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RESEARCH MEMORANDUM

ALTITUDE OPERATION OF GAS-TURBINE ENGINE WITH VARIABLE-AREA FUEL-NOZZLE SYSTEM

By H. Gold and S. Rosenzweig

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

The fuel consumption of a gas-turbine engine alternately equipped with variable-area fuel nozzles and with fixed-area fuel nozzles was investigated at altitudes up to 40,000 feet. At 40,000 feet, the engine when equipped with variable-area fuel nozzles operated with reduced fuel consumption at all engine speeds. At lower altitudes this reduction in fuel consumption occurred at progressively lower engine-speed ranges. This reduction was attributed to the increase in combustion efficiency that resulted from improved fuel atomization. A correlation between the percentage reduction in fuel consumption and the fuel consumption of the engine equipped with the fixed-area fuel nozzles is presented. On the basis of this correlation, the reduction in fuel consumption was approximately 16 percent under operating conditions at which the fuel consumption of the engine equipped with fixed-area fuel nozzles was 600 pounds per hour. The percentage reduction continually decreased until a fuel consumption of 1800 pounds per hour was reached. Above 1800 pounds per hour, the fuel consumptions of the engine equipped with the variable- and fixed-area fuel nozzles were equal.

INTRODUCTION

Current and projected service requirements of gas-turbine aircraft necessitate operation at altitudes that impose fuel-flow rates below the value at which the fuel-atomization nozzles produce a well-defined spray cone. With this type of inferior atomization the fuel is poorly distributed in the combustion chamber, combustion efficiency is low, and the flame is susceptible to blow-out. This condition is particularly acute at the low engine rotational speeds required for descent from altitude.

The variable-area fuel nozzle, described in reference 1, provides a means of maintaining a satisfactory spray cone at the low fuel-flow rates required for high-altitude flight. As shown in reference 1, this type of atomizing nozzle has the additional advantage of being capable of accommodating the high fuel-flow rates required for sea-level operation with relatively low fuel-system pressures.

In reference 1, a turbojet engine designed for operation with a fixed-area fuel-nozzle system was shown to operate with a lower specific fuel consumption when equipped with a variable-area fuel-nozzle system. This reduction in fuel consumption occurred in the low fuel-flow-rate range in which the spray from the variable-area fuel nozzles was visibly finer than the spray from the fixed-area fuel nozzles. Because the investigation of reference 1 was limited to sea-level conditions, the low range of fuel-flow rates (25 to 50 percent of fuel-flow rate for rated engine speed at sea-level static condition) occurred only at speeds below 80 percent of rated engine speed. The investigation reported herein was therefore undertaken to extend this study to altitude conditions in which the low fuel-flow rates occur over the full range of engine speeds.

The primary aim of this investigation was to determine the magnitude of the possible gains in fuel economy under altitude operating conditions. Data were obtained on a turbojet engine alternately equipped with variable-area and fixed-area fuel nozzles operating over a range of engine speeds and ram pressure ratios at altitudes of sea level and of 25,000, 30,000, and 40,000 feet. Engine performance is compared on the basis of fuel consumption and combustion efficiency.

APPARATUS

Engine

The J33-11 gas-turbine engine used in the investigation had the following components and rating:

Compressor	Centrifugal
Burner section	14 through-flow combustion chambers
Turbine	Single stage, gas
Tail pipe	Inconel, 81-inch length, 21.0-inch diameter (fig. 1)
Exhaust nozzle	Fixed area, 19.5-inch diameter (fig. 1)
Maximum engine speed	11,500 rpm
Sea-level static idle speed	4000 rpm

Engine Fuel Systems

The fixed-area fuel-nozzle system is described as follows:

Fuel pump	Engine driven, positive displacement
Barometric	Pressure-relief valve controlled by atmospheric pressure
Control valve	Manually operated restrictive-type valve consisting of stopcock and throttle
Fuel manifold	Tubular ring with individual lines to fixed-area fuel nozzles
Fuel nozzles	Fixed area, 40 gallons per hour at 100 pounds per square inch differential pressure

A cutaway drawing and a photograph of the variable-area fuel nozzle of the vortex type is shown in figure 2. The area of the tangential openings into the swirl chamber is varied by a bellows. Fuel pressure acts on the outside of the bellows and combustion-chamber pressure is vented to the inside of the bellows. A more detailed description of the nozzle is presented in reference 1.

A comparison of the fuel flow - pressure drop relation between the variable- and fixed-area fuel nozzles is shown in figure 3.

Large variations can occur in the flow resistances of variable-area fuel nozzles that operate at nearly constant pressure drop. This variation of flow resistance precludes the use of these nozzles with a simple manifold fuel-distribution system. A fuel-distribution control (fig. 4) was used in this investigation to prevent irregular nozzle-to-nozzle fuel distribution. A description of the fuel-distribution control is presented in references 1 and 2.

Installation

Engine mounting	6-foot altitude test chamber
Combustion air supply	NACA Lewis laboratory refrigerated-air supply
Exhaust	NACA Lewis laboratory exhaust system

Measurements:

Engine speed	a-c. tachometer generator coupled to chronometric tachometer
Engine fuel flow	Calibrated rotameter

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Engine fuel pressure	Calibrated pressure gage
Inlet air pressure	Total-head tube in cell plenum chamber connected to mercury manometer
Inlet air temperature	Iron-constantan thermocouples distributed in 90° intervals on front and rear compressor screens
Compressor-outlet total pressure	Total-head tubes led to calibrated manometer board
Compressor-outlet static pressure	Static tube connected to calibrated manometer board
Compressor-outlet temperature	Iron-constantan thermocouples
Air flow	Standard NACA pressure and temperature survey rake placed in tail pipe 16 inches downstream of tail-cone flange
Exhaust pressure	Static tube placed in exhaust pipe connected to mercury manometer

PROCEDURE

With variable- and fixed-area fuel-nozzle systems alternately installed on the gas-turbine engine, engine performance was studied from maximum to minimum operating engine speeds at the following simulated conditions:

Altitude (ft)	Engine ram pressure ratio
Sea level	1.00
25,000	1.00
30,000	1.25
	1.14
	1.00
40,000	1.50
	1.15
	1.00

The fuel used was MIL-F-5616.

Altitude and ram pressures were maintained within ±0.025 inches of mercury of the standard altitude pressures. At all altitudes except sea level, engine inlet temperatures were maintained within 35° of the mean

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temperature of 420° R. This mean temperature of 420° R was used instead of the standard altitude temperature because of limitations of the test facilities. At sea level, the inlet temperatures were within ±20° of standard sea-level temperature.

The investigation was limited to a maximum altitude of 40,000 feet by the exhaust capacity of the 6-foot altitude test chamber.

SYMBOLS

The following symbols are used in this report:

A	cross-sectional area, (sq ft)
c_p	mean specific heat of air at constant pressure, (0.24 Btu/(lb)(°R))
F_j	jet thrust, (lb)
F_n	net thrust, (lb)
f/a	fuel-air ratio
g	acceleration due to gravity, (32.2 ft/sec^2)
H	enthalpy of gas, (Btu/lb)
h	heating value of fuel, (Btu/lb)
J	mechanical equivalent of heat, (778 Btu/lb)
K	gas-flow calibration factor for tail-pipe outlet rake, 0.964
N	engine speed, (rpm)
P	total pressure, (lb/sq ft)
p	static pressure, (lb/sq ft)
R	gas constant, (ft-lb/(lb)(°R))
T	total temperature, (°R)
T_i	indicated temperature, (°R)
W_a	air flow, (lb/sec)

W_f fuel consumption, (lb/sec)

W_g gas flow, (lb/sec)

Y tail-pipe expansion factor $\left[1 + 1.8 \times 10^{-5} (T_7 - 520)\right]$

α thermocouple impact recovery factor, 0.86

γ ratio of specific heats, 1.40 for air and variable for exhaust gas

η_b combustion efficiency, percent

Subscripts:

0 free air stream

1 engine inlet

2 compressor outlet

3 burner inlet

4 burner outlet

5 turbine inlet

6 turbine outlet

7 tail-pipe pressure and temperature survey rake

8 exhaust-nozzle outlet

cr critical

n increment of annular area in tail pipe

METHODS OF CALCULATION

Total temperature. - Total temperature was calculated from indicated temperature by use of the relation

$$T = \frac{T_i\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}}{1 + \alpha\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

<u>Engine gas flow</u>. - Engine gas flow was calculated from pressure and temperature measurements obtained in the tail cone (station 7) by use of the relation

$$W_g = KY\left[\sqrt{\frac{2\gamma g}{(\gamma-1)R}}\right]\left\{\sum_{n=1}^{n=5} p_n A_n \sqrt{\frac{\left[\left(\frac{P_n}{p_n}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + \alpha\left[\left(\frac{P_n}{p_n}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]^2}{T_{i,n}}}\right\} \tag{2}$$

<u>Engine air flow</u>. - Engine air flow was calculated by use of the relation

$$W_a = W_g - W_f \tag{3}$$

<u>Jet thrust</u>. - Engine jet thrust was calculated as follows:

For subsonic flow in the exhaust nozzle,

$$F_j = \frac{2\gamma}{\gamma-1}\, p_0 \sum_{n=1}^{n=5} A_n \sqrt{\left[\left(\frac{P_n}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left[\left(\frac{P_n}{p_n}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{p_n}{p_0}\right)^{\frac{\gamma+1}{2\gamma}}} \tag{4}$$

For sonic flow in the exhaust nozzle,

$$F_j = \sum_{n=1}^{n=5} A_n \left(\frac{P_n}{p_0}\right)^{\frac{\gamma-1}{2\gamma}} \left[p_0(\gamma-1) + p_{cr}\right] \sqrt{\frac{\left(\frac{P_n}{p_n}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{P_n}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1}} \tag{5}$$

In equations (4) and (5), the total pressure at the nozzle outlet is assumed equal to the total pressure at the plane of the rake (station 7).

The term p_{cr} used in equation (5) was calculated as

$$p_{cr} = P_n / \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \tag{5a}$$

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Net thrust. - Engine net thrust was calculated by the use of the relation

$$F_n = F_j - W_a \sqrt{\frac{2Jc_pT_0}{g}\left(1 - \frac{1}{\left(\frac{P_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}}}\right)} \tag{6}$$

Combustion efficiency. - Combustion efficiency was calculated by the use of the relation

$$\eta_b = \frac{H_4 - H_3}{(f/a)\,h} \tag{7}$$

where the assumption was made that the work done by the turbine is equal to the work absorbed by the compressor. Bearing losses and accessory power are a minor factor and are the same for both the variable- and fixed-area fuel-nozzle runs. The variation in specific heat was taken into account by means of charts relating temperature and enthalpy with fuel-air ratio as a parameter.

Correction factors. - In order to compare the two fuel systems studied in this investigation, all data were corrected to standard pressure at the simulated altitude. Because the effect studied in this investigation is related to the actual fuel-flow rate, the altitude data were corrected to the experimental mean temperature of 420° R instead of the standard altitude temperatures. This basis for correction made the data comparable without significantly altering the numerical value of fuel-flow rate. Sea-level data were corrected to 518° R. Corrections for pressure altered the value of the engine variables no more than 0.5 percent and the corrections for temperature, no more than 4.0 percent.

Reduction in fuel consumption. - The percentage reduction in fuel consumption of the engine equipped with variable-area fuel nozzles as compared to the fuel consumption of the engine equipped with fixed-area fuel nozzles was calculated as follows:

$$\frac{\left\{\left[\begin{array}{c}\text{Fuel consumption of engine}\\ \text{equipped with fixed-area}\\ \text{fuel nozzles}\end{array}\right] - \left[\begin{array}{c}\text{Fuel consumption of engine}\\ \text{equipped with variable-}\\ \text{area fuel nozzles}\end{array}\right]\right\}\times 100}{\left[\text{Fuel consumption of engine equipped with fixed-area fuel nozzles}\right]}$$

RESULTS AND DISCUSSION

Engine Performance

Fuel consumption. - Fuel consumptions of the engine equipped with the fixed-area and variable-area fuel nozzles are compared in figure 5 for various altitudes and ram pressure ratios. The data show a reduction in fuel consumption resulting from the use of the variable-area nozzles. The percentage reduction in fuel consumption is shown in the following table:

Altitude (ft)	Ram pressure ratio	Reduction in fuel consumption, percent	
		70 percent rated engine speed	96 percent rated engine speed
25,000	1.00	9.4	0
30,000	1.25	11.8	0
	1.14	12.3	1.2
	1.00	7.5	3.3
40,000	1.50	15.4	4.4
	1.15	12.5	1.4
	1.00	13.0	6.2

Combustion efficiency. - The improved combustion efficiency corresponding to the reduced fuel consumption is shown in figure 6. The percentage increase in combustion efficiency is given in the following table:

Altitude (ft)	Ram pressure ratio	Increase in combustion efficiency, percent	
		70 percent rated engine speed	96 percent rated engine speed
25,000	1.00	8.9	0
30,000	1.25	16.2	0
	1.14	10.0	0
	1.00	11.2	1.1
40,000	1.50	20.0	3.2
	1.15	17.3	4.0
	1.00	11.3	5.7

Small differences occur between the percentage reductions in fuel consumption and the percentage increase in combustion efficiency shown in the preceding tables. These differences result from scatter in the air-flow data from which the combustion efficiencies were computed.

Thrust, air flow, and exhaust-nozzle temperature. - Typical curves of jet thrust and net thrust as functions of engine speed are shown in figures 7 and 8, respectively. There was no difference in the net thrust developed by the engine when equipped with the variable-or fixed-area fuel nozzles. Typical curves of engine air flow and tail-pipe temperature as functions of engine speed are shown in figures 9 and 10, respectively. An additional check on the equality of the air flows in the two sets of runs is shown by the compressor total-pressure ratio plot in figure 11. No thrust specific fuel consumption curves are presented because, in view of the equality of the thrust curves, they would show the same percentage differences as the fuel consumption curves of figure 5.

Correlation of Effect of Fuel Atomization on Fuel Consumption

Variation of atomization with fuel-flow rate. - Photographs presented in reference 1 comparing the fuel spray produced by the variable-area fuel nozzles and the fixed-area fuel nozzles showed that the greatest difference in the fineness of atomization occurred at the low fuel-flow rates (nozzle flow rate of approximately 40 lb/hr) and that the difference in the fineness of atomization continuously diminished as the flow rate increased. At a nozzle flow rate of approximately 150 pounds per hour, the spray produced by the two types of nozzle appeared very similar. The pressure drops across both types of nozzle at 150 pounds per hour were approximately 55 pounds per square inch.

At all higher flow rates studied the atomization appeared equal in spite of the high pressure drop across the fixed-area fuel nozzle.

Variation of reduction of fuel consumption with atomization. - Because the fuel sprays of the two types of fuel nozzle were very similar at nozzle flow rates above 150 pounds per hour, no reduction in fuel consumption would be expected under engine operating conditions at which engine fuel consumption was in excess of approximately 2100 pounds per hour (14-combustion-chamber engine). It is noted that the curves shown in figures 5 and 6 converge at a fuel consumption of approximately 1800 pounds per hour. The data in figure 5 also correlate for all altitudes and ram pressure ratios of the investigation. This correlation is shown in figure 12 where the percentage reduction in fuel consumption is plotted as a function of the fuel consumption of the engine equipped with fixed-area fuel nozzles. The magnitude of the reduction in fuel consumption can therefore be attributed to the difference between fuel-spray configurations with the variable-area and fixed-area fuel nozzles. Within the limits of this investigation, the effect of improved atomization was apparently independent of altitude and ram pressure ratio. As summarized in figure 12, the reduction in engine fuel consumption was approximately 16 percent for operating conditions during which the fuel consumption of the engine equipped with fixed-area fuel nozzles was 600 pounds per hour, whereas the fuel consumptions were equal above 1800 pounds per hour.

SUMMARY OF RESULTS

From a study of the altitude performance of a gas-turbine engine equipped with variable-area fuel nozzles and with fixed-area fuel nozzles, the following results were obtained:

1. At 40,000 feet, the engine when equipped with variable-area fuel nozzles operated with reduced fuel consumption at all engine speeds. At lower altitudes this reduction in fuel consumption occurred at progressively lower engine-speed ranges. This reduction was attributed to an increase in combustion efficiency that resulted from improved fuel atomization.

2. The percentage reduction in fuel comsumption correlated with the fuel consumption of the engine equipped with fixed-area fuel nozzles for all altitudes and ram pressure ratios. Under operating conditions at which the fuel atomization of the engine equipped with fixed-area

fuel nozzles was 600 pounds per hour, the reduction was approximately 16 percent, and above 1800 pounds per hour the fuel consumptions were equal.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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REFERENCES

1. Gold, Harold, and Straight, David M.: Gas-Turbine Engine-Operation with Variable-Area Fuel Nozzles. NACA RM E8D14, 1948.

2. Straight, David M., and Gold, Harold.: Experimental and Analytical Study of Balanced-Diaphragm Fuel Distributors for Gas-Turbine Engines. NACA RM E50F05, 1950.

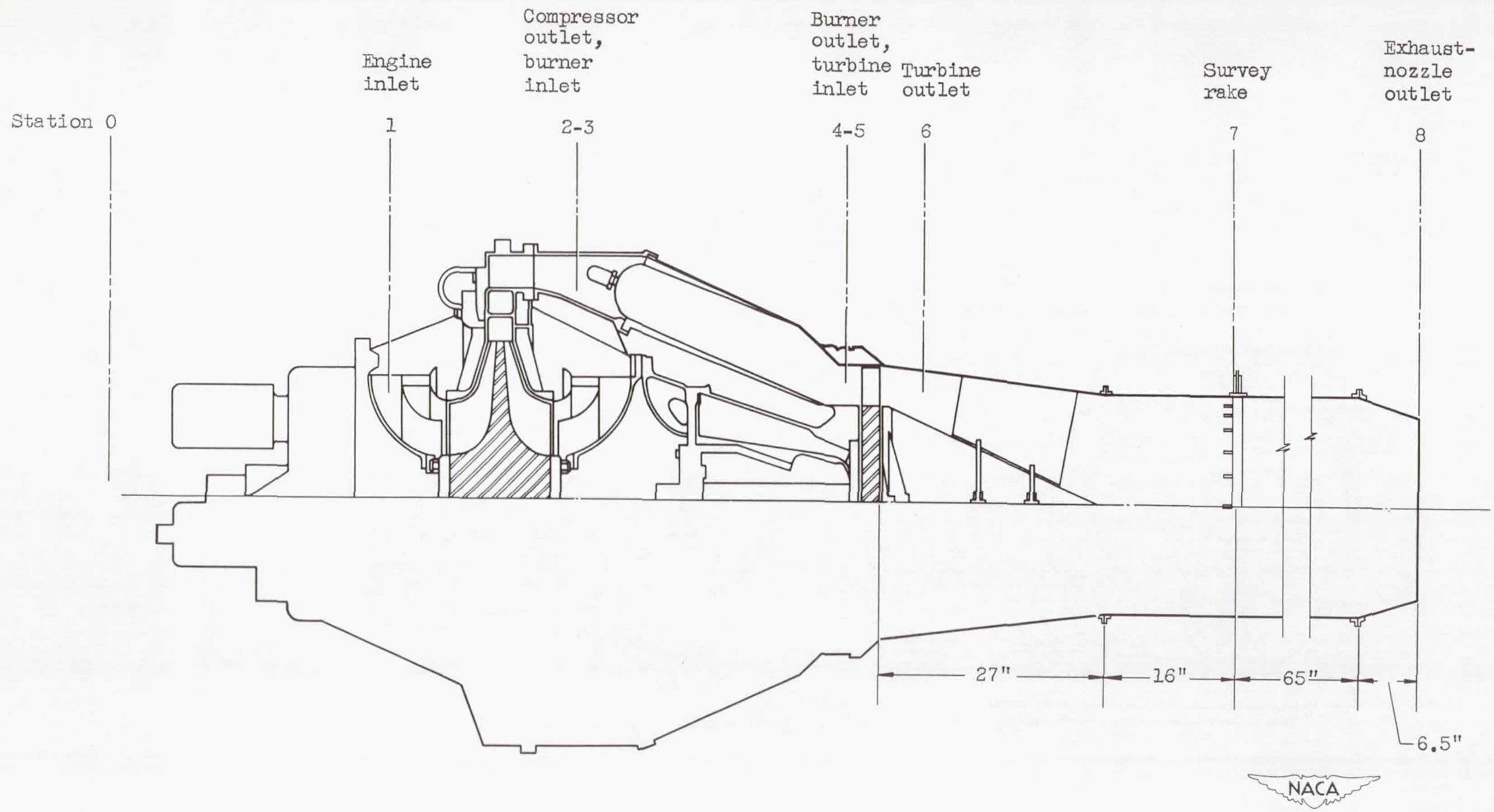
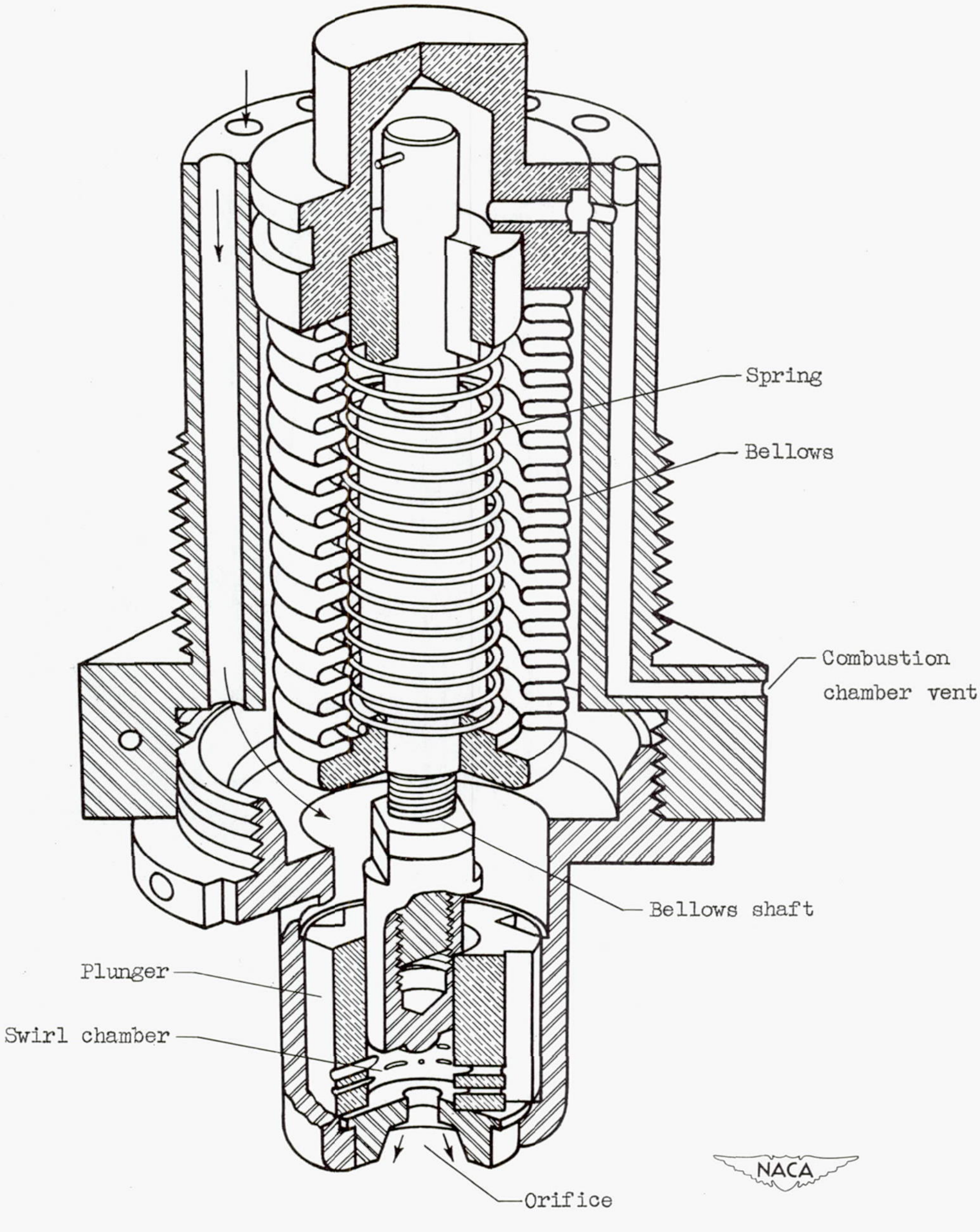


Figure 1. - Schematic diagram of gas-turbine engine.



(a) Cutaway internal view.

Figure 2. - Variable-area fuel nozzle for gas-turbine engine.

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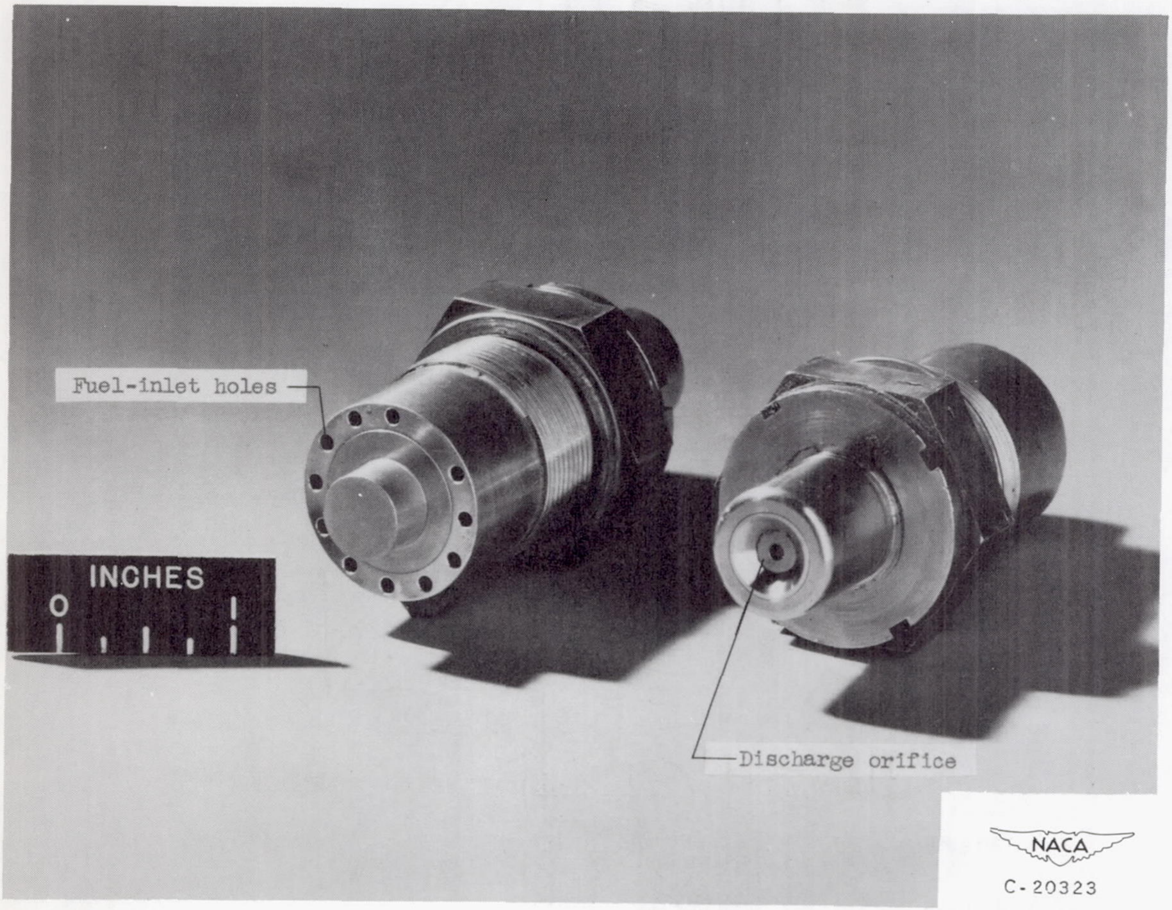

(b) Front and rear views.

Figure 2. - Concluded. Variable-area fuel nozzle for gas-turbine engine.

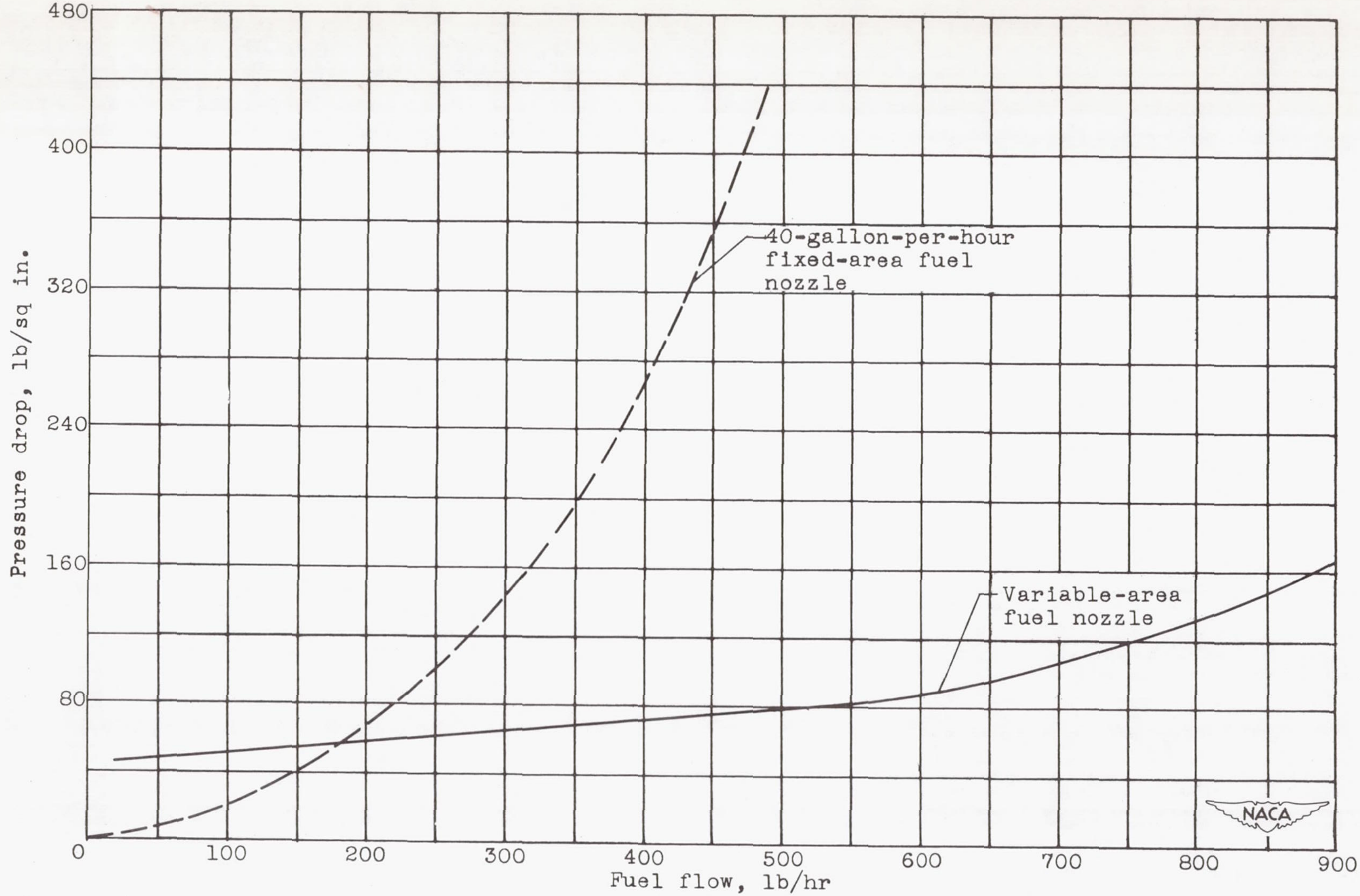

Figure 3. - Characteristic fuel flow - pressure drop relation for variable-area and fixed-area fuel nozzles.

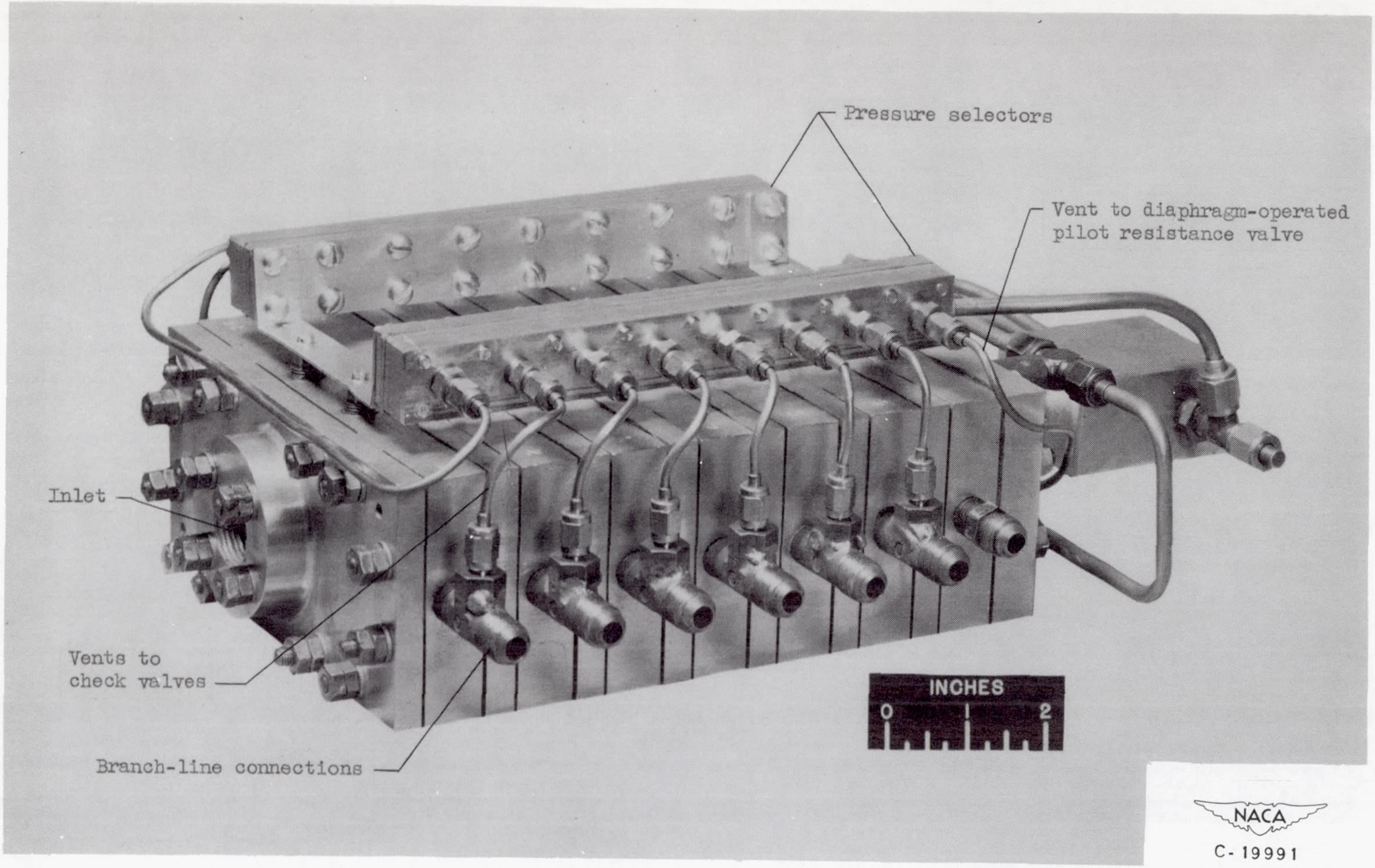

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Figure 4. - Fuel-distribution control used in gas-turbine engine operation with variable-area fuel nozzles.

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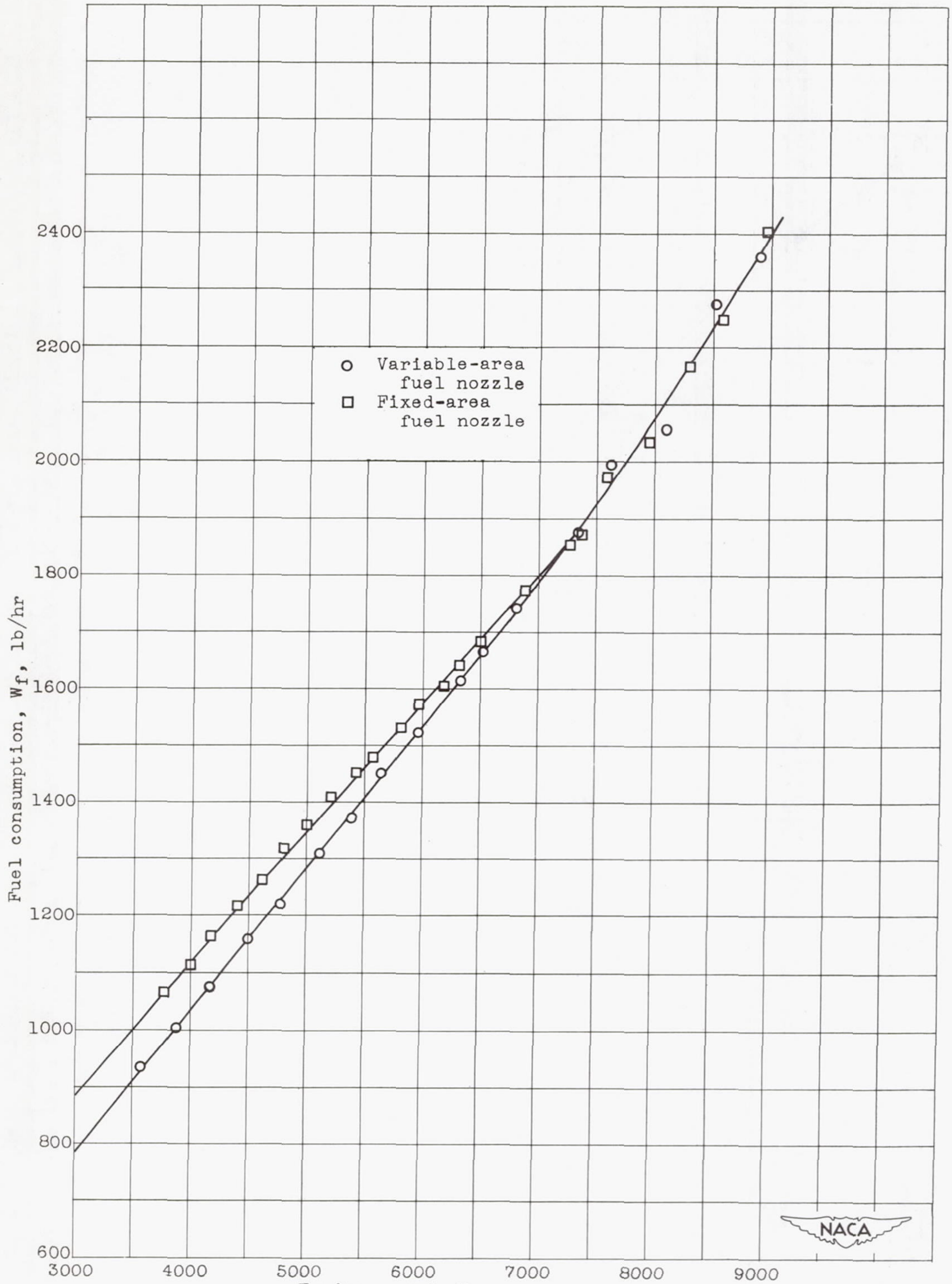
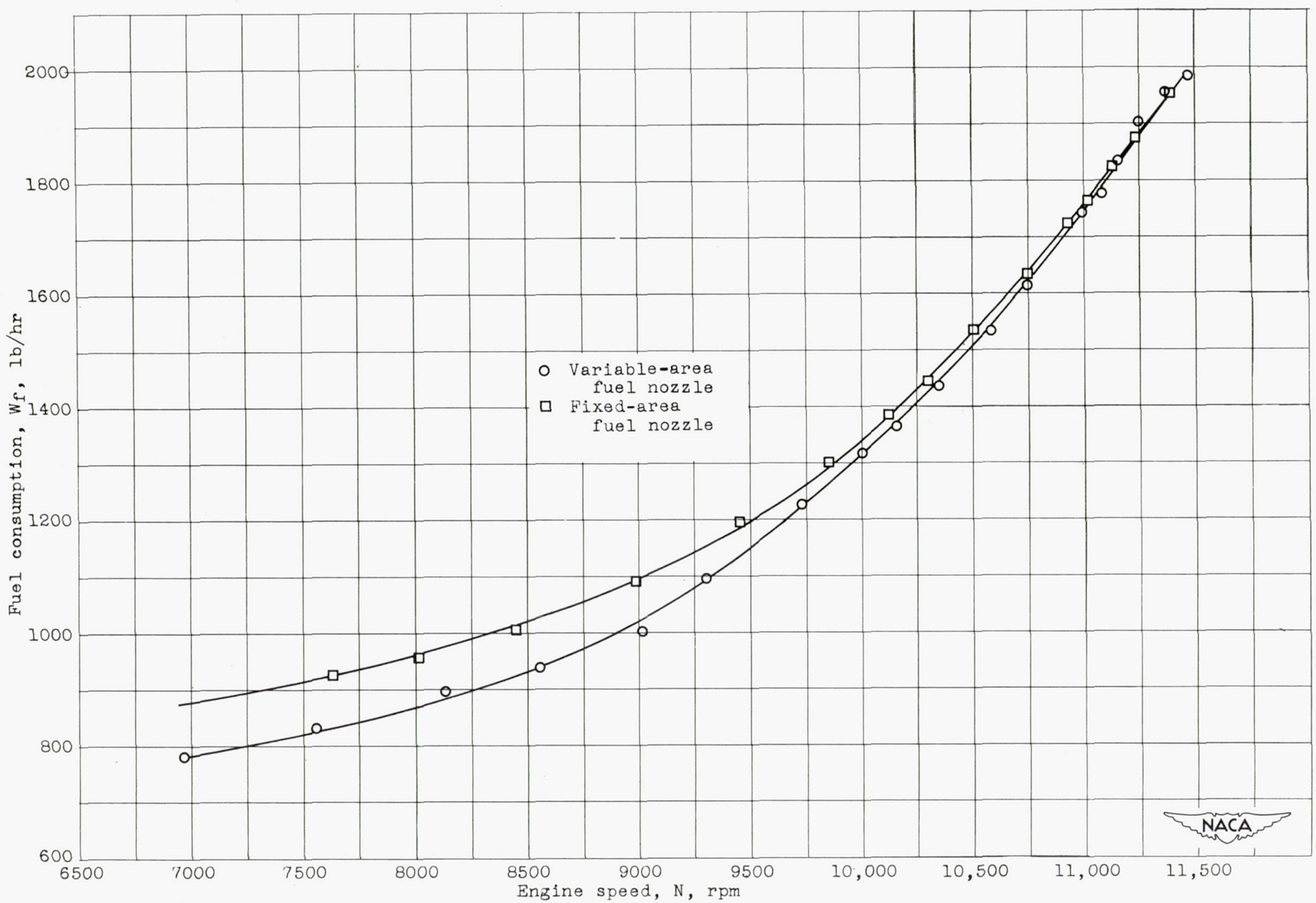


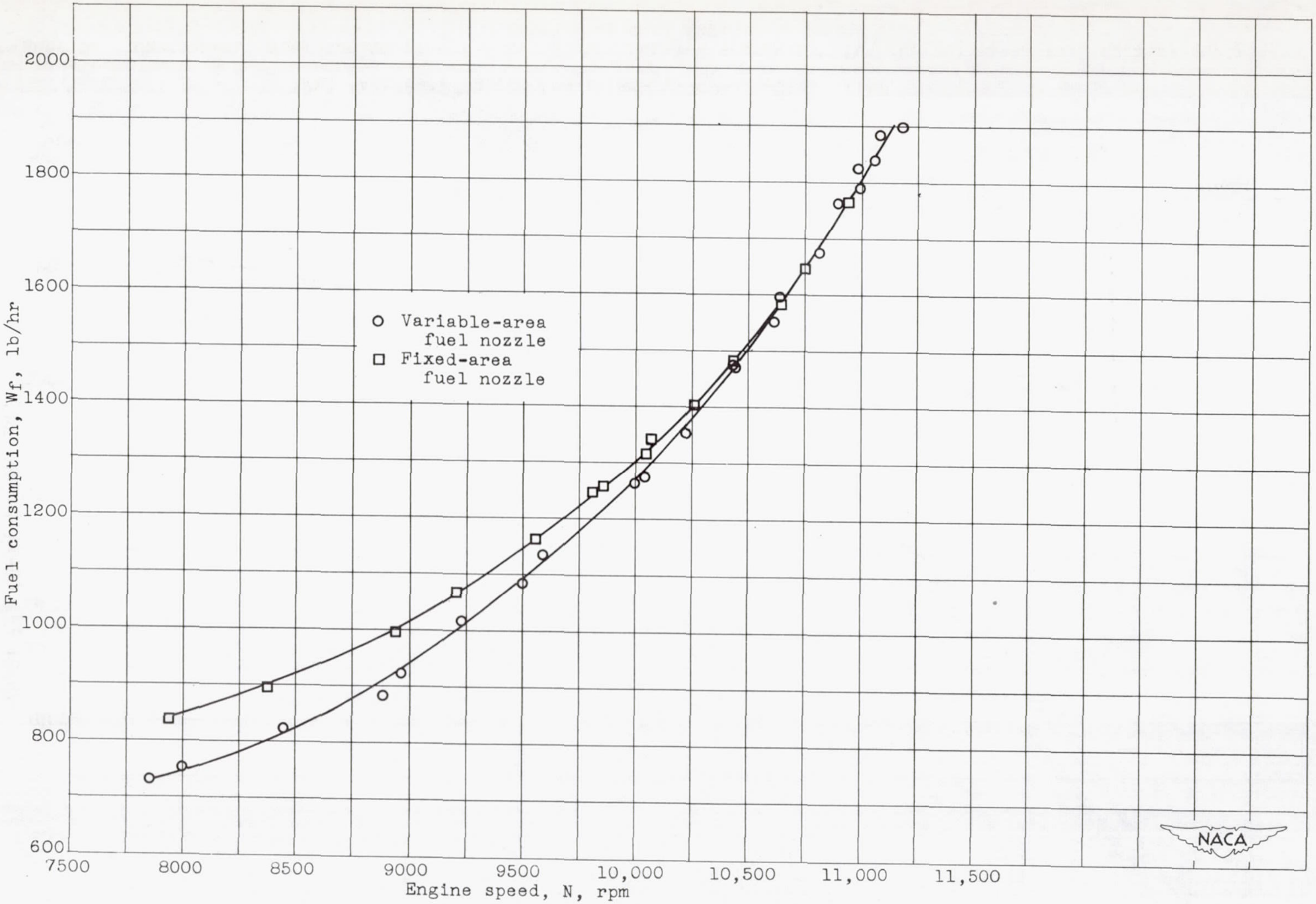
(a) Altitude, sea level; ram pressure ratio, 1.00.

Figure 5. - Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



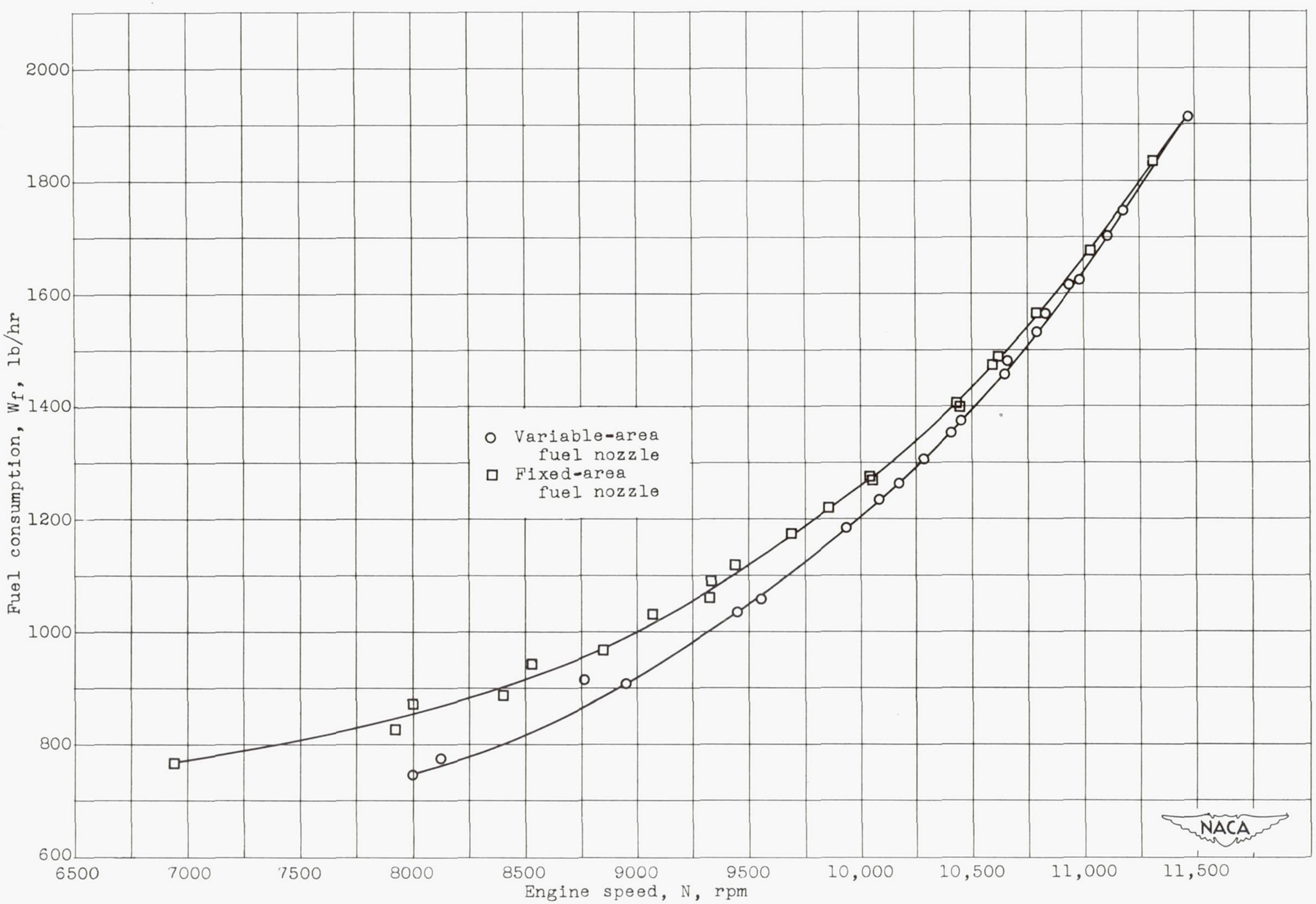
(b) Altitude, 25,000 feet; ram pressure ratio, 1.00.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



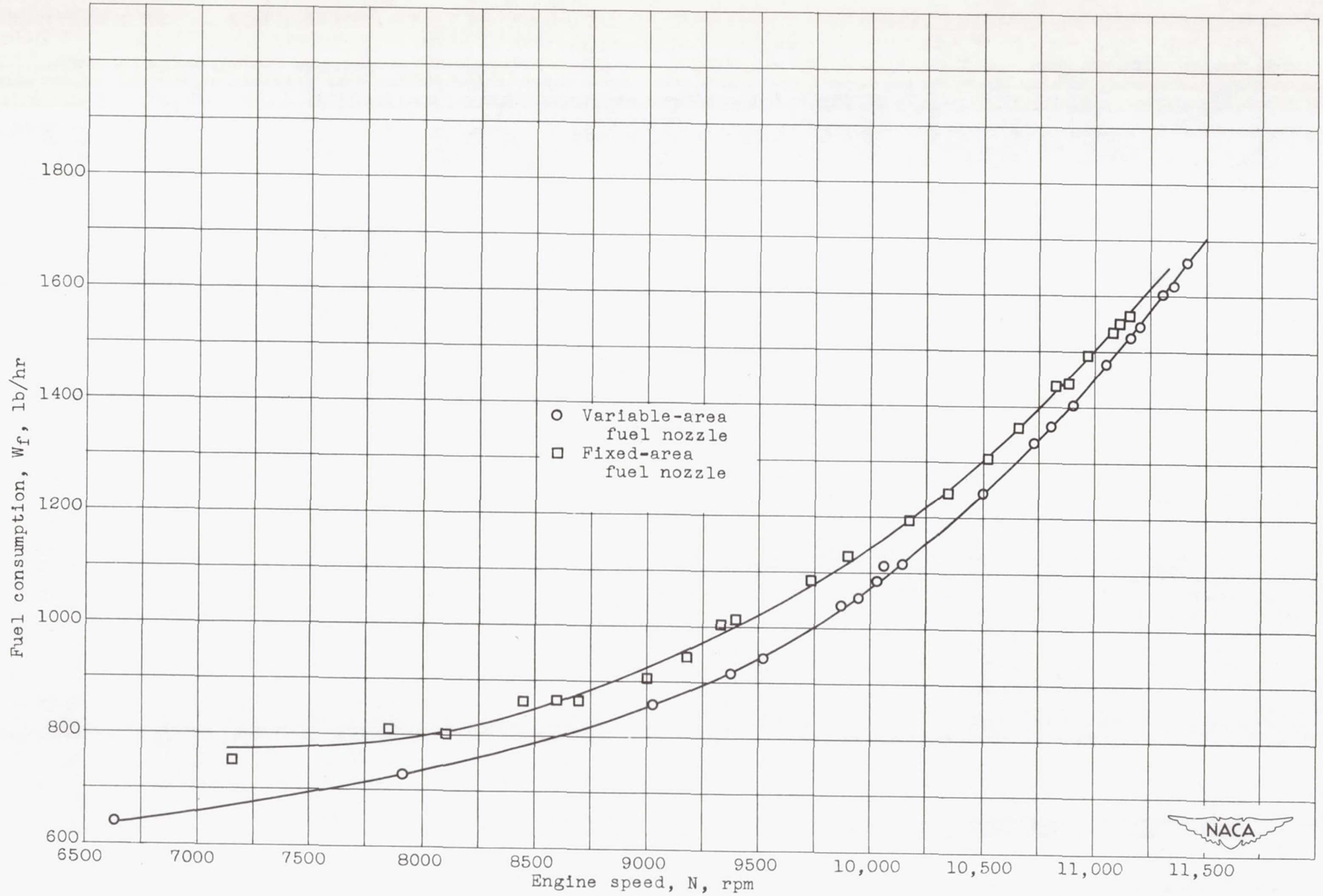
(c) Altitude, 30,000 feet; ram pressure ratio, 1.25.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



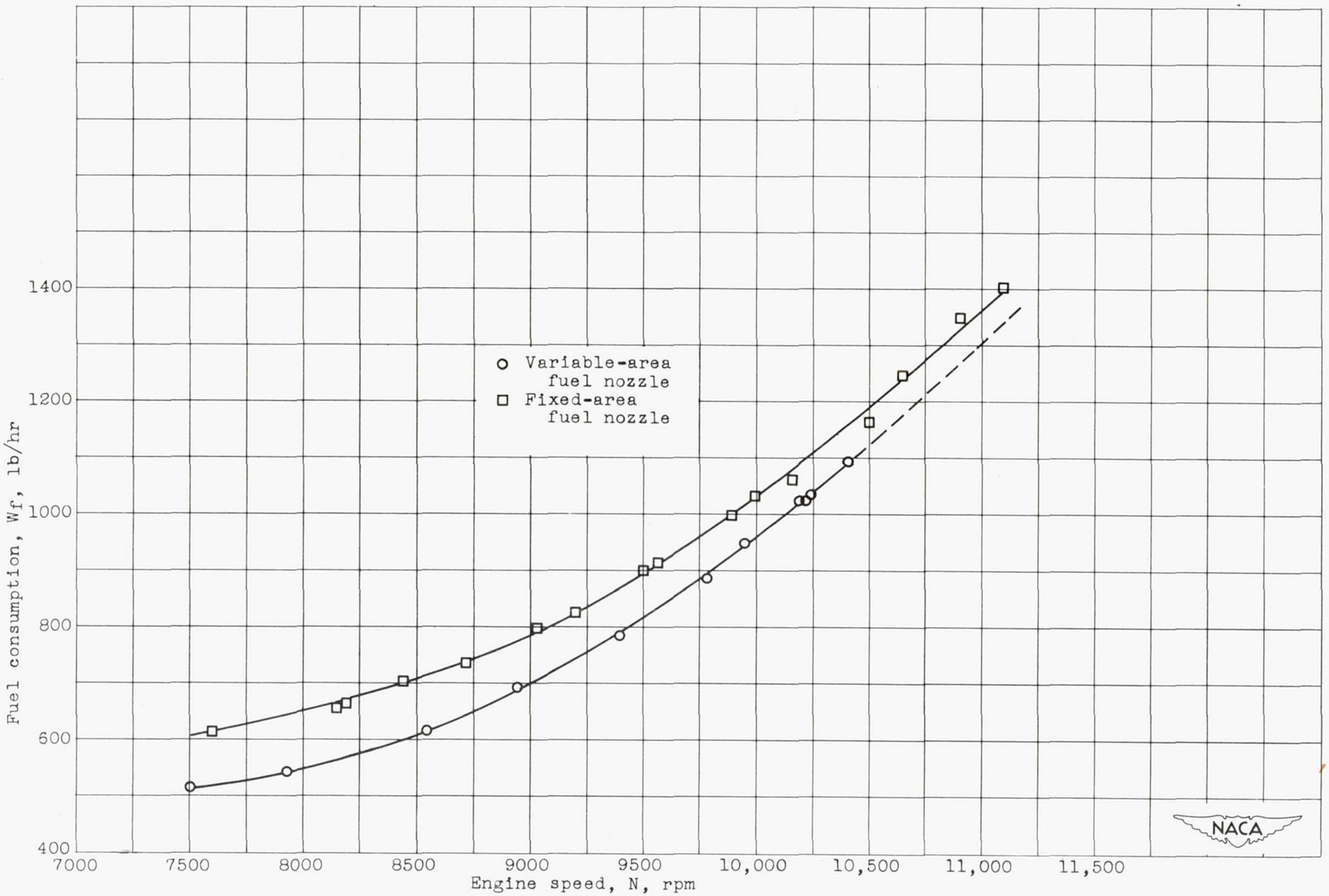
(d) Altitude, 30,000 feet; ram pressure ratio, 1.14.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



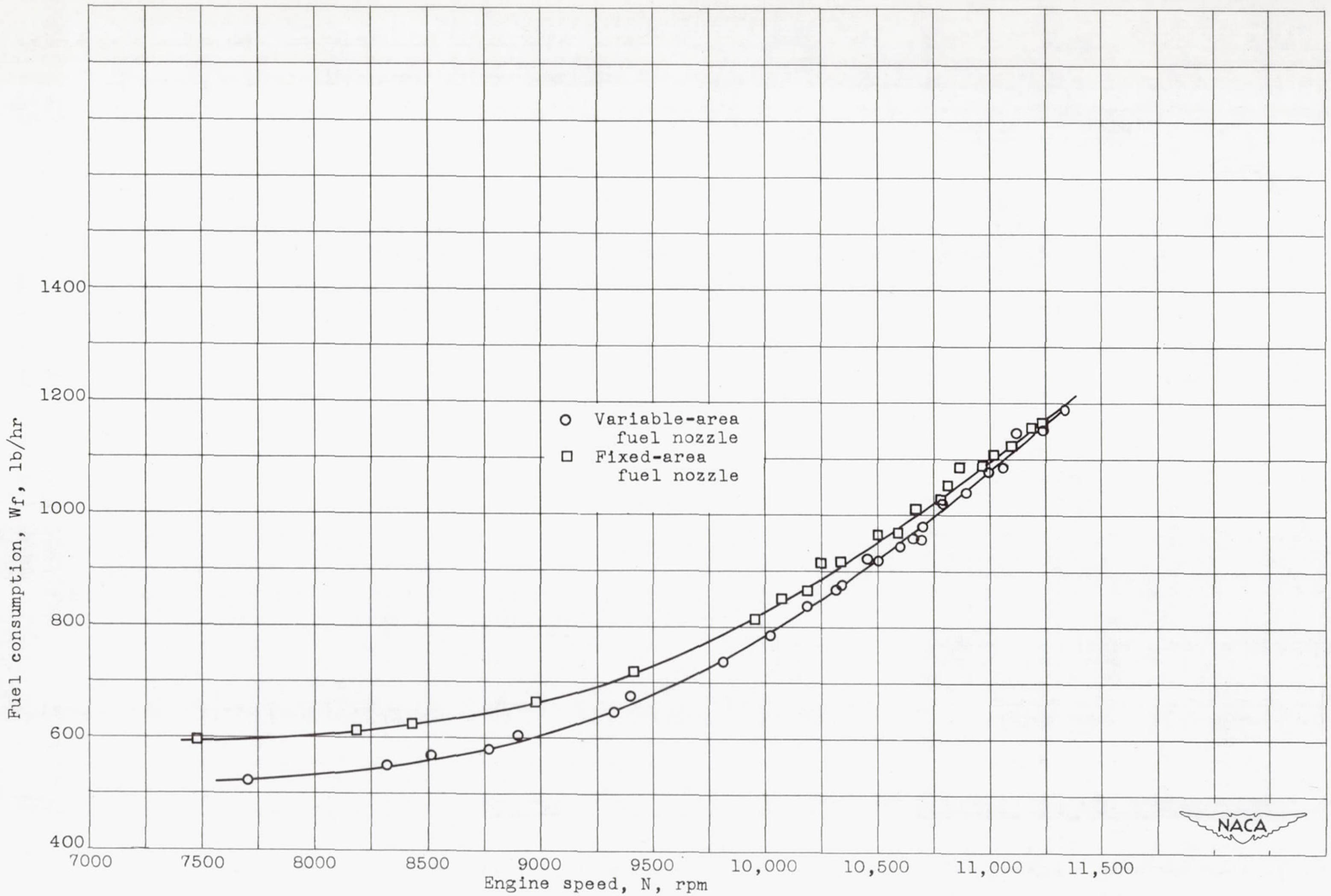
(e) Altitude, 30,000 feet; ram pressure ratio, 1.00.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



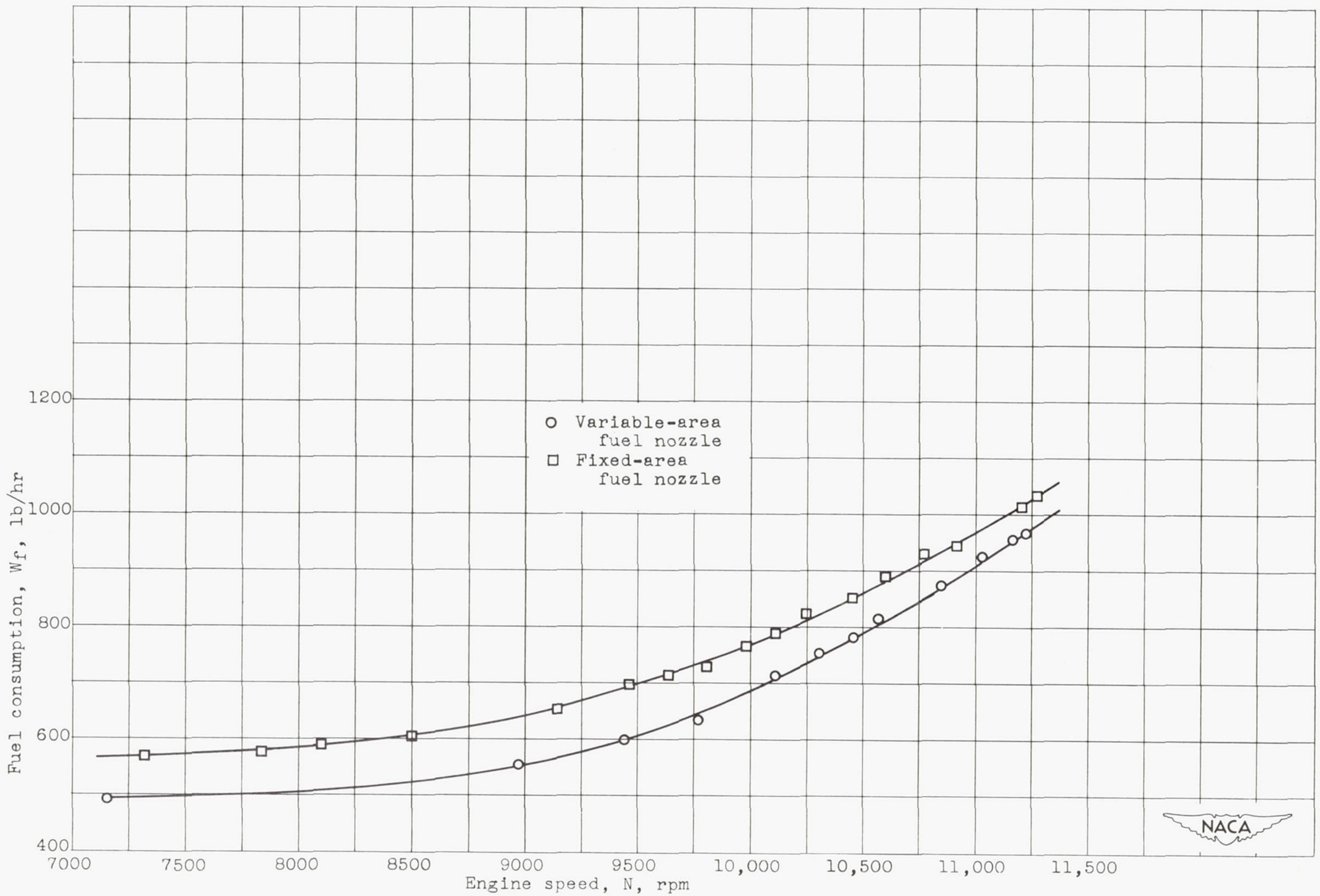
(f) Altitude, 40,000 feet; ram pressure ratio, 1.50.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



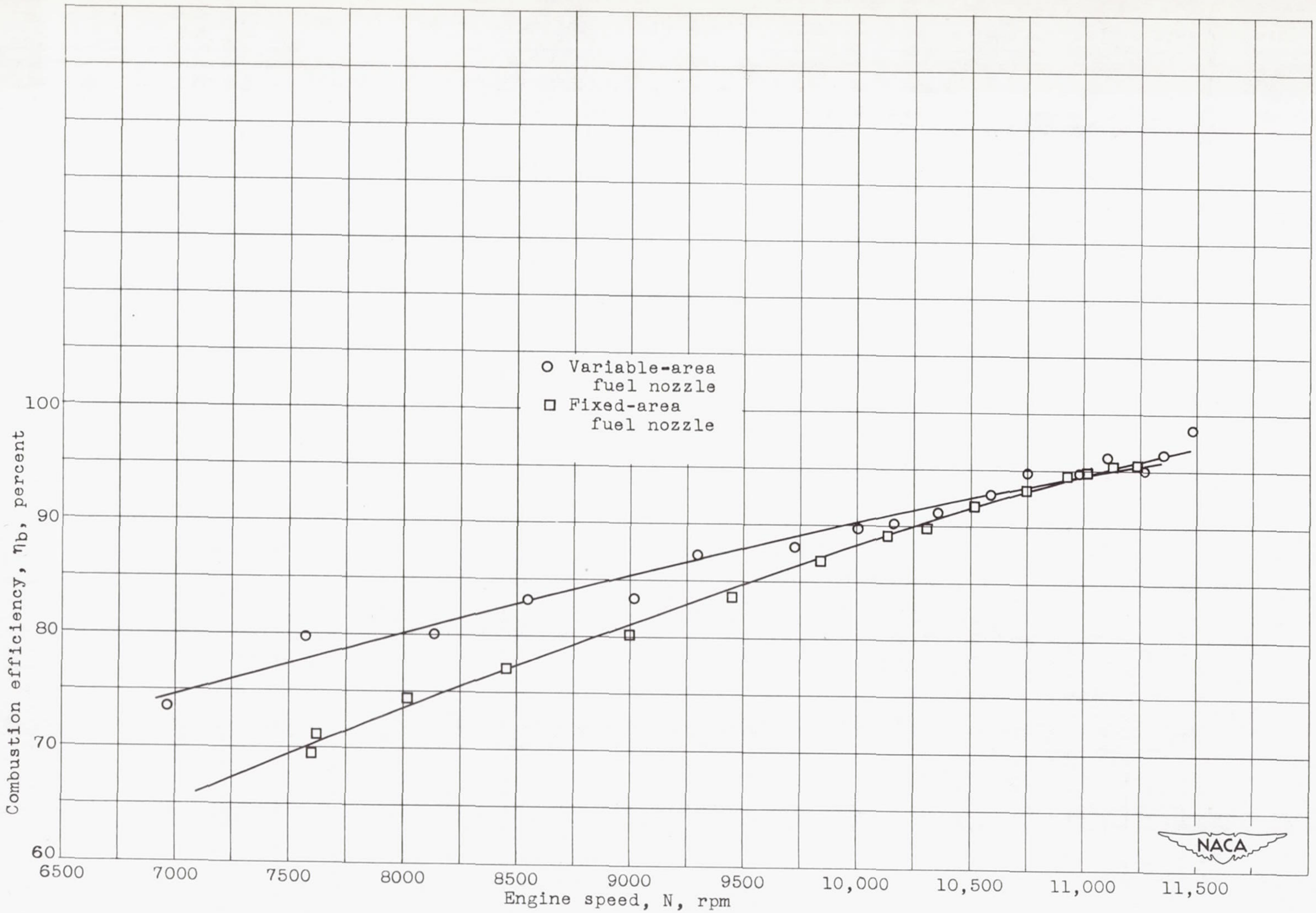
(g) Altitude, 40,000 feet; ram pressure ratio, 1.15.

Figure 5. - Continued. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



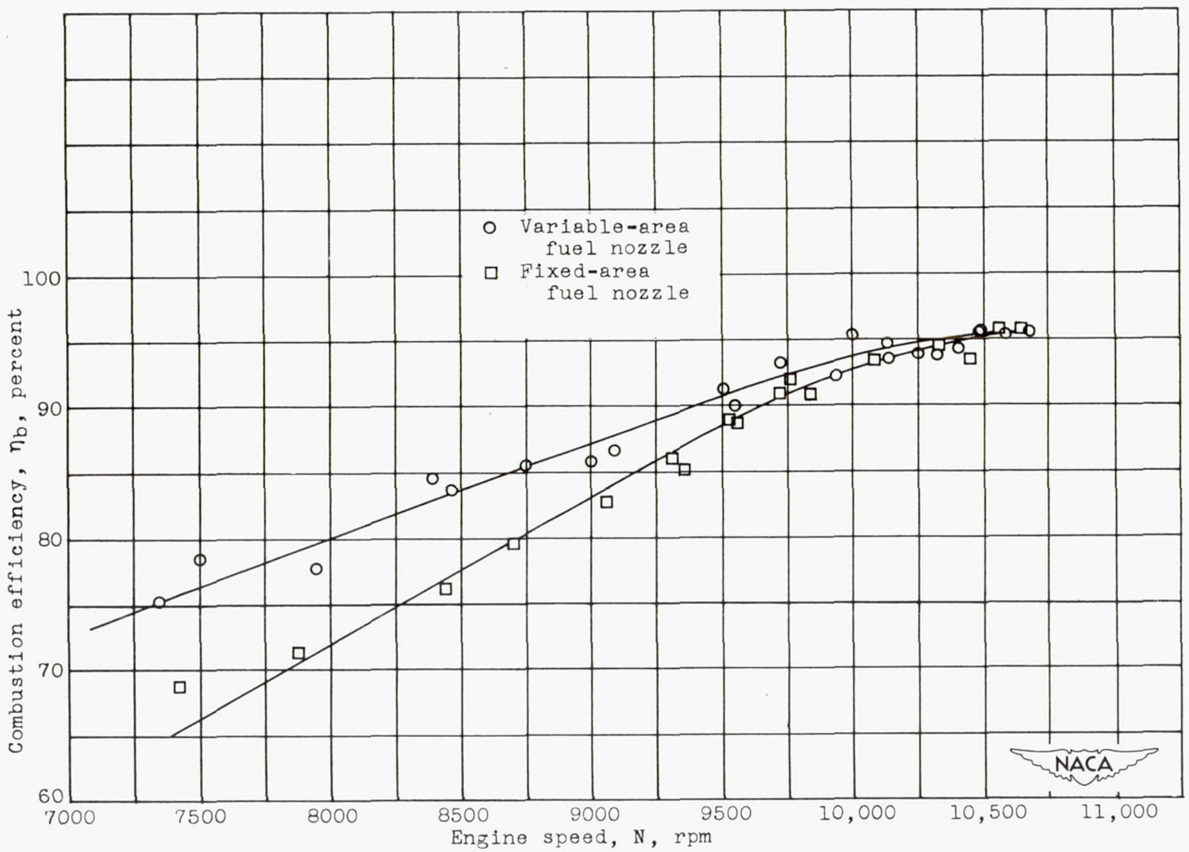
(h) Altitude, 40,000 feet; ram pressure ratio, 1.00.

Figure 5. - Concluded. Fuel consumption for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



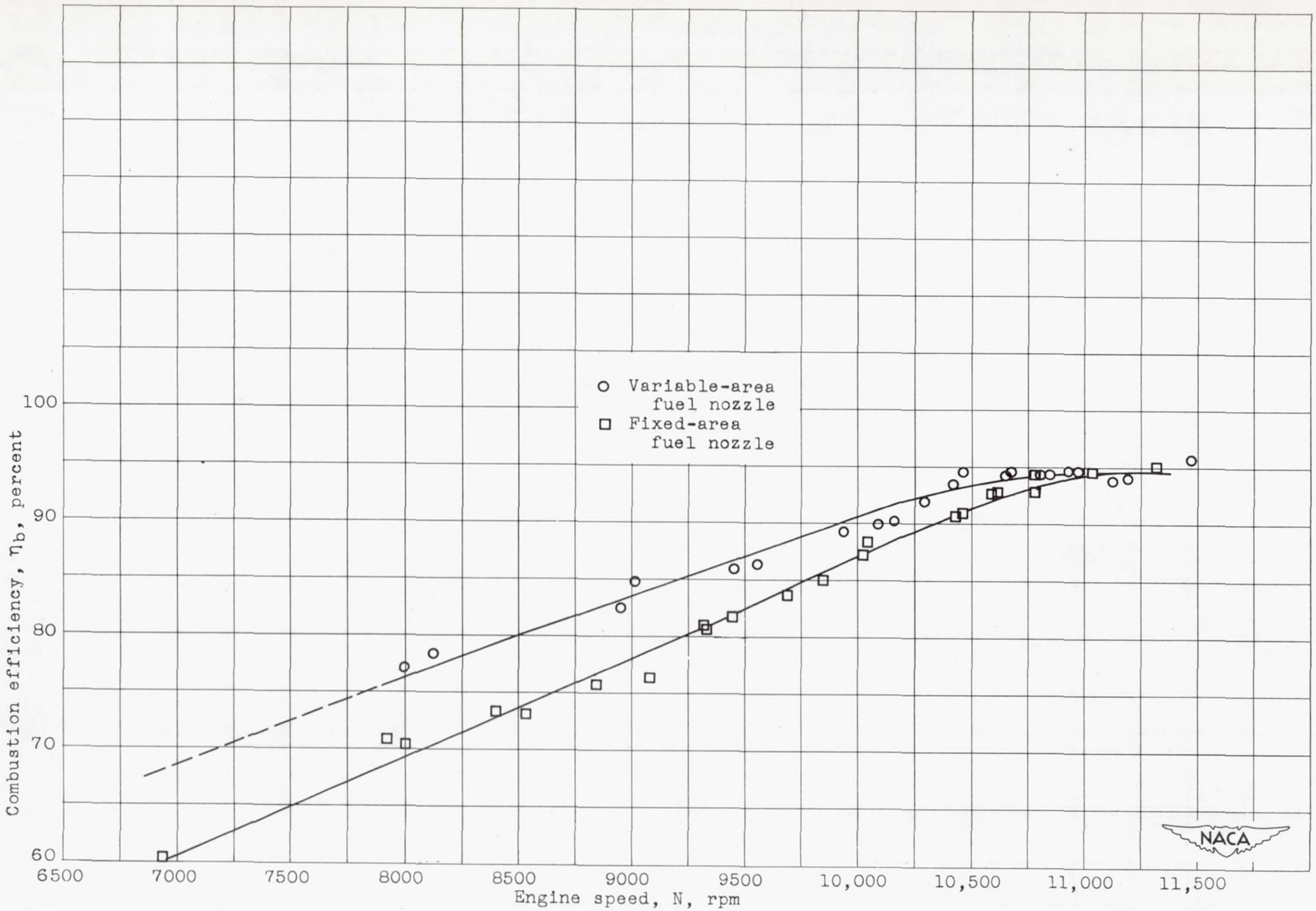
(a) Altitude, 25,000; ram pressure ratio, 1.00.

Figure 6. - Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



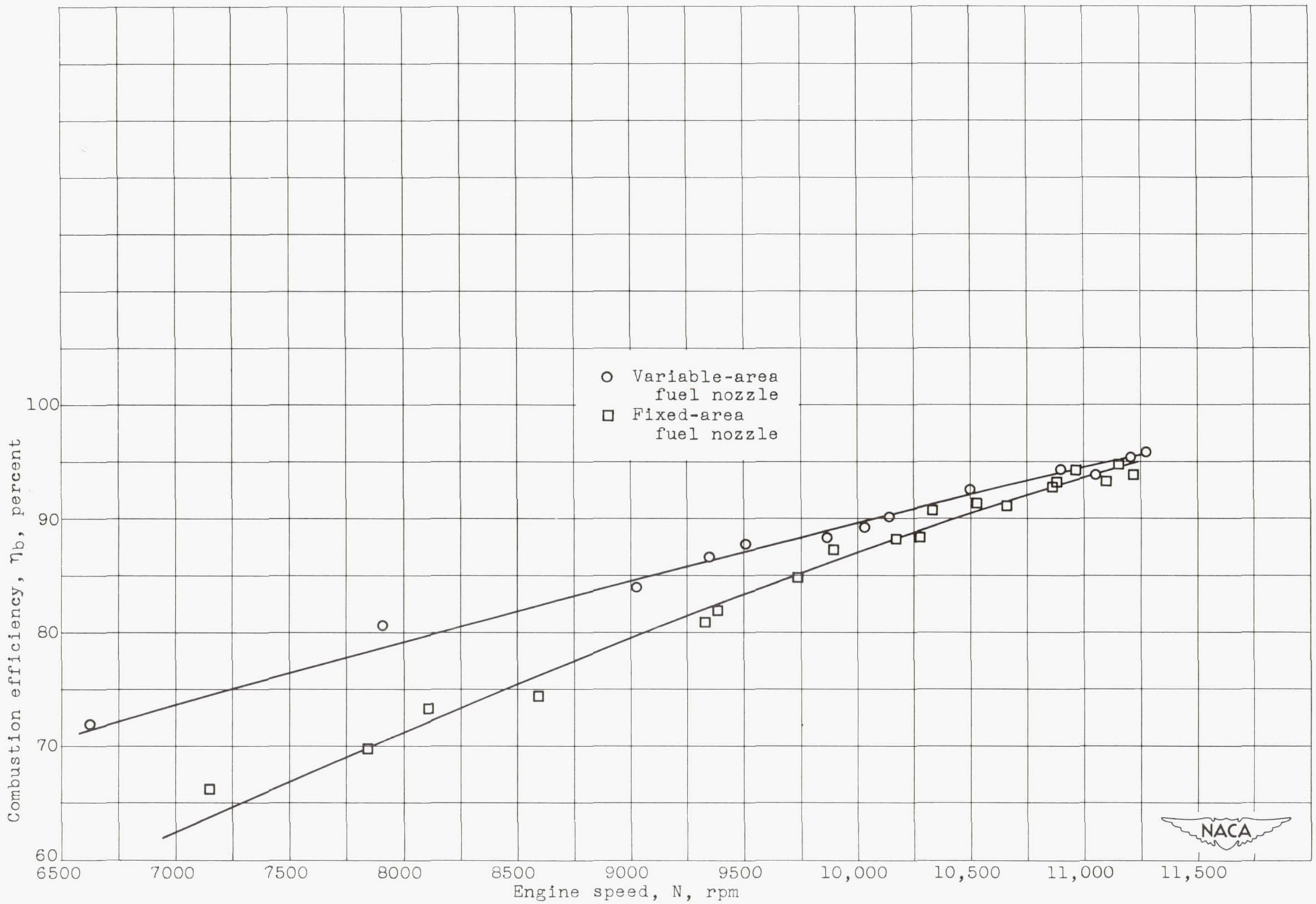
(b) Altitude, 30,000 feet; ram pressure ratio, 1.25.

Figure 6. - Continued. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



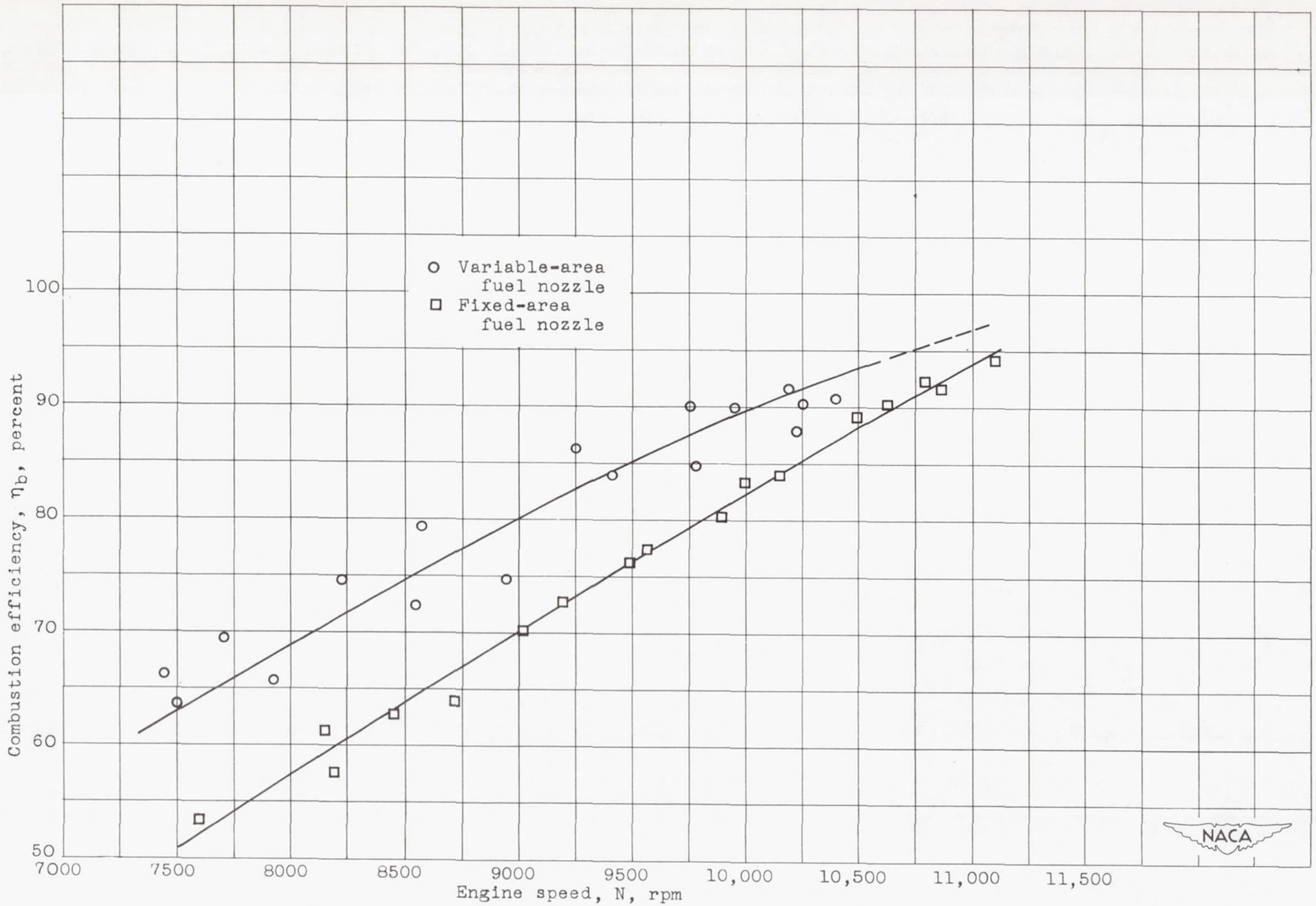
(c) Altitude, 30,000 feet; ram pressure ratio, 1.14.

Figure 6. - Continued. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



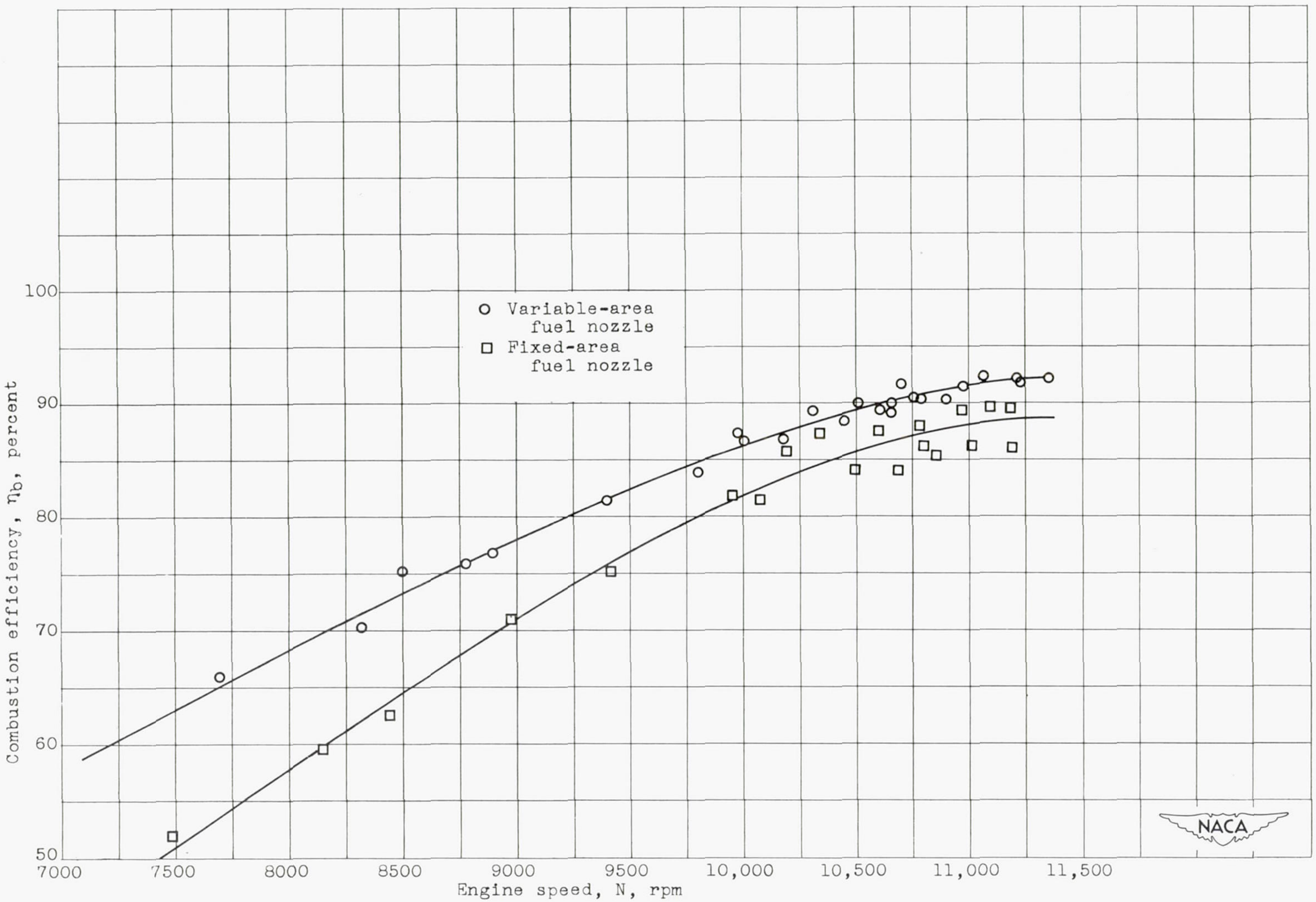
(d) Altitude, 30,000 feet; ram pressure ratio, 1.00.

Figure 6. - Continued. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



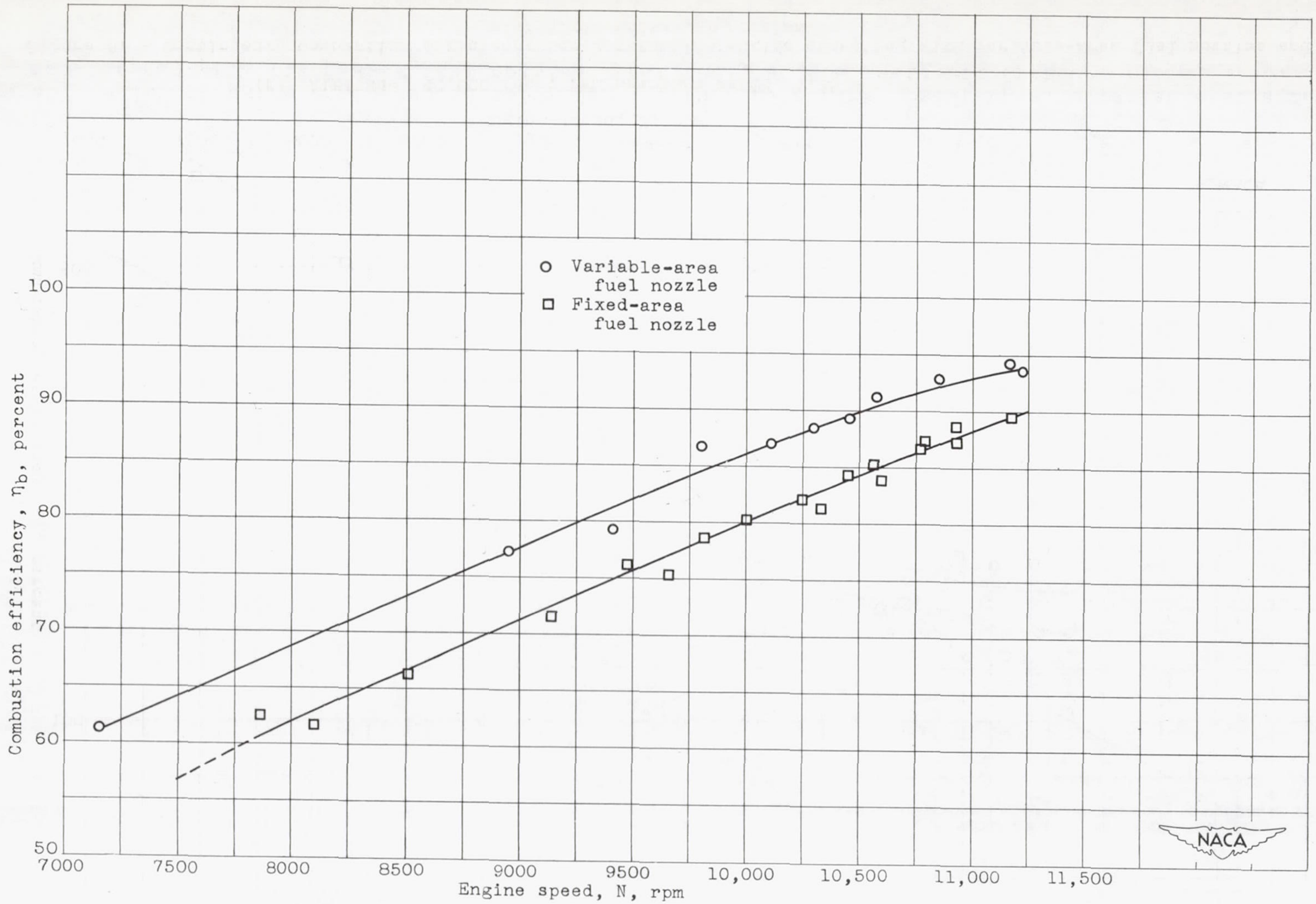
(e) Altitude, 40,000 feet; ram pressure ratio, 1.50.

Figure 6. - Continued. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



(f) Altitude, 40,000 feet; ram pressure ratio, 1.15.

Figure 6. - Continued. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.



(g) Altitude, 40,000 feet; ram pressure ratio, 1.00.

Figure 6. - Concluded. Combustion efficiency for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles.

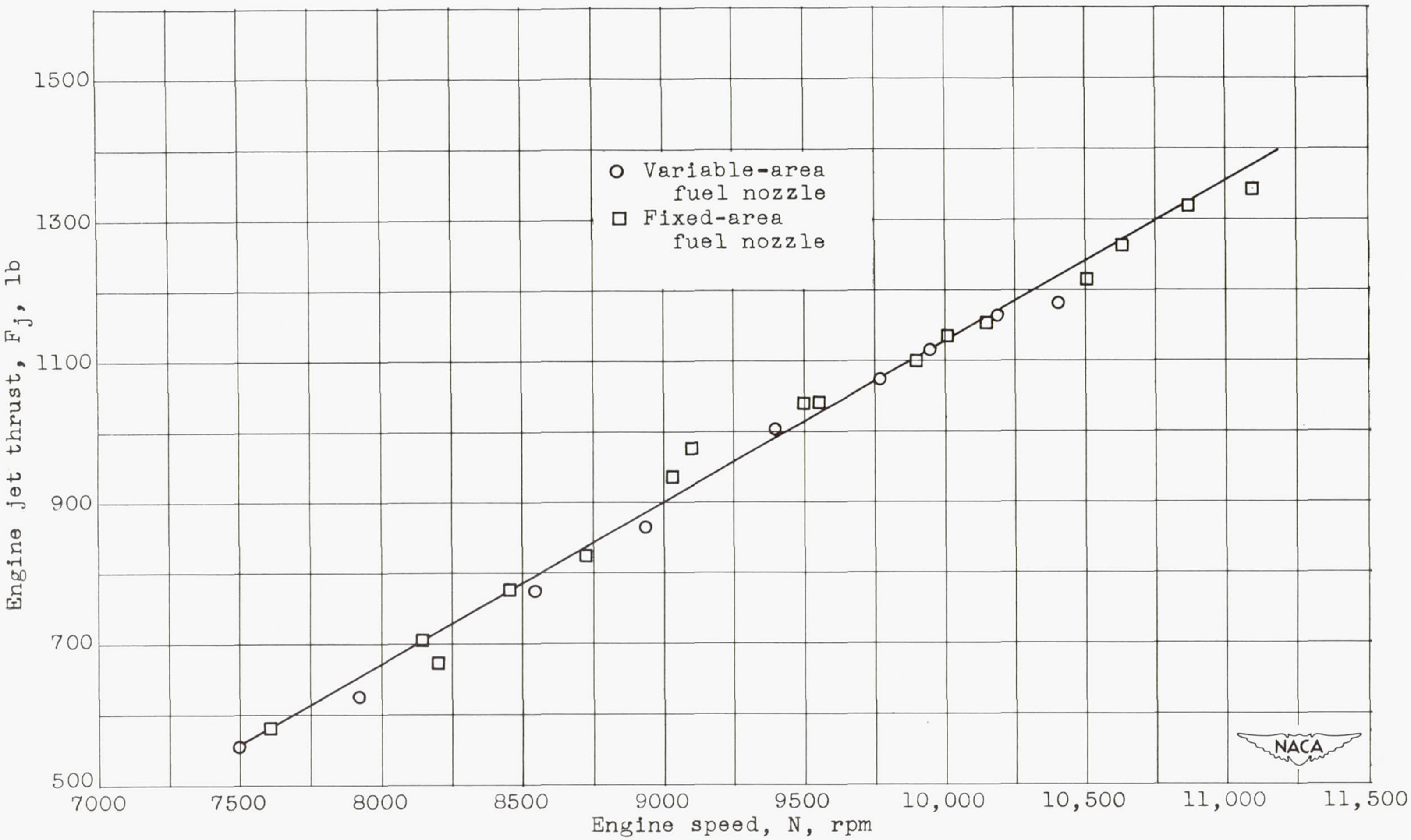


Figure 7. - Jet thrust - engine speed curve for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles. Altitude, 40,000 feet; ram pressure ratio, 1.50.

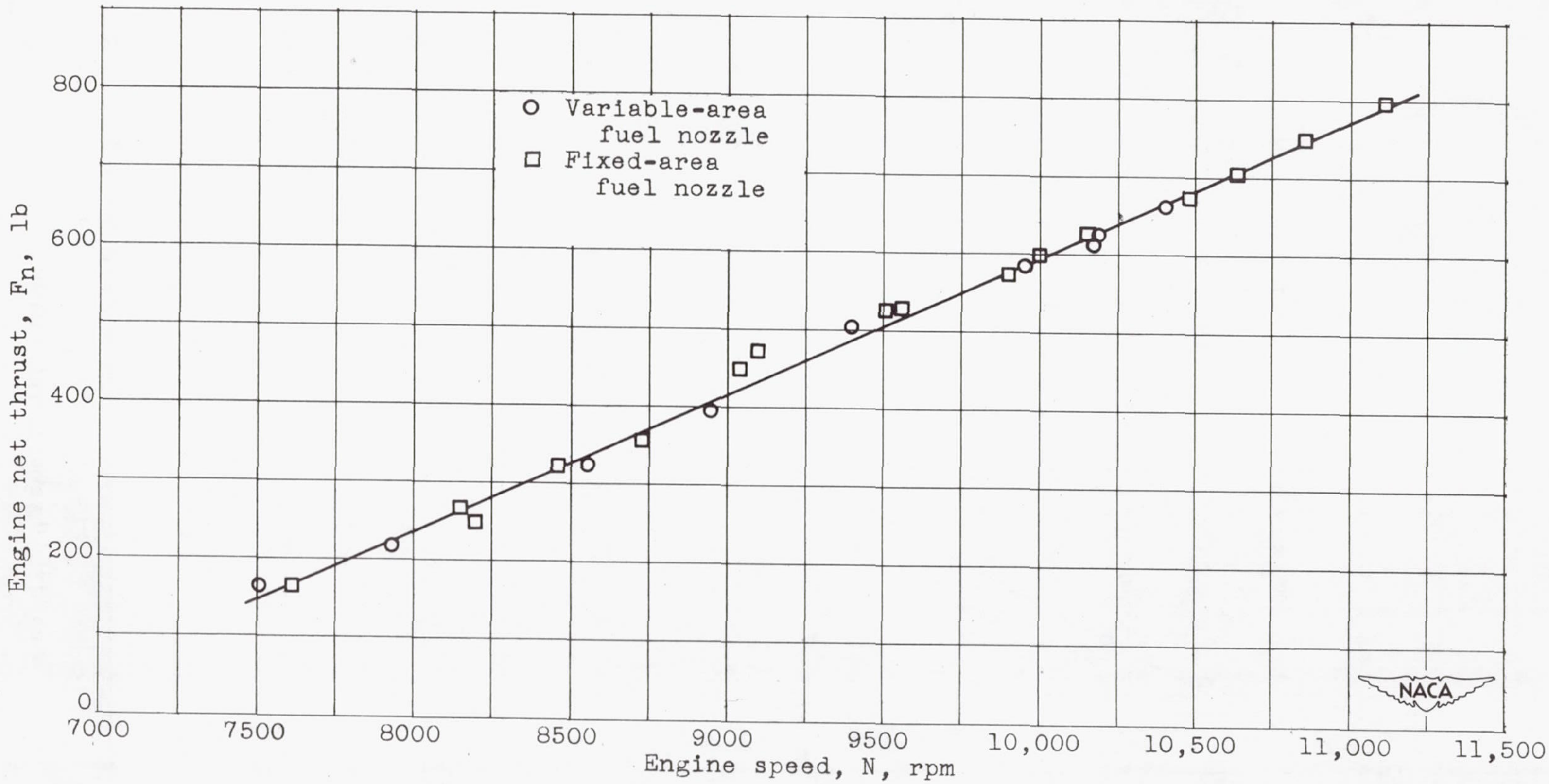


Figure 8. - Net thrust - engine speed curve for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles. Altitude, 40,000 feet; ram pressure ratio, 1.50.

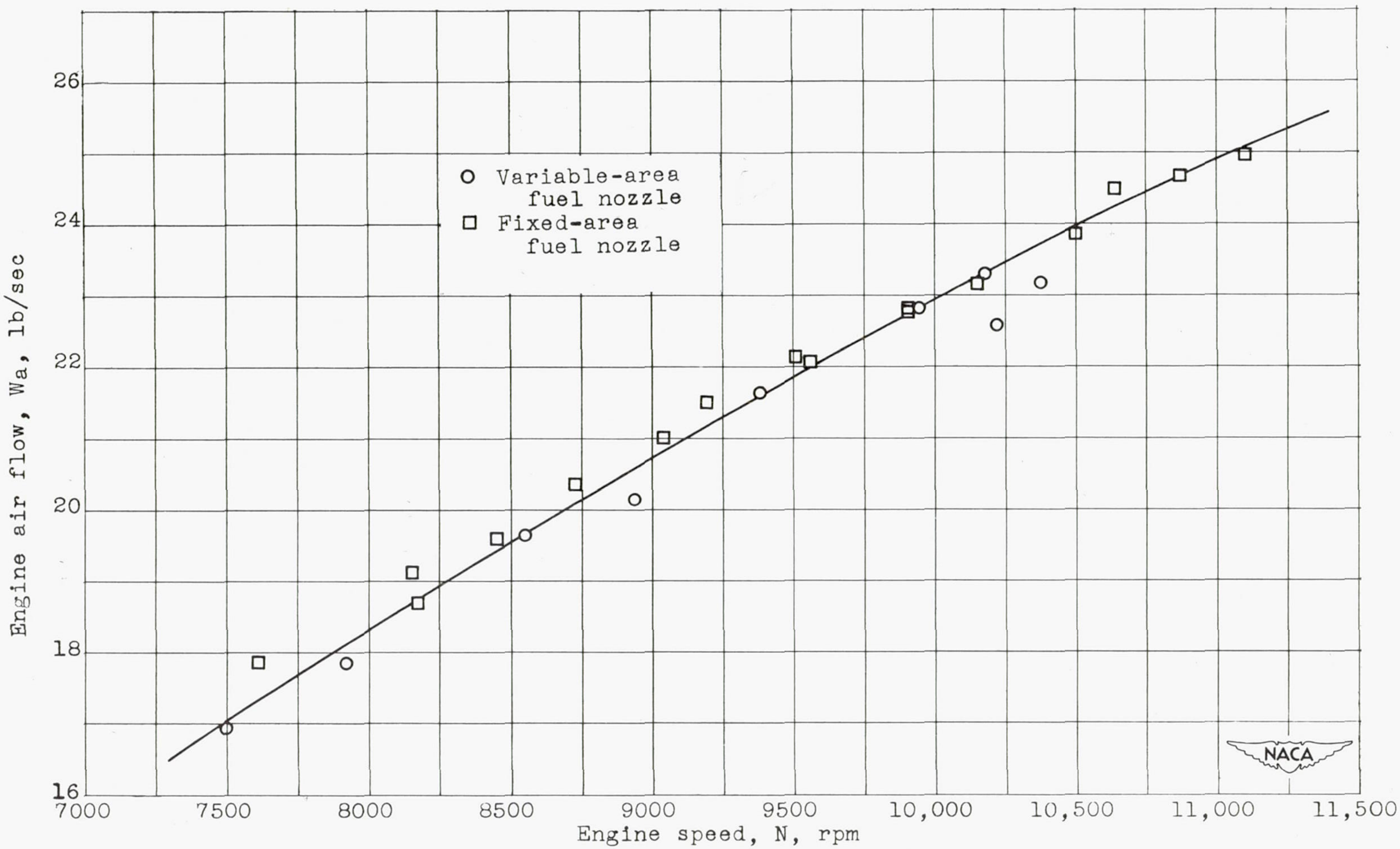


Figure 9. - Air-flow curve for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles. Altitude, 40,000 feet; ram pressure ratio, 1.50.

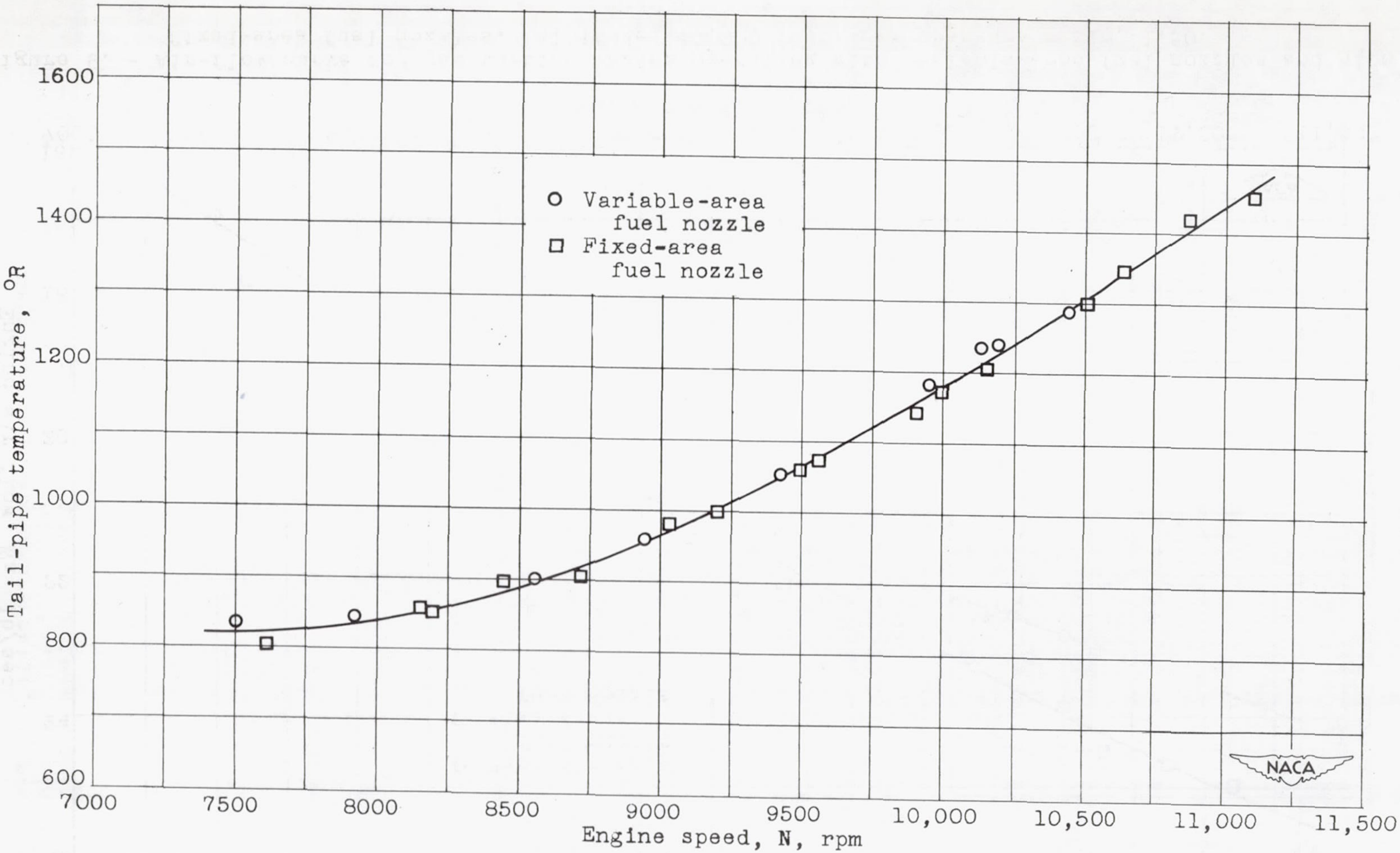


Figure 10. - Tail-pipe temperature curve for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles. Altitude, 40,000 feet; ram pressure ratio, 1.50.

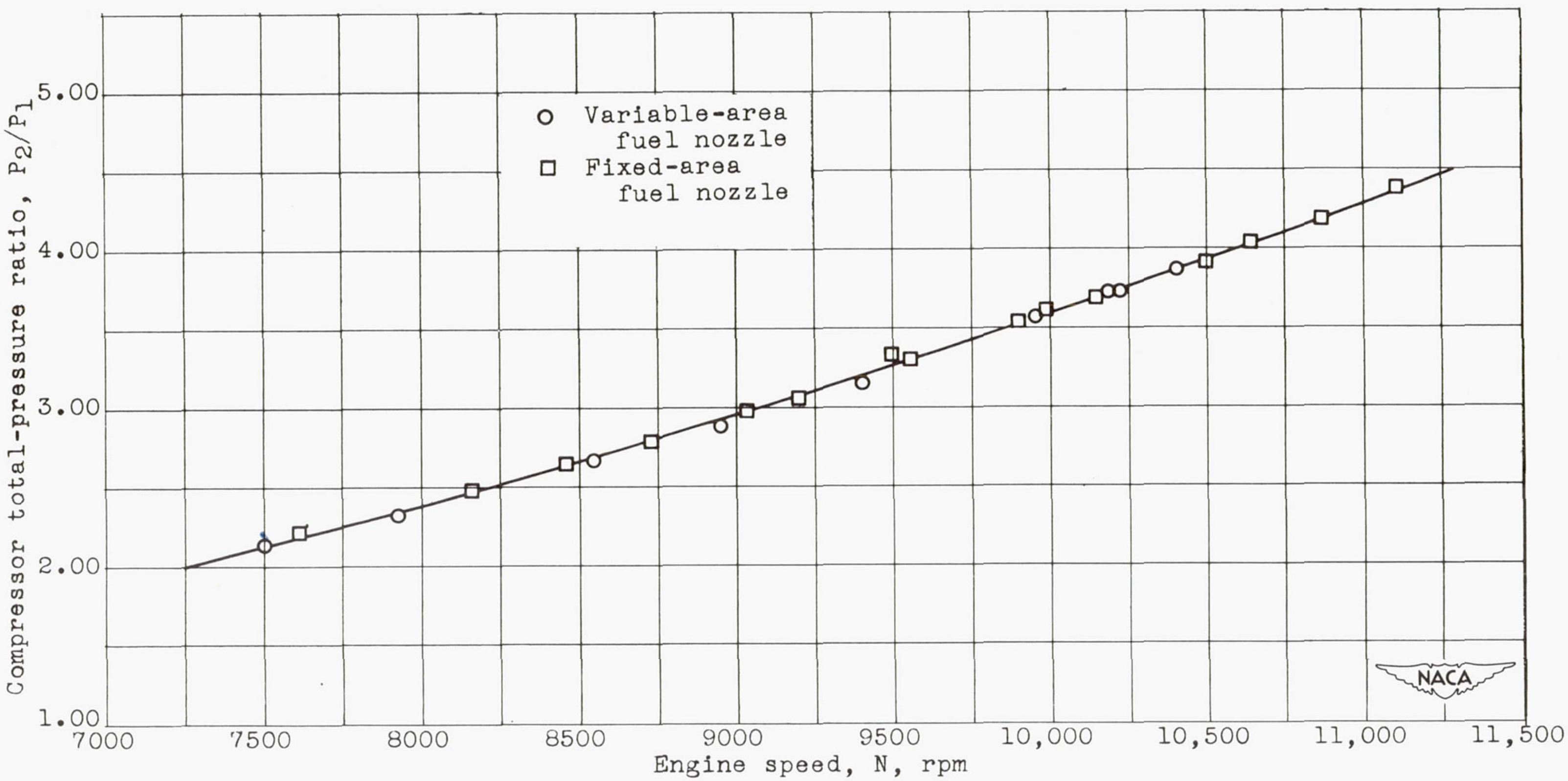


Figure 11. - Compressor total-pressure ratio curve for gas-turbine engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles. Altitude, 40,000 feet; ram pressure ratio, 1.50.

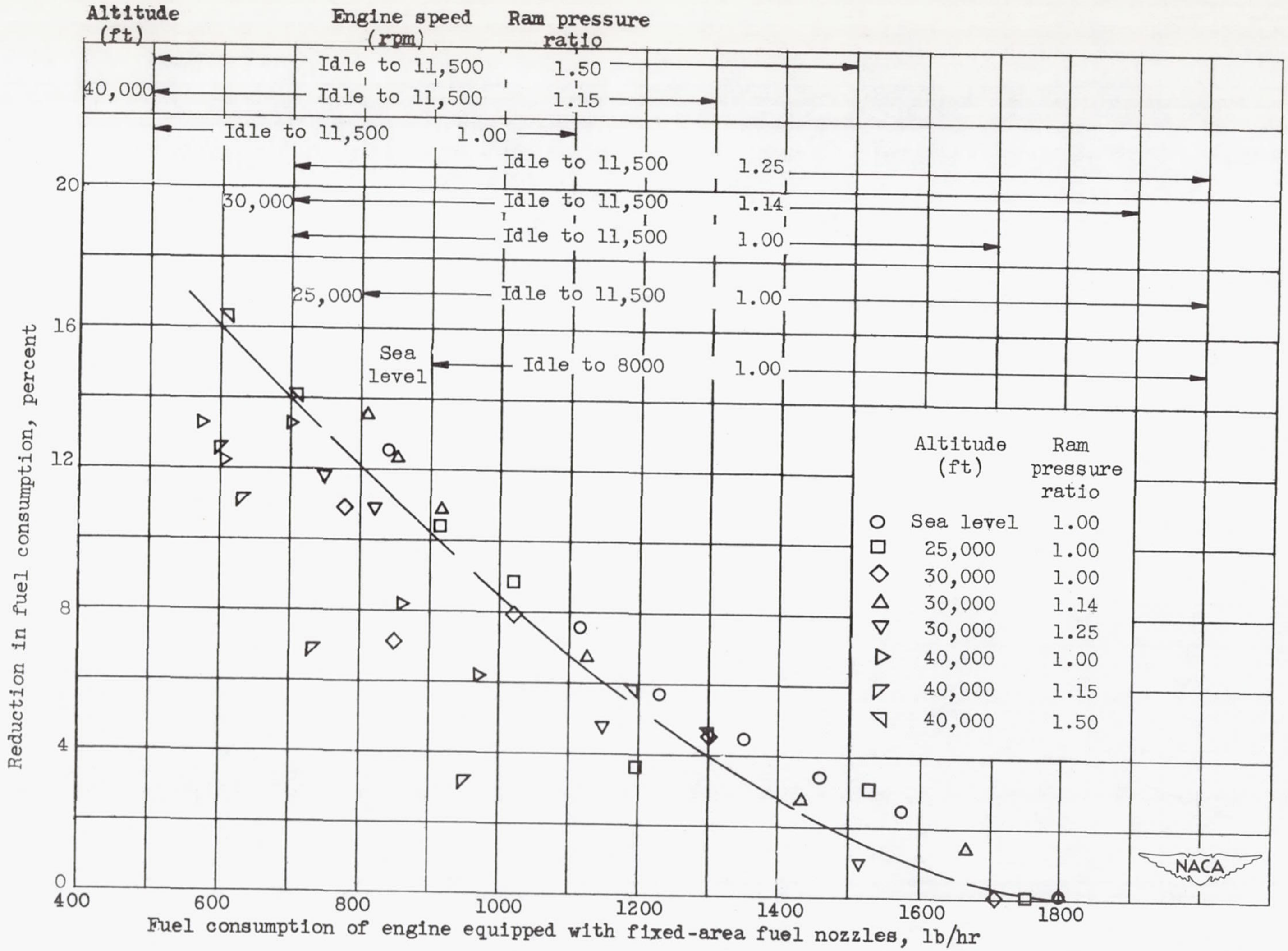


Figure 12. - Correlation of percentage reduction in fuel consumption resulting from use of variable-area fuel nozzles with fuel-flow rate. Gas-turbine engine equipped with variable-area nozzles compared with same engine equipped with fixed-area nozzle.