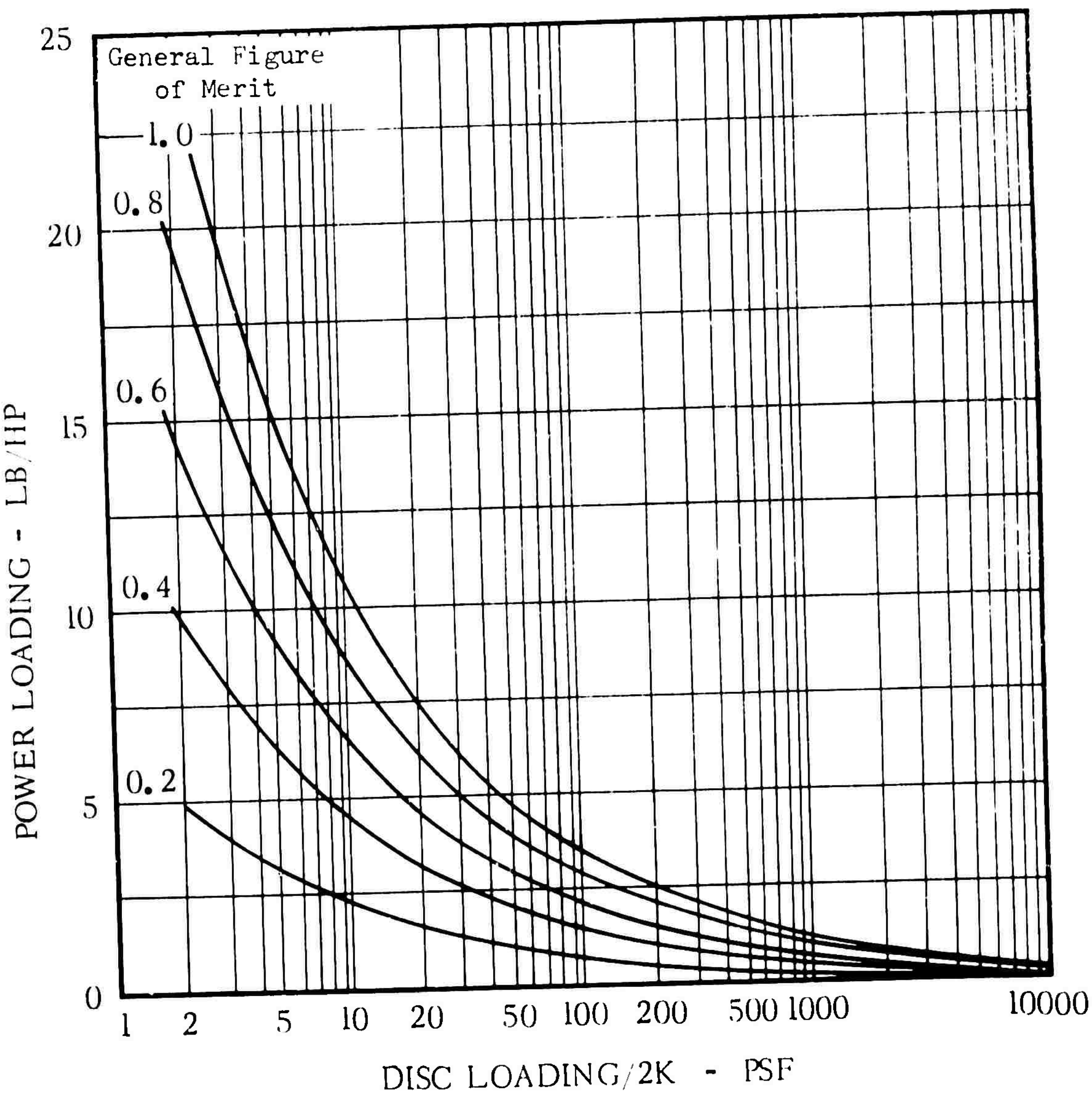


Figure 61. Thruster Power Loading Versus Effective Disc Loading.

APPENDIX IV
ROTORS, PROPELLERS, PROP-FANS, AND FANS

In this study, the Hamilton-Standard term "prop-fan" is used to describe a thrusting device conceptually midway between a propeller and a ducted fan. Table XXI illustrates the general interrelation among these three concepts and a conventional rotor. The values given are for comparison of representative values only and should not be used in analysis.

TABLE XXI. SUMMARY OF TYPICAL THRUSTER PARAMETERS

TYPICAL CHARACTERISTICS	ROTOR	PROPELLER	DUCTED PROP-FAN	DUCTED FAN
Disc Loading, psf	10-18	30-100	200-400	700-1000
Number of Blades	2-6	3-4	8-15	30-45
Relative Diameter	12-16	5-7	2-3	1-1.4
Tip Speed, fps	650-750	600-900	600-900	1200-1800
Power Loading, lb/hp	5-8	3-5	2.25-2.75	1-1.4
Effective Figure of Merit	0.65-0.7	0.7-0.8	0.8-0.9	0.75-0.9

Current conventional tail rotors employ untwisted, symmetrical-section unshrouded blades. The alternative thrusters commonly employ camber and twist. Although camber and blade twist can increase efficiency of the thruster in the design direction, they can significantly reduce efficiency in "reverse thrust" modes.

Use of a shroud increases thruster static efficiency by reducing tip loss effects and by reducing thruster induced power losses. This latter effect is discussed briefly in Appendix III.

APPENDIX V
GENERAL HELICOPTER DESIGN MODEL (GHDM) DESCRIPTION

MAIN SUBROUTINE (HELDES)

The main program consists primarily of four nested loops L0 through L4 whose feedback paths are so designated on Figure 62. L0 will calculate the design gross weight necessary for a given payload at given main rotor C_T/σ, disc loading (DL), and percentage of installed power to be absorbed by the antitorque device (PCTPR). For the first two passes through the weights equations, two gross weights must be given as a basis for the iteration. If it is desired that payload be evaluated for a given gross weight, these two inputs are entered as the same value. Options are available to govern the depth of information required to be printed out. Figure 63 shows a typical weight statement printout. Figure 64 shows the printout of a main rotor C_T/σ -aircraft efficiency trend.

L1 is the loop on main rotor C_T/σ for constant DL and PCTPR. Inputs of the initial, final, and incremental C_T/σ values define the range to be considered up to a maximum of 20 points. At each point an aircraft efficiency is calculated, based on a simple life-cycle cost model, payload, and cruise speed. Aircraft cruise speed is calculated from available maximum continuous power or stall limit, whichever is more stringent. The main rotor C_T/σ to yield the maximum aircraft efficiency is evaluated by subroutine MAXMIN. This standard routine fits a second-degree curve to every three consecutive points in the range. One of these curves will yield a maximum value of the dependent variable.

L2 is the loop on PCTPR for constant DL. At each PCTPR, a C_T/σ has been calculated to produce maximum aircraft efficiency. Subroutine MAXMIN is used again to evaluate the PCTPR to produce maximum aircraft efficiency. Subroutine SELLIN, a general-purpose interpolation program, calculates the C_T/σ at this optimum PCTPR.

L3 is the loop on DL. Subroutine MAXMIN is used to evaluate the DL value for maximum productivity. C_T/σ and PCTPR are evaluated for this optimum DL by subroutine SELLIN.

Thus we have now evaluated a set of design parameters DLSOL, PCSOL, CTSOL, which are the solution DL, PCTPR, C_T/σ values for maximum aircraft productivity. One more pass is made through the weights routine at these design values so as to present data for the solution aircraft.

SUBROUTINE WEIGHT

This subroutine:

1. Evaluates main-rotor parameters based on input design constraints.
2. Arranges required data for antitorque device design subroutine ANTORK which is called from WEIGHT.

3. Evaluates installed power based on design and alternate hover, and/or maximum speed requirements. A decision on the critical flight mode to define installed power is made by reducing all powers to sea level standard conditions.

4. Arranges required data for mission analysis subroutine, MISHN, which is called from WEIGHT.

5. Calculates all weight components and arranges them for printout on return to HELDES.

The weight components are calculated using statistical weight equations. The rotor group equations account for blade aspect ratio, tip speed, and aircraft dive speed effects. Most airframe equat'ons are normalized to a base-line configuration. Drive system weight is broken down into individual shafts and gearboxes, each weight being calculated to take proper account of shaft rpm and transmitted horsepower.

This subroutine is usually written around a particular aircraft type or configuration. The remainder of GHDM can be regarded as a framework and a set of subroutines to be called from WEIGHT. Thus, we can readily adapt GHDM to custom fit a given project by writing its own version of WEIGHT.

SUBROUTINE ANTORK

This subroutine handles the design procedures for three types of antitoruqe devices.

Conventional Tail Rotor

Tail-rotor thrust requirements based on main-rotor torques at design and alternate hover conditions, side-wind moments, and yaw control specifications are defined. At a starting value of tail-rotor disc loading, tail rotor radius is calculated iteratively to produce the thrust requirement at the alternate hover condition.

Based on input values of the maximum and alternate hover tail rotor C_T/σ 's, tail rotor blade area is calculated. Consistency of these C_T/σ 's and the thrust requirements calculated above is verified. The number of tail rotor blades is defined by a desired blade aspect ratio range.

With blade geometry defined, the power required at the tail rotor to produce the alternate hover thrust requirement is evaluated by the figure-of-merit method. This is compared with the available power defined by the value of PCTPR. The tail rotor disc loading is adjusted iteratively to define a new tail rotor radius until a power match is obtained.

With the rotor now designed, the power required at the tail rotor to produce the design hover thrust is calculated. This number will be used to calculate the overall aircraft hover efficiency.

Fan-in-Fin

Because of the high power-to-thrust ratio associated with high-disc-loading devices compared with conventional tail rotors, under the condition of maximum thrust requirement, as much power as possible can be drained from the main rotor, while the engines are delivering all available power to the device alone. (No power is being transmitted to the main rotor.) To calculate the amount of power from this source, we assume that the main rotor can decelerate by 2 percent of the rpm over a time period of 1 second. This interval was selected to represent a typical maximum control input requirement.

With this amount of power in hand, we add an amount based on the value of PCTPR to yield a total available power to the device to obtain the maximum thrust requirement. The fan radius is calculated iteratively to produce this power-to-thrust match. Fan performance maps are available in subroutine PROFAN. Effects of duct losses, lip geometry, recovery vanes, and duct length are expressed.

With the fan radius defined, we now calculate the power required at the fan to produce the design hover thrust. This power will be used to define the overall aircraft hover efficiency.

Fan-in-Tailcone

This procedure is identical with that for the fan-in-fin. Differing performance characteristics will result from the higher duct losses and improved lip efficiency.

SUBROUTINE MISHN

This subroutine is a generalized mission analysis program that can be called from HELDES if the helicopter design routines are not required. Mission elements are defined by aircraft velocity, climb rate, altitude and temperature environment, and distance or time of flight. As many as 50 elements may define a mission, or a number of missions may be stacked so long as the total number of elements does not exceed 50. Access to the desired mission in the array of element data is made through input. Aircraft gross weight is continuously adjusted to account for fuel burn-off. Changes in aircraft weight and external configuration due to the carriage of external loads, retrieval of rescuees, etc., may be represented by input values of weight and drag increments.

Hover performance is evaluated by subroutine HOVPER, which calls a general nondimensional figure-of-merit subroutine, HOV1. Effects of ground proximity and climb rate are represented.

Forward flight performance is evaluated by subroutine FWDSPD, which calls the nondimensional rotor performance subroutine, NDRPEE. This method takes proper account of blade twist, cutout and planform, ground effect, and climb or descent rates. Stall speed is calculated based on an input $bC_{Q,D}/\sigma$ criterion. Compound helicopter performance can be calculated through input wing CL, CD data, propeller efficiency, and specified lift and drag sharings.

The desired aircraft speed can be expressed as that for a given power level, engine rating, best range, best endurance, or marginal stall.

Mission fuel for a given engine horsepower is calculated in subroutine ENJIN. Figure 65 shows a typical mission printout.

SUBROUTINE ENJIN

This subroutine is provided with nondimensional engine SFC vs. SHP input data, and power rating curve data as a function of altitude and temperature. Rubber engine performance is evaluated by an input or calculated value of engine scale factor.

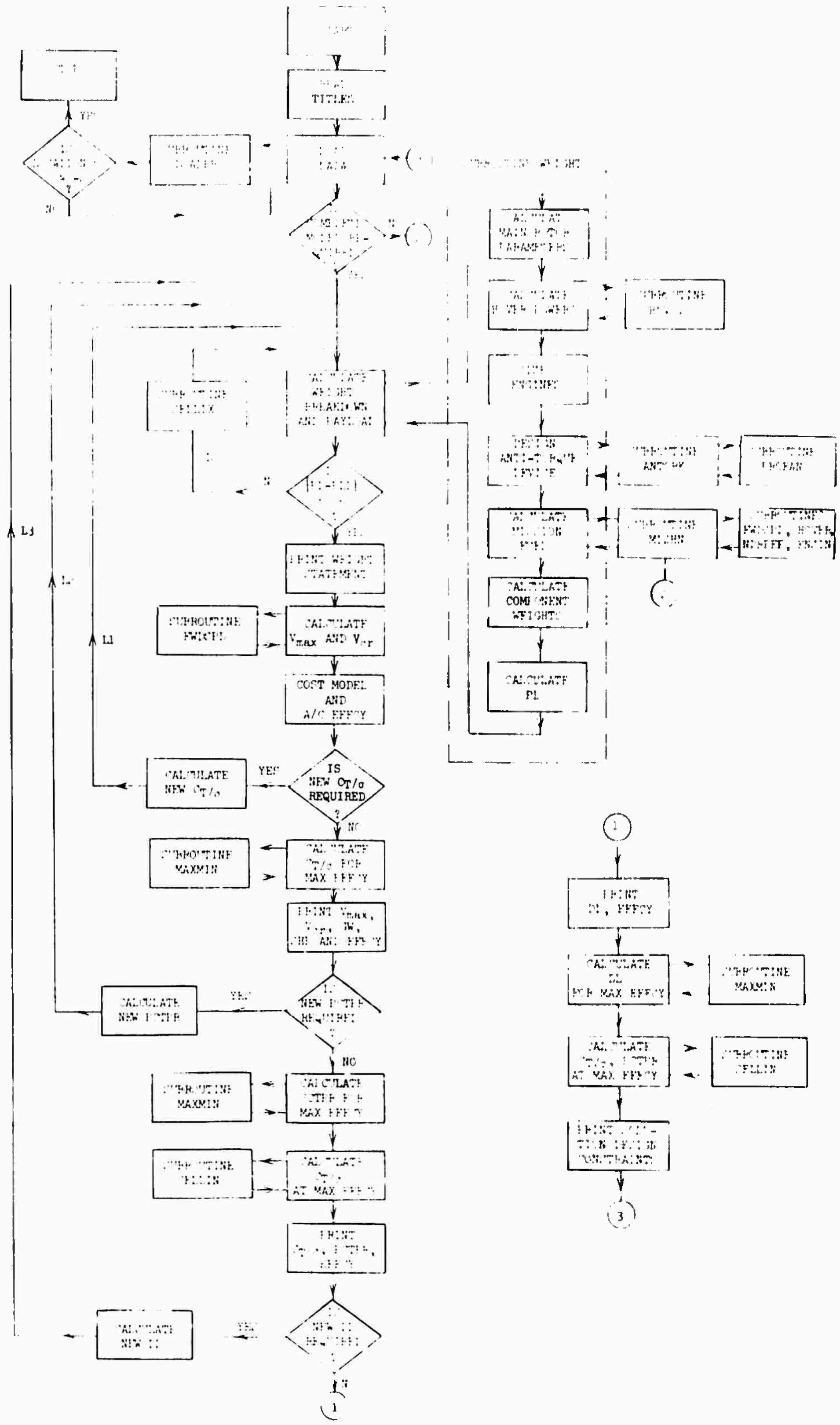


Figure 62. Schematic Flow Diagram, General Helicopter Design Model.

SUMMARY WEIGHT STATEMENT

CONDITION NO. 3 ANTI-TORQUE SCHEME STUDY

GROUP	WEIGHT
ROTOR GROUP	1633.
WING GROUP	0.
TAIL GROUP	0.
TAIL ROTOR/FAN	114.
TAIL SURFACES	100.
BODY GROUP	1813.
ALIGHTING GEAR	491.
FLIGHT CONTROLS	565.
ENGINE SECTION	121.
PROPULSION GROUP	0.
ENGINE AS INSTALLED	584.
ENGINE RELATED ITEMS	0.
AIR INDUCTION	83.
EXHAUST SYSTEM	98.
MISCELLANEOUS	0.
LUBE SYSTEM	27.
ENGINE CONTROLS	18.
STARTING SYSTEM	58.
FUEL SYSTEM	203.
PROPELLER INSTALLATION	0.
DRIVE SYSTEM	1413.
AUXILIARY POWER UNIT	121.
INSTRUMENTS	211.
HYDRAULICS	67.
ELECTRICAL	335.
AVIONICS	701.
ARMAMENT	351.
FURNISHINGS	370.
AIR CONDITIONING AND ANTI-ICE	98.
AUXILIARY GEAR	6.
CONTINGENCY	0.
WEIGHT EMPTY	9582.
CREW	600.
ENGINE OIL	43.
UNUSABLE FUEL	7.
MISSION EQUIPMENT	0.
FUEL	2232.
PAYLOAD	2640.
GROSS WEIGHT	15103.

Figure 63. Weight Statement Printout.

DISK LOADING= 6.00 PSF POWER TO TAIL DEVICE(ROTOR) = 8.0 %

CT/SIG	DGW	VDASH	VCR	SHPD	SHPC	COST-FLY	COST-OP	COST-LC	EFFIC
.0500	19804.8	191.4	172.7	2983.5	2397.8	869177.	3264299.	4133477.	.11029
.0550	18145.1	190.1	170.8	2671.3	2143.3	766219.	3057501.	3823719.	.11792
.0600	17264.8	190.5	173.9	2492.4	2004.4	714651.	2948477.	3663128.	.12532
.0650	16433.7	189.0	173.7	2343.4	1885.4	666802.	2843580.	3510382.	.13062
.0700	15819.4	186.9	173.9	2224.9	1806.4	633016.	2767118.	3400134.	.13502
.0750	15484.9	181.3	175.3	1956.7	1765.3	617774.	2731921.	3349695.	.13814
.0800	15103.1	173.3	172.9	1738.2	1723.7	598967.	2687860.	3286828.	.13884
.0850	14783.1	161.7	161.7	1499.5	1497.2	584576.	2653651.	3238228.	.13184
.0900	14600.7	149.7	149.7	1304.8	1302.4	577148.	2635820.	3212968.	.12303

CT/SIGMA= .0780 FOR MAXIMUM PRODUCTIVITY= .13948

DISK LOADING= 6.00 PSF

CT/SIG	PCTPR	PROD
.0780	8.0	.13948

PCTPR= 8.0 %FOR MAXIMUM PRODUCTIVITY= .13948

Figure 64. Main Rotor C_T/σ Trade-off Printout.

TOGW= 15103.1 LBS., ROTOR RADIUS= 28.31 FT., PARASITE DRAG= 13.4 SQ.FT.

TYPE OF ENGINES- NUMBER 8 (2.)

MISSION NUMBER- 1

MODE	GR.WT (LBS)	TEMP (DEG.F)	ALT (FT)	OPTN (ZP/FPM)	SPEED (KTS)	VSTALL (KTS)	DIST (N.MI)	TIME (MIN)	FL.AR. (SQ.FT)	SHP	FUEL (LBS)	SFC	WARNG
----	-----	----	---	----	-----	------	----	----	-----	---	----	---	-----
WARMUP	15103.	95.	4000.	--	--	--	--	3.0	--	1728.7	40.0	.4405	
TAKEOF	15063.	95.	4000.	--	--	--	--	1.0	--	2154.6	16.1	.4274	HP>NRP
CRUISE	15047.	95.	4000.	.00	150.0	173.6	175.0	70.0	13.38	1308.0	752.8	.4698	
DASH	14294.	95.	4000.	4.00	179.4	179.4	44.8	15.0	13.38	1814.3	207.9	.4365	HP>NRP
HOVER	14086.	95.	4000.	1000.000	--	--	--	20.0	--	1721.4	265.6	.4408	
CRUISE	13821.	95.	4000.	.00	150.0	182.2	175.0	70.0	13.38	1251.0	728.8	.4756	
LAND	13092.	95.	4000.	--	--	--	--	1.0	--	1728.7	13.3	.4405	
RESERVE-CRUISE	13079.	95.	4000.	.00	150.0	185.5	50.0	20.0	13.38	1218.8	204.4	.4792	

TOTAL MISSION FUEL IS 2228.8 LBS

TOTAL MISSION TIME IS 180.0 MINS

Figure 65. Mission Analysis Printout.

DISTRIBUTION

Director of Defense Research & Engineering	3
Assistant Secretary of the Army (R&D)	1
Assistant Chief of Staff for Force Development, DA	1
Deputy Chief of Staff for Logistics, DA	1
Deputy Chief of Staff for Personnel, DA	1
Third United States Army	2
Sixth United States Army	2
United States Army, Pacific	1
Chief of Research & Development, DA	3
Army Materiel Command	7
Army Aviation Systems Command	3
Hq, Army Air Mobility R&D Laboratory	2
Ames Directorate, Army Air Mobility R&D Laboratory	2
Eustis Directorate, Army Air Mobility R&D Laboratory	15
Langley Directorate, Army Air Mobility R&D Laboratory	2
Lewis Directorate, Army Air Mobility R&D Laboratory	2
Army Aviation Systems Test Activity	2
Army Scientific & Technical Information Team (Europe)	1
Army Advanced Materiel Concepts Agency	1
Army Aeromedical Research Laboratory	2
Army Land Warfare Laboratory	1
Army Human Engineering Laboratories	1
Army Natick Laboratories	2
Army Ballistic Research Laboratory	1
Army Fuels & Lubricants Laboratory	1
Army Mobility Equipment R&D Center	1
Army Materials & Mechanics Research Center	6
Army Plastics Technical Evaluation Center	1
Army Engineer Waterways Experiment Station	1
Army Test & Evaluation Command	1
Army Materiel Systems Analysis Agency	1
Army Electronics Command	4
Army Electronic Warfare Laboratory	2
Army Missile Command	2
USACDC Experimentation Command	2
USACDC Aviation Agency	4
USACDC Transportation Agency	1
Army Medical R&D Command	1
Army Tank-Automotive Command	1
Army Weapons Command	1
Picatinny Arsenal	1
Edgewood Arsenal	1
Frankford Arsenal	1