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RESEARCH MEMORANDUM

FLIGHT COMPARISON OF PERFORMANCE AND COOLING CHARACTERISTICS OF EXHAUST-EJECTOR INSTALLATION WITH EXHAUST-COLLECTOR-RING INSTALLATION

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SUMMARY

Flight and ground investigations have been made to compare an exhaust-ejector installation with a standard exhaust-collector-ring installation on air-cooled aircraft engines in a twin-engine airplane. The ground investigation showed that, whereas the standard engine would have overheated above 600 horsepower, the engine with exhaust ejectors cooled at take-off operating conditions at zero ram. The exhaust ejectors provided as much cooling with cowl flaps closed as the conventional cowl flaps induced when full open at low airspeeds. The propulsive thrust of the exhaust-ejector installation was calculated to be slightly less than the thrust of the collector-ring installation.

INTRODUCTION

As part of a program requested by the Bureau of Aeronautics, Navy Department, flight and ground investigations have been made on an exhaust-ejector installation in a twin-engine airplane. The exhaust ejectors were designed to increase the cooling-air flow through the engine and were installed in the left nacelle. The right engine was left in its standard configuration with an exhaust collector ring. The cooling-air pressure drop across the engine and the cylinder temperatures were measured in each installation to determine the improvement in engine cooling obtained with the exhaust ejectors. Brake horsepower and exhaust back pressure were measured for each installation to compare the over-all performance.

APPARATUS

A JM-1 airplane (serial No. 41-35541) (fig. 1) equipped with two R-2800-43 engines was used in the investigation. The R-2800-43 engine has a normal power rating of 1600 horsepower at a speed of 2400 rpm and a manifold pressure of 41 inches of mercury absolute; it has a military take-off rating of 2000 horsepower at 2700 rpm and 52 inches of mercury absolute. The left nacelle was modified by replacing the conventional exhaust-collector-ring installation with an exhaust-ejector installation (figs. 2 and 3). No modifications were made on the right nacelle (figs. 4 and 5).

The exhaust-ejector installation consisted of four two-stage ejectors on each side of the nacelle. Design data for exhaust nozzles and ejectors were obtained from references 1 to 4. The ejectors were designed with two stages in order that removal of the first stage would provide access to the engine accessories. Space limitations prevented the use of more than four ejectors on each side of the nacelle. Individual cylinder exhausts were therefore grouped in triple and twin stacks as follows:

Cylinder exhausts	
Outboard	Inboard
1, 17, 18	2, 3, 4
15, 16	5, 6
13, 14	7, 8
11, 12	9, 10

This grouping was selected because of space limitations and simplicity of construction at the expense of minimum valve overlap. Nozzles with an outlet diameter of 2 inches were welded to the end of each group of stacks.

The first-stage ejectors, shown mounted on the accessory skin panel in figure 6, are $14\frac{1}{4}$ square inches in cross-sectional area and $16\frac{7}{8}$ inches long (fig. 7). Flush with the outlets of the first stages are the second-stage ducts, which are 35 square inches in cross-sectional area and 20 inches long. Diffusers 9 inches long with an expansion ratio of 1.2 are welded to the ends of the second stages. Pivoted at the diffuser exits are controllable exit flaps 15 inches long that open approximately 20°. These flaps provide an outlet area of 210 square inches when closed and 350 square inches when fully open.

INSTRUMENTATION

Engine cylinder-baffle total pressures at the forward lip of the front-row cylinder baffles, engine cylinder-baffle static pressures in the rear curl of the rear-row cylinder baffles, and total and wall static pressures in the ejector ducts about 4 inches in front of the diffuser section (fig. 7) were measured with liquid manometers. The exhaust back pressures were obtained with flush orifices in the exhaust pipes at stations 13 and $2\frac{1}{4}$ inches from the exhaust ports of the front-row and rear-row cylinders, respectively. Exhaust back pressures were recorded from differential-pressure gages for the modified engine and from a liquid manometer for the standard engine.

Temperatures of the rear-spark-plug gasket, the ejectors, the carburetor screen, and the cylinders were measured by thermocouples and recorded by a flight-test recorder. The ejector thermocouples were located on the same rakes as the total-pressure tubes. A resistance-bulb thermometer was installed under the nose of the airplane for measuring free-stream air temperature.

Pressures for measuring altitude and indicated airspeed were provided by swiveling static-pressure and shrouded total-pressure tubes, located 1 chord length ahead of the right-wing tip. Engine charge-air flow was determined by carburetor metering-pressure data and air-box calibrations. Carburetor impact total-pressure and carburetor uncompensated metering-pressure differentials were obtained from sensitive absolute-pressure gages and differential-pressure gages, respectively. Engine manifold pressures were measured by sensitive absolute-pressure gages.

A position transmitter was used to measure cowl-flap openings. A deflecting-vane-type fuel flowmeter was installed in the fuel line between the carburetor and injection nozzle to measure fuel flow. Brake horsepower was determined from Pratt & Whitney torquemeters and sensitive tachometers.

All instruments were calibrated before installation in the airplane. With the exception of torque pressure, cowl-flap opening, and engine temperature, all data were recorded on photographic film.

SYMBOLS

The following symbols are used in the presentation of results. The numerical subscripts refer to stations on figure 7.

A	exhaust-nozzle or exhaust tail-pipe area, (sq ft)
c_p	specific heat at constant pressure, (Btu/(lb)(°F))
F_n	net thrust, (lb)
g	acceleration of gravity, (ft/sec^2)
H_1	total pressure in front of engine, (in. water gage)
H_3	total pressure in second-stage ejectors, (lb/sq ft absolute or in. water gage)
J	mechanical equivalent of heat, (778), (ft-lb/Btu)
M_a	mass of engine cooling-air flow, (slugs/sec)
M_c	mass of engine charge-air flow, (slugs/sec)
M_e	mass of engine exhaust-gas flow, (slugs/sec)
p_0	free-stream static pressure, (lb/sq ft absolute)
p_2	static pressure at cylinder-baffle exit, (lb/sq ft absolute or in. water gage)
p_e	engine exhaust back pressure, (in. Hg absolute)
p_m	engine manifold pressure, (in. Hg absolute)
Δp	average of engine cylinder-head and cylinder-barrel pressure drop (in. water)
Δp_h	engine cylinder-head pressure drop, (in. water)
q	free-stream dynamic pressure, (in. water)
R	gas constant for exhaust, (ft-lb)/(slug)(°F)
T_2	total temperature behind engine, (°R)
T_3	total temperature in ejectors, (°R)
T_e	exhaust-gas temperature, (°R)
T_h	cylinder-head temperature, (°F)

V_0 true airspeed, (ft/sec)

$V_{4,e}$ velocity at flap exit, ejector engine, (ft/sec)

$V_{4,s}$ velocity at flap exit, standard engine, (ft/sec)

$\overline{V}_e$ mean effective exhaust-gas velocity, (ft/sec)

γ ratio of specific heats of air, 1.4

η_p propeller efficiency

σ_0 ratio of free-stream air density to NACA standard sea-level air density

σ_2 ratio of air density at cylinder-baffle exit to NACA standard sea-level air density

METHOD OF CALCULATION

In order to determine the over-all performance of each installation, the net thrusts of the cooling air and the exhaust gas were calculated by the following compressible-flow equations. The net thrust is the change in momentum of the cooling air and the exhaust gases from true airspeed to their respective exit velocities.

For the modified engine,

$$F_n = (M_a + M_e)\ V_{4,e} - (M_a + M_c)\ V_0 \tag{1}$$

where

$$V_{4,e} = \sqrt{2gJc_pT_3\left[1 - \left(\frac{p_0}{H_3}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

In equation (1) the assumption was made that the fluid changed isentropically from the total pressure (fig. 8) and the total temperature in the ducts to free-stream static pressure and temperature. Any losses that might have occurred in the diffusers and through the closed cowl flaps were neglected.

For the standard engine,

$$F_n = M_aV_{4,s} + M_e\overline{V}_e - (M_a + M_c)\ V_0 \tag{2}$$

where

$$V_{4,s} = \sqrt{2gJc_pT_2\left[1 - \left(\frac{p_0}{p_2}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

and

$$\overline{V}_e = \frac{M_e gRT_e}{p_0A}$$

In equation (2) the total pressure was assumed equal to the static pressure behind the engine; therefore, in the calculation of cooling-air thrust an isentropic change of the fluid was assumed from the static pressure (fig. 9) and temperature behind the engine to free-stream static pressure and temperature. The losses through the closed cowl flaps were again neglected. The exhaust velocity was merely a function of exhaust-gas temperature, free-stream static pressure, and mass of engine exhaust-gas flow.

In order to determine the thrust that might be expected from jet exhaust stacks on a standard engine, calculations were based on the assumption that the exhaust stacks used with the ejectors were installed on the standard engine in place of the collector ring. The following equation was used:

$$F_n = M_aV_{4,s} + M_e\overline{V}_e - (M_a + M_c)\,V_0 \qquad (3)$$

where

$$\overline{V}_e = f\left(\frac{p_0A}{M_e}\right)$$

(See reference 4.)

With an assumed propeller efficiency of 0.85, the total net thrust horsepower available was calculated for each installation by

$$\text{thp} = \frac{F_nV_0}{550} + \text{bhp}\;\eta_p \qquad (4)$$

PROCEDURE AND DISCUSSION

Cooling-Blower Investigation

In order to determine the relation between cooling-air flow and engine pressure drop, a portable engine-cooling blower was used. This blower was set up in front of each engine (fig. 10); the blower outlet was sealed to the cowling inlet by a rubber casing and the blower was operated at various air flows. Engine pressure drop was multiplied by the density ratio at the cylinder-baffle exit to include the effect of altitude and engine temperature on cooling-air flow. Engine cooling-air pressure drop and temperatures behind the engines were measured in flight and used in conjunction with the data of figure 11 to obtain cooling-air flow under flight-test conditions.

Ground Investigation

A ground investigation was made to determine the cooling characteristics of each installation at a condition of zero ram. The results of this investigation at a free-air temperature of 35° F with cowl flaps open are shown in figure 12 where the available cylinder-head pressure drop $\sigma_0 \Delta p_h$, fuel-air ratio for both engines, and the maximum cylinder-head temperature T_h for the exhaust-ejector engine are plotted against brake horsepower. If permitted to stabilize, the cylinder-head temperatures on the standard engine would have exceeded the manufacturer's maximum limit of 500° F at test conditions using about 600 brake horsepower or more; therefore, no cylinder-head temperature data for this engine were obtained. As shown in figure 12, an increase in brake horsepower produces a greater increase in head pressure drop in the modified engine than in the standard engine. Despite slightly leaner fuel-air ratios, the modified engine cooled far better than the standard engine for all powers. For example, at take-off conditions (maximum power) with cowl flaps full open, the modified-engine installation provided a cylinder-head pressure drop of 5.5 inches of water; whereas the cowl flaps on the standard engine induced a pressure drop of only 2.5 inches of water. With a cylinder-head pressure drop of 5.5 inches of water, the maximum cylinder temperature for take-off conditions was 480° F.

Flight Investigation

The available cooling-air cylinder-head pressure-drop ratios $\Delta p_h/q$ in flight for standard and modified engines are shown in figure 13 at altitudes of 5,000, 10,000, and 15,000 feet. In order to compare the installations, the curves for the standard installation were superimposed, without test points, over those for the ejector installation.

The standard engine had a constant pressure-drop ratio of approximately 0.48 with cowl flaps full open and about 0.23 with cowl flaps closed. This pressure-drop ratio appeared to be constant for all altitudes. The pressure drop available on the modified engine was a function of brake horsepower. The ejector pumping action fell off slightly with altitude because of the increased specific volume of cooling air at higher altitudes. For a given horsepower the pressure-drop ratio was higher at low airspeeds, such as those encountered during climb or take-off. At normal rated conditions, an altitude of 5000 feet and an indicated airspeed of approximately 165 miles per hour, (q = 12.0 in. of water) the pressure-drop ratio was 0.62 with flaps open and 0.40 with flaps closed. Thus at 5000 feet and a low airspeed, the ejectors induced nearly as much pressure drop across the engine with exit flaps closed as conventional cowl flaps that are full open.

The average cylinder-head temperatures are plotted against free-stream dynamic pressure q for normal rated and maximum cruise powers at an altitude of 5000 feet in figure 14. These curves show that, at 1460 brake horsepower and at a low airspeed corresponding to a dynamic pressure q of about 12.0 inches of water, the modified engine with cowl flaps closed runs about 15° F cooler than the standard engine with cowl flaps full open.

The exhaust back pressures measured on each engine at 5000 feet are shown in figure 15. Because of the restricted exhaust nozzles, the back pressure is considerably higher in the modified engine than in the standard engine. Separate curves are shown with cowl flaps open and closed for the modified engine because the exhaust gas is discharged through the exit flaps, which affect the static pressure at the exhaust-stack outlet. Engine calibration curves at an altitude of 5000 feet are given for the standard and modified engines in figure 16 from which the effect of back pressure on engine performance may be seen. A loss of 100 brake horsepower existed for the modified engine at 2400 rpm. The results of thrust calculations at each altitude are shown in figures 17 and 18. These curves show the drag, or thrust, of the cooling air and exhaust gases for each type of installation.

The following table shows the total net thrust horsepower for both installations with cowl flaps closed at an altitude of 5000 feet and a true airspeed of 265 miles per hour, with each engine operating at the same speed and manifold pressure:

Engine	bhp	F_n (lb)	thp
Standard	1560	-31	1300
Modified	1460	65	1286
Standard with jet stacks	1460	162	1355

The data show that the loss of 100 brake horsepower due to high exhaust back pressure is almost all regained by the momentum increase of the cooling air on the modified engine and also that more thrust may be obtained from a standard engine with jet exhaust stacks than from the exhaust-ejector installation. At low airspeeds the cowl flaps on the standard engine must be open to provide sufficient engine cooling and thus they increase the form drag. Inasmuch as no form-drag measurements were made in flight, a quantitative thrust analysis at low airspeeds could not be made.

Representative temperature and pressure patterns for the two installations under similar operating conditions are shown in figures 19 and 20. No serious effect on temperature and pressure distributions resulted from the use of the exhaust-ejector installation.

SUMMARY OF RESULTS

From comparative flight and ground investigations of an exhaust-ejector installation and a standard exhaust-collector-ring installation on air-cooled engines in a twin-engine airplane, the following results were obtained:

1. At take-off operating conditions at zero ram on the ground, the ejectors provided a pressure drop across the engine of 5.5 inches of water with the exit flaps full open, which was sufficient to cool the engine 20° F below the manufacturer's limit of 500° F at a free-air temperature of 35° F; whereas the standard engine would have overheated at above 600 brake horsepower.

2. At low airspeeds, such as encountered during take-off and climb, the ejectors pumped approximately as much cooling air across the engine with the exit flaps closed as conventional cowl flaps pumped when full open.

3. The propulsive thrust of the exhaust-ejector installation was calculated to be slightly less than the thrust of the collector-ring

installation because the thrust obtained from the ejectors was slightly less than the loss in brake horsepower due to high exhaust back pressure caused by the restricted outlet area of the exhaust stacks.

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3. Marquardt, R. E.: A Theoretical and Experimental Investigation of Exhaust Ejectors for Cooling at Low Speeds. NACA ACR No. 3G05, 1943. (Classification changed from "Confidential" to "Restricted", April 1946.)

4. Pinkel, Benjamin, Turner, L. Richard, and Voss, Fred: Design of Nozzles for the Individual Cylinder Exhaust Jet Propulsion System. NACA ACR, April 1941.

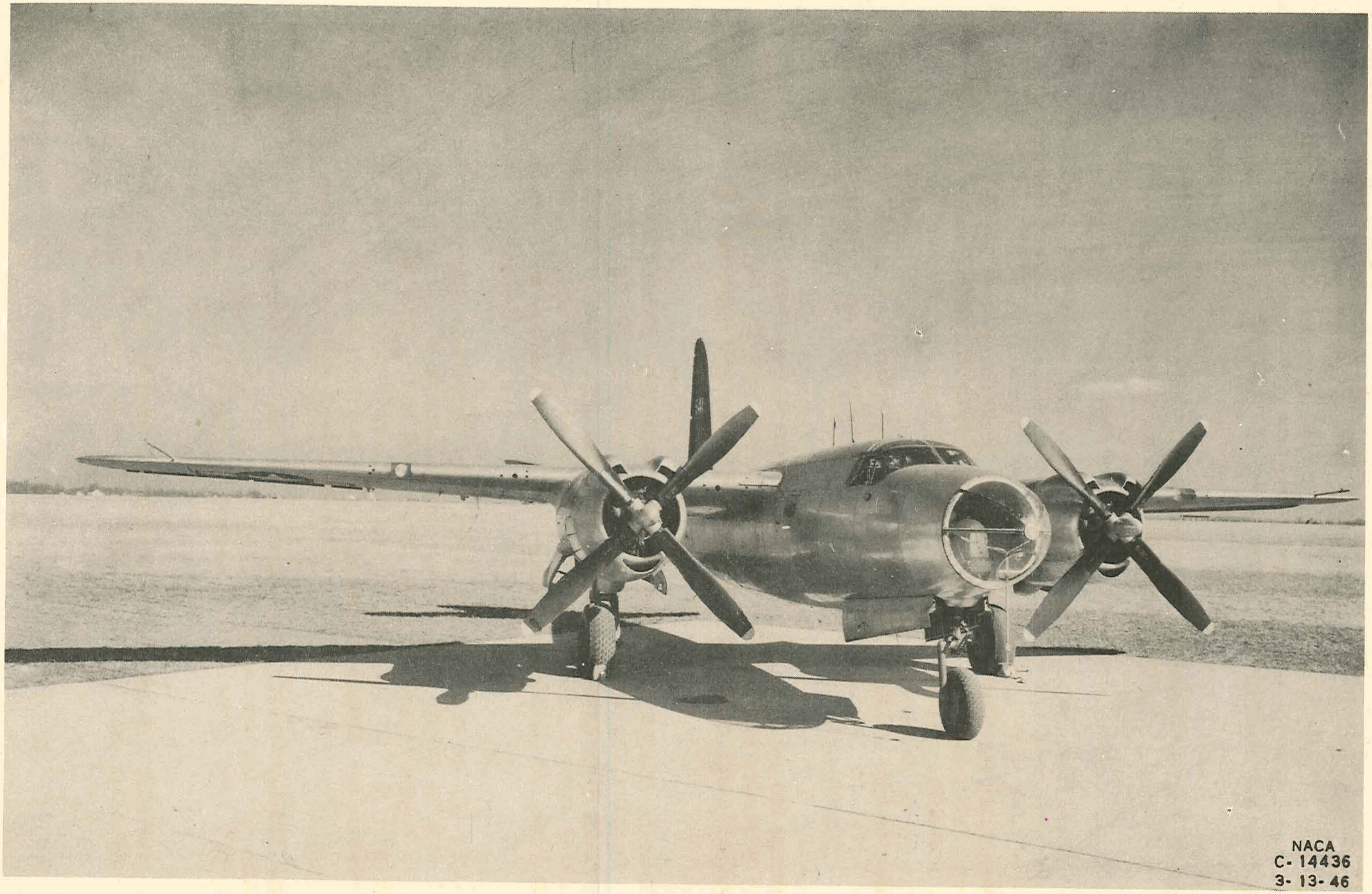

Figure 1. - Airplane used in flight investigation of exhaust-ejector installation.

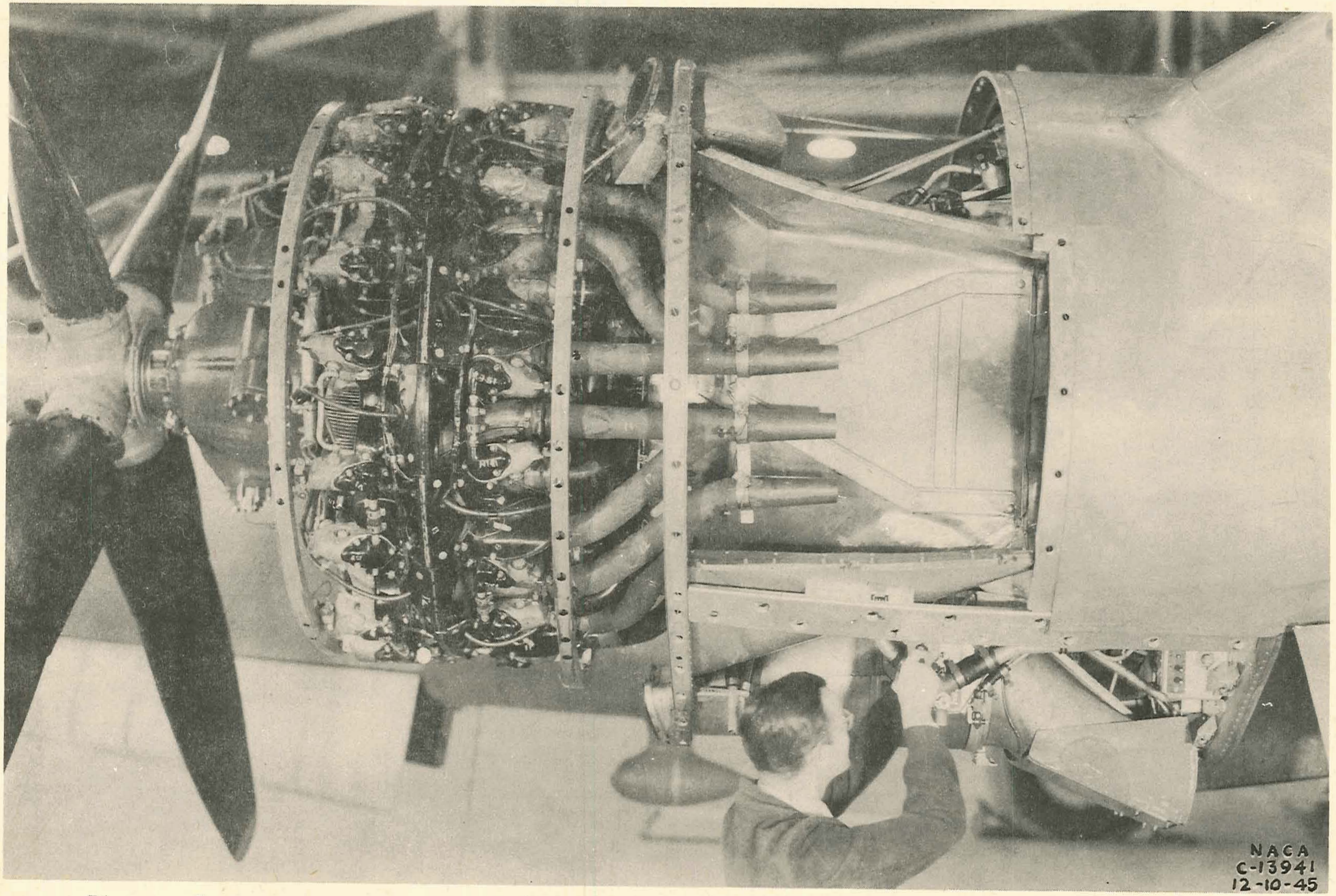

Figure 2. - Exhaust-ejector installation in left nacelle of test airplane.

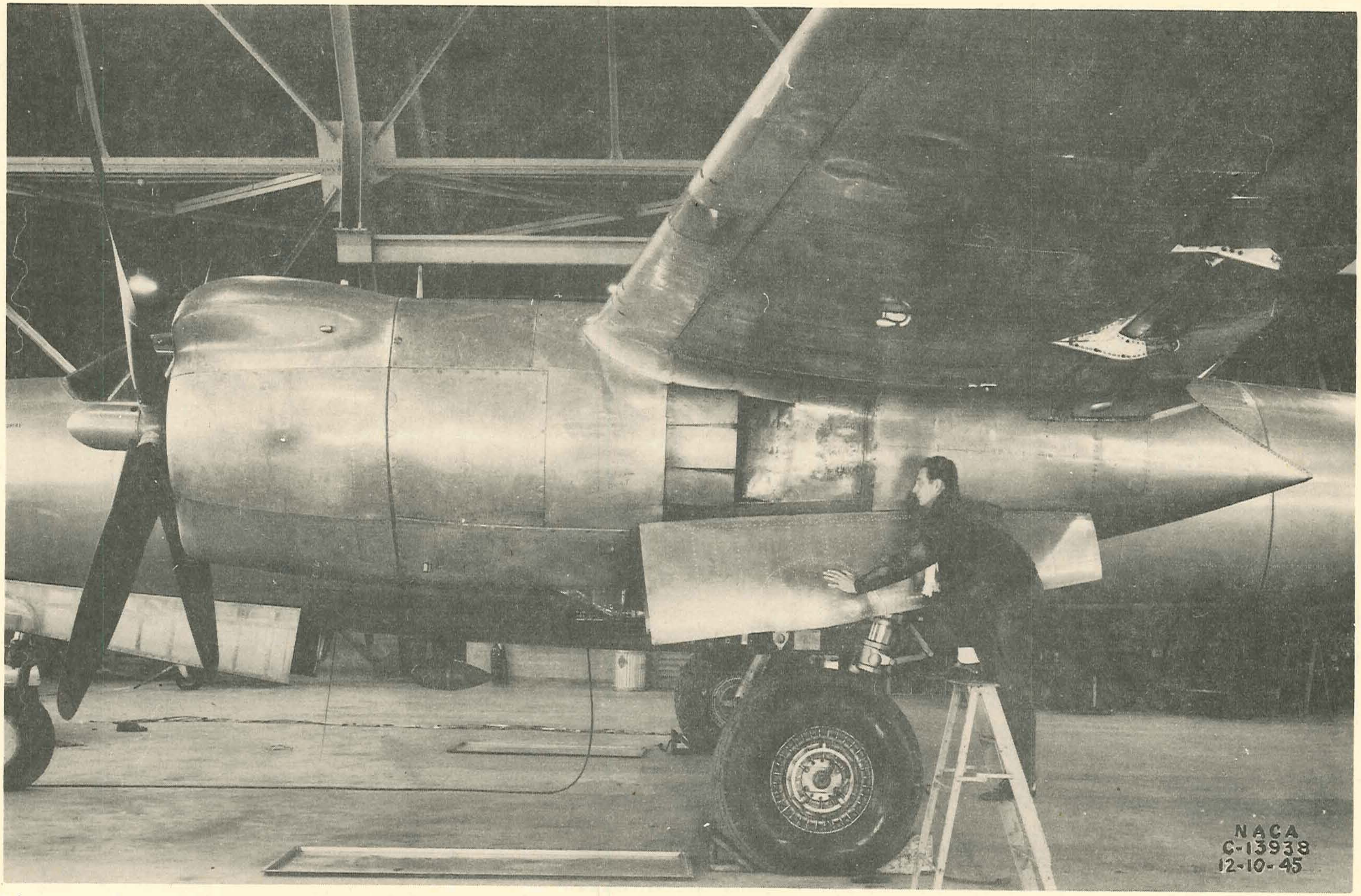

Figure 3. - General arrangement of left nacelle modified for exhaust-ejector installation in test airplane.

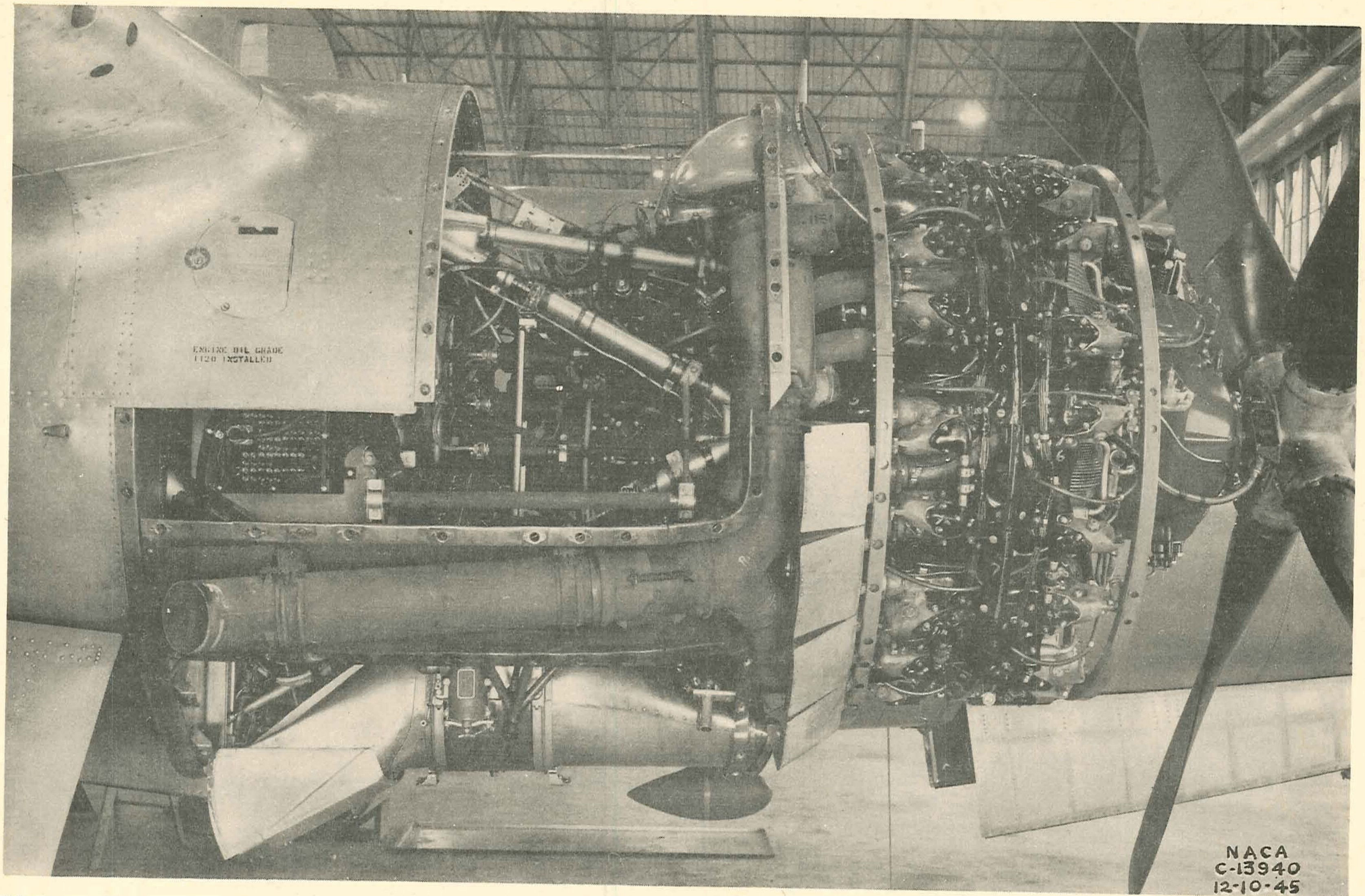

Figure 4. - Standard exhaust-collector-ring installation in right nacelle of test airplane.

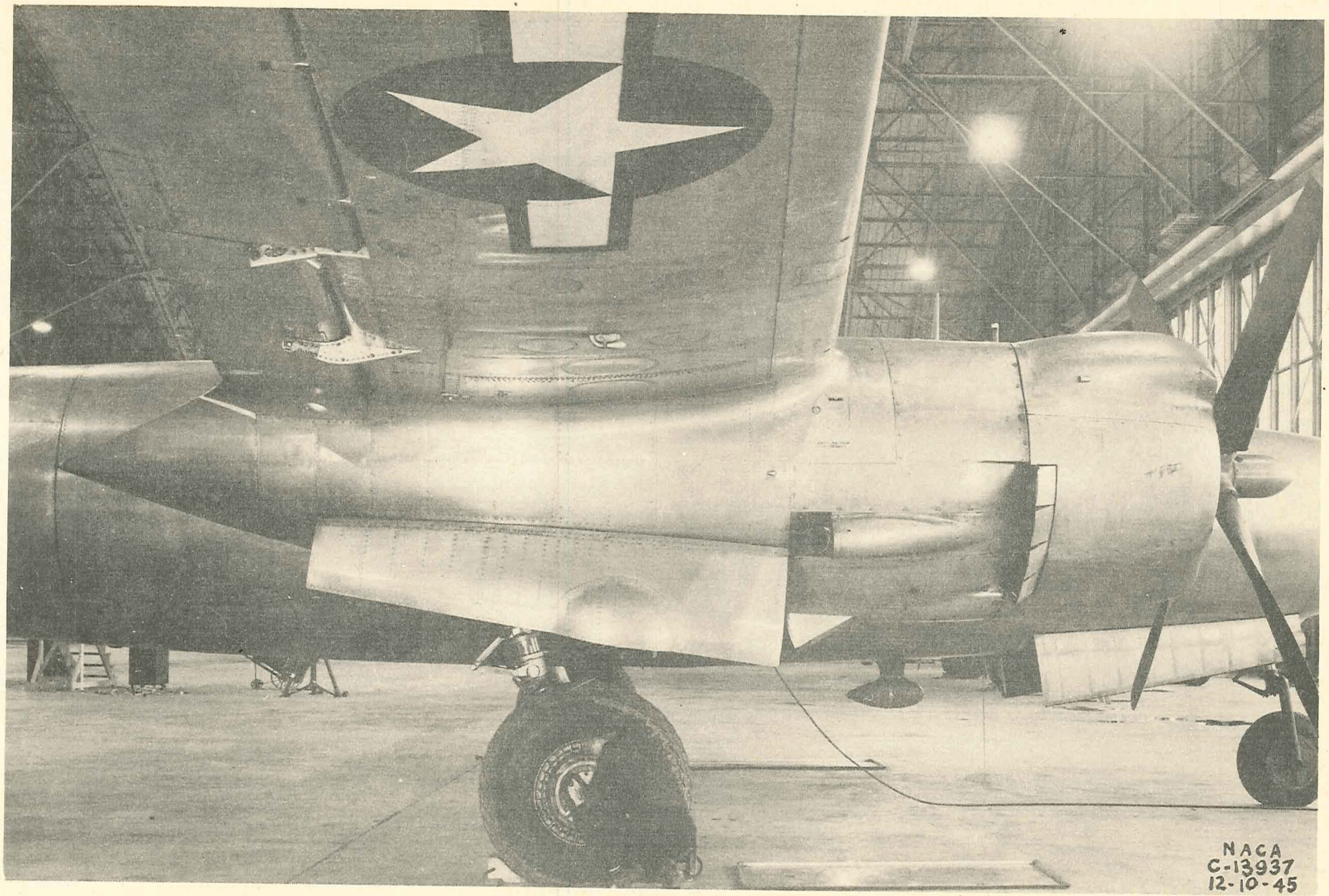

Figure 5. - General arrangement of standard right nacelle in test airplane.

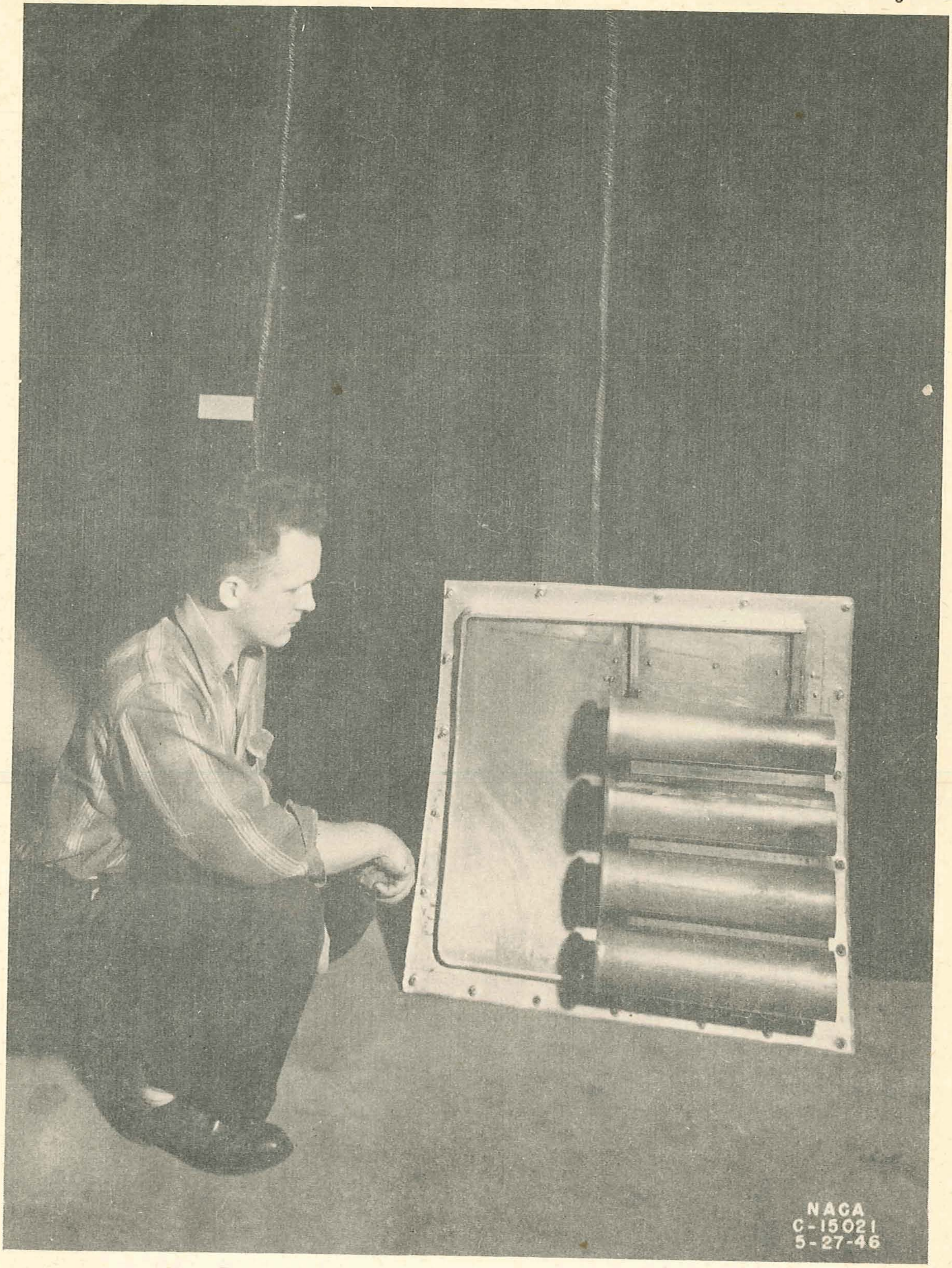

Figure 6. - First-stage ejectors mounted on removable accessory skin panel.

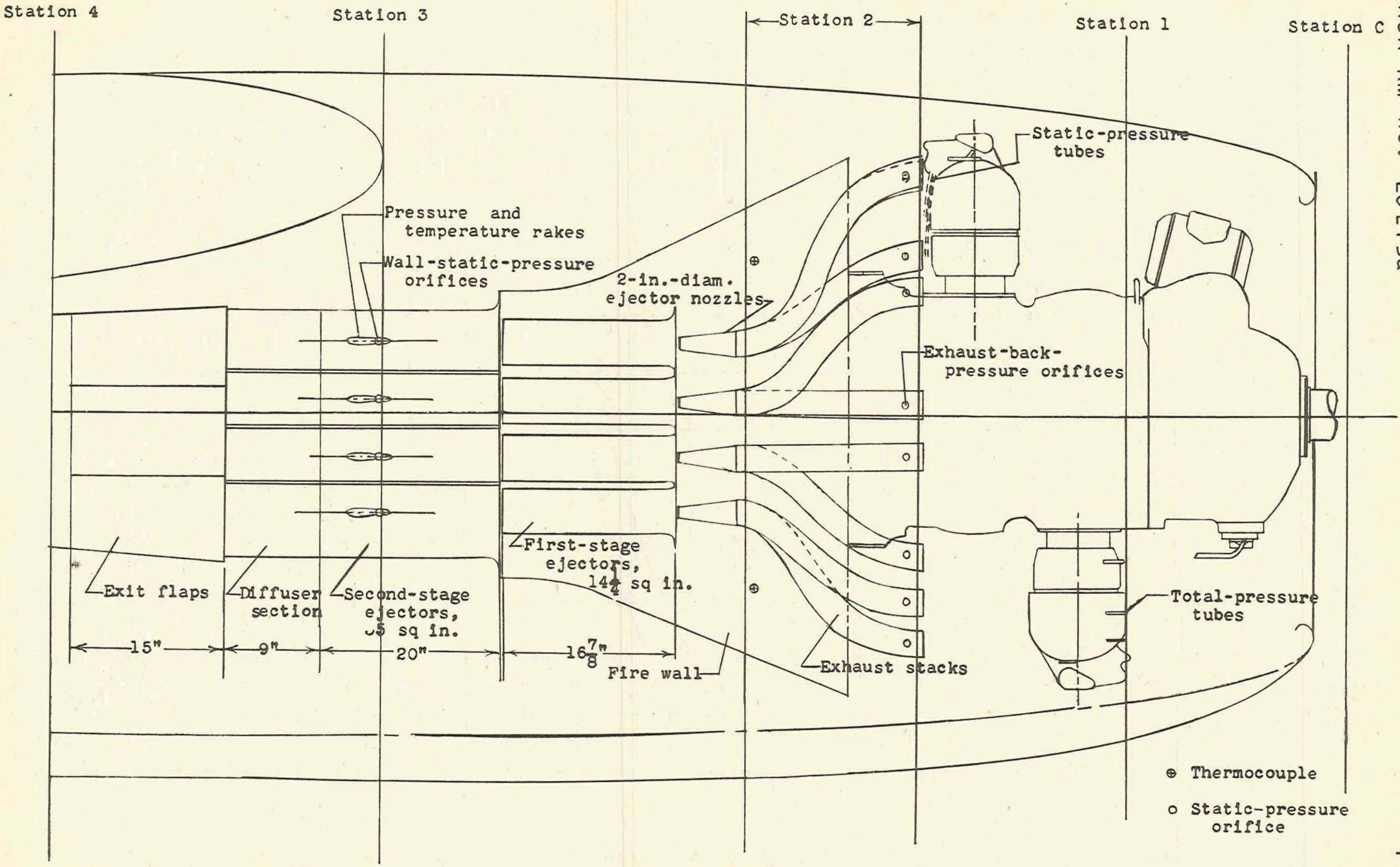

Figure 7. - Schematic diagram of exhaust-ejector installation in left nacelle of test airplane.

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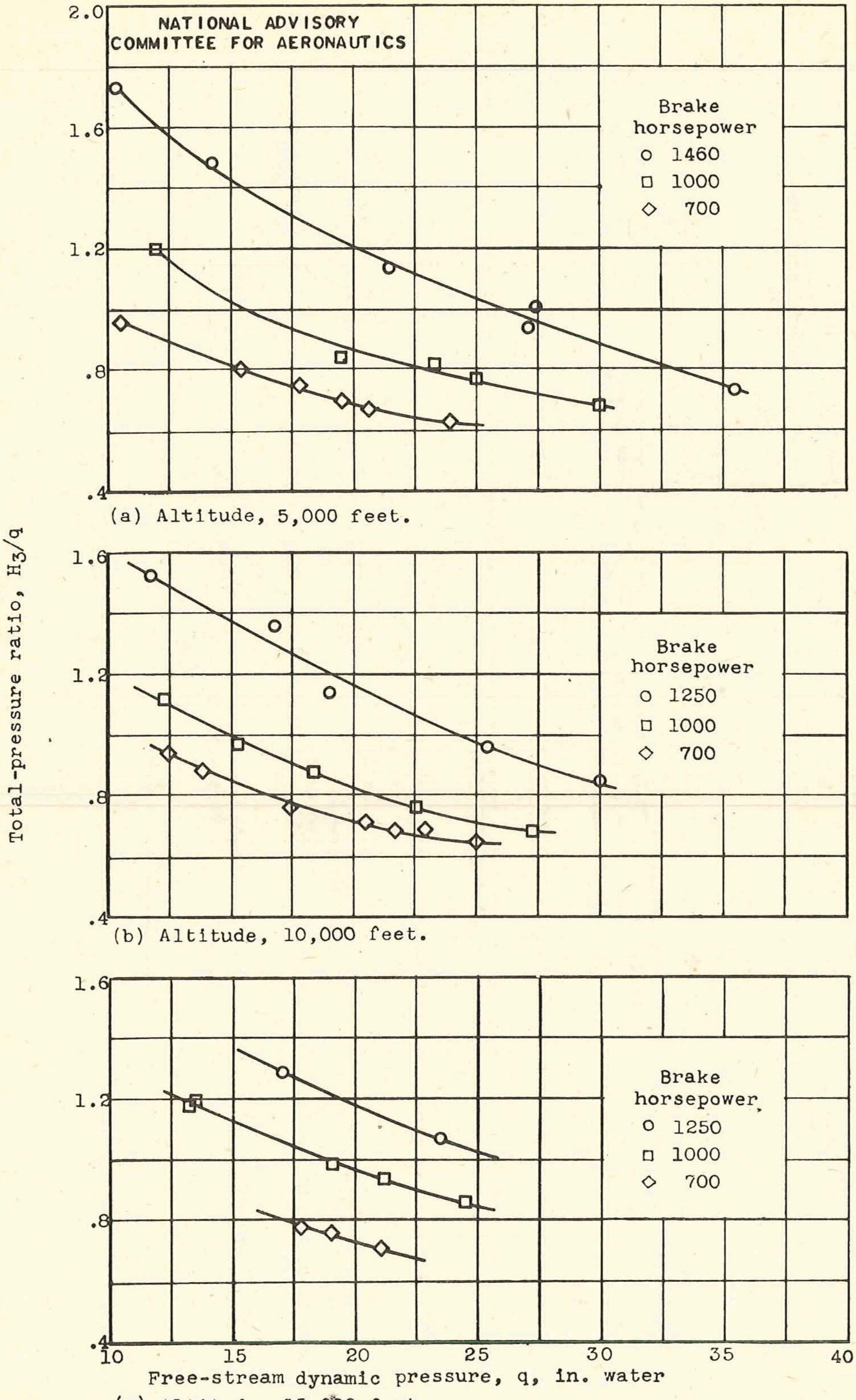


Figure 8. - Average total pressure in exhaust ejectors with cowl flaps closed.

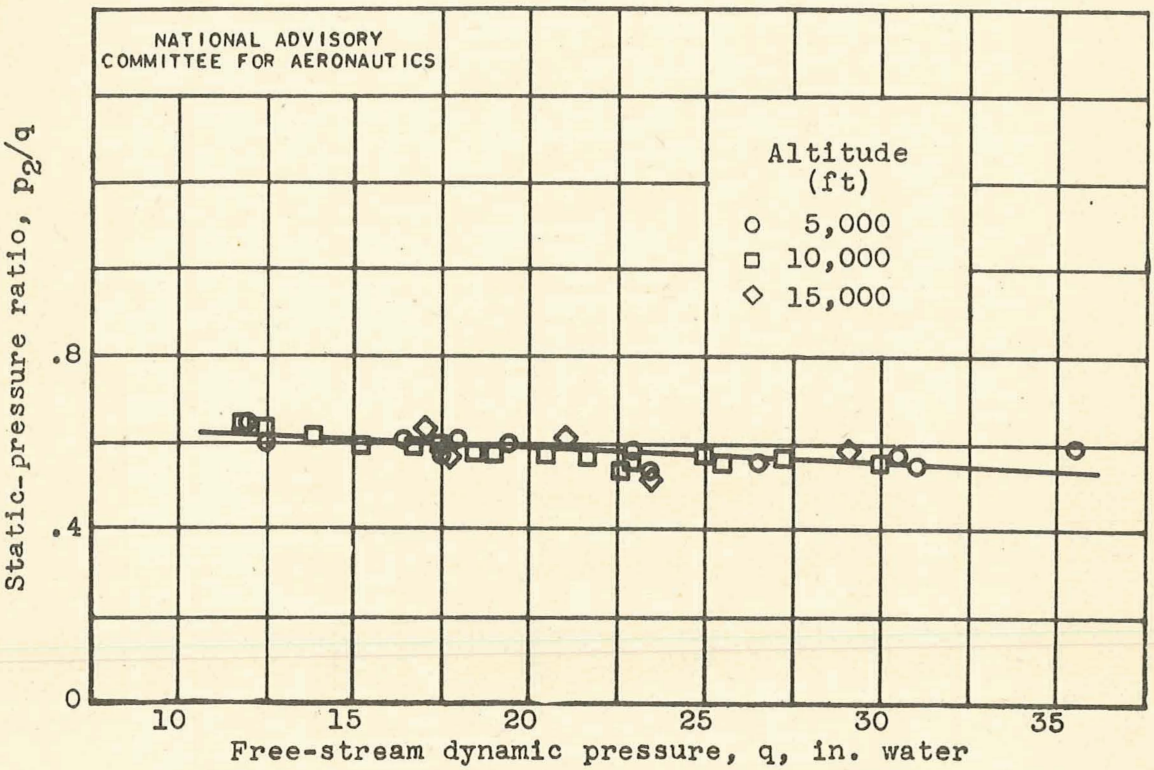


Figure 9. - Average static pressure behind standard engine with cowl flaps closed.

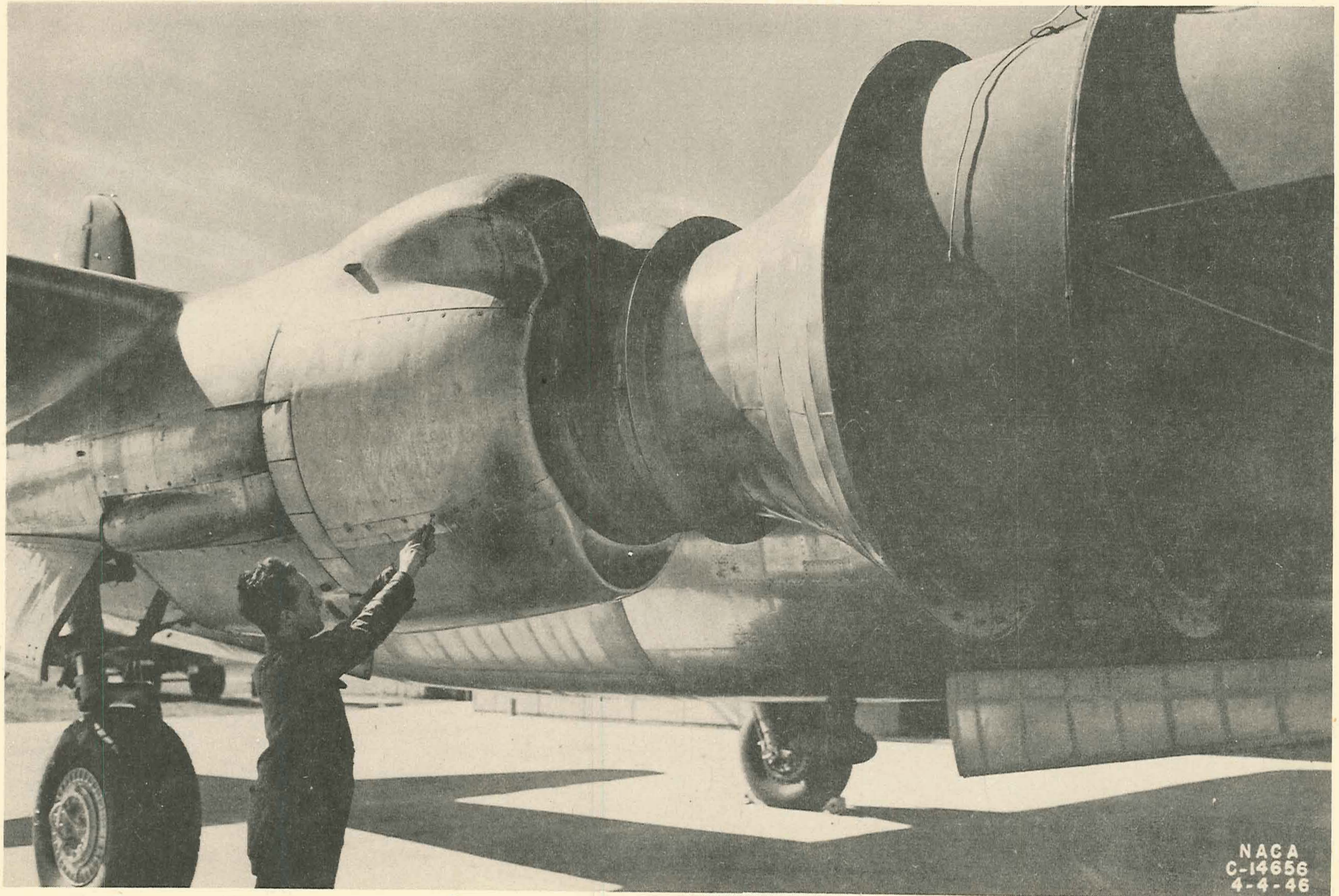


Figure 10. - Blower setup for calibrating engine cooling-air flow.

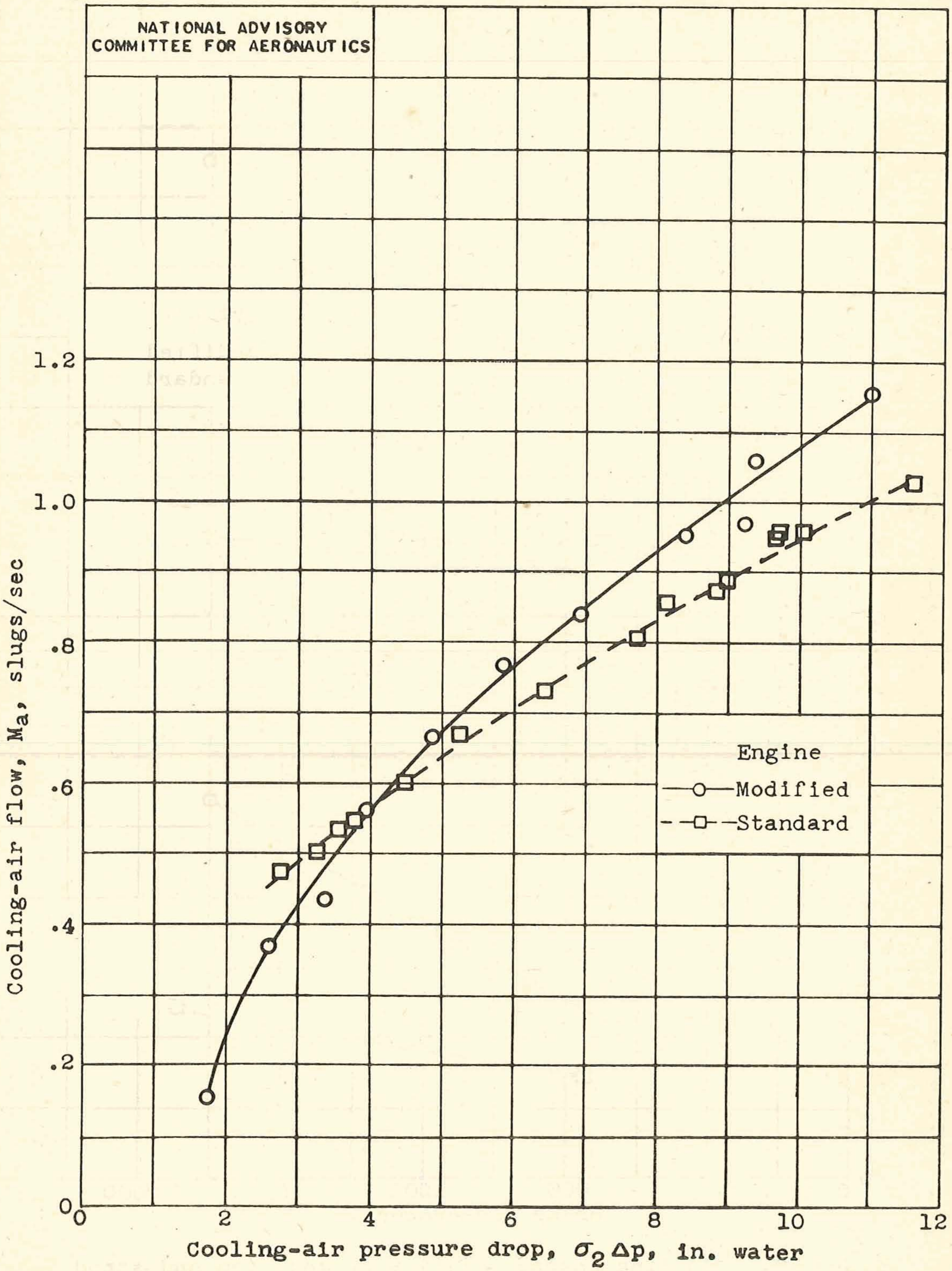


Figure 11. - Engine cooling-air-flow calibration from cooling blower.

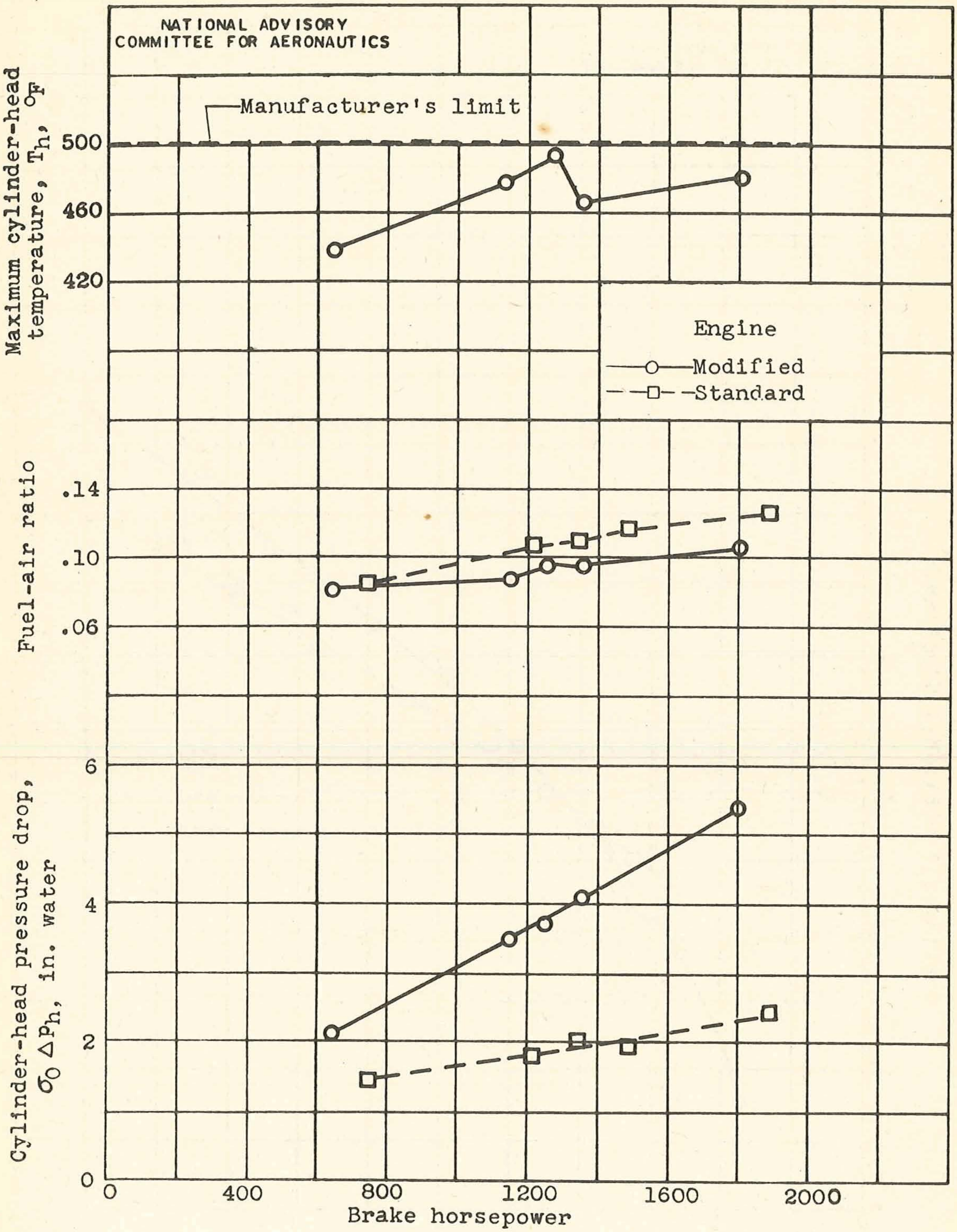
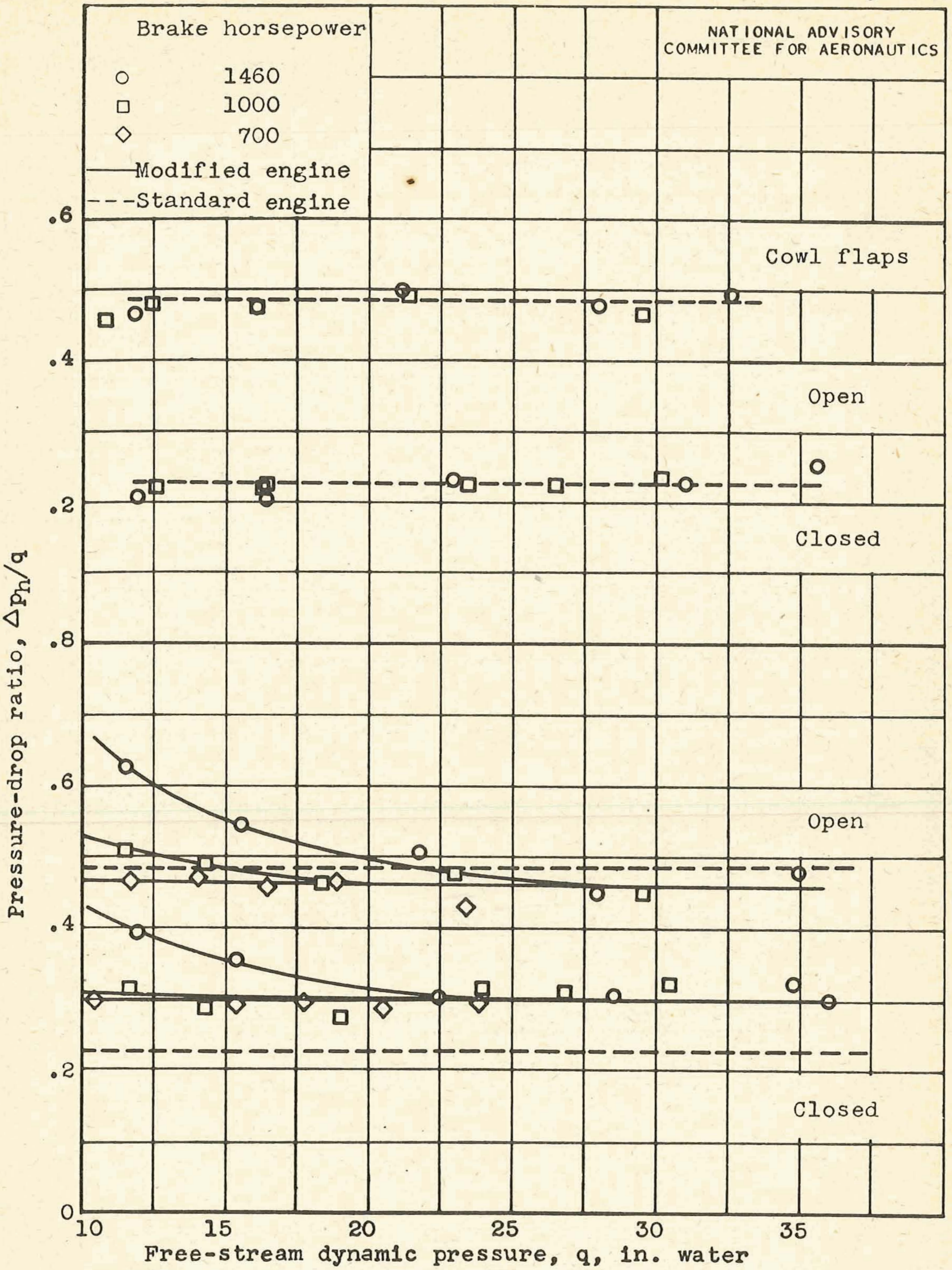
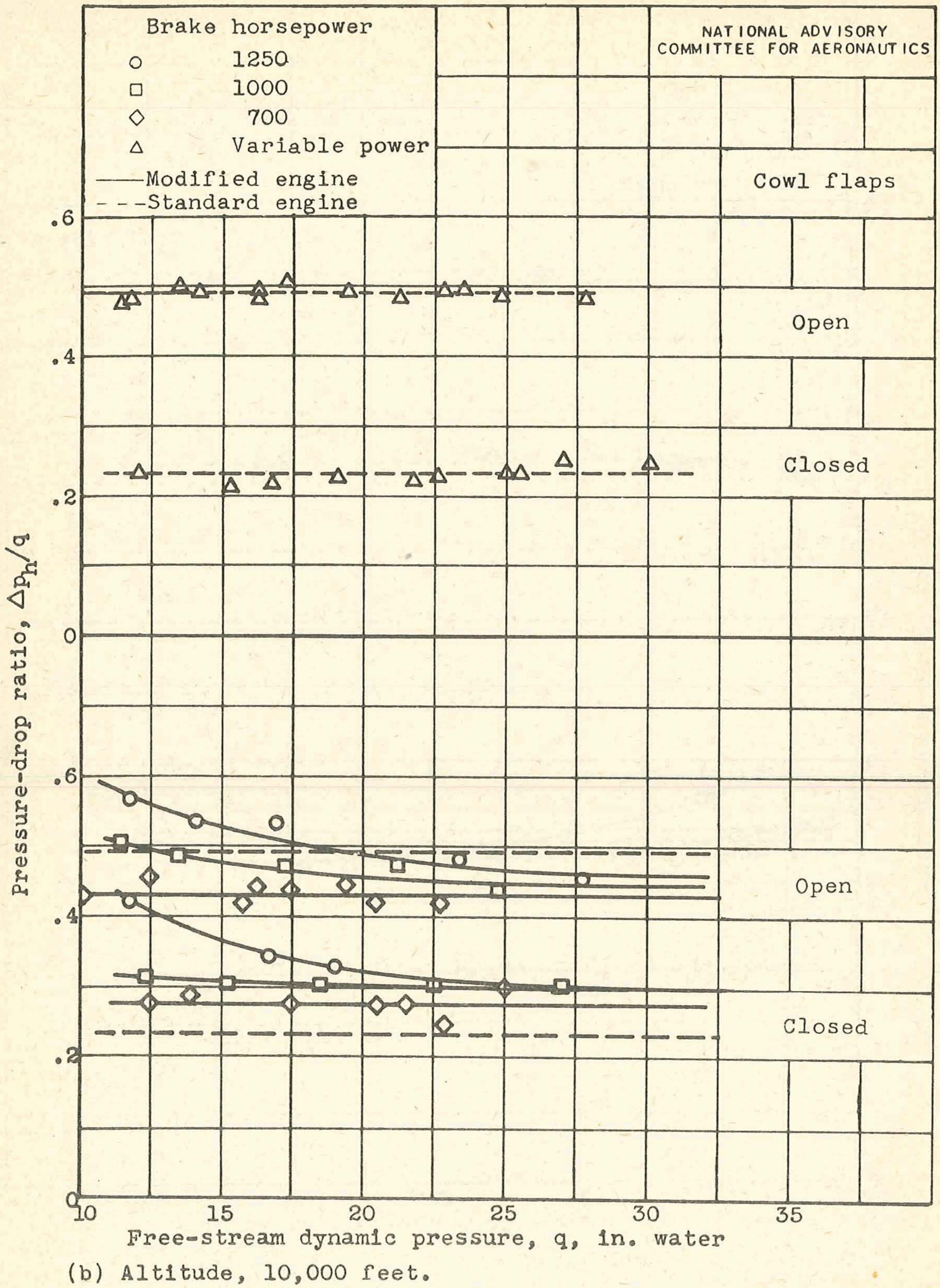


Figure 12. - Cooling characteristics of modified and standard engines on ground with cowl flaps open at free-air temperature of 35° F.



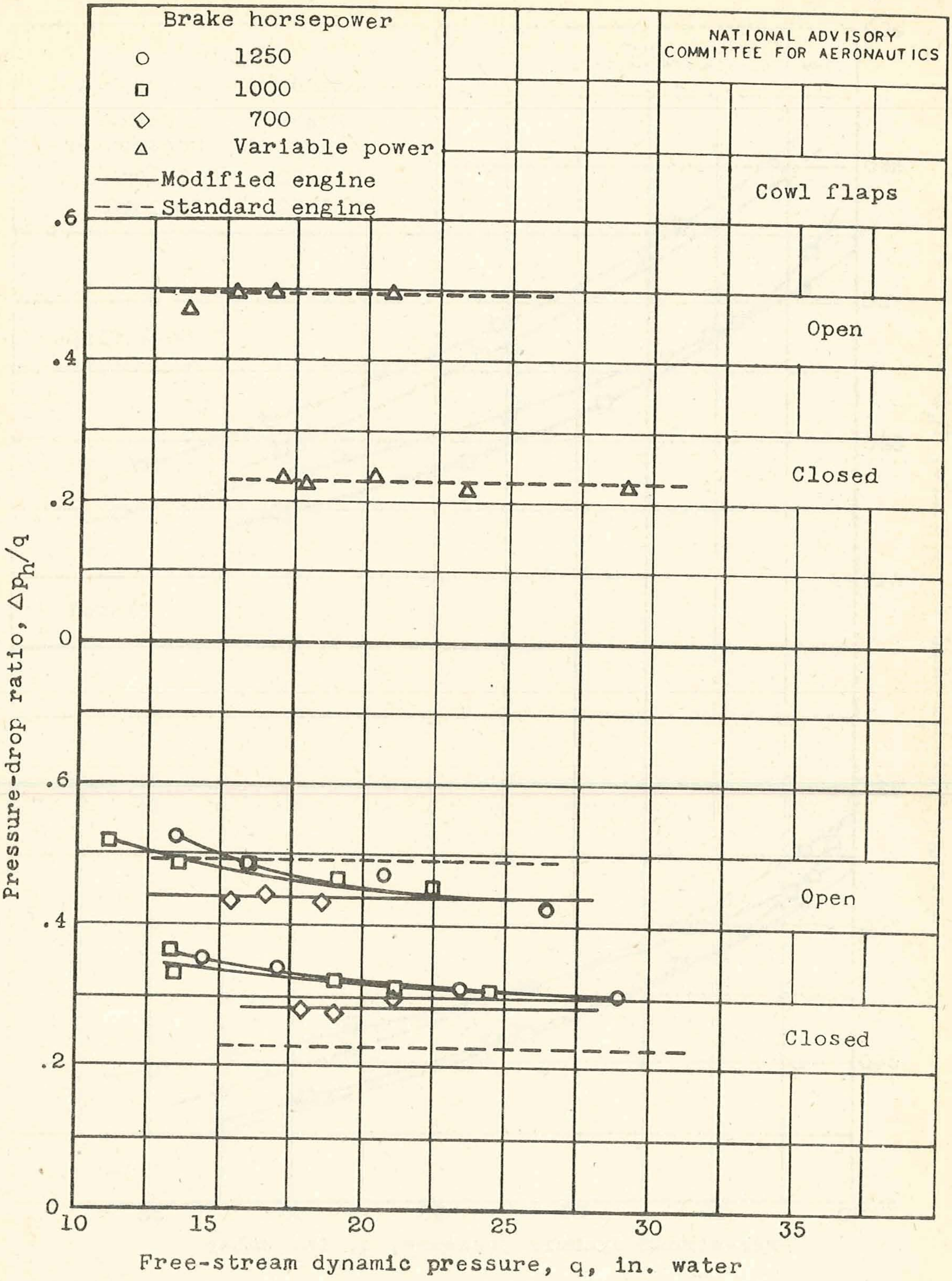
(a) Altitude, 5,000 feet.

Figure 13. - Available engine cylinder-head cooling-air pressure drop.



(b) Altitude, 10,000 feet.

Figure 13. - Continued. Available engine cylinder-head cooling-air pressure drop.



(c) Altitude, 15,000 feet.

Figure 13. - Concluded. Available engine cylinder-head cooling-air pressure drop.

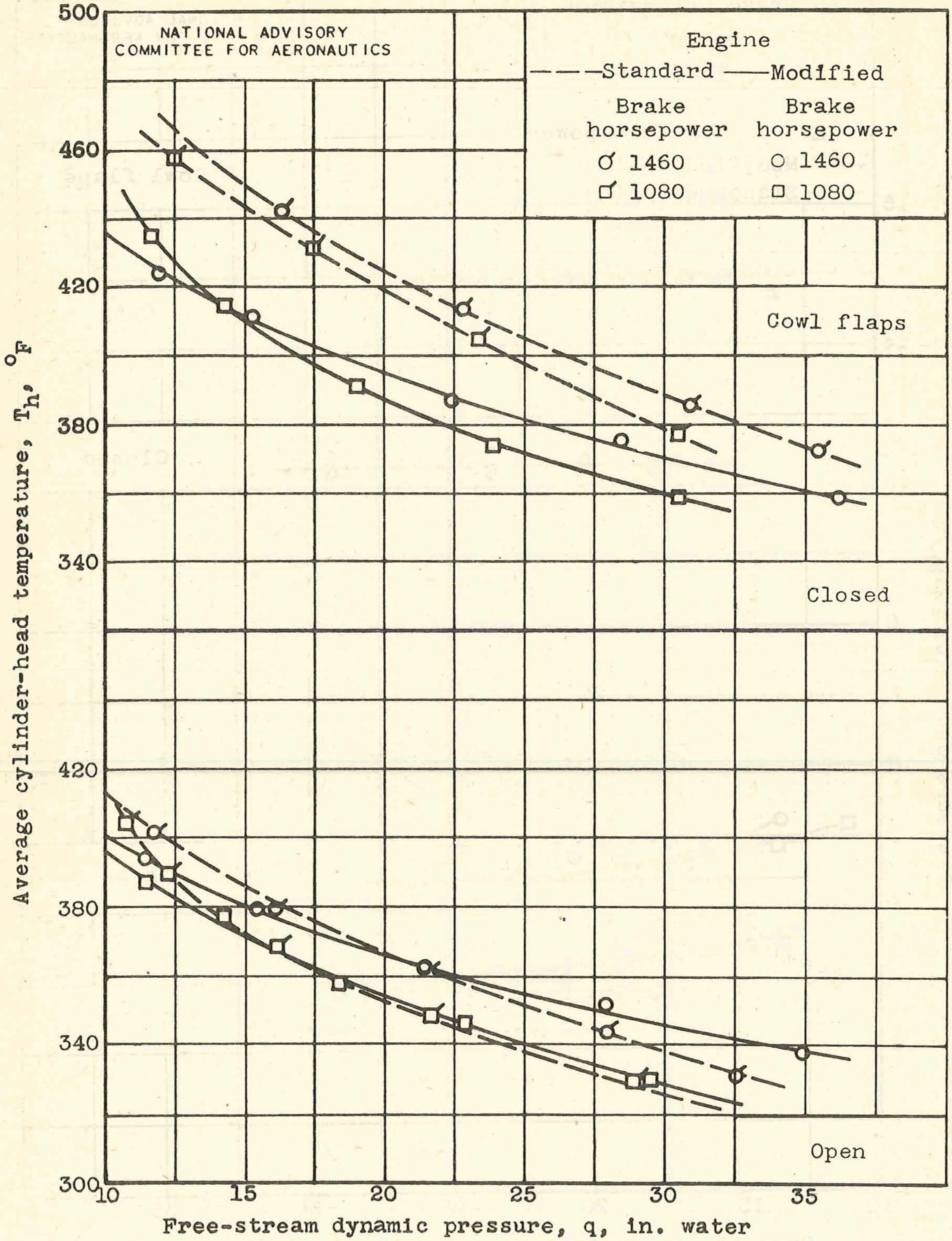


Figure 14. - Variation of average cylinder-head temperature with free-stream dynamic pressure at altitude of 5000 feet and free-air temperature of 46° F.

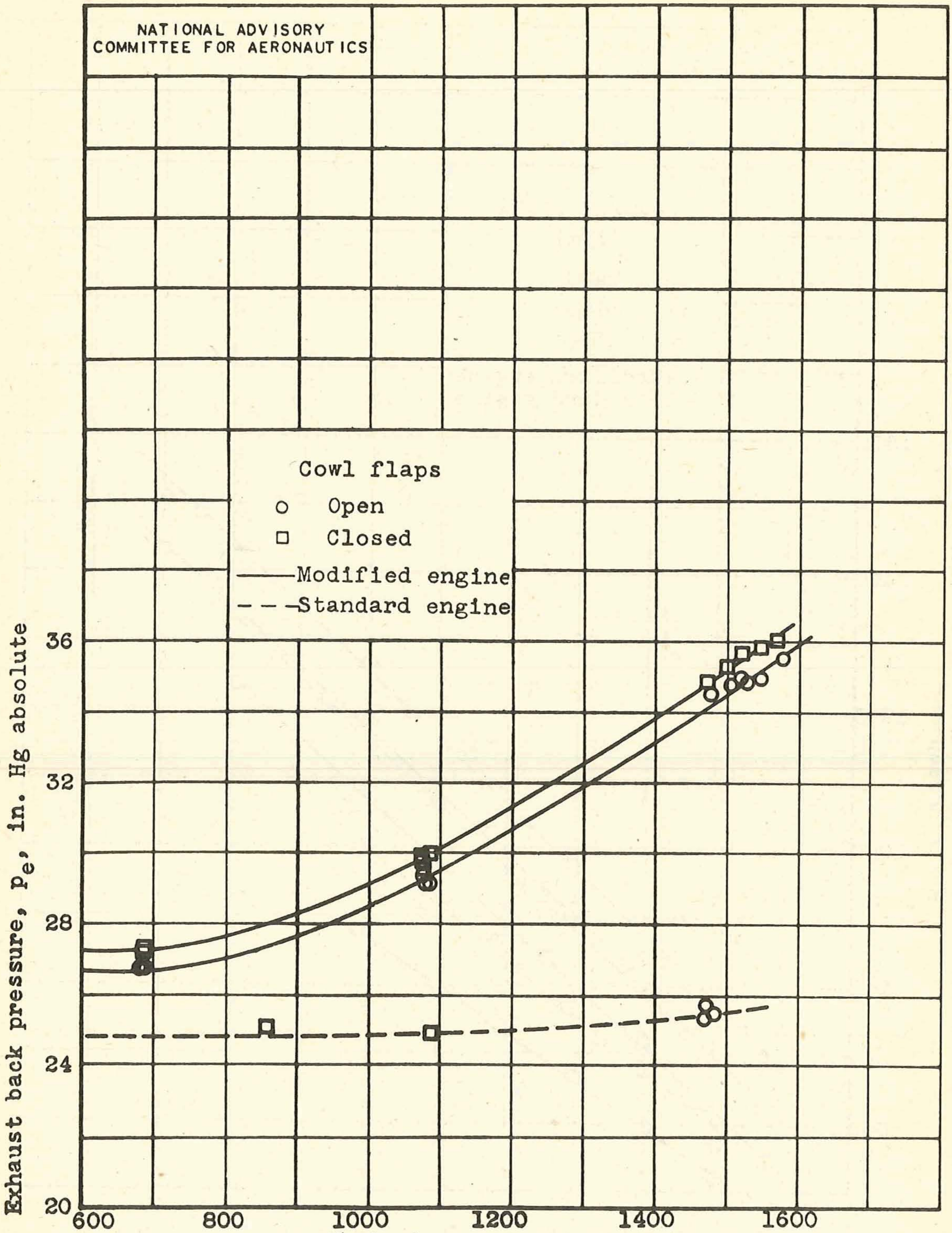


Figure 15. - Variation of exhaust back pressure with engine power at altitude of 5000 feet.

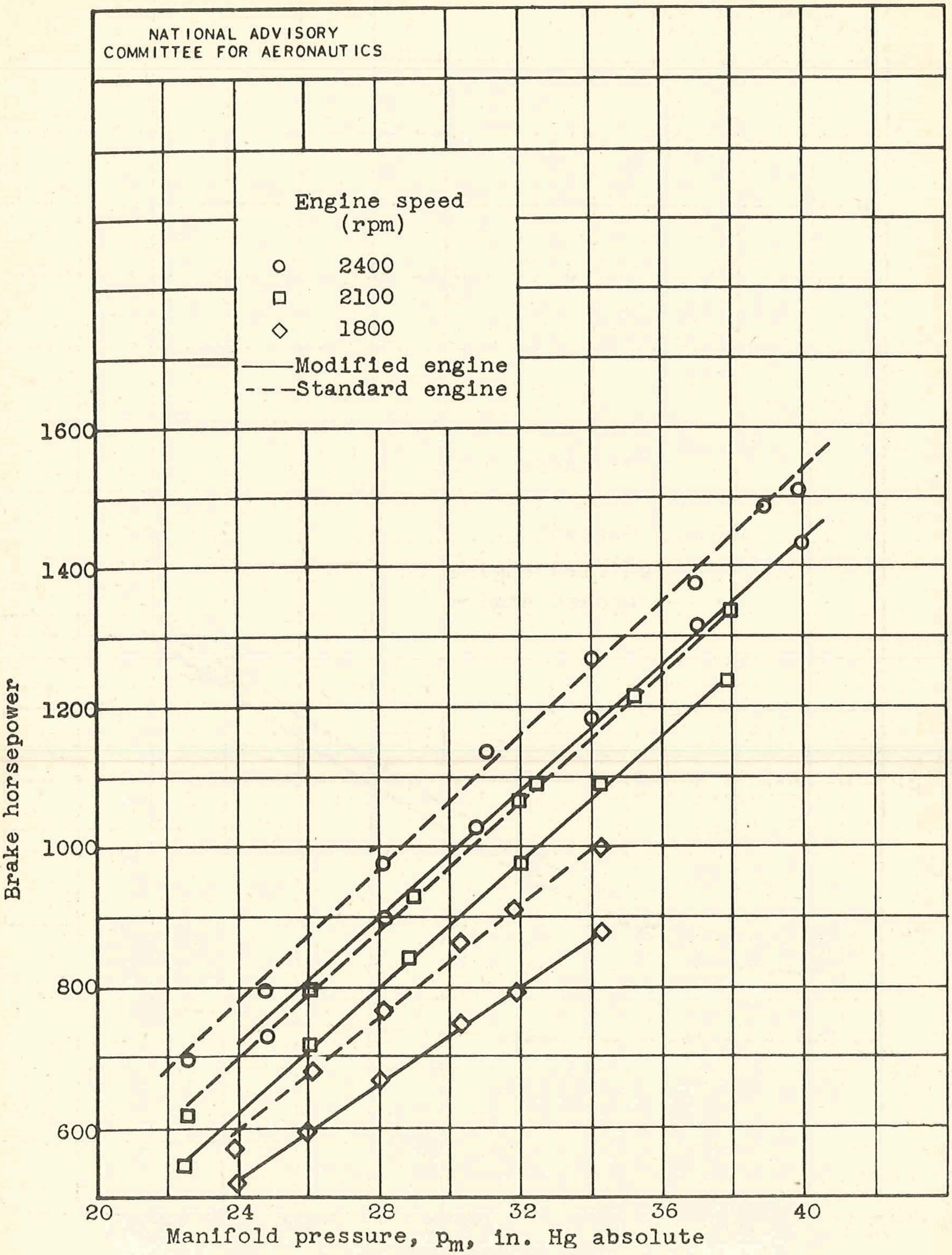
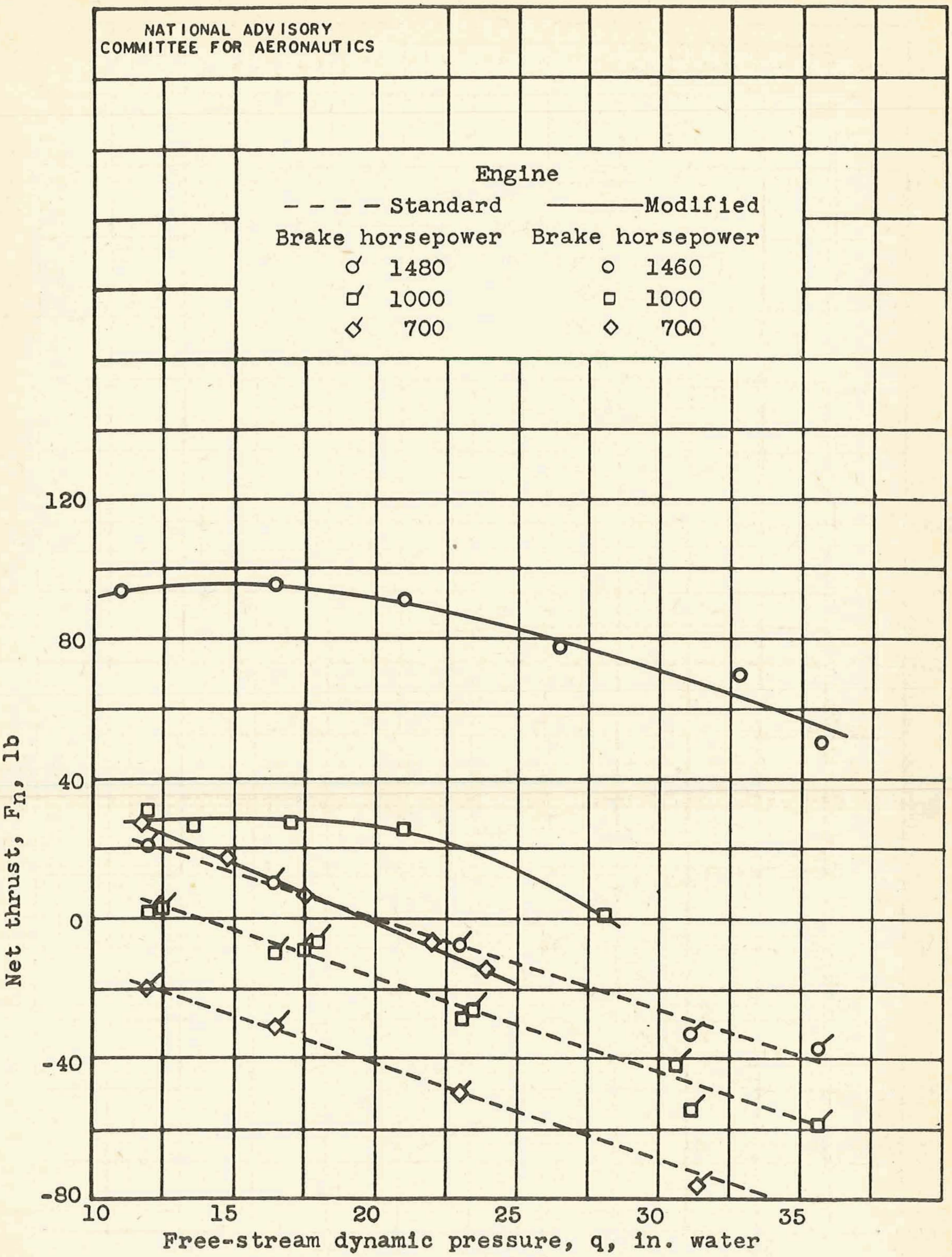
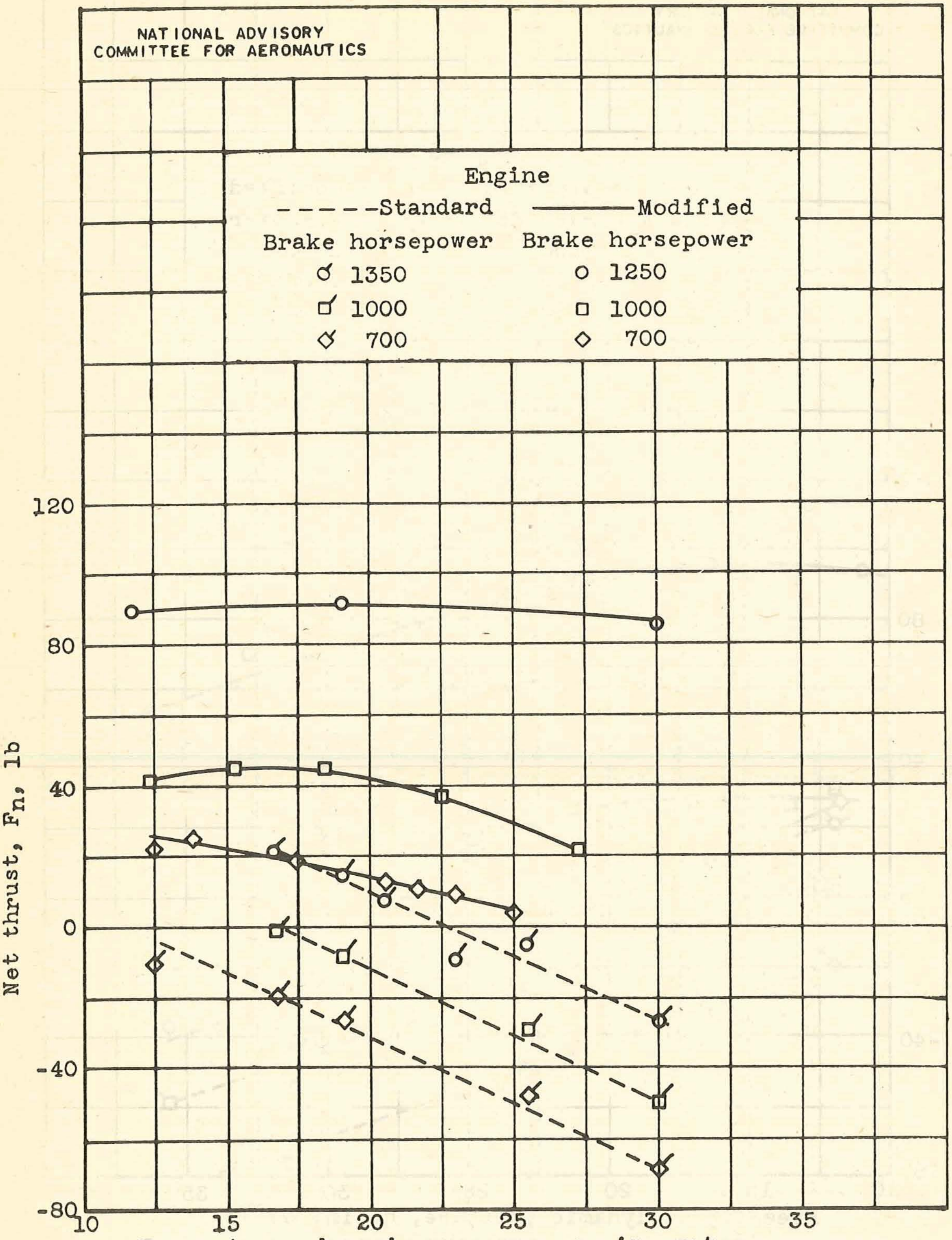


Figure 16. - Engine calibrations at altitude of 5000 feet.



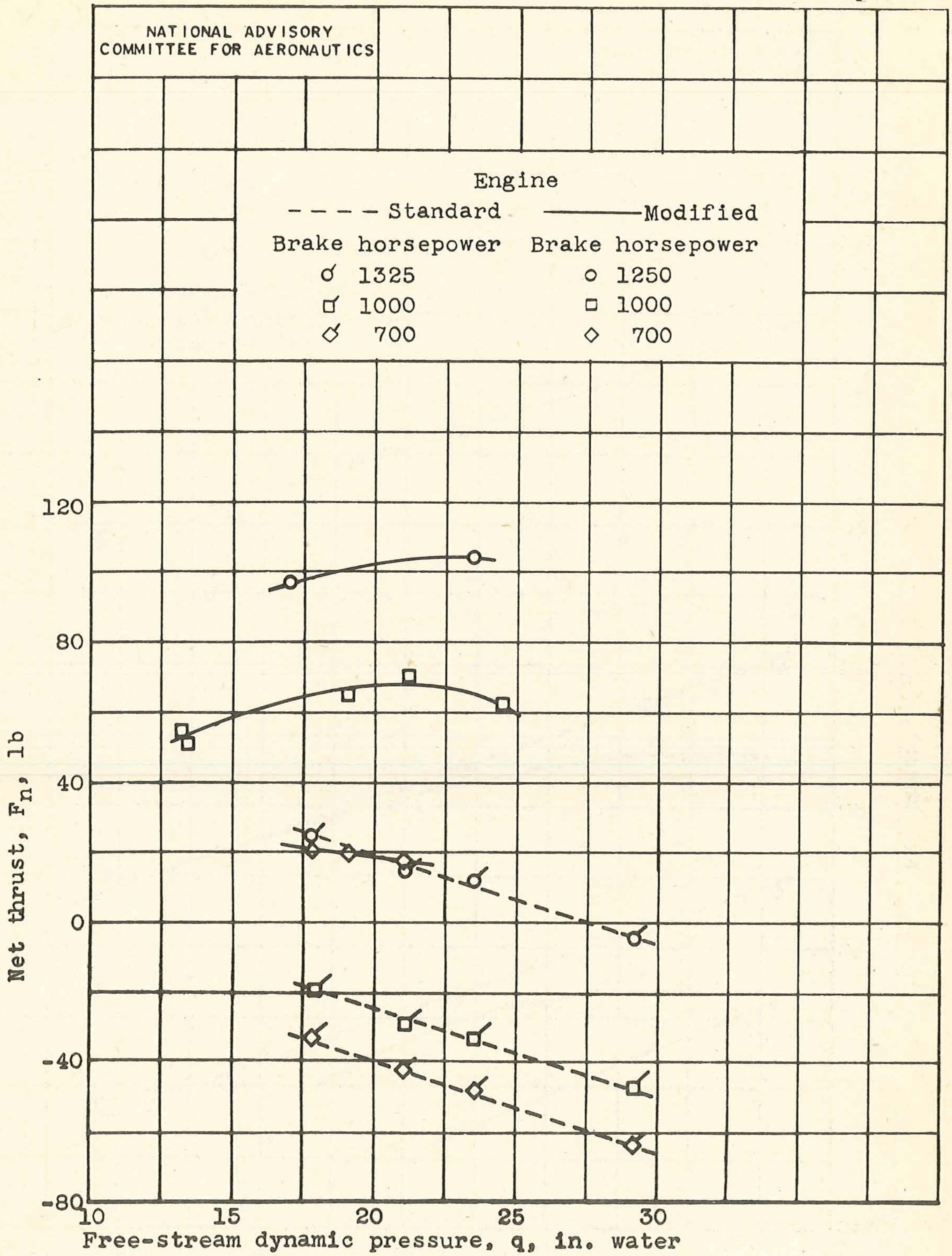
(a) Altitude, 5,000 feet.

Figure 17. - Comparison of net thrust of cooling air and exhaust gas for modified and standard engines.



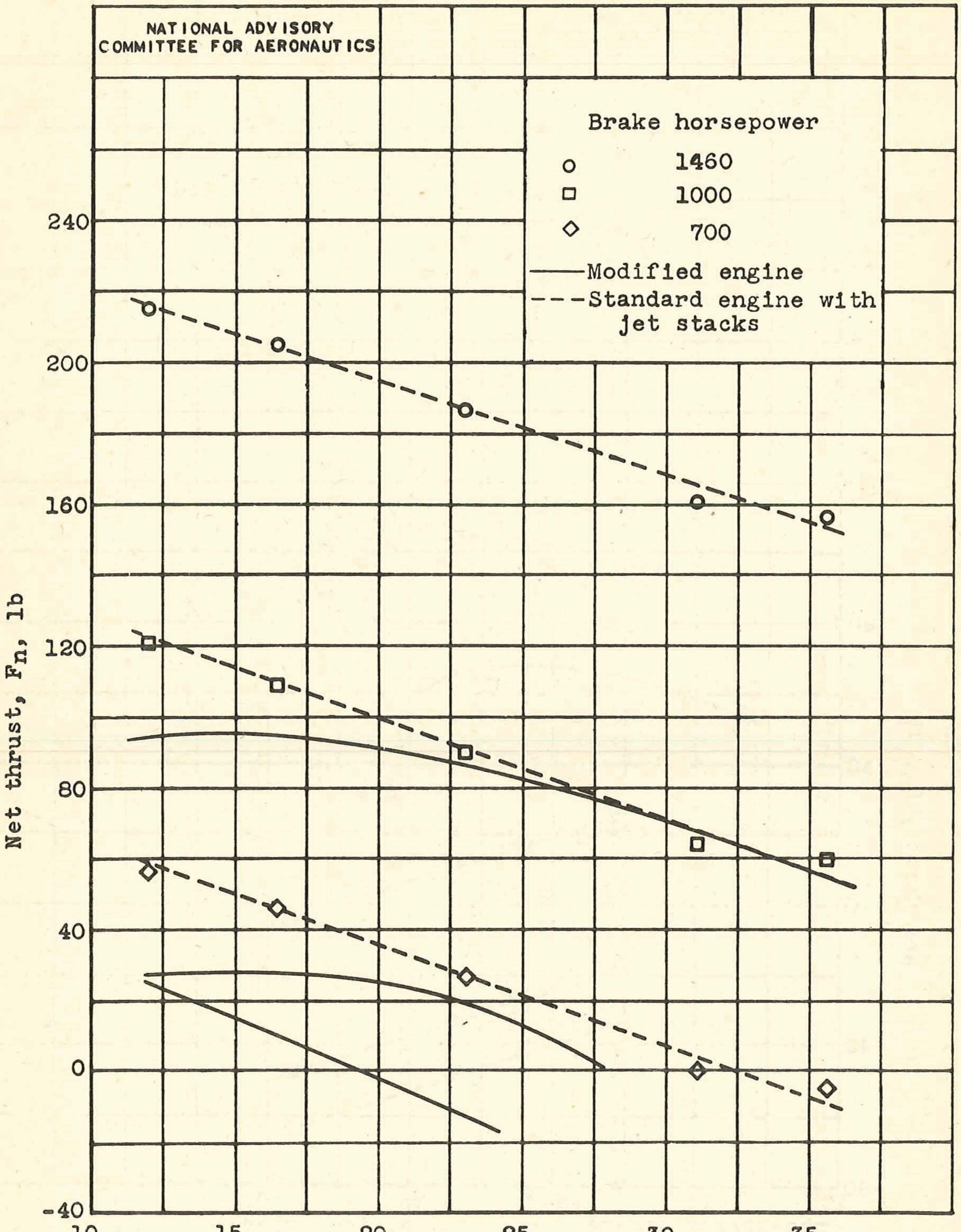
(b) Altitude, 10,000 feet.

Figure 17. - Continued. Comparison of net thrust of cooling air and exhaust gas for modified and standard engines.



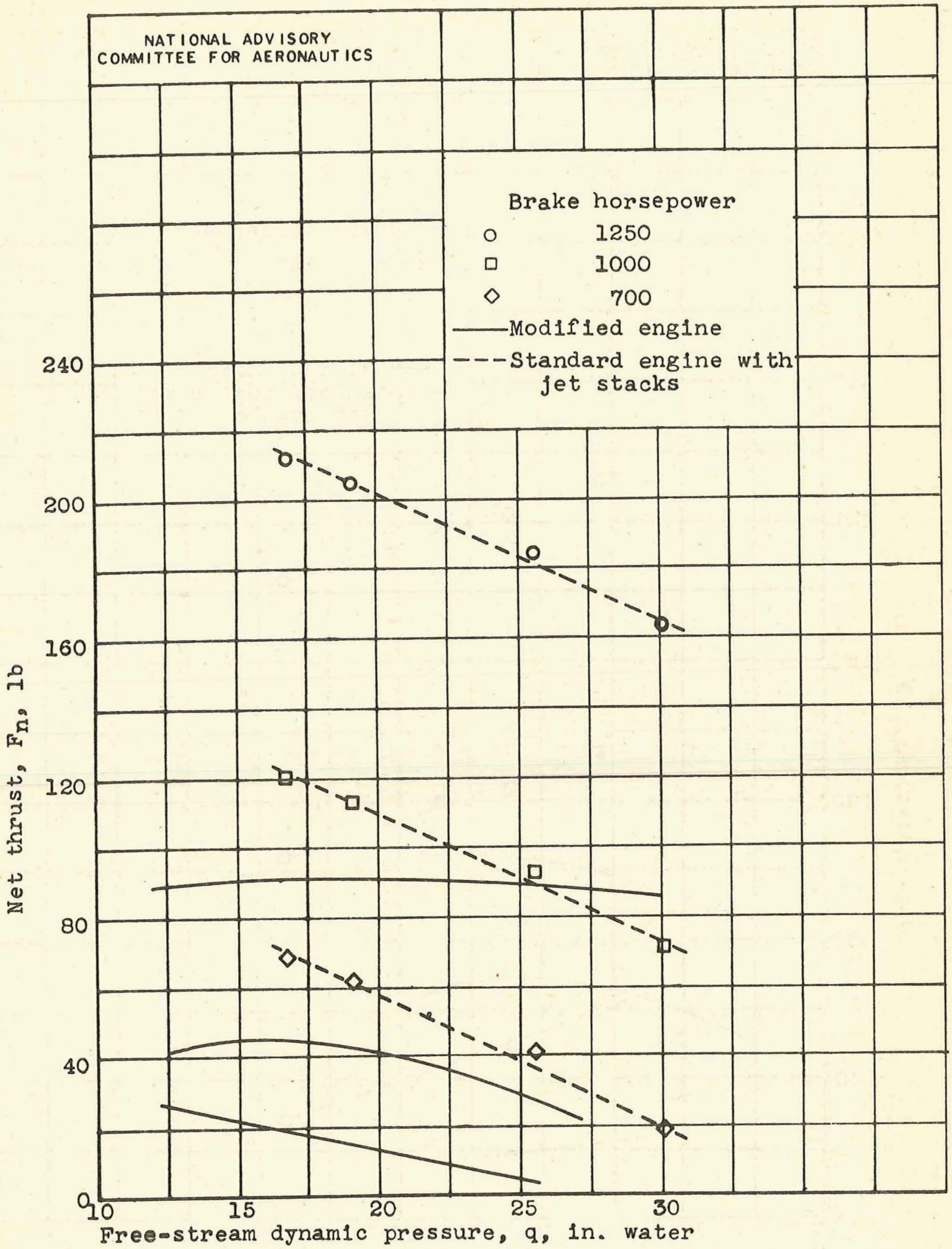
(c) Altitude, 15,000 feet.

Figure 17. - Concluded. Comparison of net thrust of cooling air and exhaust gas for modified and standard engines.



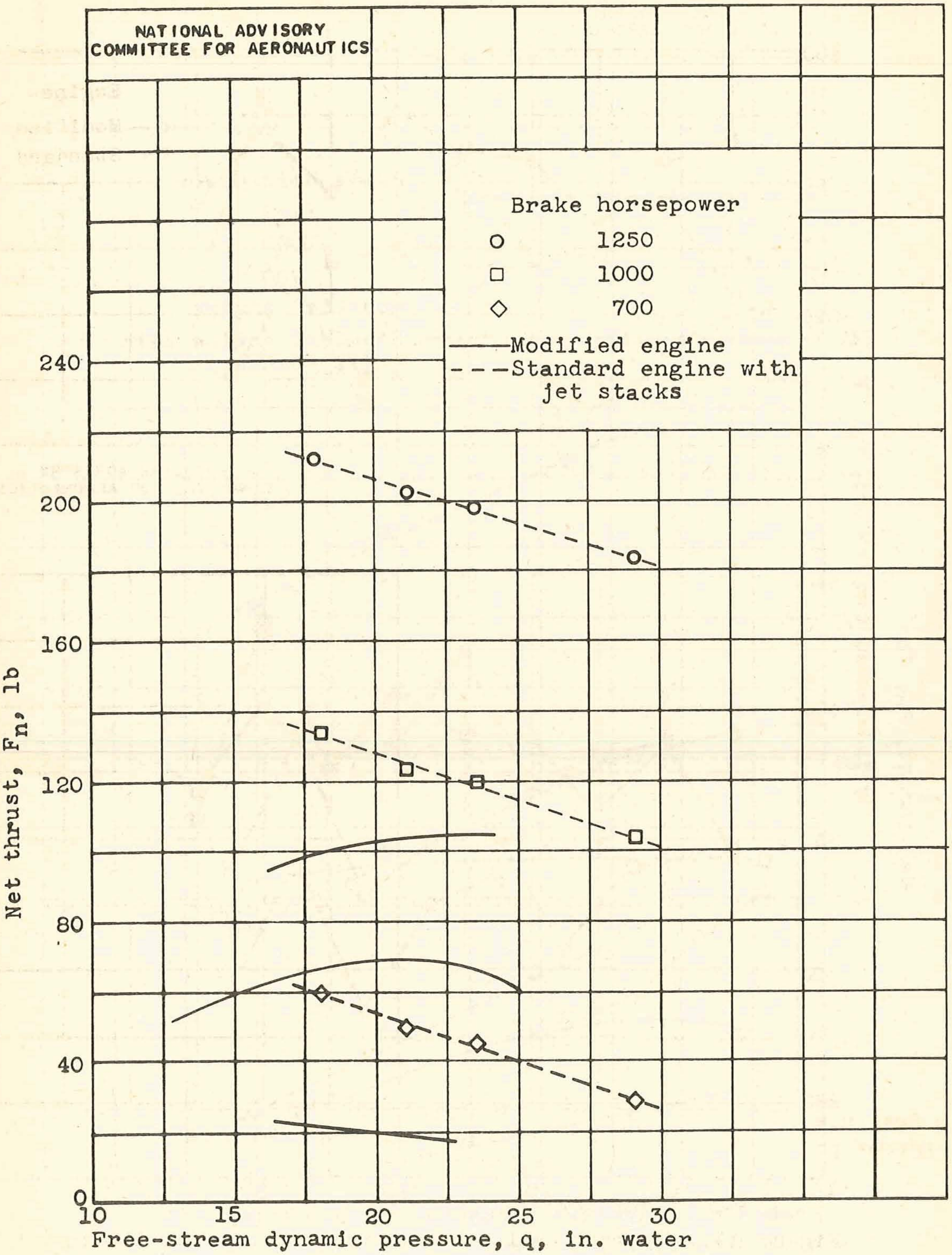
(a) Altitude, 5,000 feet.

Figure 18. - Comparison of net thrust of cooling air and exhaust gas for modified engine and standard engine with jet stacks.



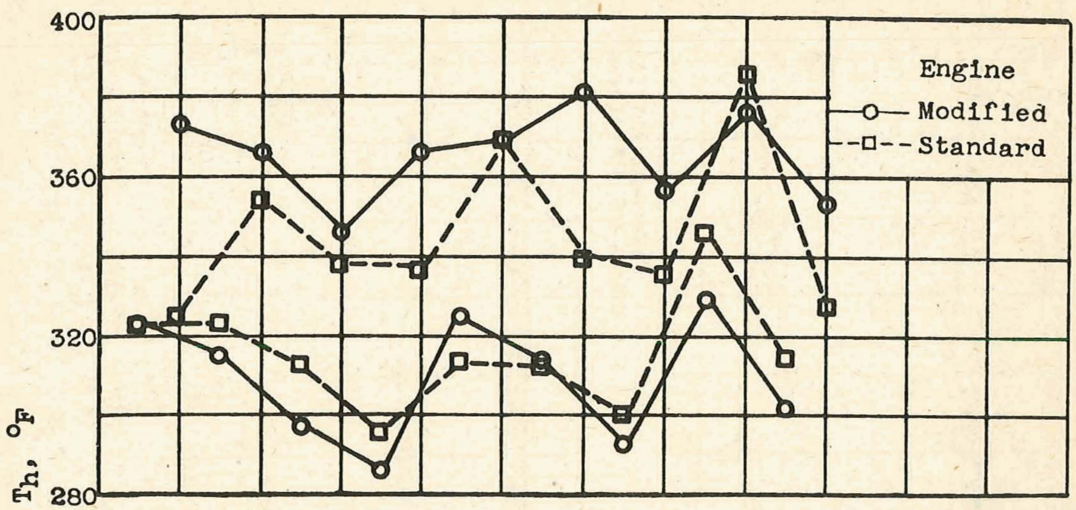
(b) Altitude, 10,000 feet.

Figure 18. - Continued. Comparison of net thrust of cooling air and exhaust gas for modified engine and standard engine with jet stacks.

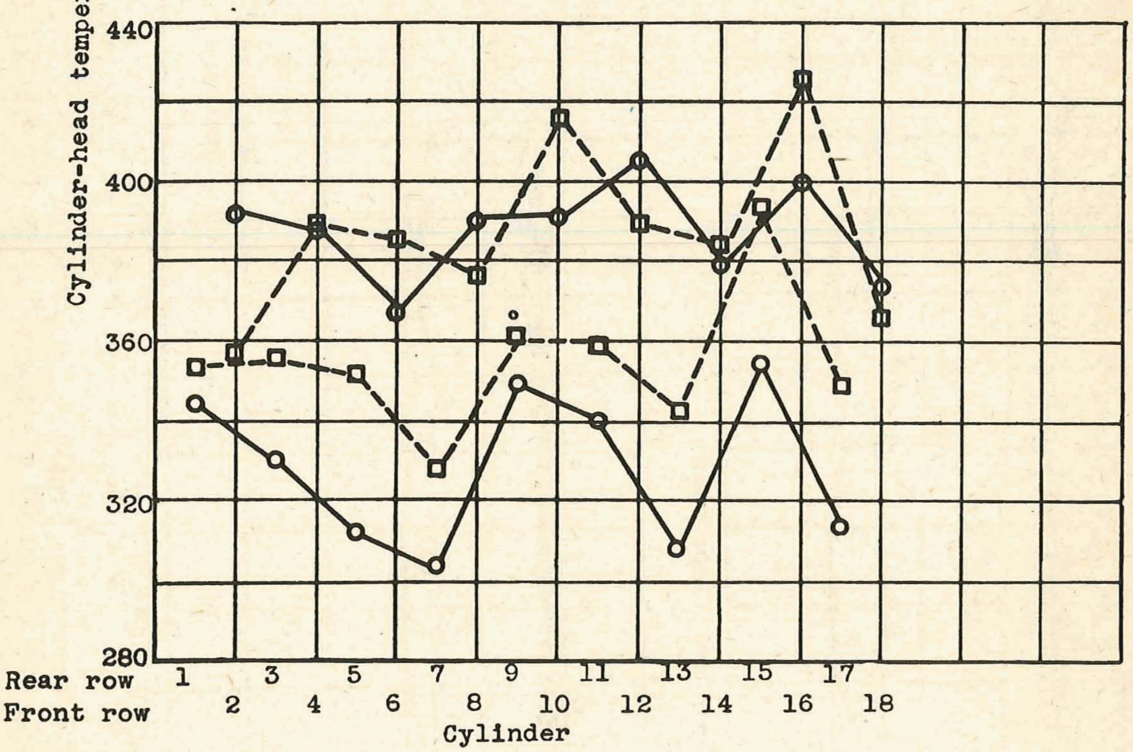


(c) Altitude, 15,000 feet.

Figure 18. - Concluded. Comparison of net thrust of cooling air and exhaust gas for modified engine and standard engine with jet stacks.

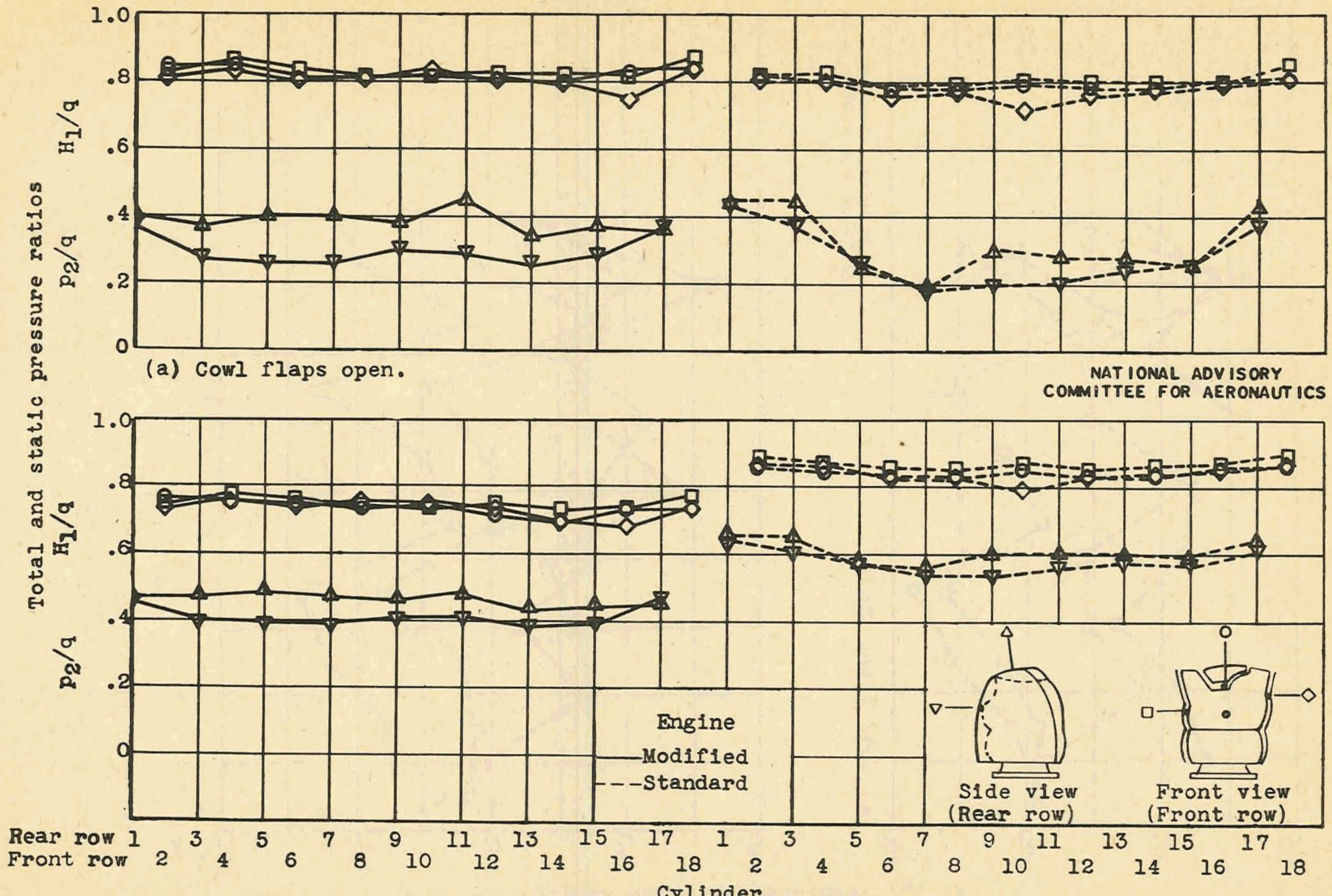


(a) Cowl flaps open.



(b) Cowl flaps closed.

Figure 19. - Typical cylinder-head temperature distribution.



(b) Cowl flaps closed.

Figure 20. - Typical cooling-air pressure distribution over engine cylinders.