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RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

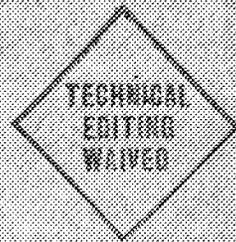
EFFECT OF EXHAUST PRESSURE ON THE COOLING CHARACTERISTICS
OF A LIQUID-COOLED ENGINE

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EFFECT OF EXHAUST PRESSURE ON THE COOLING CHARACTERISTICSOF A LIQUID-COOLED ENGINE

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SUMMARY

Data for a liquid-cooled engine with a displacement volume of 1710 cubic inches were analyzed to determine the effect of exhaust pressure on the engine cooling characteristics. The data covered a range of exhaust pressures from 7 to 62 inches of mercury absolute, inlet-manifold pressures from 30 to 50 inches of mercury absolute, engine speeds from 1600 to 3000 rpm, and fuel-air ratios from 0.063 to 0.100.

The effect of exhaust pressure on engine cooling was satisfactorily incorporated in the NACA cooling-correlation method as a variation in effective gas temperature with exhaust pressure.

Large variations of cylinder-head temperature with exhaust pressure were obtained for operation at constant charge flow. At a constant charge flow of 2 pounds per second (approximately 1000 bhp) and a fuel-air ratio of 0.085, an increase in exhaust pressure from 10 to 60 inches of mercury absolute resulted in an increase of 40° F in average cylinder-head temperature.

For operation at constant engine speed and inlet-manifold pressure and variable exhaust pressure (variable charge flow), however, the effect of exhaust pressure on cylinder-head temperature is small. For example, at an inlet-manifold pressure of 40 inches of mercury absolute, an engine speed of 2400 rpm, and a fuel-air ratio of 0.085, the average cylinder-head temperature was about the same at exhaust pressures of 10 and 60 inches of mercury absolute; a rise and a subsequent decrease of about 7° occurred between these extremes.

INTRODUCTION

The operation of reciprocating engines over a wide range of altitudes and the current interest in engine-turbine combinations have emphasized the importance of the effect of exhaust pressure on performance and cooling.

The effect of exhaust pressure on engine performance is shown in references 1 and 2 for multicylinder air-cooled engines. Data for a multicylinder liquid-cooled engine have been furnished the Army Air Forces in preliminary form.

The effect of exhaust pressure on the cooling of a multicylinder air-cooled engine was presented in reference 3, which incorporated the exhaust-pressure effect in the NACA cooling-correlation method for air-cooled engines. The correlation method was developed in reference 4 and has been extensively applied to single and multicylinder air-cooled engine data. (See, for example, reference 5.)

A cooling correlation similar to that developed in reference 4 for air-cooled engines is presented in references 6 and 7 for single-cylinder and multicylinder liquid-cooled engines, respectively. The data included in references 6 and 7 were obtained at sea-level exhaust pressure and hence did not determine the effect of variation of exhaust pressure on cooling.

The effect of exhaust pressure on the cooling of a multicylinder liquid-cooled engine as determined from an analysis of the data obtained in the investigation previously published in preliminary form is presented. These data cover a range of exhaust pressures from 7 to 62 inches of mercury absolute for various combinations of engine speed, inlet-manifold pressure, and fuel-air ratio.

The data are correlated by the method of references 6 and 7 and the effect of exhaust pressure on cooling is included as a variation in effective gas temperature in a similar manner to that used in reference 3 for the air-cooled engine.

APPARATUS AND PROCEDURE

The dynamometer-stand investigation from which the data for this analysis were obtained was conducted on a 12-cylinder, liquid-cooled V-1710 engine equipped with a single-stage supercharger having an impeller diameter of 9.5 inches and a gear ratio of 8.1:1.

The compression ratio of the engine was 6.65, reduction gear ratio 2:1, and spark advance 28° B.T.C. on the inlet side and 34° B.T.C. on the exhaust side.

A general view of the test setup is shown in figure 1. The engine was connected by an extension shaft and two flexible couplings to a 2000-horsepower eddy-current dynamometer.

The exhaust-gas collector was the type used on the P-38 airplane modified to incorporate bellows-type expansion joints to insure a gas-tight system. The collector was attached to the laboratory altitude exhaust system through a length of 8-inch pipe. A piezometer ring located approximately 1 foot downstream of the junction of the two collector halves was used in measuring the engine exhaust pressure.

The coolant used was a mixture of approximately 70 percent (by volume) ethylene glycol and 30 percent water. The actual composition of the coolant was regularly checked by determining its boiling point. Coolant-flow rates were measured with a thin-plate orifice installed according to A.S.M.E. specifications. Coolant temperatures were measured with single copper-constantan thermocouples mounted in the inlet and the outlet of each cylinder bank. The coolant temperature was taken as the average of the inlet and the outlet temperatures.

Cylinder-head temperatures were measured with 12 iron-constantan thermocouples, one embedded between each pair of exhaust valves. The cylinder-head temperature T_h was taken as the average of the 12 thermocouple readings. The location of a thermocouple in the cylinder head is shown in figure 2.

The carburetor-air temperature was measured with four iron-constantan thermocouples connected in parallel and mounted just above the carburetor top deck. Combustion-air flow was measured with a thin-plate orifice installed according to A.S.M.E. specifications and the fuel flow (AN-F-28) was measured with a rotameter.

The investigation covered a range of exhaust pressures from approximately 7 to 62 inches of mercury absolute, engine speeds from 1600 to 3000 rpm, inlet-manifold pressures from 30 to 50 inches of mercury absolute, and fuel-air ratios from 0.063 to 0.100.

The procedure followed in obtaining the data was to maintain a specified engine speed, inlet-manifold pressure, and fuel-air

ratio while the exhaust pressure was varied in increments over the range investigated. The coolant flow was held constant for each variable-exhaust-pressure series of runs and the coolant-out temperature was held constant ($220^{\circ} \pm 5^{\circ} \text{F}$) throughout the program by an automatic mixing valve on the inlet side of the engine. Sufficient time was allowed at each point to permit the cylinder-head temperatures to stabilize.

CORRELATION METHOD

Correlation equation. - In reference 6, a form of the following expression relating the cylinder-head temperatures and the engine and coolant conditions is developed:

$$\frac{T_g - T_h}{T_h - T_l} \left[B_1 \left(\frac{W_l}{\mu} \right)^{-m} \left(\frac{1}{k \text{ Pr}^s} + Z \right) \right] = W_c^{-n} \quad (1)$$

where

- B_1 constant
- c specific heat of coolant, (Btu)/(lb)($^{\circ}\text{F}$)
- k thermal conductivity of coolant, (Btu)/(sec)(sq ft)($^{\circ}\text{F}/\text{ft}$)
- m, n, s exponents
- T_g effective gas temperature, ($^{\circ}\text{F}$)
- T_h average cylinder-head temperature, ($^{\circ}\text{F}$)
- T_l average coolant temperature, ($^{\circ}\text{F}$)
- W_c charge (air plus fuel) flow, (lb)/(sec)
- W_l coolant flow, (lb)/(sec)
- Z constant of engine that accounts, in effect, for temperature drop through wall of cylinder head
- μ absolute viscosity of coolant, (lb)/(ft)(sec)
- Pr Prandtl number, c_p/k , dimensionless

For constant coolant flow and coolant temperature, hence, constant coolant properties, equation (1) reduces to

$$\frac{T_h - T_l}{(T_g - T_h)W_c^n} = B_2 \quad (2)$$

where B_2 is a constant.

Engine operating conditions, which affect cooling but are not specifically indicated in equations (1) or (2), are fuel-air ratio, inlet-manifold temperature, spark advance, and exhaust pressure. The first three of these variables have been included in the cooling correlation for both air-cooled and liquid-cooled engines through their influence on T_g (references 3 to 7). In reference 3 the exhaust-pressure effect was also represented in the cooling correlation for air-cooled engines as a variation of T_g and will be so considered in this analysis for the liquid-cooled engine.

Effect of exhaust pressure on cooling. - Equation (2) was used to determine the effect of exhaust pressure on T_g (hence cooling) inasmuch as the runs were made with the coolant flow and coolant temperature held constant for each series of variable-exhaust-pressure runs. Equation (2) was first solved for the constant B_2 by using values of T_h , T_l , and W_c from the sea-level exhaust-pressure runs and corresponding values of T_g previously established for sea-level exhaust pressure. The method of obtaining the initial values of T_g for the proper fuel-air ratios and the manner of correcting for inlet-manifold temperature is outlined in the appendix. The determination of the exponent n required for these calculations will be subsequently described.

The constant B_2 thus determined was then used in equation (2) along with values of T_h , T_l , and W_c from runs at other than sea-level exhaust pressure in the same series to determine the corresponding values of T_g and hence its variation with exhaust pressure. These values were then corrected to a standard inlet-manifold temperature of 80° F (see the appendix) and are hereinafter designated $T_{g,80}$.

Final correlation plot. - In order to present all of the data in a final correlation plot, the correlation equation (1) should be used in its complete form. Because the type of data obtained in

this investigation was unsuitable for the determination of the constants (B_1 , m , n , s , and Z), the following values obtained from a previous unpublished analysis of a large amount of data from a similar engine were applied to the present data:

$$B_1 = 0.00135$$

$$m = 0.46$$

$$n = 0.6$$

$$s = 0.33$$

The value of Z , which represents the effect of the thermal resistance to heat flow through the cylinder wall, depends on the location of the thermocouple used in determining T_h and was unknown for the present installation. A value of Z of 0.13 had been obtained in the previous analysis but for a different thermocouple location. In the present analysis, values from 0.13 to 0.16 were tried and 0.15 was found to give the best correlation of the data. The physical properties (c , μ , and k) of the ethylene-glycol and water mixture were obtained from reference 8. The substitution of the numerical values for B_1 , m , n , and s in equation (1) gives

$$\frac{T_g - T_h}{T_h - T_l} \left[0.00135 \left(\frac{W_l}{\mu} \right)^{-0.46} \left(\frac{1}{k \text{ Pr}^{0.33}} \right) + 0.15 \right] = W_c^{-0.6} \quad (3)$$

The final correlation curve may then be made by plotting the left-hand side of equation (3) against W_c .

RESULTS AND DISCUSSION

Variation of $T_{g,80}$ with exhaust pressure. - The effect of exhaust pressure on the corrected effective gas temperature $T_{g,80}$ is shown on figure 3 for fuel-air ratios of 0.100, 0.085, 0.069, and 0.063. At fuel-air ratios of 0.100, 0.085, and 0.069, curves for the air-cooled engine (dashed lines) of reference 3 are included for comparison. Except for a few data points at the extremities of the curves, good correlation of $T_{g,80}$ with exhaust pressure is obtained. The effective gas temperature increases as the exhaust pressure increases; the effect becomes slightly more pronounced at the lean mixtures.

Close examination of the data revealed no trend with engine speed. A slight effect of inlet-manifold pressure may be observed. There is a tendency for the low inlet-manifold pressures to give low values of $T_{g,80}$ at the low exhaust pressures and high values of $T_{g,80}$ at the high exhaust pressures. A similar inlet-manifold-pressure trend was also observed with the air-cooled engine of reference 3.

The difference in the absolute levels of the curves for the liquid-cooled and air-cooled engines is due to differences in the variation of T_g with fuel-air ratio. (See the appendix.) At exhaust pressures up to about 45 inches of mercury absolute and at all fuel-air ratios, the effect of exhaust pressure on the cooling of the two engines is approximately the same. At exhaust pressures above 45 inches of mercury absolute and fuel-air ratios below 0.100, however, the air-cooled engine appears to be slightly more sensitive to exhaust pressure.

For convenience, figure 3 is cross-plotted in figure 4 to show the variation of $T_{g,80}$ with fuel-air ratio for several exhaust pressures.

Final correlation plot. - Final correlation plots for the cooling data obtained at an inlet-manifold pressure of 40 inches of mercury absolute, fuel-air ratios of 0.085 and 0.100, and engine speeds of 1600, 2000, 2400, 2600, and 3000 rpm are presented in figure 5 in accordance with equation (3). Figure 5(a) was plotted to illustrate the large amount of scatter resulting when the effect of exhaust pressure is neglected. In figure 5(b) the correlation is markedly improved by taking account of the effect of exhaust pressure on cooling.

Variation of average cylinder-head temperature with exhaust pressure. - The variation of average cylinder-head temperature with exhaust pressure is presented in figure 6 for a constant charge flow of 2 pounds per second (approximately 1000 bhp), constant coolant flow of 28.4 pounds per second and temperature of 212° F, constant inlet-manifold temperature of 200° F, and fuel-air ratios of 0.069, 0.085, and 0.100. These curves were plotted from values of T_h obtained by use of the final correlation curves of figure 5(b) in conjunction with the curves of $T_{g,80}$ plotted against exhaust pressure (fig. 3). The curves indicate a large change in average

cylinder-head temperature with exhaust pressure for operation at constant charge flow. For example at a fuel-air ratio of 0.085, a change in exhaust pressure from 10 to 60 inches of mercury absolute results in an increase of approximately 40° F in cylinder-head temperature.

The average cylinder-head-temperature data for representative runs at a constant engine speed of 2400 rpm for various constant inlet-manifold pressures and fuel-air ratios are plotted in figure 7 against exhaust pressure. For this type of operation (constant manifold pressure), the effect of exhaust pressure on average cylinder-head temperature is small. For example, at 2400 rpm, a manifold pressure of 40 inches of mercury absolute, and a fuel-air ratio of 0.085, the head temperature is about the same at exhaust pressures of 10 and 60 inches of mercury absolute; an increase and subsequent decrease of about 7° F occurred between these extremes. The small change in cylinder-head temperature in this case is due to the compensating effects of increase in T_g and to the reduction in charge flow accompanying the increased exhaust pressure. For the example just given, the charge flow at the exhaust pressure of 60 inches of mercury absolute was approximately 70 percent of its value at the exhaust pressure of 10 inches of mercury absolute.

SUMMARY OF RESULTS

An analysis of cooling data obtained from a dynamometer-stand investigation on a liquid-cooled engine of 1710 cubic-inch displacement volume covering a range of exhaust pressures from 7 to 62 inches of mercury absolute, engine speeds from 1600 to 3000 rpm, inlet-manifold pressures from 30 to 50 inches of mercury absolute, and fuel-air ratios from 0.063 to 0.100 indicated that:

1. The effect of exhaust pressure on the cooling of a multi-cylinder liquid-cooled engine could be satisfactorily included in the NACA cooling-correlation method as a variation in effective gas temperature.
2. For operation at constant charge flow, exhaust pressure had a large effect on average cylinder-head temperatures. At a constant charge flow of 2 pounds per second (approximately 1000 bhp), an increase in exhaust pressure from 10 to 60 inches of mercury absolute resulted in an increase in cylinder-head temperature of 40° F.

3. The effect of exhaust pressure on average cylinder-head temperatures for operation at constant engine speed and inlet-manifold pressure (variable charge flow) was small. For a typical set of engine conditions (inlet-manifold pressure, 40 in. Hg absolute; engine speed, 2400 rpm; fuel-air ratio, 0.085), the average cylinder-head temperature was about the same at exhaust pressures of 10 and 60 inches of mercury absolute, with a rise and subsequent decrease of about 7° F occurring between these extremes.

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APPENDIX - EFFECTS OF INLET-MANIFOLD TEMPERATURE AND FUEL-AIR RATIO

Standard or reference value of T_g . - The reference value of T_g was taken as 1150°F for a fuel-air ratio of 0.08, a dry inlet-manifold temperature of 80°F , sea-level exhaust pressure, and the normal spark setting. (See references 6 and 7.)

Effect of inlet-manifold temperature T_m . - In reference 7, it was found that for a similar liquid-cooled engine a change of 1.0°F in inlet-manifold temperature resulted in a 0.21°F change in T_g . Hence, the variation of T_g from an inlet-manifold temperature of 80°F is given by the relation

$$\Delta T_g = 0.21 (T_m - 80) \quad (4)$$

where T_m is a calculated inlet-manifold temperature based on the carburetor-air temperature and the theoretical temperature rise across the supercharger assuming no temperature drop due to fuel evaporation. The equation for calculating T_m is

$$T_m = T_c + \frac{0.96 U^2}{Jg c_p} \quad (5)$$

where

c_p specific heat of air at constant pressure, Btu/lb/ $^\circ\text{F}$

g acceleration due to gravity, 32.2 ft/sec^2

J mechanical equivalent of heat, 778 ft-lb/Btu

T_c carburetor-air temperature, $^\circ\text{F}$

U impeller tip speed, ft/sec

For the engine used in this investigation, equation (5) reduces to

$$T_m = T_c + 18.00 \left(\frac{N}{1000} \right)^2 \quad (6)$$

where

N engine speed, rpm

Effect of fuel-air ratio on $T_{g,80}$. - The variation of $T_{g,80}$ with fuel-air ratio is normally determined from runs in which fuel-air ratio is independently varied for constant values of charge flow, exhaust pressure, and coolant conditions. In this investigation, some of these data were used but it was found necessary to include additional data points to clearly define the variation of $T_{g,80}$ with fuel-air ratio. For this purpose, data taken at sea-level exhaust pressure, constant coolant conditions, various fuel-air ratios, and various charge flows were included. Variations in charge flow were corrected for by the use of equation (2), which includes the term W_c^n ($n = 0.6$). (See correlation method section.)

In the determination of the variation of $T_{g,80}$ with fuel-air ratio, the constant B_2 was evaluated by substituting for the various terms in equation (2) the values obtained at the reference conditions for which the value of T_g has been established. By use of equation (2) and the constant B_2 thus determined, data from runs at fuel-air ratios other than the standard (0.08) were substituted in the equation and the corresponding values of T_g determined. These values of T_g correspond to the test inlet-manifold temperature and must be corrected to 80° F by use of equation (4).

This variation of $T_{g,80}$ with fuel-air ratio is shown in figure 8. The faired curve for the multicylinder air-cooled engine (reference 3) is also included in this figure. A marked similarity in shape of the curves may be observed for the two engines.

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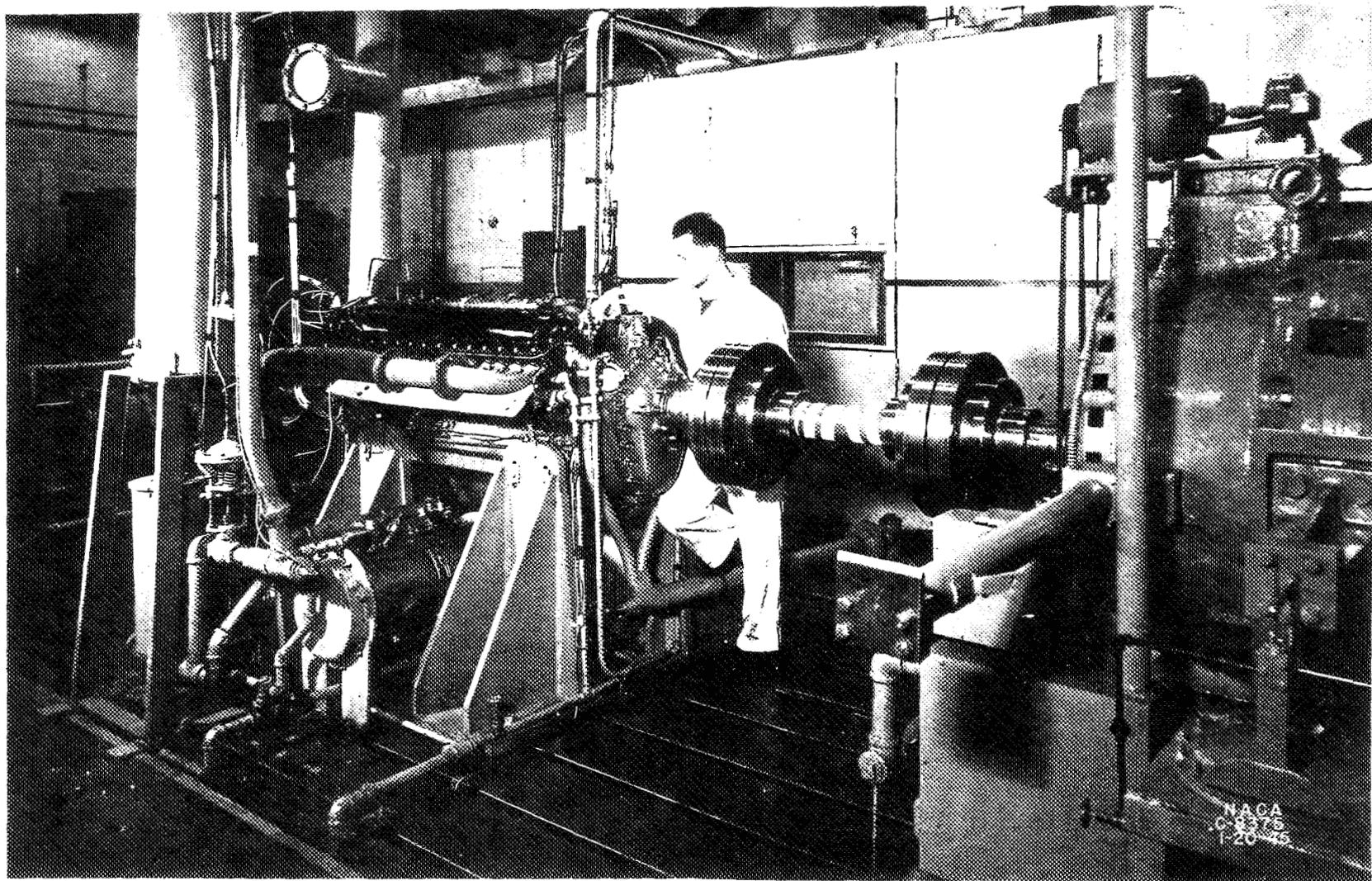
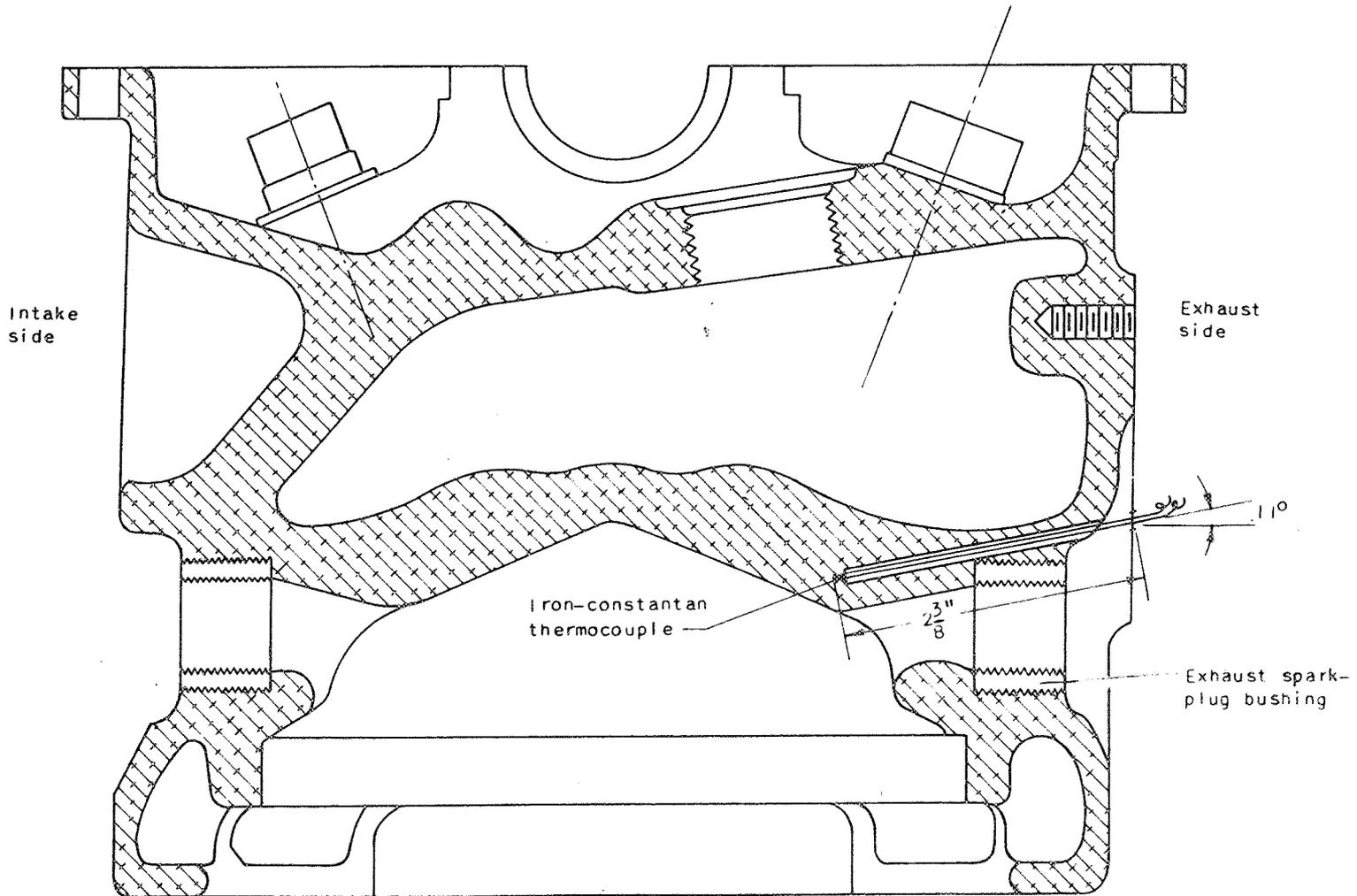


Figure 1. - General view of test setup for exhaust pressure investigation of 12-cylinder liquid-cooled engine.



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Figure 2. - Location of thermocouple in cylinder head.

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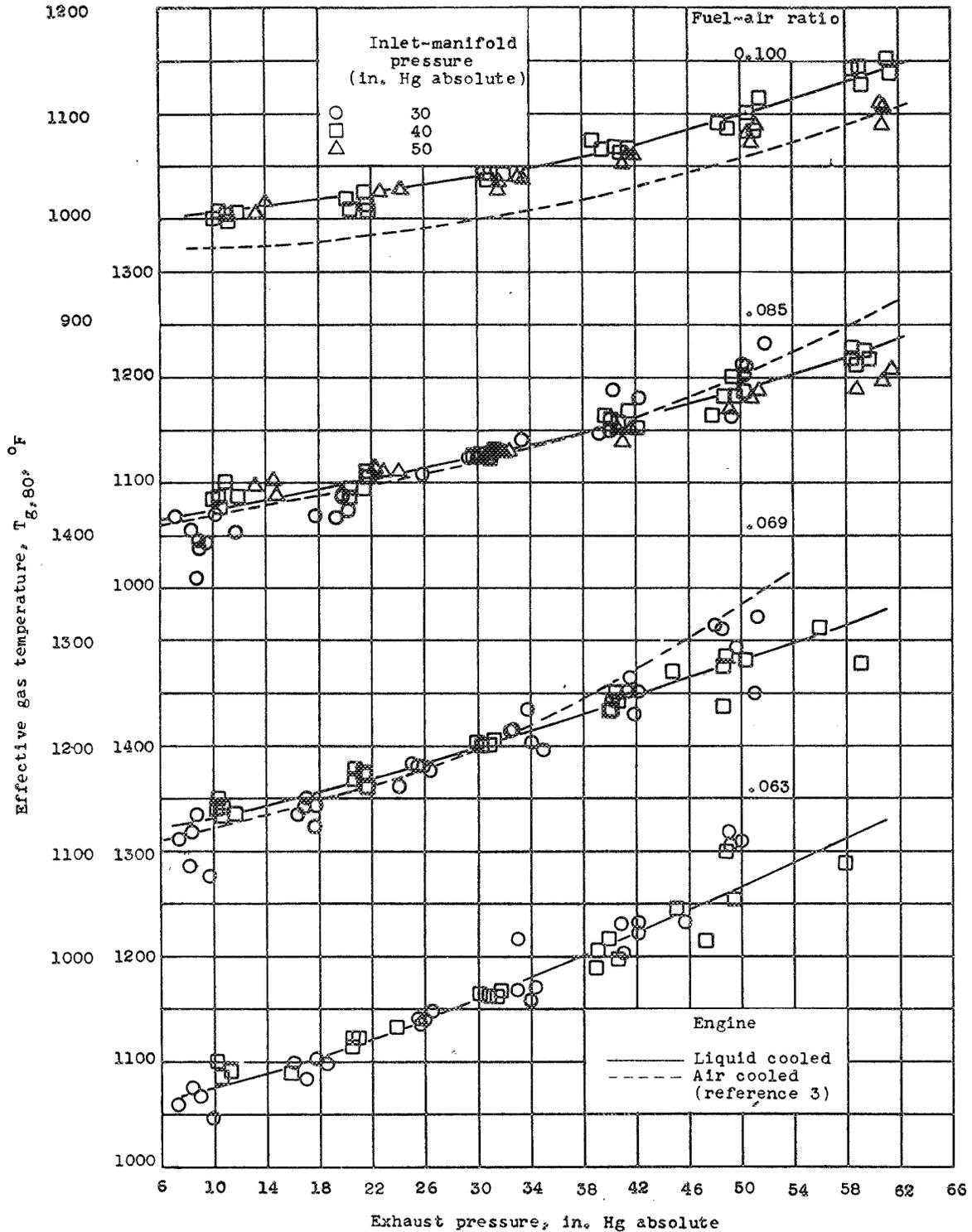


Figure 3. - Effect of exhaust pressure on the effective gas temperature at various fuel-air ratios.

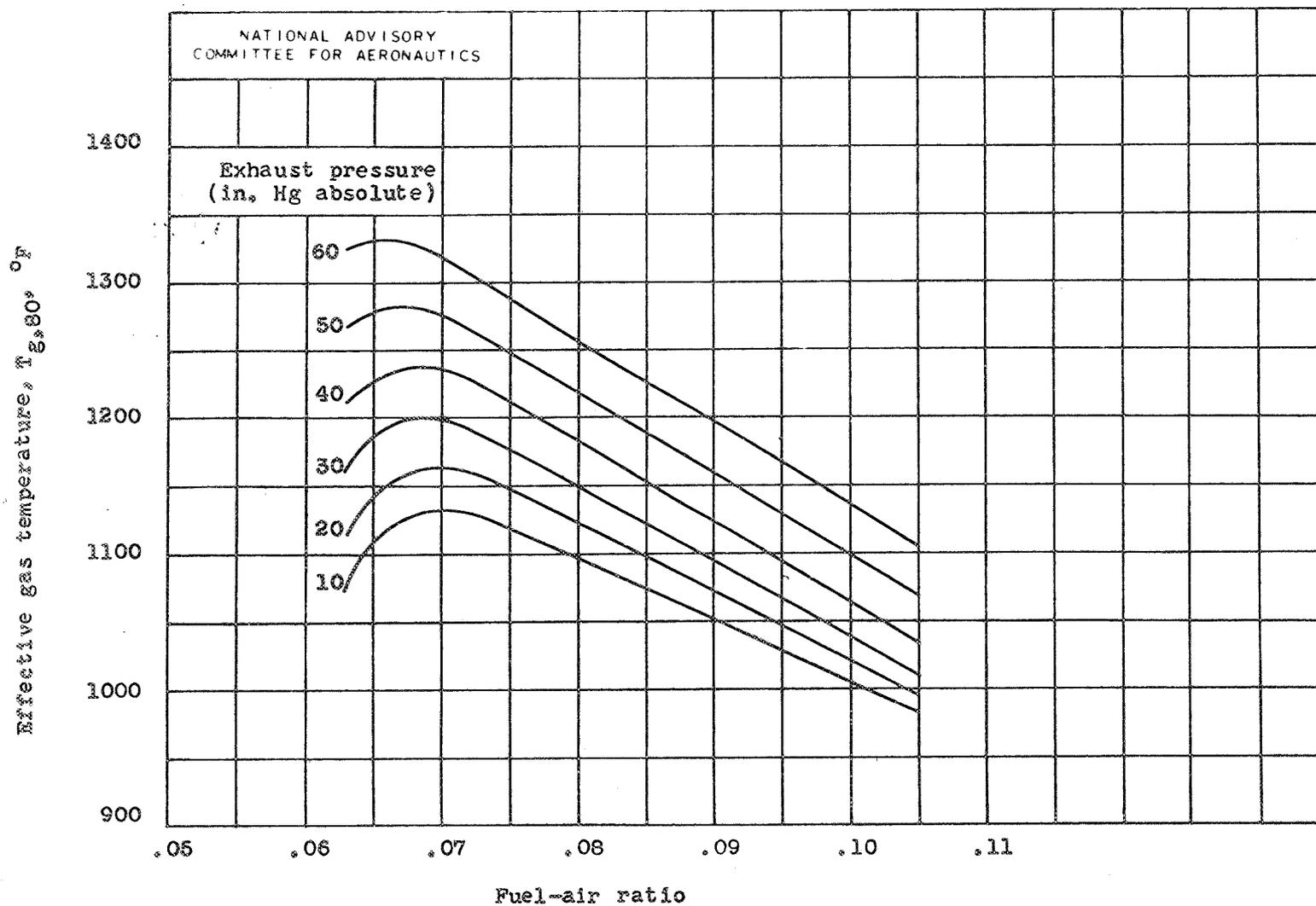
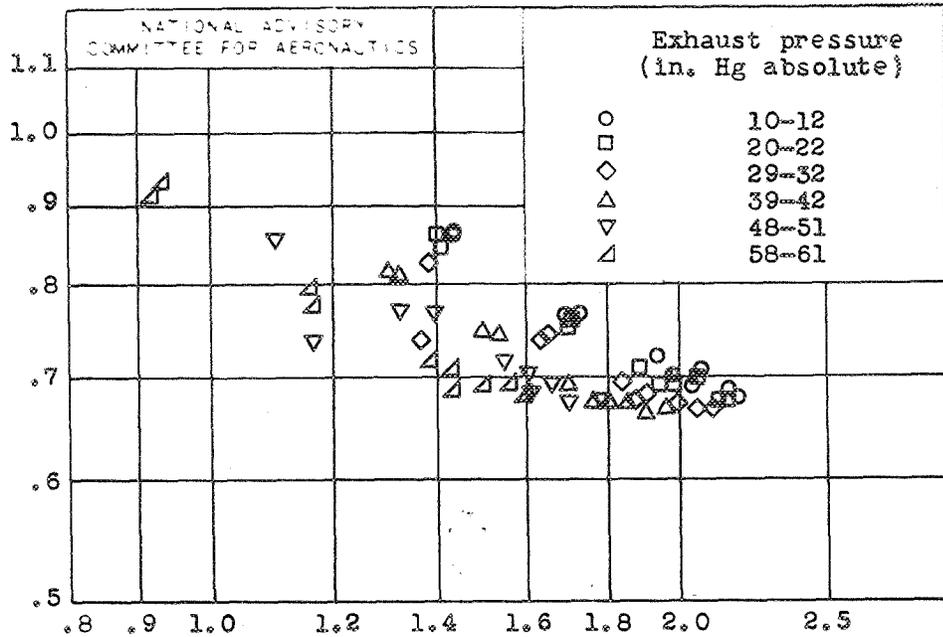


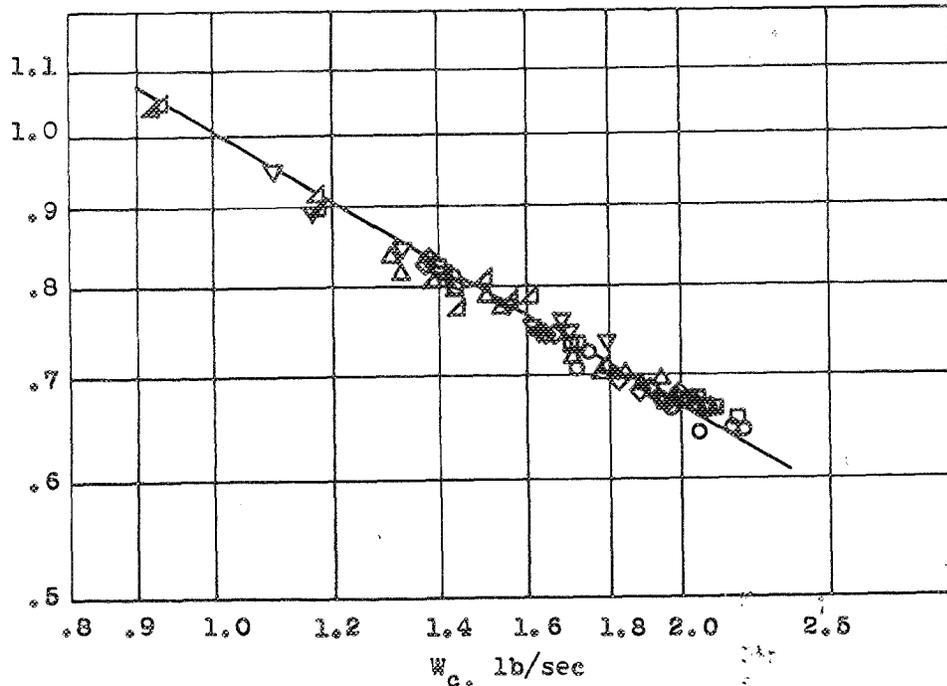
Figure 4. - Variation of effective gas temperature with fuel-air ratio at various exhaust pressures.
(Cross plot of fig. 3.)

$$\left(\frac{W_c}{\mu}\right)^{-0.46} \left[\frac{1}{k Pr^{0.35}} + 0.15 \right]$$

$$\frac{T_g - T_h}{T_h - T_l} \left[0.00135 \right]$$



(a) Correlation based on $T_{g,80}$ curve uncorrected for exhaust pressure.



(b) Correlation based on $T_{g,80}$ curve corrected for exhaust pressure.

Figure 5. - Cooling-correlation curve for cylinder-head cooling data obtained at following conditions: Inlet-manifold pressure, 40 inches of mercury absolute; fuel-air ratios, 0.085 and 0.100; engine speeds, 1600, 2000, 2400, 2600, and 3000 rpm.

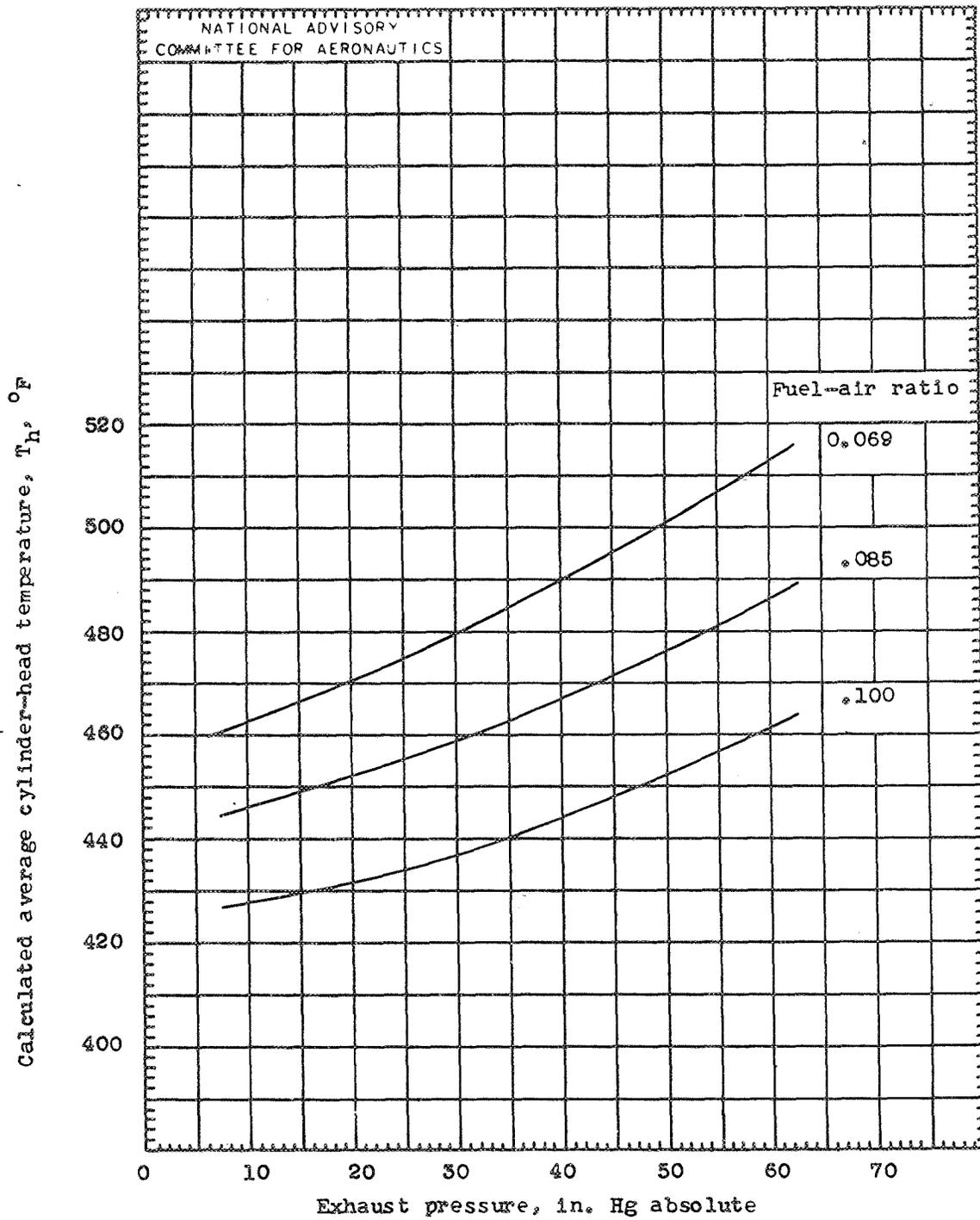


Figure 6. - Variation of average cylinder-head temperature calculated from figure 5(b) with exhaust pressure. Constant charge flow, 2 pounds per second; coolant flow, 28.4 pounds per second; coolant temperature, 212° F; inlet-manifold temperature, 200° F.

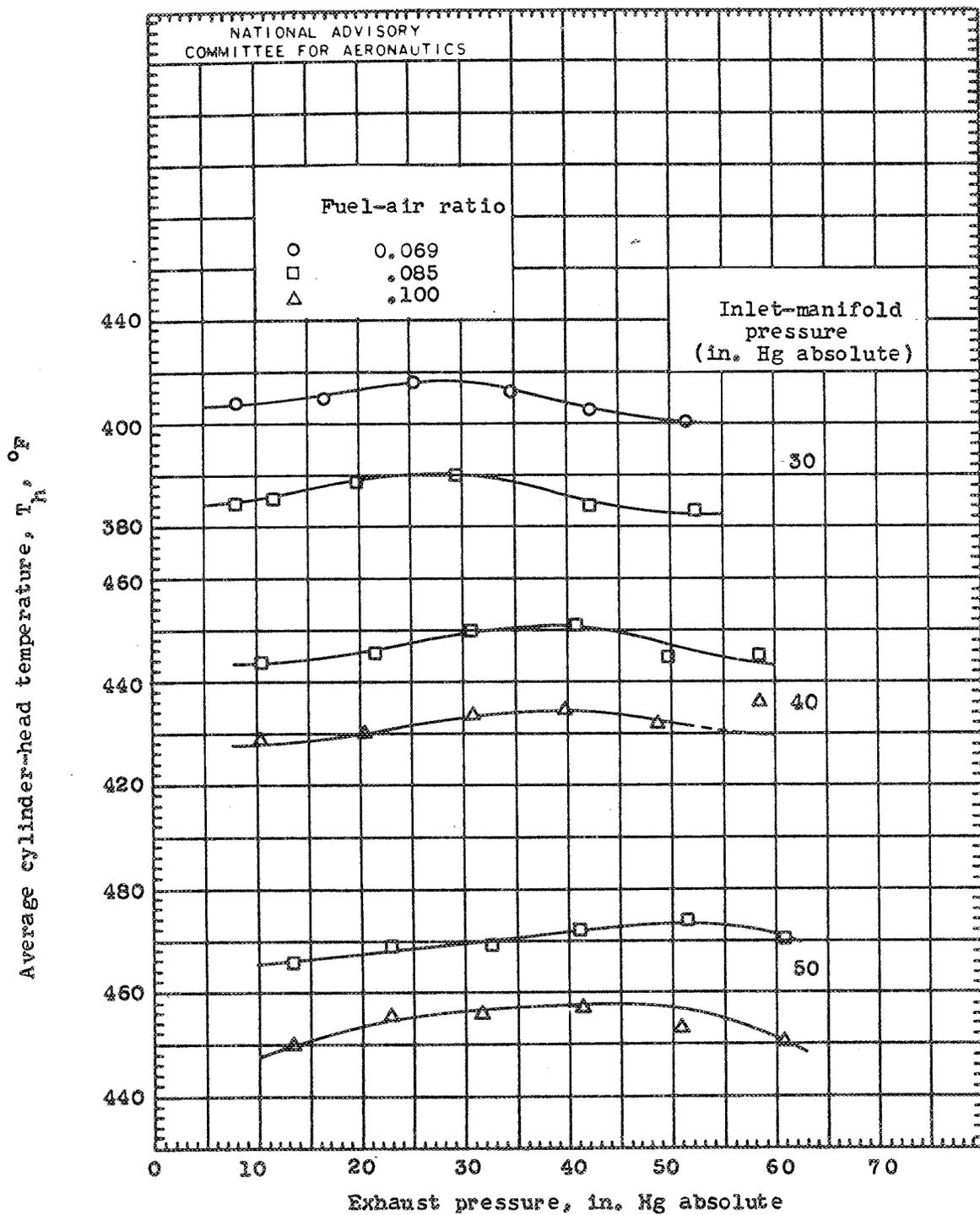


Figure 7. - Variation of average cylinder-head temperature with exhaust pressure for an engine speed of 2400 rpm.

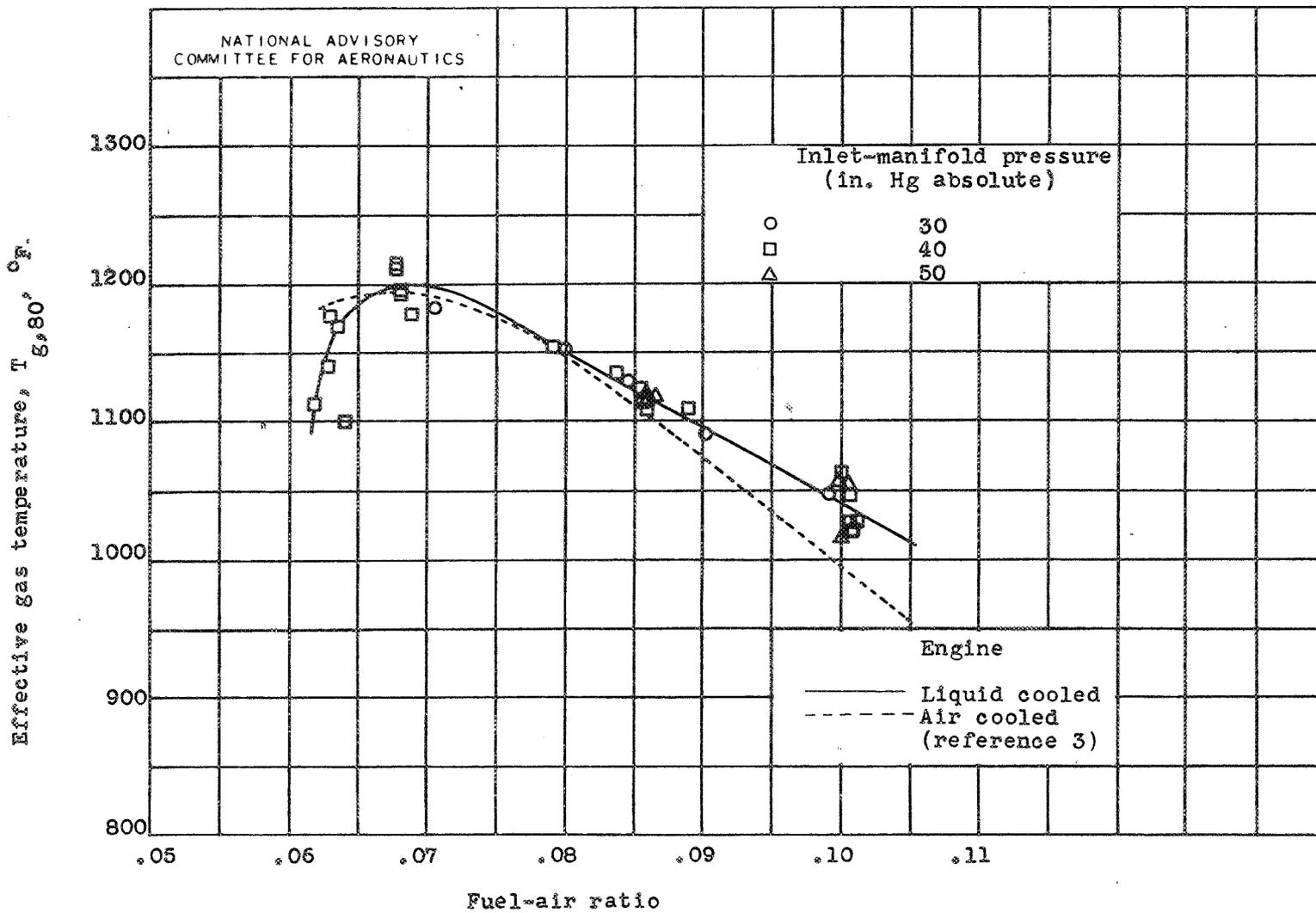


Figure 8. - Variation of effective gas temperature with fuel-air ratio. Exhaust pressure, 30 inches mercury absolute.