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Contract No. Nonr 611(00) Amendment 1
Report No. EX-0-2

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STUDIES RELATIVE TO THE DEVELOPMENT OF A ONE-MAN HELICOPTER
Part II
Performance, Flying Qualities, Powerplants, and Fuels

20 January 1954

for
Office of Naval Research
Department of the Navy

HUGHES TOOL COMPANY
AIRCRAFT DIVISION
Culver City, California

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SUMMARY

This report is the second summary report issued under Contract Nonr 611(00), Amendment No. 4, entitled 'Studies Relative to the Development of a One-Man Helicopter'. This contract was sponsored jointly by the Office of Naval Research and the Office of the Chief of Transportation, U. S. Army. The primary purpose of the program authorized under the Contract is to carry out studies and make recommendations regarding the design of various components of a one-man helicopter.

The first report, Hughes Aircraft Company Report No. EX-O-1, is concerned with missions and feasible configurations for the one-man helicopter. It is pointed out in Report No. EX-O-1 that the configurations having the lightest airframe weight are those powered by tip-mounted engines. It appears likely that portability with these machines will be marginal, even with fuel tanks empty. It does not appear that either the tip-powered machine carrying fuel for 10 nautical miles, or the gear-driven machine without fuel, will be portable items. In the tip-powered configurations the lightest airframe weights are indicated for machines powered by the rocket or ram rocket: these are most likely to be portable (with tanks empty).

It must be emphasized that the solution to the one-man helicopter problem depends primarily on development of a suitable powerplant, and that to date there is no known acceptable powerplant in the ratings required (30-35 hp for tip drives, 40-60 hp for geared drives). Thus a development program for the one-man helicopter must include powerplant development.

In partial fulfillment of the purposes stated above, this report presents the results of studies concerning performance, flying qualities, and powerplants and fuels. For convenience in evaluating proposals, and for the assistance of designers not familiar with the state of the art, data from several sources, much of which is not new or novel, is collected for presentation herein. For the most part the studies are concerned with tip-powered configurations.

From the standpoint of best range it appears that the optimum **disk** loading is about 2 psf. With the rocket powerplant, cruising fuel rate improves as tip speed is increased (with corresponding reduction in blade solidity ratio), but the practical limit appears to be reached at a tip speed of about 750 fps and a solidity ratio of .018. It is, however, recommended that tip speed be limited to about 600-650 fps and minimum solidity to about .020-.025. The gains resulting from further optimization of tip speed and solidity do not appear to be justified in view of the mechanical and structural problems which develop in the rotor and propulsion systems.

A two-bladed rotor is recommended, where tip-mounted powerplants are used. Experience with current small helicopters using tip drives indicates that isolation from either vertical or in-plane vibration is not required.

The combination of tip weights and horizontal tail appears to provide acceptable flying qualities, in both hovering and forward flight. An additional argument in favor of the tip-drives is the provision of tip weight in the form of powerplants.

Hovering flying qualities obtained by the use of the control rotor or gyroscopic stabilizing bar are likely to be somewhat better than those obtained by tip weights, especially of the order represented by rockets. However, these devices may not suffice alone to produce adequate maneuver stability at high speed (order of 70-80 mph) or to provide the normally desirable characteristic of stick position stability in the range of cruising to maximum speed.

Some provision for directional stability and control is required. A vertical tail is adequate in forward flight, but probably not in hovering, especially after flare-out to land. To insure adequate directional control in low-speed flight a small tail rotor is required. A tail rotor that is adequate for control, however, may not provide adequate directional stability in forward flight.

Flapping-hinge offsets improve the hovering flying qualities, but diminishing returns are obtained for offsets greater than about 3 inches when tip drives or suitable tip weights are used. Increase in maneuver stability due to flapping hinge offset diminishes with increasing forward speed, and in addition to a steady flapwise hub moment, hinge offset produces a vibratory flapwise hub moment at n times rotor frequency, where n equals number of blades. Use of hinge offsets with tip-mounted drives appreciably reduces blade flapping required for trim, and may be necessary if large c.g. travel or aerodynamic pitching moments develop. In general, it appears that flapping hinge offsets should be avoided, if possible. Lag hinges are quite undesirable in the case of tip-mounted powerplants. Since it is difficult to maintain thrust balance between blades, dynamic unbalance may result in a 'ground resonance' type of vibration. 'Chugging' of the engines due to combustion instability may accentuate this problem.

The development of a satisfactory rotor speed governor presents a difficult problem. This unit, in addition to being light, should also be mechanically simple, sufficiently rugged to be reliable under battle conditions, and be stable under all power-on operating conditions. In the case of the one-man helicopter a more feasible solution is the coupling of collective-pitch and throttle controls: a possible schedule is presented in this report. It must be noted that neither the speed governor or the pitch-power schedule will function under power-off conditions, and the latter may not function under off-design conditions.

From the standpoint of performance, cost and logistics (particularly safety and availability) it appears that ethylene oxide represents the most attractive monopropellant fuel. The use of hydrogen peroxide as a rocket fuel, especially in connection with the one-man helicopter, is not recommended. The specific impulse (lb thrust/lb fuel/sec) of hydrogen peroxide is about 20% less than that of ethylene oxide. The characteristics of hydrogen peroxide are such that a leak in the fuel system is likely to result in a fire, and handling of the fuel in military operations, by other than highly skilled personnel, presents a constant hazard.

Limited tests on the ram-rocket indicate that satisfactory mixing and burning may be obtained with length-diameter ratios of the order of 3:1, such as would be structurally suitable in view of the high centrifugal loading. A lengthy development program would be required to develop the ram-rocket for application to tip drive.

INDEX TO FIGURES

NOTATION

Performance

a	section lift-curve slope, $dC_l/d\alpha$
A_π	total equivalent parasite flat plate area, sq ft (Based on $C_{d_\pi} = 1.0$)
b	number of blades in rotor
BSFC	brake specific fuel consumption, lb/hp/hr
c	blade chord, ft
$C_{do\ min}$	blade section minimum drag coefficient
C_l	blade section lift coefficient. Subscript 'max' refers to maximum lift coefficient
C_{lr}	mean rotor lift coefficient $= 6C_T/\sigma$
C_T	thrust coefficient $= \frac{T}{\rho\pi R^2 V_T^{\,2}}$
C_Q	torque coefficient $= \frac{Q}{\rho\pi R^3 V_T^{\,2}}$
HP or hp	horsepower
K_π	A_π/W
K_f	fuel rate coefficient for jet drives: $K_f = \frac{550\ HP}{W/100} \cdot \frac{1}{V_T} \cdot \frac{1}{V_F}$
K_s	fuel rate coefficient for geared drives: $K_s = \frac{550\ HP}{W/100} \cdot \frac{1}{V_F}$

P/L	helicopter drag-lift ratio = 550 hp/V_FW . Subscripts 'o', 'i', and 'π' refer to profile, induced and parasite drag-lift ratios respectively.
q	dynamic pressure = $\frac{1}{2} \rho V^2$
rhp = P_r	net rotor horsepower required
R	radius to blade tip, ft
(R/C)	rate of climb, fpm or fps. Subscript 'v' refers to vertical rate of climb.
(R/D)	rate of descent, fpm or fps. Subscript 'v' refers to vertical descent
TSFC	thrust specific fuel consumption - lb/lb thrust/hr
T	rotor thrust force, vector normal to tip path plane, positive when directed upward
V_v	rate of descent in forward flight. Also denoted by (R/D).
V = V_F	forward flight velocity, fps, mph or knots
V_T	rotational tip speed, fps
W	gross weight, lbs
w	disk loading, psf
α	angle of attack of airfoil section. Angle between chord line and relative wind, degrees or radians. Positive when chord line in inclined upward with respect to relative wind.

$\alpha_{(x)(\psi)}$ — angle of attack of blade element at $x = r/R$ and azimuth station ψ. Subscript '(1.0)(90)' refers to the blade tip at $\psi = 90^{\circ}$.

α_A, α_B — $\alpha_{(1.0)(90)}$ and $\alpha_{(1.0)(270)}$ respectively

θ — blade pitch, degrees or radians. Angle between rotor disc pla[illegible] and zero lift line of blade section. Positive when zero lift line lies above rotor disc plane.

θ_o — collective pitch at blade root, degrees or radians. Steady term in Fourier series expressing θ.

θ_1 — lateral component of swash plate (cyclic) feathering. (Angle between plane of swash plate and rotor disk plane, viewed along lateral axis from azimuth 270°, positive when advancing edge or rotor disc plane lies below swash plate plane.) First-harmonic term in Fourier series expressing θ.

θ_{ε} — blade geometric twist, degrees or radians. (Angle between zero lift lines of blade root and tip sections. Positive when zero lift line at tip lies above zero lift line at root.)

μ — tip speed ratio $= V_F/V_T$

ρ — mass density of air, slugs/cubic ft

σ — rotor solidity ratio $= \frac{bc}{\pi R}$

σ_o — rotor solidity ratio based on root chord $= \frac{bc_o}{R}$

ψ — azimuth angle, degrees or radians. Positive in direction of rotation, measured from downstream end of fore-aft axis.

ω, Ω — rotor angular velocity, radians/second or rpm

Stability and Control

γ	Lock's factor $= \frac{\rho a c R^4}{I_1}$
ζ	rotor blade damping coefficient $= \gamma/16$
ζ_{1c}	control rotor damping coefficient $= \frac{\rho a c \bar{R}^3}{4 I_1}$
ζ_{1g}	gyroscopic bar damping coefficient $= B/2I_1\omega$
ω, Ω	rotor angular velocity
ω_p	helicopter natural pendular frequency for rotation about c.g. $= \frac{hg}{b^2}$
B	gyroscopic bar damping coefficient
b	helicopter radius of gyration about c.g., including rotor mass concentrated at rotor center
e	blade flapping hinge offset, inches or feet
I_1	mass moment of inertia of rotor blade about its flapping hinge, slug-ft^2
I_Y	mass moment of inertia of helicopter about lateral (pitching) axis through c.g., slug-ft^2
I_Z	mass moment of inertia of helicopter about rotorshaft axis, slug-ft^2
$\bar{R}$	mean radius of control rotor paddle

For explanation of other symbols used in Section II refer to nomenclature of Reference 18.

INTRODUCTION

This report is the second summary report issued under Contract Nonr 611(00), Amendment No. 4, entitled 'Studies Relative to the Development of a One-Man Helicopter'. This contract was sponsored jointly by the Office of Naval Research and the Office of the Chief of Transportation, U. S. Army. The primary purpose of the program authorized under the Contract is to carry out studies and make recommendations regarding the design of various components of a one-man helicopter.

The one-man helicopter is defined as follows in the Statement of Work of Reference 1:

> ". . . the smallest rotary wing type aircraft which will:
>
> (1) transport one man
>
> (2) have satisfactory flight characteristics (performance, stability, and control)
>
> (3) accomplish a basic mission to be defined
>
> (4) have a minimum of instrumentation and means for automatic maintenance of proper rotor speed and collective pitch for all flight conditions
>
> (5) be simple, cheap, capable of rapid assembly and insensitive to poor servicing and exposure to weather."

In addition to the above it is desired that the machine shall be easily transportable, and if possible, portable by one man.

Items (1) and (3) are dealt with at some length in the first summary report, Reference 3. Items (2), (4), and (5) are discussed herein.

The purposes of this report are:

(a) Establish suitable criteria for selection of rotor and powerplant configurations.

(b) Summarize the results of studies based on these criteria.

(c) Establish suitable minimum requirements in terms of flying qualities.

(d) Determine the feasibility of achieving these requirements in terms of practical weight and cost.

(e) Summarize existing information regarding powerplants and fuel suitable for the one-man helicopter.

For convenience in the evaluation of one-man helicopter proposals, and for the assistance of designers not familiar with the state of the art, data from several sources, much of which is not new or novel, is presented herein. Wherever possible this data is summarized in a form convenient for use in optimization studies. Examples are the data on vertical flight (Figures 4, 5 and 6), and on airfoil characteristics (Figures 14 and 15).

In Reference 3 it is pointed out that the lightest airframe weights are obtained with configurations using tip-mounted powerplants, and, therefore, that these configurations are the most feasible from the standpoint of of transportation by one man. This report is, therefore, most concerned with studies relative to tip-driven configurations.

SECTION I - PERFORMANCE CONSIDERATIONS REGARDING SELECTION OF ROTOR SYSTEMS

1. Selection of Configuration - General

It is emphasized that selection of a rotor configuration for the one-man helicopter is closely allied to selection of a powerplant. It is also noted that, in general, development of a one-man helicopter involves development of a powerplant, since in most possible configurations a suitable powerplant does not at this time exist.

As an introduction to the discussion which follows, a brief review of missions and configurations, reported in Reference 3, is presented below.

Various investigators have proposed the following one-man helicopter configuratio :

a. Tip-Mounted Powerplants

Monopropellant liquid rocket
Monopropellant solid rocket
Ramjet
Pulse jet
Ram rocket

b. Geared Drives

Reciprocating
Gas turbine
Monopropellant turbine

c. Jump Take-Off and Gyrodyne

Solid rockets for climb, autorotation in forward flight.
Same as above, but with propeller driven by reciprocating engine to maintain cruise flight (gyrodyne configuration).

d. Ducted Propeller (possibly with pilot located above rotor or rotors)

e. Rotor Arrangements

Single rotor
Coaxial

f. Tail Rotor

Tail rotor for anti-torque and control
Tail rotor for control only (tip-mounted drives)

Reviewing Reference 3 briefly, it appears that airframe weights of the order of 100 lbs or less can only be achieved by the use of tip-mounted powerplants. Items (b) are eliminated, unless empty weights of the order of 200 lbs are acceptable. In the case of Items (c) the jump take-off autogyro cannot maintain level flight at low forward speed and in hovering, while the solid rocket does not permit of power control once started: the gyrodyne configuration is not portable, due to combined engine, propeller and airframe weight if adequate power is provided.

Item (d) is not feasible for the one-man helicopter due to the extremely high disk loadings required. The arrangement with pilot above rotor or rotors also appears to have poor flying qualities compared to conventional arrangements.

Referring to Items (e), only single rotor arrangements are considered. The main function of the coaxial system is to overcome the torque problem of the geared drives; since geared drives are not considered feasible from the standpoint of portability, the coaxial need not be considered. Even if portability is disregarded, the coaxial has the additional disadvantages of mechanical complexity and reversal of yaw control in autorotation. From the standpoint of performance and fabrication the single rotor configuration is superior to all others.

Items (f) are presented here to call attention to the fact that a control tail rotor may prove necessary even with the tip drives. Even if the directional control requirements of Reference 15 are waived (and they cannot, in general, be fully met by a fin and rudder), conditions immediately after flare-out and when hovering in gusting winds may require a small tail rotor for safety.

2. Comparison of Configurations having Tip-Mounted Powerplants

a. Discussion

Again it is noted that for most, if not all, configurations suitable powerplants for the one-man helicopter have yet to be developed.

A major point in favor of tip-mounted powerplants is the fact that the large contribution of the powerplant to rotor moment of inertia increases the damping in pitch of the helicopter. This results in two desirable effects: a reduced rate of control response in hovering, and an increase in energy available during the flare-out to land. Thus the hovering flying qualities are improved by the addition of the tip powerplants: however, as pointed out in Reference 17, damping in pitch due to the rotor is reduced as forward flight speed is increased. In the case of a typical one-man helicopter (without flapping hinge offset) rotor damping in pitch actually becomes destabilizing at about 100 mph in level flight. Thus the contribution to stability provided by the tip weights is reduced in forward flight, though the reduction is less severe if flapping hinge offsets are provided. Since it appears that tip-weights are highly desirable on small helicopters to reduce their otherwise excessive control response and improve the flare characteristics, the tip-mounted powerplants serve a double purpose.

It is often argued that the centrifugal relief due to tip weights reduces blade bending moments, particularly flapwise, both steady and cyclic, so that the increased centrifugal loading is partly compensated. Further discussion of this point is presented in Paragraph I (5); however, it should be noted that an increased steady stress level reduces the allowable cyclic stress level for a given life, and that the tip weights modify the blade natural frequencies and, therefore, either increase or reduce the blade response to various harmonics of airload exciting forces. (In the case of current tip-powered helicopters, blade chordwise stationary first mode frequency is low - about 50-60% of rotor frequency, apparently with beneficial effects both on blade stress levels and vibration transmitted to the hub.)

b. Some Comparisons of the Most Promising Tip-Mounted Powerplants

(1) Fuel Rates (lb/lb thrust/hr in cruise)

Pulse Jet	7-9	(Gasoline or Kerosene)
Ramjet	10-12	(Gasoline or Kerosene)
Rocket	20-30	(Monopropellant Fuels)

(2) Starting

Pulse Jet:	static start, using compressed air and spark.
Ramjet:	rotor must be brought up to about 100 fps tip speed by some mechanical means. Ram air plus spark.
Rocket:	static start, using decomposition means (pressurization plus catalyst or heat).

(3) Autorotation Descent Rates (as affected by cold drag of powerplant)

Pulse Jet: increase about 50% - about 2200 fpm

Ramjet: approximately doubled - about 3000 fpm

Rocket: approximately conventional - about 1500 fpm

Large amount of kinetic energy in rotor available in flare partly offsets disadvantage of increased descent rates of Pulse Jet and Ramjet (See Figure 36).

(4) **Weight (lb/lb thrust)**

Pulse Jet: 0.5 to 0.6

Ramjet: 0.3 to 0.4

Rocket: 0.1 to 0.2

(5) Cost and Complexity - data not available - probably in increasing order as follows:

Rocket

Ramjet

Pulse Jet

(6) Comments on Ram Rocket

This powerplant is still in very early stages of development, and no operating hardware suitable for use with a helicopter has been developed. Indications are that fuel rates may be equal to or better than those of the ramjet, with the advantage that a static start may be obtained using the rocket thrust. Weight probably aquivalent to that of a ramjet.

(7) Airframe Weights

Least with rocket and possibly ram rocket (information on the ram rocket does not yet permit of definite conclusions). Next in increasing order, ramjet, pulse jet. These results are due not only to relative engine weights, but also to increased rotor solidities required by low design tip speed (pulse jet) and low autorotational speeds resulting from engine cold drag (ramjet).

(8) Tip Speeds

Pulse Jet:	tip speed limited to about 400 fps by operational characteristics of engine
Ramjet:	tip speed limited by functioning and structural limitations of engine
Rocket:	tip speed limited by overall rotor efficiency

3. Choice of Number of Blades

There appears to be no reason for using more than two blades when tip-mounted powerplants are used. Three or more blades have been used to reduce the level of vibration transmitted to the hub from the rotor. However, small pulse jet and ramjet helicopters having teetering two-bladed rotors have operated successfully for considerable periods of time. Obviously, the number of tip powerplants and complexity of fuel system should be kept to a minimum.

The in-plane vibration which has appeared in transition from hovering to forward flight in gear-driven helicopters having teetering two-bladed rotors does not appear to be a problem in the tip-drive configurations. In current tip-driven machines, chordwise first mode stationary natural frequencies of the engine-blade combination are relatively low (about 50-60% of rotor frequency). This may be the reason for the reduced in-plane vibration.

In the case of the gear-driven one-man helicopter there may be some argument in favor of using three or more blades to avoid the need for isolation of rotor and power system from the pylon.

While the use of a single-blade counterbalanced rotor offers some simplification of the upper control system, it results in increased weight of the rotor system. Obviously, blade area cannot be reduced, so the single blade must be larger and heavier than one blade of a two-bladed system: in addition, the counterweight will be heavier than the blade. With two engines level flight may be maintained on one engine with rocket or pulse jet: due to its cold drag, the ramjet probably cannot maintain level flight on one engine, but descent rate can be greatly reduced compared to power-off condition. Obviously, with one blade (and consequently one engine) this advantage is lost.

4. Choice of Rotor Geometry

a. Fuel Rate Coefficient as a Criterion

The airframe weight is proportional to the gross weight, and in the tip-driven helicopters, the fuel consumption of which is high, gross weight increases rapidly with range. Meeting the requirement of portability with a range of 7-10 nautical miles, even with empty tanks, presents a severe problem in the case of the tip-driven helicopter, while portability does not appear to be feasible with geared drives. It is suggested, therefore, that rotor geometry for tip drive should be optimized primarily in terms of fuel consumption. As a basis for optimization, a coefficient directly proportional to the ratio of required tip thrust to gross weight, and inversely proportional to forward speed, is suggested. This coefficient is denoted by K_f where:

$$K_f = \left(\frac{100}{V_F}\right)\left(\frac{T_j}{W}\right) = \frac{550\ HP}{(W/100)} \cdot \frac{1}{V_T} \cdot \frac{1}{V_F} \qquad (1)$$

The coefficient K_f, while dependent only on the rotor configuration, parasite flat plate area, and gross weight, may also be regarded as a measure of fuel rate, since:

$$\text{Fuel rate in lb/n.miles} = K_f(\text{TSFC})(\text{Gross Weight}/100) \qquad (2)$$

In selecting a rotor configuration for each tip powerplant configuration a useful assumption for preliminary purposes is that TSFC does not vary with tip speed. Over the useful range of cruising tip speeds corresponding to each type of tip powerplant, this assumption is reasonable. (Typical TSFC values are: 20 lb/lb thrust for ethylene oxide rocket, 12 lb/lb thrust for a small ramjet.)

As shown in Reference 3, the gross weight is similar for all configurations of the one-man helicopter with tip drive, for 10 nautical miles range. Thus it appears reasonable, when making preliminary comparisons of rotor systems in terms of optimum fuel rates (and, therefore, of range, gross weight, and airframe weight), to regard K_f as the most important variable in the above expression for fuel rate in lb/n.mile. Thus K_f is seen to be an important criterion for optimization of rotor geometry for best range in the tip-driven one-man helicopter configurations.

The use of K_f as a criterion for selection of rotor configuration leads to the following conclusions, as pointed out in more detail in later paragraphs:

(1) The minimum K_f occurs at a speed of, or close to, 45 knots for all values of rotor geometry and fuselage drag that are practical for the one-man helicopter.

(2) A disk loading of 2 psf is close to optimum over a large range of solidities and tip speeds. A disk loading of 2 psf is also a good compromise from the standpoints of reasonable values of rotor radius and vertical power-off descent rate.

(3) The optimization of tip speed and solidity appears to afford relatively small reductions in K_f at tip speeds above about 600 fps, at the same time introducing mechanical problems due to the small chord of the blades and the probable necessity for a large amount of blade twist.

It is felt that the geared drives are not portable. However, as a matter of interest, optimization charts are presented in terms of K_s, which is directly proportional to the ratio of horsepower required to gross weight, and inversely proportional to forward speed:

$$K_s = \frac{(HP)}{(W/100)} \cdot \frac{1}{V_F} \qquad (3)$$

As in the case of K_f, the coefficient K_s may be regarded as a measure of fuel rate for gear-driven helicopters, since:

$$\text{Fuel rate in lb/n. mile} = K_s(\text{BSFC})(\text{Gross Weight}/100) \qquad (4)$$

It is of interest to note, when K_s is used as a criterion, that conclusions (1) and (2) also apply to geared drives. However, in contrast to conclusion (3), optimization is in the direction of reduced tip speed and increased solidity with geared drives.

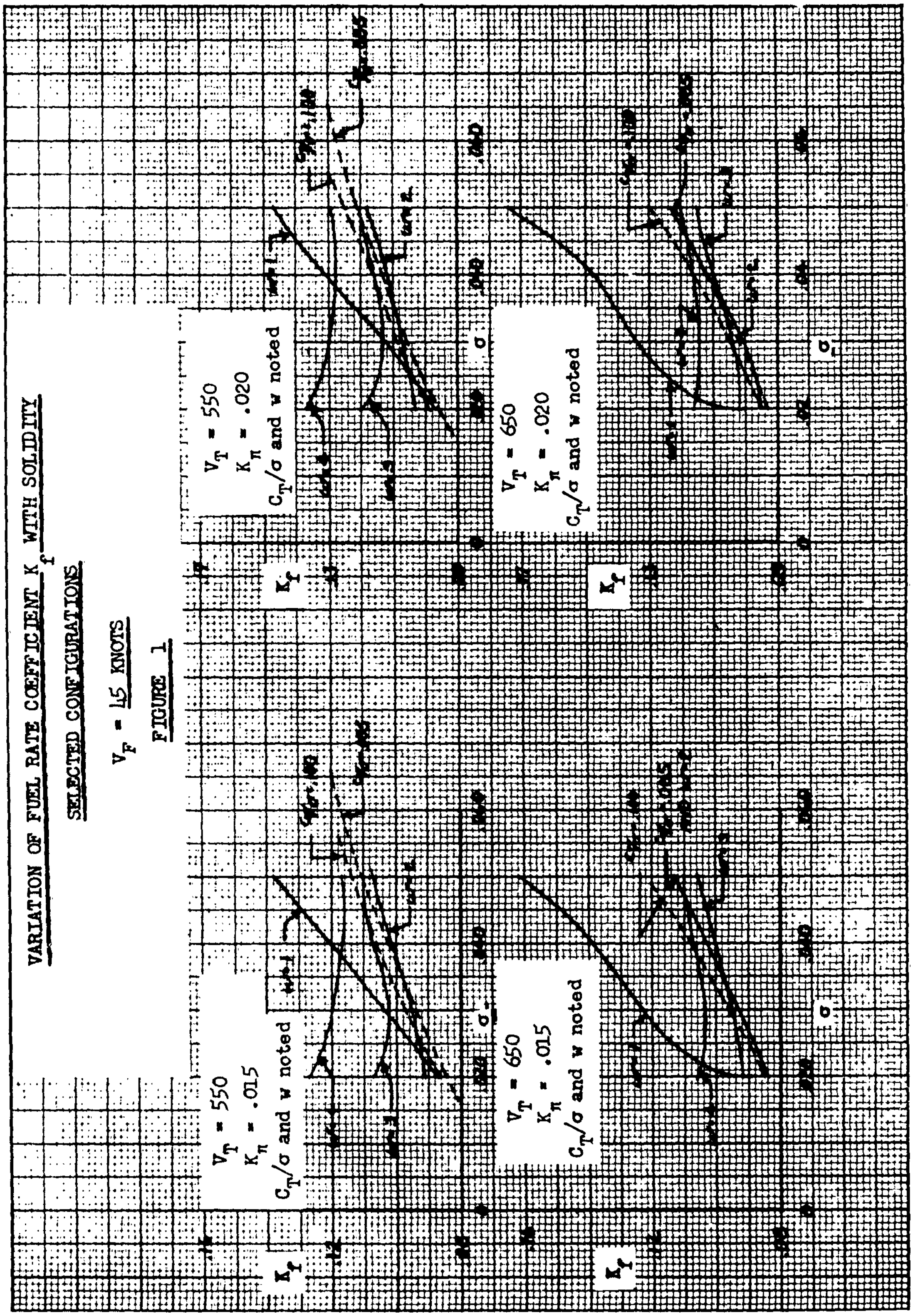
b. Choice of Disk Loading

(1) Fuel Rates in Cruise

Figure 1 presents curves of K_f at 45 knots versus σ for selected disk loadings at two values of tip speed and flat plate area ratio $K_\pi = A_\pi/W$. (Values of K_π of .015 and .020 represent effective parasite flat plate areas A_π of 6 and 8 square feet respectively, values which are representative of the one-man helicopter.) For all optimum configurations of the one-man helicopter, the speed of 45 knots is very close to best cruising speed. From the standpoint of comfort, it is also a reasonable speed for the pilot when unfaired and unprotected from the free stream.

It is seen from Figure 1 that, in general, a disk loading of 2 psf results in values of K_f close to optimum. A disk loading of 2 also results in reasonable values of rotor diameter and autorotational descent rate.

Figure 2 presents curves of K_s versus solidity, at a disk loading of 2 psf, for selected values of tip speed and A_π, and for a cruising speed of 45 knots. It is seen from Figure 2 that a disk loading of 2 psf also gives values of K_s that are close to optimum.

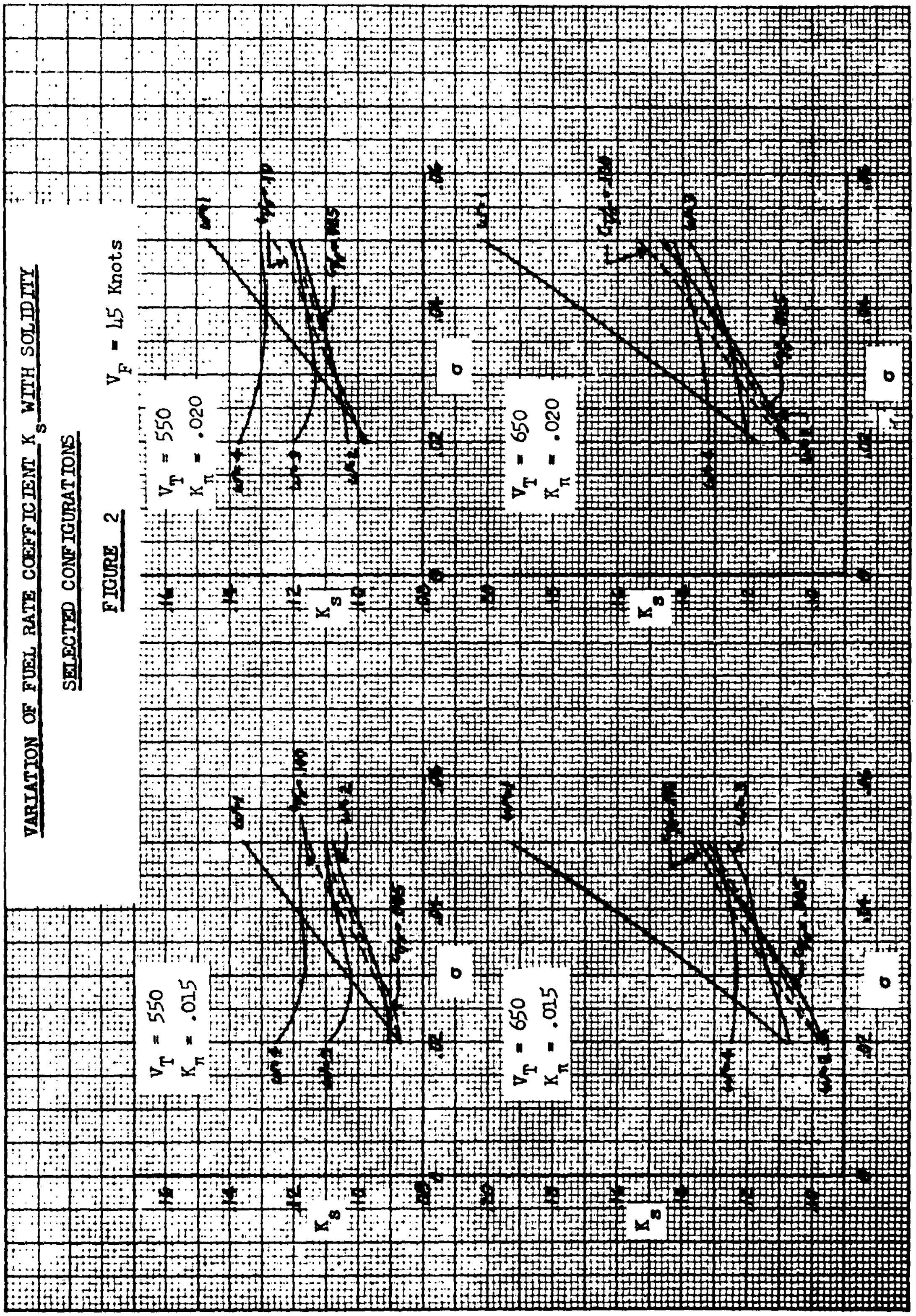


VARIATION OF FUEL RATE COEFFICIENT K_f WITH SOLIDITY

SELECTED CONFIGURATIONS

V_F = 45 KNOTS

FIGURE 1



VARIATION OF FUEL RATE COEFFICIENT K_s WITH SOLIDITY

SELECTED CONFIGURATIONS

FIGURE 2

V_F = 45 Knots

(2) Vertical Descent in Autorotation

There is some question as to whether vertical power-off descent rate is in any way a significant criterion, since this rate is so high, even with quite moderate disk loadings, that in the great majority of cases helicopters **make autorotational descents in forward flight. It may be** that under battle conditions, with pinpointed landing areas, vertical descent will sometimes be necessary. Some comments follow regarding rate of vertical descent power-off.

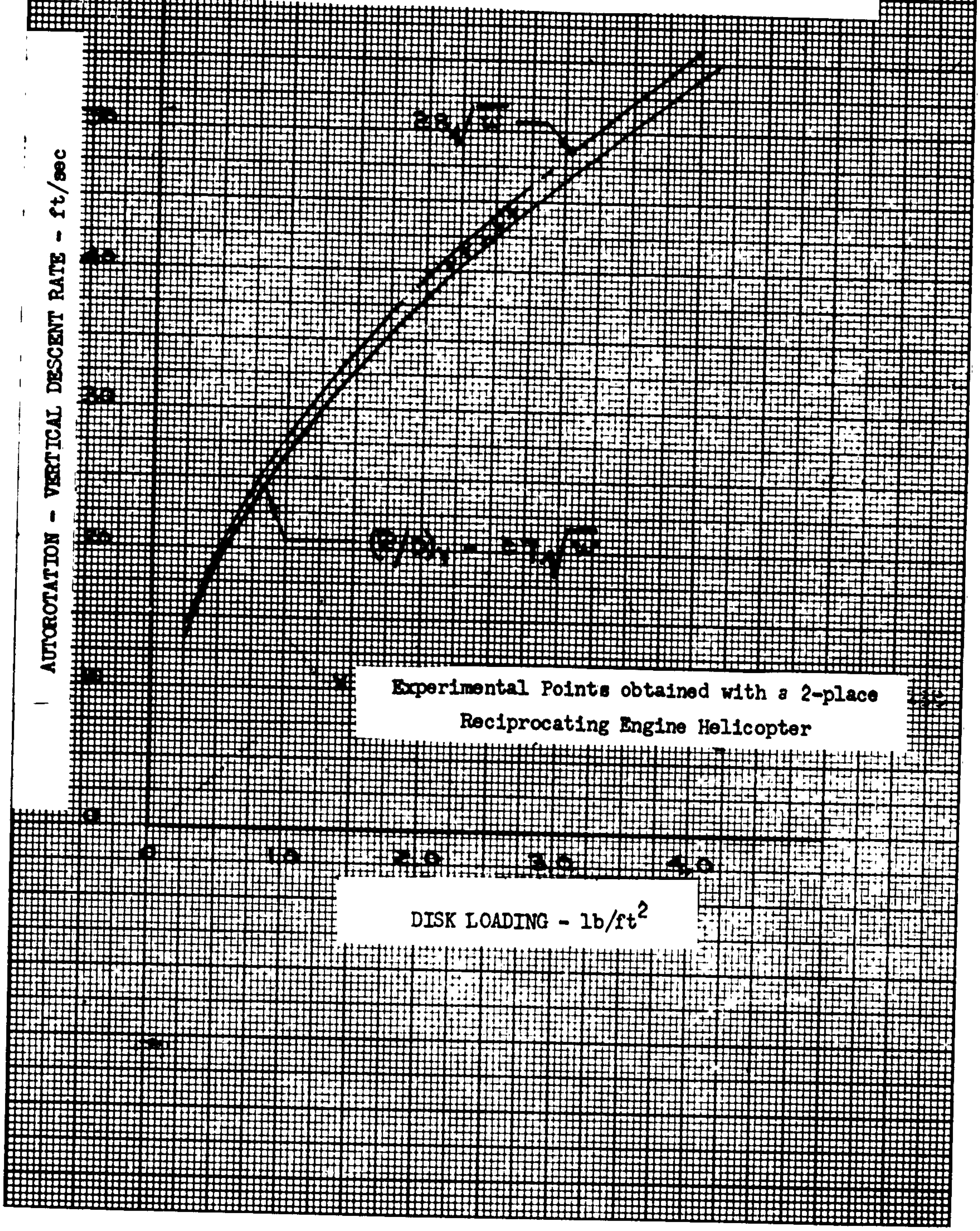
Over the conventional range of tip speeds (that is, up to a Mach number of about .7), vertical descent rate in autorotation is a function of the disk loading, and is given very approximately by:

$$(R/D)_v = k\sqrt{w} \qquad (5)$$

Figure 3 presents $(R/D)_v$ versus disk loading for values of k equal to 27 and 28, with experimental points from unpublished data for a two-place gear-driven helicopter currently in service. It appears that k = 28 gives results that are slightly conservative. For a ramjet helicopter the vertical descent rate will be increased 30-40%, and the increase will be about half this for a pulse jet.

FIGURE 3

VARIATION WITH DISK LOADING OF VERTICAL DESCENT RATE IN AUTOROTATION



A disk loading of 2.0 with k = 28 gives a vertical descent rate of approximately 40 fps. This appears to be a reasonable upper limit for the one-man helicopter, considering required reaction time and use of the feet for landing.

(3) Power Required in Vertical Flight

The charts discussed in this paragraph present information which is available elsewhere in the literature. The data is included for convenience in evaluating one-man helicopter proposals, and for the guidance of designers not familiar with the state of the art.

Figure 4 presents P_r/W = (Net Rotor Power Required)/(Gross Weight) versus C_T/σ in hovering out of ground effect, at sea level, for selected values of disk loading, tip speed, and solidity. For operating C_T/σ values of .08 and greater, disk loading is the most important parameter, and P_r/W decreases with decreased disk loading.

Figures 5 and 6 present corresponding curves of P_r/W for rates of initial vertical climb of 500 and 1000 fpm respectively.

c. Tip Speed V_T and Solidity Ratio, σ

It is desirable to discuss the influence of σ and V_T together, since the rotor profile power losses are directly proportional to σ and V_T^2. Furthermore, blade loading coefficient C_T/σ is dependent on these two variables. (See discussion in Paragraph I.4.d.)

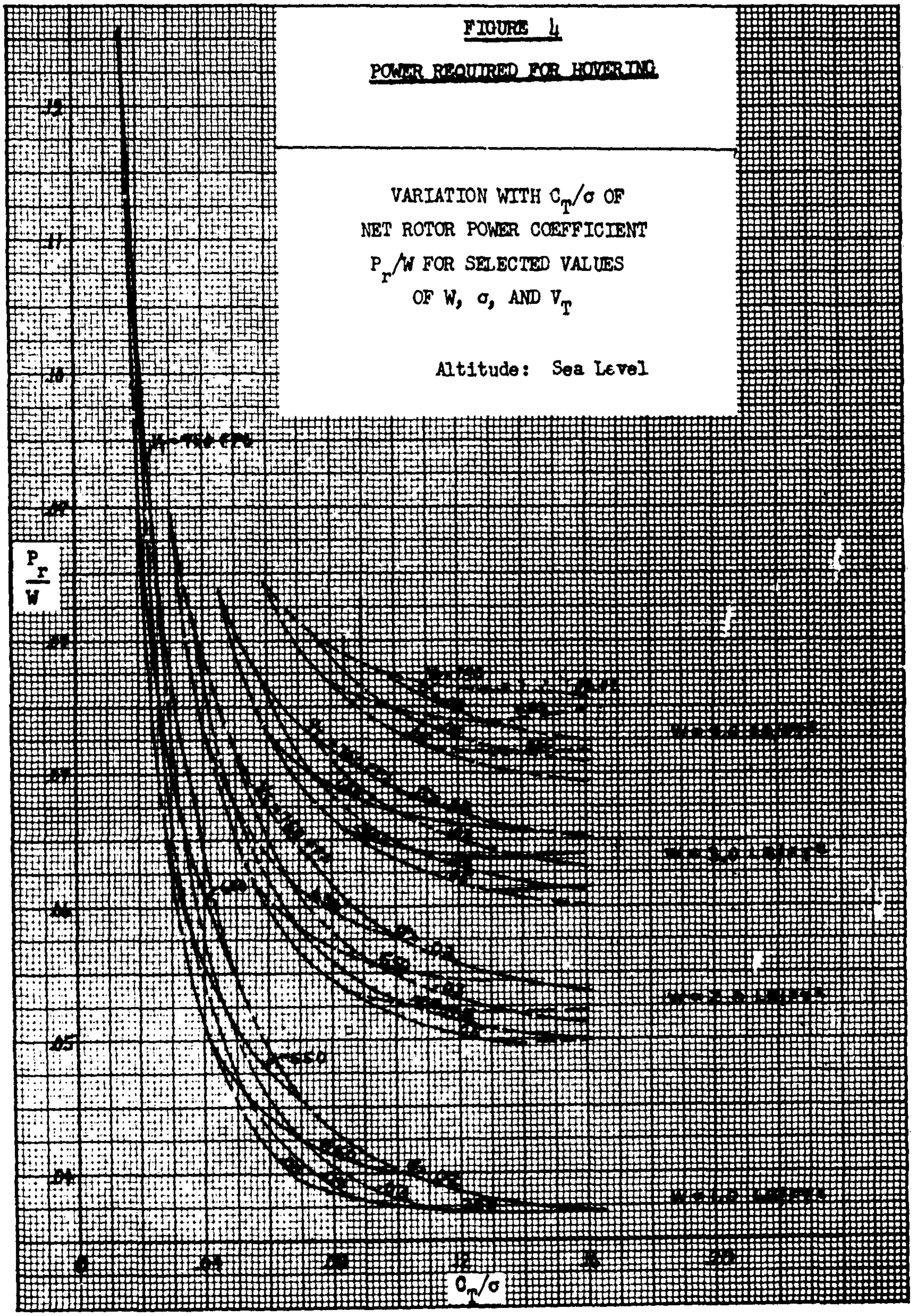


FIGURE 4

POWER REQUIRED FOR HOVERING

VARIATION WITH C_T/σ OF NET ROTOR POWER COEFFICIENT P_r/W FOR SELECTED VALUES OF W, σ, AND V_T

Altitude: Sea Level

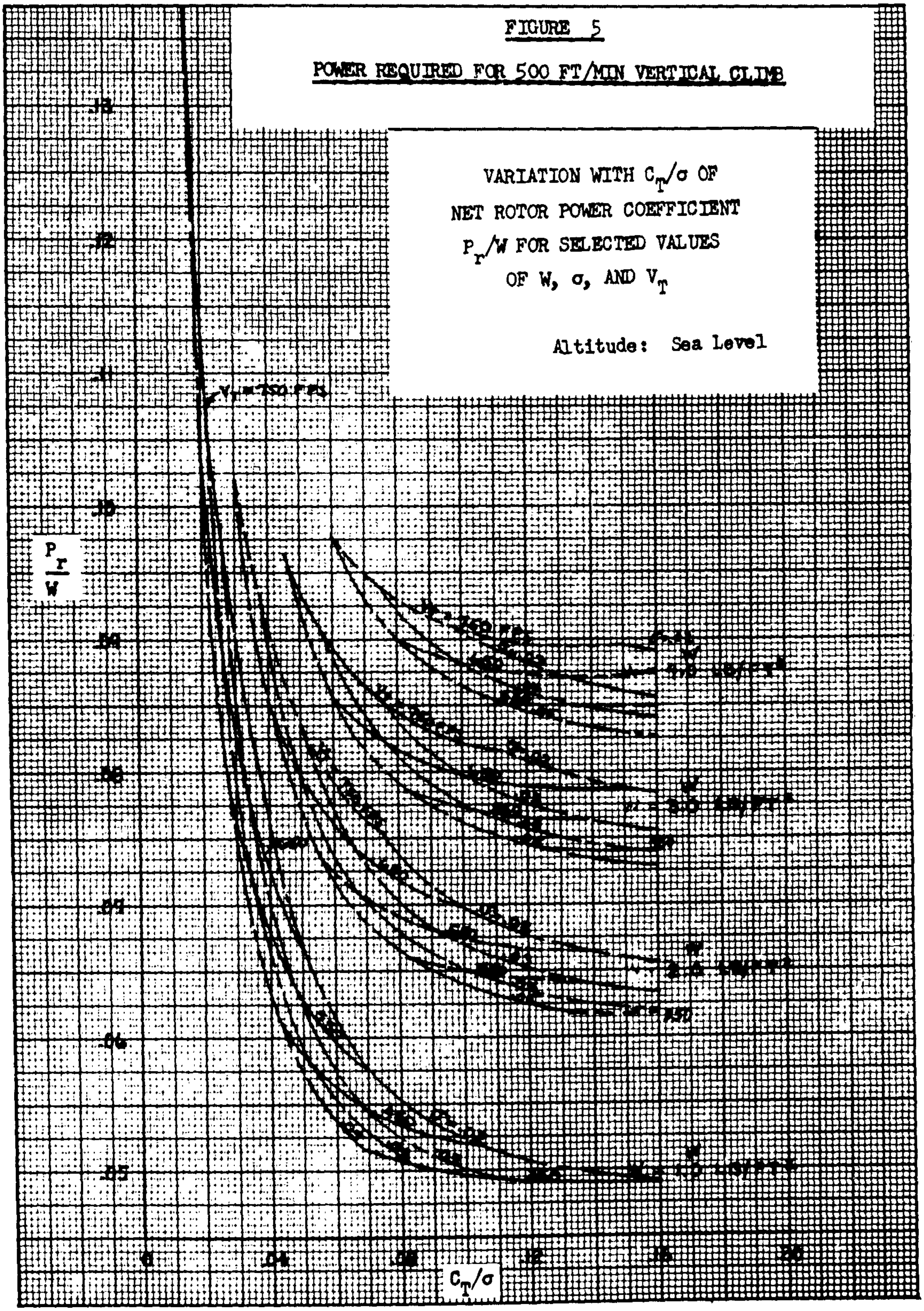


FIGURE 5
POWER REQUIRED FOR 500 FT/MIN VERTICAL CLIMB
VARIATION WITH C_T/σ OF
NET ROTOR POWER COEFFICIENT
P_r/W FOR SELECTED VALUES
OF W, σ, AND V_T
Altitude: Sea Level
$\frac{P_r}{W}$
C_T/σ

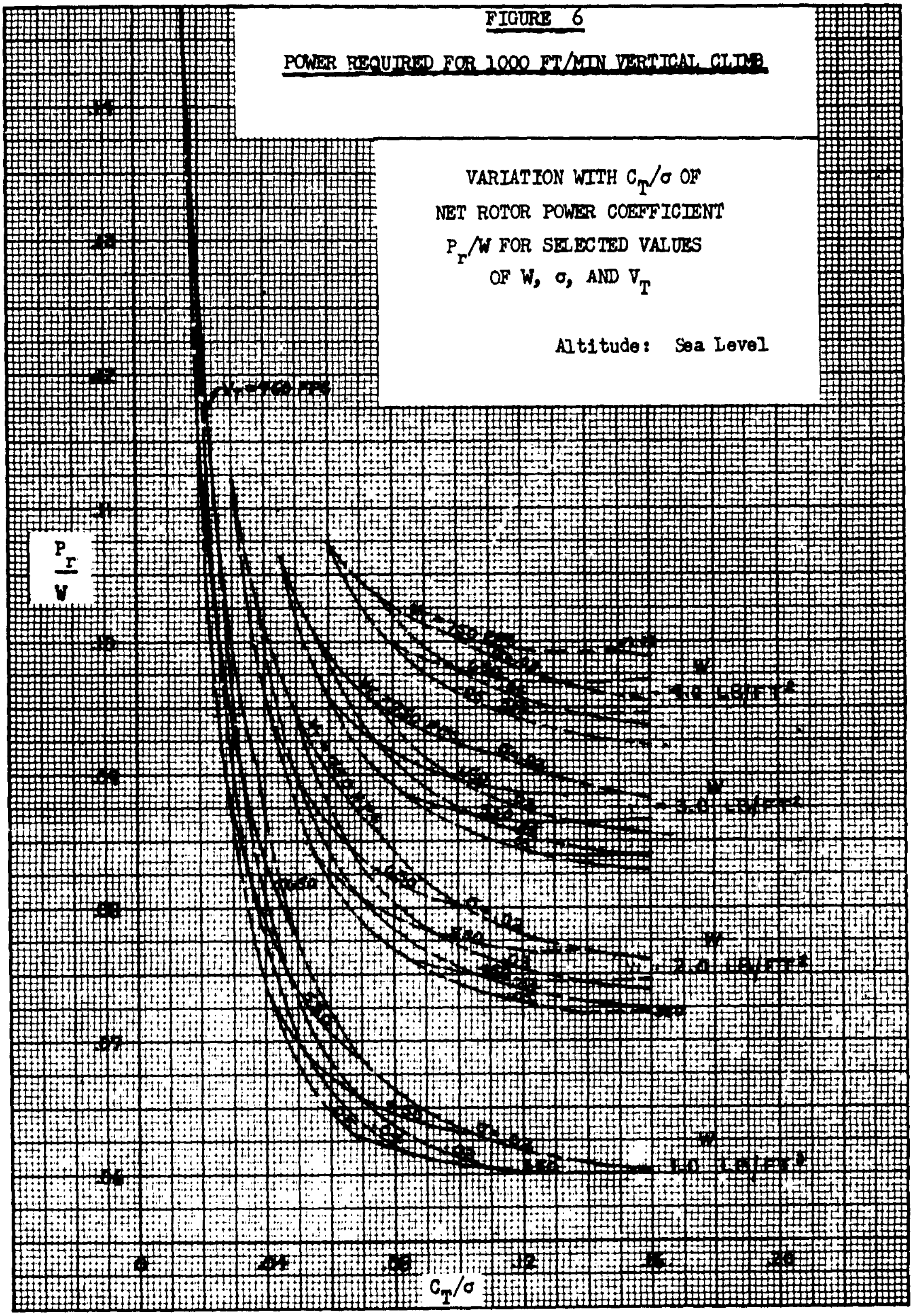


FIGURE 6

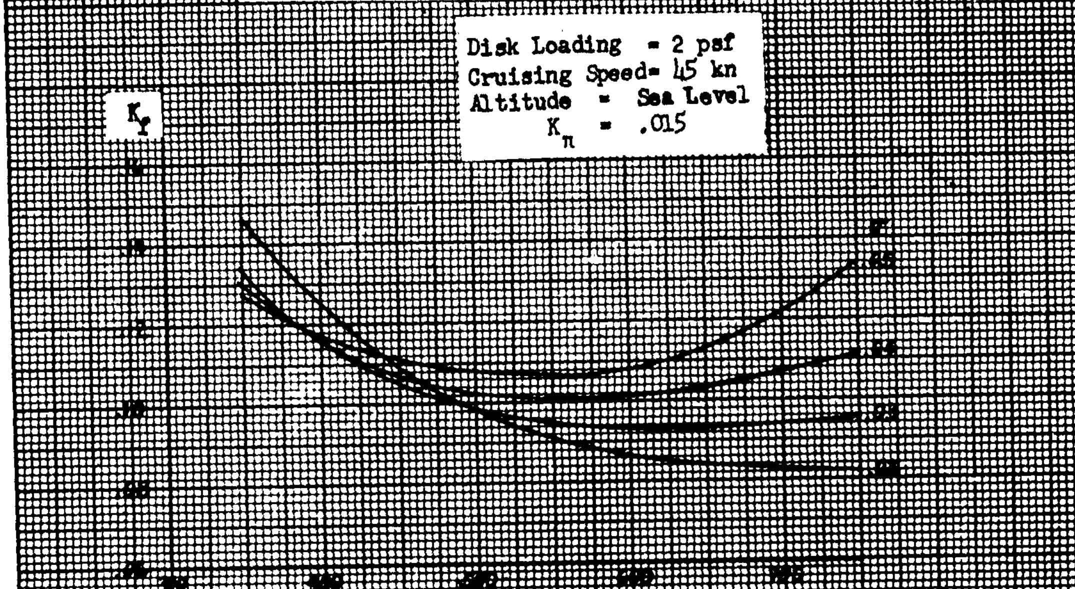
POWER REQUIRED FOR 1000 FT/MIN VERTICAL CLIMB

(1) Fuel Rate in Cruise

Figure 7(a) presents K_f versus tip speed for selected values of solidity, and Figure 7(b) presents K_f versus solidity for selected values of tip speed. Both of the above figures are presented for a cruising speed of 45 knots, a disk loading of 2 psf, and a K_π of .015. The line for V_T = 850 fps on Figure 7(b) is shown dotted, since this curve was obtained by extrapolation of the curves of Figure 7(a). It is clear from Figure 7(a) that for tip speeds in excess of 600 fps, K_f remains approximately constant in the range of solidities between .02 and .03, and increases with tip speed for higher values of solidity. It is seen from Figure 7(b) that solidity must be reduced well below .02 to benefit from tip speeds above 650 fps. At best relatively small reductions in K_f are indicated. Even these small reductions may not be achievable in practice due to mechanical difficulties in connection with fairing of the engines on blades of the small chords required.

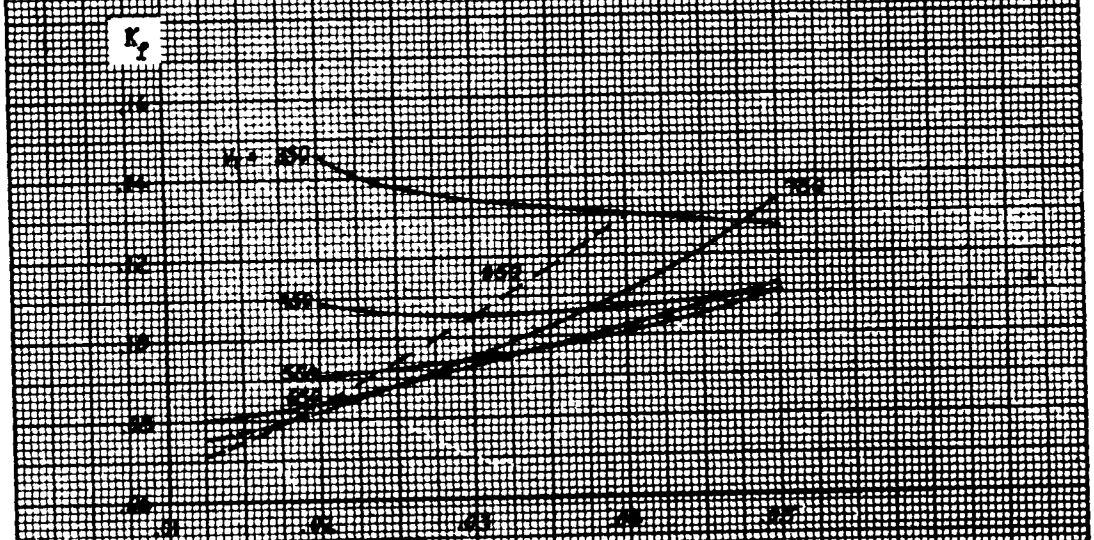
Thus it may be concluded that reductions in fuel rate resulting from optimization of tip speed and solidity lie in the region of diminishing returns, unless appreciable decreases in TSFC result from increasing tip speed. The following general statements apply concerning the effect of tip speed on TSFC:

VARIATION WITH TIP SPEED AND SOLIDITY RATIO OF FUEL RATE COEFFICIENT - K_f



TIP SPEED - fps

FIGURE 7(a)

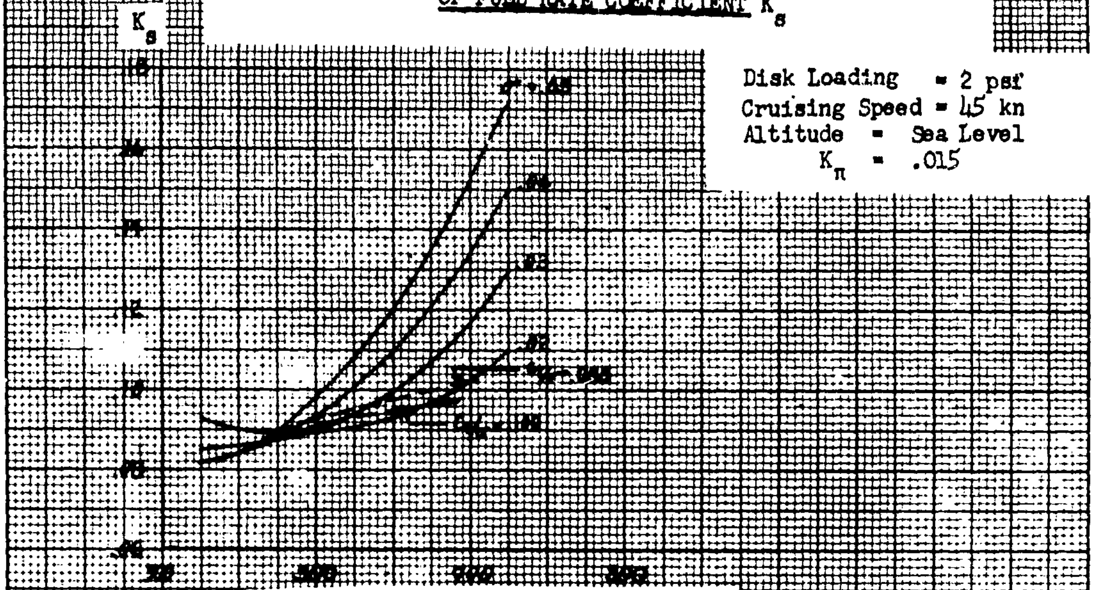


SOLIDITY RATIO - σ

FIGURE 7(b)

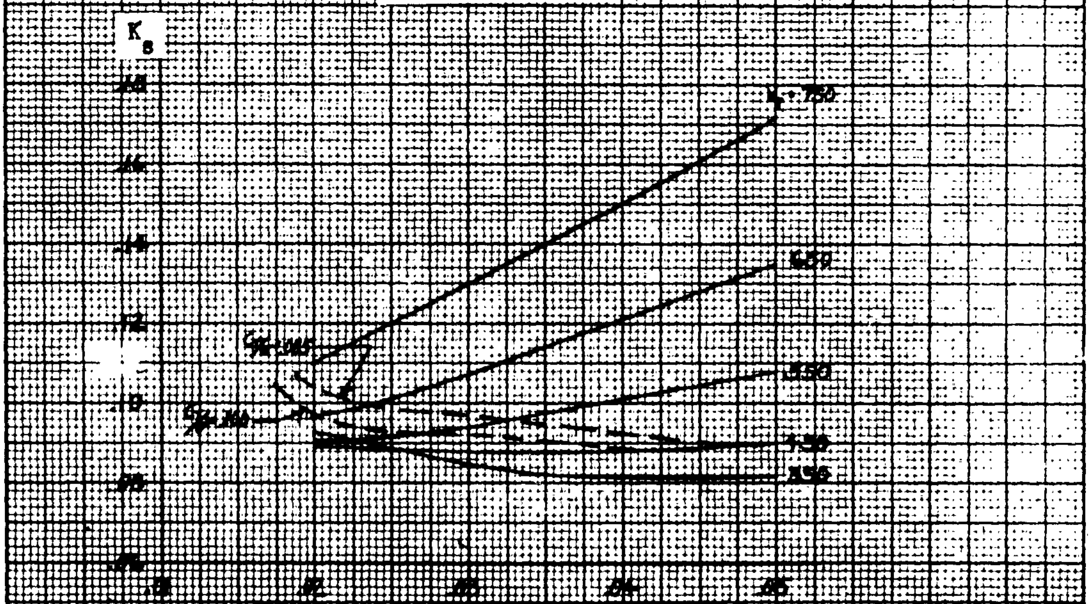
VARIATION WITH TIP SPEED AND SOLIDITY RATIO OF FUEL RATE COEFFICIENT K_s

Disk Loading = 2 psf
Cruising Speed = 45 kn
Altitude = Sea Level
K_π = .015



TIP SPEED - fps

FIGURE 8(a)



SOLIDITY RATIO - σ

FIGURE 8(b)

TSFC of a rocket powerplant is independent of tip speed.

TSFC of a pulse jet increases with tip speed, being a minimum at static thrust.

TSFC of a ramjet decreases with tip speed. However, data is not available to analyze actual performance of tip-mounted ramjets at speeds much in excess of 700 fps. Limited tests with a tip-mounted ramjet at speeds in excess of 700 fps resulted in failure of the shell: thrust and noise levels prior to failure indicated the possibility that the engine was operating as a valveless pulse jet.

A study has been made of the best fuel rate that may reasonably be expected from optimization of tip speed and solidity for a rocket-powered system, taking into account overall performance as affected by compressibility and tip stall. The results of this study are summarized in Paragraph I,5.

(2) Performance Limitations

The following generally accepted comments regarding tip speed are presented as a matter of interest:

(a) For a given rotor geometry, stall at the retreating blade tip ($\psi = 270^\circ$) is retarded by increase in tip speed. (See Figures 18 and 20).

(b) The tip speed and maximum forward speed as limited by drag divergence are related as follows:

$$M_{dd} = \text{Drag Divergence Mach Number} = \frac{\text{Forward Speed + Tip Speed}}{\text{Velicity of Sound in Air}} = \frac{V_F + V_T}{V_s} \quad (6)$$

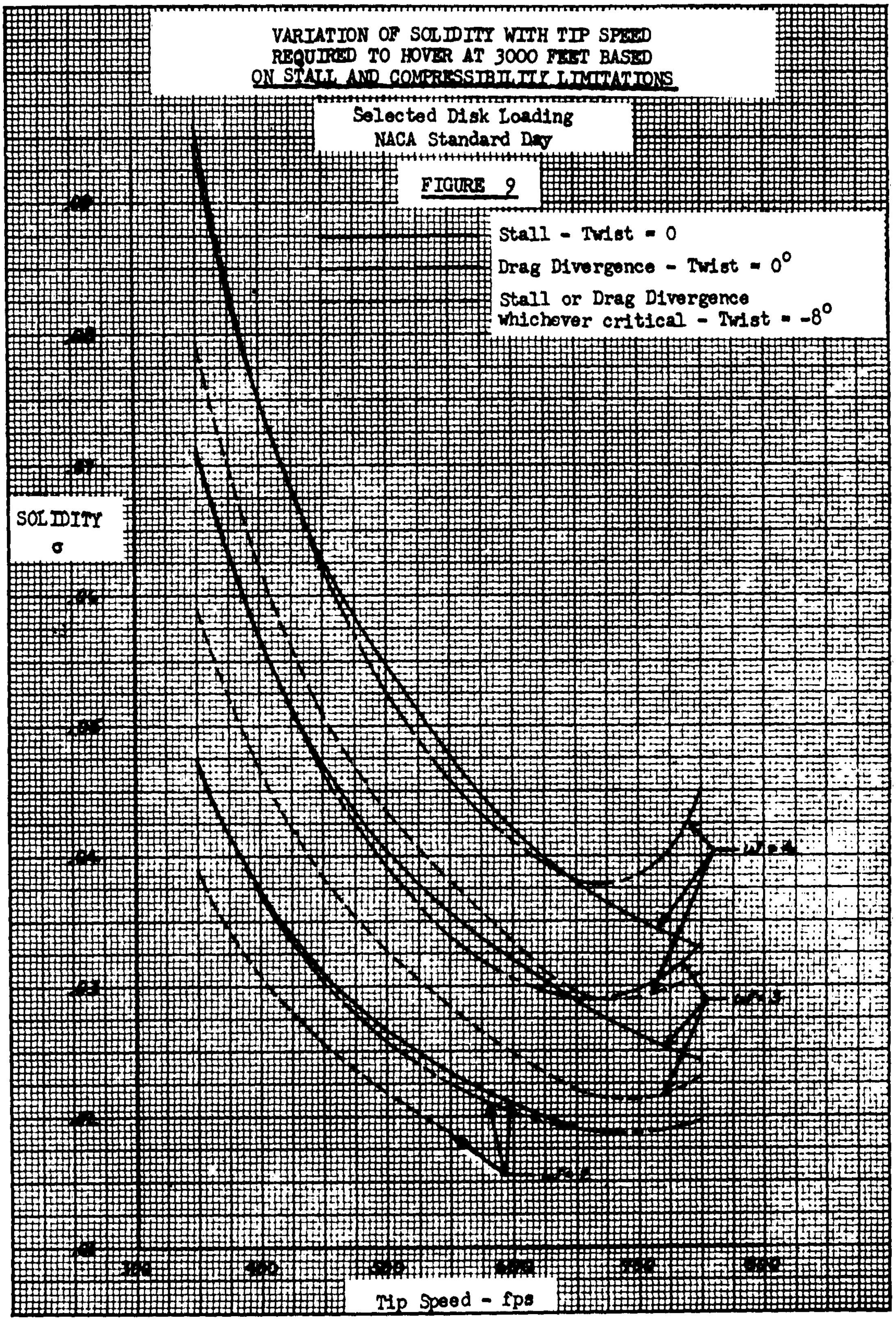
(c) Airfoil Sections which have unusually high values of M_{dd} have relatively inferior maximum lift characteristics, and are, therefore, generally not suitable for helicopter applications.

An additional, and not generally recognized generalization regarding tip speed is Item (d) below:

(d) Optimization of rotor geometry requires that σ vary as $1/V_T^2$, so that blade cross-sectional area varies as $1/V_T^4$. Thus the ratio (centrifugal load due to tip weight) /(Blade tip cross-sectional area) varies as V_T^8. It may, therefore, prove necessary, on blades operating at high tip speed to modify tip structure for attachment of the powerplant, in such a way as to increase profile losses. Thus, some if not all the reduction in K_f indicated by theory may not be realized in practice.

(3) Hovering at Altitude

As a matter of interest Figure 9 is presented to show the variation of required solidity ratio with tip speed at selected disk loadings to permit hovering out of the ground effect at 3000 feet. The criteria are stall and drag divergence at the blade tips. In the case of the blade with no twist, both criteria are shown, and it is seen



VARIATION OF SOLIDITY WITH TIP SPEED REQUIRED TO HOVER AT 3000 FEET BASED ON STALL AND COMPRESSIBILITY LIMITATIONS

FIGURE 9

that for tip speeds up to 650 fps the solidities indicated by both criteria are similar: for tip speeds above 650 fps the drag divergence criterion governs the choice of solidity. In the case of the blade with -8° twist the curves present the only critical values of required solidity, whether due to drag divergence or stall.

d. Blade Loading Coefficient C_T/σ

This coefficient represents an important design parameter. For the hovering rotor, the blade mean lift coefficient, represented by the value at approximately 72% radius for the untwisted blade, is approximately given by:

$$C_{lr} = 6C_T/\sigma \tag{7}$$

Helicopter performance is generally limited by tip stall and compressibility, and is, therefore, sensitive to tip angle of attack. For this reason it is current practice to design for a sea-level C_T/σ not to exceed about .08 at gross design weight, with overload operation about 25% greater.

Figures 10 and 11 illustrate the importance of C_T/σ as a design parameter. Figure 10(a) presents maximum C_T/σ versus μ based on blade stall. Figure 10(b) presents the corresponding compressibility limitation on the advancing blade tip, the criterion being M'_{dd} from Figure 15. Figures 10(a) and 10(b) are for an untwisted blade. Figures 11(a) and 11(b) are for the blade with -8° twist. In Figures 10(a) and 11(a) stall is assumed to occur at an angle of attack of 10°: as shown in Figure 14, the maximum lift coefficient decreases with increasing Mach number, and it is shown below that for tip speeds and forward speeds which are reasonable for a one-man helicopter, a $C_{l_{max}}$ of 1.0

(corresponding to 10° angle of attack at the blade tip) represents a reasonable first approximation.

The vertical lines labeled C/V_T in Figures 10(a) and 11(a) represent drag divergence boundaries on the retreating blade: to avoid this it is necessary to operate to the right of these lines.

As an example in the use of the charts, the following is presented as typical for a one-man helicopter:

Gross Weight = 400 lbs

Disk Loading = 2 psf

Tip Speed = 600 fps

Tip-Speed Ratio at V_{max} (based on C/V_T line, by interpolation)	= .185
V_{max} (limited by retreating tip drag divergence)	= .185(600) = 110 fps
Horsepower required at 110 fps (Figure 17)	= 28
P/L = (28)(550)/(110)(400)	= .35

From Figure 10(a), for P/L = .35 and μ = .185, the design C_T/σ based on drag-divergence at the retreating blade tip = 0.072.

At a tip speed of 600 fps, a disk loading of 2 psf, and C_T/σ of .072, the resulting solidity required is:

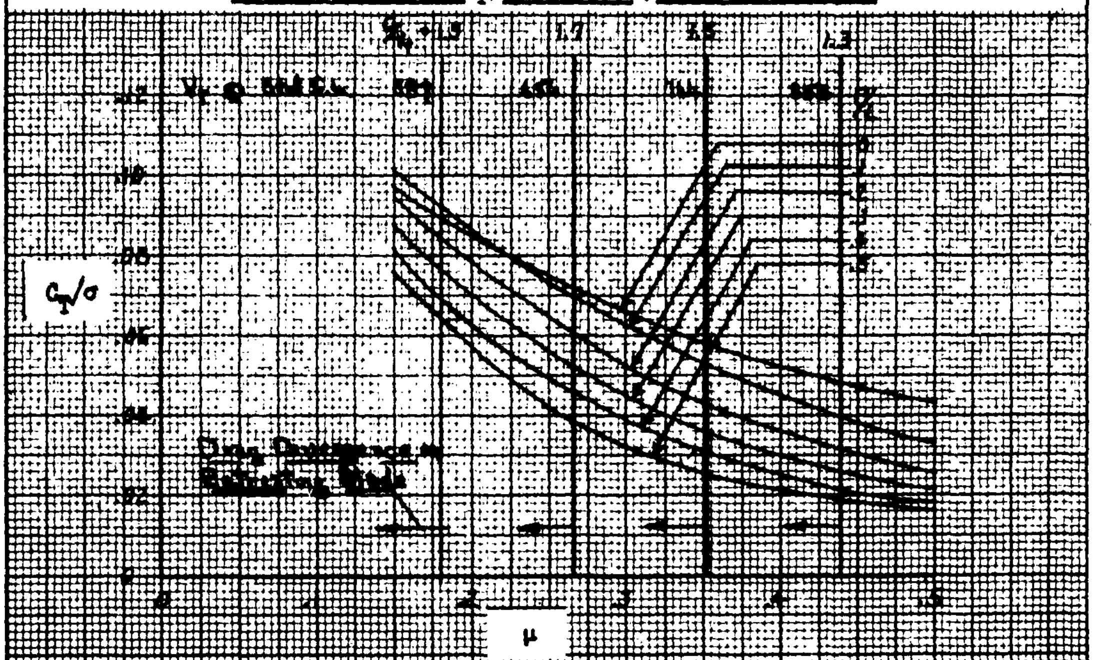
$$\sigma = \frac{C_T}{C_T/\sigma} = \frac{.00233}{0.072} = .032$$

FIGURE 10

CHART FOR ESTABLISHING STALL & COMPRESSIBILITY LIMITATIONS TO V_{MAX}

Blade Twist $\theta_s = 0$ $C_{l_{max}} = 1.0$

(a) RETREATING STALL C_T/σ VERSUS μ (from ACR L4H07)



(b) DRAG DIVERGENCE ON ADVANCING BLADE TIP VERSUS μ

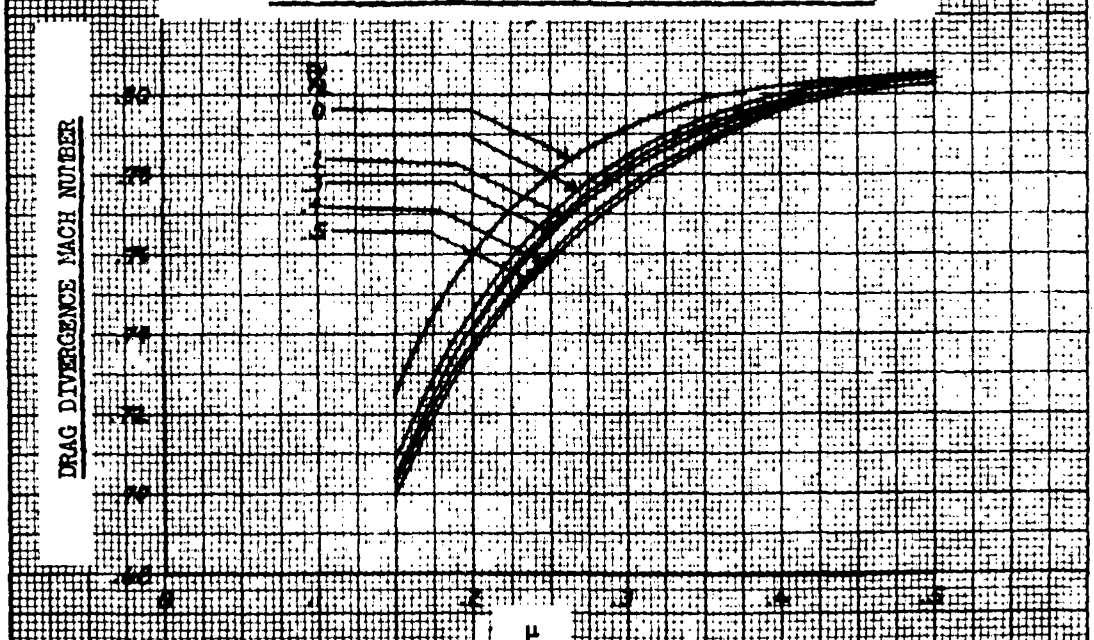
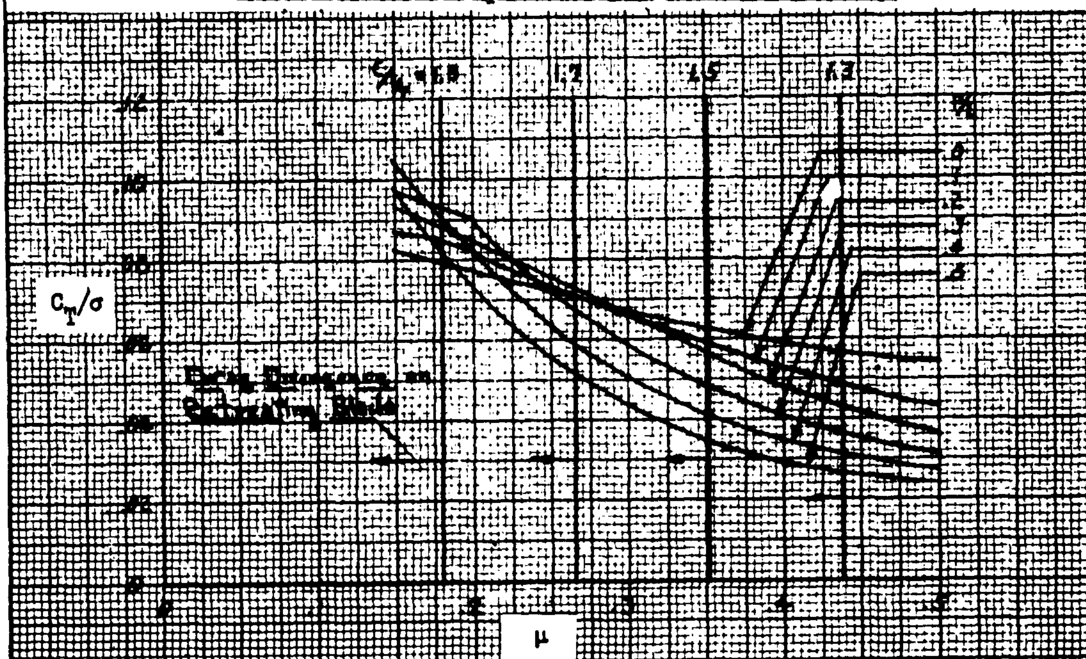


FIGURE 11

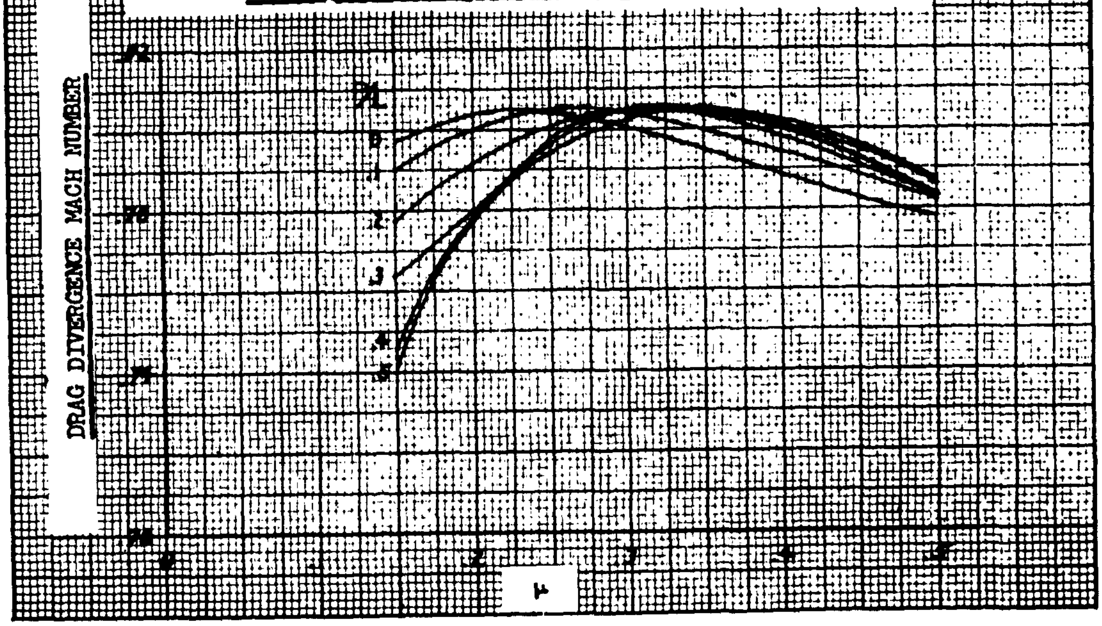
CHART FOR ESTABLISHING STALL & COMPRESSIBILITY LIMITATIONS TO V_{MAX}

Blade Twist $\theta_s = -8^\circ$ $C_{l_{max}} = 1.0$

(a) RETREATING STALL C_T/σ VERSUS μ (from ACR L4H07)



(b) DRAG DIVERGENCE ON ADVANCING BLADE TIP VERSUS μ



The following is presented as a check on the assumed value of 10° for blade stall angle of attack, and on the advancing blade tip Mach number as a criterion in selection of design C_T/σ :

$$\text{Retreating blade tip Mach number at } V_{max} = \frac{(1-\mu)(600)}{1116} = .44$$

$$\text{Advancing blade tip Mach number at } V_{max} = \frac{(1+\mu)(600)}{1116} = .64$$

From Figure 14 the $C_{l_{max}}$ for a Mach number of .44 is 0.96. This corresponds, for a lift-curve slope of 0.1/degree, to 9.6° angle of attack. Thus, for preliminary purposes, the assumption of 10° is reasonable.

From Figure 10(b) the limiting M'_{dd} at the advancing tip is .73, so that the value of .64 is not critical. Choice of design C_T/σ is thus governed by drag divergence and stall on the retreating blade tip, both occurring at the same tip angle of attack.

From Figures 11(a) and 11(b) it is found that with a blade twist of -8°, a C_T/σ of .090 is permissible, so that required blade solidity = .026. The mechanical and aerodynamic problems associated with low solidity and with blade twist may not justify this step, however. These problems are discussed in Paragraph I.5.

e. Blade Twist

The purpose of blade twist (washout at tip) is to reduce blade tip angle of attack, and thus retard stall and drag divergence. Theoretically, a linear blade twist of -8° reduces blade tip angle of attack (compared to the untwisted blade) by approximately 2°. In practice, it appears that only about one-half of the expected reduction occurs, at the critical forward speeds and altitudes, due to a modification of inflow distribution resulting from the blade twist.

Blade twist may be used to effect the occurrence of stall and drag divergence (on retreating and advancing blade tips) at the same forward speed, thus optimizing rotor geometry to obtain maximum speed and/or ceiling. It does not appear that any appreciable power savings in forward flight result from the use of twist, though a saving of about 5% in hovering is obtainable.

Since the one-man helicopter is not a high-performance machine, optimization of rotor geometry is desirable only in relation to range. In the case of the rocket, ram rocket and ramjet, fuel rate may decrease as tip speed increases, but with increasing tip speed the problem of drag divergence appears. It is then desirable to maintain the advancing tip angle of attack as close to zero lift as possible. Blade twist is the most effective means to achieve this.

In addition to the manufacturing complication involved in accurately building twist into a blade, it appears that there is a structural problem. The effect of blade twist is to induce an appreciable first harmonic component of airload, which may result in an increase in the steady and vibratory stress levels on the blade. For these reasons it is desirable to avoid the use of twist in the rotor blades of the one-man helicopter.

A discussion of optimization of blade geometry and tip speed to obtain low fuel rates with a rocket powerplant is presented in Paragraph I.5.

f. Minimum Power-Off Rates of Descent in Forward Flight

Figures 12 and 13 present charts of estimated minimum rates of descent for a one-man helicopter in forward flight. Figure 12 is presented for a design C_T/σ of .085, corresponding to autorotation at normal rpm. Figure 13 is presented for a design C_T/σ of .125, corresponding to autorotation at minimum desirable rotor speed from the standpoint of adequate control and rotor kinetic energy for flare.

The data is presented for three values of tip engine drag coefficient C_{Dj} . These values are 0, .10, and .20, representing clean blades, pulse jet, and ramjet engines respectively. The rocket powerplant C_{Dj} lies somewhere between 0 and .10, depending on the method of mounting the engine. The data is based on the assumption that autorotation rates are increased from 'clean blade' values 100% for ramjets and 50% for pulse jets. A tip-mounted rocket in a 'tip tank' nacelle may increase autorotation rates about 5% to 15%.

Study of the charts indicates that minimum descent rates at a given C_T/σ are obtained by use of low disk loading and low tip speed with high solidity. However, at a given disk loading variation of V_T and σ at constant C_T/σ has relatively little effect on descent rate, especially with 'clean' blades. Increase in operating C_T/σ , other things being equal, results in reduced descent rate.

g. Design Considerations as Affected by Tip Stall and Compressibility Effects

Rotor profile losses increase when the angle of attack for stall on the retreating blade tip, or drag divergence on the advancing tip, are exceeded.

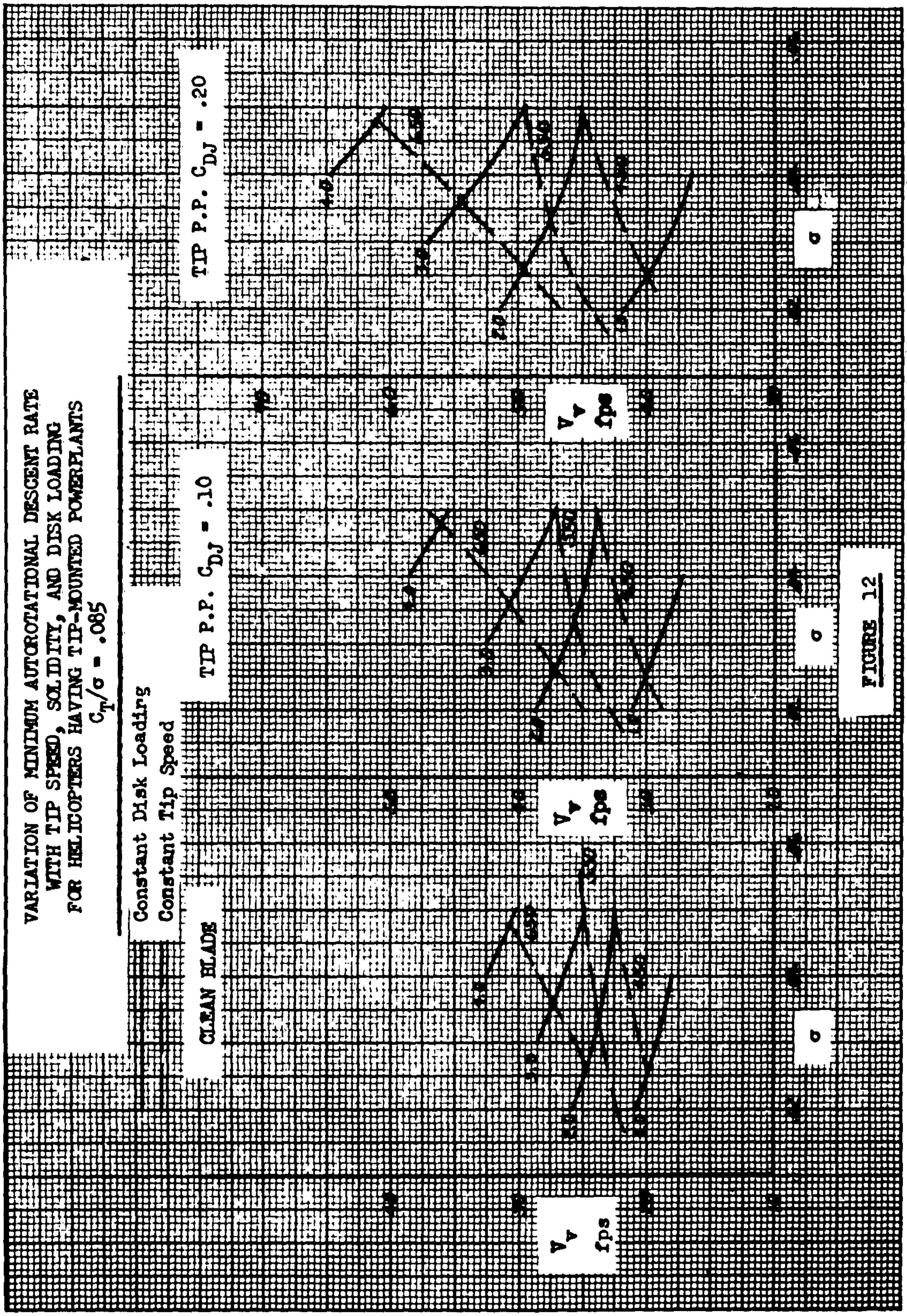

VARIATION OF MINIMUM AUTOROTATIONAL DESCENT RATE
WITH TIP SPEED, SOLIDITY, AND DISK LOADING
FOR HELICOPTERS HAVING TIP-MOUNTED POWERPLANTS
C_T/σ = .085
Constant Disk Loading
Constant Tip Speed
CLEAN BLADE
TIP P.P. C_{DJ} = .10
TIP P.P. C_{DJ} = .20
V_v fps
V_v fps
V_v fps
σ
σ
σ

FIGURE 12

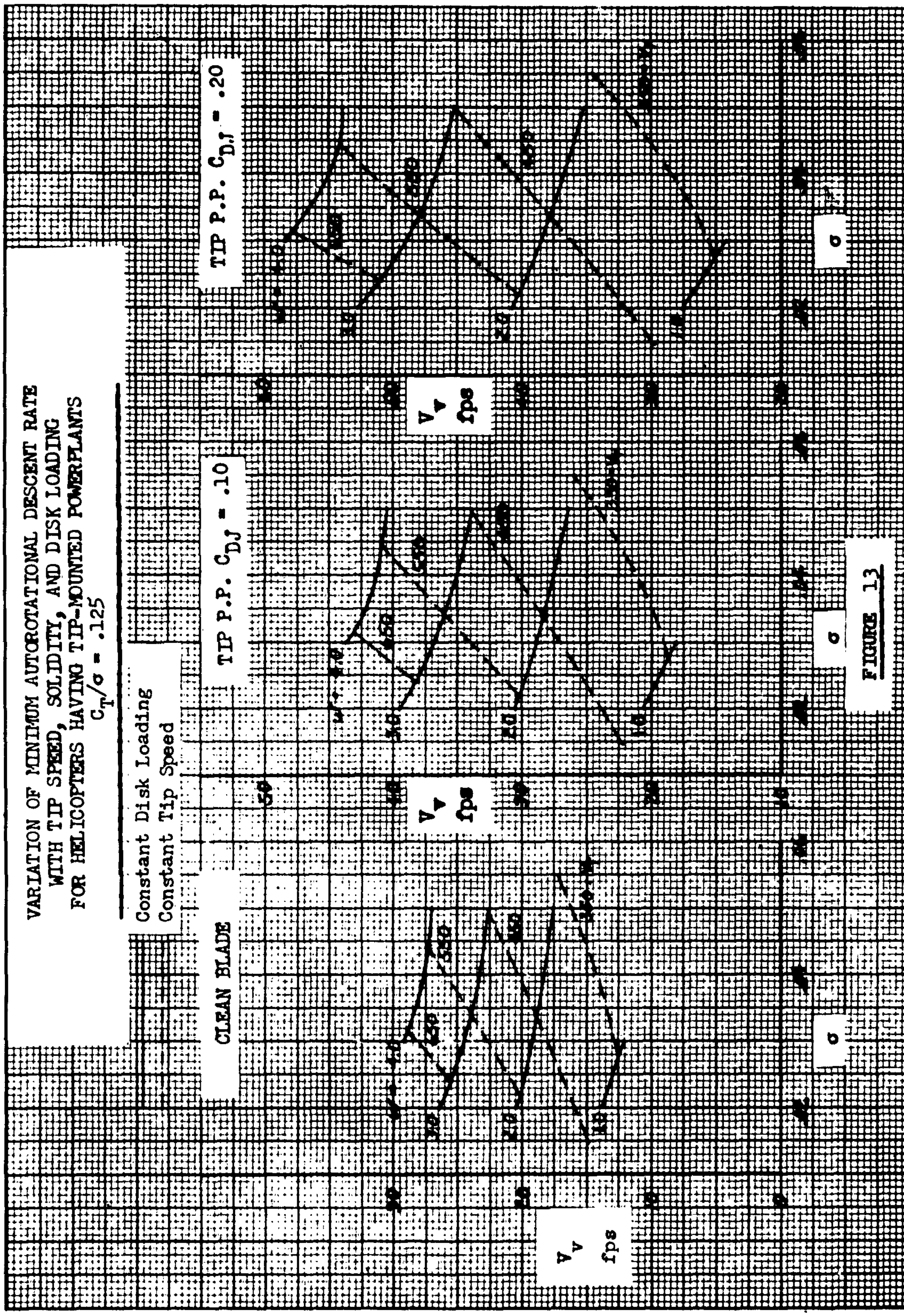

VARIATION OF MINIMUM AUTOROTATIONAL DESCENT RATE
WITH TIP SPEED, SOLIDITY, AND DISK LOADING
FOR HELICOPTERS HAVING TIP-MOUNTED POWERPLANTS
C_T/σ = .125
Constant Disk Loading
Constant Tip Speed
CLEAN BLADE
TIP P.P. C_{DJ} = .10
TIP P.P. C_{DJ} = .20
V_v fps
V_v fps
V_v fps
σ
σ
σ

FIGURE 13

Reference 24 indicates that when the stall angle at the retreating blade tip is exceeded by 4°, vibration and loss of control exceed tolerable limits. From Reference 2, Figure 2, it appears also that profile power required is approximately doubled under these conditions. Similarly, increased profile losses and vibration may be expected to occur when drag divergence occurs at the advancing blade tip.

Among the various factors affecting blade tip angles of attack are operating C_T/σ, P/L, and blade twist. The calculation of these angles of attack involves much computation. Figure 10 indicates that as C_T/σ and/or P/L are increased, the stall occurs at a lower tip-speed ratio (and for the same reason attainable ceiling is reduced). Establishment of rotor geometry and tip speed must, therefore, be based on careful consideration of performance requirements.

In addition to the large amount of computation required for establishment of blade tip angles of attack, considerable care is required in selecting suitable airfoil data from the available literature. Paragraph I.4.h. presents a brief discussion of airfoil selection, and Figures 14 and 15 present data on $C_{l_{max}}$ and drag divergence for the NACA 0015 airfoil section which appears fairly reliable.

h. Airfoil Section Data - Selection of Airfoil Sections for Rotor Blades

(1) Discussion

The literature contains a great deal of information regarding airfoil section data. The important characteristics are: lift curve slope, maximum lift, nature of stall, profile drag versus angle of attack, minimum profile drag, center of pressure travel, drag divergence Mach number versus angle of attack, pitching moment divergence Mach number versus angle of attack. The most important items, since they tend to limit helicopter forward speed, ceiling, and maximum load-carrying ability, are blade tip stall and drag divergence Mach number.

Unless great care is exercised in the use of airfoil data as a bsis for the selection of rotor airfoil sections, the results may be misleading. For example, it is common to consider values of $C_{l max}$, in connection with blade tip stall, as high as 1.4, whereas it is shown in Figure 14 that for a Mach number of .41 (corresponding to a forward speed of 115 fps and a blade rotational speed of 575 fps), the $C_{l max}$ for practical construction sections is about 1.0.

The following should be considered when using airfoil data in the selection of rotor blade airfoil sections:

(a) The condition of the boundary layer at the airfoil surface can seriously affect some of the above-mentioned characteristics, in particular the maximum lift coefficient, minimum profile drag coefficient, and nature of the stall. Since the condition of the boundary layer (laminar, turbulent, or in transition) is affected by the Reynolds number, initial turbulence, and surface condition, it is obvious that great care must be taken in comparing the results of tests to determine the above-mentioned characteristics. In general, airfoil data for helicopter studies should be obtained on sections representing airfoils of practical construction, or made in conditions of high turbulence and, consequently, at high values of effective Reynolds number. Under these conditions the 'bucket' which exists on the profile drag curves of some airfoil sections generally disappears, and relatively little difference is found in $C_{d_{omin}}$ among the sections otherwise suitable for helicopter use. Comparisons of the maximum lift coefficient should also be made at the operating Mach numbers (see paragraph (b) below); this is likely to cause considerable revision of comparisons based on the low-speed C_{lmax} data.

(b) At high subsonic Mach numbers the drag divergence lift coefficient may be lower than the lift break C_l. The C_{lmax} is effectively based on drag divergence when this occurs. Use of two-dimensional data (M_{cr} versus C_l) is misleading. Figures 12 to 16 of Reference 7 show that not only is the drag divergence Mach number greater than the two-dimensional M_{cr} throughout the operating range of C_l, but the shape of the curves is different in each case. In general, it is found that thickness ratio is the most important item affecting the drag-divergence Mach number; for a given thickness ratio most of the sections suitable for helicopter use have similar drag divergence characteristics, even though M_{cr} characteristics may differ considerably.

(c) An extremely important helicopter airfoil section characteristic is the center of pressure travel. This information is generally presented in terms of aerodynamic center location and moment coefficient about the aerodynamic center ($C_{M_{ac}}$) versus C_l. Helicopter blades, of necessity, have high slenderness ratio, and relatively low torsional stiffness. The possibility of blade flutter is accentuated at the relatively high tip speeds (550-650 ft/second) at which the rotors are operated. Thus it is extremely desirable to eliminate all mass and aerodynamic unbalance about the a.c. from the blade. Mass balancing of blades is standard procedure in helicopter manufacture. Since the structure of the blades is such that the unbalanced blade section centroid usually falls close to 30% chord, whereas the a.c. generally lies in the range 23-25% chord addition of balance weight forward of the a.c. is required. Obviously, the further aft the a.c. is located, the less balance weight is required.

(d) Section lift-curve slope varies little between airfoil sections, at low subsonic Mach number. Since lift-curve slope is affected by compressibility, no general statement may be made in connection with high subsonic lift-curve slopes.

(e) Moment break generally occurs at a higher Mach number than the drag break, throughout the range of operating lift coefficients. Therefore, in general, the moment break is not considered when comparing airfoil sections for helicopters.

(f) Several airfoil sections, for one reason or another, have been proposed as suitable for helicopter blades, usually because of low drag characteristics in low turbulence flow, or high two-dimensional M_{cr} Among these sections are the NACA OOXX, 230XX, 63 OXX and 8-H-XX series. (Note: The XX is replaced by numbers representing thickness ratio. For example, NACA 0012 is a symmetrical section having a thickness/chord ratio of 12%.) In general, in the absence of other than random data on practical-construction sections, the following may be stated:

Symmetrical sections are most desirable, since they have zero center of pressure travel up to the moment divergence Mach number. The NACA OOXX series are, therefore, favorable for use as helicopter airfoil sections.

The peak drag divergence Mach number occurs at the angle of zero lift, and, consequently, at zero angle of attack for symmetrical sections. Peak value varies inversely with thickness ratio; however, the curve of drag divergence Mach number versus C_l steepens with decreasing thickness ratio. As a result, thicker sections are favored in this regard, at C_l greater than about 0.2. In addition, low subsonic $C_{l_{max}}$ decreases with thickness ratio. Smooth airfoil data indicate that the NACA 23012 is the best all-around helicopter airfoil section. As indicated above, however, this data is probably unreliable for practical construction airfoils. The NACA 63_1012 and 63_2015 sections also appear to have good characteristics for smooth airfoil data. A possible advantage of these sections is that the a.c. location is at the 27% chord station, thus requiring less mass balancing than sections having the a.c. further forward. All sections referred to in these discussions have zero or very small center-of-pressure travel. However, for practical construction sections the NACA OOXX probably compares favorably with other series; the OOXX series has the additional advantage that it is simple to construct, having no camber or reflex contours.

(g) From all standpoints the NACA 0015 is probably the optimum blade section for the one-man helicopter. Figures 14 and 15 present section data for the NACA 0015. Figures 10 and 11 are also based on 0015 section characteristics.

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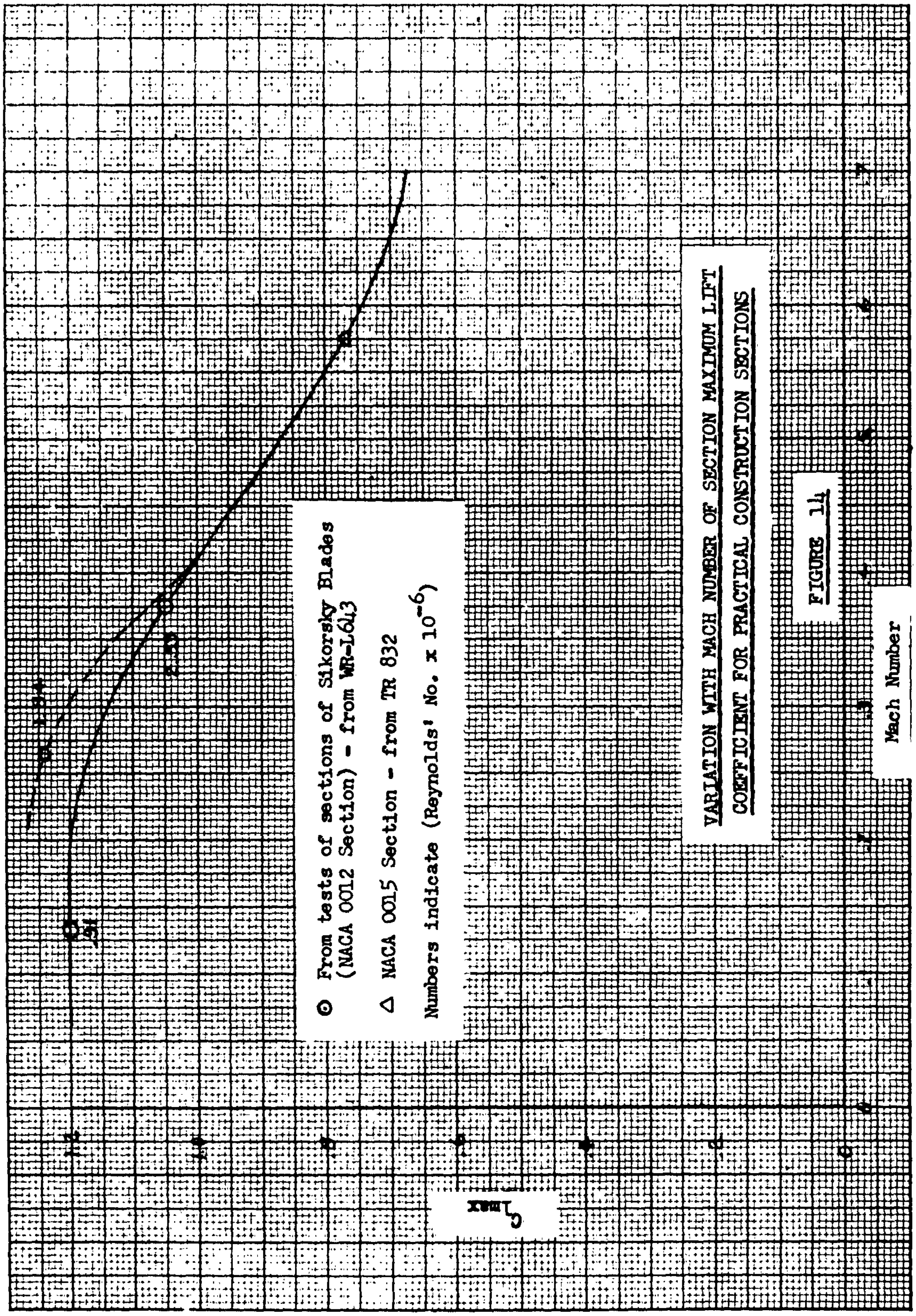

FIGURE 14

VARIATION WITH MACH NUMBER OF SECTION MAXIMUM LIFT COEFFICIENT FOR PRACTICAL CONSTRUCTION SECTIONS

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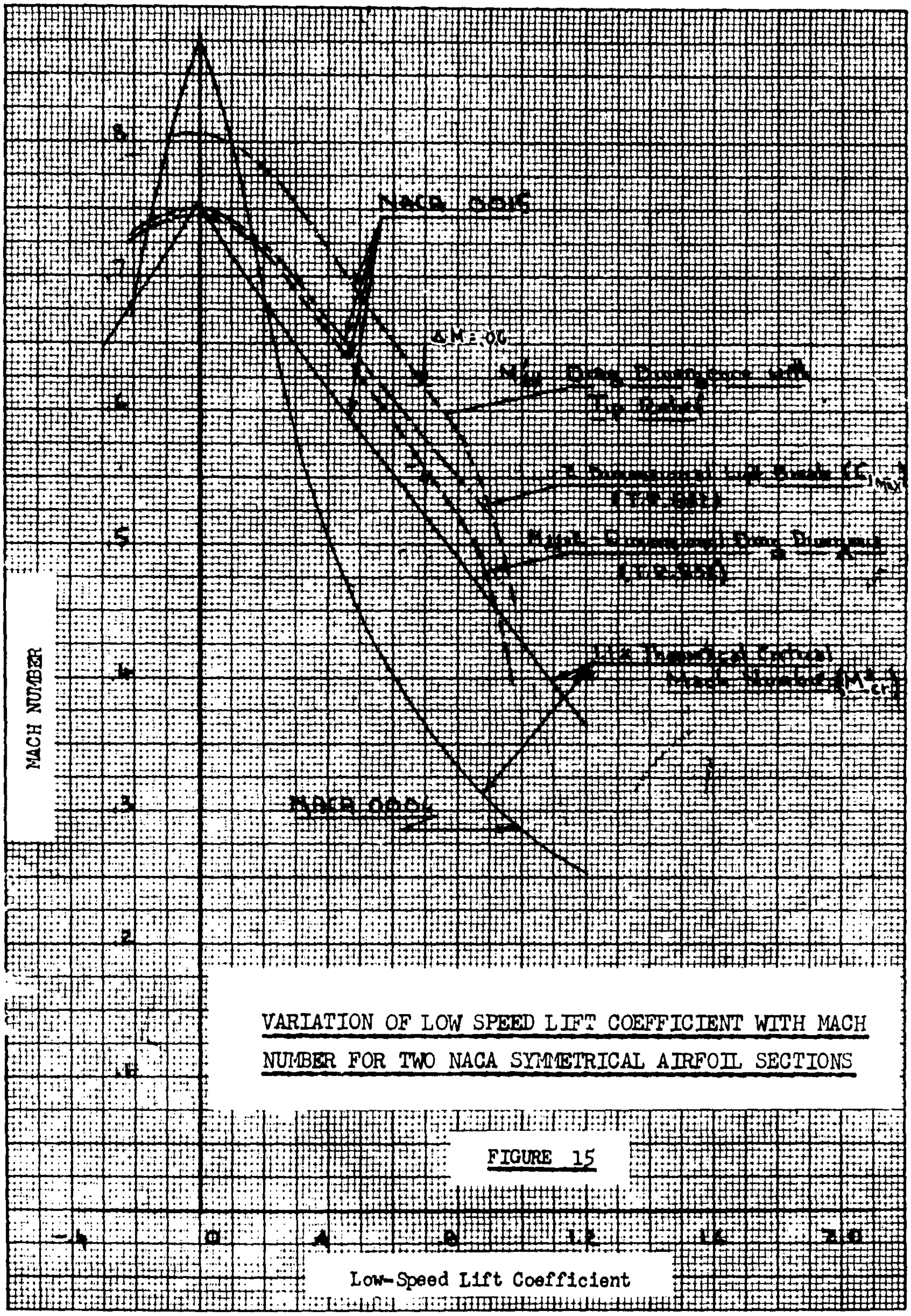


VARIATION OF LOW SPEED LIFT COEFFICIENT WITH MACH NUMBER FOR TWO NACA SYMMETRICAL AIRFOIL SECTIONS

FIGURE 15

5. Operation of Rocket-Powered Helicopter at High Subsonic Tip Speeds

It has been suggested that the rocket-powered helicopter should be operated at very high tip speeds to obtain optimum performance. In the following study it is shown that reductions in fuel rate of the order of 20% are theoretically obtainable by optimization of tip speed and solidity. This is achieved at the cost of an appreciable reduction in maximum forward speed and ceiling, due to stall and compressibility limitations. At the same time, due to the small blade chord required for optimization, serious mechanical problems are introduced in design of the rotor system and attachment of the tip power-plants.

The possibilities of optimizing rotor geometry and tip speed are brought out by Figure 7. As previously pointed out in Paragraph I.4.c.(1), at tip speeds above 550 fps the reduction in fuel rate coefficient K_f attainable by optimization diminishes with increasing tip speed.

The curves of Figure 7 include no allowance for losses due to stall and compressibility. From Figure 15 it is seen that maximum drag-divergence Mach number is approximately 0.8 for the 0015 section: allowing about 80 fps forward speed a tip speed of 800 fps brings the advancing blade tip to this Mach number. As pointed out later in this discussion, little if any reduction in cruising fuel rate is gained by operating at tip speeds greater than 750 fps Blades of lower than 15% thickness ratio have higher values of maximum drag-divergence Mach number, but also have lower $C_{l_{max}}$ and sharper stall characteristics, so that using thin sections is most unlikely to result in significant improvement in cruising fuel rate. Proposals to operate at very high rotational tip Mach numbers (in excess of about Mach .75) must, therefore, be regarded with scepticism, from the standpoints of fuel rate and power required, and the mechanical difficulties involved with engine and blade retention.

The gains from optimization are very soon lost if stall occurs. From Figure 2 of Reference 2, which is based on experimental data, it is found that rotor profile power losses are increased about 25% per degree angle of attack beyond the stall at the retreating blade tip. Since the profile power at cruising speed for the typical one-man helicopter is about 45% of total power required, exceeding stall by one degree results in an increase of about 11% in power required and in cruise fuel rate - more than half the theoretical gain from optimization referred to above. While losses due to drag divergence are not documented for rotor systems, they are likely to be of the same order. Thus the rotor configuration must be chosen to avoid stall and drag divergence in the cruising condition. The minimum rotor solidity results when drag divergence on the advancing blade tip, and blade stall and/or drag divergence at the retreating blade tip, occur at the same forward speed and tip speed. Thus the optimum rotor airfoil section for use at high subsonic tip speeds must offer a good compromise between zero-lift drag divergence Mach number and maximum permissible operating lift coefficient. On the basis of data currently available the NACA 0015 section appears to offer a favorable compromise, compared to other sections.

The maximum two-dimensional M_{dd} of the NACA 0015 section is seen from Figure 15 to be 0.75. It is pointed out in Reference 5 that two-dimensional M_{dd} may be exceeded by .060 before increase in profile power becomes noticeable.

An optimization study was made for a one-man helicopter having a gross weight of 400 pounds, a disk loading of 2.0 psf, K_{π} = .015, and using the NACA 0015 blade section. Solidity ratio, fuel rate coefficient K_f and forward speed were calculated for various tip speeds. The criteria of required solidity were avoidance of stall and drag divergence. The data are presented in Figure 16 for M_{dd} and $(M_{dd} + .06) = M'_{dd}$.

From a study of K_f versus tip speed **(Figure 16)**, it at once appears evident that little is to be gained in terms of fuel economy by running at tip speeds above 750 fps. The design problems become increasingly troublesome as tip speed increases, as pointed out later in the discussion. At the 750 fps tip speed the fuel rate coefficient = .080; at a tip speed of 600 fps and a solidity of .030, which permit a V_{max} of approximately 80 mph, K_f = .095 (Figure 7(a)). Thus, the fuel rate is reduced 16% by increasing tip speed from 600 fps to 750 fps, while reducing solidity ratio from .030 to .018. Assuming initial gross weight of 400 pounds and a TSFC of 20 lb/lb/hr (corresponding to an I_{sp} of 180 seconds), the fuel required for a range of ten nautical miles (without reserves) at a cruising speed of 45 knots is then reduced from 70 pounds to 59 pounds. At a tip speed of 700 fps and solidity of .023, K_f = .087 and fuel for ten miles is approximately 64 pounds.

While the theoretical saving in fuel by going to a tip speed of 750 fps is appreciable, the design problems involved are considerable. Blade chord is approximately 2-3/4 inches, and maximum thickness approximately 0.4 inches. Thus, attachment of the rocket powerplants in an aluminum blade requires that the section be at least 60% solid at the tip, and more material is required as the blade root is approached.

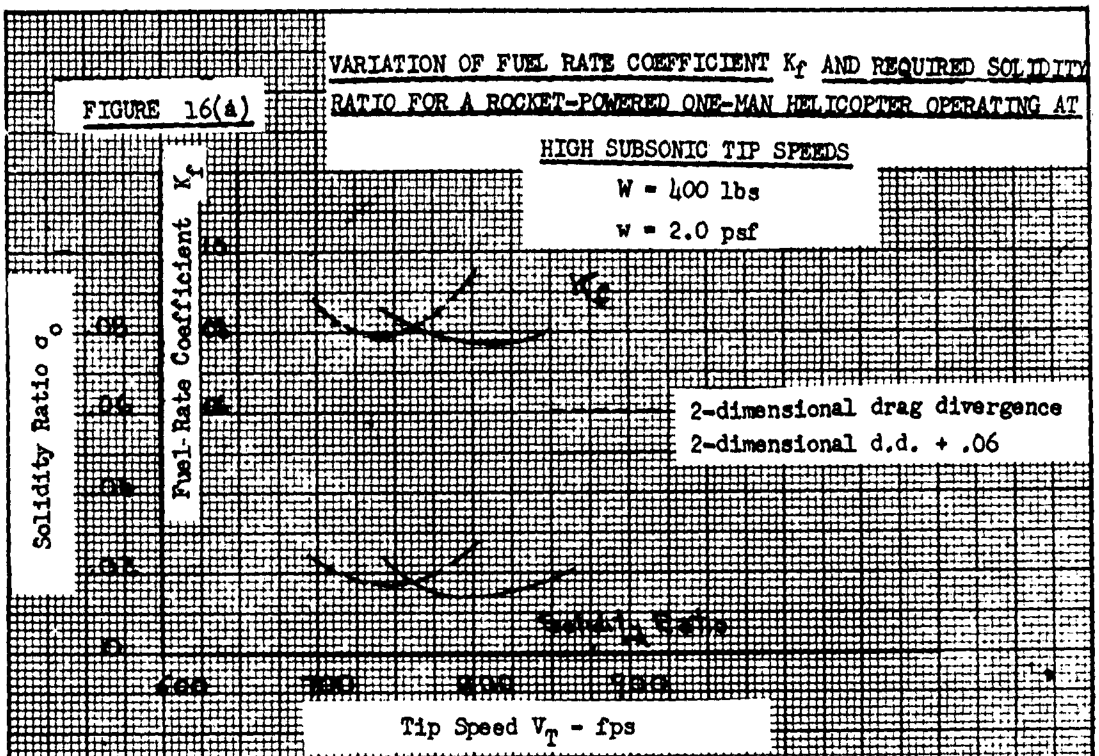


FIGURE 16(a)

VARIATION OF FUEL RATE COEFFICIENT K_f AND REQUIRED SOLIDITY RATIO FOR A ROCKET-POWERED ONE-MAN HELICOPTER OPERATING AT HIGH SUBSONIC TIP SPEEDS

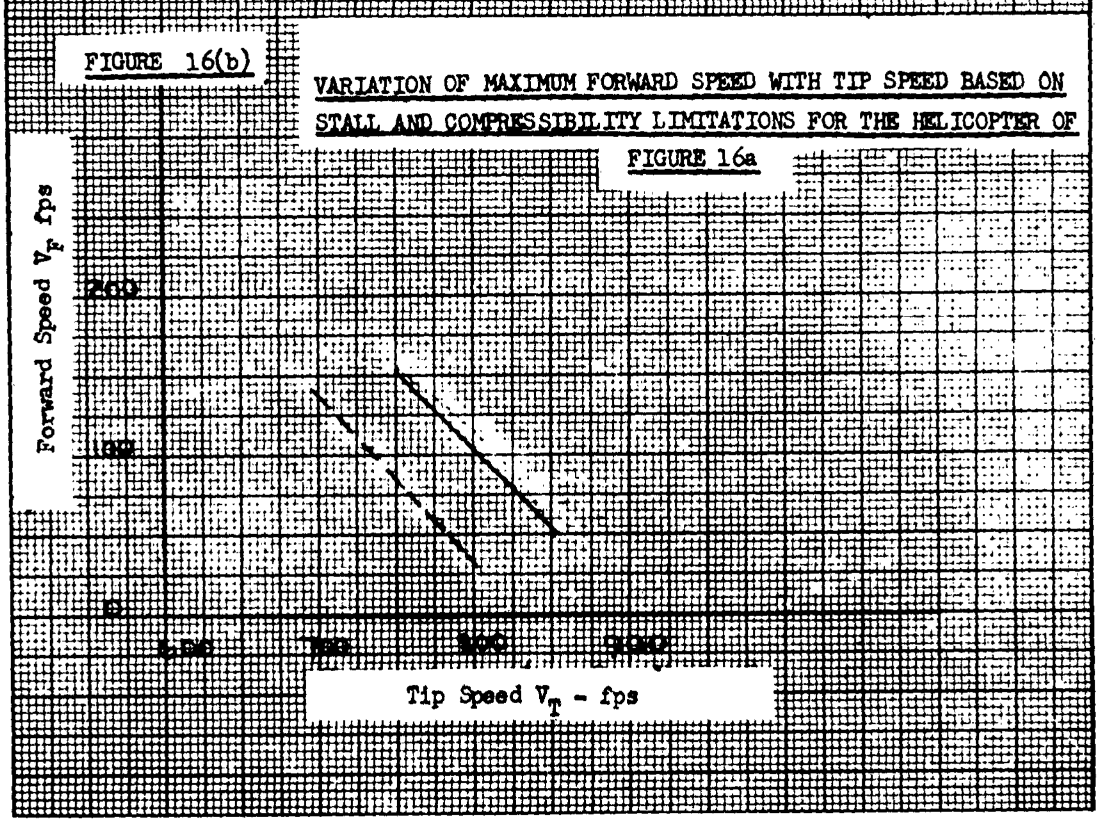


FIGURE 16(b)

VARIATION OF MAXIMUM FORWARD SPEED WITH TIP SPEED BASED ON STALL AND COMPRESSIBILITY LIMITATIONS FOR THE HELICOPTER OF FIGURE 16a

In the calculations of K_f it is assumed that the rocket engines can be faired without increase in blade profile losses. While losses due to engine fairing are probably small with the larger blades associated with the lower tip speeds, it is not likely that engine diameter can be decreased appreciably with tip speed, so that the gain in fuel rate may not be fully realized. The blade having a tip speed of 600 fps and .030 solidity is assumed to be untwisted. The low-solidity high-speed rotor must be twisted about -16° to permit operation at the tip angles of attack required to attain the required values of drag-divergence Mach number. An error of $\frac{1}{2}^{\circ}$ in retreating blade tip angle of attack can result in a reduction of 20 fps in the limiting forward speed; such an error could easily be caused by aeroelastic effects. In addition, severe twist of the blade will probably result in a considerable increase in the steady and one-per-rev flapwise bending moments; this is due to the fact that the spanwise center of pressure is moved inboard when the blade is twisted, while mass distribution is not appreciably affected. The relatively large amount of material required to withstand the centrifugal force of the rocket powerplant results in a considerable aft movement of the section c.g., resulting in chordwise balance problems. Either a nose weight must be added, or the engine c.g. must be moved forward of the blade quarter-chord station; the latter step results in appreciable local blade chordwise bending moments due to engine centrifugal loads. From the foregoing discussion it appears unlikely that any appreciable saving in rotor system weight can be realized when optimizing rotor tip speed and solidity to reduce fuel consumption.

In addition to the design and fabrication problems outlined above, reduction in solidity and increase in tip speed affects adversely the helicopter flying qualities. Assuming no reduction in γ , θ_o , or C_T/σ when reducing solidity from .030 to .018, and increasing tip speed from 600 to 750 ft/second, study of Figure 22 herein indicates that the hovering flying qualities will be changed from those shown for the rocket powered helicopter to something closely approaching those of the helicopter powered by a reciprocating engine. The percent overshoot, control sensitivity and ratio (height of second peak/height of first peak) in hovering are increased 50-60%. The reason for this is that the damping in pitch of the rotor system is inversely proportional to the rotor speed. Not only the hovering flying qualities but also the flying qualities in forward flight are adversely affected by reduction in damping in pitch. It is pointed out in Paragraph II,5,b that some means of providing angle of attack stability is required in forward flight to permit the one-man helicopter to meet the pull-up requirements of MIL-H-8501, and that the amount required varies inversely with damping in pitch. Angle of attack stability is most easily provided by means of a horizontal tail. Thus it may be inferred that the optimization in rotor geometry discussed here will result in a requirement for an increase in angle of attack stability, probably by means of additional horizontal tail area.

6. <u>The Ducted Propeller or Ring-Wing</u>

The use of a ducted propeller has been suggested for use as a rotor in one-man helicopter applications. Reference 21 presents theory and some test data in connection with a ducted propeller. A summary, with comments regarding application to the one-man helicopter, follows:

An increase in static thrust with very small increase in power is obtained by use of a circular duct, fabricated from a ring of airfoil cross-section. Physically, this results from an increase in mass flow through the duct, due to interaction of propeller and duct. A large proportion of the increase in thrust acts on the duct, and must, therefore, be transmitted through the structure attaching the duct to the airframe.

However, and most important, the propeller must be operated at very high values of thrust coefficient to realize this increase in thrust-power ratio. Experimental data presented in Figure 6-10 of Reference 21 indicates that in order to obtain best results the propeller should be operated at a thrust coefficient C_T of the order of 0.15, at which value thrust of the ducted unit is about three times that of the nonducted propeller, without appreciable increase in power required. When the ducted unit is operated at a C_T of .10, the increase in thrust drops to about 25%.

However, at a tip speed of 600 fps, a C_T of .10 represents a disk loading of 86 psf - obviously not a practical value for the one-man helicopter. Under optimum conditions the ducted propeller shown in Figures 6-10 of Reference 21 will be operating at a disk loading of 164 psf (with tip speed 600 fps), at a power corresponding to a disk loading, for the unducted propeller, of about 40 psf. (If tip speed is reduced to 300 fps, the above disk loadings become 41 and 10 psf respectively. Hovering power required for a disk loading of 10 psf is almost twice that for a disk loading of 2 psf.) Thus the ratio of lb/hp for the ducted propeller is considerably lower than that achievable with a conventional rotor. For example, in the case referred to above, with therefore, be regarded with scepticism, from the standpoints of fuel rate and power required, and the mechanical difficulties involved with engine and blade retention.

The gains from optimization are very soon lost if stall occurs. From Figure 2 of Reference 2, which is based on experimental data, it is found that rotor profile power losses are increased about 25% per degree angle of attack beyond the stall at the retreating blade tip. Since the profile power at cruising speed for the typical one-man helicopter is about 45% of total power required, exceeding stall by one degree results in an increase of about 11% in power required and in cruise fuel rate - more than half the theoretical gain from optimization referred to above. While losses due to drag divergence are not documented for rotor systems, they are likely to be of the same order. Thus the rotor configuration must be chosen to avoid stall and drag divergence in the cruising condition. The minimum rotor solidity results when drag divergence on the advancing blade tip, and blade stall and/or drag divergence at the retreating blade tip, occur at the same forward speed and tip speed. Thus the optimum rotor airfoil section for use at high subsonic tip speeds must offer a good compromise between zero-lift drag divergence Mach number and maximum permissible operating lift coefficient. On the basis of data currently available the NACA 0015 section appears to offer a favorable compromise, compared to other sections.

The maximum two-dimensional M_{dd} of the NACA 0015 section is seen from Figure 15 to be 0.75. It is pointed out in Reference 5 that two-dimensional M_{dd} may be exceeded by .060 before increase in profile power becomes noticeable.

An optimization study was made for a one-man helicopter having a gross weight of 400 pounds, a disk loading of 2.0 psf, $K_\pi = .015$, and using the NACA 0015 blade section. Solidity ratio, fuel rate coefficient K_f and forward speed were calculated for various tip speeds. The criteria of required solidity were avoidance of stall and drag divergence. The data are presented in Figure 16 for M_{dd} and $(M_{dd} + .06) = M'_{dd}$.

From a study of K_f versus tip speed **(Figure 16)**, it at once appears evident that little is to be gained in terms of fuel economy by running at tip speeds above 750 fps. The design problems become increasingly troublesome as tip speed increases, as pointed out later in the discussion. At the 750 fps tip speed the fuel rate coefficient = .080; at a tip speed of 600 fps and a solidity of .030, which permit a V_{max} of approximately 80 mph, $K_f = .095$ (Figure 7(a)). Thus, the fuel rate is reduced 16% by increasing tip speed from 600 fps to 750 fps, while reducing solidity ratio from .030 to .018. Assuming initial gross weight of 400 pounds and a TSFC of 20 lb/lb/hr (corresponding to an I_{sp} of 180 seconds), the fuel required for a range of ten nautical miles (without reserves) at a cruising speed of 45 knots is then reduced from 70 pounds to 59 pounds. At a tip speed of 700 fps and solidity of .023, $K_f = .087$ and fuel for ten miles is approximately 64 pounds.

While the theoretical saving in fuel by going to a tip speed of 750 fps is appreciable, the design problems involved are considerable. Blade chord is approximately 2-3/4 inches, and maximum thickness approximately 0.4 inches. Thus, attachment of the rocket powerplants in an aluminum blade requires that the section be at least 60% solid at the tip, and more material is required as the blade root is approached.

tip speed of 300 fps and disk loading of 41 psf, the ratio P_r/W is approximately 0.1, compared to a value of 0.058 for a conventional rotor at a disk loading of 2 psf, a tip speed of 600 fps, and a solidity ratio of .030.

The above figures are presented for static thrust only. If the ducted unit is to be moved laterally through the air (as would be expected for the one-man helicopter) the parasite drag of the units will be considerable. Assuming that a disk loading of 40 psf can be tolerated (from the standpoint of power-off descent), a duct diameter of approximately 4 feet would be required for a 400 pound helicopter. With a duct length of 1.0 feet, the additional equivalent flat plate area due to the duct is 4.0 square feet - an increase of about 60% from the conventional configuration with unfaired pilot.

The weight required for the duct and support structure must be considered as additional penalty. For the 'lateral' configuration structure must be provided to attach both ducts rigidly to the pylon, and for rotor drive, if a geared system is used.

7. Performance of a One-Man Helicopter

Figures 17 through 21 present estimated performance for a one-man helicopter. The calculations were based on the following characteristics:

Gross Weight: 400 lbs

Disk Loading: 2 psf

Solidity Ratio: .030

Tip Speeds: 550, 600, 650

Flat Plate Area Coefficient $K_\pi = A_\pi/W = .015$

VARIATION WITH FORWARD SPEED OF NET ROTOR
HORSEPOWER REQUIRED
SELECTED ALTITUDES AND TIP SPEEDS

Disk Loading = 2.0 psf
Solidity Ratio = .030
K_π = .015

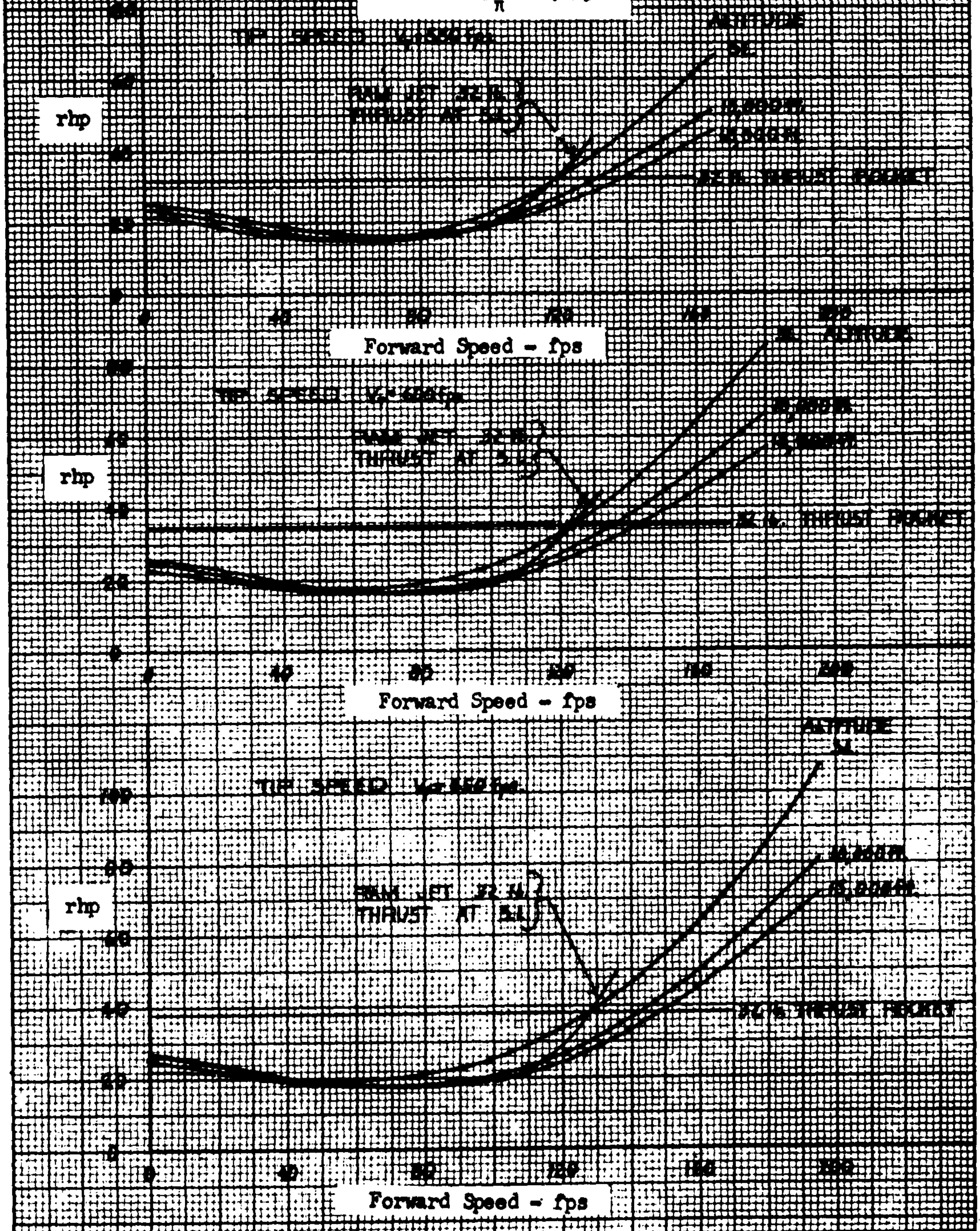


FIGURE 17

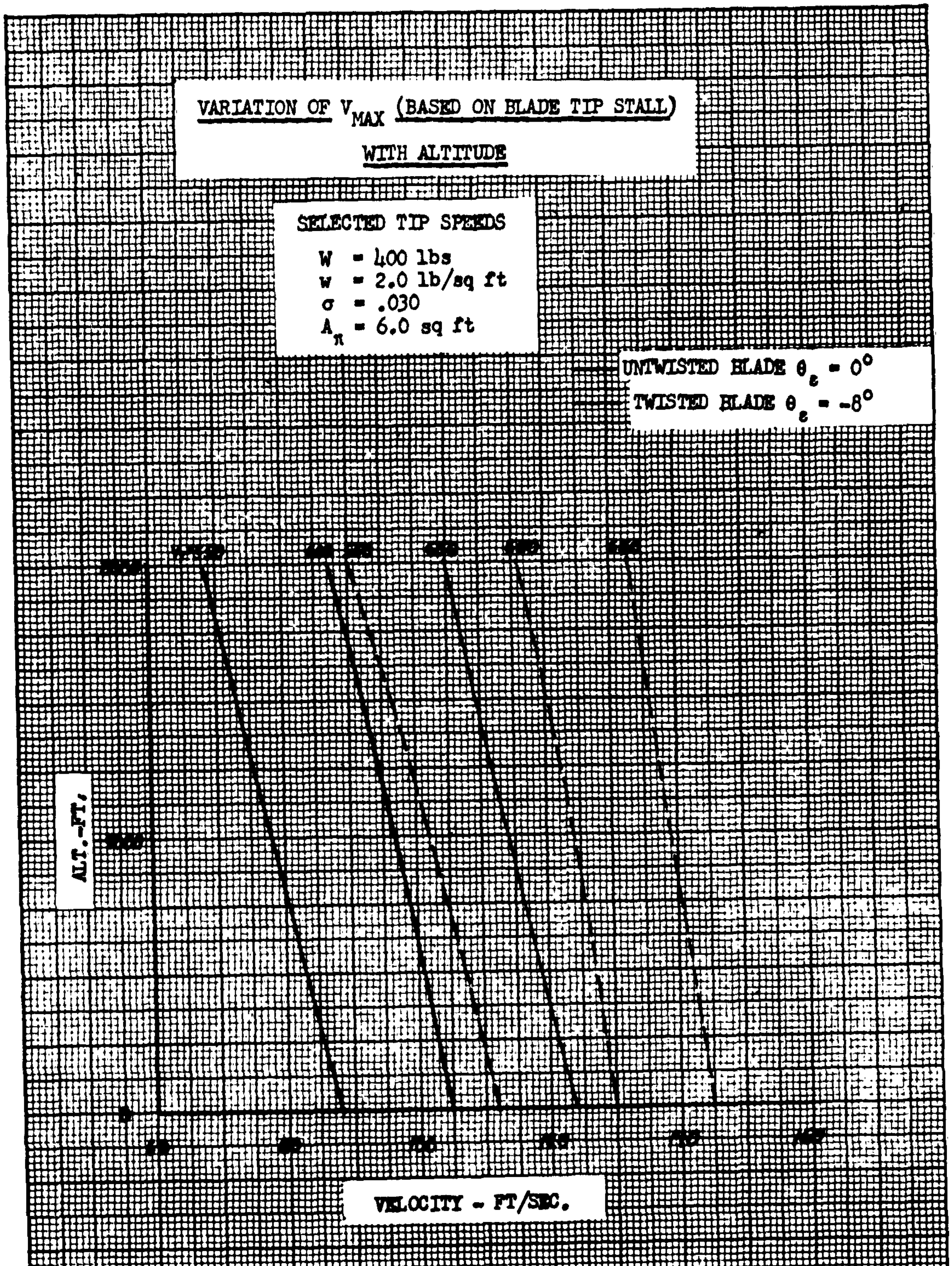

VARIATION OF V_{MAX} (BASED ON BLADE TIP STALL)
WITH ALTITUDE
SELECTED TIP SPEEDS
W = 400 lbs
w = 2.0 lb/sq ft
σ = .030
A_π = 6.0 sq ft
UNTWISTED BLADE $\theta_\varepsilon = 0^\circ$
TWISTED BLADE $\theta_\varepsilon = -8^\circ$
ALT.-FT.
VELOCITY - FT/SEC.

FIGURE 18

CONFIDENTIAL

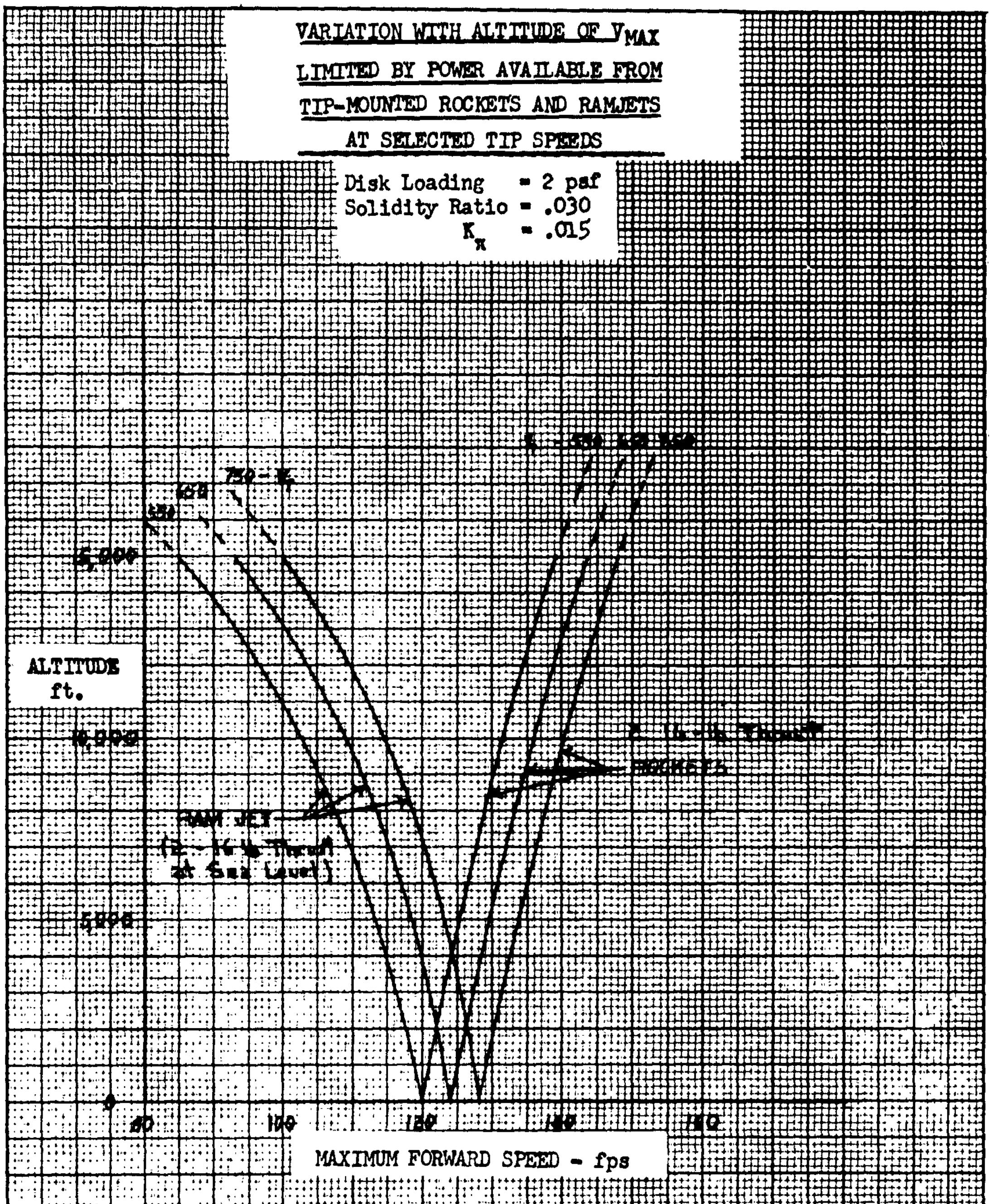
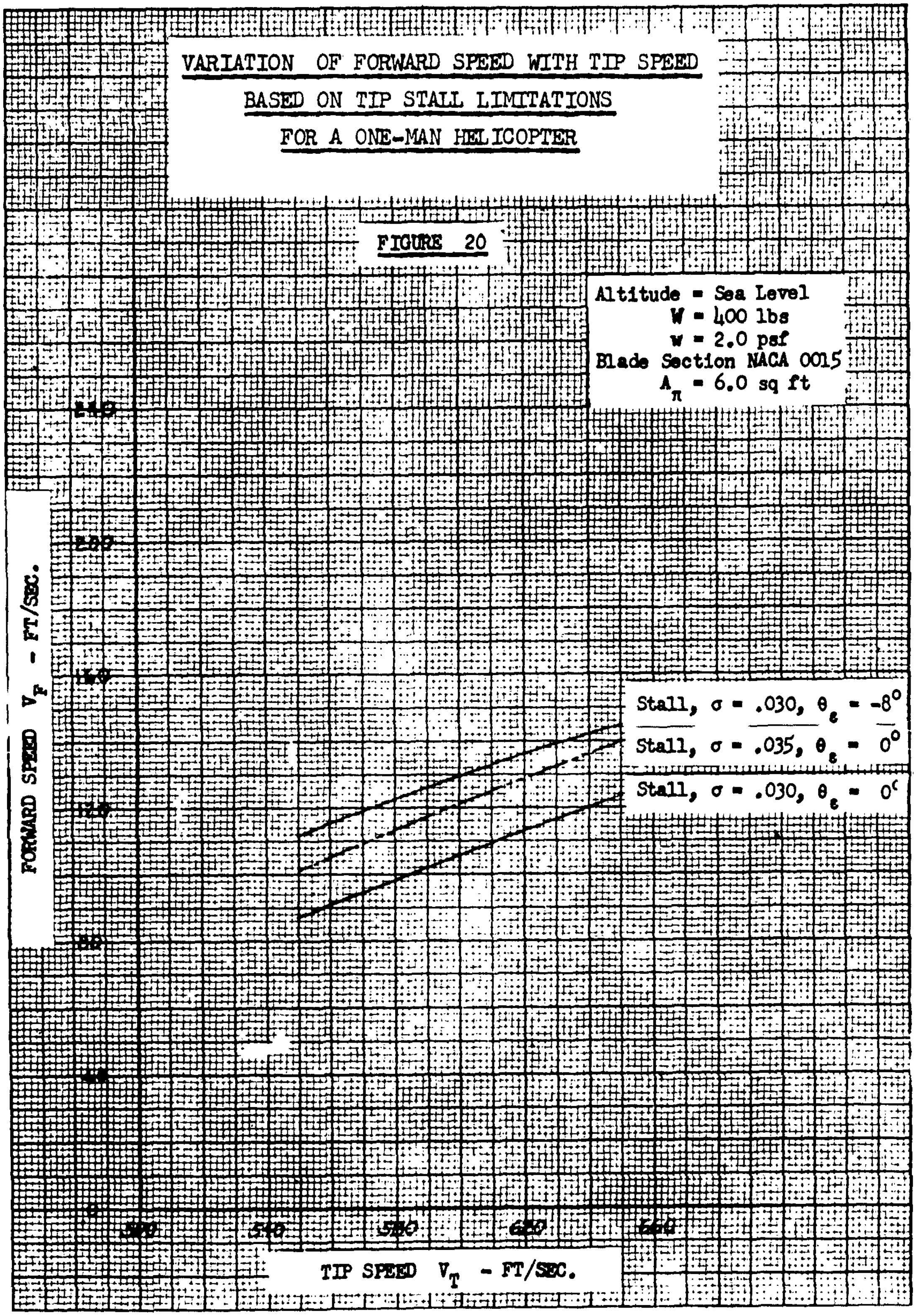


FIGURE 19

CONFIDENTIAL


VARIATION OF FORWARD SPEED WITH TIP SPEED
BASED ON TIP STALL LIMITATIONS
FOR A ONE-MAN HELICOPTER
FIGURE 20
Altitude = Sea Level
W = 400 lbs
w = 2.0 psf
Blade Section NACA 0015
A = 6.0 sq ft
Stall, σ = .030, θ = -8°
Stall, σ = .035, θ = 0°
Stall, σ = .030, θ = 0°
FORWARD SPEED V - FT/SEC.
TIP SPEED V - FT/SEC.

VARIATION WITH FORWARD SPEED
OF COLLECTIVE PITCH θ_o
SELECTED TIP SPEEDS AND ALTITUDES

Disk Loading = 2.0 psf
Solidity Ratio = 0.030
K_π = 0.015

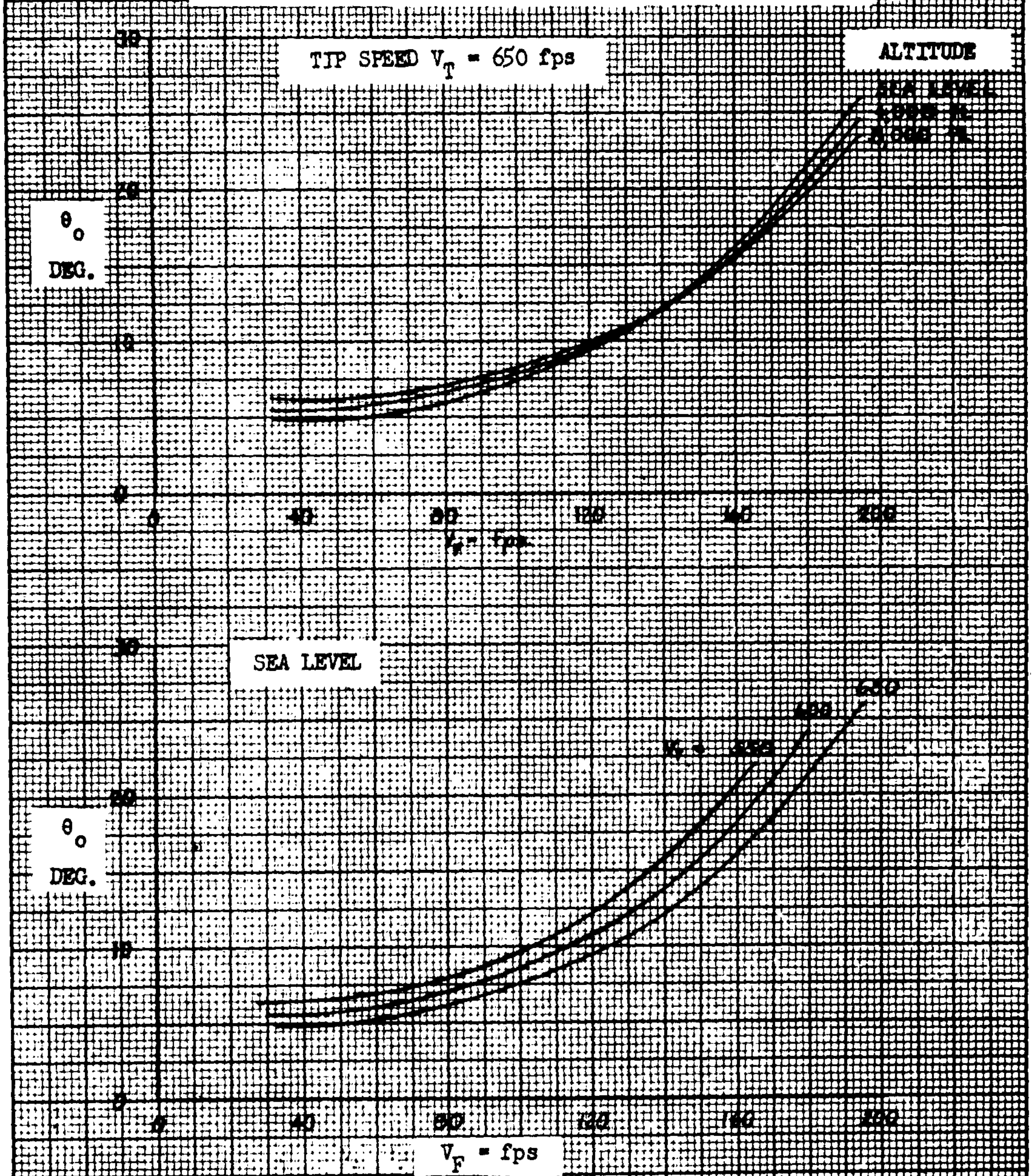


FIGURE 21

The Figures are self-explanatory, in general, and only the following comments are necessary:

Maximum speed is based on stall at retreating blade tip (Figures 19 and 21); with $C_{l_{max}}$ based on Figure 14.

Compressibility limitations at the advancing blade tip are not critical, and are not shown on the charts.

From Figure 18 it is seen that V_{max} based on power available increases with altitude for the rocket, and decreases with altitude for the ramjet (as it would for all air-breathing engines unless supercharged). Thus altitude limitations for the rocket powerplant are aerodynamic, and in the case of the one-man helicopter are likely to be based on tip stall.

8. Methods of Performance Calculation

The performance calculations used in preparing Figures 17 through 21 are based on methods developed at Hughes Aircraft Company. References 10, 12, and 13 present procedures developed by the NACA for performance estimation and the results obtained by use of these methods will be very similar, and in general slightly more optimistic than those presented here.

Other sources of performance methods are References 14, 19 and 23. Reference 19 discusses in detail the NACA procedures, and presents a comprehensive bibliography on the subject. Reference 23 presents a very complete discussion of rotor aerodynamics, and of helicopter stability and control.

SECTION II - FLYING QUALITIES OF THE ONE-MAN HELICOPTER

1. Flying Qualities of the Ideal One-Man Helicopter

The proponents of airborne assault by means of one-man helicopters visualize a machine which may be flown by relatively unskilled personnel. The ideal machine is first described. In contrast, Paragraph II.2. discusses the flying qualities which may prove feasible for the one-man helicopter. As would be expected, these fall short of the idealized requirements.

a. Rotor speed held constant by a speed governor, or:

Throttle connected to collective pitch stick, scheduled so that power required at constant rotor speed is obtained, independent of pitch setting.

b. Ship will have fairly long natural period in pitch and roll (15-20 seconds) so that normal pilot control motions will not tend to amplify oscillations. Slow motion of ship will then permit ample recovery time after a displacement.

c. Reduced control response. A control response 35% to 50% less than that of a one-man helicopter having geared drive appears to be satisfactory.

d. The machine should be at least neutrally stable in hovering and at cruising speed. Hovering 'hands-off' for periods of 30 seconds or more should be possible.

e. It should be possible to fly an assault mission with only three collective pitch settings, and without any need for throttle adjustment. The operation might be carried out as follows:

(1) Run-up with collective pitch on low-pitch stop.

(2) Take-off, hover and cruise on level flight stop.

(3) Autorotation on low-pitch stop.

(4) Flare-out on level flight stop.

(5) High pitch stop available for maneuver and full-power climb.

f. In addition to the above characteristics, the ideal machine should meet the Flying Qualities Requirements of Reference 15 (MIL-H-8501).

2. Recommendations Regarding Achievable Flying Qualities of the One-Man Helicopter.

In contrast to the idealized requirements for the one-man helicopter, discussed in Paragraph II.1., minimum flying qualities requirements, which are regarded as being achievable and highly desirable, are discussed below:

a. The helicopter shall meet the maneuver stability requirements of Reference 15, Paragraphs 3.2.11.1 and 3.2.11.2. (It is the opinion of the author of Reference 18 that a helicopter which meets Paragraph 3.2.11.1 will probably meet Paragraph 3.2.11.2 without modification.)

b. It is probably not imperative to provide hovering stability. The hovering flying qualities obtained for values of the hovering stability parameter (see Paragraph II.3.c. herein) between 5 and 10 appear to be satisfactory.

c. Stable stick travel in the flight range from about 30 mph to top speed should be provided.

The simplest and most reliable way to achieve items (a), (b), and (c) above is by use of tip weights and a horizontal stabilizer. A control rotor or a gyroscopic stabilizing bar will, up to a certain point, also provide maneuver stability, in addition to superior hovering characteristics. However, it is doubtful whether they will provide stick position stability.

In addition to the above requirements, the following provisions are desirable to obtain adequate flying qualities:

d. Either a movable vertical fin with an effective tail volume (= tail area x tail arm) of 15-25 cubic feet, or a control tail rotor with maximum moment of about 30 ft-lbs should be provided. The tail rotor is more desirable from the standpoint of safety to the pilot, but is obviously more dangerous to surrounding personnel. A blade which shatters on impact without severe injury to the body is desirable, but a suitable material has not yet been suggested. The alternative is a rotor guard, similar to that used on bandsaws.

e. In view of the weight and complication of suitable speed governor, it is probable that the pitch-power schedule (Paragraph II.7.b.) will prove more practical. Monitoring by the pilot will be required. This schedule does not function power-off.

f. In general, the use of offset flapping hinges is not recommended. The offset hinges improve hovering flying qualities, but with rapidly diminishing returns for offsets greater than about 3% of rotor radius. Additional advantages are greater permissible c.g. travel, and improvement in stick position stability. Disadvantages are increased hub weight and vibration, due to steady and vibratory moments caused by blade flapping and directly proportional to amount of offset. Maneuver stability is improved at low speed, but the improvement becomes less with increasing speed. The stress and vibration effects due to offset probably outweigh the advantages.

3. Flying Qualities - General

a. Discussion of Criteria

The literature contains a considerable amount of analytical work in connection with helicopter stability, most of it concerned with the period and damping of free oscillations. In seeking suitable flying qualities criteria, the following points must be considered:

The most important flying qualities requirements are those relating to maneuver stability in forward flight, specified in MIL-H-8501 (see Paragraph II.3.c. herein).

The next most important requirement (hovering or forward flight) is that relating to control sensitivity. This is stated in Paragraph 3.3.14 of MIL-H-8591 (Reference 15).

In hovering, except for control sensitivity, **the most important requirements for rotorcraft are those concerning directional flying qualities.**

Both civil and military specifications state a requirement for stick position stability in forward flight (stick travel directly proportional to forward speed).

The maneuver stability requirements were arrived at as the result of an NACA flight test program for the study of helicopter flying qualities (discussed in Reference 16). It is concluded in Reference 16 that the most important factor in the longitudinal characteristics in both pull-ups and steady flight is whether or not a prolonged stick-fixed divergence will occur; that the degree of pilot satisfaction with the characteristics of a pull-and-hold maneuver correlated with his satisfaction with the normal-flying characteristics; and that a requirement based on long-period oscillations could not be used as a substitute for the pull-and-hold requirements.

The control sensitivity problem is discussed in Reference 20, where it is pointed out that the maximum roll rate of a conventional two-place helicopter is about twice that for a conventional two-place airplane, while the helicopter has only about one-fourth the damping in roll of the airplane. Thus a serious danger of overcontrolling exists in the helicopter, which is accentuated as the machine is reduced in size. It is, therefore, important that some means for achieving a reduced control response be incorporated in the one-man helicopter.

b. Means of Obtaining Satisfactory Flying Qualities

The paragraphs which follow present a discussion of means for predicting the flying qualities of a helicopter and the improvement in flying qualities obtainable with various devices. A brief discussion of recommended methods for improving one-man helicopter flying qualities is also included.

Increase in the rate damping of the helicopter will result in less sensitive control response, and improve the maneuver stability. The simplest method of increasing rate damping is by use of blade tip weights. In the case of tip drives the engine will provide some, if not all, of the required weight. Offset hinges also increase the rate damping, and help offset the reduction in rate damping of the main rotor that occurs as forward speed is increased. However, since angle of attack stability is adversely affected by offset hinges, the overall effect tends to be destabilizing in forward flight.

With rate damping obtained by means of tip weights, the helicopter may be stabilized to the flight path by providing angle of attack stability.

This is best obtained by means of a horizontal tail, which also helps to produce stick position stability. While it is true that the horizontal tail is ineffective in hovering and at low forward speeds, its simplicity compared to other stabilizing devices, plus the fact that adequate hovering stability is achievable by means of tip weights, are in its favor.

The gyroscopic stabilizer bar and the control rotor have been used for stabilizing helicopters. Of the two, it is probable that the control rotor is preferable for the one-man helicopter. Both devices as generally used increase the rate damping of the helicopter; in the case of the control rotor this may be varied by varying the aspect ratio of the control rotor paddles, and in the gyro bar by varying the characteristics of the viscous dampers. The control rotor also acts as an aerodynamic servo in the control system, resulting in a greatly reduced control response and the isolation of force feedback from the main rotor to the stick.

It does not appear likely that a small autopilot, sufficiently rugged and light for the one-man helicopter, will become available in the near future.

Figures 23 and 24 are maneuver stability charts, both based on the methods of Reference 18. Figure 23 was obtained as the result of an analogue computer program, using the helicopter equations of motion of Reference
The most important derivatives are the damping in pitch parameter M_q/I_y, and the angle of attack stability parameter M_α/I_y. An additional, but considerably less important stability parameter is gL_α/WV. Plots of $(M_\alpha/I_y)(WV/gL_\alpha)$ and M_α/I_y versus M_q/I_y for marginal maneuver stability (two-second requirement, Paragraph 3.2.11.1, Reference 15) are presented in

Figures 23(a) and 23(b). Figure 2 of Reference 18 presents similar curves.

Figure 3 of Reference 18 presents a plot of damping in pitch parameter versus modified angle of attack stability parameter for marginal maneuver stability. This chart is reproduced in Figure 21 herein, and the estimated characteristics of the one-man helicopter over a range of tip-speed ratios, with various stabilizing devices (including horizontal tail) are plotted on the chart.

Figure 24 is more general than Figures 23(a) and 23(b). The modified angle of attack stability parameter plotted in Figure 24 includes the term L_q, which is dependent on pitch change proportional to angle of attack: this term occurs in connection with devices such as the gyro bar, control rotor, and autopilot. When evaluating the maneuver stability of horizontal stabilizer and tip weights Figures 23(a) and 23(b) are adequate. However, when stabilizing devices with proportional control are investigated, use of Figure 24 is desirable.

c. Prediction of Flying Qualities

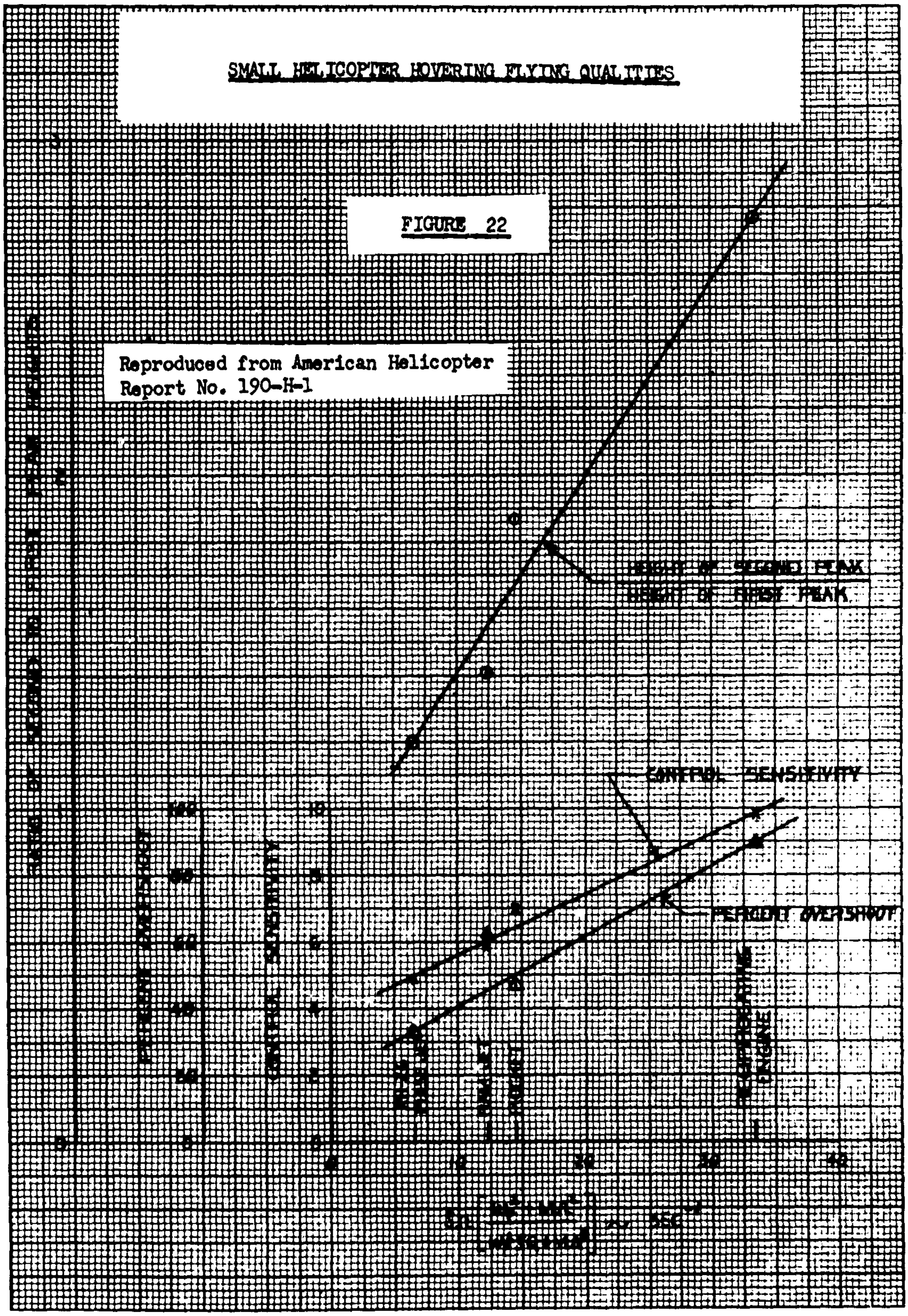
Reference 4 presents the most comprehensive studies to date on the hovering flying qualities of small helicopters. Reference 18 presents a chart method for predicting the ability of a helicopter to meet the maneuver stability requirement of Reference 15, Paragraph 3.2.11.1. This requirement is presented below:

> The following is intended to insure good maneuvering characteristics. After the longitudinal control stick is suddenly displaced approximately one inch rearward from trim

in steady flight and then held fixed, the time history of normal acceleration shall become concave downward within two seconds following the start of the maneuver, and remain concave downward until the attainment of maximum acceleration. Preferably, the time history of normal acceleration should be concave downward throughout the period between the start of the maneuver and the attainment of maximum acceleration.

In Reference 4 the hovering flying qualities of four small helicopters, powered respectively by pulse jet, ramjet, rocket and reciprocating powerplants, are analyzed. The first three have blade tip weights in the form of powerplants, the fourth has geared drive and, consequently, no tip weight on the blades.

Figure 22 is reproduced from Figure 2 of Reference 4. It is seen that the hovering flying qualities are related to a hovering stability parameter, which is approximately equal to the ratio of applied control moment to damping moment. The value of this parameter (and consequently control sensitivity, etc.) is greatly reduced by use of tip weights to increase rotor mass moment of inertia. It is probable that a one-man helicopter having a value of the parameter between 7 and 10 will have satisfactory hovering flying qualities. (It should be noted that the rocket helicopter referred to on the chart is powered by hydrogen peroxide rockets. These units are relatively light, which accounts for the relatively high value of 14.5 for the hovering stability parameter of this machine.)


SMALL HELICOPTER HOVERING FLYING QUALITIES
FIGURE 22
Reproduced from American Helicopter
Report No. 190-H-1
CONTROL SENSITIVITY
PERCENT OVERSHOOT
0
10
20
30
40

4. Discussion of Important Stability Derivatives, M_α and M_q.

a. Angle of Attack Stability Derivatives, M_α

According to the sign convention of Reference 18, used here, positive M_α is destabilizing. The following contributions to M_α are discussed:

M_{α_r} - contribution due directly to rotor. This is destabilizing.

$M_{\alpha_{rt}}$ - contribution of rotor due to use of thrust moment to trim out fuselage moments. Destablizing or for nose-down moments on fuselage.

M_{α_f} - direct contribution of fuselage.

M_{α_t} - contribution from a horizontal tail.

Figure 25 presents some 'fuselage' characteristics obtained from wind-tunnel tests of a one-man helicopter, reported in Reference 6. (Note: 'fuselage' includes pilot.) It should be noted that these results were obtained for a very smooth, streamlined model, which may not be representative of the one-man helicopter. The pilot of such a machine is likely to be wearing flight clothing having much rougher texture than that represented by the smooth surface of the model pilot used in the tests. It may not prove practical to fair the hub and pylon of the service article as was done for the model. Therefore, the aerodynamic characteristics of the service article may not reflect those found for the model. This is particularly important in relation to pitching-moments, which appear to be surprisingly high for the model, and which are such as to have an adverse effect on the maneuver stability characteristics, particularly on $M_{\alpha_{rt}}$. The model tests indicate that the 'fuselage' causes nose-down moments in forward flight (C_m negative over range of altitudes tested).

Also, the slope of C_m versus α_c for all configurations of the model is shown to be stable, so that M_{α_f} is stabilizing. It may be shown, however, for the magnitude and sense of C_m reported, that the destabilizing contribution of $M_{\alpha_{rt}}$ greatly exceeds the stabilizing contribution of M_{α_f}, so that the overall effect of the fuselage is destabilizing. As indicated above, the values of C_m reported are somewhat larger than would normally be expected; with a configuration having different stability characteristics the 'fuselage' contribution to maneuver stability may be less adverse than for the case considered.

The unstable contributions of rotor and fuselage to M_α may be countered by use of a horizontal stabilizer, or by displacement input (denoted by k_1 in Reference 4) to the controls. The displacement input may be obtained by such means as an autopilot, a gyro bar, or a stabilizer attached to the swashplate. However, it appears to be much simpler, and in general effective, to use the fixed horizontal stabilizer.

b. Damping in Pitch, M_q

As pointed out in Paragraph II.3.b. , the stability derivative M_q is important in relation to maneuver stability. Its importance in relation to hovering flying qualities is discussed below.

The hovering stability parameter presented in Reference 4 and in Figure 22 herein may also be expressed as follows:

$$\frac{\text{Applied Control Moment}}{\text{Damping Moment}} = \frac{Th + (CF)(e)}{M_{qr} + (CF)(e)(16/\gamma_1\Omega)} \tag{8}$$

This is increasingly the case as forward speed increases.

The expression for M_{qr} , derived in Reference 18 is:

$$M_{qr} = Th \left(\frac{-27}{\gamma_1 \Omega}\right)\left[1.0 - 0.29 \frac{\theta_o}{C_T/\sigma}\right] \quad (9)$$

In Reference 4, 24 is substituted for 27 (the latter number accounts for tip loss) and a/18 is substituted for 0.29.

With zero flapping hinge offset, Equation (8) reduces to Th/M_{qr} , and in hovering Equation (9) for the one-man helicopter is approximately $\gamma_1 \Omega/13.5$. **Thus with zero offset hinges the value of the hovering stability** parameter is approximately given for the one-man helicopter by:

$$\frac{\text{Applied Control Moment}}{\text{Damping Moment}} \text{ with zero flapping hinge offset} = \frac{\gamma\Omega}{13.5} \quad (10)$$

If a value of 10 is desired for this parameter (see Figure 22), it appears that $\Omega\gamma = 135$. Blade I_1 for a typical one-man helicopter (R = 8 ft, tip speed 600 fps, σ = .030) must then be approximately 12 slug-ft^2. Since I_1 for blade alone will be of the order of 6 slug-ft^2, **it appears** that with zero offset a tip weight of about 3 pounds is required to reduce the value of the hovering stability parameter to 10.

At speeds in excess of speed for minimum power, θ_o increases with speed (see Figure 17). From Equation (9) it is seen that M_{qr} decreases with increase in θ_o . In the case of the one-man helicopter described above, M_{qr} reduces to about 30% of its hovering value at 80 mph. From Figure 24 it is seen that a three inch flapping hinge offset provides maneuver stability approximately equal to that provided by a tail carrying no download, but considerably less than that provided by the tail set to balance the fuselage nose-down moment.

5. Effect of Various Items on Flying Qualities

a. Tip Weights

Figure 26(a), reproduced from Reference 4, presents the response of a small reciprocating engine driven helicopter with and without stabilization. It is seen that the effect of a three-pound tip weight on each blade makes the helicopter almost neutrally stable, and reduces the control sensitivity about 40%. The characteristics are then similar to those of the unstabilized pulse jet helicopter, as presented in Figure 26(b).

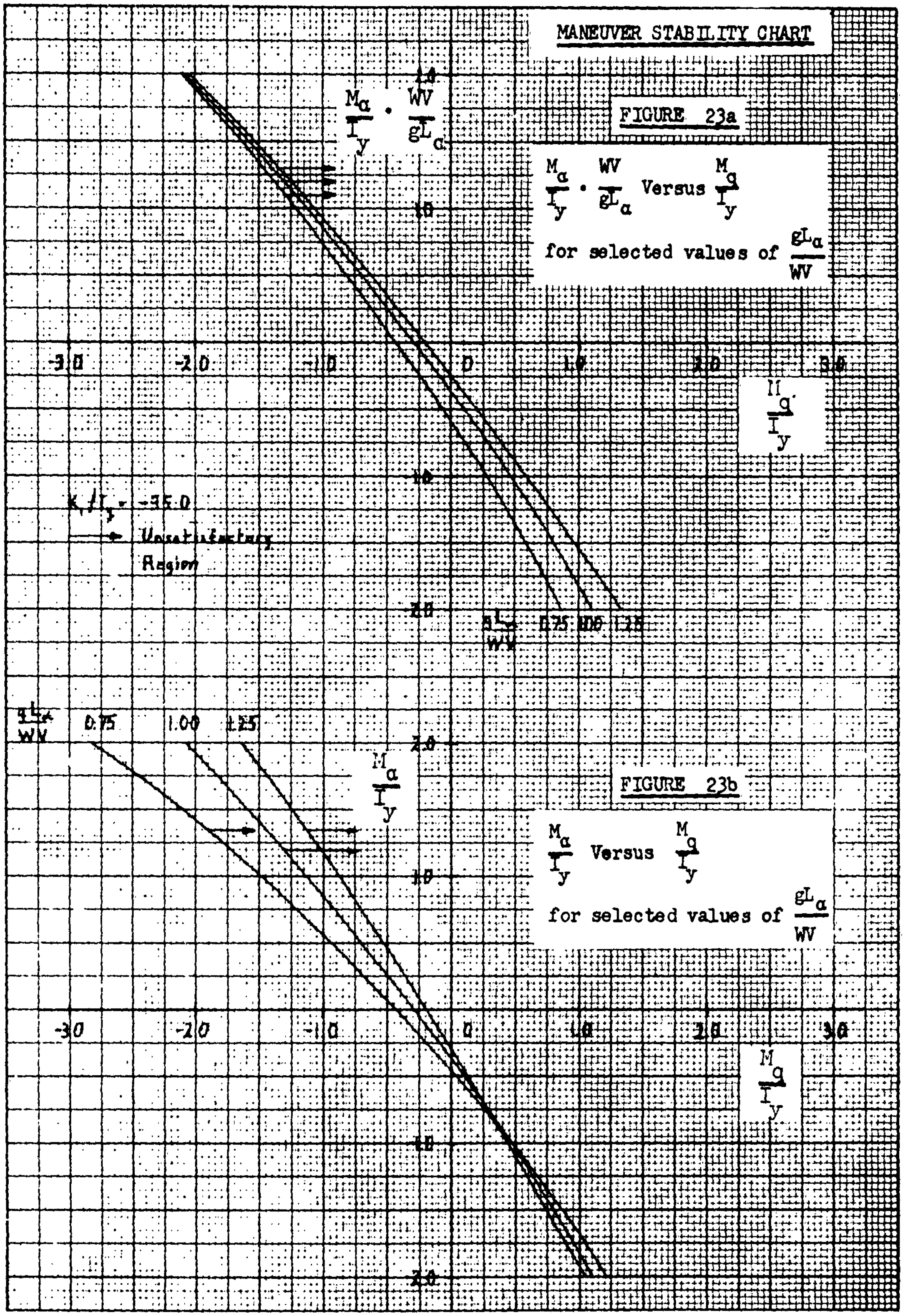
b. Horizontal Tail

Figure 24 presents the characteristics of a rocket-powered one-man helicopter plotted on the maneuver stability chart of Reference 18. It is seen that with no horizontal tail the maneuver stability margin is reached at $\mu = .11$; with tail carrying no download the margin is reached at about $\mu = .15$ (corresponding to about 90 fps). When the fuselage pitching moments are trimmed out by the horizontal tail (see discussion in Paragraph II.4.a. the machine possesses maneuver stability for μ in excess of .25.

Figure 27(a) presents M_α/I_y for the above configurations versus tip-speed ratio. It is seen that M_α is stabilizing only with the tail carrying download.

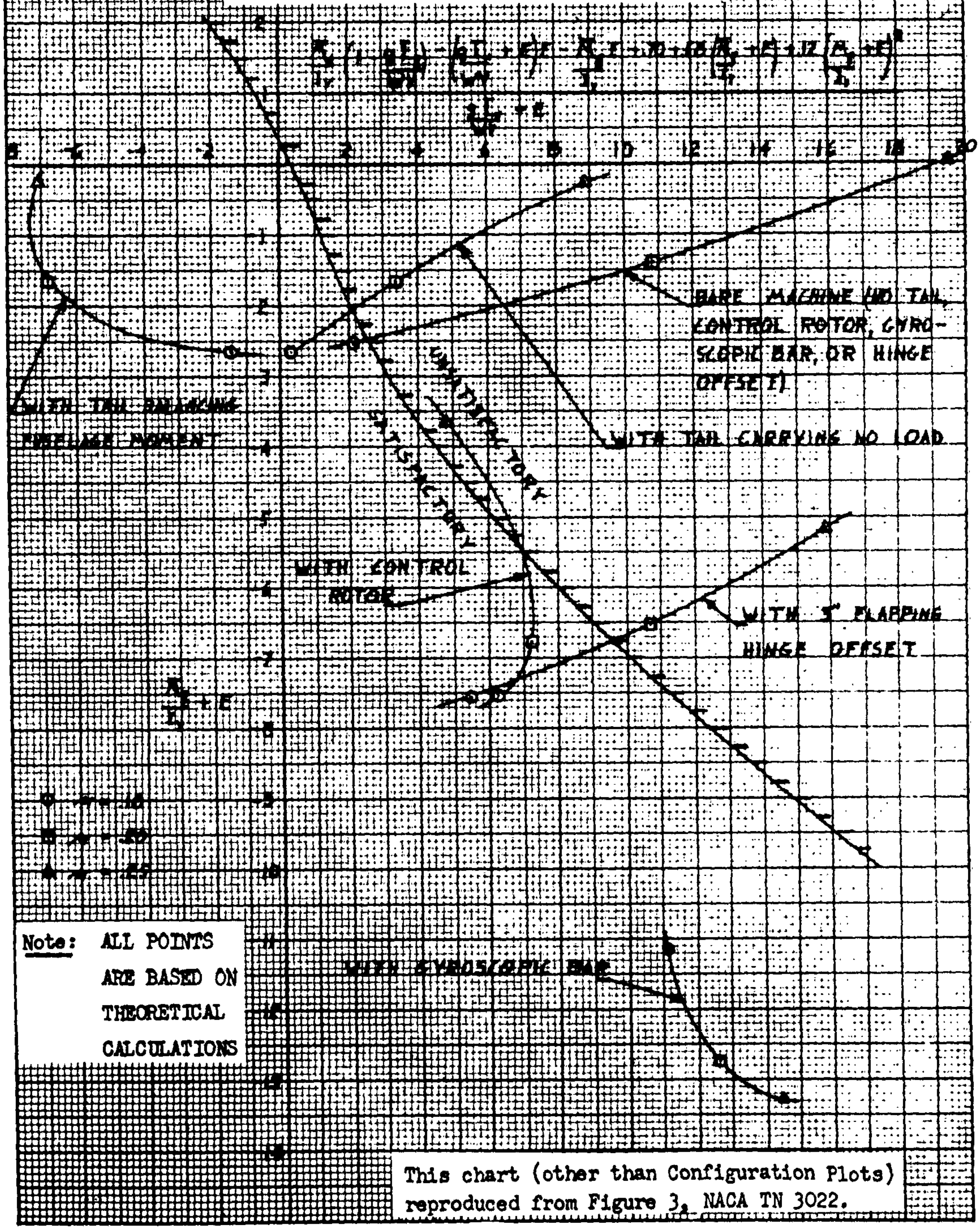
From Figure 27(b) it is seen that the horizontal tail has relatively small effect on M_q. (Note: $I_y = 40$ slug-ft^2 in these examples.)

Figure 28 illustrates the effect of various tail configurations on the stick position versus speed of the rocket-powered helicopter. It is seen that the horizontal tail, in addition to providing maneuver stability,


MANEUVER STABILITY CHART
FIGURE 23a
$\frac{M_\alpha}{I_y} \cdot \frac{WV}{gL_\alpha}$ Versus $\frac{M_q}{I_y}$
for selected values of $\frac{gL_\alpha}{WV}$
$\frac{M_\alpha}{I_y} \cdot \frac{WV}{gL_\alpha}$
-3.0 -2.0 -1.0 0 1.0 2.0 3.0
$\frac{M_q}{I_y}$
Unsatisfactory Region
$\frac{gL_\alpha}{WV}$ 0.75 1.00 1.25
FIGURE 23b
$\frac{M_\alpha}{I_y}$ Versus $\frac{M_q}{I_y}$
for selected values of $\frac{gL_\alpha}{WV}$
$\frac{gL_\alpha}{WV}$ 0.75 1.00 1.25
$\frac{M_\alpha}{I_y}$
-3.0 -2.0 -1.0 0 1.0 2.0 3.0
$\frac{M_q}{I_y}$

MANEUVER STABILITY MAP FOR SEVERAL CONFIGURATIONS OF A ONE-MAN HELICOPTER

FIGURE 24



Note: ALL POINTS ARE BASED ON THEORETICAL CALCULATIONS

This chart (other than Configuration Plots) reproduced from Figure 3, NACA TN 3022.

VARIATION OF PITCHING-MOMENT COEFFICIENT WITH PITCH ANGLE OF A 1/3-SCALE MODEL OF THE PINWHEEL HELICOPTER

$\delta_e = 0^{\circ}$, $\delta_r = 0^{\circ}$

(Data from Reference 6)

Note: $C_m = M/9q$

α_s = Shaft Longitudinal Tilt - Positive Aft

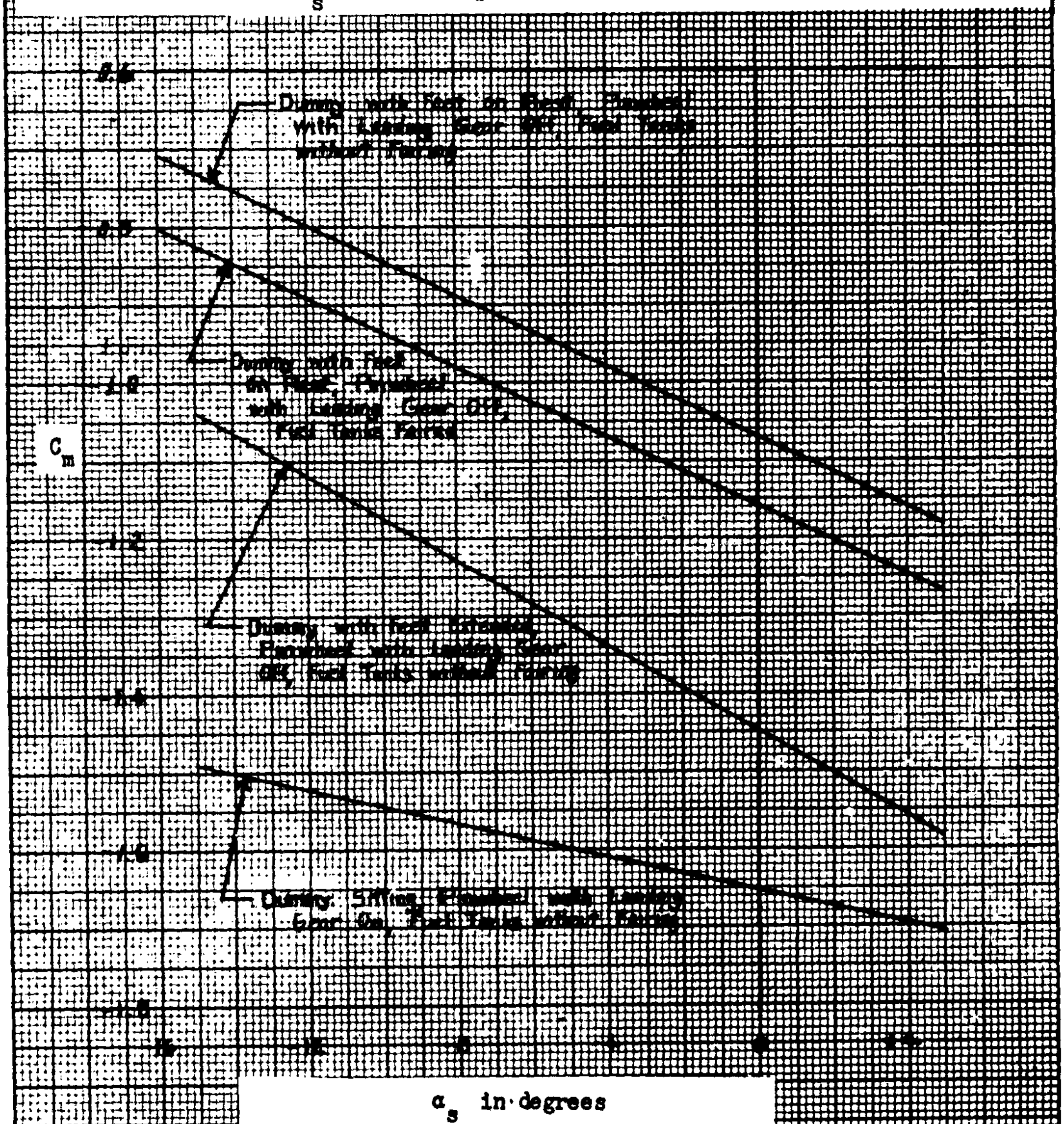
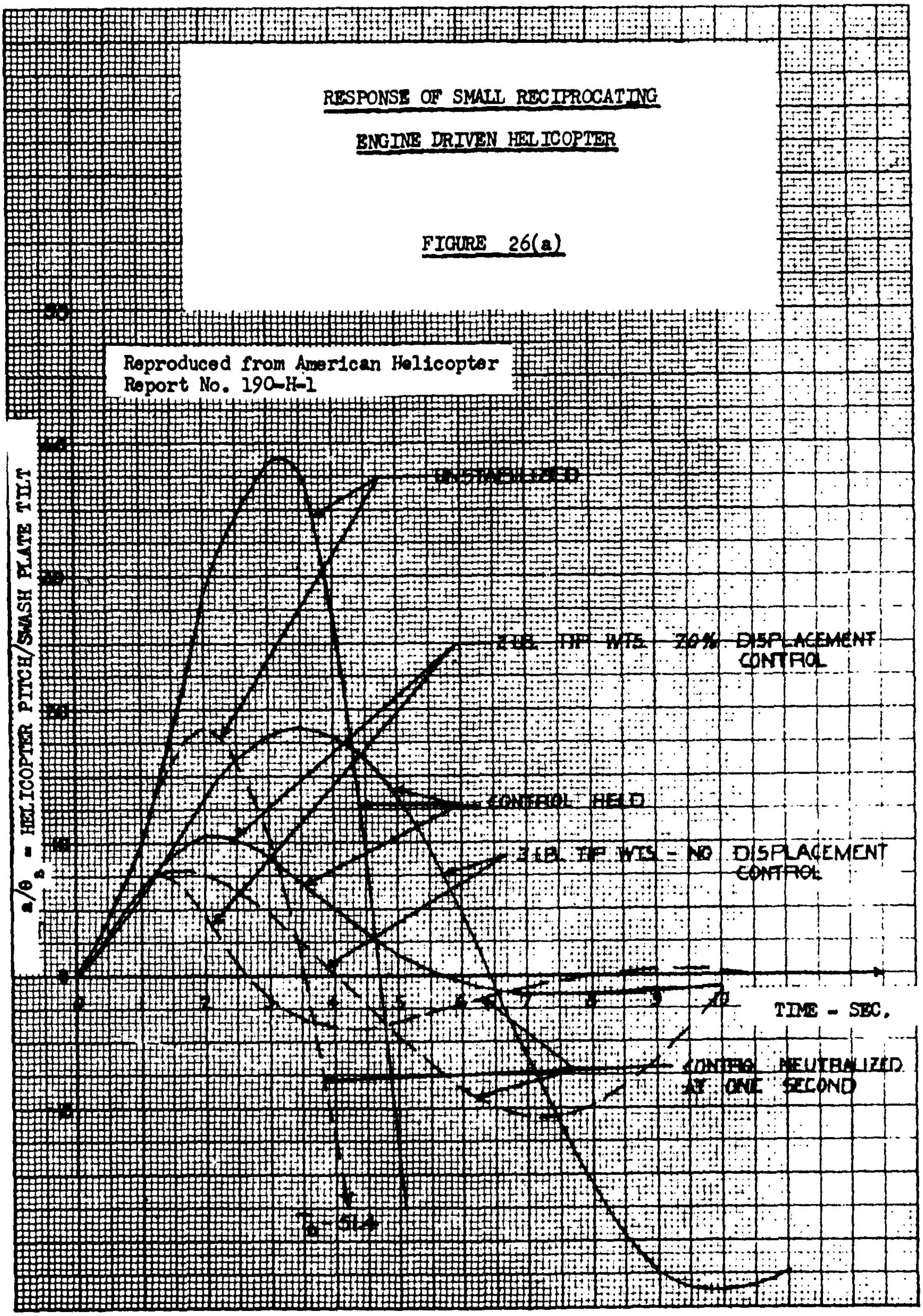


FIGURE 25



RESPONSE OF SMALL RECIPROCATING
ENGINE DRIVEN HELICOPTER
FIGURE 26(a)
Reproduced from American Helicopter
Report No. 190-H-1
UNSTABILIZED
DISPLACEMENT CONTROL
CONTROL HELD
NO DISPLACEMENT CONTROL
CONTROL NEUTRALIZED AT ONE SECOND
TIME - SEC.

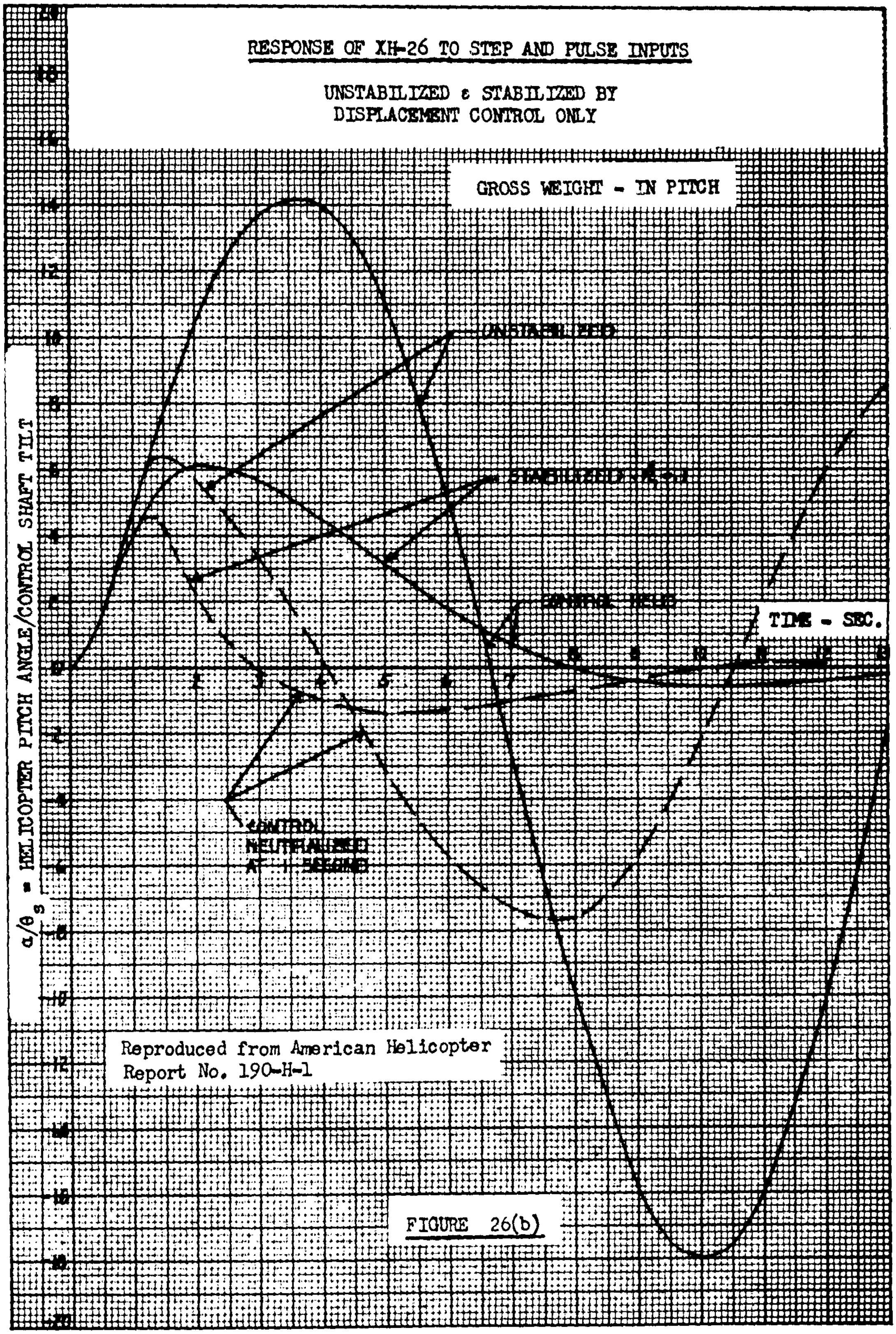

RESPONSE OF XH-26 TO STEP AND PULSE INPUTS
UNSTABILIZED & STABILIZED BY
DISPLACEMENT CONTROL ONLY
GROSS WEIGHT - IN PITCH
UNSTABILIZED
CONTROL HELD
TIME - SEC.
CONTROL
NEUTRALIZED
AT 1 SECOND
α/θs = HELICOPTER PITCH ANGLE/CONTROL SHAFT TILT
Reproduced from American Helicopter
Report No. 190-H-1

FIGURE 26(b)

EFFECT OF TIP SPEED RATIO ON

STABILITY DERIVATIVES

FOR ONE-MAN HELICOPTER

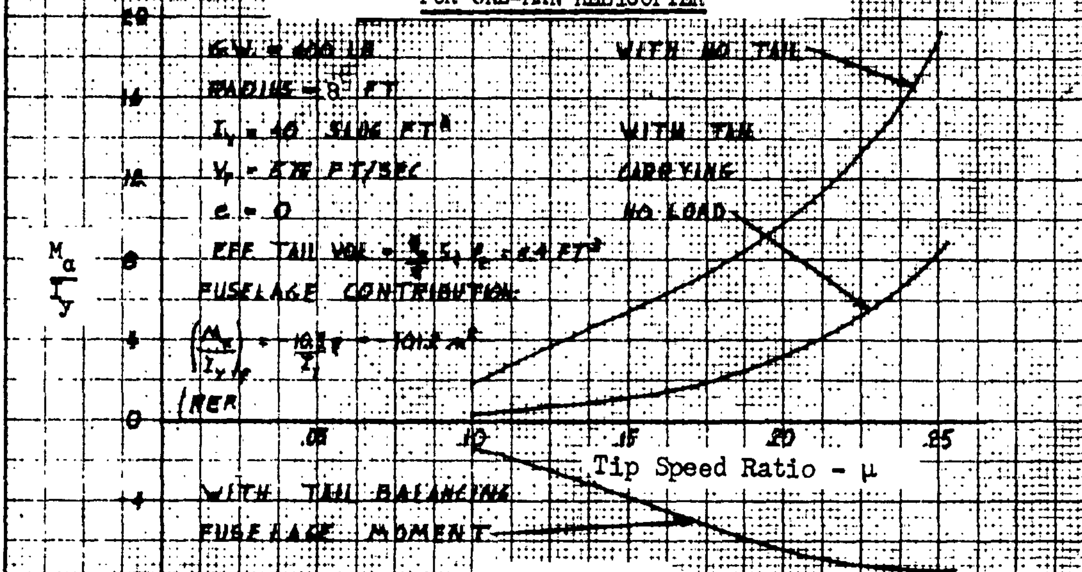


FIGURE 27(a)

Tip Speed Ratio - μ

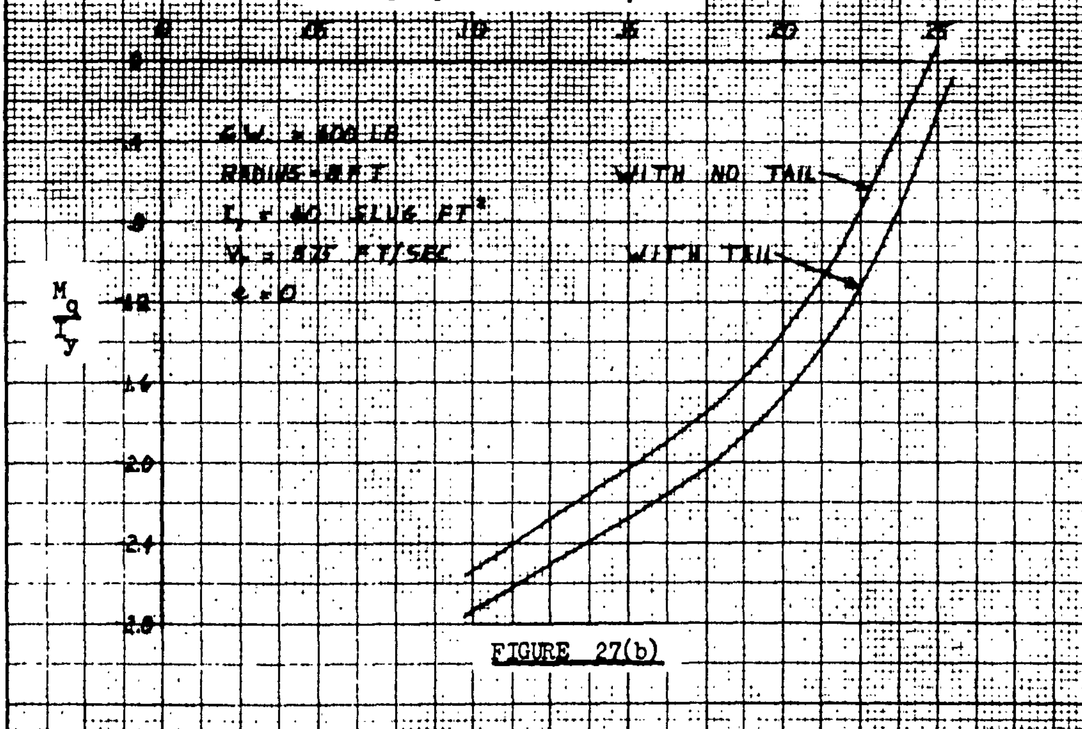
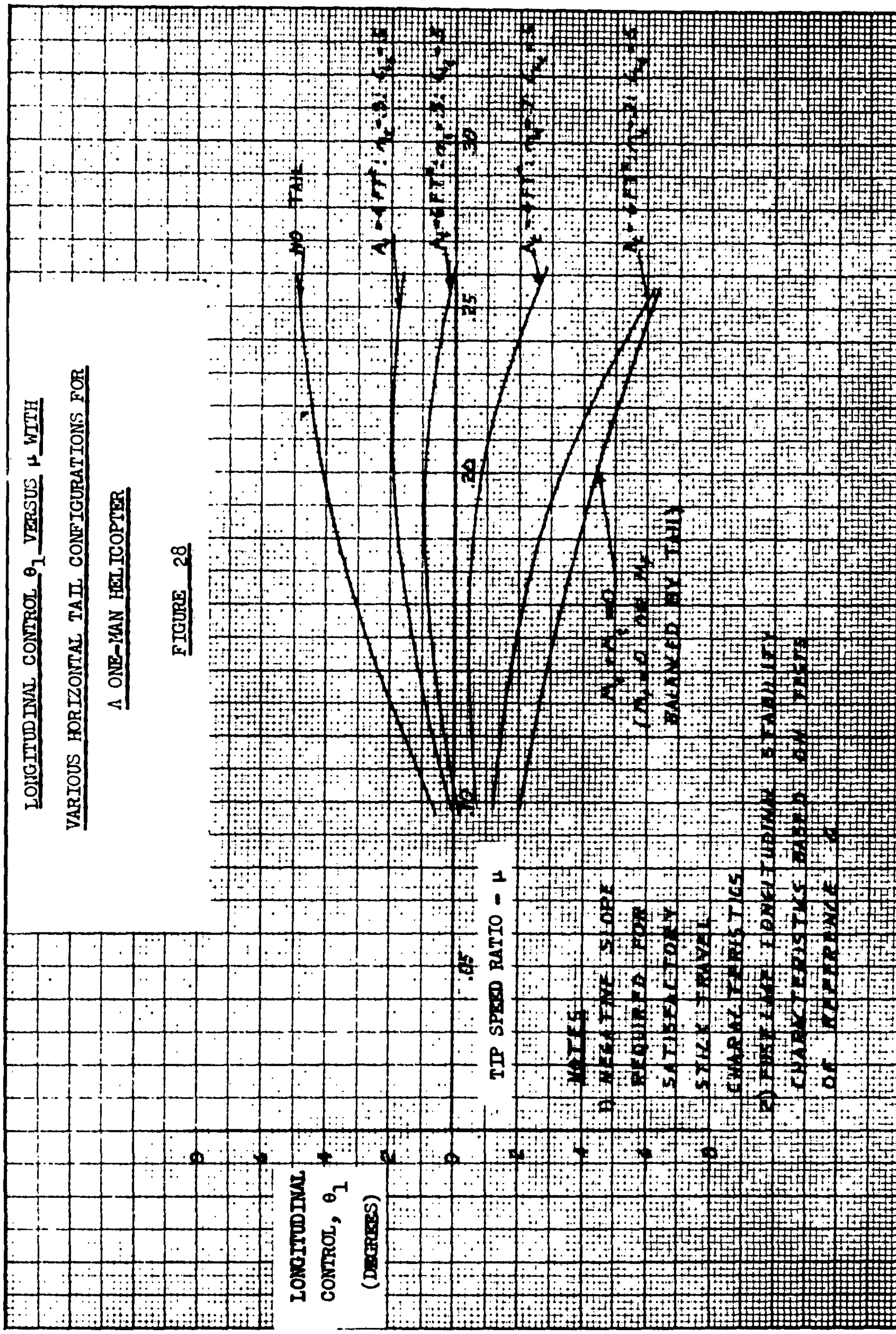


FIGURE 27(b)



LONGITUDINAL CONTROL θ_1 VERSUS μ WITH VARIOUS HORIZONTAL TAIL CONFIGURATIONS FOR A ONE-MAN HELICOPTER

FIGURE 28

also improves the stick position stability characteristics.

Tests reported in Reference 6, on a model of a one-man helicopter, indicated horizontal tail effectiveness of .3. This is probably due to the reduction in dynamic pressure behind the pylon. (Effectiveness is here defined as: measured tail power/estimated tail power in free stream.) Obviously a low effectiveness necessitates increase in tail area required for stabilization. This is also brought out by Figure 28.

c. Flapping Hinge Offset

Prior to discussing the effect of hinge offsets on other flying qualities, it should be pointed out that hinge offsets produce both steady and vibratory moments on the hub. In the case of the two-bladed rotor the steady moment (assuming lateral tilt of the tip path plane is zero) on the hub is equal to $(CF)(e)(a_1)$, and the vibratory moment = $(CF)(e)(a_1)(\cos 2\psi)$. For a three-bladed rotor,the coefficient of the steady moment is 3/2: a three-per-rev vibratory moment is also developed, but it is of small amplitude compared to the steady. Assuming that 2° of flapping are required for trim (possible either for c.g. offset or fuselage pitching moments) a vibratory two-per-rev moment of amplitude about 35 ft-lbs per inch of offset will be developed on the hub of a two-bladed rocket-powered helicopter.

Obviously, offset not only results in vibration, but results in increased hub and pylon structural loads and weights, which rapidly become prohibitive for the one-man helicopter as offset is increased.

Points in favor of hinge offset are:

(1) Improvement of hovering flying qualities. However, this is apparently true only for small offsets. Figure 29 presents hovering stability parameter versus flapping hinge offset for the rocket-powered helicopter of Figure 19. It is seen that little improvement results for offset greater than about three inches. The improvement from three inch offset could also be equalled by about two pounds additional weight on each tip.

(2) Considerable increase of M_q in forward flight (see Figure 30(b) for rocket-powered helicopter, at $\mu = .20$). **However, overall influence of hinge offset on maneuver stability is not large due to generally adverse effect on M_α (see Figure 24).**

(3) Reduction in control travel required for trim (Figure 31). If fuselage pitching moments are as large as Figure 25 indicates, some hinge offset is essential if moments are not balanced by horizontal tail.

(4) Improvement in stick position stability.

d. <u>**Effect** of Forward Speed on M_α and M_q</u>

Figure 27(a), previously discussed, illustrates the effect of speed on the stability parameter M_α/I_y for a one-man, rocket-powered helicopter. It is seen that for the case with no horizontal tail, and the case where a stabilizer is provided but does not carry download to balance pitching moments, M_α becomes increasingly destabilizing with increasing tip-speed ratio. When the tail is set to carry a download for balancing fuselage pitching moments, M_α is stabilizing throughout the speed range.

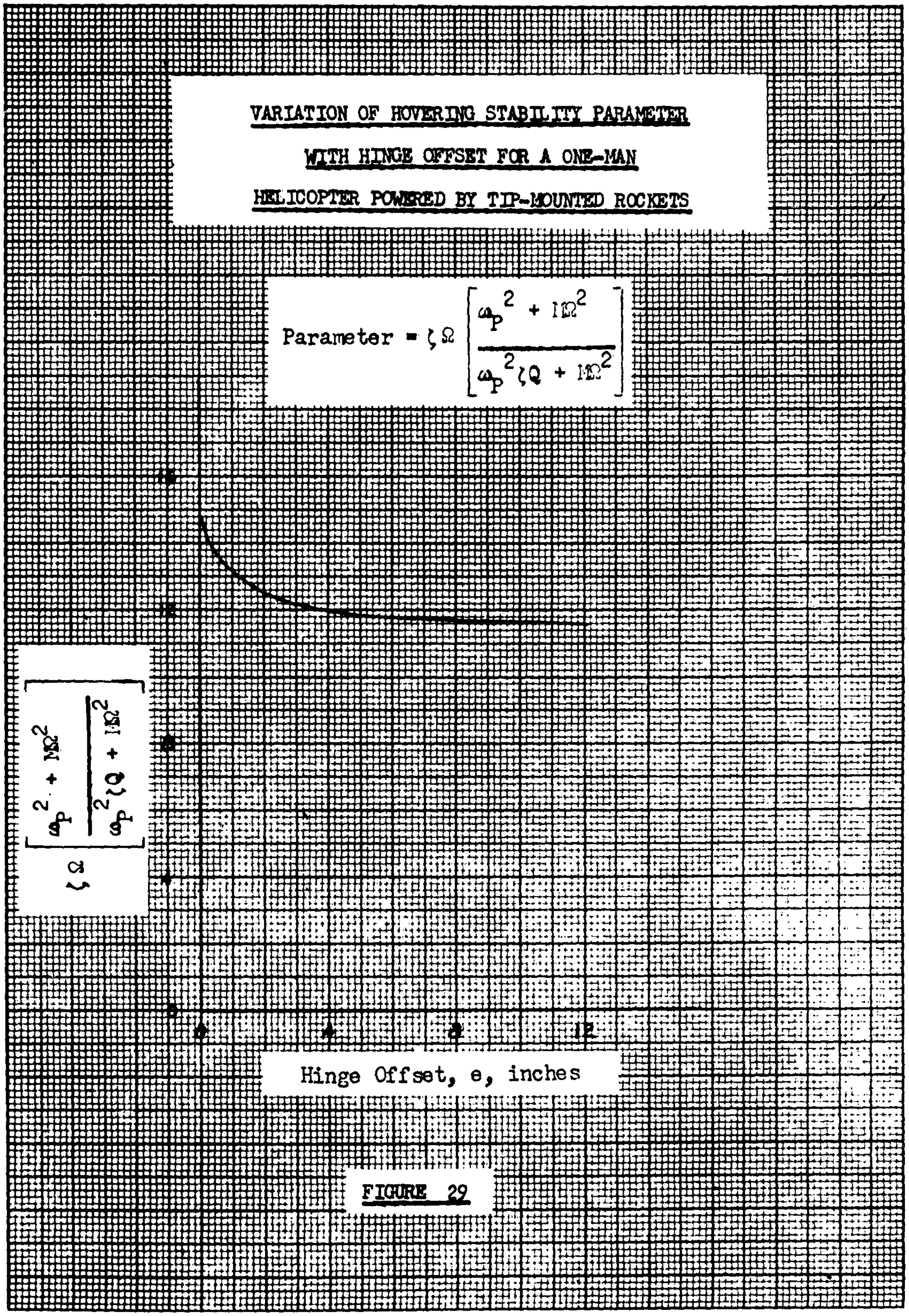

VARIATION OF HOVERING STABILITY PARAMETER WITH HINGE OFFSET FOR A ONE-MAN HELICOPTER POWERED BY TIP-MOUNTED ROCKETS
Parameter = $\zeta\Omega\left[\frac{\omega_p^2 + M\Omega^2}{\omega_p^2\zeta Q + M\Omega^2}\right]$
$\zeta\Omega\left[\frac{\omega_p^2 + M\Omega^2}{\omega_p^2\zeta Q + M\Omega^2}\right]$
0
4
8
12
Hinge Offset, e, inches

FIGURE 29

EFFECT OF HINGE OFFSET ON

STABILITY DERIVATIVES

FOR ONE-MAN HELICOPTER

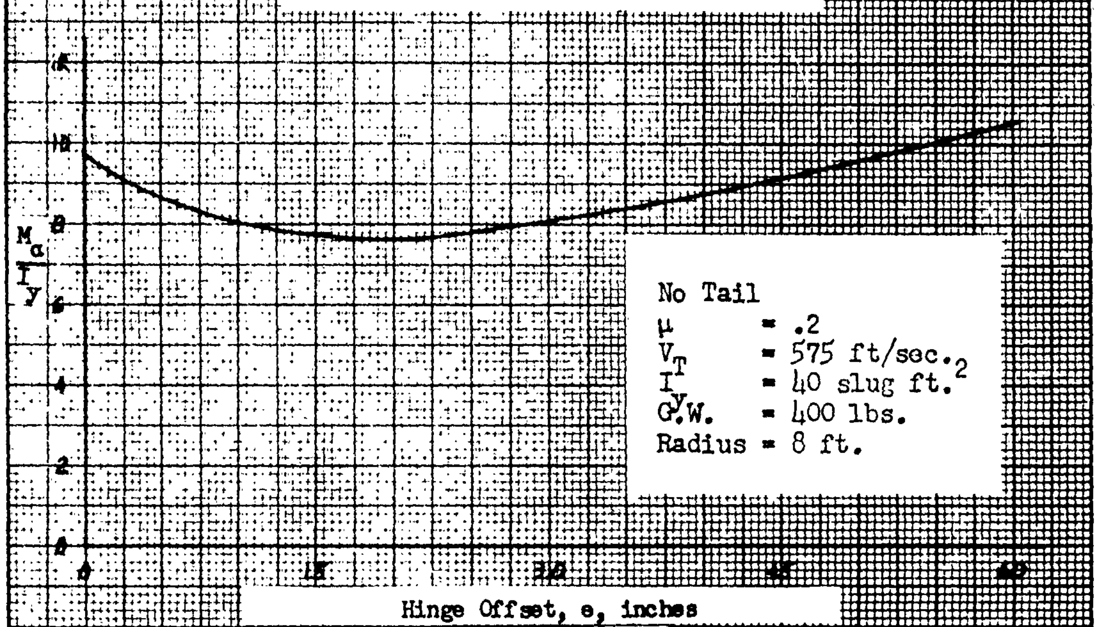


FIGURE 30(a)

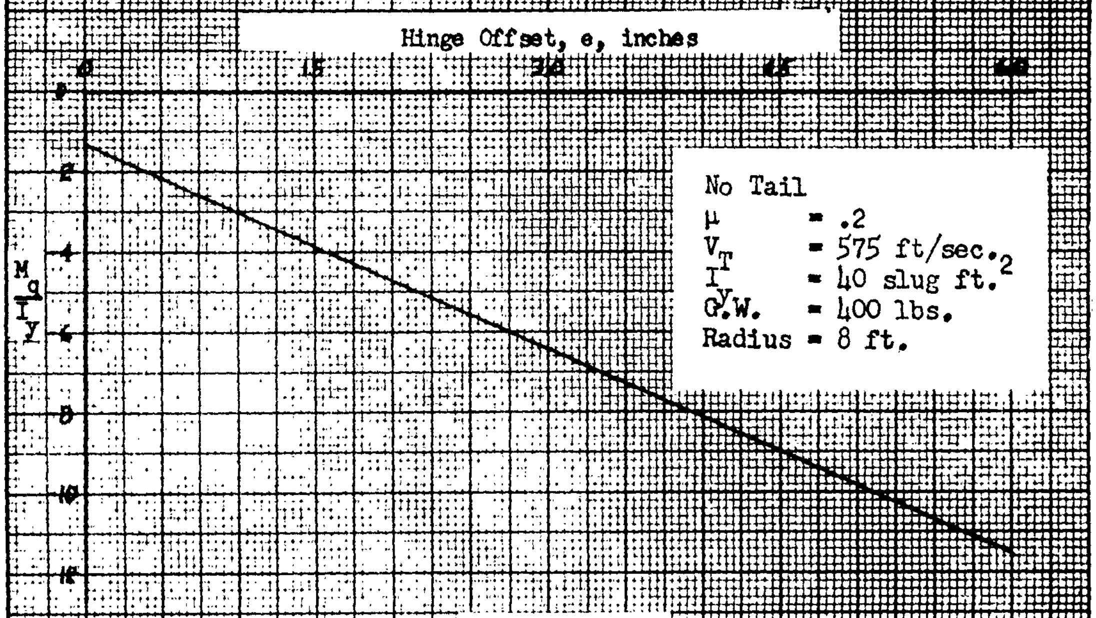


FIGURE 30(b)

CONTROL REQUIRED TO BALANCE CENTER OF GRAVITY TRAVEL

Gross Weight = 400 lbs.

C.G. Located 30" below Plane of Rotation

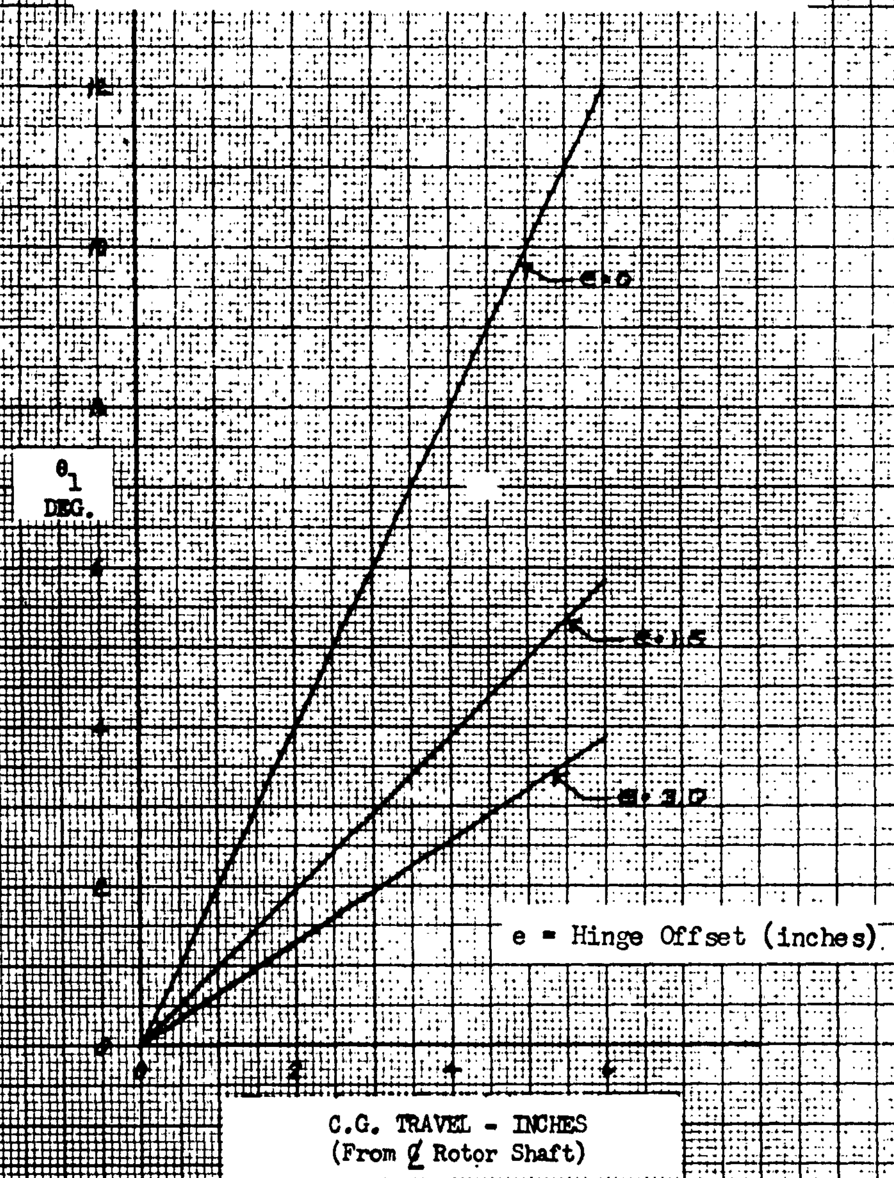


FIGURE 31

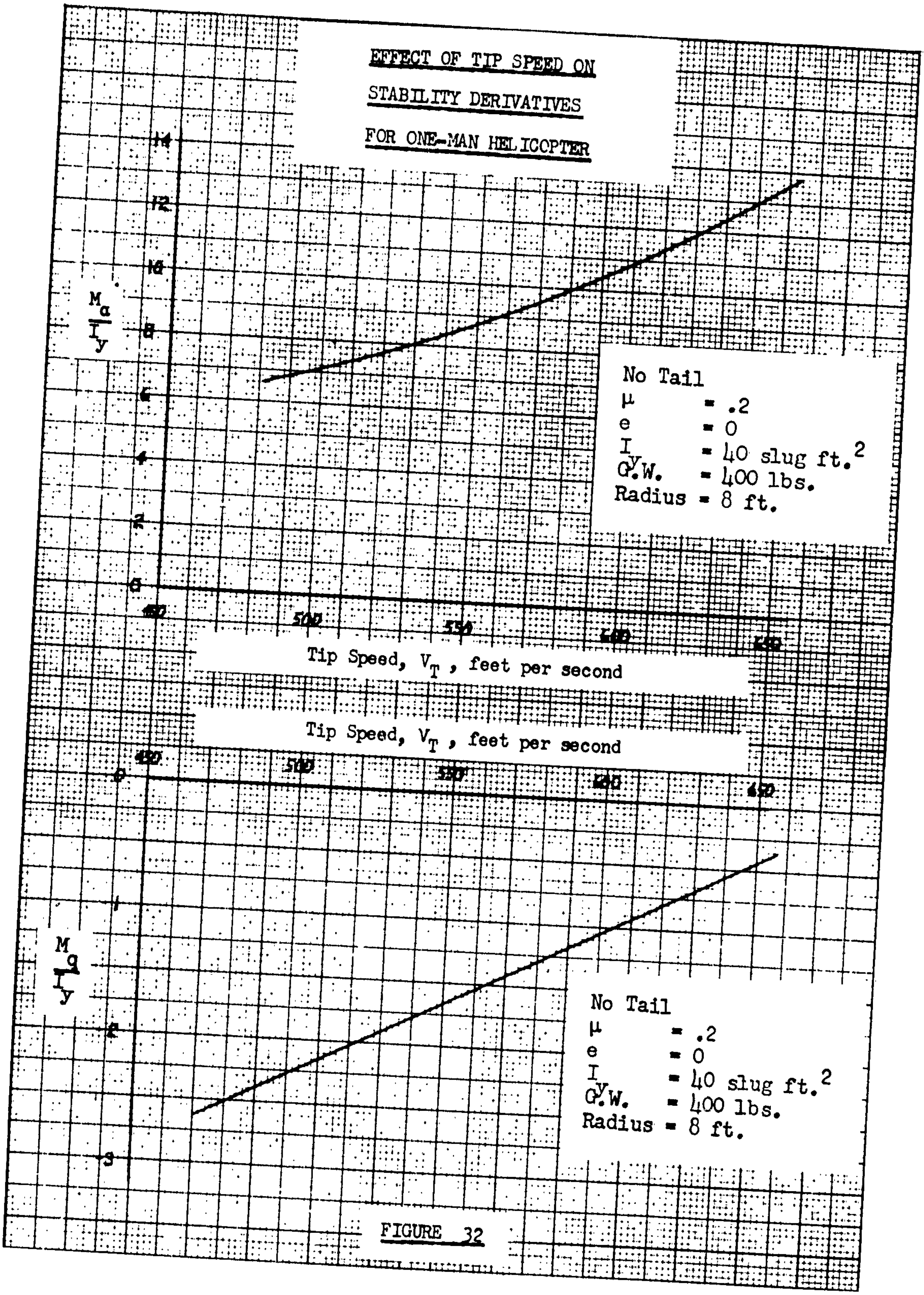

EFFECT OF TIP SPEED ON
STABILITY DERIVATIVES
FOR ONE-MAN HELICOPTER
14
12
10
8
6
4
2
0
$\frac{M_\alpha}{I_y}$
No Tail
μ = .2
e = 0
I_y = 40 slug ft.^{2}
G.W. = 400 lbs.
Radius = 8 ft.
450
500
550
600
650
Tip Speed, V_T, feet per second
Tip Speed, V_T, feet per second
450
500
550
600
650
0
$\frac{M_q}{I_y}$
No Tail
μ = .2
e = 0
I_y = 40 slug ft.^{2}
G.W. = 400 lbs.
Radius = 8 ft.

FIGURE 32

Figure 27 indicates that for the one-man rocket-powered helicopter, M_q with or without horizontal tail is stabilizing at low speed, but becomes rapidly less so as tip-speed ratio increases. At approximately $\mu = .25$, M_q with zero flapping hinge offset becomes zero, for this helicopter.

e. Effect of Tip Speed on M_q and M_α

Figures 32(a) and 32(b) present M_α/I_y and M_q/I_y versus tip speed at a tip-speed ratio of .20 for a rocket-powered one-man helicopter. It is seen that both parameters increase almost linearly, in a destabilizing sense, with tip speed. This point should be borne in mind when considering operation of tip-powered helicopters at very high tip speeds (700 fps and above).

f. Control Rotor and Gyro Stabilizing Bar

Both the control rotor and the gyro bar, as generally used, are devices for increasing the rate damping of the helicopter rotor. It is pointed out in Reference 4 that this can be done with less penalty in weight and complexity by means of blade tip weights. Since the tip-mounted powerplants also act as tip weights, it appears doubtful whether either the control rotor or the stabilizing bar are necessary in the case of one-man helicopters powered in this manner.

In Reference 4 the characteristics of the control rotor and stabilizing bar are discussed in terms of N_1/N, which is the ratio of the rate damping of the stabilizing device to that of the main rotor, and k_1, the displacement control ratio. The definition of k_1 in Reference 4 is:

k_1 = main rotor cyclic pitch change per unit of control rotor (or gyro bar) tip path plane tilt with respect to shaft

Displacement control provides angle of attack stabilization. At a speed of 45 knots a horizontal tail volume of about five cubic feet provides angle of attack stabilization equivalent to a k_1 of .10.

As a result of analogue computer studies it is concluded in Reference 4 that for tip-powered helicopters (for which main rotor rate damping is appreciably increased by the tip powerplants) the value of N_1/N should be less than 0.1, and preferably zero. That is, the device should be essentially a displacement gyro. In addition, the values of k_1 should lie between .05 and .10. A value of $k_1 = 1.0$ was found in the studies to introduce a poorly damped high frequency in the control response, and to greatly decrease control sensitivity.

A ramjet-powered helicopter in the 1000-pound gross weight class has been equipped with a control rotor and flown for a considerable number of hours. The ratio N_1/N is considerably higher than the value of 0.1 recommended (in connection with tip-powered helicopters) in Reference 4, and a k_1 of 1.0 is used. The control response, although greatly reduced, is not considered objectionably so. The high-frequency response predicted by the analogue computer is not noticeable. These results are fortunate, since a value of N_1/N of 0.1 in connection with a control rotor would result in an impractically low control response, and a k_1 of 1.0 permits simplification of hub mechanism.

No flight record is available of the combination of gyro bar and tip-driven rotor. Low values of N_1/N do not in this case affect the control response, as they would for the control rotor; however, use of the bar effectively as a displacement gyro will result in large bar flapping angles during maneuvers, introducing problems of clearance in the control system.

In the case of the one-man helicopter, where weight is at a premium, it would be preferable to avoid the use of both tip weights and control rotor (or stabilizing bar) for rate stabilization. This is especially true where tip weight is already available in the form of tip powerplants.

As a matter of interest the characteristics of a one-man helicopter with control rotor and stabilizing bar are plotted on the maneuver stability chart of Figure 24. The values of N_1/N and k_1 are typical of those used in practice. These are, respectively, .30 and 1.0 for the control rotor, .30 and .80 for the stabilizing bar. (It should be noted that N_1 is varied in the case of the control rotor by changing the aspect ratio of the paddles, and in the case of the gyro bar by changing the rate of the viscous dampers.)

It is seen from Figure 24 that the gyroscopic bar with the above characteristics appears to provide satisfactory maneuver stability over the computed range of tip-speed ratios, and that the control rotor provides satisfactory maneuver stability up to a tip-speed ratio of about 0.22, a range which should be adequate for the one-man helicopter. It should be noted that these devices probably will not provide stick-position stability.

6. Directional Characteristics

a. Directional Stability

The most important contributions to the directional characteristics of the one-man helicopter come from the pilot, landing gear (if provided) and vertical tail and/or tail rotor (if provided). From Reference 6 it appears that the one-man helicopter with unfaired pilot, whether seated or with legs extended (in standing position) is directionally unstable. The vertical tail is approximately 50% effective in the location tested (about 5 feet aft of rotor shaft, and centered at level of pilot's shoulders.) Assuming 50% effectiveness, and conventional plan-form, it appears from Reference 6 that tail volume of 15 cubic feet is required to provide approximately neutral directional stability. To provide the minimum desirable amount of positive directional stability, about 25 cubic feet of vertical tail volume is required.

b. Directional Control

The following is reproduced from Reference 15:

Paragraph 3.3.5. Directional control effectiveness shall be such that when the helicopter is hovering in still air at the maximum overload gross weight or at rated take-off power (in and out of ground effect), the directional control shall afford at least the following yaw displacements in the first second following initiation of pedal displacement from trim:

Class I (less than 2,500 lbs. gross weight): 6° for 1-inch pedal displacement, and 20° for full pedal displacement.

Paragraph 3.3.6. It shall be possible to execute a complete turn in each direction while hovering over a given spot at the maximum overload gross weight or at take-off power (in and out of ground effect), in a wind of at least 20 knots for class I.....To insure adequate margin of control during these maneuvers, sufficient control shall remain at the most critical azimuth angle relative to the wind, in order that when starting at zero yawing velocity at this angle, the application of full directional control in the critical direction results in a corresponding yaw displacement of at least 6° in the first second for class I .....helicopters.

Paragraph 3.3.7. The sensitivity of the helicopter to directional control deflection, as indicated by the maximum rate of yaw per inch of sudden pedal displacement from trim while hovering shall not be so high as to cause a tendency for the pilot to overcontrol unintentionally. In any case, the sensitivity shall be considered excessive if the yaw displacement is greater than 50° in the first second following a sudden pedal displacement of 1 inch from trim while hovering at the lightest service loading.

Experience with currently operating tip-powered helicopters indicates that the requirements specified in Paragraphs 3.3.5 and 3.3.6 of Reference 15 cannot consistently be met with a rudder. A tail rotor is required if compliance is considered necessary.

While it may not be considered essential to meet the above requirements in the case of the one-man helicopter, it should be noted that the directional control afforded by a rudder, immediately after flare-out, is apt to be inadequate. When landing in rough terrain, or under battle conditions, the desirability of positive directional control at all times may require use of a tail rotor.

Judging by the results of the tests reported in Reference 6 on the partial full scale model of a one-man helicopter, the critical angles from the standpoint of directional control occur at azimuth angles of about 90° with respect to the wind. Since a rather large landing gear (for a one-man helicopter) was used in the tests, and since this landing gear appeared to affect considerably the directional characteristics, it is not considered desirable here to discuss tail rotor requirements in terms of the requirement 3.3.6 above. It is somewhat simpler to discuss these requirements in terms of the requirement 3.3.7; that is, to determine the maximum desirable rather than the minimum tail rotor thrust required.

The I_z of a one-man helicopter will be of the order of 10 slug-ft^2 at overload and 5 slug-ft^2 at the lightest service gross weight. For the light weight condition, a yawing moment of approximately 10 ft-lbs will result in a yaw displacement of 50° from trim in one second. Thus it appears that the tail rotor of the one-man helicopter should not produce more than 10 ft-lbs of yawing moment for one inch of pedal displacement. Assuming a pedal travel of 3 inches and a tail rotor arm of 5 feet, this corresponds to a tail rotor thrust at full displacement of 6 lbs.

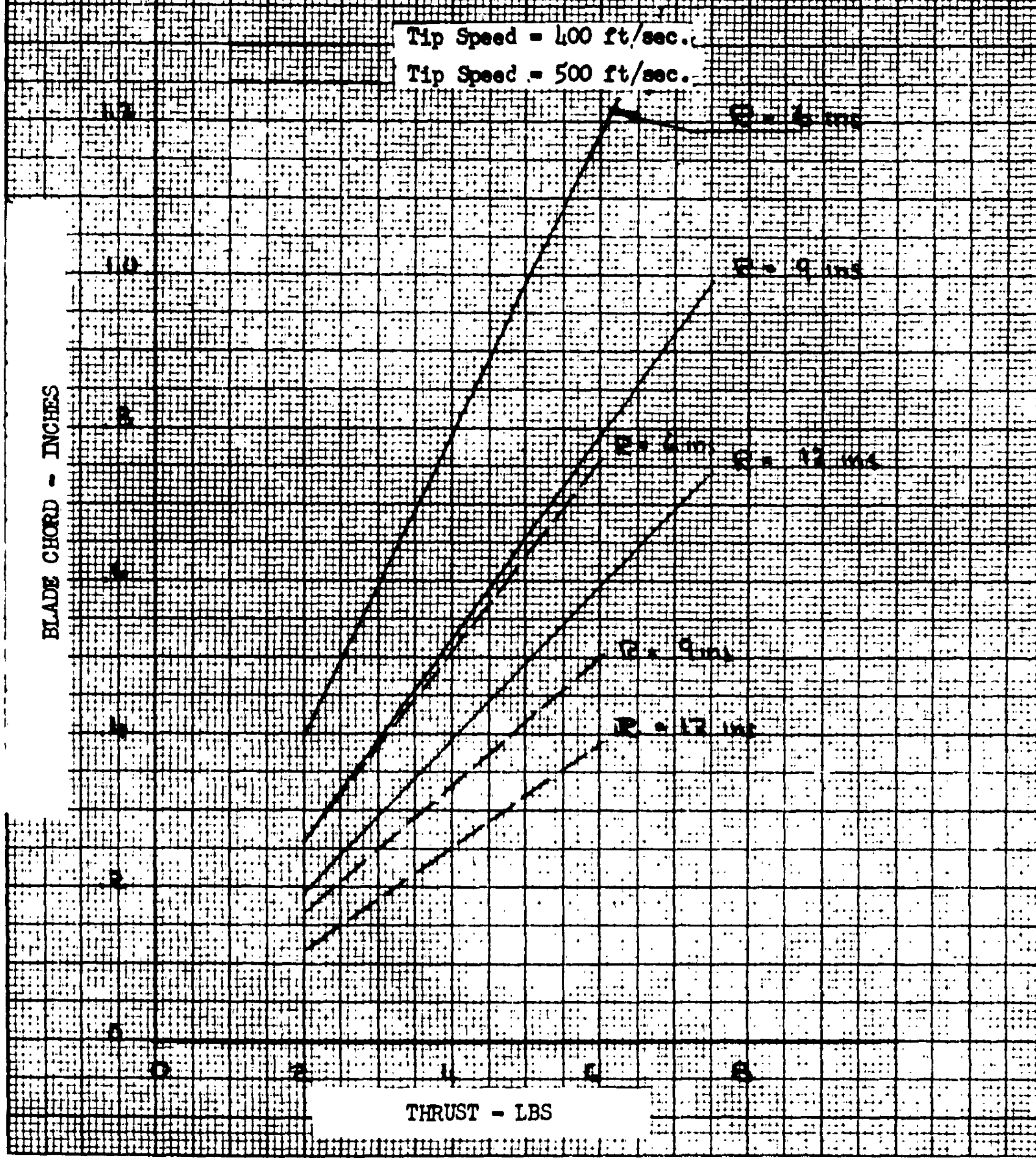
Figure 33 presents design data in the form of blade chord versus maximum thrust for a two-bladed tail rotor , with selected values of tip speed and blade radius. Assuming that a maximum thrust of 4 lbs is found to be more than adequate

VARIATION OF TAIL ROTOR BLADE CHORD WITH ROTOR MAX THRUST

(MAX C_T/σ = .16)

Selected Values of Tip Speed and Radius

FIGURE 33



to meet the requirement 3.3.6, without exceeding requirement 3.3.7, it is seen from Figure 33 that for a tip speed of 500 fps and a radius of 6 inches the required chord is only 1/2 inch. For a one-bladed rotor a 1 inch chord is required. Although such blades are extremely small, and therefore apt to be flimsy, the extremely high rpm (9560 rpm) renders the rotor dangerous to near-by personnel. A material which would fracture on impact with the body, without damage to the body, is desirable in this application. At this time no suitable material has been suggested.

7. Speed Governing of Rotor

a. Rotor Speed Governor

A rotor speed governor which maintains constant rotor rpm throughout the operating power range, regardless of collective pitch setting, would be especially desirable for the one-man helicopter. Presumably the unit would respond to changes in centrifugal force by changes in fuel flow.

A drawback to this type of control is the fact that it would be inoperative power-off. In the case of tip-mounted drives, with high fuel rates and low endurance, the possibility of running out of fuel in flight is considerable.

The following characteristics are desirable for the unit:

(1) Mechanical simplicity and light weight

(2) High gain (sensitive to small changes in rpm)

(3) Absence of hunting. To meet items (2) and (3) it is probably necessary to provide 'anticipation', that is, response to acceleration as well as rpm. This will most probably conflict with item (1).

(4) Stable system - this probably requires 'anticipation' response also.

(5) Absence of governor droop - that is, change in rpm maintained by governor with change in power demand.

(6) Provision of over-riding throttle control, so that ship may be controlled if governor malfunctions.

Obviously, a system meeting the above requirements must be more complex than the pitch-power scheme discussed in Paragraph 1.7.b. This is especially true if the 'anticipation' requirement is met. If possible electronic systems must be avoided, due to the ruggedness generally required of all systems in the one-man helicopter.

b. Correlation Between Collective Pitch and Throttle Controls

Since a helicopter will fly in any one of several stabilized flight conditions at the same value of collective pitch (the local angle of attack at the blades will, of course, vary with the rotor attitude, velocity and thrust), it would be difficult to provide a correlating mechanism which would accurately correlate in all conditions of flight. It is found in practice, however, that systems which are designed so that the rotor speed will remain substantially constant for rapid and large changes in collective pitch will, for reasons subsequently discussed, prove generally satisfactory.

The power required by the rotor is a function of blade collective pitch angle and rotor inflow conditions. Blade collective pitch is determined by the pilot; rotor inflow by the rotor operating conditions. Whereas the pilot can change the collective pitch setting through large angles in time intervals substantially less than a second, changes in blade angle of attack resulting from inflow changes due to variation in rotor attitude or velocity generally take several seconds to become important. Accordingly, if correlation is provided between collective pitch and throttle so that changes in collective pitch will produce simultaneous scheduled adjustment of throttle, the pilot will have sufficient time in all other conditions to adjust the throttle as required to maintain constant rotor speed.

Figure 34 presents curves of net rotor horsepower required versus collective pitch for a one-man helicopter in hovering, and forward speeds of 60

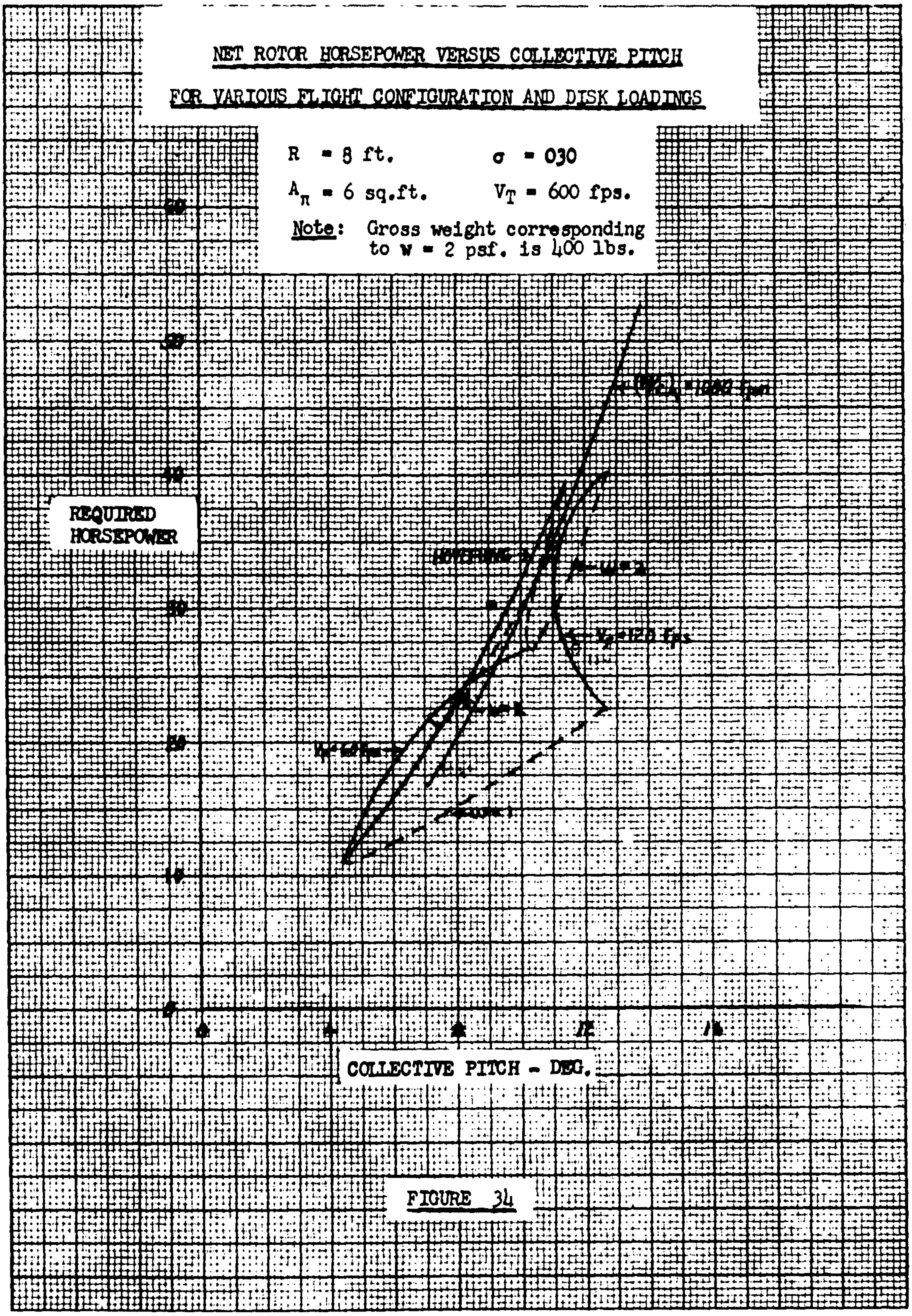
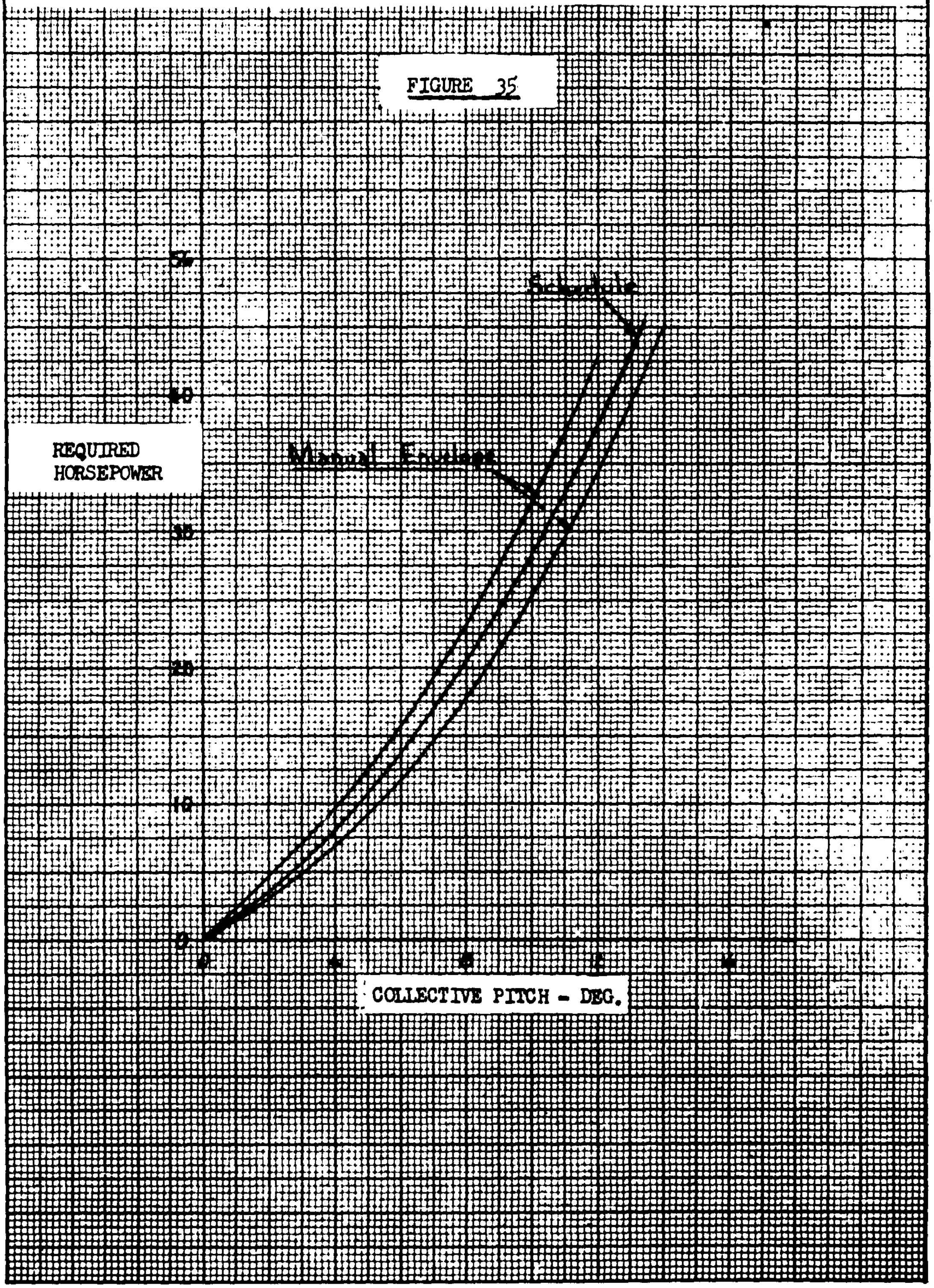

NET ROTOR HORSEPOWER VERSUS COLLECTIVE PITCH
FOR VARIOUS FLIGHT CONFIGURATION AND DISK LOADINGS
R = 8 ft.
σ = 030
A_π = 6 sq.ft.
V_T = 600 fps.
Note: Gross weight corresponding to w = 2 psf. is 400 lbs.
REQUIRED HORSEPOWER
HOVERING
COLLECTIVE PITCH - DEG.
12

FIGURE 34

CONFIDENTIAL

PITCH-POWER SCHEDULE PROPOSED FOR A TYPICAL ONE-MAN HELICOPTER

(Based on Pitch-Power Relationships of Figure 34)



CONFIDENTIAL

and 120 fps, at selected disk loadings. Similar data is presented for vertical climb at a disk loading of 2 psf. All curves are for a constant value of tip speed. The rotor radius corresponds to a design gross weight of 400 lbs at a disk loading of 2 psf. The range of disk loadings 1.0 to 3.0 psf will cover amply any range likely to be encountered in operation with this machine. Figure 35 presents an operating envelope which includes all the points covered in Figure 34 except that corresponding to a disk loading of 1 psf at a forward speed of 120 fps. (The envelope cuts across the 120 fps line at approximately 1.5 psf, which corresponds to a 25% reduction in gross weight from design gross, and is therefore apt to be close to the minimum attainable disk loading.) A schedule is shown in Figure 35 which will permit a correlation between pitch and power such that small adjustments in throttle setting will be required to maintain constant tip speed. The schedule could be obtained by means of a cam, operated by the collective pitch stick, and connected to the throttle mechanism.

While this system does not provide automatic governing of rotor speed for any flight configuration, it provides a light and simple correlation between pitch and power which will serve to aid the pilot. As pointed out in Paragraph 3.b. , a speed governor with suitable characteristics is likely to be complicated and expensive, and also somewhat heavy. Use of a pitch-power schedule obviously requires monitoring from the pilot, although for the design conditions throttle adjustment should be small. However, a rotor speed indicator will be necessary with this scheme.

8. Autorotative Parameters for the One-Man Helicopter

Paragraph 3.4.5 of Reference 15 reads as follows:

> The helicopter shall be capable of entering into autorotation at all speeds from 20 knots rearward to maximum forward speed. The transition from powered flight to autorotative flight shall be established smoothly and with adequate controllability and with a minimum loss of altitude. It shall be possible to make this transition safely when initiation of the necessary manual collective pitch control motion has been delayed for at least 2 seconds following loss of power. At no time during this maneuver shall the rotor speed fall below a safe minimum autorotative value (as distinct from power-on values.)

No method has been devised for predicting the ability of a helicopter to meet the above requirements, and in general helicopters in operation today cannot meet the 2-second requirement. R. A. Wagner has suggested that a criterion of the ability of a helicopter to transition safely into autorotation after power failure is given by the ratio of rotor kinetic energy to gross weight, and that a minimum value for this ratio should be 75. (It may be noted that the value is approximately 80 for the Sikorsky R-5. This machine does not meet the 2-second requirement, but it has autorotation characteristics which are generally considered to be acceptable.)

Another criterion which may be used for comparison with current designs is the ratio of rotor kinetic energy to hovering power required, given by:

$$K' = \frac{I_r \omega^2}{2(550)(rhp)_H} \quad \text{seconds}$$

Effectively, K' represents the number of seconds of energy dissipation, at the rate required to maintain hovering out of the ground effect, corresponding

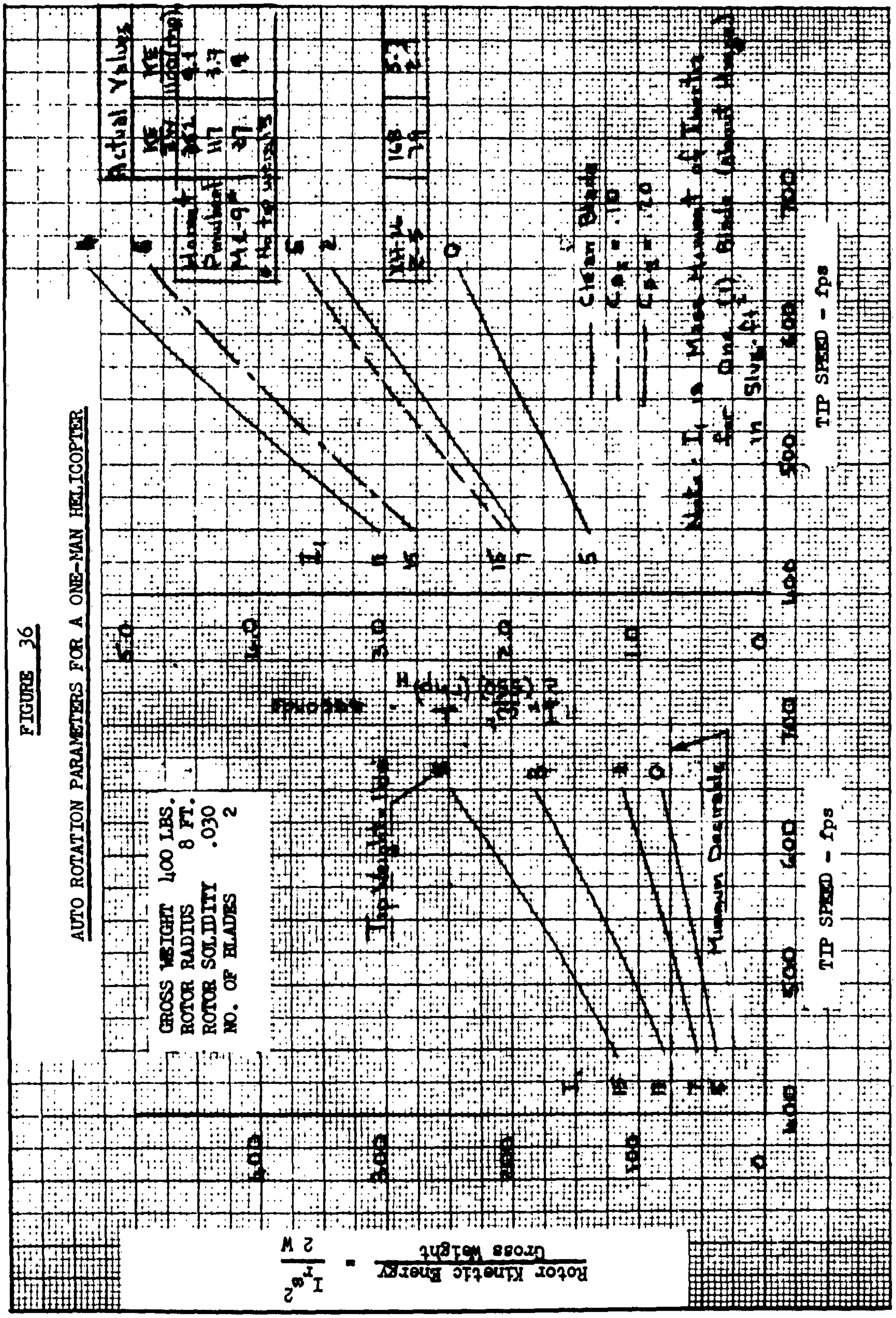


FIGURE 36

AUTO ROTATION PARAMETERS FOR A ONE-MAN HELICOPTER to the stored kinetic energy of the rotor at a given (constant) tip speed. If $K' = 5$, it is seen that in the first second after loss of power the kinetic energy loss in the rotor is approximately 20%, resulting in a reduction of 10% in tip speed. If $K' = 1.0$, a 10% reduction in tip speed would take place in approximately 1/5 second, assuming energy dissipation at the rate required to maintain hovering out of the ground effect.

Figure 36 presents curves of the autorotation parameters suggested above, versus tip speed, for selected values of I_1 and blade tip weight. It is seen that for a blade having $I_1 = 5$ slug-ft^2, and zero tip weight (corresponding to the blades of a one-man helicopter having a two-bladed rotor and geared drive), the ratio $I_r\omega^2/2W$ is below the minimum desirable value of 75 for all tip speeds up to 625 fps. Thus, in addition to the desirability of improving the rate damping (and therefore the stability) of the geared machine by means of tip weights, this also improves power-off autorotation characteristics of the configuration.

As a matter of interest, some actual values of the autorotation parameters are presented on Figure 36, in a table. The influence of tip-weight is illustrated in the comparison between the geared and the rocket-powered one-man helicopter (although the hydrogen peroxide rockets used are probably no more than one-half the weight of the corresponding ethylene oxide rocket). The influence of tip speed is shown by the comparison between the ramjet and pulse jet machines, especially since the pulse jet powerplants are about 50% heavier than the ramjets.

SECTION III - POWERPLANTS AND FUELS IN RELATION TO THE ONE-MAN HELICOPTER

1. Availability of Powerplants

a. Ratings Required

The power requirements for the one-man helicopter are as follows:

40-50 horsepower for the geared drive configurations.

Jet thrust to develop 30-35 hp in the tip drive configurations, corresponding to a jet thrust of 15-17.5 lb thrust per engine on the tips of a two-bladed rotor at tip speed of 550 fps.

b. Availability

There are no operationally proven powerplants available at this time in the above ratings.

The following summarizes the present state of the art in small aircraft powerplants:

(1) Reciprocating - several small two-stroke cycle engines for target drones or powered glider applications. None modified for use with helicopter.

(2) Turbine - none available in the rating required.

(3) Ramjet - units in ratings 30-40 lbs thrust have been successfully used in helicopter application. No information available on smaller powerplants.

(4) Pulse Jet - units having 35-45 lbs thrust ratings have been successfully used in helicopter application. No information available on smaller powerplants.

(5) Rocket - some work has been done with gas generators using Hydrogen Peroxide and Ethylene Oxide as fuel. Considerably more work remains to be done before powerplants are acceptable.

(6) Ram Rocket - some basic research work has been done with Methyl Acetylene (Propyne), and Ethylene Oxide fuels. While the configuration is promising, tests have not proceeded to the point where specific fuel consumption data may be approximated. Most test work has been done with engines having L/D (length/diameter) ratios of 8:1 to 12:1. For use with a one-man helicopter, operating at the blade tip under a 1500g-2000g centrifugal loading, L/D ratios should be considerably less. A small amount of test work has been done with L/D ratios of 3:1.

c. <u>Characteristics of Various Powerplants</u>

(1) <u>Reciprocating</u>

The following is generally applicable to current aircraft engines in the 40-50 hp class (all data is, of course,approximate):

Dry weight	1 lb/hp
Installed weight (with cooling provision and accessories)	1.3 - 1.5 lb/hp
Drive system weight	.5 - .7 lb/hp
Operating cycle/rpm	2-stroke/4000-6000
Fuel rate - lb/hp/hr	.80 - 1.2
Reduction ratio engine/rotor	8:1 to 12:1

From the above it is seen that a reciprocating engine installed, plus drive system, will weigh about 2 lb/hp. A 40 hp engine, plus drive, then weighs 80 lb, with airframe 180-200 lb. Obviously, an adequate landing gear must be provided, so that total airframe weight is likely to be well in excess of 200 lb. (A point not generally appreciated is that motorcycle engines have specific weights (lb/hp) much higher than those of target drone engines.)

(2) Turbine

While some small high-output reciprocating engines are in operation, no small turbine in the class required is available, other than a small 80 hp auxiliary powerplant. This unit weighs about 2 lb/hp, and does not appear suitable for modification to helicopter use. It may be assumed that weight and performance of a geared turbine suitable for use with the one-man helicopter will not be notably different from that of the high-output reciprocating engine described above. The gear ratio is likely to be of the order of 40:1.

(3) Ramjet

Two helicopters in the 750-1000 lb. class have been operated extensively in the U.S. While the engine is extremely simple in conception, development of a reliable, approved type powerplant is time-consuming and expensive. The strong centrifugal field and high operating temperatures introduce structural problems, particularly in connection with the flameholder assembly. The centrifugal field introduces fuel distribution problems. The high air velocities introduce flameholding difficulties, and relighting in the air can become a problem. The engine retention for a typical one-man helicopter must be built to withstand a continuous centrifugal load of about 9000 pounds, and yet must be sufficiently small to fit neatly into a suitable rotor blade.

Fuel rate for a small ramjet engine suitable for a one-man helicopter is likely to be of the order of 12 pounds per lb-thrust per hour.

The above development problems have been encountered, and to some extent overcome, in current ramjet-powered helicopters. Two major operating problems still exist with the powerplant. These are:

> High engine cold drag, resulting in minimum power-off descent rates approximately double those of 'clean' rotor configurations.

> Necessity for mechanically bringing rotor up to speed (about 100-150 rpm) before engine will start.

Among suggestions put forward for reducing cold drag in power-off descent are:

> Use of 'eyelids' and/or tail-cone. While cold drag may be reduced about 50% by means such as these, no workable system has been proposed for achieving them. Such problems as actuation (under high centrifugal loading), and suitable fairing of the devices when not in use, are not easily solved. The weight and cost penalties do not appear worth while in the one-man helicopter.

> Use of a flat (rectangular) engine cross section. This has obvious structural as well as aerodynamic advantages. No reliable information is available, since very little has been done with the configuration. The problems of nozzle location, fuel distribution and mixing in the centrifugal field appear to be severe. There may be difficulties with warping of the structure.

It has been suggested that solid rockets be used to bring the rotor up to speed. One experiment of this nature has been reported, but the rotor speed developed was only about one-half of that predicted. It was felt that the rockets required for a successful start would be too heavy to justify their use. Obviously,from both the tactical and weight standpoint, use of solid rocket start has drawbacks in connection with the one-man helicopter. A hand-cranked start appears to be feasible, but burdensome to the pilot.

(4) Pulse Jet

Many of the problems discussed in relation to the ramjet are somewhat alleviated in the case of the pulse jet, due to the low centrifugal loading on the powerplant. It has proved necessary to operate the engine at tip speeds less than 400 fps; while this is an advantage from the standpoint of engine structure, it requires relatively large-chord blades to avoid blade tip stall. The engine length introduces structural problems; a length-diameter ratio in excess of 6:1 must be maintained, resulting in engine length, for the one-man helicopter, in excess of two feet (see Figure 37 For a 400 pound machine with a disk loading of 2.0, centrifugal load factor on the engine is of the order of 600, compared to about 380 on a current pulse jet helicopter.

The inlet valves are the only moving parts in the pulse jet, and represent the most frequent source of engine failure.

Cold drag data for the pulse jet has not been published, but power-off descent rates are probably increased about 50% from 'clean blade' values by the pulse jet, as compared to about 100% for the ramjet.

At rated thrust, the TSFC of the pulse jet is considerably better than that of the ramjet. However, TSFC is approximately constant for the ramjet over a large power range, whereas TSFC of the pulse jet increases considerably with reduction in output. Cruise fuel rates, in terms of BSFC, are approximately equal in ramjet and pulse jet.

The pulse jet may be started by means of a small compressed air charge. The air bottle may be recharged by means of a rotor driven pump, once the rotor is started.

(5) Rocket

(a) Discussion

It is pointed out in Reference 3 that, providing a suitable powerplant can be developed, either the tip-mounted rocket or ram rocket using liquid fuel offer the most promise in connection with the portable one-man helicopter. This is because the airframe weight appears to be lighter with these configurations than with any other. Paragraphs III.5.b. and III.5.c. present some comments on the rocket and ram rocket powerplants. Paragraph III.6. presents a brief discussion of suitable fuels for each of these powerplants.

(b) Liquid Rocket

The rocket powerplant considered here is a device for decomposing a liquid monopropellant fuel, and for creating jet thrust by exhausting the products of decomposition to atmosphere through a suitable nozzle or nozzles, located at the blade tip. An interesting characteristic of this type of powerplant is that the jet thrust is not directly affected by tip speed. However, the fuel specific impulse, at relatively low decomposition chamber pressures is somewhat affected by chamber pressure; if this pressure is built up by centrifugal pumping along the blade, the specific impulse will be to a small extent affected by rotor rpm, though in a range which is likely to be well below rated rpm.

Two possible methods for decomposition of the fuel are considered. These are by catalytic bed and by heat. Only relatively unstable fuels can be decomposed by a catalyst - this is at once the advantage and the danger of these fuels. (As pointed out in the discussion on fuels, Hydrogen Peroxide decomposes in contact with most organic impurities, and thus presents a fire hazard.) The majority of monopropellant fuels which are promising in connection with the one-man helicopter are not readily, if at all, subject to catalytic action, and require heat for decomposition. Thus, design of a liquid monopropellant rocket involves development of suitable catalytic bed methods, or of a suitable heat source, as applicable.

It is probably generally true that use of a fuel which may be catalyzed results in a lighter rocket powerplant, and one that is less complicated than the configuration requiring heat decomposition. There are, however, reasons for preferring the latter. In the first place, the tip weight required for stability reasons is likely (in the one-man helicopter) to be greater than that provided by a catalytic type rocket. Second, the most promising monopropellant using heat decomposition (Ethylene Oxide) has a specific impulse at least 20% greater than that of the most promising monopropellant using catalytic decomposition (Hydrogen Peroxide). Third, Ethylene has a considerable advantage over Hydrogen Peroxide in terms of safety, availability, and cost.

(6) Ram Rocket

The ram rocket may be crudely described as a combination of rocket and ramjet powerplants. The rocket nozzles are placed just aft of the diffuser of a shell similar to that of a ramjet. The products of decomposition of the monopropellant fuel are mixed with air entering the shell, and burned. In contrast to gasoline or jet fuels used in the ramjet, the products of decomposition have considerable energy in the form of heat and pressure, which in the optimum design is used as a heat pump to augment the mass flow of air into the shell. For this reason, the aerothermodynamic efficiency of a ram rocket is superior to that of a ramjet of the same rated output, even though the ramjet fuel has considerably greater heat content than the monopropellant fuel (for example, gasoline has 50% more heat content than Ethylene Oxide). It should also be noted that the decomposition products of Hydrogen Peroxide, being steam, are not combustible, and therefore this fuel is not suitable for use in a ram rocket.

Obviously, at low rotor tip speeds the engine operates almost entirely as a rocket; at very high tip speeds the operation approaches that of a tip-mounted ramjet. Even assuming that the cruise specific fuel consumption of the ram rocket is no better than that of the ramjet, the ram rocket has two obvious advantages for a helicopter powerplant when compared to the ramjet. These are a smaller shell, resulting in a reduction of cold drag of the shell; and the ability to accelerate from zero rotor speed without external means. (The lower shell cold drag will reduce the power-off descent rates of the machine.)

d. Liquid Rocket Fuels

Providing a suitable powerplant can be developed, the tip-mounted liquid rocket engine offers the most promise as a powerplant for the one-man helicopter. This is because airframe weight appears to be lighter for this configuration than for any other.

Table I presents characteristics of several monopropellant fuels that have been suggested for use in the tip-mounted rocket.

The use of Hydrogen Peroxide is not recommended. Since the fuel will ignite spontaneously on contact with most organic impurities, it presents a danger in storage, in transport, or in the fuel system. Careful 'passivation' of the fuel system is required before the fuel may be used. A leak may result in fire or explosion. The major advantage of Hydrogen Peroxide as a rocket fuel is indeed the fact that decomposition is easily initiated by a variety of catalysts. The products of decomposition, being steam and oxygen, cannot be afterburned, so that this fuel is not suitable for a ram rocket.

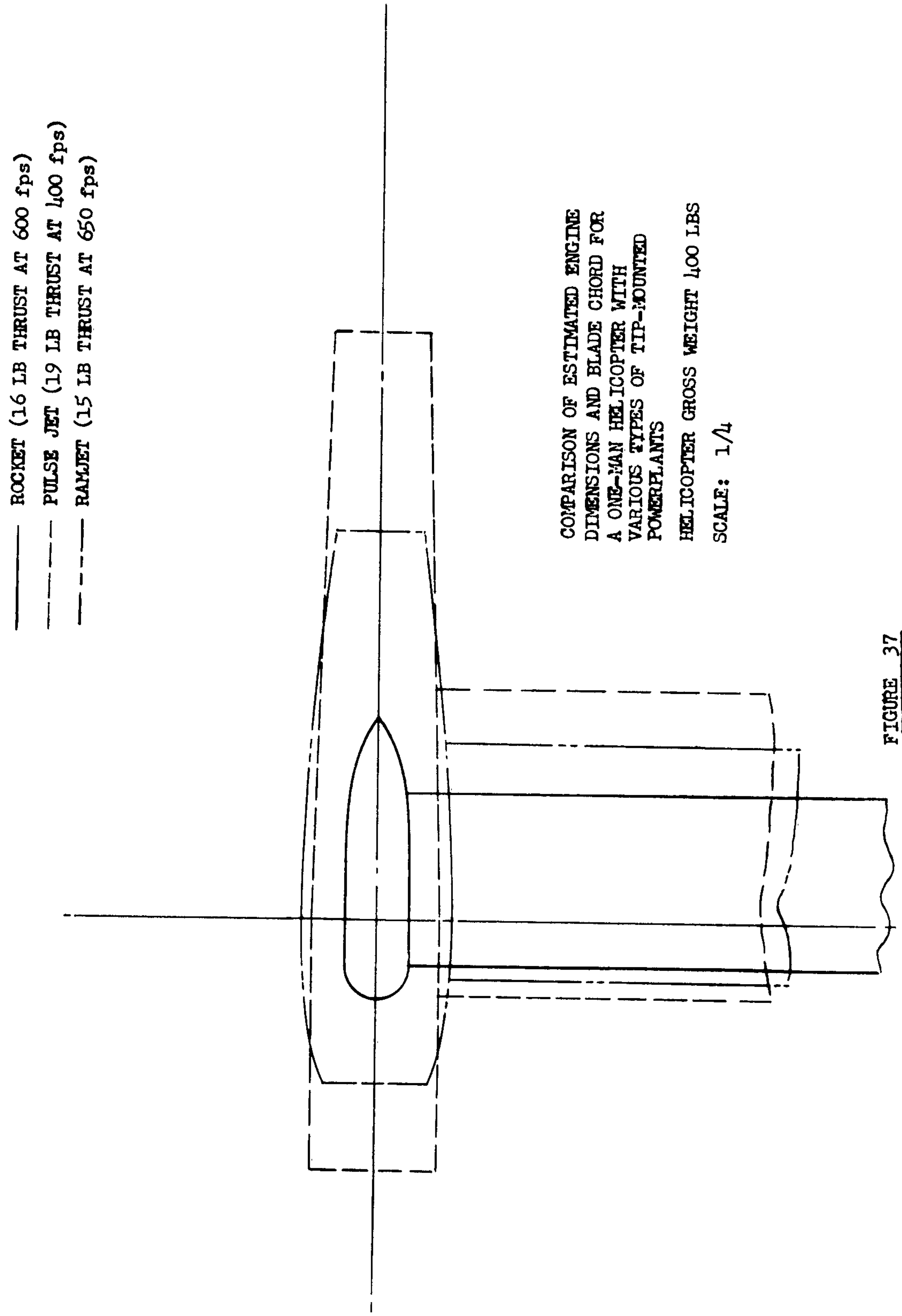
Ethylene Oxide appears to be the most promising monopropellant fuel, with handling characteristics little different from those of gasoline. Its heat content is, however, only about 60% of that of gasoline, and it must be stored under pressure (50-100 psia) to prevent vaporization. Heat release in decomposition is about 9% of total fuel heat content. Not only is the fuel relatively safe to handle, with a rocket performance about 20% better than that of Hydrogen Peroxide, but it is also available in great quantities at a relatively low price. The products of decomposition are very suitable for ram rocket operation.

Propyl Nitrate has characteristics similar to those of Ethylene Oxide but, in general, somewhat inferior. Cost is about three times higher, I_{sp} about 10% lower. Its major advantage is that no pressurization is required for storage or in a fuel tank. It is suitable for a ram rocket fuel, since the decomposition products burn in air.

Methyl Acetylene may be decomposed by heat and is therefore useable as a monopropellant fuel. The products of decomposition form a thick, greasy smoke, and are highly inflammable. The heat content of the fuel is high (about the same as gasoline), but the fuel is at present quite expensive. Requirement for large quantities would no doubt bring down the price considerably. The fuel is very promising for use with the ram rocket, due to the high heat content.

e. Relative Sizes of Various Tip-Mounted Powerplants for the One-Man Helicopter

Figure 37 shows, approximately, relative sizes of pulse jet, ramjet and Ethylene Oxide rocket powerplants for a typical one-man helicopter, with corresponding blade chords for these configurations. The ram rocket is not shown; however, preliminary calculations indicate that a diameter of about three inches and a length of nine to twelve inches would be required for the ram rocket shell.



COMPARISON OF ESTIMATED ENGINE DIMENSIONS AND BLADE CHORD FOR A ONE-MAN HELICOPTER WITH VARIOUS TYPES OF TIP-MOUNTED POWERPLANTS

HELICOPTER GROSS WEIGHT 400 LBS

SCALE: 1/4

FIGURE 37

DATA ON MONOPROPELLANT FUELS SUITABLE FOR USE IN TIP-MOUNTED ROCKETS OR RAM ROCKETS

NAME	HYDROGEN PEROXIDE	ETHYLENE OXIDE
Empirical formula	H_2O_2	$C_2H_4O_2$
Products of decomposition	$H_2O + O_2$	$CO + CH_4$
Heat of decomposition (BThU/lb)	590	1065
Exhaust temperature °F	1360	1750
Auto. decomposition temperature °F	60	1060
Heating value - BThU/lb	-	11925
I_{sp} - Secs (Max) (as monopropellant)	140 (90% pure)	170-180
I_{sp} (probable in cruise)	120-130	160-170
I_{sp} - ram rocket performance (estimated)	-	350
Freezing temperature 90% pure - °F 60-70% pure - °F	12 -40	-170
Vapor Pressure at 68°F	-	22 psia
Producer	Buffalo Electro Chemical	Union Carbon and Carbide
Cost-tank car lots	40 cents lb	18 cents lb
Reaction initiated by	catalyst	heat
Weight - lb/cu ft	11.6	7.2
Storage requirements	vented	sealed
Flammability lower limit at standard atmospheric pressure	decomposes at room temperature on contact with most organic substances	1060°F
Suitable fuel for ram rocket	No	Yes

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