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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF OVER-ALL PERFORMANCE OF EXPERIMENTAL TURBOJET ENGINE FOR GUIDED MISSILES

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

A preliminary investigation of the over-all performance of a simply constructed, short-life, turbojet engine was conducted. The unit was operated at a pressure altitude of 15,000 feet for ram-pressure ratios of 1.2 to 1.8. The corrected engine speed was varied from the minimum for good combustion to about 17,000 rpm, which is approximately 75 percent of rated speed. The performance is given by generalized parameters that permit the calculation of performance at any altitude.

The corrected net thrust of the turbojet engine increased with ram-pressure ratio for a given corrected engine speed above 14,500 rpm and reached a maximum of 425 pounds at a ram-pressure ratio of 1.8 and a corrected engine speed of 16,650 rpm. The corrected thrust specific fuel consumption decreased with flight speed for corrected engine speeds higher than 13,600 rpm. The minimum corrected thrust specific fuel consumption of 1.48 was obtained at a ram-pressure ratio of 1.8 and a corrected engine speed of 15,000 rpm. For all ram-pressure ratios, choking occurred in the engine for corrected engine speeds greater than 14,500 rpm.

INTRODUCTION

A simply constructed, short-life, turbojet engine has been designed, constructed, and operated at the NACA Cleveland laboratory. The engine was constructed with the intention of using it for guided-missile application. The engine was designed to operate at an altitude of 10,000 feet, a flight speed of 550 miles per hour, a compressor pressure ratio of 3.0, and a turbine-inlet temperature of 1800° F.

Restriction/Classification Cancelled

The performance of the engine was investigated at pressure altitudes of 10,000 and 15,000 feet, ram-pressure ratios of 1.2 to 1.8, and a compressor-inlet temperature of -60° F. The corrected engine speed was varied from the minimum for stable combustion to about 17,000 rpm. Generalized performance curves present the corrected net thrust and the corrected thrust specific fuel consumption as functions of corrected engine speed, corrected flight speed, and ram-pressure ratio. Curves of corrected fuel consumption and corrected air consumption are also presented. The engine was designed to produce a corrected thrust of 914 pounds at a corrected engine speed of 22,400 rpm with a corrected air weight flow of 20.2 pounds per second.

SYMBOLS

The following symbols are used in this report:

A	cross-sectional area, square feet
C	thrust specific fuel consumption, pounds fuel per hour per pound thrust
F	net thrust, pounds
f	fuel-air ratio
g	acceleration of gravity, 32.174 feet per second per second
M_{cr}	~~Mach number~~ Critical velocity ratio
N	engine speed, rpm
P	total pressure, pounds per square foot
p	static pressure, pounds per square foot
R	gas constant, foot-pounds per pound per °R
T	total temperature, °R
V	velocity, feet per second
v	flight speed, miles per hour
W	weight flow, pounds per second
γ	ratio of specific heats

δ ratio of compressor-inlet total pressure to NACA standard sea-level pressure, $P_0/2116.8$

η efficiency, percent

θ ratio of compressor-inlet total temperature to NACA standard sea-level temperature, $T_0/518.4$

Subscripts:

a air

b burner

cr critical

f fuel

i indicated

0 free stream

5 exhaust-nozzle outlet

6 station in duct after exhaust nozzle

DESCRIPTION OF ENGINE

The experimental turbojet engine (fig. 1) for guided missiles comprises a mixed-flow single-stage compressor with a semivaneless diffuser, an annular combustion chamber, an axial-flow single-stage turbine, and a fixed convergent exhaust nozzle. The maximum diameter of the engine is 24 inches and the over-all length is 70.25 inches. The weight of the experimental unit is about 650 pounds.

The engine was designed around an existing mixed-flow impeller that could be simply constructed and combined the qualities of high mass flow, moderate pressure ratio, and moderate efficiency. Inasmuch as the turbojet engine should be inexpensive, the use of a cast impeller was considered desirable. Accordingly, the impeller was selected following results obtained in bursting tests of this type of cast impeller. With proper selection of material, it was found that a tip speed of more than 1640 feet per second could be attained before the wheel burst; the design speed of the compressor in this case is 1470 feet per second. An existing machined impeller was used in this investigation.

The annular combustion chamber has 24 fuel nozzles each with a 45° spray angle and a capacity of 10.5 gallons per hour. Preliminary bench investigations of the burner showed a temperature distribution with a maximum variation of about 1000° F and a loss in total pressure between 5 and 10 percent of the total pressure of the entering air.

A single-stage, free-vortex, axial-flow turbine of 13.7-inch tip diameter was designed to drive the compressor. At design conditions, the turbine-discharge velocity is nearly axial but straightening vanes after the turbine were provided to improve operation at other than design conditions. Water-cooled radiation cooling caps are provided on each side of the turbine to prolong the life of the engine for investigation purposes and would be unnecessary for a service requiring short engine life. A small quantity of air, which is directed on each side of the turbine wheel near the shaft, flows radially outward. This air, which cooled the turbine wheel by convection, was supplied by the laboratory system during the investigation but would normally be supplied by the compressor.

This would have to be taken into account as a power loss

The rotating assembly is mounted in four antifriction bearings. The shaft is 35.5 inches long from the rear of the impeller to the front of the turbine. Three of the bearings are mounted in the main housing in line-bored supports and the fourth bearing, the thrust bearing, is mounted in front of the impeller. All bearings are lubricated by an oil-and-air mist. Air is also supplied to bearings from the laboratory air system instead of from the compressor.

Provision was made to start the turbojet engine by driving the compressor end of the shaft through a geared starting motor. This method of starting was not required for the experimental unit because of the laboratory altitude-exhaust facilities.

APPARATUS AND PROCEDURE

Experimental Equipment

The engine was set up in a test rig that supplied refrigerated air through a depression tank and bellmouth and discharged the air at the exhaust nozzle at a pressure corresponding to the desired altitude. A photograph of the engine in the test rig is shown in figure 2 and a diagrammatic sketch of the flow system and instrumentation, in figure 3.

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The inlet refrigerated air was supplied at a temperature near -60° F and the inlet-air pressure was controlled to simulate the pressure altitude and ram-pressure ratio desired. The low inlet temperature was used to reduce the actual engine speed required for a given corrected engine speed. Ram-pressure ratios of 1.2 to 1.8 were obtained when the engine was operated at a pressure altitude of 15,000 feet. At a pressure altitude of 10,000 feet, runs were made only for ram-pressure ratios of 1.2 and 1.4 because of limited air facilities.

Instrumentation

The measuring stations for the engine are shown in figure 3 and the location of some of the instruments is indicated in figure 1. The compressor-inlet conditions were measured in the depression tank in front of the compressor. The compressor-outlet or burner-inlet conditions were measured by four rakes equally spaced around the annulus. The burner-outlet or turbine-inlet conditions were measured by four equally spaced rakes located 2 chord lengths in front of the turbine-nozzle blades. The conditions at the turbine outlet were measured by four rakes and the conditions in the jet were measured by rakes extending across the jet. Pressures were indicated on a manometer board and temperatures were read from a rapid-response, electronic potentiometer.

The air weight flow through the engine was determined by a calibrated, adjustable orifice in the refrigerated-air line.

The fuel flow was measured with a calibrated rotameter. The speed was observed from an electronic-impulse counter operated from a magnetic pickup.

Experimental Procedure

The engine was operated at simulated pressure altitudes by setting the exhaust pressure (station 6) to correspond to the altitude pressure and setting the inlet pressure to correspond to the altitude pressure plus ram pressure. The inlet temperature was held as near -60° F as the services would permit. For high engine speeds and high ram-pressure ratios, the temperature rose to -37° F. The engine speed was varied by adjusting the fuel flow. The fuel used throughout the investigation was 62 octane fuel.

METHOD OF CALCULATION

Temperature

The indicated temperature is less than the total temperature because the thermocouple recovery coefficient is less than unity. For unshielded thermocouples similar to those used in this investigation, a recovery coefficient of about 0.85 was found from calibration. The true total temperature therefore is

$$T = \frac{T_i}{1 - 0.15\,\frac{\gamma-1}{\gamma+1}\,M_{cr}^2} \tag{1}$$

By use of the observed temperature and the fuel-air ratio calculated from the fuel- and air-weight flows, the value of γ is selected from a chart relating γ, temperature, and fuel-air ratio.

Velocity

The critical-velocity ratio of the fluid is related to the ratio of the static to the total pressure by the expression

$$M_{cr} = \left\{\left[1 - \left(\frac{p}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]\frac{\gamma+1}{\gamma-1}\right\}^{\frac{1}{2}} \tag{2}$$

where M_{cr} is defined as V/V_{cr} and

$$V_{cr} = \sqrt{\frac{2\gamma}{\gamma+1}\,gRT}$$

When the total temperature is known, the velocity at any station is found by the equation

$$V = M_{cr}\sqrt{\frac{2\gamma}{\gamma+1}\,gRT} \tag{3}$$

The flight speed was found by determining the critical-velocity ratio corresponding to the ram-pressure ratio and using equation (3) with the total temperature corresponding to that at station 0.

Net Thrust

The thrust of a jet engine that is useful in propelling an airplane may be calculated by the summation of the momentum and the pressure forces on the engine. The equation for thrust is

$$F = \frac{W\left[(1 + f)\, V_5 - V_0\right]}{g} + (p_5 - p_6)\, A_5 \tag{4}$$

The pressure term of equation (4) is zero when the exhaust-nozzle-pressure ratio is subcritical because $p_5 = p_6$. This expression for thrust neglects cooling-air flow and thus does not credit the engine with the cooling air from the laboratory system. Check runs made with and without cooling air showed no measurable influence of the cooling air.

Thrust Specific Fuel Consumption

The thrust specific fuel consumption is defined as the pounds of fuel consumed per hour per pound of thrust. The equation is

$$C = \frac{W_f}{F} \tag{5}$$

RESULTS AND DISCUSSION

The performance of the turbojet engine for guided missiles is presented by generalized parameters to permit calculation of performance at any altitude. The corrected net thrust is plotted against corrected engine speed for constant values of ram-pressure ratio in figure 4. The net thrust increases rapidly with engine speed for all ram-pressure ratios. A maximum corrected thrust of 425 pounds was reached at a ram-pressure ratio of 1.8 and a corrected engine speed of 16,650 rpm; this thrust is 46.5 percent of the design value. When the data in figure 4 are cross-plotted (fig. 5), it is clear that for corrected engine speeds above 14,500 rpm the thrust increases with increasing flight speed. For lower engine speeds, the thrust decreases with increasing flight speed for most of the flight-speed range investigated, showing a slight increase in thrust for intermediate engine speeds. These trends are expected in a unit with low pressure ratio or low efficiency. At the low engine speeds, the thrust is low for the high flight speeds because the engine is almost windmilling and the heat input is low.

For higher engine speeds, the thrust increases with ram-pressure ratio because for this engine, the total pressure at the exhaust nozzle is near the total inlet pressure for the range of conditions investigated and the engine acts effectively like a ram jet.

The corrected thrust specific fuel consumption decreases with increasing engine speed, as shown in figure 6. With an increase in ram-pressure ratio, the thrust specific fuel consumption decreases for corrected engine speeds from 13,600 rpm to the maximum speed investigated. The minimum thrust specific fuel consumption value of 1.48 was reached at a ram-pressure ratio of 1.8 and a corrected engine speed of 15,000 rpm. The effect of flight speed is clearly shown in figure 7, a cross plot of figure 6.

The trends shown in figures 6 and 7 are evident from a correlation of figures 4 and 8. The plot of corrected fuel flow against corrected engine speed shown in figure 8 is a single line for all ram-pressure ratios at high speeds. The curve of thrust specific fuel consumption (fig. 6), which is the quotient of fuel flow divided by net thrust, would therefore be the inverse of the thrust curve (fig. 4). The curve of corrected fuel flow (fig. 8) would be a single line for all ram-pressure ratios if the component efficiencies were constant for a given corrected engine speed. The divergence of the curves for the lower speeds in figure 8 is probably due largely to the decrease in burner efficiency for lower inlet pressures. A better fuel flow parameter might be $W_f/\delta\sqrt{\theta}\,\eta_b$.

The corrected air flow is plotted against corrected engine speed in figure 9. For all ram-pressure ratios, the corrected air flow reaches a maximum at a corrected engine speed of 14,500 rpm, which indicates the occurrence of choking in the engine. This condition, which limited the mass flow through the engine, caused the maximum thrust to be 53.5 percent less than the design value.

SUMMARY OF RESULTS

In a preliminary investigation of the performance of a turbojet engine for a guided missile at a pressure altitude of 15,000 feet and ram-pressure ratios of 1.2 to 1.8, the following results were obtained:

1. The corrected net thrust of the engine increased with increasing flight speed for corrected engine speeds above 14,500 rpm and reached a maximum of 425 pounds at a ram-pressure ratio of 1.8 and a corrected engine speed of 16,650 rpm.

2. The corrected thrust specific fuel consumption decreased with increasing flight speed for corrected engine speeds above 13,600 rpm and reached a minimum of 1.48 at a ram-pressure ratio of 1.8 and an engine speed of 15,000 rpm.

3. For all ram-pressure ratios, choking occurred in the engine for corrected engine speeds greater than 14,500 rpm.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 22, 1947.

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1. Laskin, Eugene B., and Kofskey, Milton G.: Performance of a Mixed-Flow Impeller in Combination with a Semivaneless Diffuser. NACA RM No. E7C05a, 1947.

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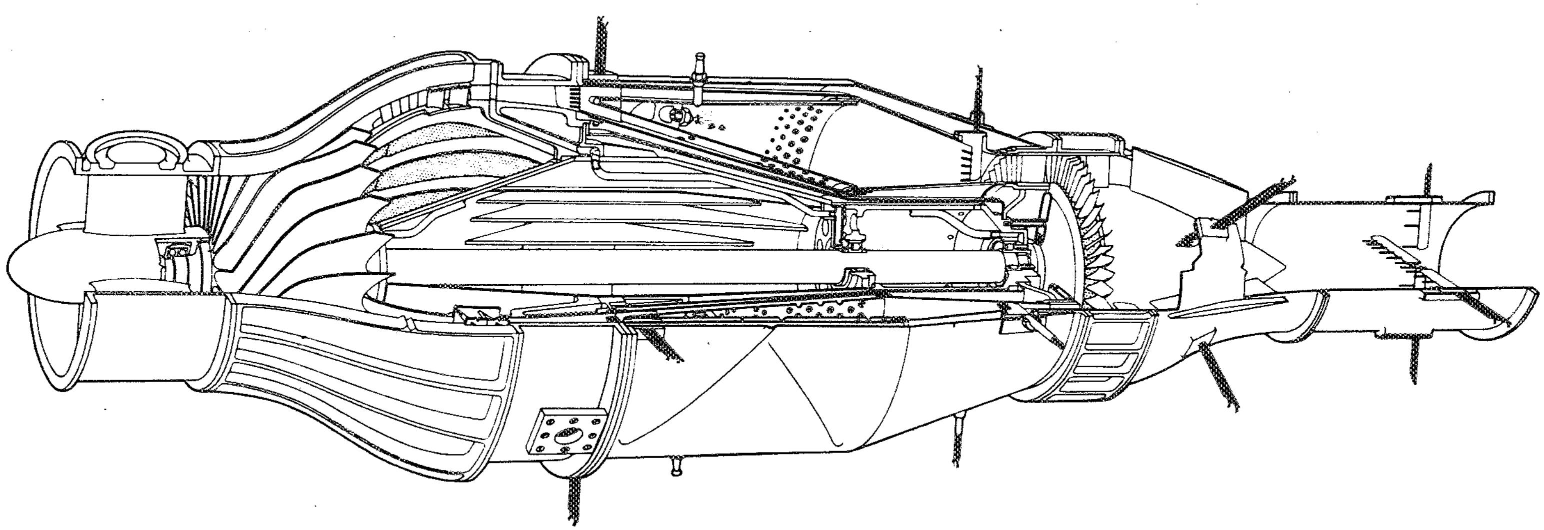

Figure 1. - Cutaway view showing components and instrumentation of turbojet engine for guided missile.

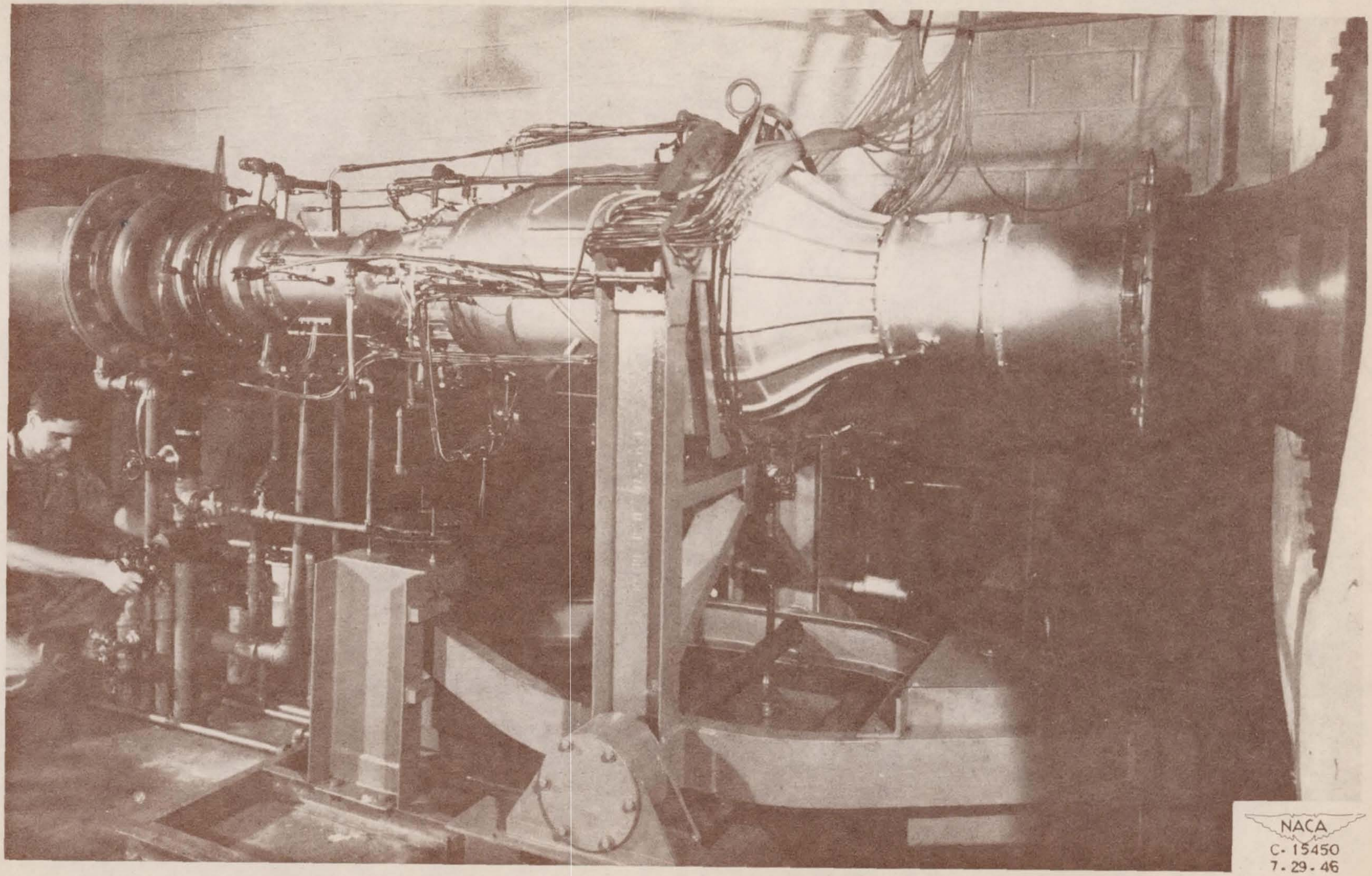

Figure 2. - Installation of turbojet engine for guided missile.

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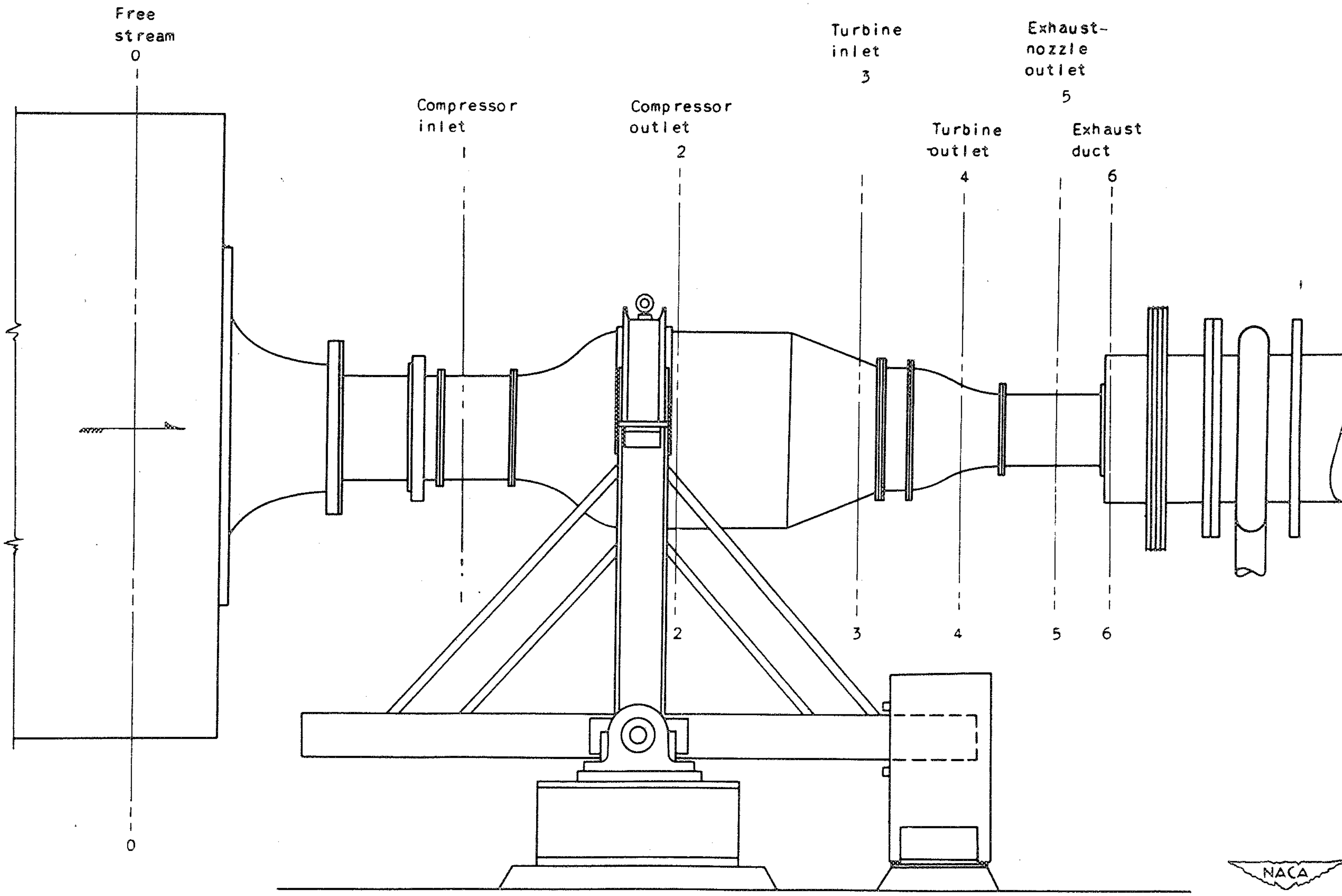

Figure 3. - Schematic view of turbojet engine for guided missile in test rig showing measuring stations.

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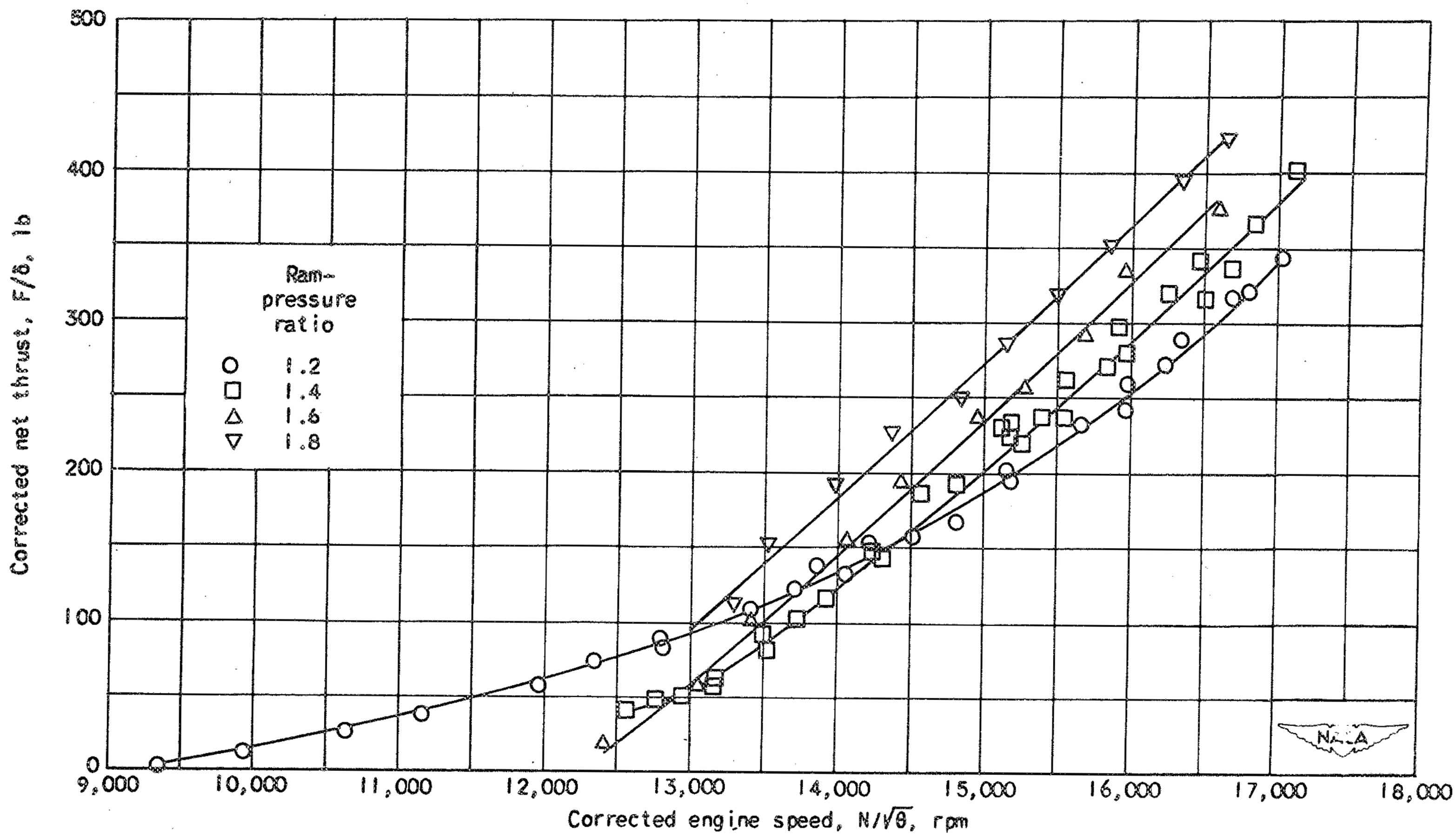

Figure 4. - Effect of corrected engine speed and ram-pressure ratio on corrected net thrust of turbojet engine for guided missile.

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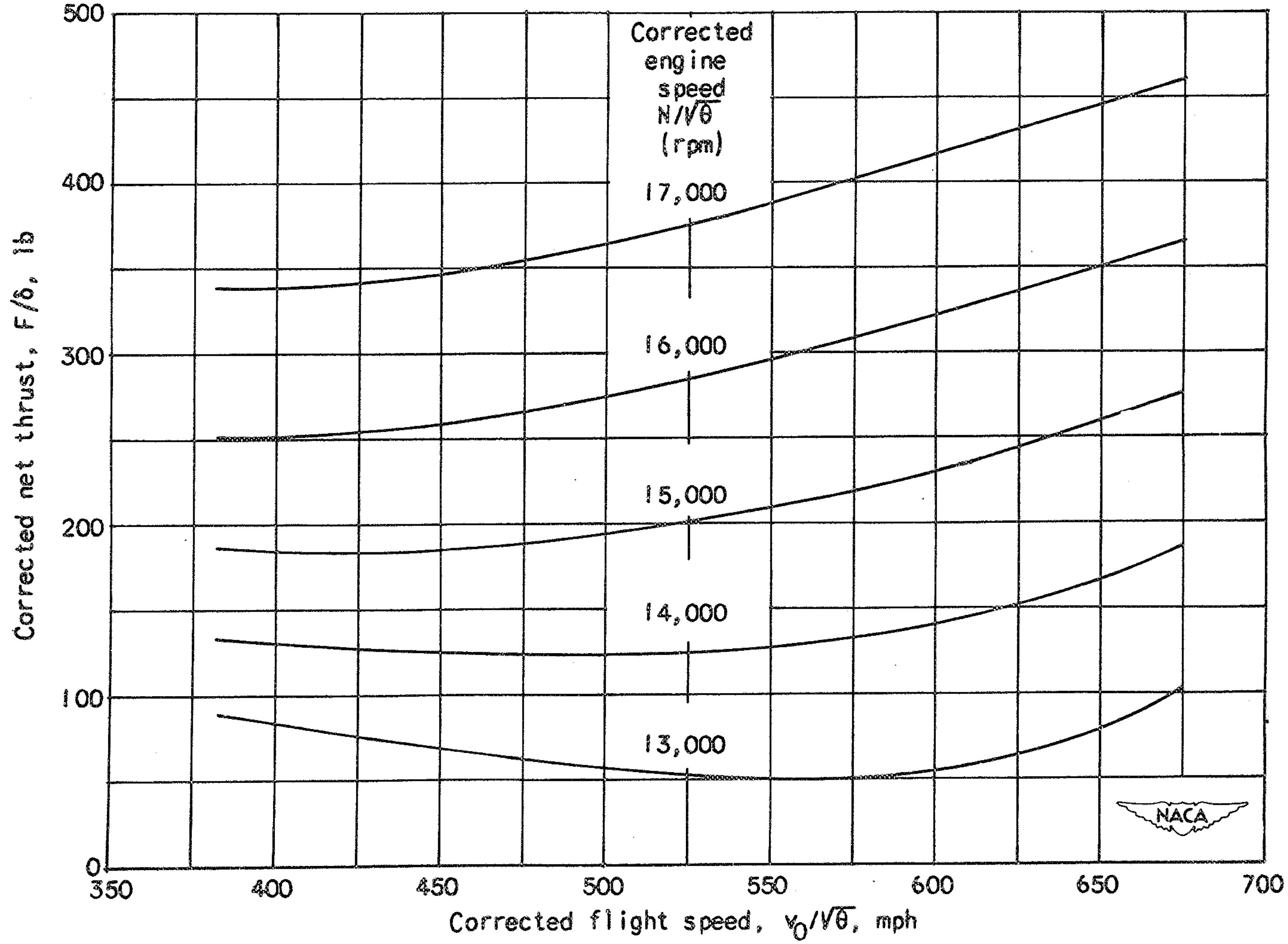

Figure 5. - Effect of corrected flight speed and corrected engine speed on corrected net thrust of turbojet engine for guided missile.

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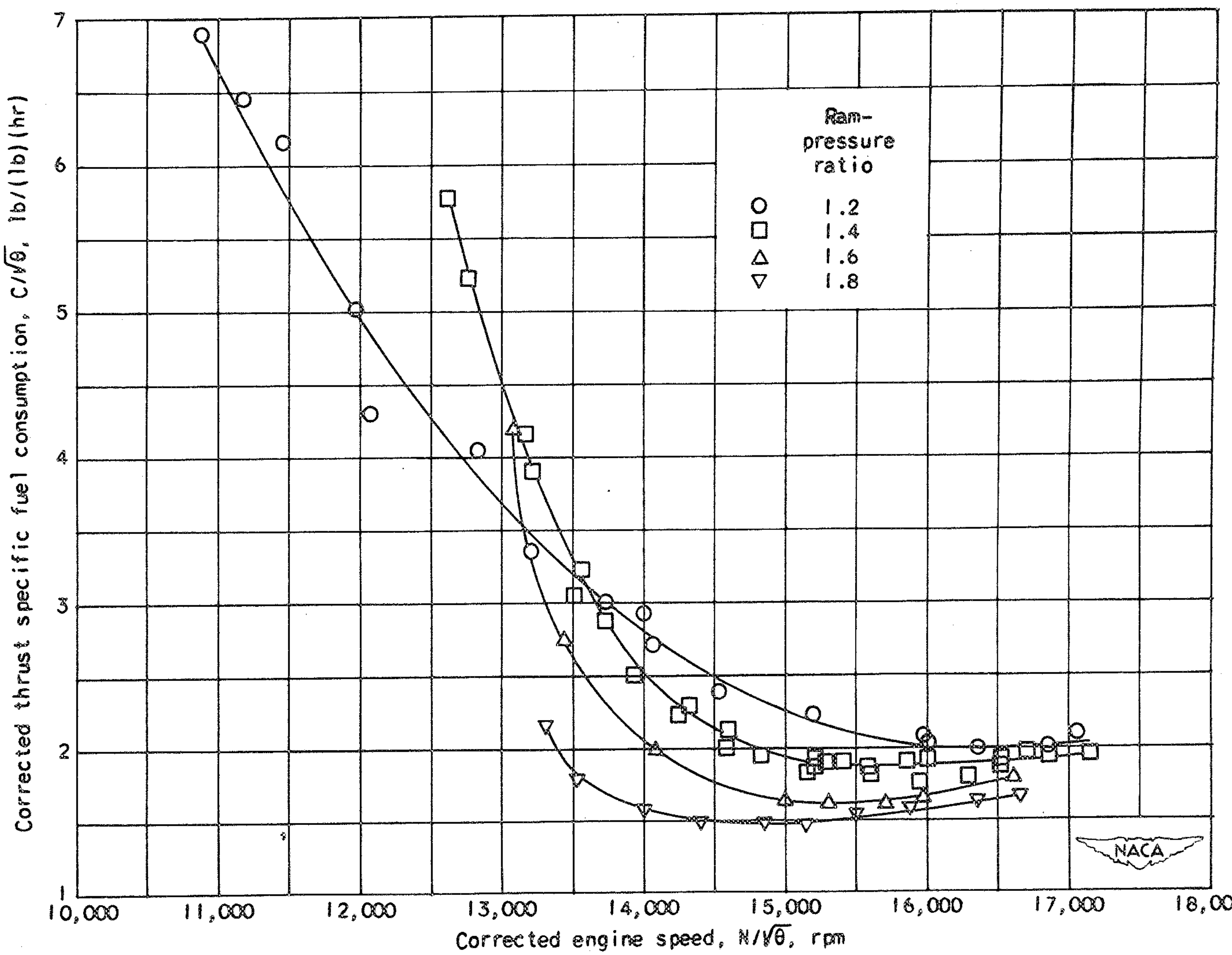

Figure 6. - Effect of corrected engine speed and ram-pressure ratio on corrected specific fuel consumption of turbojet engine for guided missile.

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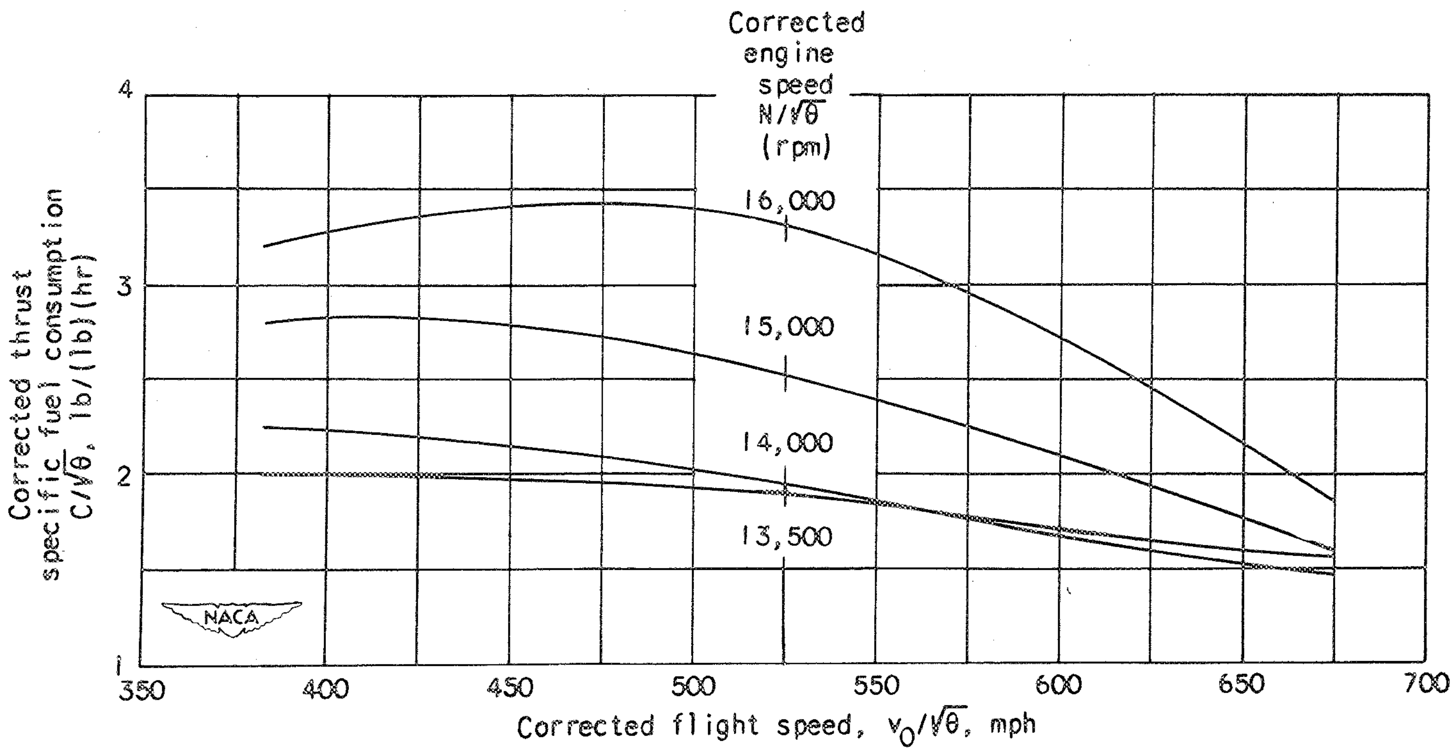

Figure 7. - Effect of corrected flight speed and corrected engine speed on corrected specific fuel consumption of turbojet engine for guided missile.

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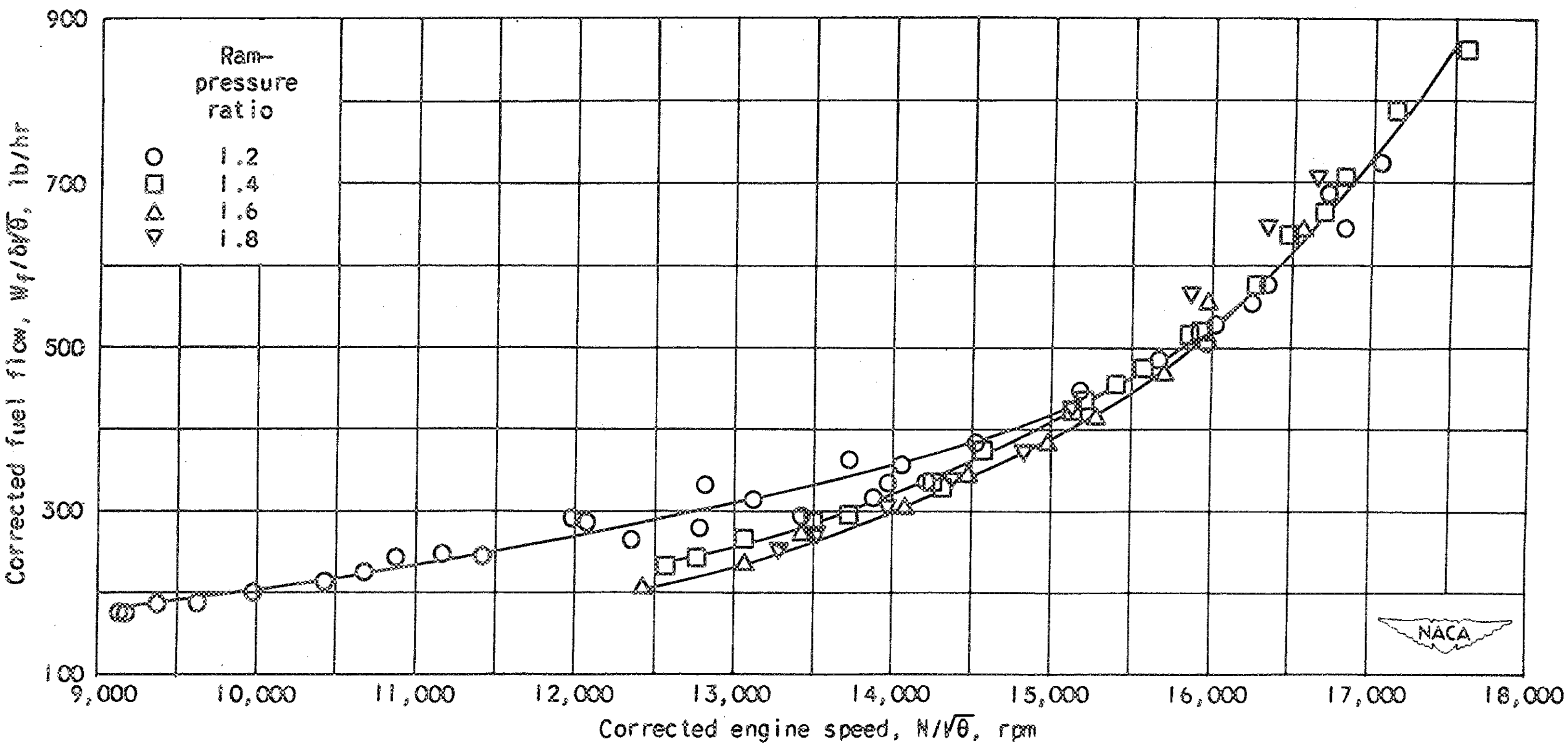

Figure 8. - Effect of corrected engine speed and ram-pressure ratio on corrected fuel flow of turbojet engine for guided missile.

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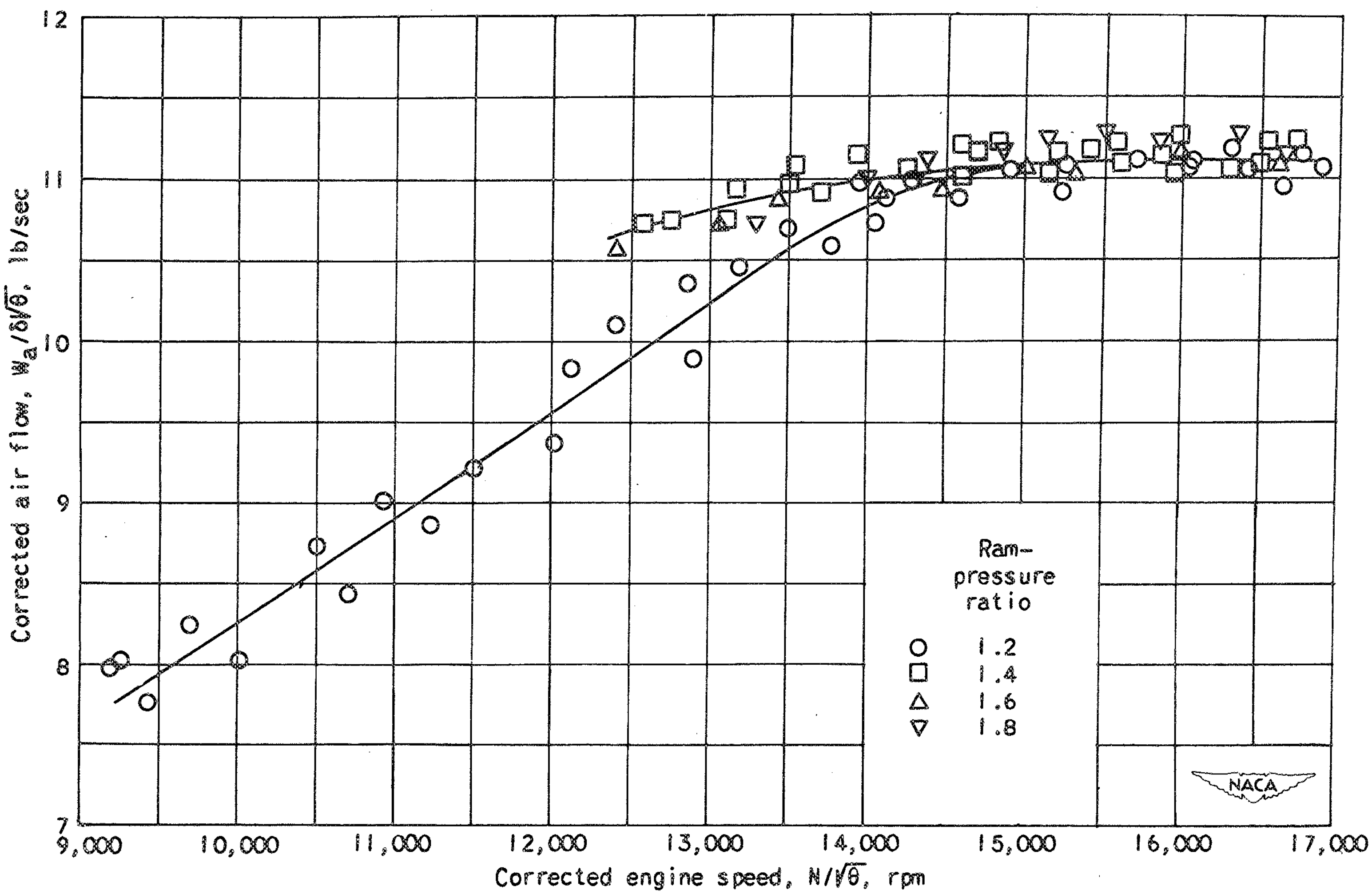

Figure 9. - Effect of corrected engine speed and ram-pressure ratio on corrected air flow of turbojet engine for guided missile.