UNCLASSIFIED

No. 132

(1)

[redacted]

A952 662

PROJECT SQUID

TECHNICAL MEMORANDUM PR-20

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED. afe

C
AD-A 15-839

APPLICATION OF THE RAM ROCKET AS A HELICOPTER PROPULSION SYSTEM

By

J. V. Charyk and J. E. Scott, Jr.

PRINCETON UNIVERSITY

DTIC
ELECTE
NOV 14 1983
S D
B

DOWNGRADED
TO
Unclassified
Authority: ONR: #29. B.III
Jan. 1963. Ralph Robi
4/16/63 J

Project SQUID is a cooperative program of basic research in Jet Propulsion. It is supported jointly by the United States Army, Navy, and Air Force and is administered by the Office of Naval Research through contract N6-ori-105, Task Order III NR-098-038.

January 23, 1953

UNCLASSIFIED

83 11 10 016

DTIC FILE COPY

[redacted]

[redacted]

PROJECT SQUID

TECHNICAL MEMORANDUM Pr-20

APPLICATION OF THE RAM ROCKET AS A HELICOPTER PROPULSION SYSTEM

by

J. V. Charyk and J. E. Scott, Jr.
Princeton University

This work was supported by the
Office of Ordnance Research, the Office of Naval Research,
and the Air Research and Development Command
under Contract No. N6-ori-105, T. O. 3,
NR-098-038

The James Forrestal Research Center
Princeton, New Jersey

January 23, 1953

[redacted]

[redacted]

Table of Contents

Page

Abstract

List of Symbols

I. Introduction 1

II. Analysis of Propulsion Systems 5
  A. Conventional Geared Piston Engine 5
  B. Rocket 6
  C. Ramjet 8
  D. Pulsejet 9
  E. Ram Rocket 11
  F. "Hybrid" System 14

III. Discussion of Results and Conclusions 16

IV. Acknowledgement 24

V. References 25

VI. Graphical Results 27

VII. Appendices
  A. Simplified Rotary Wing Performance Equations i
  B. Evaluation of Power Required Because of Powerplant Drag iii
  C. Performance Analysis of the Ram Rocket Helicopter vi
  D. Performance Analysis of the "Hybrid" Helicopter viii

[redacted]

[redacted]

List of Symbols

A_E = maximum powerplant frontal area, sq. ft.

A = rotor disc area, sq. ft.

A_W = wing area, sq. ft.

c = specific fuel consumption, lb/hp-hr or lb/lb T - hr

C_{D_o} = airfoil section drag coefficient

D = range, miles

f = equivalent flat plate area representing parasite drag, sq. ft.

g = gravitational constant, 32.2 ft/sec^2

Hp = rotor power required, horsepower

I_{SP} = specific impulse, sec.

R = rotor radius, ft.

R^* = ratio of secondary air mass flow to rocket mass flow

T = thrust, lb.

V = horizontal flight velocity, ft/sec.

W = gross weight of aircraft, lbs.

W_u = useful load minus fuel load, lb.

μ = ratio of forward speed to rotor tip speed

σ = rotor solidity ratio; (ratio of wing area to disc area)

Ω = rotor angular velocity, rad/sec.

ΩR = tip speed, ft/sec.

[redacted]

[redacted]

ρ = density of air; (0.002378 slugs/ft^3 for std. air at s. l.)

α = effective angle of attack of rotor wing airfoil, radians

Subscripts

H = hovering

L = level flight

D = drag

Superscripts

$'$ = conditions at end of flight

[redacted]

[redacted]

Abstract

A theoretical analysis of the influence of powerplant type on the range and load carrying capacity of conventional rotary wing aircraft is presented. Those propulsion systems considered for the conventional helicopter are the reciprocating engine, rocket, ramjet, pulsejet, and ram rocket. It is shown that the ram rocket helicopter is superior in range and load carrying capacity to all other propulsion schemes considered for tip speeds of 600 ft/sec and above and for ranges less than 88 miles.

The theoretical analysis of a "hybrid" helicopter composed of two ram rocket engines mounted at the wing tips and used in conjunction with a conventional piston engine shows that this system can realize improvements in load carrying capacity for a given range up to as much as 100% when compared to the conventional helicopter. Similarly, improvements in range of up to 90% for the same load carrying capacity can be obtained with this helicopter propulsion system. A conventional liquid rocket motor is shown to be the optimum jet propulsion device for use on the "hybrid" helicopter, and the effect of rocket specific impulse is shown to be negligible for the short operating time required of the rocket motors.

Samples of the details of the theoretical analysis are presented and the conclusions are synthesized in graphical form.

[redacted]

[redacted]

I. Introduction

The development of aircraft propulsion systems has been a principal factor in the increase in load carrying capacity, speed, and range of all aircraft. The powerplant characteristics of rotary wing aircraft as compared to those of fixed wing aircraft are complicated by the inherent characteristic of rotary wing aircraft which requires greater power for vertical flight than for hovering and similarly requires greater power for hovering than for forward flight. The helicopter power plant must deliver the power required for climbing as well as for cruising; and since the climbing condition for any given flight in general represents a very short interval of the total flight duration, the helicopter in the hovering and cruising condition is penalized by an excessive power plant weight. It seems feasible, therefore, that the powerplant of a helicopter should be as light as possible in order to reduce the weight penalty. Another possibility would be to modify the conventional helicopter propulsion system to provide a system which would use either separate systems or a combination of propulsive systems for the climbing and cruising conditions.

The application of jet propulsion schemes to helicopters has been only recently considered. The main advantages of such a system are listed as follows:

1. The helicopter design can be greatly simplified and its weight reduced by the elimination of the anti-torque tail rotor.
2. The power plant weight, which usually accounts for about 25% of the gross weight for a conventional helicopter may be substantially reduced. This results in an increased load carrying capacity for a given helicopter.

[redacted]

[redacted]

Johnson and Eustis (1) have carried out a detailed analysis[1] of helicopter propulsion systems in which the various types were compared on the basis of hovering endurance and maximum range. Recently, Falconer (3) analyzed helicopter propulsion systems based on load carrying capacity, and suggested the utilization of separate propulsion systems for vertical and high speed horizontal flight. In both of these papers, the ramjet, pulsejet, and pressure jet have been compared to the conventional geared reciprocating engine and to the geared gas turbine engine. This paper complements those calculations with the inclusion of the ram rocket powerplant in order to point out the specific advantages and disadvantages associated with such a system in this application. In addition, detailed calculations have been made for a "hybrid" helicopter which utilizes a ram rocket to provide the power for hovering and climbing and a geared reciprocating engine to deliver the power for horizontal flight. This propulsion system appears to be very attractive for increasing the load carrying capacity of conventional piston engine driven helicopters while maintaining at the same time the long range associated with this type of propulsion system. The ram rocket powerplant also shows advantages in load carrying capacity over the ramjet and also over the pulsejet at high tip speeds.

In this report, the comparison of various propulsion systems is made on the basis of maximum range at a forward flight speed of 75 mph. The preformance calculations for each propulsion system were carried out in the conventional manner with the exception of the reciprocating engine and the pulse-

---

[1] Since this report was written, another more detailed analysis has come to the attention of the authors. See Reference (2).

[redacted]

[redacted]

jet. For the reciprocating engine, a constant value of 0.58 lb/hp-hr. was taken to be a representative value for the specific fuel consumption of current conventional reciprocating engines. Performance data for the subsonic pulsejet were taken from Reference 2. This data was extrapolated to the high tip speeds.

The extrapolation in this particular instance can be in considerable error. No effective methods exist for the calculation of performance of pulsejets and experimental results reveal the very rapid increase in specific fuel consumption with flight Mach number. It might also be expected that the performance of the pulsejet under the action of centrifugal forces, as in the case of this application, might be considerably different than performance data available for cases of non-rotary operation. However, an attempt has been made to obtain a realistic and uniform comparison by presuming the most favorable conditions for the pulsejet, the ram rocket, and the ramjet.

The airframe weight estimates used in the computations are an average weight based on the recently licensed reciprocating-engine-driven helicopters as indicated in Reference 1. The compnent weights which were considered are listed as follows:

Airframe weight (including blades) = 0.40 W
Tail rotor & supporting structure = 0.05 W
Powerplant (piston engine) = 0.249 W
Total dry weight = 0.699 W
Maximum useful load (no fuel) = 0.301 W

From the above structural weights, it is evident that the gross weight of the jet propelled helicopter can be reduced by 5%; i.e., 0.05W, since no torque-

[redacted]

[redacted]

reacting rotor is required for this type of propulsion. Even though no anti-torque rotor is required for a jet propelled helicopter, experience has showen that a tail rotor is often necessary to provide directional control. However, the weight of this rotor and its supporting structure would be much less than the conventional anti-torque rotor. This weight has been neglected in this analysis.

[redacted]

[redacted]

II. Analysis of Propulsion Systems

In this section, the characteristics and performance of a typical helicopter will be presented and analyzed. The bulk of this information appears in Reference 1. The following assumptions were used in carrying out the computations and are considered to be representative of current helicopters:

1. Disc loading, W/A = 2.5 lb. per sq. ft.
2. Solidity Ratio, σ = 0.042
3. Cruising Speed = 75 mph.
4. Fuselage equivalent flat plate area, $f = 0.008\,A$

These data will be utilized in the comparison of the various propulsion systems.

A. Geared Reciprocating Engine

As mentioned previously, the specific fuel consumption for this engine was assumed to be 0.58 lb/hp-hr. The specific engine weight was assumed to be 3.15 lb/hp. which includes a 5% cooling loss, a 3% power transmission loss, and a tail rotor power requirement equal to 8% of the main rotor. Reference (1). In order to consider helicopters of a very general nature, a reserve power of 35% of the hovering power for altitude and climbing performance has been assumed to be representative of present practice for good performance. This assumption eliminates the necessity of postulating additional performance quantities such as rate of climb, maximum altitude, etc. All calculations have been carried out on the basis of sea level flight.

The simplified rotary wing performance equations based on a helicopter of unit weight are presented in Appendix A. By use of equations (1), (2), (3), and (4) of Appendix A, the rotor horsepower per pound of gross weight

[redacted]

[redacted]

for the various flight velocities may be determined. These results are presented in Figure 1 for various tip speeds. The usual present day helicopter has a rotor-tip speed near 500 ft/sec. which represents a compromise between aerodynamic performance in forward flight and in hovering. Values of tip speed (ΩR) of 600, 700, and 800 ft/sec. have been considered for each power plant. A tip speed for the reciprocating engine helicopter which is used as the basis of comparison has been taken as 500 ft/sec. It is realized that tip speeds as high as 800 ft/sec. for helicopter rotors introduce serious aerodynamic and structural problems, but calculations at these speeds have been carried out to show the effect of increased performance ability of the various jet propulsion systems on the overall helicopter range and load carrying capacity. Recent developments indicate the feasibility of the attainment of even higher tip speeds. The characteristic trends summarized in this study will be even more accentuated in such instances. It is obviously undesirable to operate a piston-engine-driven helicopter at these high tip speeds.

From Equations 5, 6 and 7 of Appendix A and the above assumed helicopter parameters, the maximum cruising range for a reciprocating-engine-driven helicopter can be computed for various values of useful load minus fuel load expressed as a percentage of the gross weight. The calculated results for the piston engine are shown graphically in Figures 4, 5, and 6.

B. Rocket Propulsion System

Since a program of study of the performance characteristics of methyl acetylene (propyne, C_3H_4) is in progress at the present time in this laboratory,

[redacted]

[redacted]

this propellant was chosen as the monopropellant to be used in the helicopter rocket propulsion system. For comparative purposes, calculations were also made for a bipropellant motor operating with nitric acid and JP-4.

In order to evaluate the power plant weight for this propulsion system, the specific weight of the rocket, including propellant lines, valves, controls, and tanks, was assumed to be 0.10 lb/lb T. This value can probably be obtained using current design practice. The rocket was also assumed to be small enough so that it could be buried within the wings at the tips thus eliminating any aerodynamic drag considerations other than those associated with the wings themselves. The pumping of the propellant from the tanks to the rockets was assumed to occur under the influence of the centrifugal force associated with the rotating rotor. For starting, a small, light weight pressurizing system would probably be used; but this particular problem was not considered in detail.

The range calculations for the rocket powered helicopter were computed using the same analysis and helicopter parameters considered previously for the piston engine power plant, together with a new power plant weight and specific fuel consumption. As was mentioned previously, for the case of reaction at the wing tips, the 5% weight requirement for the anti-torque tail rotor can be eliminated. The results of the rocket calculations are shown graphically in Figures 4, 5, and 6. The curves representing the rocket helicopter performance at various tip speeds have been plotted on the same sheet as the conventional helicopter performance curves in order to obtain a more direct comparison.

[redacted]

[redacted]

C. Ramjet Propulsion System

The calculations of ramjet performance were based on the use of methyl acetylene (C_3H_4) as a fuel. Since the energy content of the methyl acetylene as a fuel is somewhat in excess of that for JP-4 the ramjet performance predictions really represent maximum values. In addition, no stagnation pressure losses are assumed in the flow other than that associated with the combustion process, the effects of varying forward velocity, due to the advancing and retreating wings, are neglected, and no adverse effects on performance are assumed as a result of the centrifugal forces acting on the engine. It is clear that under these conditions the results represent an ultimate potential for the ramjet. The external configuration of the ramjet was taken to be identical with that of the ram rocket, and performance calculations were made for two air-fuel operating conditions; viz. 15 and 30 with the stoichiometric air-fuel ratio being 13.87 for the case of methyl acetylene-air mixtures. The ramjet was equipped with a conventional diverging subsonic diffuser which was assumed to be of variable geometry such that the burner inlet Mach number was maintained at a value of 0.15. These operating conditions were chosen in order to provide a direct comparison with the ram rocket performance calculations of Charyk and Sutherland (4).

The ramjet performance based on the above assumptions are presented graphically in Figures 2 and 3. The range calculations for the ramjet helicopter are based on the same component weight estimates used for the piston engine and rocket helicopter systems. The powerplant weight, however, was taken to be 0.10 lb/lb thrust which is probably a representative value for cur-

[redacted]

[redacted]

rent subsonic ramjets. By applying Equation 5 of Appendix A and the above assumptions, the range performance of the ramjet helicopter can be determined. As in the case of the piston engine and rocket helicopters, performance calculations were carried out for tip speeds of 600, 700, and 800 ft/sec. In this particualr case, however, it was necessary to account for the external drag of the ducted bodies mounted on the wing tips. Values of drag coefficients for ducted bodies at subsonic speeds vary widely in the literature. Drag coefficients of 0.10 and 0.20 for the ramjet were chosen based on References (5) and (6), and these values were used in computing the power required for the various flight conditions of the ramjet helicopter. The analysis of the evaluation of the additional power required because of the external drag other than wing drag is presented in Appendix B.

The final range and load-carrying performance of the ramjet helicopter are presented graphically in Figures 4, 5, and 6. These curves can be compared directly to the previously computed performance curves for the helicopter powered by a conventional piston engine and the rocket propelled helicopter.

D. Pulsejet Propulsion System

The pulsejet powerplant was also considered in this paper to provide a comprehensive comparison study of the various possible jet propulsion schemes which could be utilized for high load-carrying capacity, short range helicopter operation. Detailed gas dynamic calculations were not carried out for the subsonic pulsejet, but the performance data presented by Falconer in Reference (3) was used in this study. The pulsejet is essentially a low speed

[redacted]

[redacted]

propulsion system so that the helicopter design incorporating this powerplant system would necessarily be such as to provide a low tip speed rotor. Regardless of this fact, the pulsejet performance was extrapolated to tip speeds of 600, 700 and 800 ft/sec in order to provide a direct comparison with the other propulsion systems considered here. It is realized that this extrapolation of Falconer's data to the high tip speeds can be in considerable error since the performance of the pulsejet falls off very rapidly as flight Mach number is increased. In fact, it is doubtful if the pulsejet system can even operate satisfactorily at these high tip speeds without ducting.

Very little information is available, however, on performance of ducted pulsejets at these speeds. It should be emphasized that the pulsejet engine is much more sensitive to such factors as centrifugal force effects, continual variation in inlet flow conditions, etc. It would be particularly important, in the case of such a power plant, to analyze the performance experimentally by direct simulation of the conditions to be expected in the actual application. No satisfactory methods exist for extrapolating pulsejet performance data. As in the previous instance, however, the performance assumed probably represents the maximum attainable; and hence the conclusions are accurate on a comparative basis.

The range performance of the pulsejet helicopter system are presented graphically in Figures 4, 5, and 6. These results were computed as for the previously considered powerplant systems, the only change being in the actual performance of the powerplant, i.e., its specific fuel consumption and its value of thrust per unit frontal area. The specific weight of the pulsejet was also

[redacted]

[redacted]

taken to be 0.10 lb/lb thrust which is probably a conservative value, and the range calculations were carried out for values of the external drag coefficient (based on maximum cross sectional area) of 0.10 and 0.20. Tip speeds of 600, 700, and 800 ft/sec. were also considered for this case.

E. Ram Rocket Propulsion System

Detailed performance calculations for the ram rocket engine have been made by Charyk and Sutherland (4) for the high subsonic and low supersonic ranges of flight Mach number. Some experimental verification of these calculations have already been obtained in this laboratory (7). These calculations were extended to the subsonic range which would include flight Mach numbers corresponding to the chosen tip speed values of 600, 700, and 800 ft/sec. The necessary thermochemical data for the propyne-air system was taken as that reported by Experiment Incorporated (8). The engine performance was carried out for R * values ranging from 2 to 30, and the results are shown in Figures 2 and 3 together with the results for the ramjet and pulsejet. The powerplant performance is expressed as specific fuel consumption and thrust per unit frontal area as a function of flight Mach number.

The ram rocket curves of Figures 2 and 3 clearly bring out the diversified potential of the ram rocket powerplant. In considering the specific fuel consumption values presented in Figure 2, it is seen that a ram rocket operating at $R^* = 2$ shows a specific fuel consumption vs. flight Mach number curve which gives an approximately constant specific fuel consumption for all flight Mach number values. This is clearly the case of the ram rocket operating essentially as a conventional rocket giving a high accelerating thrust po-

[redacted]

[redacted]

tential with a high specific fuel consumption. The value of R * (ratio of air mass flow to rocket mass flow) of 2 indicates that only a small amount of air is taken into the engine so that the rocket portion of the powerplant constitutes the entire powerplant from a performance point of view. As the R * value is increased, however, it is seen that for a given flight Mach number the ram rocket performance curves more nearly approach those of the ramjet for the same operating value of R *; i.e., air-fuel ratio, for the case of the ramjet. Thus these performance curves clearly show that the ram rocket operating at a low R * can provide the high accelerating thrust potential necessary for take-off or super performance, and it can also provide for the comparatively low specific fuel consumption required for cruising conditions when operating at a high R * value. This means, for the specific case of the ram rocket helicopter, that the ram rocket propulsion system will be a self starting system providing for rapid take-off under its own power; and then it can cruise at a reasonably low specific fuel consumption value to give a very high load-carrying capacity for a reasonable range. It is required only that the rocket mass flow in the ram rocket engine can be properly throttled in order to give the desired operational value of R *.

Experimental information is available to illustrate that rocket throttling over the range suggested here is well within the limits of practical attainment.

Following the procedure of Charyk and Sutherland, the ram rocket performance was determined for the case of a methyl acetylene monopropellant rocket mounted at the diffuser exit in a conventional subsonic ramjet-type

[redacted]

[redacted]

duct. The rocket is assumed to operate at a chamber pressure of 20 atm, and its decomposition products are burned with the air coming in through the nose of the unit under ram pressure. These products of combustion are then expanded to atmospheric pressure in a conventional exhaust nozzle.

As in the case of the ramjet, the ram rocket is assumed to be equipped with a variable geometry diffuser such that the burner inlet Mach number is maintained at a value of 0.15. A small loss in stagnation pressure is considered in the diffuser (roughly 6%), but the other thermodynamic processes taking place are assumed to occur without loss. This means, as in the case of the ramjet, that the ram rocket engine considered here is an optimum engine so that this performance represents an upper limit to the possibilities for the ram rocket helicopter. The helicopter range computations for the case of the ram rocket engine were based on the component weight estimates discussed previously and on the calculated theoretical ram rocket performance data. The specific engine weight of the ram rocket was taken to be the same as that of the rocket. This appears to be a justifiable assumption in view of the fact that for the same overall thrust the duct weight associated with the ram rocket powerplant should be approximately compensated by the reduction in the size of the rocket motor used in the ram rocket as compared to the pure rocket system.

The results of the helicopter range calculations are shown in Figures 4, 5, and 6 together with the range performance of the other propulsion systems in order to provide for a direct comparison of the different powerplants which might possibly be used in a short range helicopter with a high load-carrying capacity. The curves [redacted] the ram rocket system are for two val-

[redacted]

ues of R *, namely 15 and 30 representing the condition for the cruising helicopter at the three different tip speed values and for the two assumed values of external drag coefficient. A detailed analysis of the range performance of the ram rocket helicopter is presented in Appendix C.

F. Hybrid Propulsion System

This type of propulsion system was first proposed by Goland and Hayes (9) and later by Falconer (3). By examining the power required vs flight speed curves in Figure (1), it is seen that the hovering power requirement essentially governs the powerplant size for rotary wing aircraft. Since the duration of flight in climbing and hovering represents only a relatively small portion of the total flight time, the rotary wing aircraft is penalized by an excessive powerplant weight for the cruising condition. Therefore, it would be desirable to have a power available curve as a function of flight speed such that this curve would more nearly parallel the power required curve than is the case for the constant power conventional reciprocating engine. This system can be provided by a "hybrid" powerplant; i.e., a combination of the piston engine and a suitable jet propulsion device.

The hybrid system to be proposed here is a conventional reciprocating engine used in conjunction with two ram rockets mounted on the wing tips. The ram rockets will be of a size such as to provide the power required for climbing and hovering flight while the piston engine will provide the power necessary for horizontal flight at the selected flight speed. This power plant arrangement can be easily analyzed in terms of the analysis proposed previously for the reciprocating engine and ram rocket helicopters. By use of Equation 3 of appendix A, the power required for forward flight can be computed; and with the

[redacted]

reciprocating engine specific weight of 3.5 lb. per hp, the piston engine weight is thus determined. Equation 4 of Appendix A determines the hovering power requirement. Assuming 35% excess power over that required for hovering, and using the ram rocket specific weight of 0.10 lb/lb thrust, the weight of the ram rocket engine is then determined. Proceeding in the same manner as followed in the conventional helicopter analysis, the total dry weight is determined; and the range for a given cargo weight follows immediately from Equation 5 of Appendix A. The details of this analysis are presented in Appendix D.

It is suggested that the combination of a gas turbine power plant with a ram rocket would also offer interesting possibilities for long range helicopters.

The results of the "hybrid" helicopter calculations are presented graphically in Figures (7), (8), and (9) for tip speeds of 600, 700, and 800 ft/sec repectively. The conventional helicopter range curve is also shown on these figures for comparative purposes. Values of external drag coefficients for the ram rockets located at the wing tips have again been chosen as 0.10 and 0.20. In order to determine the best condition of ram rocket operation, the performance of the ram rockets on the "hybrid" helicopter have been presented for R* values of 2, 5, 10, 15, and 30 which represents the complete practical range of the ram rocket engine. These curves show that the "hybrid" powerplant system shows advantages over the conventional helicopter only for certain conditions of R* and external drag coefficient. The implications of these results will be brought out in the next section.

[redacted]

III. Discussion of Results and Conclusions

The results of the helicopter range calculations for the different propulsive systems are shown in Figures (4), (5) and (6). It is apparent from these curves that the external drag coefficient assumed in the calculations does not have a pronounced effect on the final helicopter range performance.

From the graphical results of the range calculations, it can be seen that the range performance of all of the air breathing jet propulsion engines with the exception of the pulsejet are improved by increasing the tip speed. The deleterious effect of higher tip speeds on pulsejet performance is due to such factors as valve malfunctioning, change in reverse flow conditions at the tailpipe, etc. It is clear that the simple pulsejet ceases to be attractive in this application at the higher tip speeds. However, the situation can probably be improved by considering the possibility of a ducted pulsejet or one of the other similar engines operating on the wave principle.

The ramjet and ram rocket, are both very attractive at high tip speeds. The significant performance improvements at higher tip speeds with the use of either the ramjet or the ram rocket power plants suggests the value of work directed toward the attainment of higher rotor speeds for heavily loaded short range helicopters. The final selection of a jet propulsion device and rotor tip speed must necessarily be a compromise between rotor aerodynamic considerations and powerplant performance.

The rocket engine considered in these calculations has been assumed to be buried in the rotor wing tips so that it is not subject to the external drag loss associated with the ducted powerplants. Since the specific fuel consumption (or specific impulse, I_{SP}) of the rocket remains at a constant value re-

[redacted]

[redacted]

gardless of the rotor tip speed, the rocket powered helicopter suffers a decreased performance as the tip speed is increased because of the additional drag losses without compensation by improvement in specific fuel consumption.

In the comparison which follows, the different propulsion systems will be compared to the reciprocating-engine-driven helicopter with a tip speed of 500 ft/sec, which is representative of a conventional present-day helicopter. At a tip speed of 600 ft/sec (Figure 4), it is seen that the ram rocket is superior to the conventional helicopter from the point of view of load carrying capacity up to a range of 88 miles. This range corresponds to a loading density of 27%; i.e., the useful load minus the fuel load amounts to 27% of the gross take-off weight. This value is probably near the optimum value which could be realized in practice, and it shows that the ram rocket helicopter is always superior to the conventional helicopter for short range operation, viz; up to 88 miles. For extremely short range operation, say for a 25 mile range, the ram rocket helicopter can carry approximately 62% more useful load for the same gross helicopter take-off weight than can the conventional helicopter. This operational range corresponds to a ram rocket helicopter loading density of 53% with a fuel load of approximately 6% of the take-off weight, a system which could easily be realized in practice.

At 700 ft/sec., (see Figure 5), the superiority of the ram rocket helicopter over the conventional helicopter is increased to a range of 108 miles corresponding to a loading factor of approximately 27%. For the case of the 25 mile range helicopter, the ram rocket helicopter can carry approximately 72% more load than the conventional helicopter of the same gross weight.

[redacted]

[redacted]

At 800 ft/sec, (Figure 6) the ram rocket helicopter exceeds the conventional helicopter in load carrying capacity to a range of 115 miles; i.e., for applications requiring a helicopter range of less than 115 miles, the ram rocket system is definitely superior to the conventional system for a given helicopter size. For a 25 mile range, the ram rocket helicopter carries 75% more load than does the conventional helicopter. It should be emphasized that the external drag of the ram rocket engines has been considered in these calculations. Even though the engine drag increases rapidly with increasing tip speed, providing for an increased powerplant weight, the improved engine performance at the high tip speeds as evidenced by the decreased specific fuel consumption provides for an improvement in helicopter range performance.

These comparisons of the ram rocket and conventional helicopter are for the case of the ram rocket engine operating at an R* of 30. This is probably near the optimum practical operating condition which is determined by the maximum allowable engine frontal area from drag considerations and by the maximum allowable engine weight from rotor structural considerations. The ram rocket helicopter range is decreased for the lower R* conditions and as $R^* \rightarrow 0$, the ram rocket approaches the performance of a conventional rocket whose range curves have been discussed previously. This again illustrates that the ram rocket helicopter range curve for a given rotor tip speed lies somewhere between the rocket and the ram rocket for R* = 30. Thus the ram rocket powerplant would be able to meet any operational requirement simply by the proper selection of a suitable R* value.

The range curves for the ramjet helicopter follow the same trend as those of the ram rocket helicopter; but in all cases, the ram rocket system

[redacted]

[redacted]

is superior to the ramjet system. This superiority in range and load carrying capacity is due to the lower specific fuel consumption of the ram rocket engine as compared to the ramjet in the subsonic range of flight speeds. As the rotor tip speed is increased, however, the ramjet more nearly approaches the ram rocket in performance; and in the limit of very high tip speeds, the performance of these two propulsion systems would be approximately the same. The ramjet helicopter range performance shown in Figures (4), (5), and (6) has been calculated for two R* (air-fuel ratio) conditions. Since current ramjets usually operate at very lean air-fuel ratios, the ramjet curves for $R^* = 30$ are representative for present-day ramjets. It can be seen that the ramjet helicopter is superior to the rocket helicopter for all three tip speeds considered. The superiority is, of course, directly due to the lower specific fuel consumption even though an increased powerplant weight is required because of the increased external drag of the ducted bodies at the wing tips. At low tip speeds, however, the ramjet is an inferior powerplant as compared to the ram rocket; at tip speeds lower than 600 ft/sec, it will also be found that the ramjet propulsion system is inferior to that of the rocket because of its rapid increase in specific fuel consumption in the low subsonic speed range.

Even though the ram rocket helicopter has only a small advantage over the ramjet helicopter in the high rotor tip speed range, it has a pronounced advantage over the ramjet because of its inherent method of operation. It is well known that the ramjet cannot produce static thrust so that a ramjet helicopter requires an additional device to bring the rotor up to a sufficiently high speed such that the ramjets can operate satisfactorily, or else this is done at the expense of a v[redacted]tion. The ram rocket, on the

[redacted]

other hand, can produce static thrust and can accelerate up to speed with relatively modest values for specific fuel consumption. High thrust values for emergency conditions are also readily available. In addition to these important advantages, it is believed that fuel injection and combustion will not be as adversely affected by the large centrifugal forces associated with the high tip speeds as in the case of the ramjet engine. This follows from the fact that the ram rocket injects its fuel as a high velocity stream of high temperature combustible gas which readily mixes and burns with the incoming air. The ramjet, on the other hand injects its fuel in liquid form so that the fuel must be atomized, vaporized, and mixed with the incoming air before combustion can occur; the ram rocket tends to insure, on the other hand, a high combustion efficiency over a wide range of flow conditions.

Thus it has been shown that the ram rocket propulsion system possesses strong possibilities as a powerplant for a short range helicopter of high load-carrying capacity. Its performance as a helicopter propulsion scheme exceeds that of the ramjet, rocket, pulsejet, and conventional helicopter in the tip speed ranges considered; it can also be a self-contained, self-starting, self-accelerating, propulsion unit. Perhaps its biggest disadvantage as a helicopter propulsion unit is the fact that it requires a special fuel type for satisfactory operation. It follows, then, that the fuel for the ram rocket engine will be expensive and more difficult to store and handle than kerosene or gasoline which is being used in present day ramjets. The fuel considered in this analysis, however, is not a dangerous fuel; and it can be stored, transported, and handled as easily as gasoline.

Although it is fairly obvious that the conventional reciprocating engine

[redacted]

[redacted]

driven helicopter has a poor range performance at high rotor tip speeds, the range curves for this helicopter have been presented in Figures (4), (5), and (6) for comparison purposes. Like the rocket, the piston engine has a constant specific fuel consumption independent of rotor tip speed. This means that a helicopter powered by this type of engine suffers the disadvantage of increased powerplant weight with increasing tip speed without the accompanying decrease in specific fuel consumption common to both the ramjet and ram rocket. Also since the specific engine weight of the piston engine is so high and since the conventional helicopter requires an anti-torque tail rotor, the load carrying capacity for a given helicopter size is greatly diminished. With the low specific fuel consumption of the reciprocating engine, however, the conventional helicopter can be considered as a long range device. The problem of increasing its load carrying capacity while maintaining the same range leads to the consideration of the "hybrid" helicopter.

The "hybrid" helicopter system analyzed in this paper has been discussed in Section II, and the details of the analysis are shown in Appendix D. This helicopter propulsive system is composed of a conventional reciprocating engine providing the power required for horizontal flight and two tip mounted ram rockets providing the power required for hovering and vertical flight. In evaluating the performance of this device, it has been assumed that an allowable operating time of the ram rocket engines of 120 seconds will be sufficient for most flight purposes. The results of these calculations are shown in Figures (7), (8) and (9) for tip speeds of 600, 700, and 800 ft/sec. It is seen from these curves that the values of the drag coefficient and R* for the ram rockets have a pronounced effect on the range of the "hybrid"

[redacted]

[redacted]

helicopter. At high values of R *, the "hybrid" helicopter does not show nearly as much improvement over the conventional helicopter as it does when operating at low R * values. Since the specific fuel consumption of the ram rocket engine decreases with increasing R * values, the curves show that the effect of ram rocket specific fuel consumption is not important for this type of helicopter. This follows from the fact that since the ram rockets only operate for a short period of time, the quantity of fuel consumed during this period is only a small percentage of the take-off weight. Thus, the total dry weight or the load carrying capacity is not affected very much by the specific fuel consumption of the ram rockets used for climbing and hovering. On the other hand, the drag of the ram rockets determines to a considerable extent the size and weight of the piston engine supplying the power for horizontal flight. It is seen from Figures (7), (8), and (9) that the improvement in range performance of the "hybrid" helicopter over that of the conventional helicopter decreases with increasing drag coefficient; and at high R * values, the "hybrid" helicopter is inferior to the conventional helicopter. The cause of this result can readily be seen by referring to Appendix B. Here it is shown that the additional power required because of the aerodynamic drag of the ram rockets increases very rapidly with decreasing values of thrust per unit frontal area of the engine. Since the T/A value for the ram rocket decreases with increasing R *, the power requirement due to powerplant drag increases with increasing R * and engine drag coefficient. These facts clearly indicate the use of a low R * ram rocket for the " hybrid" helicopter with as low an engine drag coefficient as possible. The limiting case of $R^* = 0$ corresponding to the conventional rocket would be the optimum situation. For this case the

[redacted]

[redacted]

rocket motors could probably be buried within the wing tips thus eliminating the engine drag problem and also any adverse effects on the autorotating characteristics of the wings.

Figures (7), (8), and (9) also show the rapid fall of helicopter range performance with increasing tip speed. This is an inherent characteristic of the reciprocating engine driven helicopter as has been discussed previously. Therefore, the "hybrid" helicopter should be set up to include a pair of rockets buried in the wing tips and a conventional piston engine. The tip speed should have a comparatively low value in order to minimize the required weight of the reciprocating engine.

The improvement which might be realized from such a system can be seen in Figure (7) for the case of a ram rocket with $R^* = 2$, tip speed = 600 ft/sec, and external engine drag coefficient of 0.10. For a range of 500 miles, the "hybrid" helicopter can carry approximately twice as much load as the conventional helicopter. For the same load carrying capacity, this means that the "hybrid" helicopter shows a 90% improvement in range over the equivalent loaded conventional helicopter. Thus the "hybrid" helicopter exhibits very attractive advantages over the conventional helicopter when the requirement of high load carrying capacity together with a long range is considered. The "hybrid" helicopter is useful only for this type of long range operation, however, and it could not compete with any of the previously discussed helicopters for short range operation.

As pointed out above, the rocket engine appears to be the optimum jet propulsion device for use in the "hybrid" helicopter system. Although no definite calculations have been made for this system, the trend of the range per-

[redacted]

[redacted]

formance is illustrated by the effect of ram rocket R *. Goland and Hayes (9) have made similar calculations for the case of a rocket assisted helicopter which is essentially the same as the "hybrid" helicopter presented here. Their calculations show advantages similar to those presented in this paper. In addition, they also show that the effect of rocket specific impulse or specific fuel consumption is not important for short operating times, but that it does have an effect on the helicopter range performance for longer operating times, say from 3 to 5 minutes.

The main disadvantage of this system is the requirement that the rockets use a special fuel. To provide for a simple propellant system, the rockets used on the "hybrid" helicopter should be of the monopropellant type. Such monopropellants as ethylene oxide and propyne both offer good possibilities.

Acknowledgement

The authors would like to express their appreciation to Prof. A. A. Nikolsky and Dr. I. Glassman for their assistance during the course of this investigation and to Mr. J. P. Layton for originally suggesting the study.

[redacted]

[redacted]

References

1. Johnson, J.A., and Eustis, R.H., "An Analysis of Helicopter Propulsion Systems," Trans. A.S.M.E., vol. 73, no. 5, July, 1951.

2. Johnson, J.A., Flannery, J.L., Spencer, C.D., and Reisse, C.W., "Helicopter Propulsion System Study", a report for USAF Contract AF 33(038) - 22185 leg Thermal Research and Engineering Corp., Conshohocken, Pa., Sept. 1952 (CONFIDENTIAL).

3. Falconer, R. W., "The Application of Jet Propulsion to Helicopters," Aero. Eng. Review, Sept. 1952.

4. Charyk, J.V., and Sutherland, G.S., "A Performance Study of the Ram Rocket Power Plant and Related Problems," Project SQUID T.R. 36, March, 1952, (RESTRICTED).

5. Spreiter, J.R., "Aerodynamic Properties of Slender Wing-Body Combinations at Subsonic, Transonic, and Supersonic Speeds," N.A.C.A. T.N. 1662, July, 1948.

6. Goldstein, S., "Modern Developments In Fluid Dynamics," Oxford, 1938.

7. Charyk, J.V., Glassman, I. and John, R.R., "The Mixing and Burning of Two Concentric Fluid Streams", presented at Fourth International Symposium on Combustion, Boston, Sept. 1952.

8. "Interim Status Report on Monofuel Rocket Development," Experiment Inc. Tech. Pub. No. 55, April 1, 1952 (CONFIDENTIAL).

9. Goland, L., and Hayes, F.G., "Performance of a Rocket Assisted Helicopter," Reaction Motors, Inc., Sept. 18, 1951, (CONFIDENTIAL).

[redacted]

[redacted]

[redacted]

[redacted]

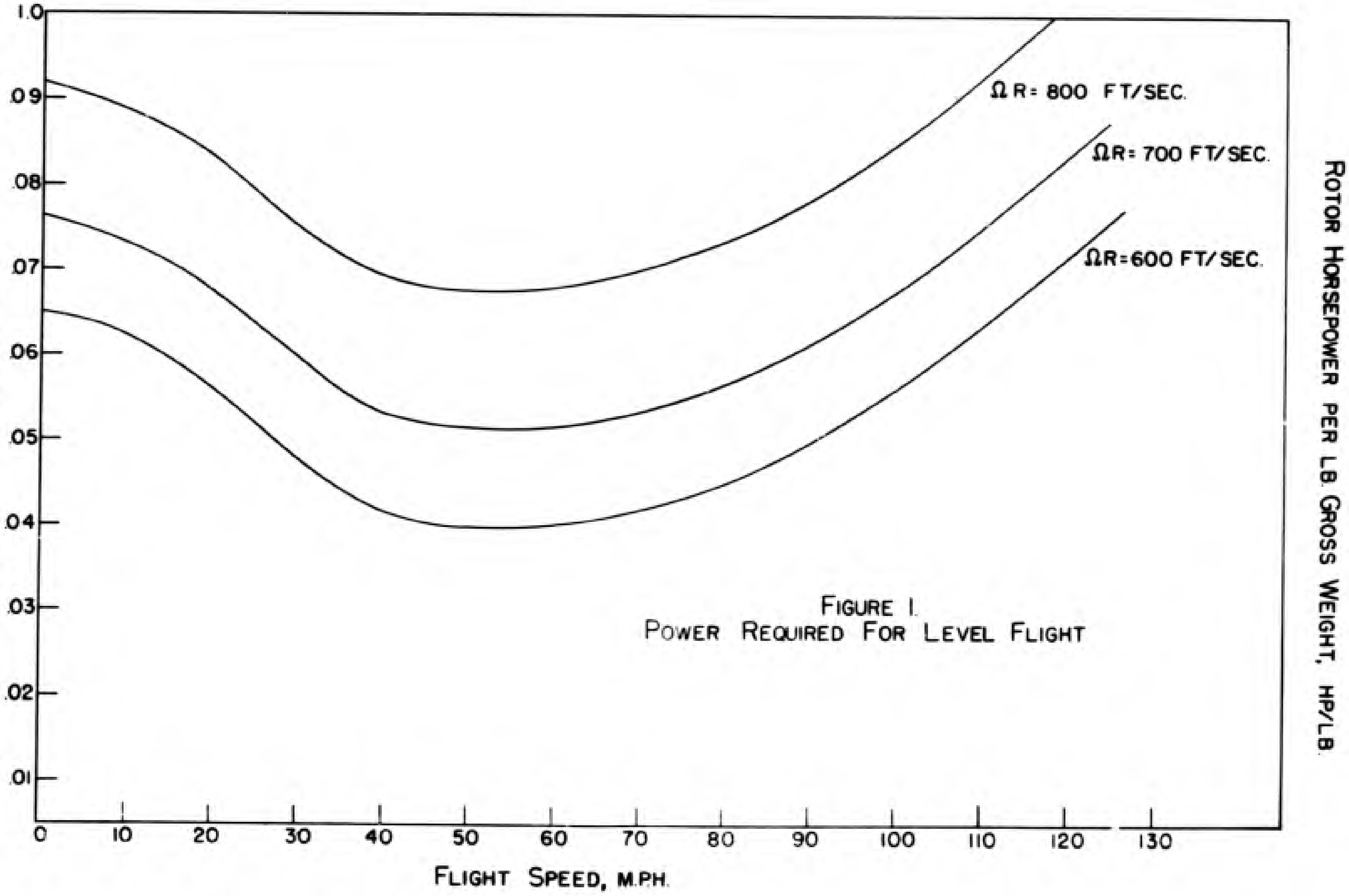


Fig. 1. Power Required For Level Flight

[redacted]

[redacted]

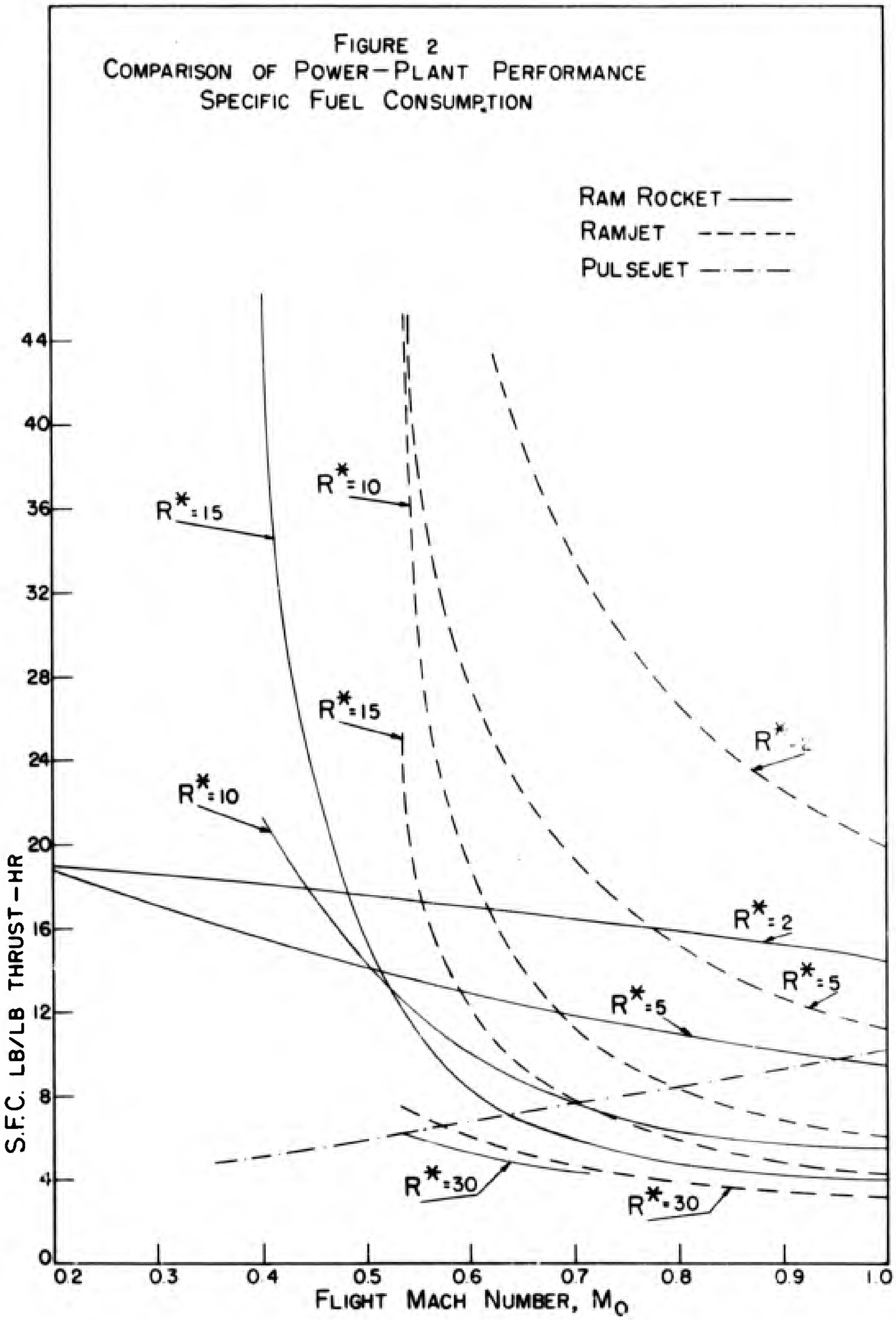


Fig. 2. Comparison of Po[redacted]Specific Fuel Consumption

[redacted]

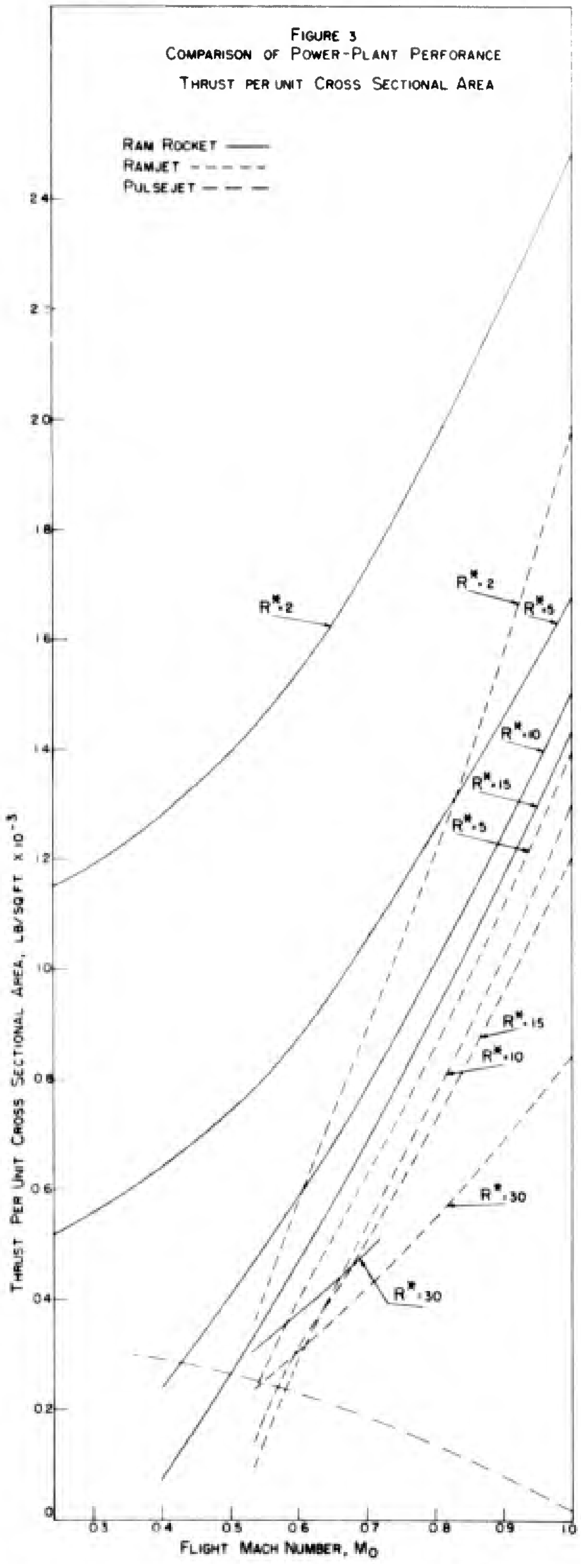


Fig. 3. Comparison of Power-[redacted]t Per Unit Cross Sectional Area

[redacted]

[redacted]

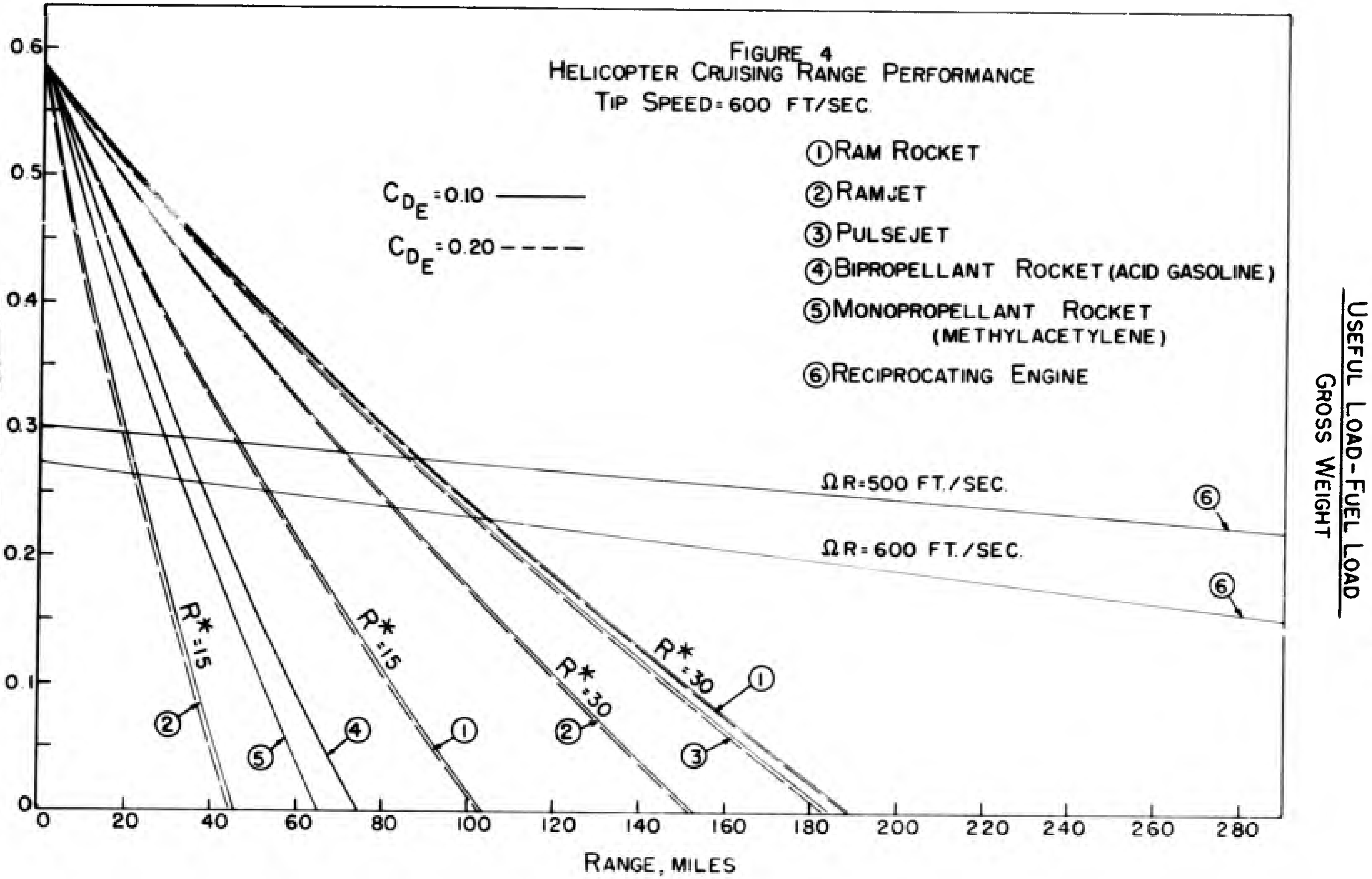


Fig. 4. Helicopter Cruising Range Performance Tip Speed = 600 Ft/Sec.

[redacted]

[redacted]

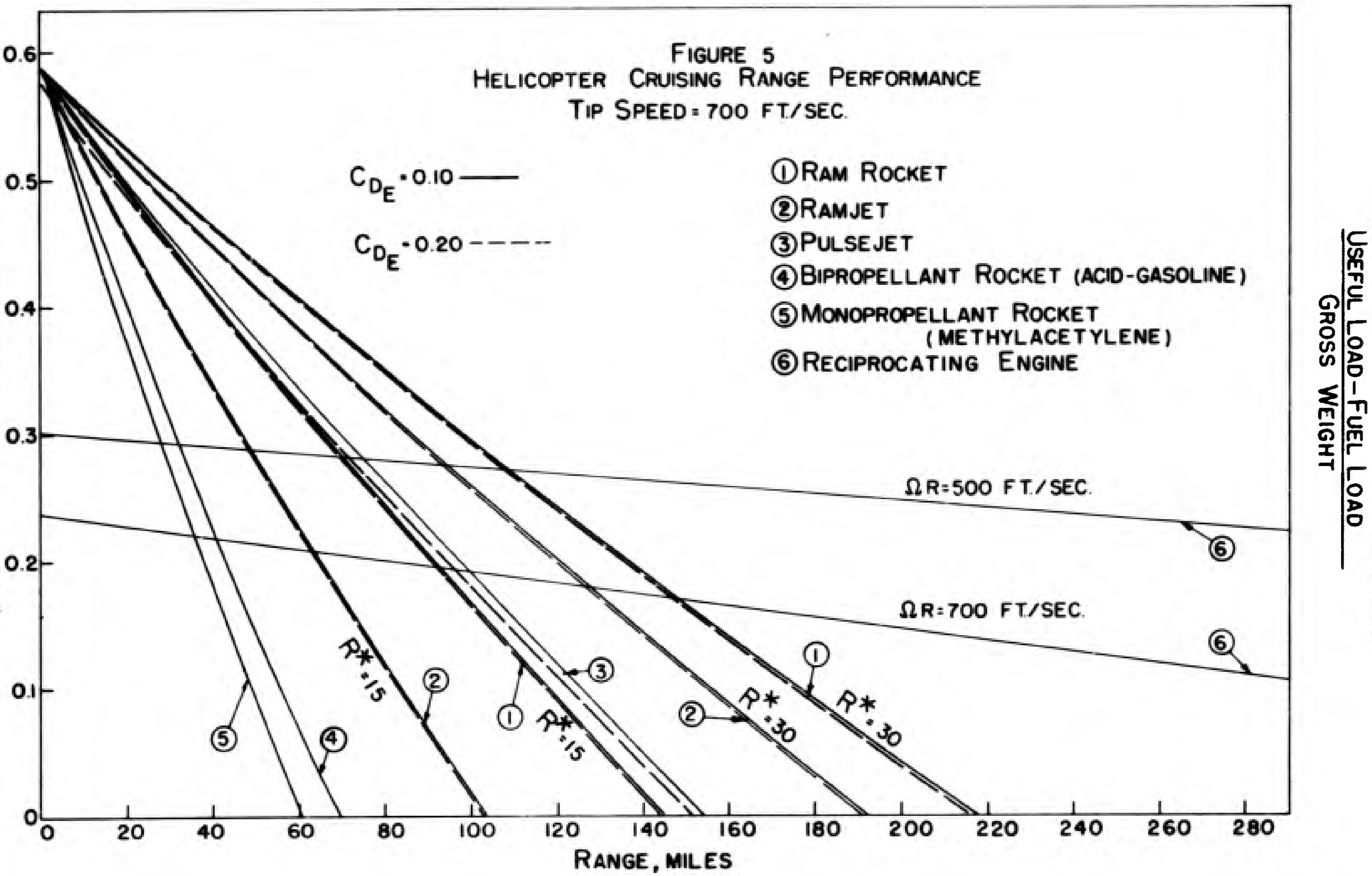
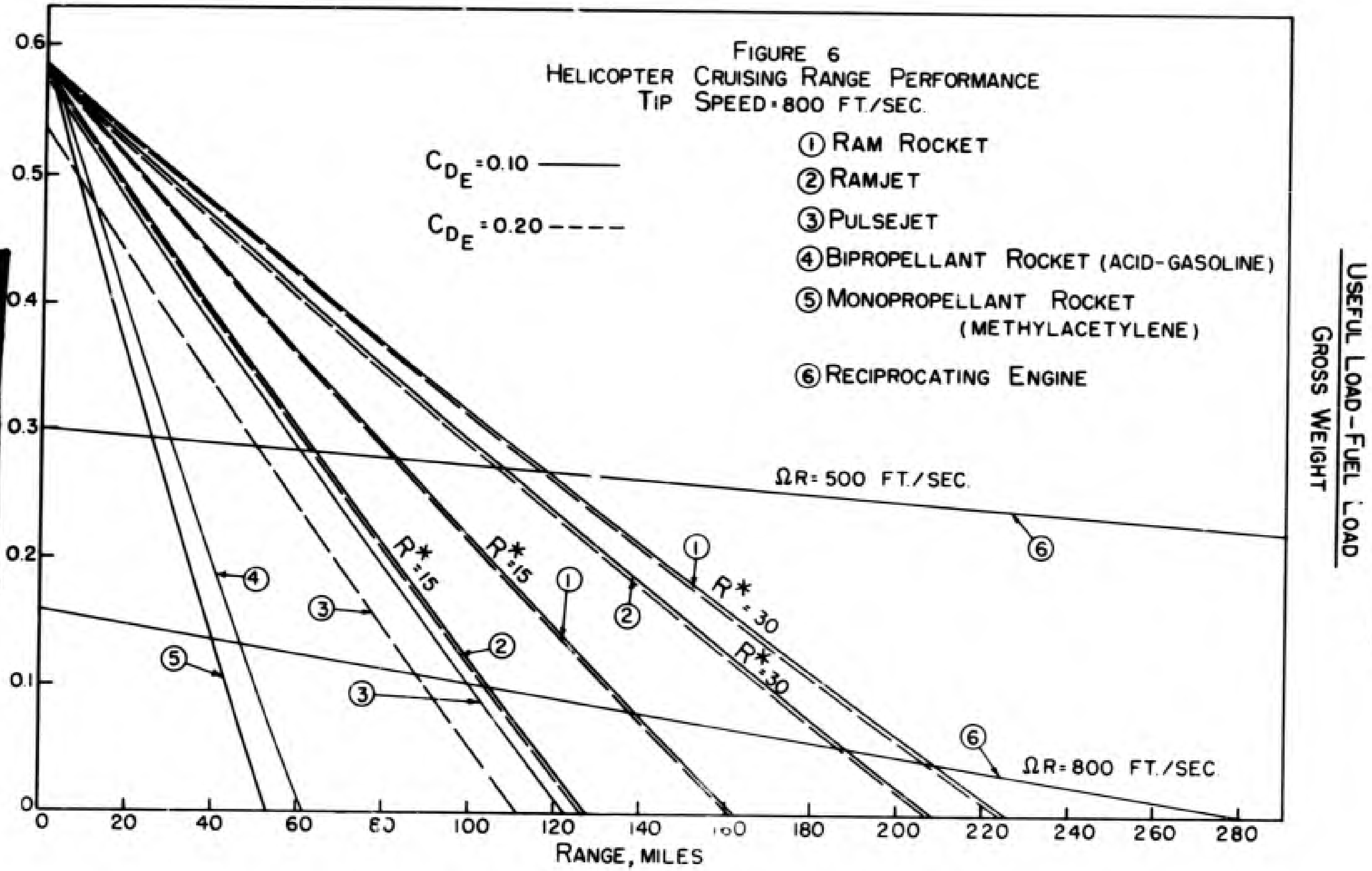


Fig. 5. Helicopter Cruising Range Performance Tip Speed = 700 Ft. /Sec.

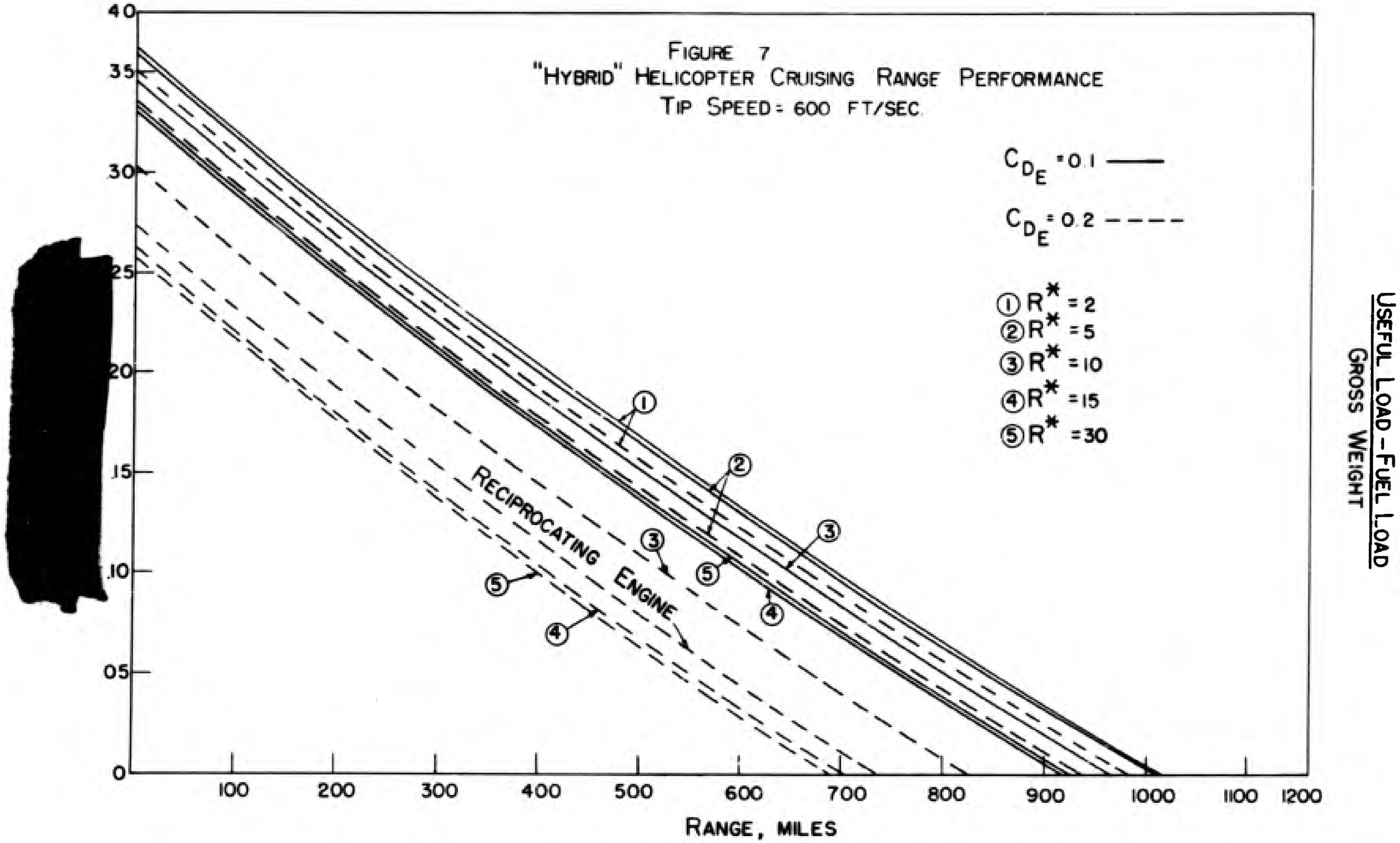
[redacted]

[redacted]



[redacted]

Fig. 6. Helicopter Cruising Range Performance Tip Speed = 800 Ft. /Sec.

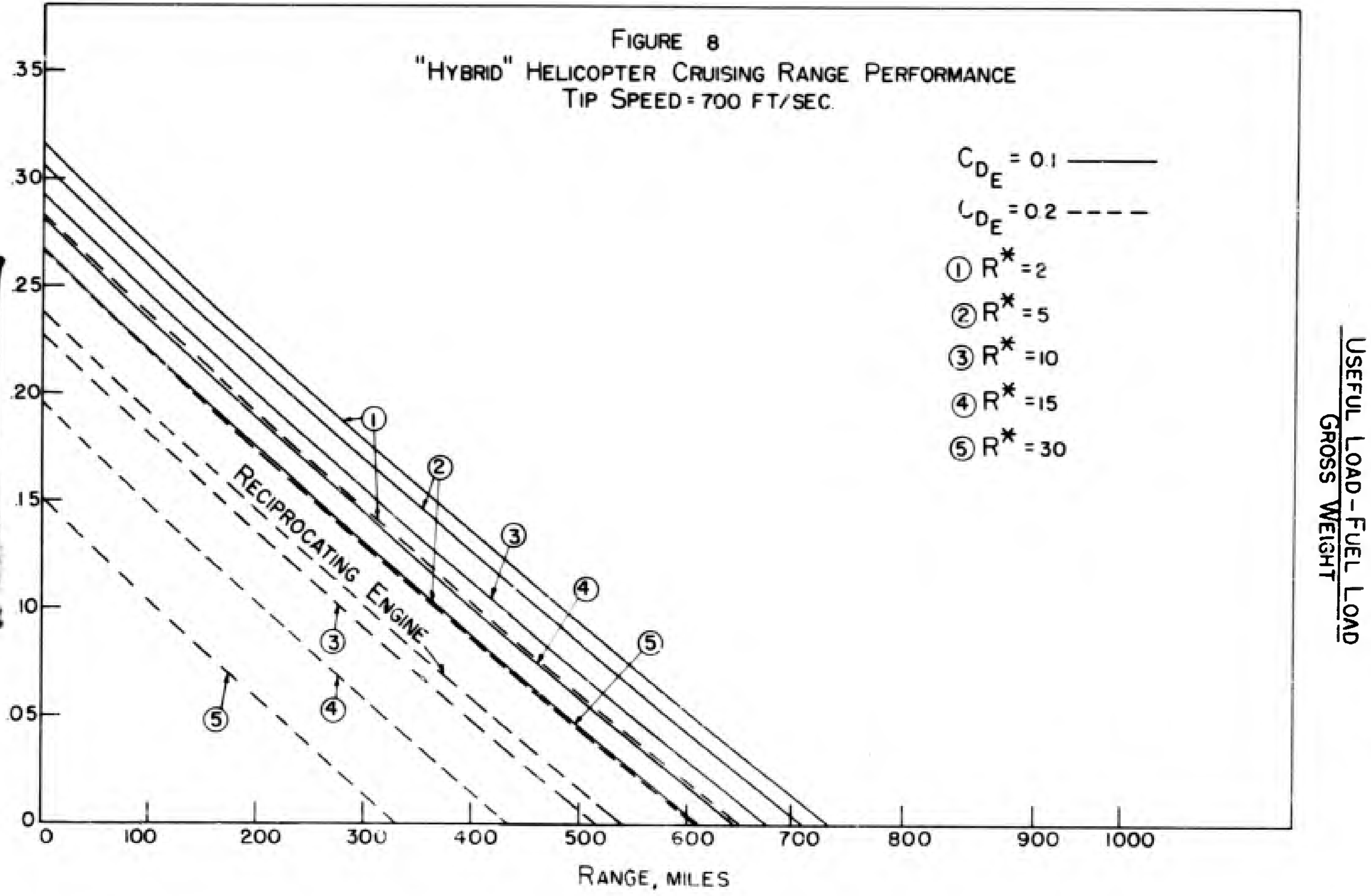


[redacted]

[redacted]

Fig. 7. "Hybrid" Helicopter Cruising Range Performance Tip Speed = 600 Ft. /Sec.

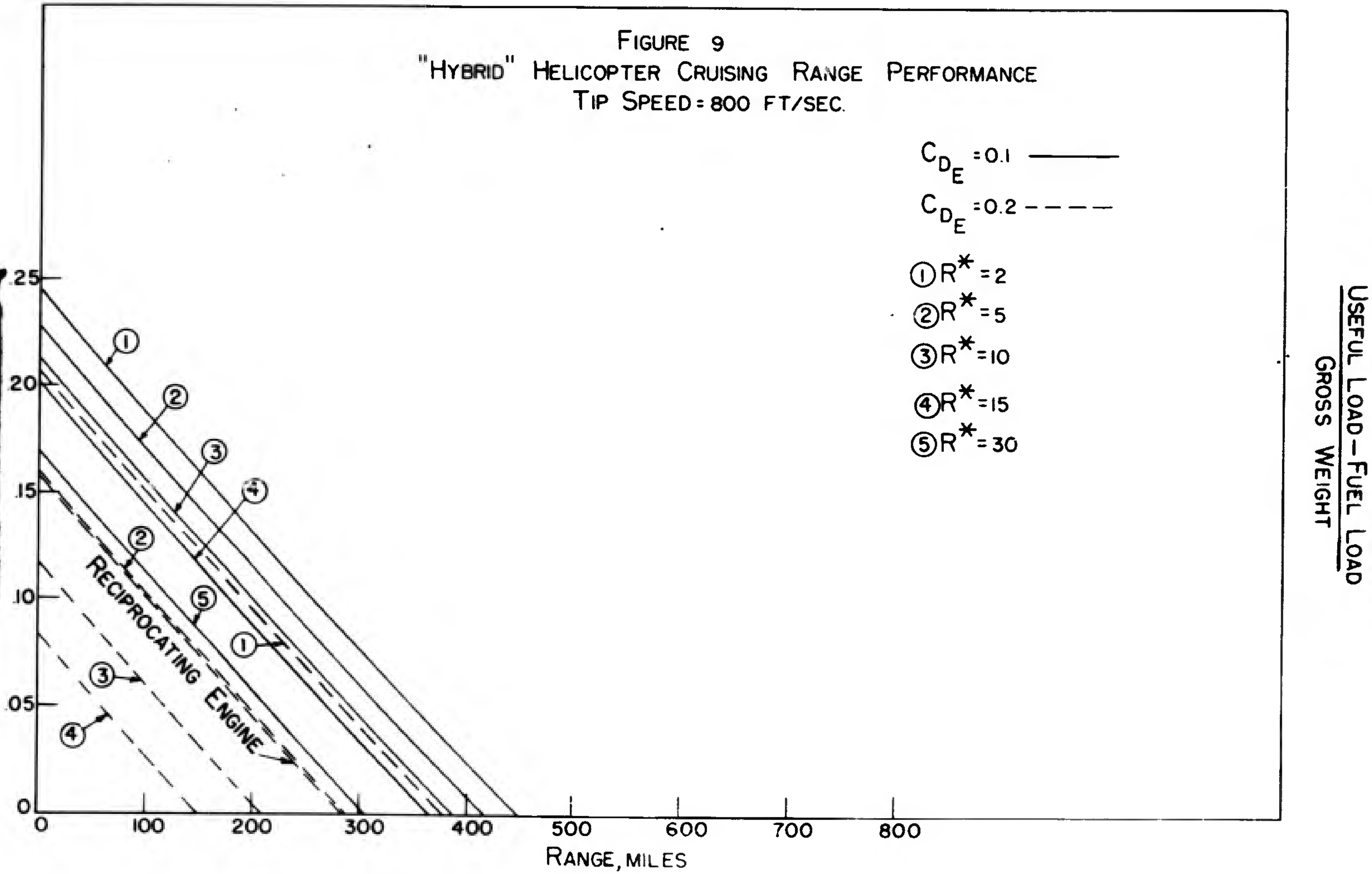
[redacted]



[redacted]

Fig. 8. "Hybrid" Helicopter Cruising Range Performance Tip Speed = 700 Ft. /Sec.

[redacted]



[redacted]

Fig. 9. "Hybrid" Helicopter Cruising Range Performance Tip Speed = 800 Ft. /Sec.

[redacted]

[redacted]

[redacted]

Appendix A

Airfoil Section Drag Coefficient

$$C_{D_o} = 0.011 - 0.025\,\alpha + 0.50\,\alpha^2 \qquad (1)$$

where

$$\alpha = \frac{W/A}{\frac{1}{6}\rho(\Omega R)^2 \sigma (5.75)} \qquad (2)$$

Rotor Horsepower Required for Level Flight

$$\left(\frac{Hp}{W}\right)_L = \frac{1}{550}\left\{ \frac{\rho C_{D_o} \sigma (\Omega R)^3}{8(W/A)}(1+\mu^2) + \frac{1}{2}\rho v^3 \left|\frac{f}{A}\right| + \frac{1}{4}\,\frac{\rho C_{D_o} \sigma v^2 (\Omega R)}{8(W/A)} + \frac{(W/A)}{2\rho v}\right\} + \left\{\left(\frac{Hp}{W}\right)_D\right\} \quad * \; (3)$$

*It has come to the attention of the authors that Equation 3 of Appendix A for the level flight power requirement is slightly in error. By combining the first and third terms on the right hand side of this equation, and taking into consideration the radial component of velocity over the wings, Equation 3 can be written as:

$$\left(\frac{Hp}{W}\right)_L = \frac{1}{550}\left\{\left[\frac{\rho C_{D_o} \sigma (\Omega R)^3}{8(W/A)}\right]\left[(1+4.65\mu^2)\right] + \frac{1}{2}\rho v^3 \left(\frac{f}{A}\right) + \frac{(W/A)}{2\rho v}\right\} + \left\{\left(\frac{Hp}{W}\right)_D\right\}$$

This equation gives the correct value of the level flight power requirement.

In the analysis presented in this report, Equation 3 was used to determine the reciprocating engine and ram rocket powerplant weights for the "hybrid" propulsion system. The error introduced by the use of this equation

[redacted]

[redacted]

amounts to approximately 3% of the level flight power requirement. However, due to a compensating effect of decreased ram rocket weight and increased reciprocating engine weight, the error in range of the "hybrid" helicopter is less than 1%. In addition, this same error applies to the conventional helicopter; i.e., one powered by a reciprocating engine, so that the analysis and conclusions can still be considered as correct on a comparative basis.

Rotor Horsepower Required For Hovering

$$\left(\frac{H_p}{W}\right)_H = \frac{1}{550}\left\{\frac{\rho C_{Do}\,\sigma(\Omega R)^3}{8\,(W/A)} + \left[\frac{W/A}{2\rho}\right]^{1/2}\right\} + \left\{\left(\frac{Hp}{W}\right)_D\right\} \tag*{4}$$

Cruising Range in Miles

$$D = \frac{750\,\mu^2}{c}\left\{\left[\frac{1}{\sqrt{\frac{\mu\sigma C_{Do}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\,\mathrm{TAN}^{-1}\frac{\frac{(W/A)}{R^2}}{\sqrt{\frac{\mu\sigma C_{Do}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\right.\right.$$

$$\left.\left.\left[\frac{1}{\sqrt{\frac{\mu C_{D'o}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\,\mathrm{TAN}^{-1}\frac{\frac{(W/A)}{\rho(\Omega R)^2}\left(\frac{Wu}{W}+\mathrm{T.D.W.}\right)}{\sqrt{\frac{\mu\sigma C_{Do}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\right]\right\} \tag{5}$$

where

$$C_{D'o} = 0.011 - 0.025\,\alpha' + 0.50\,\alpha'^2 \tag{6}$$

$$\alpha' = \frac{(W/A)\left[\frac{Wu}{W}+\mathrm{T.D.W.}\right]}{\frac{1}{6}\rho(\Omega R)^2\sigma\,(5.75)} \tag{7}$$

[redacted]

[redacted]

Appendix B

Evaluation of Power Required Because of Powerplant Drag

From Equation (3) of Appendix A, the horsepower required for level flight of a helicopter of unit gross weight is given by:

$$\left(\frac{H_p}{W}\right)_L = \frac{1}{550}\left\{\frac{\rho C_{D_0}(\Omega R)^3}{8\left(\frac{W}{A}\right)}(1+\mu^2) + \frac{1}{2}\,\frac{\rho v^3\left(\frac{f}{A}\right)}{\left(\frac{W}{A}\right)} + \frac{1}{4}\rho C_{D_0}\sigma\frac{v^2}{\left(\frac{W}{A}\right)}(\Omega R) + \frac{(W/A)}{2\rho v}\right] + \left\{\left(\frac{Hp}{W}\right)_D\right\} \quad *$$

For the case of the conventional helicopter powered by a reciprocating engine and for the rocket powered helicopter with the rocket motors buried in the wing tips, the drag term is zero. The drag term for the ramjet, pulse jet and ram rocket powerplants is evaluated as follows:

For equilibrium at a given tip speed, thrust = drag; i.e.,

$$T = C_{D_E}\frac{1}{2}\rho(\Omega R)^2 A_E + C_{D_0}\frac{1}{2}\rho(\Omega R)^2 A_W$$

$$T = C_{D_E}\frac{1}{2}\rho(\Omega R)^2 A_E + C_{D_0}\frac{1}{2}\rho(\Omega R)^2 \sigma A$$

since $\sigma = \frac{A_W}{A}$

$$\frac{T}{A_E} = C_{D_E}\frac{1}{2}\rho(\Omega R)^2 + C_{D_0}\frac{1}{2}\rho(\Omega R)^2\sigma\frac{A}{A_E}$$

---

*See footnote on page i.

[redacted]

[redacted]

$$\frac{A}{A_E} = \frac{\left[\frac{T}{A_E} - C_{D_E}\frac{1}{2}\rho(\Omega R)^2\right]}{C_{D_o}\frac{1}{2}\rho(\Omega R)^2\sigma}$$

$$= \left[\frac{\dfrac{\frac{T}{A_E}}{\frac{1}{2}\rho(\Omega R)^2} - C_{D_E}}{C_{D_o}\sigma}\right] \qquad (8)$$

The horsepower equivalent of the drag force at a given tip speed is given by

$$\left(\frac{Hp}{W}\right)_D = \frac{D_E\,\Omega R}{550W}$$

and
$$\frac{D_E}{A_E} = C_{D_E}\frac{1}{2}\rho(\Omega R)^2$$

$$\left(\frac{Hp}{W}\right)_D = \frac{D_E}{A_E}\,\frac{\Omega R\,A_E}{550W} = \frac{C_{D_E}\frac{1}{2}\rho(\Omega R)^3 A_E}{550W} = \frac{C_{D_E}\frac{1}{2}\rho(\Omega R)^3}{}\left(\frac{A_E}{A}\right)$$

Then from Equation (8) above and Eq. (9),

$$\left(\frac{H_p}{W}\right)_D = \left[\frac{C_{D_E}\frac{1}{2}\rho(\Omega R)^3}{550\left(\frac{W}{A}\right)}\right]\left[\frac{C_{D_o}\sigma}{\dfrac{T/A_E}{\frac{1}{2}\rho(\Omega R)^2} - C_{D_E}}\right] \qquad (10)$$

[redacted]

[redacted]

Thus for the case of the ramjet, pulse jet, and ram rocket, we have

$$\left(\frac{H_p}{W}\right)_L = \frac{1}{550}\left\{\frac{\rho C_{D_0}(\Omega R)^3}{8\left(\frac{W}{A}\right)}(1+\mu^2) + \frac{1}{2}\,\frac{\rho v^3\left(\frac{f}{A}\right)}{\left(\frac{W}{A}\right)} + \frac{1}{4}\rho C_{D_0}\sigma \frac{v^2}{\left(\frac{W}{A}\right)}(\Omega R)\right.$$

$$\left. + \frac{(W/A)}{2\rho v}\right\} + \left[\frac{C_{D_E}\frac{1}{2}\rho(\Omega R)^3}{550(W/A)}\right]\left[\frac{C_{D_0}\sigma}{\frac{T/A_E}{\frac{1}{2}\rho(\Omega R)^2} - C_{D_E}}\right] *$$

and for hovering

$$\left(\frac{H_p}{W}\right)_H = \frac{1}{550}\left\{\frac{\rho C_{D_0}\sigma(\Omega R)^3}{8\left(\frac{W}{A}\right)} + \frac{\left(\frac{W}{A}\right)^{\frac{1}{2}}}{(2\rho)^{\frac{1}{2}}}\right\}$$

$$+ \left[\frac{C_{D_E}\frac{1}{2}\rho(\Omega R)^3}{550\left(\frac{W}{A}\right)}\right]\left[\frac{C_{D_0}\sigma}{\frac{T/A_E}{\frac{1}{2}\rho(\Omega R)^2} - C_{D_E}}\right]$$

For the case of the conventional helicopter with reciprocating engine and for the rocket powered helicopter, $C_{D_E} = 0$.

*See footnote on page i.

[redacted]

[redacted]

Appendix C

Performance Analysis of the Ram Rocket Helicopter

The sample calculations which follow are for the case of $\Omega R = 600$ ft/sec. and $C_{D_E} = 0.10$ with $R^* = 15$.

From Equation (4) of Appendix A, and making use of the drag expression derived in Appendix B, the horsepower required for hovering per pound of gross weight is found to be 0.07868.

The total ram rocket thrust is then

$$(1.35)\ (.07868)\ \left(\frac{550}{600}\right) = 0.09737$$

and the ram rocket engine weight is

$$(0.10)\ (0.09737) = 0.00974.$$

Using the estimated airframe weights presented on page 3, the total dry weight of the ram rocket helicopter is

$$0.40 + 0.00974 = 0.40974$$

Thus the maximum value of useful load minus fuel load expressed as a percentage of gross weight is

$$1 - 0.40974 = 0.59026$$

The expression for helicopter range given as Equation (5) of Appendix A is written:

$$D = \frac{750\,\mu^2}{c} \left\{ \left[\left[\frac{1}{\sqrt{\frac{\mu\sigma C_{D_0}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}} \tan^{-1} \frac{\frac{W/A}{\rho(\Omega R)^2}}{\sqrt{\frac{\mu\sigma C_{D_0}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}} \right] \right.\right.$$

[redacted]

[redacted]

$$-\left[\frac{1}{\sqrt{\frac{\mu\sigma C_{D'o}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\tan^{-1}\frac{\rho(\Omega R)^2\left(\frac{W_u}{W}+T.D.W.\right)}{\sqrt{\frac{\mu\sigma C_{D'o}}{4}(1+3\mu^2)+\mu^4\left(\frac{f}{A}\right)}}\right]\Bigg]\Bigg\}$$

The value of c for the ram rocket is given in Figure (2) for a free stream Mach number, M_o, corresponding to $\Omega R = 600$ ft/sec.

By selecting various values of W_u/W from zero to 0.59026, the range curve shown in Figure (4) is determined from the above equation.

[redacted]

[redacted]

Appendix D

Performance Analysis of the "Hybrid" Helicopter

The sample calculations which follow are for the case of $\Omega R = 600$ ft/sec, and $C_{D_E} = 0.10$ with $R^* = 15$.

From Equation (3) of Appendix A, the power required for horizontal flight at 75 mph. is found to be 0.05723. This value includes the additional horsepower required to overcome the aerodynamic drag of the external ram rockets. (See Appendix B.)

Since the piston engine must supply this power, the weight of the piston engine required is

$$3.15 \times 0.05723 = 0.18027$$

Now assuming that the power required to pump the ram rocket propellant amounts to 10% of the level flight requirement and that this power is supplied by the piston engine, the total piston engine weight is

$$0.18027 + (0.10)\ (3.15)\ (0.05723) = 0.19830$$

From Equation 4 of Appendix A, the power required for hovering is determined. Assuming 35% excess hovering power and a ram rocket specific weight of $0.10^{\mathrm{lb}}/\mathrm{lb.T}$, the ram rocket engine weight is

$$\left[(1.35)\ (0.07868) - (0.05723)\right]\ \left[\left(\frac{550}{600}\right)\ (0.10)\right] = 0.00449$$

The specific fuel consumption of the ram rocket engines is given in Figure 2 as $11.3^{\mathrm{lb}}/\mathrm{lb}$ T-hr. for $\Omega R = 600$ Ft/sec.

Thus the ram rocket fuel weight for an operating time of 2 minutes is

$$\left(\frac{11.3}{3600}\right)\ (2)\ (60)\ (0.04491) = 0.01692$$

The component weights of the "hybrid" helicopter are as follows:

[redacted]

[redacted]

Airframe & Wings	0.40 W
Tail Rotor	0.05 W
Piston Engine	0.19830 W
Ram Rocket Engines	0.00449 W
Ram Rocket Fuel	0.01692 W
Total Dry Weight	0.66971 W

The maximum value of W_u/W is then

$$1 - 0.66971 = 0.33029$$

By utilizing Equations 5, 6, and 7 of Appendix A for various values of W_u/W from 0.33029 to zero, the "hybrid" range curves of Figure 7 are determined.

[redacted]

[redacted]

[redacted]

DISTRIBUTION LIST

Part A of the GMTI List MML/2 February 16, 1953

1. Princeton University, Forrestal Research Center Library, Att: Librarian (2cc)
2. Project SQUID Headquarter Office (8cc)
3. Chief of Naval Research, Code 429, Washington, D.C. (4cc)
4. Director, ONR, New York, New York
5. Director, ONR, Chicago, Illinois
6. Director, ONR, Boston, Massachusetts
7. Director, ONR, Pasadena, California
8. Director, ONR, San Francisco, California
9. Commanding Officer, Office of Ordnance Research, Att: T. J. Killian
10. National Advisory Comm. for Aeronautics, Attn: Dr. Rothrock (2cc)
11. Commanding General, Air Research and Development Command, Attn: Dr. Horney
12. Bureau of Aeronautics, Attn: R. Zirkind
13. Office of Chief of Ordnance, Dept. of the Army, Attn: ORDTB (4cc)
14. Chief, Bureau of Aeronautics, Dept. of the Navy, Washington, D.C. Attn: RS-91, SI,GM,AC-4 (4cc)
15. Chief of Naval Operations, Dept. of the Navy, Washington, D. C. Attn: Op-51, Op-55
16. Commanding Officer, Naval Air Rocket Test Station, Dover, New Jersey
17. Aerojet Engineering Corp., Azusa, California
18. Marquardt Aircraft Co., Van Nuys, California, Attn: R.E. Marquardt
19. Purdue University, Lafayette, Indiana, Attn: M. J. Zucrow
20. Reaction Motors, Inc., Stickle Ave. and Elm St., Rockaway, New Jersey
21. Experiment, Inc. Richmond, Va.
22. Hiller Helicopter Co., Palo Alto, California, Attn: Ray Young

[redacted]

23. American Helicopter Co., Manhattan Beach, California

24. Sikorski Aircraft Co., Bridgeport, Conn.

25. Bell Aircraft Co. Helicopter Div., Dallas 1, Texas, Attn: Bertram Kelly

26. Piasecki Helicopter Co., Morton, Pa., Attn: Mr. Stepnevski

27. University of Wichita, Wichita, Kansas, Attn: K. Razik

28. Kaman Aircraft Corporation, Windsor Locks, Conn.

29. North American Aviation Inc., Downey Califronia, Attn: Aerophysics Lab.

30. United Aircraft Corp., Research Div., East Hartford, Conn. Attn: R.C. Sale, Librarian (2cc)

[redacted]