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# RESEARCH MEMORANDUM

## COMPARISON OF THE PERFORMANCE OF A HELICOPTER-TYPE RAM-JET ENGINE UNDER VARIOUS CENTRIFUGAL LOADINGS

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## SUMMARY

An 18-foot-radius helicopter rotor powered by tip-mounted ram-jet engines has been investigated on the Langley helicopter test tower. The engine performance determined in these tests is compared with that determined in a previous investigation of a 9-foot-radius rotor using the same engines operating at similar speeds but with twice the centrifugal forces. The reduction in centrifugal loading reduced the minimum specific fuel consumption at all ram-jet velocities and increased the maximum ram-jet-engine thrust by approximately 12.5 percent at an engine velocity of 630 fps.

## INTRODUCTION

The over-all performance of a helicopter powered by jet engines mounted on the rotor-blade tips is dependent on the aerodynamic and propulsive characteristics of the engine. A study of various jet-rotor systems therefore has been undertaken by the National Advisory Committee for Aeronautics to supplement investigations of the separate components of such systems.

The first investigation was of a small ram-jet-propelled rotor on the Langley helicopter test tower (ref. 1). One of the main findings of the investigation was the detrimental effect of the high centrifugal forces on the propulsive characteristics of the ram-jet engine. The primary purpose of this investigation, also conducted on the Langley helicopter test tower, was to determine the effect on the engine propulsive characteristics of reducing the centrifugal forces with the rotor tip speeds held constant. The centrifugal loading of the engines was halved by adding a blade extension between the rotor head and the original rotor blade so that the jet-engine radius was 18 feet as compared to 9 feet for the original configuration. The results are also compared with the free-jet thrust-stand results of reference 1 for which the centrifugal loading was zero.

## SYMBOLS

| | |
|---|---|
| $R$ | blade radius (measured to inboard side of jet engine), ft |
| $T$ | rotor thrust, lb |
| $Q$ | rotor torque, ft-lb |
| $\rho$ | air density, slugs/ft$^3$ |
| $\Omega$ | rotor angular velocity, radians/sec |
| $C_T$ | rotor thrust coefficient, $\frac{T}{\pi R^2 \rho (\Omega R)^2}$ |
| $C_Q$ | rotor torque coefficient, $\frac{Q}{\pi R^2 \rho (\Omega R)^2 R}$ |
| $g$ | acceleration due to gravity, 32.2 ft/sec$^2$ |
| $V$ | velocity of ram-jet engine, fps |
| $V_c$ | corrected velocity of ram-jet engine, $V/\sqrt{\theta}$, fps |
| $F_p$ | propulsive thrust of jet engine (resultant of internal thrust, external drag, and interference drag), lb |
| $D_{t_{cold}}$ | power-off drag of jet engine, $(\text{External drag})_{cold} + (\text{Internal drag})_{cold}$, lb |
| $W_f$ | mass flow rate of fuel, lb/hr |
| $W_{f_c}$ | corrected mass flow rate of fuel, $W_f/\delta\sqrt{\theta}$, lb/hr |
| $\delta$ | ratio of absolute ambient pressure to standard NACA sea-level absolute pressure |
| $\theta$ | ratio of absolute static temperature to standard NACA sea-level absolute temperature |

# APPARATUS

The investigation was conducted on the Langley helicopter test tower which is described in reference 2; however, the fuel and ignition systems are described in reference 1. For the power-on tests, the tower drive motor was disconnected from the tower drive shaft so that all the torque required to turn the rotor and tower shaft was furnished by the ram-jet engines. A view of the extended-radius ram-jet-powered rotor mounted on the helicopter tower is shown in figure 1.

## Rotor

The rotor was identical to the one described in reference 1 except that a blade extension was added between the rotor head and the original blade so that the distance from the center line of the jet engine to the center of rotation was increased from the original 9 feet to 18 feet. The juncture of the blade extension and the original blade was covered by a fairing to minimize profile-drag losses. For both rotors the tip engines were mounted so that the jet shell was horizontal when the blade pitch was 4°. The blades were of all-metal construction and had a constant chord of 8.22 inches and an NACA 0009.5 airfoil section. The blade-engine juncture is shown in figure 2 and is the same as that described in reference 1.

## Ram-Jet Engine

The ram-jet engines were the same as those used for the previous investigation reported in reference 1, except for the addition of an aluminum stabilizer tab which is shown in figures 2 and 3 and a change in the location of the spark plug. The stabilizer tab was needed to prevent the ram-jet engines from oscillating in pitch at tip speeds above 400 fps. This condition was caused by the reduced torsional stiffness of the blades and was brought about by the large extension to the blade radius. The stabilizer tab had an area of 13.5 square inches and was alined with the blade chord line.

# METHODS AND ACCURACY

## Test Conditions

The investigation was conducted under conditions as similar to those of reference 1 as possible so that a comparison of results for the two installations could be made. All the studies on the helicopter tower were conducted with ambient wind velocities less than 5 mph and all measurements were obtained under steady-state operating conditions. The test procedure was to hold the rotor tip speed constant by varying the tower or ram-jet-engine power as the rotor thrust was varied through the desired range by changing the blade pitch angle.

## Rotor Characteristics

Blades alone.- The performance of the rotor without the ram-jet engines attached was determined in the conventional manner by measurement of the thrust and torque for a range of tip speeds and pitch-angle settings.

Blades with engines attached, power off.- In order to perform an analysis similar to that presented in reference 1, the performance of the rotor with the engines inoperative was needed as a basis for determining the power-off engine drag characteristics. Because of the torque limitations of the rotor hub, it was not possible to obtain this information experimentally for the larger 36-foot-diameter rotor at the same tip speeds as employed in the tests of reference 1. It was shown in reference 1, however, that the rotor thrust and torque with the engines inoperative could be reasonably approximated by adding the lift and drag forces on the isolated jet engines at the blade-tip angle of attack to the forces on the rotor alone. The calculated curve presented in the present paper was obtained by using this procedure and assuming no effect of blade twist due to the addition of the engines to the basic rotor and no effects of the stabilizing tabs on the rotor forces. In the limited range of blade-root angles of attack ($0^\circ$ to $3^\circ$) covered in the power-on tests (engine angles of attack from $-4^\circ$ to $-1^\circ$ for no twist), the blade twist could be expected to be small and calculations showed that even appreciable amounts of twist would have negligible effects on the results due to the insensitivity of the thrust-torque polar to blade twist. Any such effects would be well within the accuracy of the basic measurements. Calculations also indicated that any lift contribution of the tab would be negligible compared to the total rotor lift. The drag force on the tabs, however, could have been as much as 1 pound in the extreme cases and would, therefore, be a significant amount compared to the maximum net thrust of the engines. The neglect of this drag force is believed to make the engine-thrust values presented somewhat conservative.

Power-on rotor characteristics.- For the engine-operating condition, the rotor thrust was determined directly from the tower thrust balance. From the shaft torque measurements, however, it was not possible to obtain the engine thrust or the rotor torque which it counterbalanced. The propulsive thrust of the engine, therefore, was calculated indirectly by the method outlined in the appendix of reference 1. This method assumes that the torque overcome by the jet engines is equal to the torque of the basic rotor without tip engines measured at the same rotor thrust coefficient and tip speed, plus the torque chargeable to fuel pumping within the blade, plus an increment in torque corresponding to the mutual interference drag between the rotor and the tip engines.

## Estimated Accuracies

The estimated accuracies of the basic quantities measured in the tower tests are: rotor thrust, ±15 pounds; rotor torque, ±10 foot-pounds; blade pitch angle, $\pm0.1^\circ$; fuel-flow rate, ±10 pounds per hour; rotor rotational speed, ±1 rpm. The over-all accuracy of the plotted results are believed to be ±3 percent.

## RESULTS AND DISCUSSION

The measured thrust and torque characteristics of the blades alone are given in figure 4 in coefficient form, together with the calculated power-off characteristics of the blades having the ram-jet engines attached at $-4^\circ$ incidence. The dashed curve is the performance curve for the power-off operating condition and was calculated according to the previously discussed procedure. As previously mentioned, the calculated curve was needed to make the analysis of the propulsive characteristics similar to that presented in the appendix of reference 1.

### Propulsive Characteristics

The variation of the ram-jet thrust plus total power-off engine drag for the engine on the 18-foot-radius rotor is shown in figure 5 as a function of fuel-flow rate for various corrected ram-jet speeds. These data have been corrected to standard sea-level conditions by the method outlined in reference 3 for ambient pressure and ambient temperature plus an average temperature rise of $30^\circ$ F in the paths of the ram jets due to flow contamination by the preceding engine. This temperature rise was determined by subtracting the calculated adiabatic temperature rise from the reading of a thermocouple located 2 inches ahead of the engine inlet. This temperature actually fluctuated $\pm10^\circ$ over the range of blade pitch angles from $0^\circ$ to $3^\circ$ but was assumed to be constant. This temperature rise was applicable only to the present configuration hovering out of ground effect and was introduced only to make the engine performance results directly comparable with those of reference 1. The corrected ram-jet engine velocities $V_c$ were 650, 626, 532, and 458 fps; whereas the uncorrected velocities were 688, 658, 563, and 485 fps, respectively. The range of blade-root pitch angles for the power-on data was from $0^\circ$ to approximately $3^\circ$, resulting in ram-jet angles of attack from $-4^\circ$ to $-1^\circ$.

For comparison purposes, a curve of propulsive thrust plus power-off drag obtained with the 9-foot-radius blades at a corrected rotational tip speed of 630 fps, together with a curve obtained on the free-jet thrust stand at a corrected air velocity of 613 fps, is shown.

The flattening of the tops of the curves of figure 5 indicates that stoichiometric fuel-air mixture may have been attained, inasmuch as the addition of more fuel did not increase the engine thrust. The increase in maximum thrust between the 9-foot-radius-rotor results and the 18-foot-radius-rotor tests (at velocities of 630 and 626 fps, respectively) is attributed mainly to increased combustion efficiency at stoichiometric fuel-air mixtures due to reduced centrifugal distortion of the fuel spray pattern. It will be noted that the thrust of the engine on the 18-foot-radius rotor at a tip speed of 626 fps falls below that for the 9-foot-radius rotor for fuel-flow rates less than 250 pounds per hour despite the reduced centrifugal loading. There are at least two possible explanations for this occurrence. One is the neglect of the drag of the stabilizing tabs which tends to reduce the thrust of the engines on the 18-foot-radius rotor below this value. The other is a possible favorable effect of the centrifugal forces at low fuel-air ratios. Other ram-jet investigations have shown that regions of local rich mixtures (such as are caused by centrifugal forces in the present case) tend to act as flame pilots and thus increase the combustion efficiencies at the low fuel-air ratios. This effect would be expected to be greatest in the case of the engine on the 9-foot-radius rotor which experiences the greatest centrifugal effects and would therefore increase the thrust of the engine on this rotor relative to the thrusts of the engines on the 18-foot-radius rotor and the free-jet thrust stand.

It will be noted that the crossing-over of the curves at the low fuel-flow rates, discussed in the preceding paragraph, does not indicate any inherent advantage of operating under high centrifugal loadings. If local regions of rich fuel-air ratios are found to be advantageous at the lower over-all fuel-flow rates, such regions could probably be provided for in the low-centrifugal-loading case by modifications to the flameholders or the fuel-injection system, or both, which would not decrease the maximum thrust obtainable.

The results given in figure 5 are replotted in figure 6 in terms of propulsive thrust against fuel-flow rate. The same conclusions can be drawn from figure 6 as from figure 5. At a corrected velocity of 630 fps, the maximum propulsive thrust of the engines on the 18-foot-radius blade (centrifugal loading of 750g) was approximately 12.5 percent greater than the thrust obtained for the engine on the 9-foot-radius blade at a centrifugal loading of 1,500g. This increase in maximum propulsive thrust is again attributed to the reduced centrifugal distortion of the fuel spray pattern. At a corrected velocity of 613 fps, the maximum propulsive thrust for the 18-foot-radius rotor was approximately 10 percent less than that measured on the free-jet thrust stand as compared to 21 percent less for the 9-foot-radius rotor.

## Minimum Specific Fuel Consumption and Corresponding Propulsive Thrust

The lowest specific fuel consumptions and the corresponding propulsive thrusts are shown in figure 7 for the engine on the 18-foot-radius rotor, the 9-foot-radius rotor, and the free-jet thrust stand as a function of corrected ram-jet-engine velocity. These curves show that the minimum specific fuel consumption decreased and the propulsive thrust at minimum specific fuel consumption increased progressively with decreases in the centrifugal loading. At a corrected velocity of 630 fps, the minimum specific fuel consumption of the engine on the 18-foot-radius rotor was 10.3 lb/hr/hp as compared to 12.1 lb/hr/hp for the engine on the 9-foot-radius rotor and 9.4 lb/hr/hp for the engine on the free-jet thrust stand. Thus the minimum specific fuel consumption was 29 and 10 percent greater for the 9- and 18-foot-radius rotors than for free-jet-thrust-stand operation. This difference of 19 percent between the 9- and 18-foot-radius rotors was attributed to the decreased effects of centrifugal forces on the fuel spray pattern. At a lower velocity (and therefore lower centrifugal forces) of 480 fps, the specific fuel consumption of the engine on the 18-foot-radius rotor was nearly the same as that obtained for the engine on the free-jet thrust stand. This result indicates that at 480 fps (corresponding to about a 400g loading) there was little effect of whirling on the propulsive characteristics of this particular jet engine.

Cross plots of minimum specific fuel consumption against centrifugal acceleration are presented in figure 8 for various corrected ram-jet velocities. The centrifugal accelerations are based on the uncorrected engine velocity. The curves show a greater increase in specific fuel consumption against centrifugal loading at the low velocities than at the higher velocities. It appears that this is primarily an effect of higher combustion-chamber velocities which allow less of the fuel particles to strike the outer combustion chamber wall and thereby result in better specific fuel consumption.

## Operational Characteristics

The reduction in centrifugal loading (ram-jet engine on the 18-foot-radius rotor) eliminated the rough and erratic operation and the rich and lean blowouts encountered in the previous tests of the engine on the 9-foot-radius rotor at high centrifugal loadings. The engine on the 18-foot-radius rotor experienced an average 30° F temperature rise in excess of the adiabatic value as compared to the average rise of 50° F obtained with the 9-foot-radius rotor. This 30° F contamination temperature rise resulted in a loss of approximately 4 percent in maximum engine thrust. It should be pointed out that the 30° F temperature rise only applies to hovering out of ground effects and would be decreased or entirely eliminated in forward flight.

## CONCLUSIONS

The effect of centrifugal loading on the propulsive characteristics of a ram-jet engine attached to the tip of a helicopter rotor blade has been determined on the Langley helicopter test tower. The more pertinent findings of the investigation are as follows:

1. An increase of approximately 12.5 percent in maximum engine thrust and a decrease of 19 percent in the corresponding minimum specific fuel consumption were realized at a tip speed of 630 fps by decreasing the centrifugal forces on the engine from 1500g to 750g by doubling the radius of the rotor. These changes are attributed to decreased distortion of the fuel spray pattern.

2. The minimum specific fuel consumption and the corresponding propulsive thrust also improved progressively with reductions in centrifugal loading at all ram-jet velocities.

3. The reduction in centrifugal loading eliminated the rough and erratic operation and the rich and lean blowouts encountered in the previous tests at high centrifugal loadings.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 14, 1953.

## REFERENCES

1. Carpenter, Paul J., and Radin, Edward J.: Investigation of a Ram-Jet-Powered Helicopter Rotor on the Langley Helicopter Test Tower. NACA RM L53D02, 1953.

2. Carpenter, Paul J.: Effect of Wind Velocity on Performance of Helicopter Rotors as Investigated With the Langley Helicopter Apparatus. NACA TN 1698, 1948.

3. Sanders, Newell D.: Performance Parameters for Jet-Propulsion Engines. NACA TN 1106, 1946.

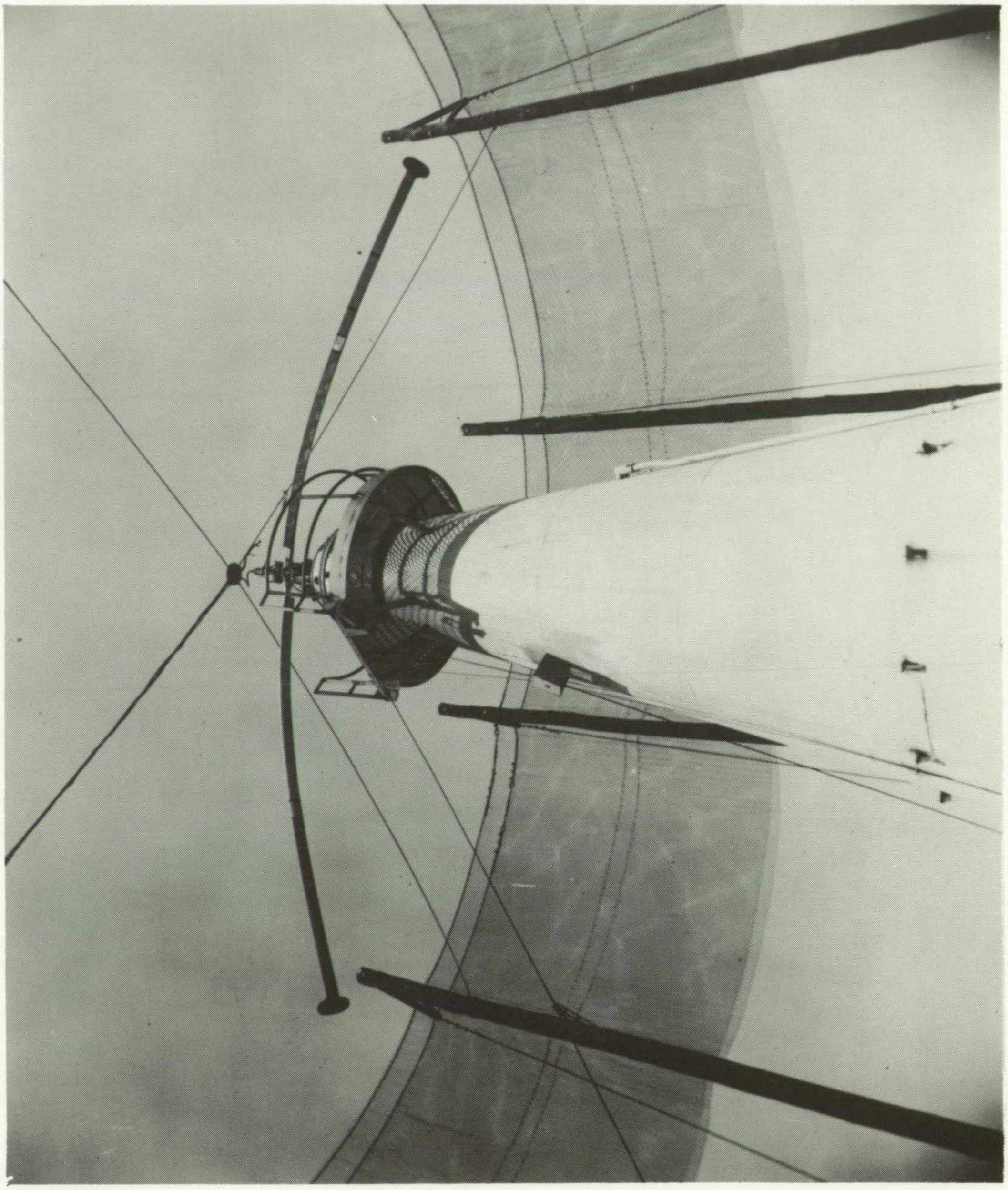

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Figure 1.- View of ram-jet-powered helicopter rotor mounted on Langley helicopter test tower.

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Figure 2.- Outer portion of the engine-blade combination as used for the whirling test on the Langley helicopter test tower.

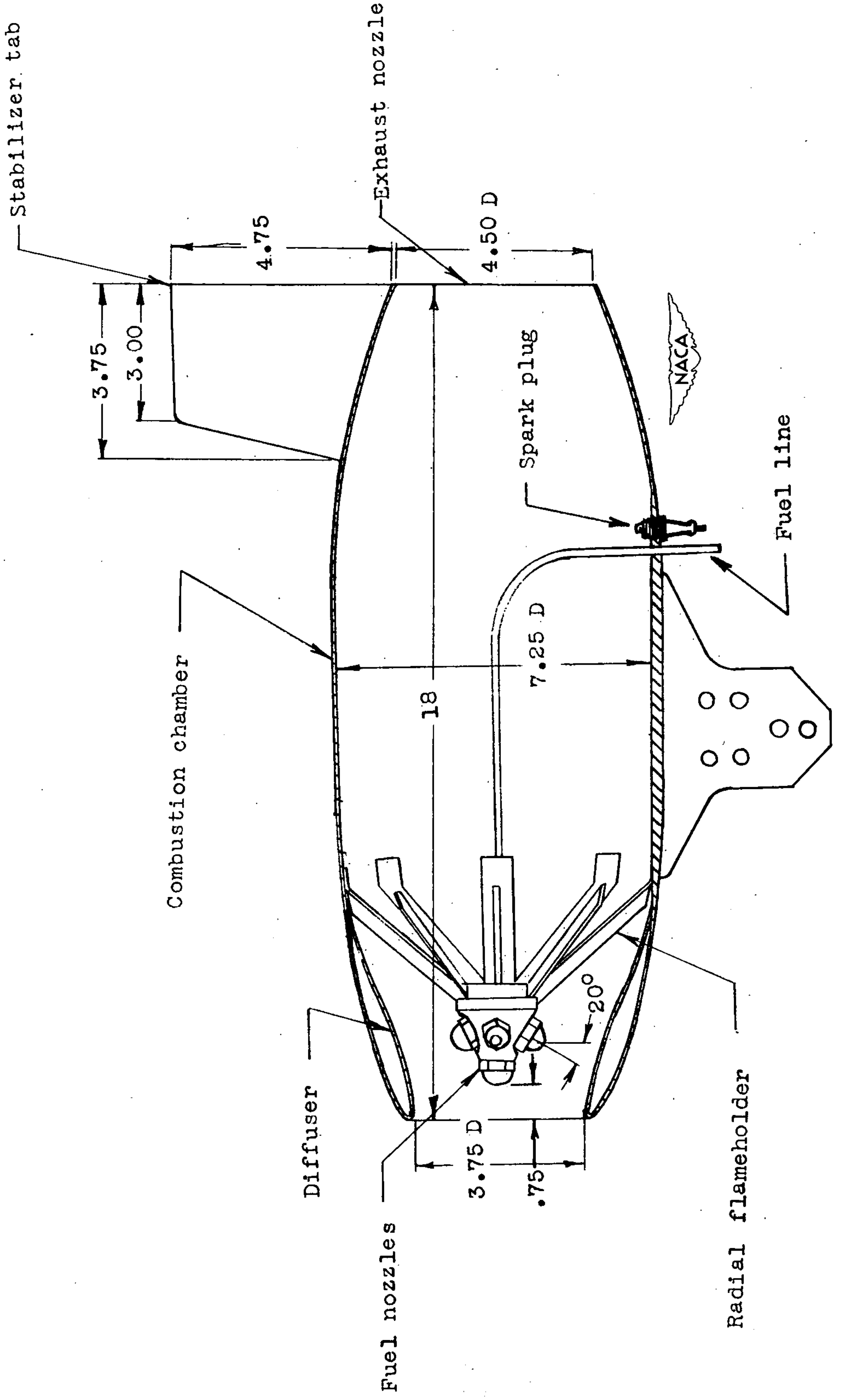

Figure 3.- Sketch of ram-jet engine. Jet-engine shell and flameholder made of Inconel X steel. All dimensions are inches.

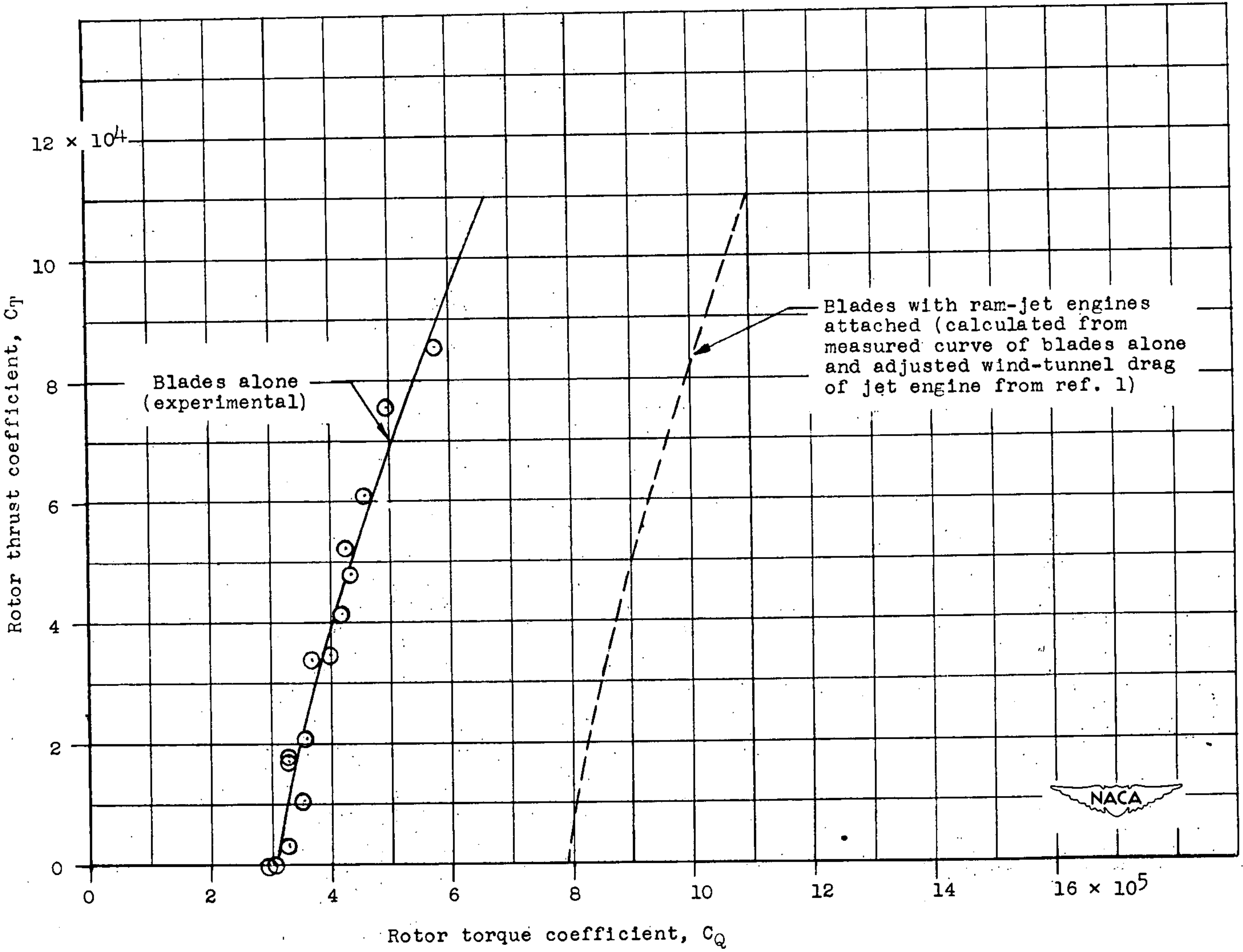

Figure 4.- Rotor thrust coefficient against rotor torque coefficient for the blades alone and blades alone plus ram-jet engine. Tip speed, 555 fps.

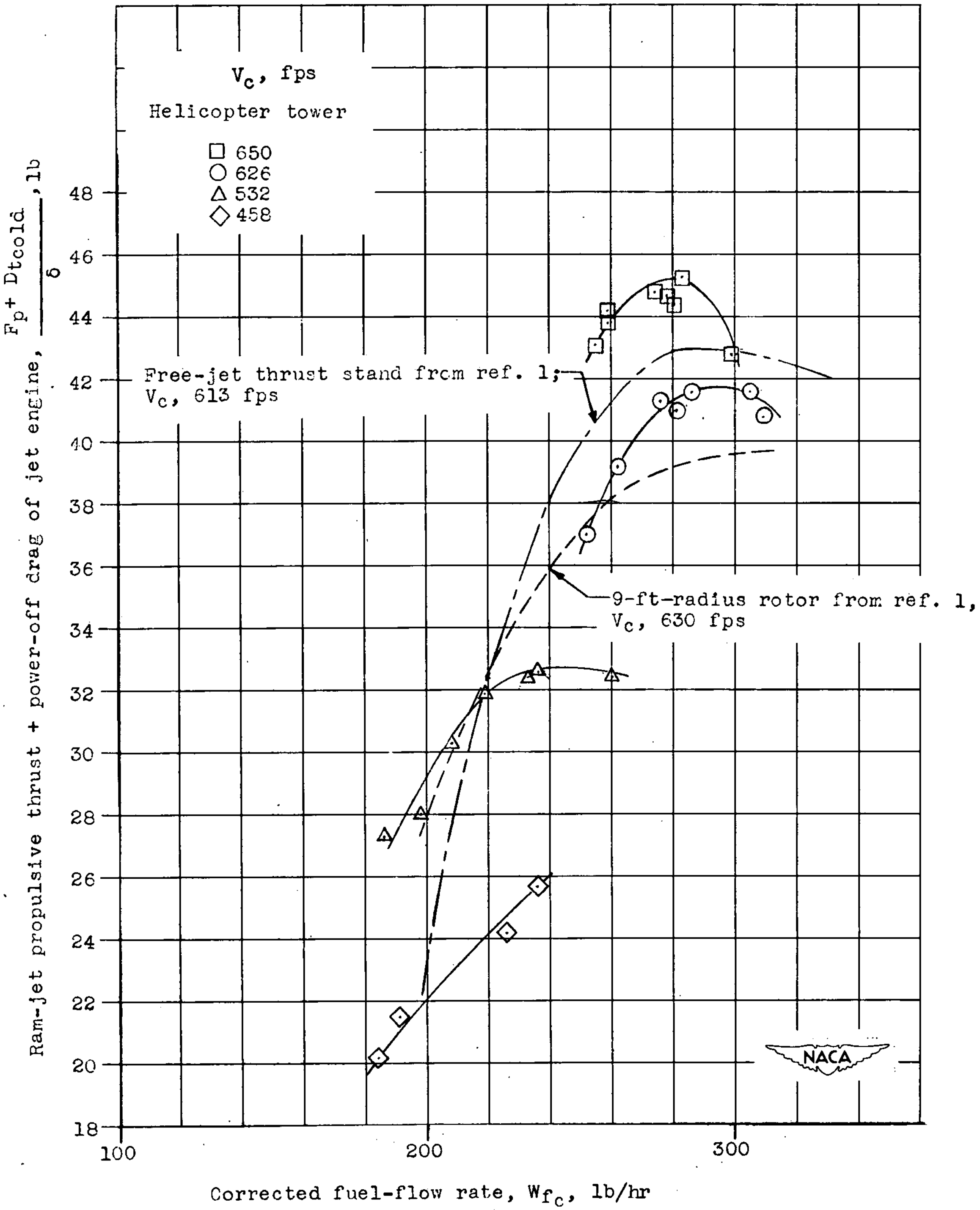

Figure 5.- Corrected ram-jet propulsive thrust plus power-off drag against corrected fuel consumption for 1 engine for a range of tip speeds from 458 to 650 fps.

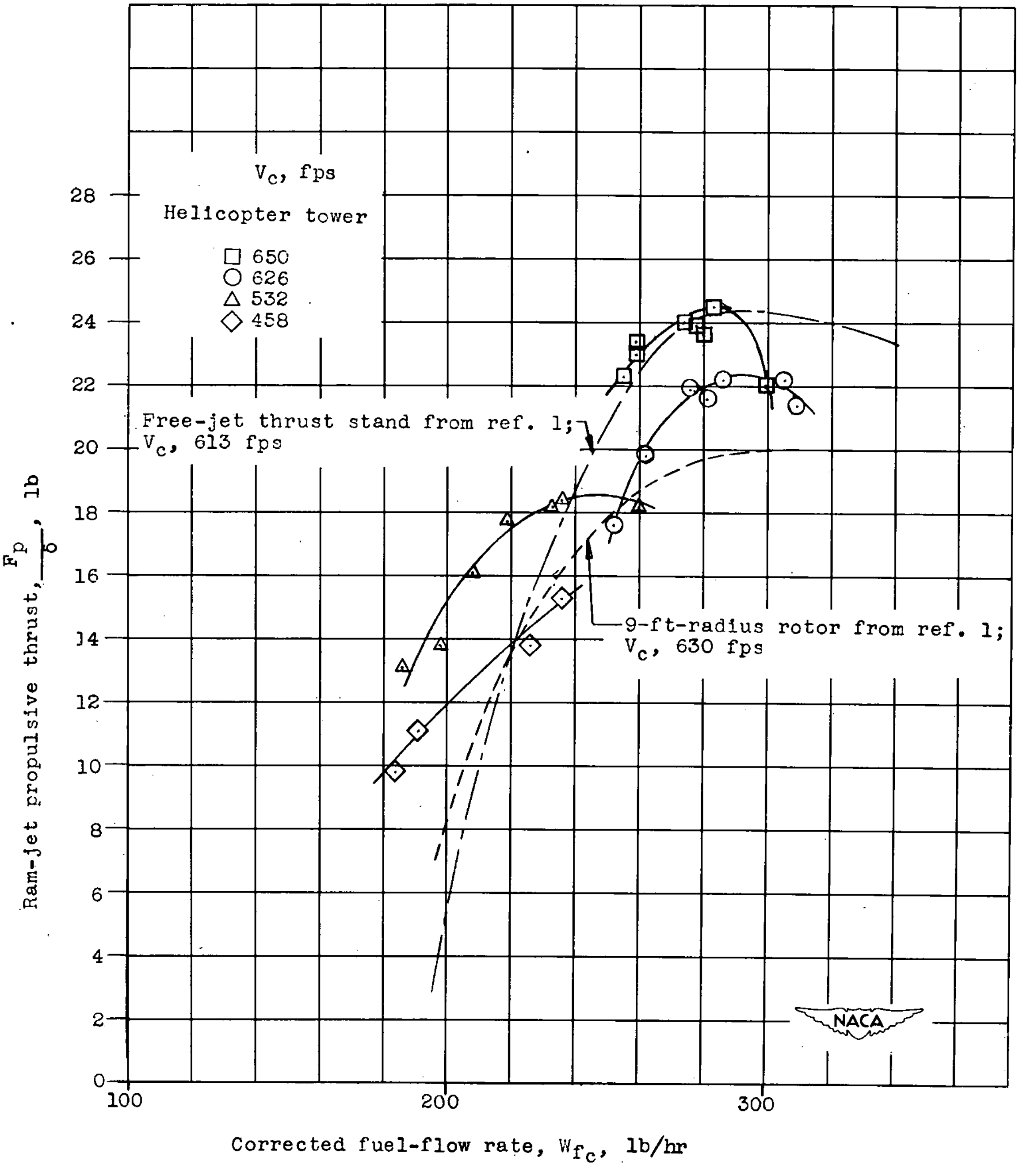

Figure 6.- Corrected ram-jet propulsive thrust against fuel consumption for 1 engine for a range of tip speeds from 458 to 650 fps.

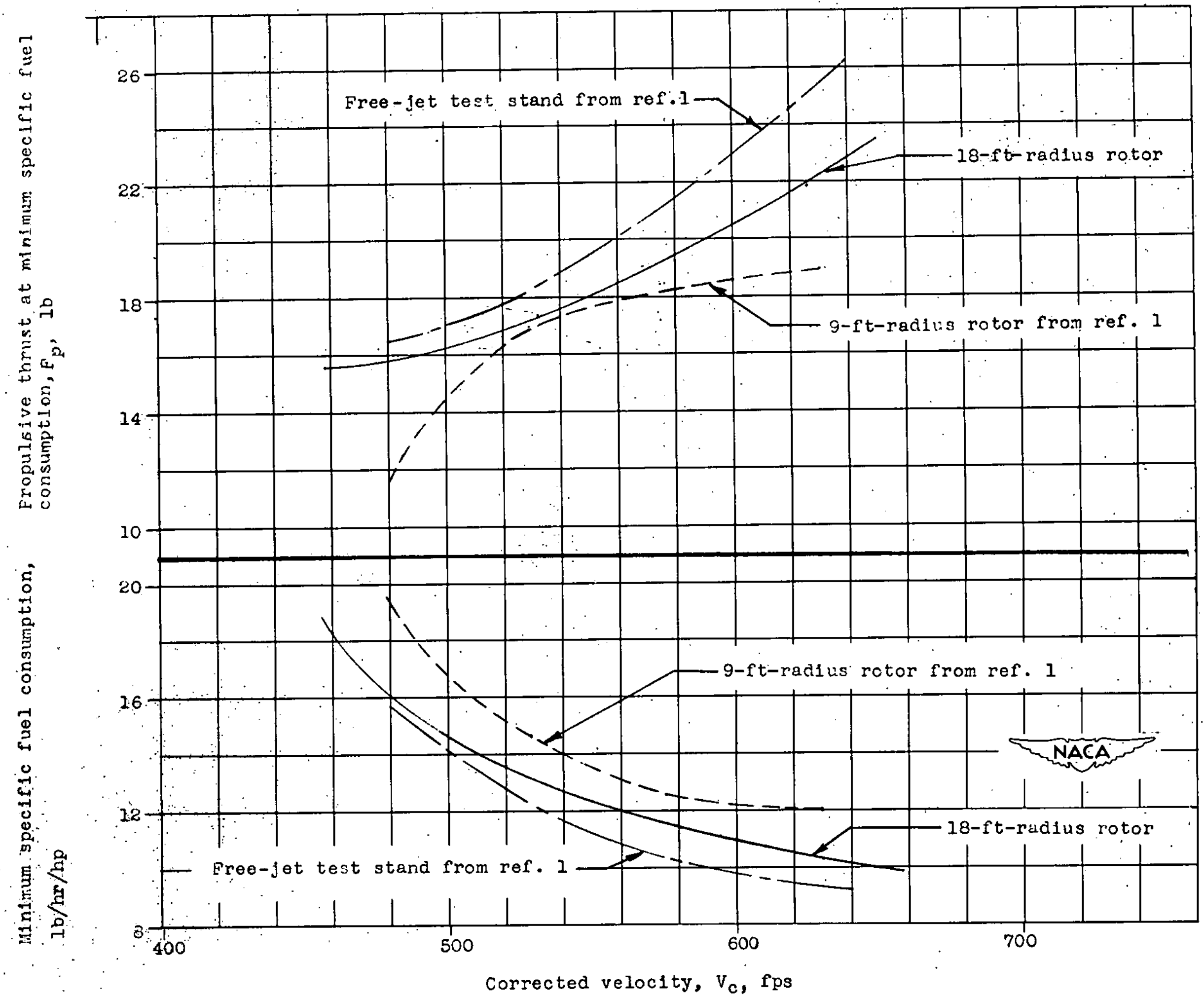

Figure 7.- Comparison of minimum specific fuel consumption and propulsive thrust at minimum specific fuel consumption for three configurations as a function of corrected ram-jet velocity.

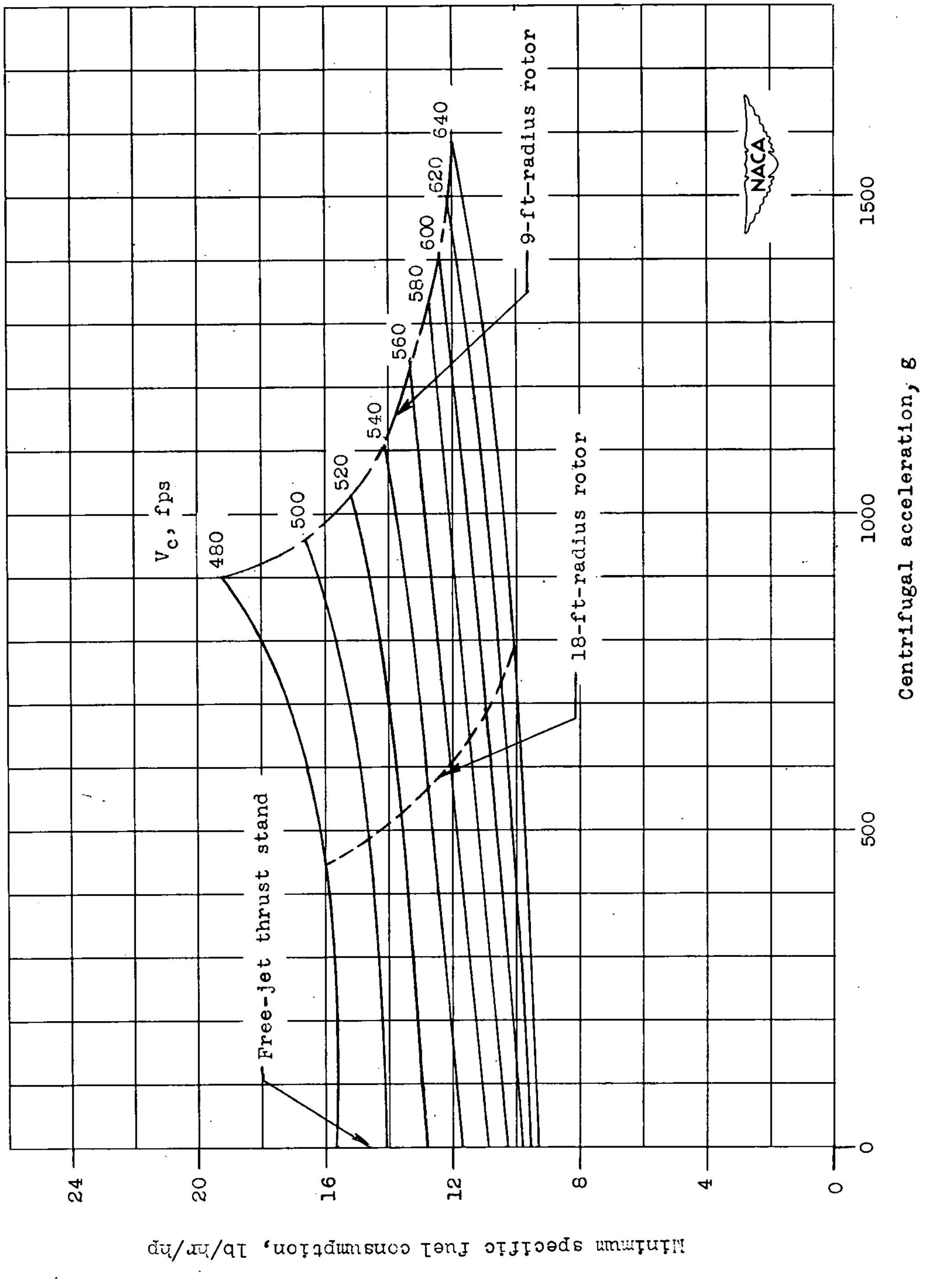

Figure 8.- Minimum specific fuel consumption as a function of corrected ram-jet velocity and centrifugal acceleration. The values of g are based on the uncorrected engine velocities.