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FLIGHT AND TEST-STAND INVESTIGATION OF HIGH-PERFORMANCE FUELS IN DOUBLE-ROW RADIAL AIR-COOLED ENGINES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

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SUMMARY

The cooling characteristics of a 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane have been investigated. All cooling data were obtained during a single flight at a pressure altitude of 7000 feet. The investigation was conducted in such a manner that the effects of charge-air flow, cooling-air pressure drop, and fuel-air ratio on the engine cooling characteristics could be separately investigated.

The flight cooling data were correlated by the method developed in NACA Report No. 612. Predictions of maximum engine temperatures and cooling-limited engine performance were then made from the correlation results for normal flight conditions of the airplane. Maximum temperatures at the rear middle of the cylinder barrel were greater than 350° F for all conditions investigated. Temperature-limited performance was predicted for head limits of 400° and 450° F. The temperature-limited performance predicted for 400° F and cowl flaps one-third open agreed very well with the manufacturer's specified maximum cruising power in combination with the carburetor-metering characteristic curve.

INTRODUCTION

At the request of the Army Air Forces, Air Technical Service Command, a general investigation on the evaluation of triptane and other high-antiknock fuel compounds as components of aviation fuels is being conducted at the NACA Cleveland laboratory. The first phase of the flight program - the determination of cooling characteristics of the engine - is presented herein. A correlation of the cooling characteristics is necessary in order to compare the cooling-limited power of the engine with the knock-limited power and thereby evaluate test fuels.

A flight was made with a 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane at a pressure altitude of 7000 feet, low blower ratio, an engine speed of 2230 rpm, and a spark advance of 25° B.T.C. The fuel was 28-R. The installation of cylinder thermocouples and cooling-air pressure tubes conformed to current NACA practice. The results obtained are described herein and a correlation of the engine cooling data based on the method developed in reference 1 is presented.

EQUIPMENT AND INSTRUMENTATION

The investigation was conducted with an R-1830-90C engine mounted in the left inboard nacelle of a B-24D airplane shown in figure 1. The engine is a 14-cylinder double-row radial air-cooled engine with a normal rated power of 1100 brake horsepower at 2550 rpm and take-off power of 1200 brake horsepower at 2700 rpm. The test engine differs from the engines which are standard equipment in the airplane in that it is equipped with a single-stage, two-speed supercharger having a low blower ratio of 7.15:1 and a high blower ratio of 8.47:1. A manual control was installed for the waste gate of the turbosupercharger to provide better boost control. The engine was equipped with a three-blade propeller and was fitted with a hydraulic torquemeter having a gear ratio of 16:9. A PD-12F2-16 injection carburetor, provided with a special mixture-control plate, was used on the test engine.

The airplane was so equipped that all data could be recorded within 10 seconds after stabilization. A 100-tube liquid manometer and a 60-cell NACA recording manometer were utilized for measuring the engine cooling-air pressures. The temperatures were indicated by means of two NACA recording galvanometers capable of recording 100 temperatures within a 10-second period. The carburetor was calibrated in an air box in order that the rate of air flow could be determined in flight by measuring the carburetor-air metering pressures. The air-box calibration was corrected for installation effect by a recalibration with the carburetor on the engine in the airplane and all ducting in place. Fuel flows were manually recorded from a rotameter and were checked by a deflecting-vane-type indicator. Fuel-air ratio was determined from fuel- and air-flow calculations and was checked by Orsat analysis of the oxidized exhaust gas.

Engine cooling-air pressure drop for the cylinder heads was taken as the average differential pressure between the three total pressures at the baffle entrance of the front-row cylinder heads and the two static pressures in the stagnation region behind the head baffle and in the baffle-exit curl of the rear-row cylinder heads. The cooling-air pressure drop across the engine for the barrels was taken in a similar manner using the two front pressures and the one static pressure in the baffle curl. The location of the pressure tubes on the cylinder baffles is illustrated in figure 2.

Cylinder-head temperatures used in the cooling analysis were measured by 14 embedded thermocouples, designated T_{38} in figure 2, inserted one third of the head-metal thickness into the rear-spark-plug boss of the cylinders. The thermocouple junction was located at the bottom of a brass bushing (1/8-in. diam.), as shown in figure 3. Figure 2 also shows the rear-spark-plug-gasket thermocouple T_{12} used in determining temperature limits in accordance with manufacturer's specifications.

The barrel temperature was measured by thermocouple T_6 in the rear middle of the cylinder outer wall between fins 6 and 7, counting from the top fin. (See fig. 2.) The junction of this thermocouple was spot-welded to the cylinder outer wall.

Free-air static pressure was measured by an NACA swiveling static-pressure boom and free-air temperature was indicated by a special six-junction pyrometer.

TEST PROCEDURE

The flight test was divided into three parts:

1. Charge-air flow was varied while the fuel-air ratio was held as close to 0.08 as possible and the engine cooling-air pressure drop was maintained approximately constant.

2. Cooling-air pressure drop was varied while fuel-air ratio and engine-air consumption were maintained approximately constant.

3. The fuel-air ratio was varied while cooling-air pressure drop and charge-air flow were maintained approximately constant.

CORRELATION PROCEDURE

The engine cooling data were reduced by the correlation method developed in reference 1. The standard equation developed in reference 1 may be presented in the form

$$\frac{T_h - T_a}{T_{g_h} - T_h} \text{ or } \frac{T_b - T_a}{T_{g_b} - T_b} = K \frac{M_e^{\,n}}{(\sigma \Delta p)^m}$$

where

T_a	cooling-air temperature, °F (computed stagnation temperature)
T_h	average (of 14 cylinders) cylinder-head temperature, °F
T_b	average (of 14 cylinders) cylinder-barrel temperature, °F
T_{g_h}	mean effective gas temperature for head, °F
T_{g_b}	mean effective gas temperature for barrel, °F
M_e	charge-air weight flow, $\frac{\text{pounds per hour}}{1000}$
σ	ratio of cooling-air stagnation density at face of engine to NACA standard density at sea level (stagnation density calculated from free-air pressure and temperature at each flight velocity)
Δp	cooling-air pressure drop, inches of water
n, m, K	constants derived from cooling data

The cooling equation can also be presented in the form

$$\frac{T - T_a}{T_g - T} = K \left(\frac{M_e^{\,n/m}}{\sigma \Delta p}\right)^m$$

where T designates engine temperature, either head or barrel.

The mean effective gas temperature T_g represents the average cycle gas temperature effective in the transfer of heat from gases within the cylinder chamber to the cylinder wall. The values of T_g, according to NACA cooling recommendations, are 1086° and 536° F for heads and barrels, respectively, at a fuel-air ratio of 0.08 and a carburetor-air temperature of 0° F. The calculations necessary for developing the correlation were based on a portion of a T_{g_0} curve parallel to the $T_{g_{80}}$ curves obtained with the same model double-row radial air-cooled engine mounted on a test stand. This portion of the assumed T_{g_0} curve was necessary for determining the constants in the cooling equation because flight conditions prevented maintaining a constant fuel-air ratio of 0.08 and because of the limitations in carburetor metering. The analysis presented in this report is based on T_{g_0}.

The mean effective gas temperature T_g was arrived at in the conventional manner (reference 2). Because of fuel vaporization in the intake manifolds, the temperature of the charge T_m could not be accurately measured by a thermocouple and was therefore taken as the sum of the carburetor-inlet temperature T_c and the computed temperature rise across the supercharger. The values of T_g were then determined from the following equations, which are completely derived in reference 2.

$$T_{g_h} = T_{g_{0h}} + 0.8\,T_m = T_{g_{0h}} + 0.8\left[T_c + 19.5\left(\frac{\text{engine rpm}}{1000}\right)^2\right] \quad \text{(heads)}$$

$$T_{g_b} = T_{g_{0b}} + 0.8\left(\frac{T_{g_b}}{T_{g_h}}\right)T_m = T_{g_{0b}} + 0.42\left[T_c + 19.5\left(\frac{\text{engine rpm}}{1000}\right)^2\right] \quad \text{(barrels)}$$

Curves used for determining the exponents n and m are presented in figures 4 and 5. The exponents n were determined from the slopes of the curves in figure 4 in which charge-air flow is plotted against $\dfrac{T - T_a}{T_g - T}$ at a constant cooling-air pressure drop Δp and a fuel-air ratio of 0.08. The exponents m were determined in a similar manner from figure 5 in which $\sigma\Delta p$ is the variable instead of charge-air flow. Correlation curves were then obtained by plotting $\dfrac{T - T_a}{T_g - T}$ against $\dfrac{M_e^{n/m}}{(\sigma\Delta p)}$ for heads and for barrels.

Constant conditions were difficult to maintain in flight; therefore, corrections had to be made for variations of M_e and $\sigma\Delta p$ during runs when either of these factors was supposedly held constant. A series of preliminary graphs was made for both the construction curves and the correlation lines until the error due to the variations of $\sigma\Delta p$ and M_e was reduced to a negligible amount. The final correlation curves are shown in figure 6.

Curves of T_{g_0} against fuel-air ratio for heads and barrels (fig. 7) were determined from runs at variable fuel-air ratio during which Δp and engine charge-air flow were maintained as nearly constant as possible.

RESULTS AND DISCUSSION

The final correlation curves (fig. 6) represents the cooling characteristics of the engine at a pressure altitude of 7000 feet. These characteristics may be mathematically expressed by the following equations:

$$\frac{T_h - T_a}{T_{g_h} - T_h} = 0.324\left[\frac{M_e^{0.636}}{(\sigma\Delta p)^{0.321}}\right] \text{ or } 0.324\left(\frac{M_e^{1.98}}{\sigma\Delta p}\right)^{0.321} \quad \text{(heads)}$$

$$\frac{T_b - T_a}{T_{g_b} - T_b} = 0.791\left[\frac{M_e^{0.737}}{(\sigma\Delta p)^{0.438}}\right] \text{ or } 0.791\left(\frac{M_e^{1.68}}{\sigma\Delta p}\right)^{0.438} \quad \text{(barrels)}$$

The equations apply for values of T_g obtained from the T_{g_0} curve established in this test.

The deviations of the maximum cylinder temperature from the average cylinder temperature, as determined in flight, are shown for heads and barrels in figures 8 and 9, respectively. These curves are included to permit the prediction of maximum temperatures from the average temperatures, which were obtained by means of the cooling equation. In order to compare the temperatures predicted by the cooling equation with the maximum cylinder temperatures specified by the engine manufacturer (reference 3), a curve showing the relation between the average rear-spark-plug-boss temperature T_{38} used for the correlation and the maximum rear-spark-plug-gasket temperature $T_{12_{max}}$ was plotted. (See fig. 10.) For the normal operating conditions of the airplane specified in the flight manual (reference 4), the maximum temperatures tabulated in the last column of table I could be expected. These predicted temperatures are based on Army summer air. The barrel temperatures predicted by the cooling equation were in all cases higher than those corresponding to the limitations set by the manufacturer for the rear of the cylinder flange; the manufacturer's maximum head-temperature limitations appear to be satisfied within a reasonable margin. The top rear-row cylinders were the hottest during the cooling test and were usually in a decreasing order of 3, 1, 13, and 5.

Figure 11 shows the predicted temperature-limited manifold pressure, brake horsepower, and rear middle-barrel temperatures expected during flight of the airplane of 50,000 pounds gross weight at a density altitude of 7000 feet for maximum rear-spark-plug-gasket temperatures of 400° and 450° F. Calculations were made by the use of the cruise control chart for the B-24D airplane (reference 4) and air-flow manifold-pressure data obtained with high-performance fuels. Inasmuch as the maximum cowl-flap opening specified by the airplane manufacturer is one-third open, no wider settings were investigated. The engine manufacturer's instructions for maximum cruise with the test engine specify a manifold pressure of 28 inches of mercury absolute at 2250 rpm, low blower ratio, and automatic-lean setting. The automatic-lean, carburetor-metering characteristic curve in figure 11 indicates that this cruising power falls close to the estimated temperature-limited performance curve for a maximum rear-spark-plug-gasket temperature of 400° F with cowl flaps one-third open.

Cooling of the double-row radial air-cooled engine is more critical for cylinder barrels than for heads, according to the manufacturer's temperature limits. This limit for cylinder barrels is 335° F at the rear of the cylinder flange, which was found to be approximately equivalent to a rear middle-barrel temperature of 350° F on the same model engine on a test stand upon which both temperatures were simultaneously measured. Barrel temperatures predicted by the cooling equation exceed the limitations set by the manufacturer by a considerable amount. The predicted temperatures have been substantiated by measured temperatures above 400° F on the rear middle barrel during take-off, cruise, and normal landing approach. Because the engine cooling-air pressure drop for the airplane is exceptionally high, temperatures higher than those observed during these tests could be expected for this engine when installed in certain other airplanes. The cooling-air pressure drop for the installation investigated varied from 0.5 of the free-stream impact pressure with cowl flaps closed to 0.95 of the free-stream impact pressure with cowl flaps full-open.

SUMMARY OF RESULTS

The following cooling characteristics were determined for a 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane:

1. The cooling equation for the engine was:

$$\frac{T_h - T_a}{T_{g_h} - T_h} = 0.324 \left[\frac{M_e^{0.636}}{(\sigma \Delta p)^{0.321}} \right] \text{ (heads)}$$

$$\frac{T_b - T_a}{T_{g_b} - T_b} = 0.791 \left[\frac{M_e^{0.737}}{(\sigma \Delta p)^{0.438}} \right] \text{ (barrels)}$$

2. The predicted rear middle-barrel temperatures for the flight conditions investigated exceeded 350° F, which corresponds to the manufacturer's limit of 335° F at the rear of the cylinder flange.

3. The predicted cooling-limited manifold pressure, based on assumed operation of the airplane with four double-row radial air-cooled engines at 2230 rpm with cowl flaps one-third open, varies from 28 inches of mercury absolute at a fuel-air ratio of 0.067 to 52 inches of mercury absolute at a fuel-air ratio of 0.10 for a maximum rear-spark-plug-gasket temperature of 400° F (desired operating temperature); the range of manifold pressure was from 44 to 85 inches of mercury absolute for cowl flaps one-third open and a maximum rear-spark-plug-gasket temperature of 450° F (maximum cruising temperature).

4. The manufacturer's specified maximum cruising power at an engine speed of 2250 rpm agreed closely with the temperature-limited power for a maximum rear-spark-plug-gasket temperature of 400° F with cowl flaps one-third open.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 20, 1944.

REFERENCES

1. Pinkel, Benjamin: Heat-Transfer Processes in Air-Cooled Engine Cylinders. NACA Rep. No. 612, 1938.

2. Corson, Blake W., Jr., and McLellan, Charles H.: Cooling Characteristics of a Pratt & Whitney R-2800 Engine Installed in an NACA Short-Nose High-Inlet-Velocity Cowling. NACA ACR No. L4F06, 1944.

3. Anon.: Operators Handbook (Part No. 51548). Twin Wasp C4 Engine. Pratt & Whitney Aircraft, 3d ed., March 1942.

4. Anon.: Flight Manual, B-24D and J Heavy Bombardment Airplane. Consolidated-Vultee Aircraft Corp., Jan. 1944.

TABLE I - COMPARISON OF MANUFACTURER'S TEMPERATURE LIMITS WITH PREDICTED MAXIMUM TEMPERATURES FOR NORMAL OPERATING CONDITIONS

Operating condition	Engine speed (rpm)	Manifold pressure (in. Hg abs.)	Brake horsepower	Mixture setting	Cowl-flap position	Location	Manufacturer's temperature limits[a] (°F)	Predicted maximum temperatures[b] (°F)
Military power	2700	45	1200	Automatic rich	1/3 open	Head Barrel	500 [c]350	417 386
Take-off	2700	48	1200	Automatic rich	1/4 to 1/3 open	Head Barrel	500 350	506 450
Normal rated power	2550	41	1100	Automatic rich	1/4 to 1/3 open	Head Barrel	450 350	409 380
Maximum cruise	2250	28	700	Automatic lean	Closed	Head Barrel	450 350	413 395
Minimum specific fuel consumption	1750	31	550	Automatic lean	Closed	Head Barrel	450 350	396 390
Normal landing approach	2550	20 (approx.)	------	Automatic rich	Closed	Head Barrel	------------ ------------	435 418

[a]Manufacturer's temperature limit. Head temperatures are rear-spark-plug-gasket temperatures T_{12}; barrel temperatures are rear middle-barrel temperatures T_6.

[b]Calculations except for take-off power based on Army summer air at pressure altitude of 7000 feet, cooling-air and carburetor-air temperatures of 60° F. Temperatures given are as in footnote a.

[c]Rear middle-barrel temperature of 350° F was found to correspond to a temperature of 335° F at the rear cylinder flange specified by the manufacturer.

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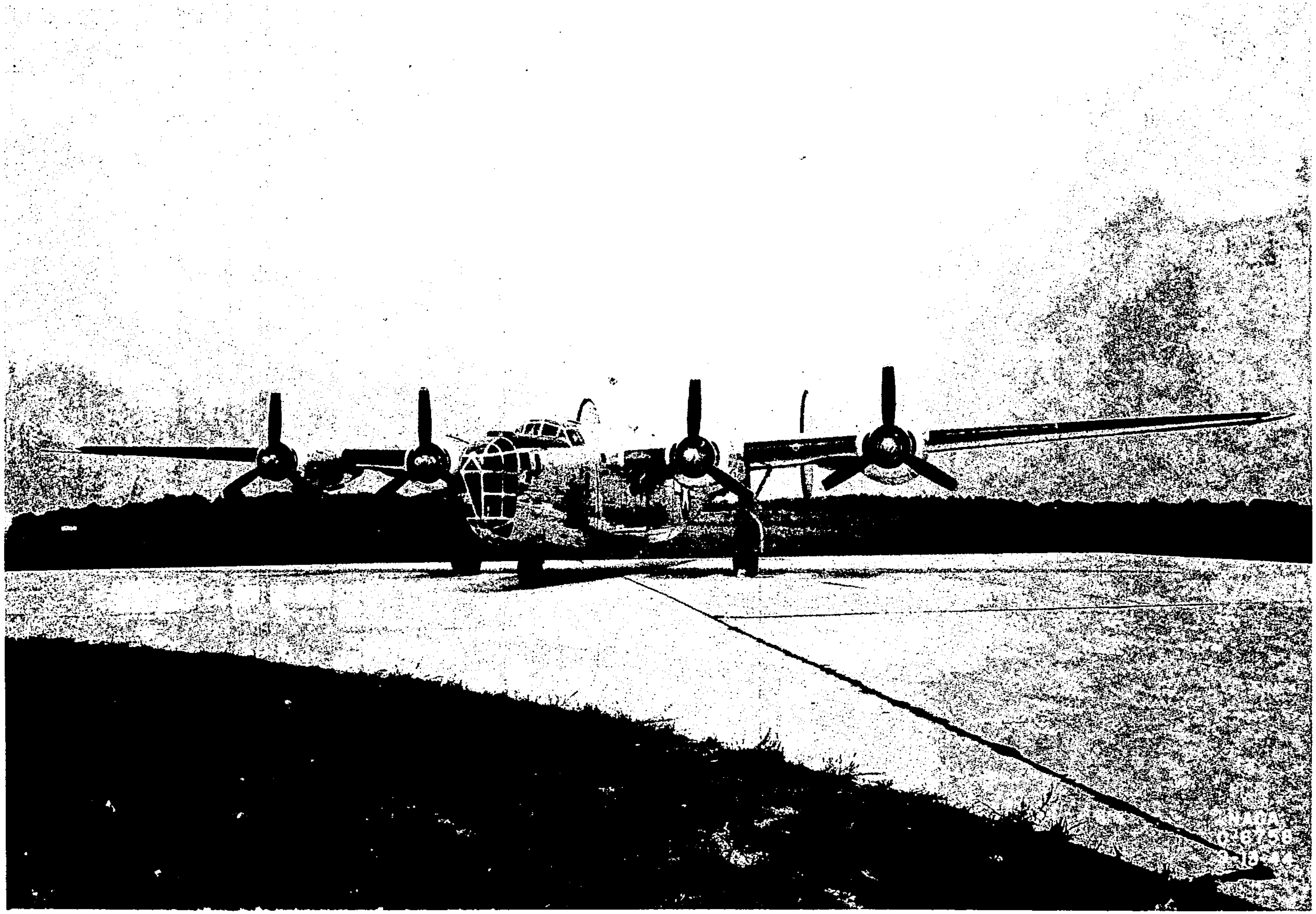


Figure 1. - View of four-engine airplane used for flight knock and cooling investigation.

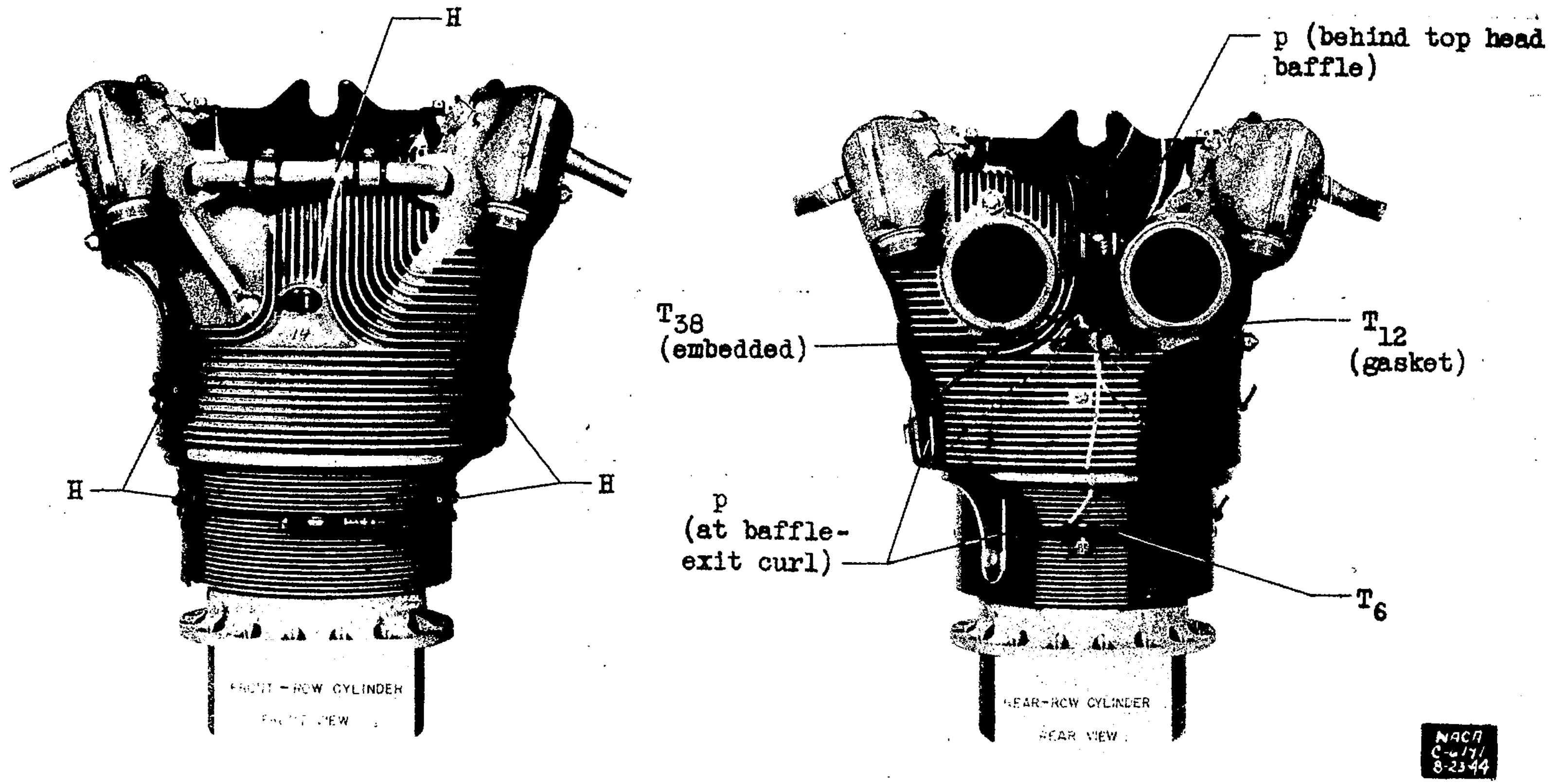
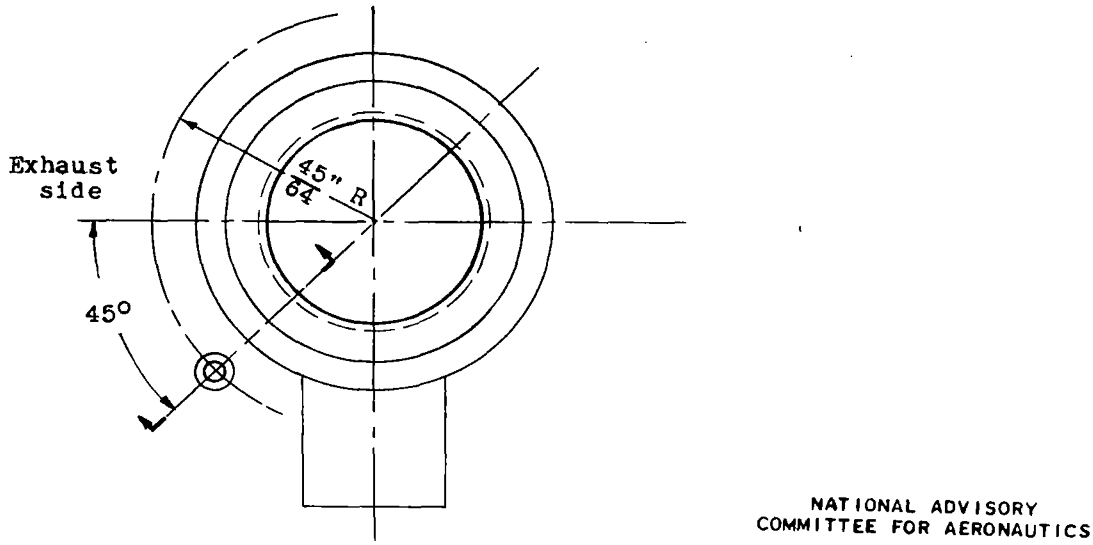
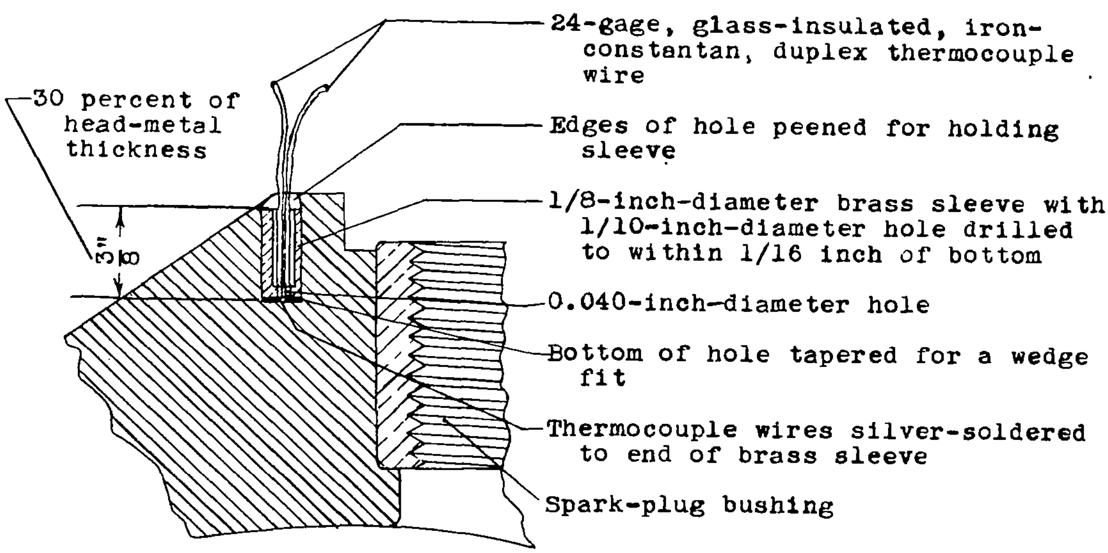


Figure 2. - Typical installation of total-pressure tubes H, static-pressure tubes p, and thermocouples T used on air-cooled cylinders.



(a) Method of locating thermocouple.



(b) Method of installing thermocouple.

Figure 3. - Methods of locating and installing embedded thermocouple T_{38} in rear-spark-plug boss on cylinder head of double-row radial air-cooled engine.

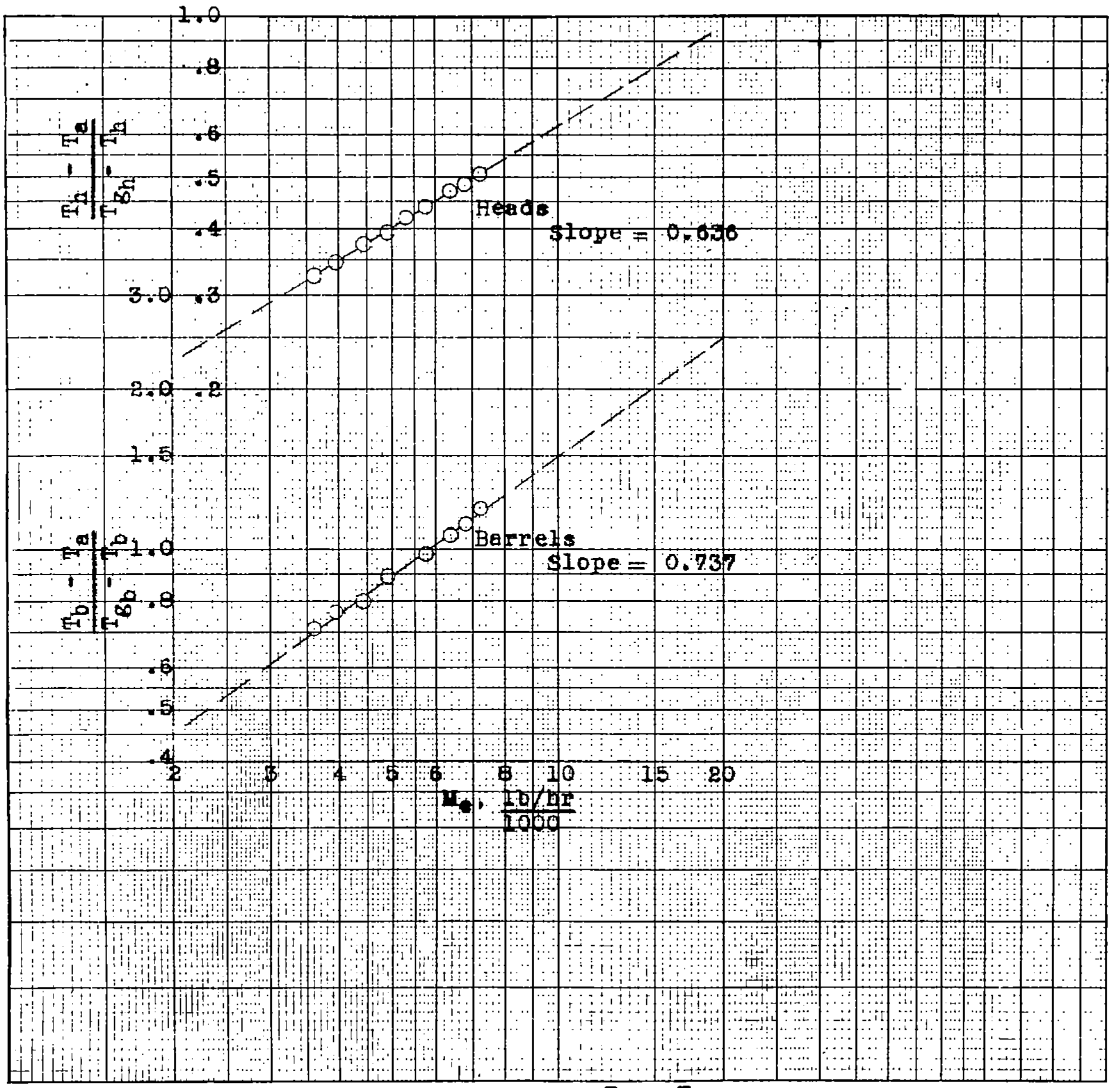


Figure 4. - Variation of $\frac{T_h - T_a}{T_{g_h} - T_h}$ and $\frac{T_b - T_a}{T_{g_b} - T_b}$ with M_e at a pressure altitude of 7000 feet. $\sigma\Delta p$, 12.5 inches of water for head and 11.7 inches of water for barrel; low blower ratio; fuel-air ratio, 0.08; engine speed, 2230 rpm; spark advance, 25° B.T.C.

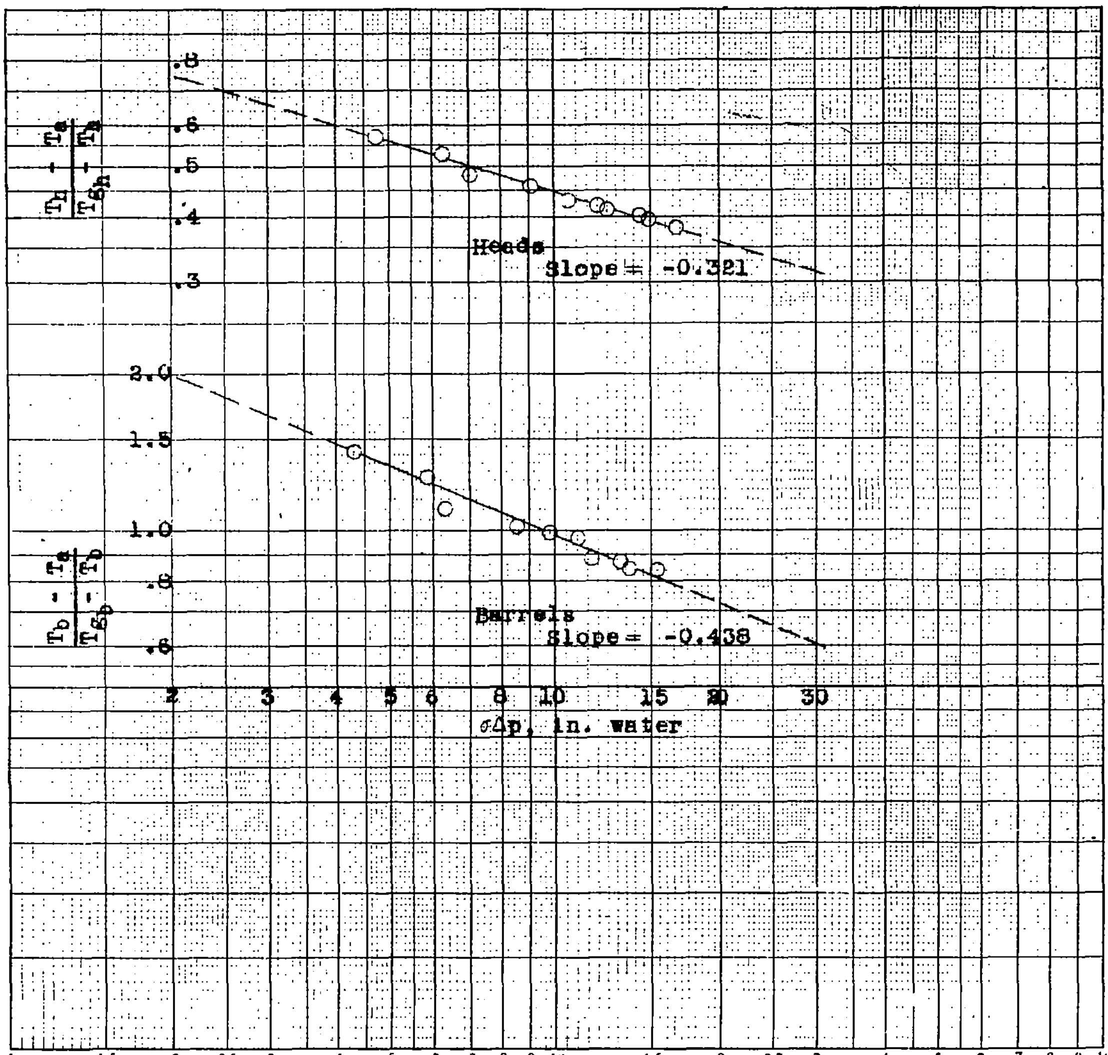


Figure 5. - Variation of $\frac{T_h - T_a}{T_{g_h} - T_h}$ and $\frac{T_b - T_a}{T_{g_b} - T_b}$ with $\sigma\Delta p$ at a pressure altitude of 7000 feet. Charge-air flow, 5000 pounds per hour; low blower ratio; fuel-air ratio, 0.08; engine speed, 2230 rpm; spark advance, 25° B.T.C.

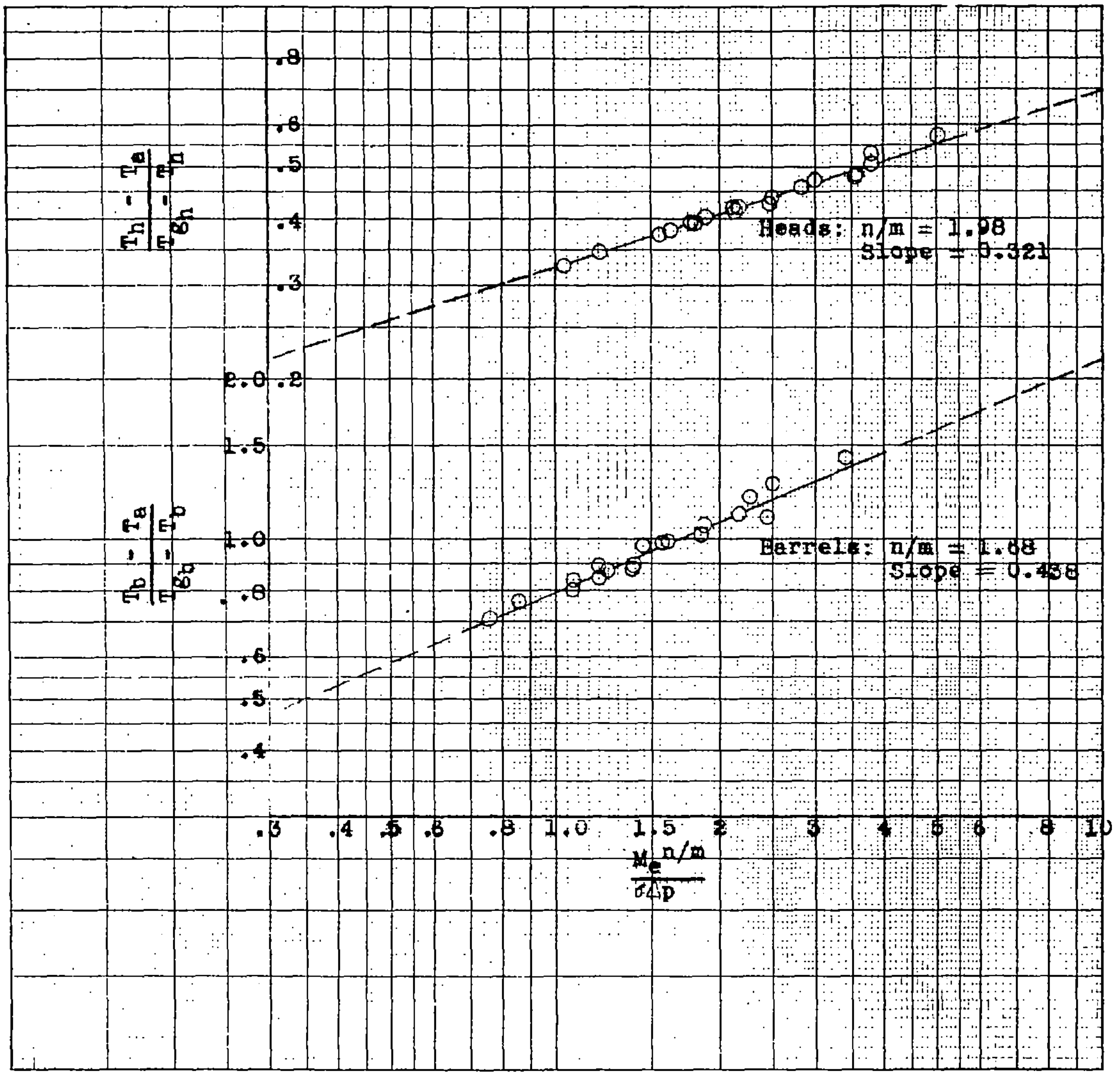


Figure 6. - Cooling-correlation curve at a pressure altitude of 7000 feet. Low blower ratio; engine speed, 2230 rpm; spark advance, 25° B.T.C.

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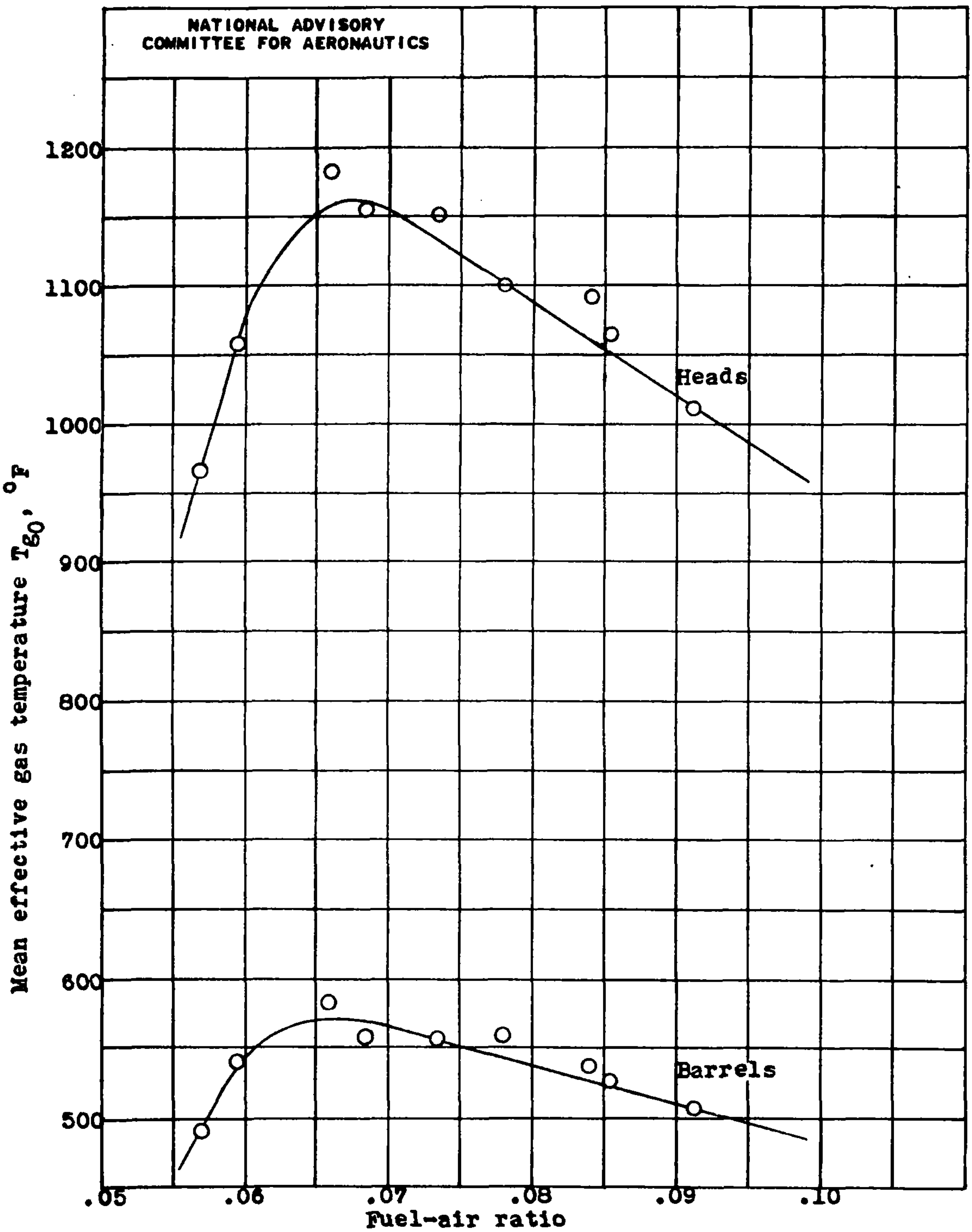

Figure 7. - Variation of mean effective gas temperature T_{g0} with fuel-air ratio. $\sigma\Delta p$, 12 to 14 inches of water; charge-air flow, 5210 to 5360 pounds per hour; low blower ratio; engine speed, 2230 rpm; spark advance, 25° B.T.C.

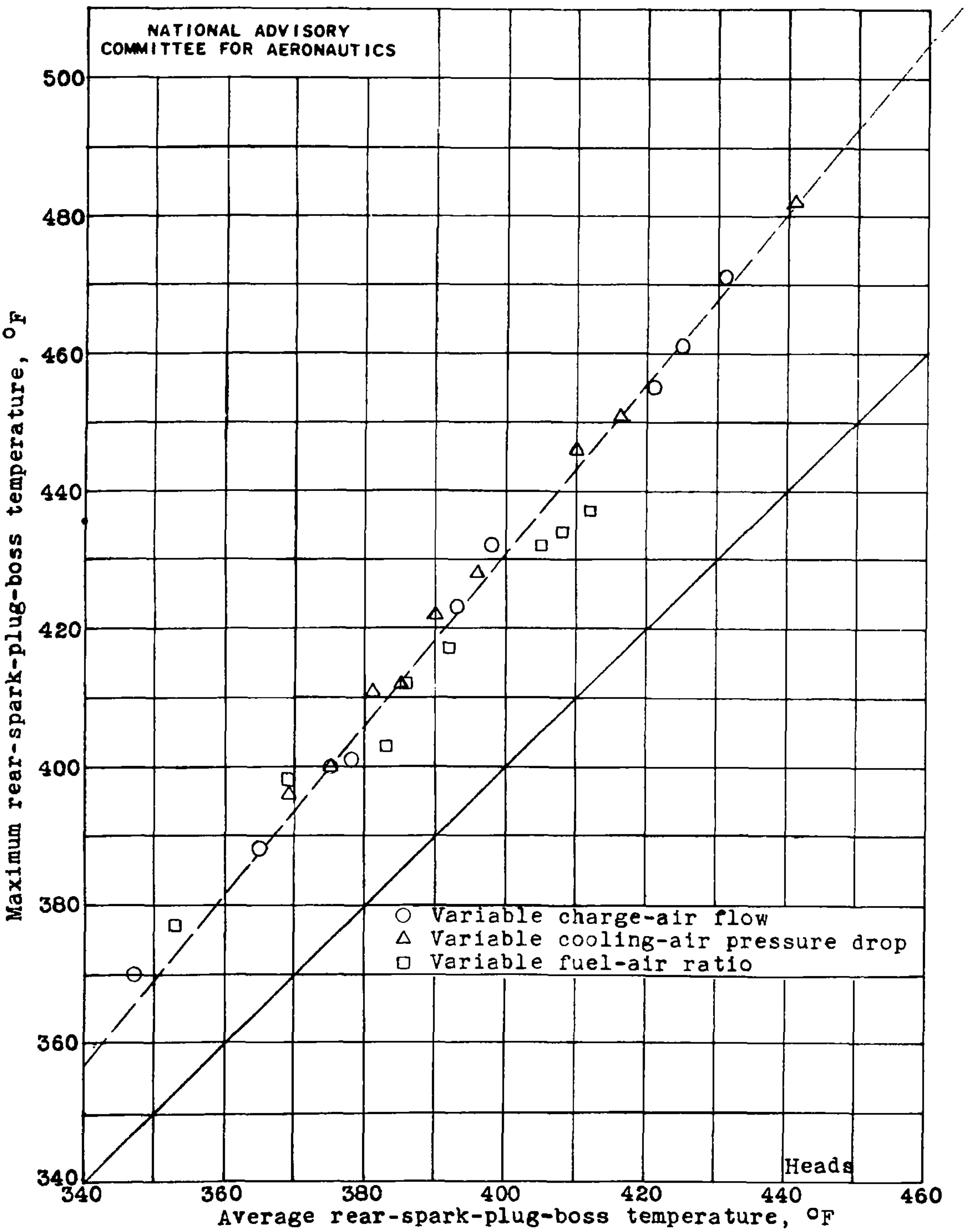

Figure 8. - Deviation of maximum from average rear-spark-plug-boss temperature measured by embedded thermocouples.

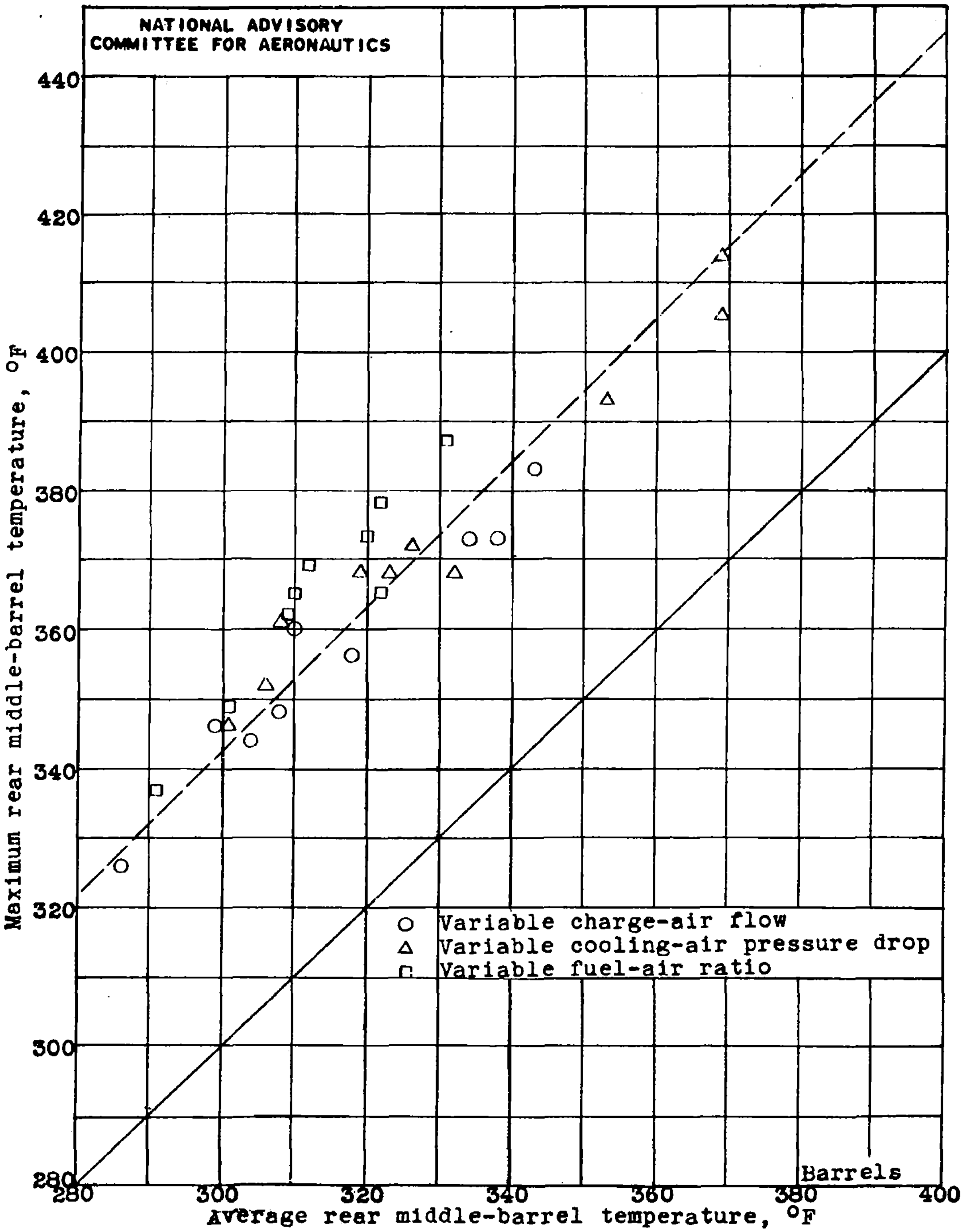

Figure 9. - Deviation of maximum from average rear middle-barrel temperature.

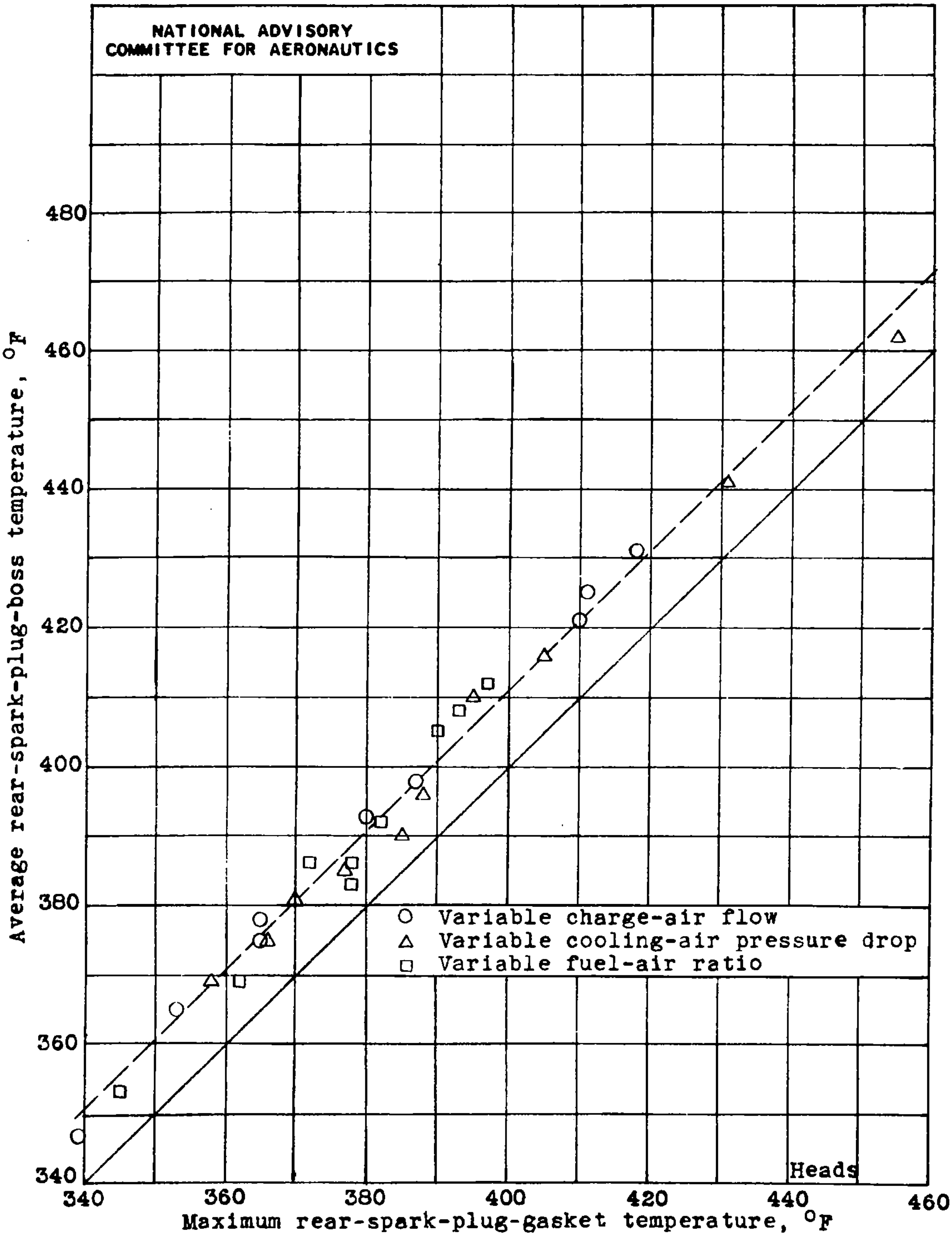

Figure 10. - Comparison of average rear-spark-plug-boss temperature, measured by embedded thermocouples, with maximum rear-spark-plug-gasket temperature.

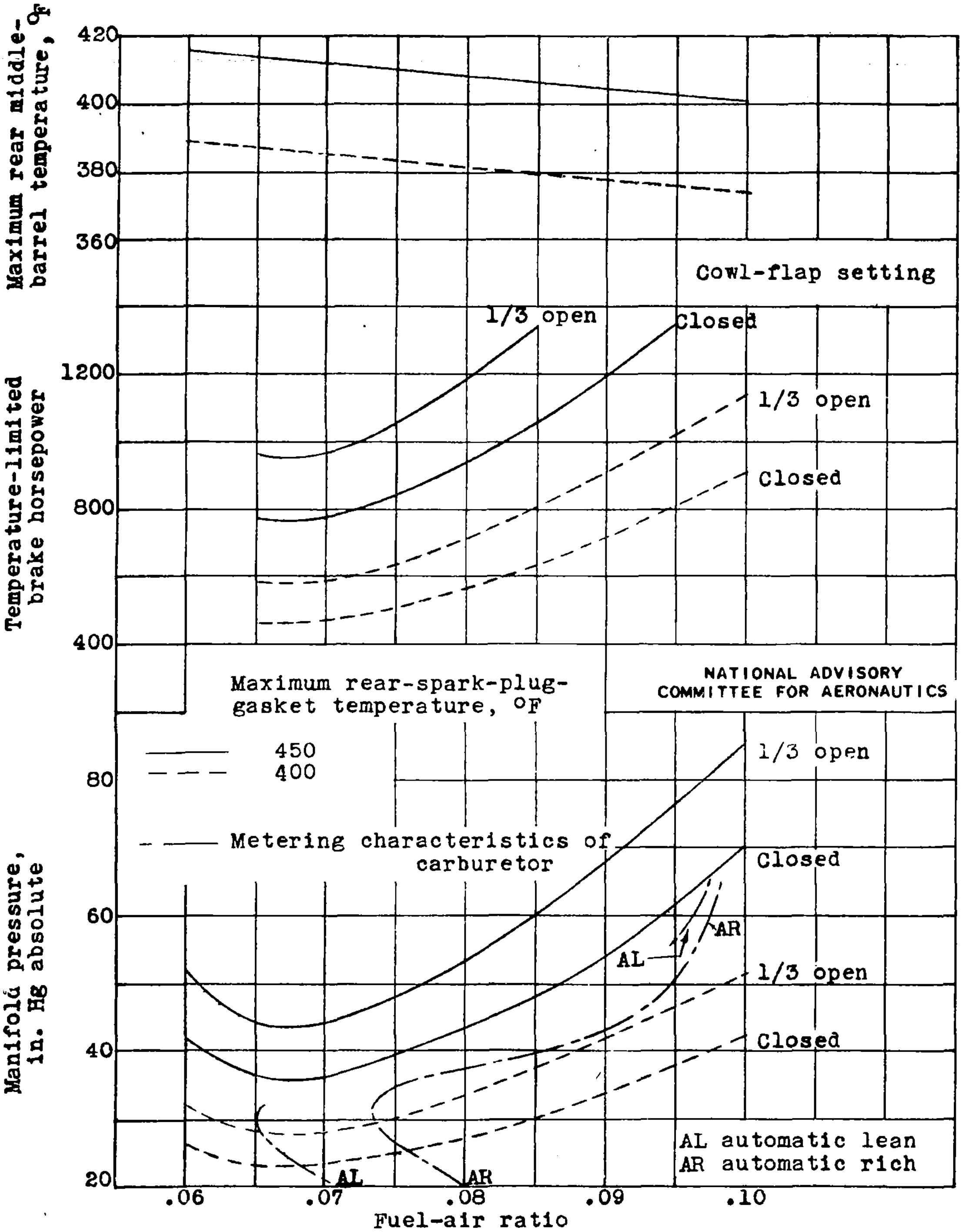

Figure 11. - Predicted temperature-limited manifold pressure, brake horsepower and corresponding maximum rear middle-barrel temperatures for normal flight of four-engine airplane with maximum rear-spark-plug-gasket temperatures of 400° and 450° F. Army summer-air; altitude, 7000 feet; low blower ratio; engine speed, 2230 rpm; spark advance, 25° B.T.C.