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CORRELATION OF WRIGHT AERONAUTICAL CORPORATION COOLING DATA ON THE R-3350-14 INTERMEDIATE ENGINE AND COMPARISON WITH DATA FROM THE LANGLEY 16-FOOT HIGH-SPEED TUNNEL

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ADVANCE CONFIDENTIAL REPORT

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SUMMARY

A comparison is made herein of the cooling-test data obtained by the Wright Aeronautical Corporation and by the NACA on the identical Wright R-3350-14 engine equipped with the same cooling pressure-tube installation. The Wright Aeronautical Corporation test was made in a test stand and the NACA test was made in the 16-foot high-speed tunnel.

The comparison reveals the large difference in cooling pressure drop that may be obtained in different test installations with the identical engine and pressure-tube installation because of an injudicious choice of pressure-tube locations The requirements of a good cooling pressure-tube installation are discussed.

INTRODUCTION

The results of engine-cooling tests on test stands and in wind tunnels are being used to determine the cooling performance of an engine in an airplane. In order to obtain results that are indicative of flight cooling conditions, it is important that the test installation be correctly designed. The present report relates to difficulties that may arise from a poor choice of cooling pressure-tube locations. The requirements of a good pressure-tube installation are discussed.

A Wright R-3350-14 engine was received from the Wright Aeronautical Corporation for test in the Langley 16-foot high-speed tunnel for the Bureau of Aeronautics. This identical engine had been placed through extensive cooling tests by the Wright Aeronautical

Corporation and came equipped with the cooling-air pressure-tube installation used in these tests. A copy of the Wright Aeronautical Corporation data was also received.

Cooling tests of this engine, from which data were obtained on the Wright Aeronautical Corporation pressure-tube installation, were made by the NACA in the 16-foot high-speed tunnel at Langley Field, Va. Test data from both the Wright Aeronautical Corporation and the NACA are correlated by the method given in reference 1 and a comparison of the results is made. A brief summary of the correlation procedure is given.

CORRELATION PROCEDURE

One form of the correlation equation given in reference 1 is

$$\frac{T_h - T_a}{T_g - T_h} = K \frac{W^n}{(\sigma\Delta p)^m} \qquad (1)$$

where

T_h cylinder-head temperature, °F

T_a cooling-air temperature, °F

T_g mean effective gas temperature, °F

W weight flow of charge air to engine, pounds per second

Δp cooling-air pressure drop, inches of water

σ density of cooling air relative to standard density of 0.0765 pound per cubic foot

n, m, K constants derived in reducing the cooling data

Additional symbols used are

A constant equal to engine mechanical friction horsepower divided by square of engine speed

c_p specific heat of air at constant pressure, 0.24 Btu per pound per °F

g acceleration of gravity, 32.2 feet per second^2 or 32.2 pounds of mass per slug

J	Joule's constant, 778 foot-pounds per Btu
K_1	supercharger factor near unity in value
N	engine speed, rpm
p_e	exhaust-manifold pressure, inches of mercury
p_m	inlet-manifold pressure, inches of mercury
r	square of ratio of impeller tip speed in feet per second to engine speed in rpm
T_c	carburetor inlet-air temperature, $^{\circ}F$
T_m	dry effective inlet-manifold temperature, $^{\circ}F$
U	tip speed of engine-stage blower, feet per second
v_d	engine-displacement volume, cubic feet
η_g	efficiency of supercharger gears

Equation (1) may be written

$$\frac{T_h - T_a}{T_g - T_h} = K\left(\frac{W^{n/m}}{\sigma\Delta p}\right)^m \qquad (2)$$

A plot of $(T_h - T_a)/(T_g - T_h)$ against $\frac{W^{n/m}}{\sigma\Delta p}$ should give a straight line on logarithmic coordinates.

The quantity T_g is a function of fuel-air ratio, inlet-manifold temperature, exhaust-manifold pressure, and spark timing. In the conventional multicylinder engine the true inlet-manifold temperature is indefinite and difficult to measure because an unknown amount of fuel is vaporized in the carburetor and the blower. For the present computation, the expedient has been adopted of using, instead of true manifold temperature, a dry effective manifold temperature T_m defined as the sum of the carburetor-air temperature and the rise in air temperature in passing through the primary supercharger on the assumption that no vaporization of the fuel occurs. In the nondetonating range the variation in cylinder temperature is only a fraction of the variation in inlet-manifold temperature and, for this reason, the following approximation for T_m is sufficiently accurate for the present purpose:

$$T_m = T_c + \frac{U^2}{gc_pJ} \qquad (3)$$

The blower tip speed U can be given in terms of the engine speed, the impeller diameter, and the impeller gear ratio. In the case of the Wright R-3350-14 engine, the impeller diameter is 13 inches and the gear ratio is 6.08 for low blower and 8.52 for high blower. The equation for T_m then becomes

$$\text{Low blower, } T_m = T_c + 20.0 \left(\frac{N}{1000}\right)^2 \qquad (4)$$

$$\text{High blower, } T_m = T_c + 39.2 \left(\frac{N}{1000}\right)^2 \qquad (5)$$

In the absence of data on the effect on T_g of variation in T_m for the Wright R-3350-14 engine, the test results given in reference 2 for a Wright 1820 G engine have been used, namely

$$\Delta T_g = 0.60\ \Delta T_m \qquad (6)$$

The effect of fuel-air ratio on the gas temperature is obtained from the test data. From the results of tests of a large number of air-cooled cylinders (references 1, 2, and 3), it was found that a value for T_g of 1150° F at a T_m of 80° F and a fuel-air ratio of 0.08 could be chosen. Small differences in the choice of the initial or reference value of T_g do not seriously change the accuracy of the correlation. It is of greater importance, once the initial value of T_g is chosen, that the variation of T_g from the initial value with variation in T_m and fuel-air ratio be accurate. Inasmuch as T_m is the dry effective manifold temperature, the variation of T_g with fuel-air ratio includes both the cooling effect of the fuel in evaporating and the effect of the excess fuel on the composition of the products of combustion and the heat generated by combustion. For the tests cited in this report, the effect of spark timing on T_g was not involved because all tests were run at a fixed spark advance as specified by the manufacturer.

Correlation of test data is simplified if the test program is arranged as follows:

(a) Variable $\sigma\Delta p$ run with W held constant and fuel-air ratio equal to 0.08

(b) Variable W run with $\sigma\Delta p$ held constant and fuel-air ratio equal to 0.08

(c) Variable fuel-air-ratio run

In this case the data of run (a) provide a plot of $(T_h - T_a)/(T_g - T_h)$ against $\sigma\Delta p$ for a constant W on logarithmic coordinates. The slope of the resulting line gives the exponent m. The value of T_g is taken equal to 1150° F plus the correction for variation of T_m from the value of 80° F (equations (4), (5), and (6)). Similarly, run (b) provides data for a plot of $(T_h - T_a)/(T_g - T_h)$ against W from which the exponent n is obtained. The data of runs (a) and (b) are now presented on a single correlation curve by plotting $(T_h - T_a)/(T_g - T_h)$ against $\frac{W^{n/m}}{\sigma\Delta p}$ (equation (2)). This correlation curve is then used to compute T_g from the data of run (c). In each case the value of T_g is corrected to correspond to a value of T_m of 80° F in the manner previously described. The values of T_g are plotted against fuel-air ratio and are used for plotting all remaining data on the correlation curve.

In the correlation used in this report the value of σ at the front of the engine will be used because it is a convenient quantity to determine and its use has been found satisfactory over a range of moderate altitudes. For large variations in altitude, the use of σ at the rear of the engine, although less convenient, gives better correlation of the data than σ at the front. The most correct procedure from a theoretical standpoint is to correlate on the basis of mass flow of cooling air rather than $\sigma\Delta p$. Accurate measurement of the mass flow of cooling air, however, is extremely difficult to obtain.

CORRELATION OF WRIGHT AERONAUTICAL CORPORATION DATA

The procedure outlined in the preceding section was applied as far as possible to the Wright Aeronautical Corporation data, which, although extensive, lacked runs of the type most readily correlated. A run equivalent to run (a) with only slight variations in fuel-air ratio was found from which the exponent m was obtained. Data corresponding to run (b), except that $\sigma\Delta p$ was varied, were also found. A plot of $(\sigma\Delta p)^m$ $(T_h - T_a)/(T_g - T_h)$ against W was made from which the exponent n was determined. The correlation curve $(T_h - T_a)/(T_g - T_h)$ against $\frac{W^{n/m}}{\sigma\Delta p}$ was then plotted and, with this curve and variable fuel-air-ratio runs, the curve of T_g against fuel-air ratio was obtained (corrected to $T_m = 80°$ F). The determination of n and m was then repeated, making corrections in T_g for the small variation in fuel-air ratio that existed in these runs and, with the new correlation curve, a new T_g against fuel-air-ratio curve was computed. Substantially all the remaining data were then plotted on the correlation curve using the values of T_g obtained from the new curve of T_g against fuel-air ratio. In each case the correction for variation in T_m from 80° F was applied. It can be seen that the work necessary to correlate data of the type just discussed is much greater than that required for data from runs of the type described in the section Correlation Procedure.

In the results and analysis given in reference 1, the quantity T_h is the average cylinder-head temperature. In multicylinder tests it is usually the practice to use the temperature of the rear spark-plug gasket as an indication of the head temperature. The rear spark-plug-gasket temperature is subject to error, depending on the tightness of the spark plug and other installation conditions, and a thermocouple embedded on the cylinder head proper is believed to be more reliable. In the absence of other head-temperature measurements, however, the method of correlation was applied to the temperature measurements of the rear spark-plug gasket. The quantity T_h was taken as the average of the temperatures of the 18 rear spark-plug gaskets.

The final correlation curve for the Wright Aeronautical Corporation data on the R-3350-14 engine is presented in figure 1. Figure 2 shows the variation of mean effective gas temperature with fuel-air ratio. A supplementary plot of the maximum temperature of the rear spark-plug gaskets against the average temperature of the rear spark-plug gaskets is shown in figure 3. The points are coded to indicate the hottest cylinder for each case.

The cooling-correlation relation (equation (1) and fig. 1) contains the engine air consumption W. It is necessary to know the relation between the engine air consumption and the engine power in order to determine the cooling requirements for any given power. The rate of air consumption (in the range of mixtures richer than stoichiometric) depends primarily on indicated horsepower and secondarily on mixture ratio, engine speed, and inlet- and exhaust-manifold pressures. The most concise presentation of these data appears to be a plot of indicated specific air consumption (W/ihp) against the secondary variables. The indicated horsepower is defined as the indicated power contributions of only the compression and the expansion strokes of the engine. It is obtained by adding to the brake horsepower the following:

(a) Supercharger horsepower

(b) Indicated power of the exhaust stroke minus that of the intake stroke of the engine (the so-called pumping loop)

(c) Mechanical friction of only the engine proper

Thus

$$ihp = bhp + K_1 r \frac{WN^2}{550\ g\eta_g} + v_d\ (p_e - p_m) \frac{N}{933} + AN^2 \qquad (7)$$

The factor K_1 in the term for supercharger power varies only slightly from unity and for the present purpose can be taken equal to unity when the exact value of the supercharger power is not known.

The pumping work in equation (7) is derived on the assumption that the intake-manifold pressure prevails during the entire suction stroke and that the exhaust-manifold pressure prevails during the exhaust stroke. These assumptions are not very precise and a more exact relation should be used when available. Fortunately, error in this quantity has only a small effect on the final results in cooling computations.

The engine mechanical friction horsepower varies nearly proportionally with the square of the engine speed and is represented by the term AN^2 in equation (7). The value of A calculated from a known value of mechanical friction power at one speed can be used in computation of the friction power at other speeds with sufficient accuracy for the present purpose.

The equations for indicated horsepower for the present case on the assumption that

$$A = 28 \times 10^{-6}\ hp/(N)^2$$

$$K_1 = 1$$

and

$$\eta_g = 0.85$$

are

Low blower, $$ihp = bhp + \left[28 + 7.94\ W\right] \left(\frac{N}{1000}\right)^2 - 2.08\ (p_m - p_e) \frac{N}{1000} \qquad (8)$$

High blower, $$ihp = bhp + \left[28 + 15.6\ W\right] \left(\frac{N}{1000}\right)^2 - 2.08\ (p_m - p_e) \frac{N}{1000} \qquad (9)$$

The values of indicated specific air consumption obtained from equations (8) and (9) and from the Wright Aeronautical Corporation data are shown in figure 4.

CORRELATION OF NACA DATA

The Langley 16-foot high-speed-tunnel tests of the Wright R-3350-14 engine installed in the Douglas XSB2D-1 nacelle were conducted in the manner suggested in the Correlation Procedure. In addition to an otherwise very complete instrumentation the pressure-tube installation used in the Wright Aeronautical Corporation tests was duplicated in the NACA setup and was used with indicating instruments to obtain data for preliminary checking. These NACA data have been correlated in the same way as the Wright Aeronautical Corporation data, including the use of cooling-air density at the front of the engine, and provide a direct comparison with Wright Aeronautical Corporation tests.

In the calculation of T_h, sporadic errors in the temperatures of the rear spark-plug gaskets have been corrected by reference to data from the more reliable embedded thermocouples. The correlation line for the NACA data is given in figure 5 and the corresponding curve for mean effective gas temperature for a dry manifold temperature of 80° F is given in figure 6.

Curves illustrating the variation of static pressures at the front and the rear of the engine with distance from crank axis are shown in figure 7. The large difference in pressure drop that may be obtained in a given cooling test by merely changing the tube location is apparent and indicates the need for standardizing instrumentation in order that tests made by different organizations may be compared. The pressure drops for the NACA correlation curve (fig. 5) were taken at the same location as those for the Wright Aeronautical Corporation tests. The pressure at the front of the engine was measured at the top of the cylinder head by a total-pressure tube and the pressure at the rear was measured by means of a shielded static-pressure tube near the cylinder base. As will later be discussed in greater detail, tubes in these locations are not desirable for comparing the cooling of an engine in different installations.

COMPARISON OF RESULTS

The correlation lines from the NACA data, together with those from the Wright Aeronautical Corporation tests, are shown in figure 8. Both lines have the same slope, indicating essentially the same relation of head-temperature change to variation in power and cooling-air pressure drop. The line from the NACA data, however, lies considerably lower than that from the Wright Aeronautical Corporation results and indicates a required pressure drop of 50 percent of that given by the Wright Aeronautical Corporation line for the same head temperature and engine conditions. It is believed that the lack of agreement is largely due to the differences in cowling used in the two tests and the consequent effects on the direction of air flow over the engine and on the pressure measurements.

The schematic diagram of figure 9 shows the direction of air flow through the engine and cowling as installed in the nacelle for the NACA tests. A similar direction of flow is expected in flight. The considerably higher pressure at the rear of the cylinder base than at the rear of the cylinder head (fig. 7) for this arrangement probably results from the added resistance to flow from the base to the cowl exit caused by obstructions in the flow path and by the curvature of the flow path.

It was learned from representatives of the Wright Aeronautical Corporation that for their tests the cooling air discharged from the engine was drawn off through a tube with considerable inflow of air around the exhaust stacks where they pierced this tube. This arrangement is shown schematically in figure 10. Such a difference in flow direction would be expected to reverse the direction of whatever radial pressure gradient might exist behind the engine. That this effect is responsible for the entire difference between NACA and Wright Aeronautical Corporation results cannot be conclusively demonstrated here because the variation in pressure with radial position for the Wright Aeronautical Corporation data is not known.

It may be concluded, however, that the choice of tube location for measuring the cooling pressure drop in the data under discussion is poor. With the pressure at the front of the engine measured at the top of the cylinder heads and the pressure at the rear measured at the base of the cylinders, it is evident that variation in radial-pressure distribution with change in installation will introduce changes in the measured pressure drop that bear no relation to the mass flow of cooling air over the head fins. The pressure-tube locations should be chosen with a view to minimizing the effect of variation in radial-pressure distribution or other effects introduced by changes in installation.

The flow through each fin passage is determined by the total pressure at the entrance of the passage and the static pressure at the exit of the passage. In installations in which the propeller sets up considerable swirl, appreciable difference between the total pressures at the various fin-passage entrances exists because of the difference in angle of the fin-passage entrances with respect to the resultant velocity in front of the engine. Obstructions ahead of the cylinders, such as generators and valve push-rod guides, also affect the total pressure in the fin passages in their wake. A survey of the pressure drop in all the fin passages would be the most complete index of the cooling mass flow. Pressure tubes in each passage would, of course, be impracticable and it is necessary to choose judiciously the tube locations that will give an accurate indication of average mass flow. In the case of the cylinder head, total-pressure tubes should be located in the entrance of representative fin passages on the top, the exhaust-valve side, and the inlet-valve side of the head. These tubes should be placed in fin passages that supply air to the vicinity of the head thermocouples. The static-pressure tubes at the rear of the head should be placed near the exit of the fin passages in which the total-pressure tubes are located. These static-pressure tubes should preferably be located in zones sheltered from air flow, such as the curl of the baffle. The average of the pressure drops read by these tubes would be a good index of the cooling mass flow. The location of the tubes for measuring the barrel pressure drops are predicated by the same considerations as for the head. Total-pressure tubes should be located on the exhaust and the inlet sides of the cylinders at the entrance of the fin passages that deliver air to the vicinity of the barrel thermocouples. Static-pressure tubes should be located at the rear of the barrel in the vicinity of the same fin passages.

Even when these tube locations are used, it is not certain that the cooling tests on one installation of an engine will correctly predict the cooling performance on another. For example, in an E-type cowling, in which an air blast may be directed at the front of the cylinder heads, the flow at the front of the engine is different from that for the engine mounted in a tube to which suction is applied to induce a cooling-air flow. This difference in flow will introduce a difference in temperature distribution around each cylinder and may result in a different pressure drop required for cooling. A difference in propeller design that causes a difference in air swirl at the cowling entrance is another example of a change in installation that may affect the pressure drop required for cooling. Thus, where considerable difference in flow conditions is introduced by the change in installation, it may be expected that a difference in required cooling pressure drop will result.

The curves of mean effective gas temperature are compared in figure 11. For fuel-air ratios richer than 0.075 the agreement between the NACA and the Wright Aeronautical Corporation tests is good. The NACA tests were not sufficiently extensive to provide reliable values of mean effective gas temperature at fuel-air ratios leaner than 0.075.

CONCLUSIONS

A comparison of the Wright Aeronautical Corporation and the NACA results on the R-3350-14 engine presented in this report leads to the following conclusions:

1. This method of correlation markedly reduces the amount of test data required and makes possible representation of the results in a concise and very useful form.

2. The comparison of the correlation curves obtained from the Wright Aeronautical Corporation test stand and from the flight installations in the Langley 16-foot high-speed tunnel demonstrates the desirability of constructing cooling test-stand setups more closely simulating flight installations. Data thus obtained would then be more directly applicable for use in design of new installations.

3. The large variation of cooling pressure drop with location on the pitot tubes indicates the need for standardizing instrumentation in cooling tests.

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2. Pinkel, Benjamin, and Ellerbrock, Herman H., Jr.: Correlation of Cooling Data from an Air-Cooled Cylinder and Several Multicylinder Engines. NACA Rep. No. 683, 1940.

3. Schey, Oscar W., Pinkel, Benjamin, and Ellerbrock, Herman H., Jr.: Correction of Temperatures of Air-Cooled Engine Cylinders for Variation in Engine and Cooling Conditions. NACA Rep. No. 645, 1938.

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	Run	Brake horse-power	Engine speed (rpm)	Fuel-air ratio	
◁	16-31	836	1410	0.0611-0.0948	Low blower
□	32-41	2000	2400	0.0951-0.1080	Low blower
○	66-77	1490	2190	0.0846-0.0879	Low blower
△	78-83	990	1685	0.0753-0.0764	Low blower
×	110-117	2230	2600	0.100	Low blower
◇	84-105	950	1685	0.0761-0.0878	High blower
+	106-108	1390	2180	0.0864-0.0980	High blower

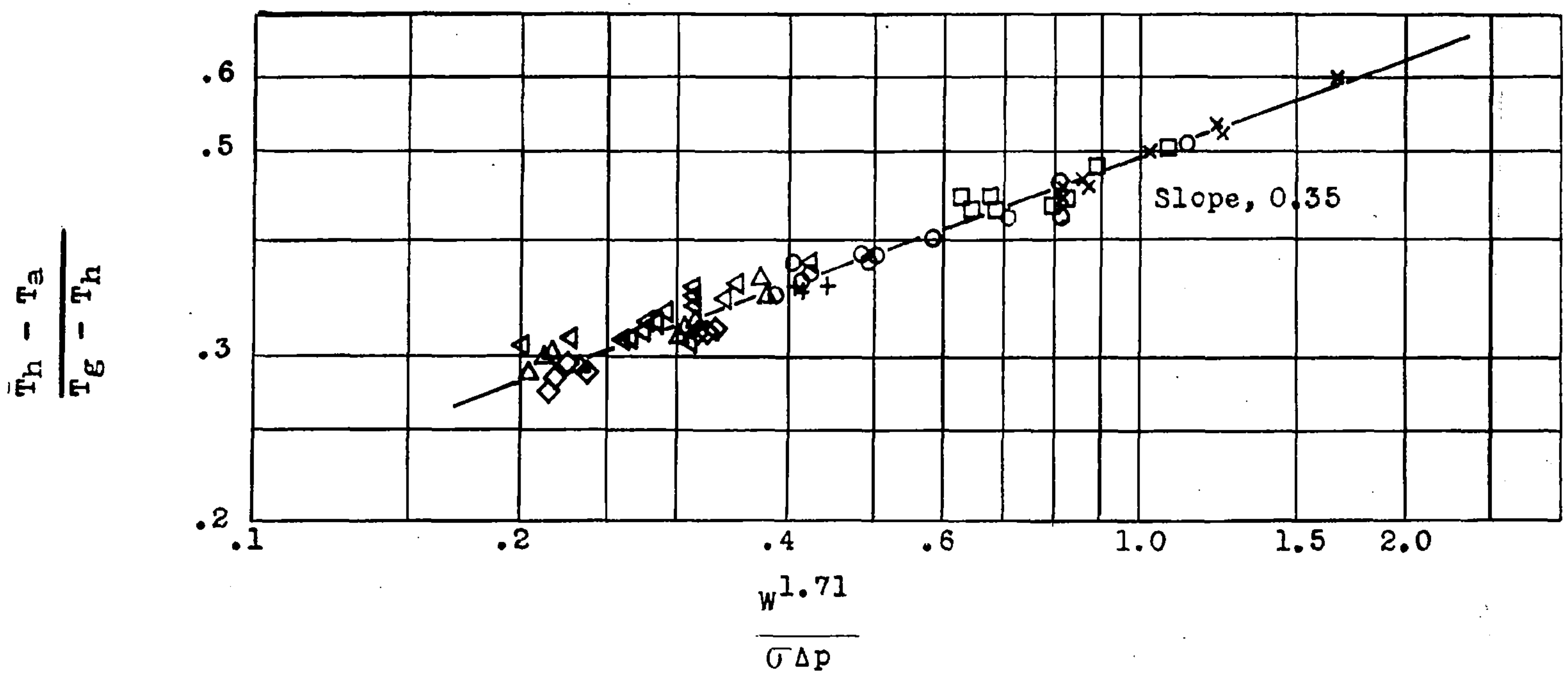

Figure 1.- Cooling correlation curve from Wright Aeronautical Corporation data.

$T_m = T_c + 20\ (rpm/1000)^2$, low blower
$T_m = T_c + 39.2\ (rpm/1000)^2$, high blower
$\Delta T_g = 0.80\ (T_m - 80)$
(Effective gas temperatures corrected to
80° F manifold temperature)

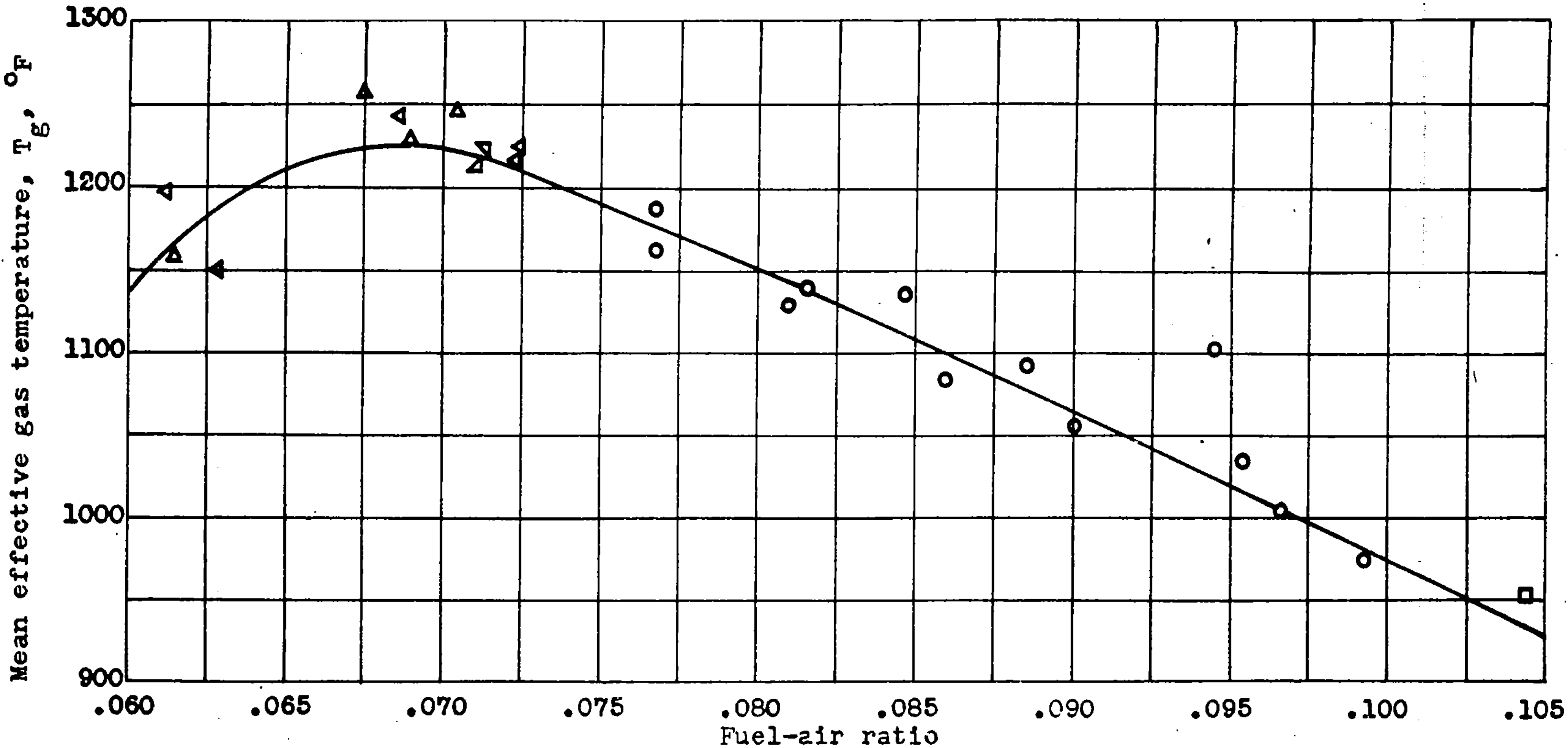

Figure 2.- Variation of mean effective gas temperature with fuel-air ratio using Wright Aeronautical Corporation data.

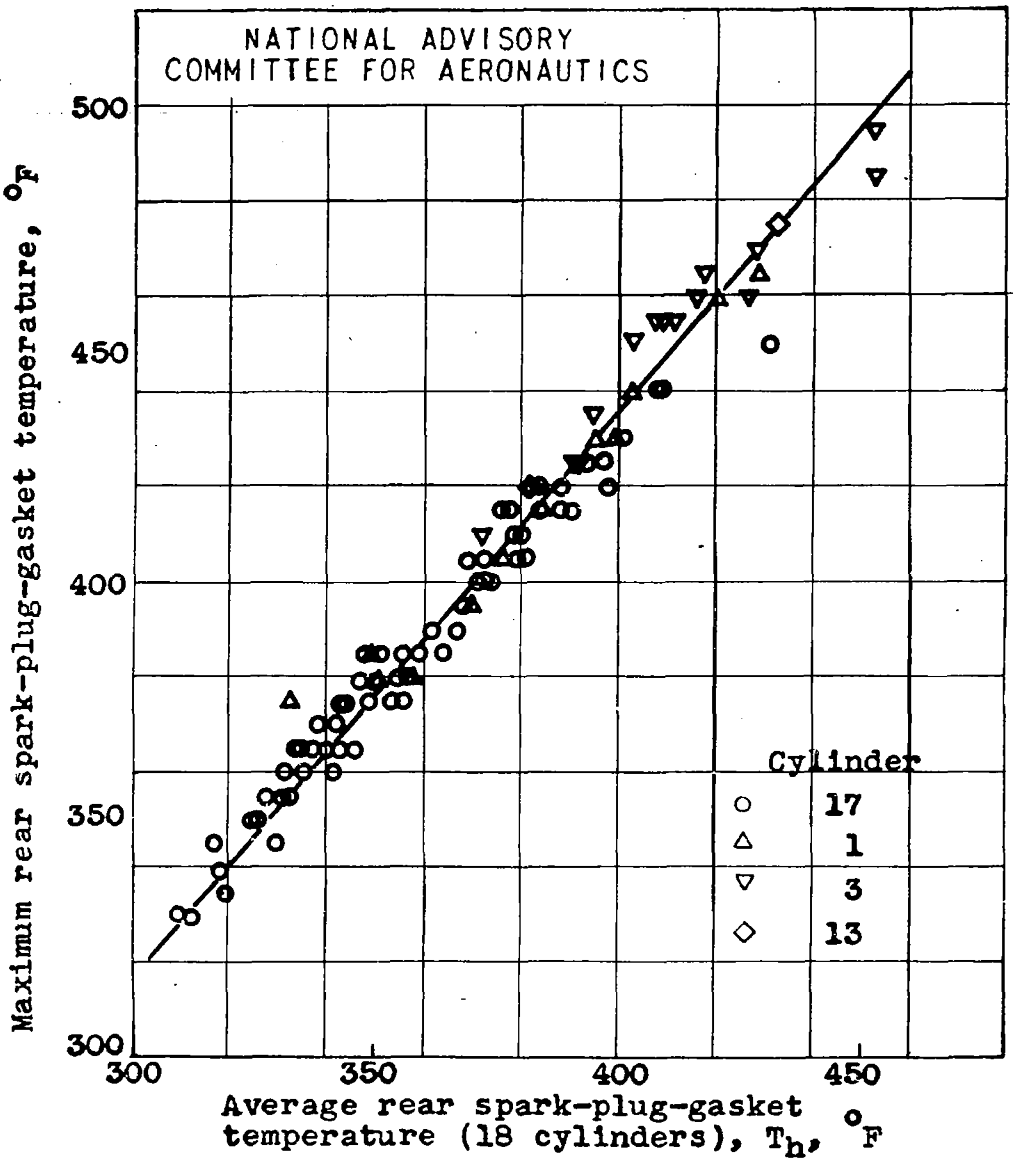

Figure 3.- Variation of maximum rear spark-plug-gasket temperature with average rear spark-plug-gasket temperature. Wright Aeronautical Corporation data.

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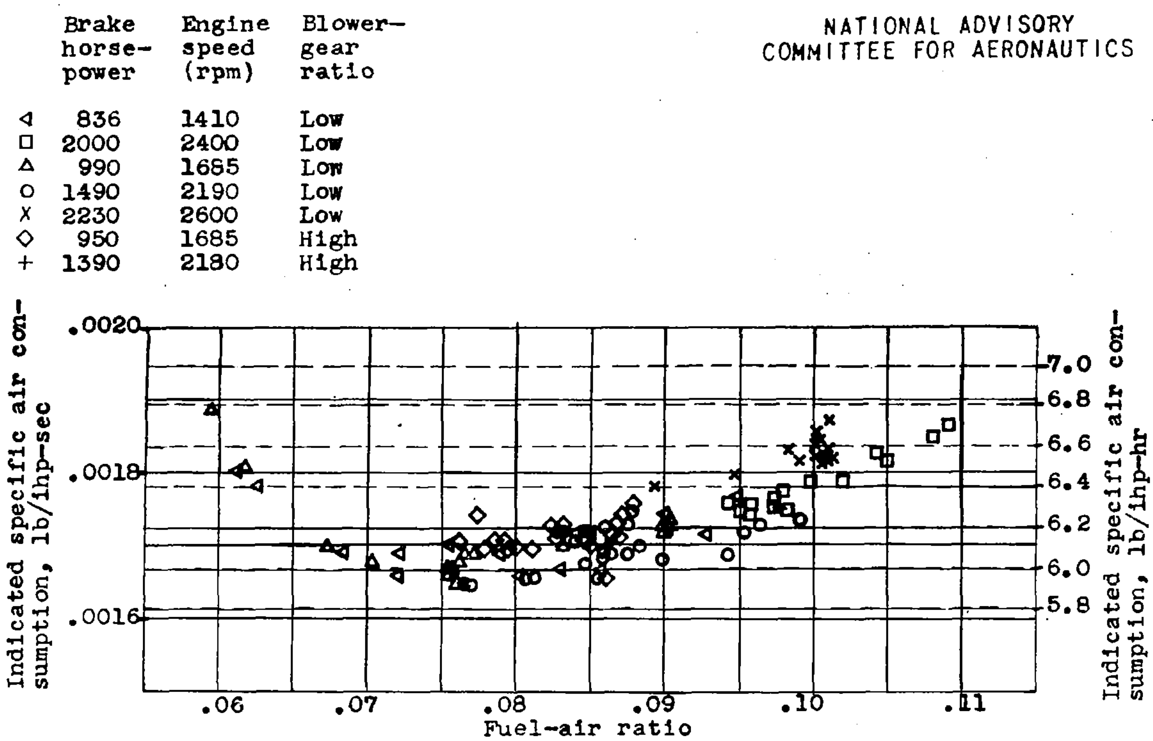

Figure 4.- Variation of indicated specific air consumption with fuel-air ratio. Wright Aeronautical Corporation data. Scale on the left is read on solid lines; scale on the right is read on dotted lines.

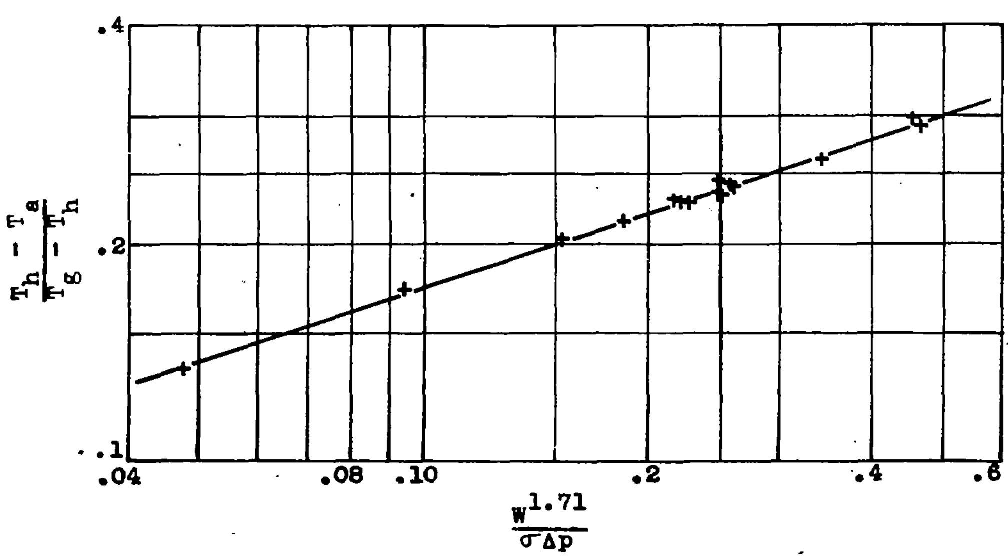

Figure 5.- Cooling correlation curve from NACA data.

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$T_m = T_c + 20\ (\text{rpm}/1000)^2$, low blower

$T_m = T_c + 39.2\ (\text{rpm}/1000)^2$, high blower

$\Delta T_g = 0.80\ (T_m - 80)$

(Effective gas temperatures corrected to 80° F manifold temperature)

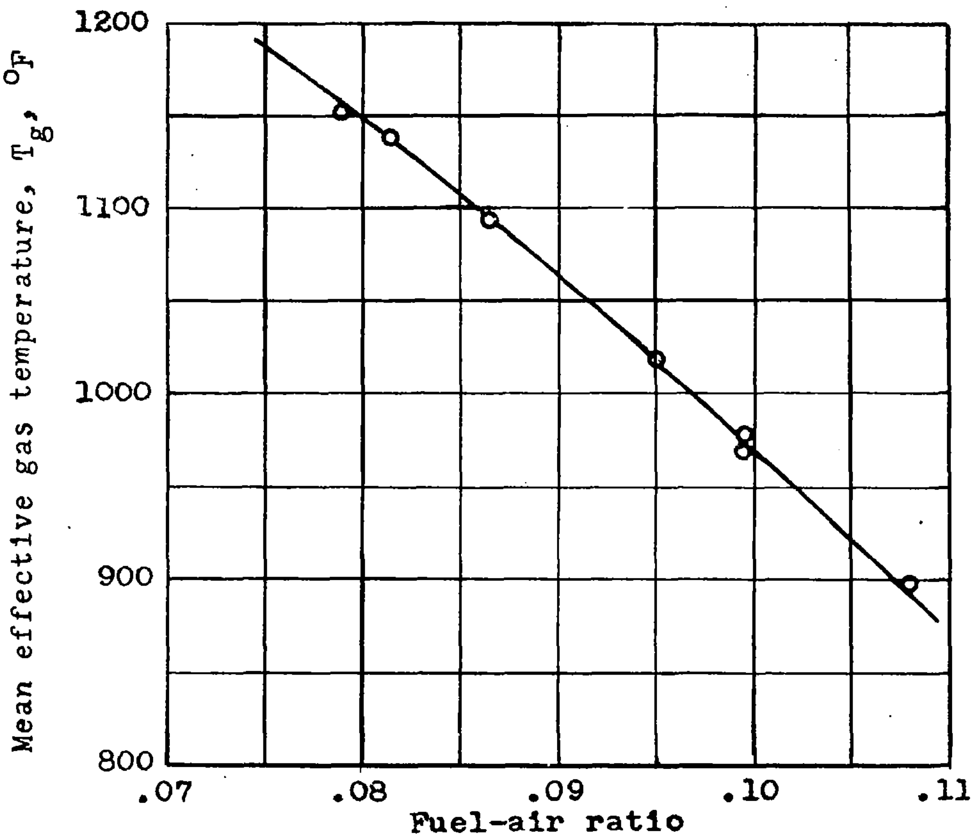

Figure 6.- Variation of mean effective gas temperature with fuel-air ratio using NACA data.

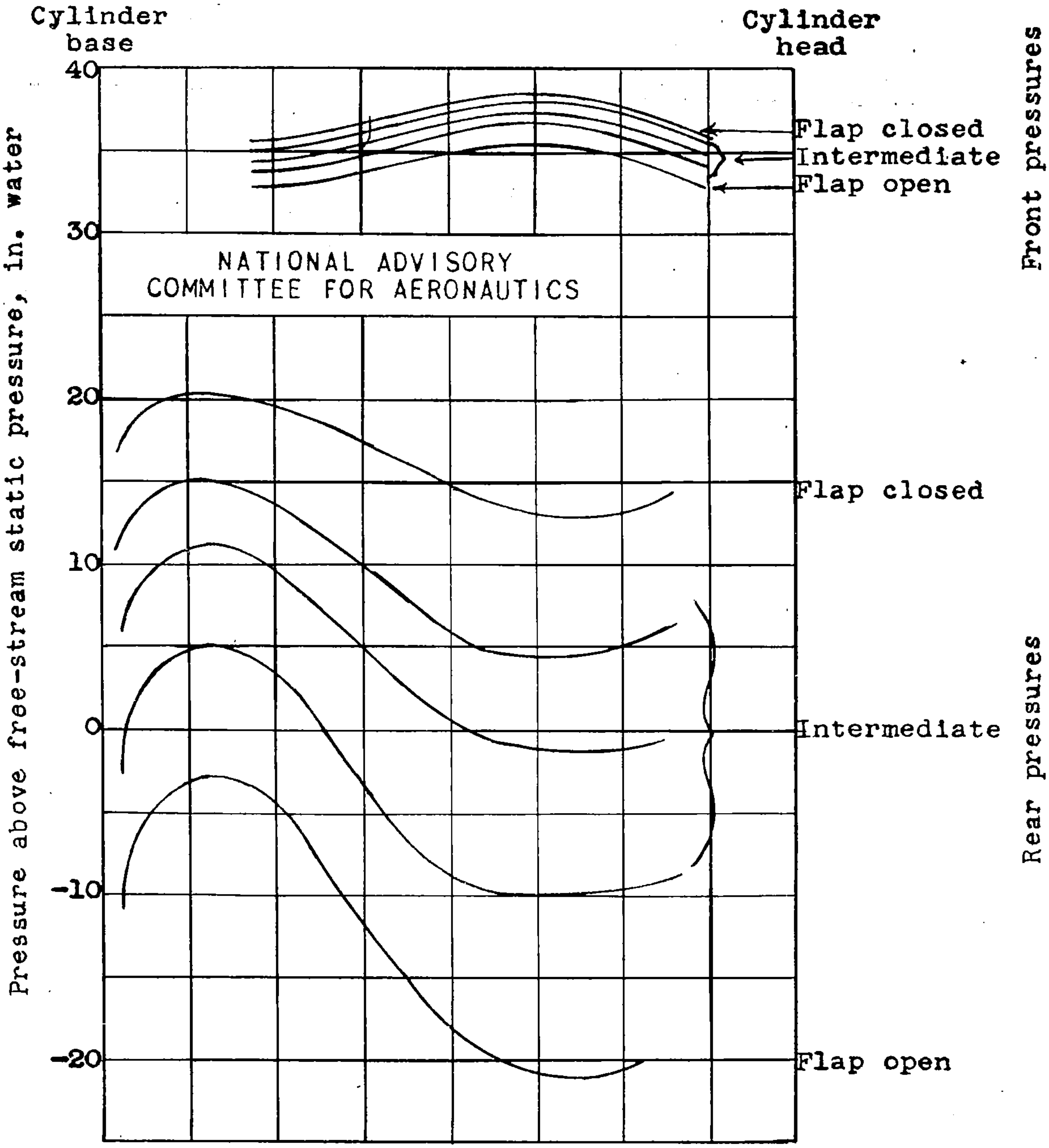

Figure 7.- Radial pressure distribution for Wright R-3350-14 intermediate engine in Douglas XSB2D-1 airplane.

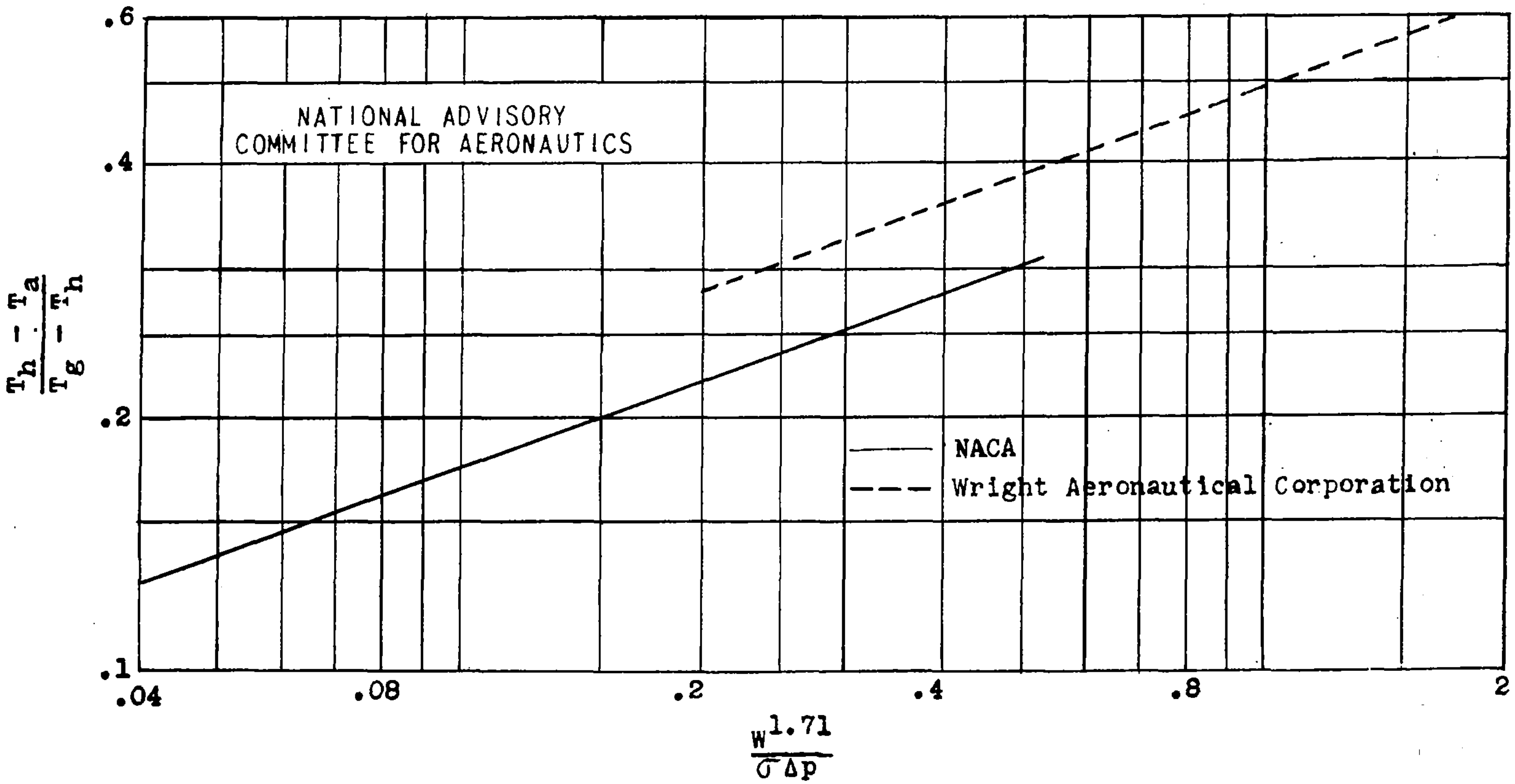

Figure 8.- Comparison of cooling correlation from Wright Aeronautical Corporation data with that from NACA data.

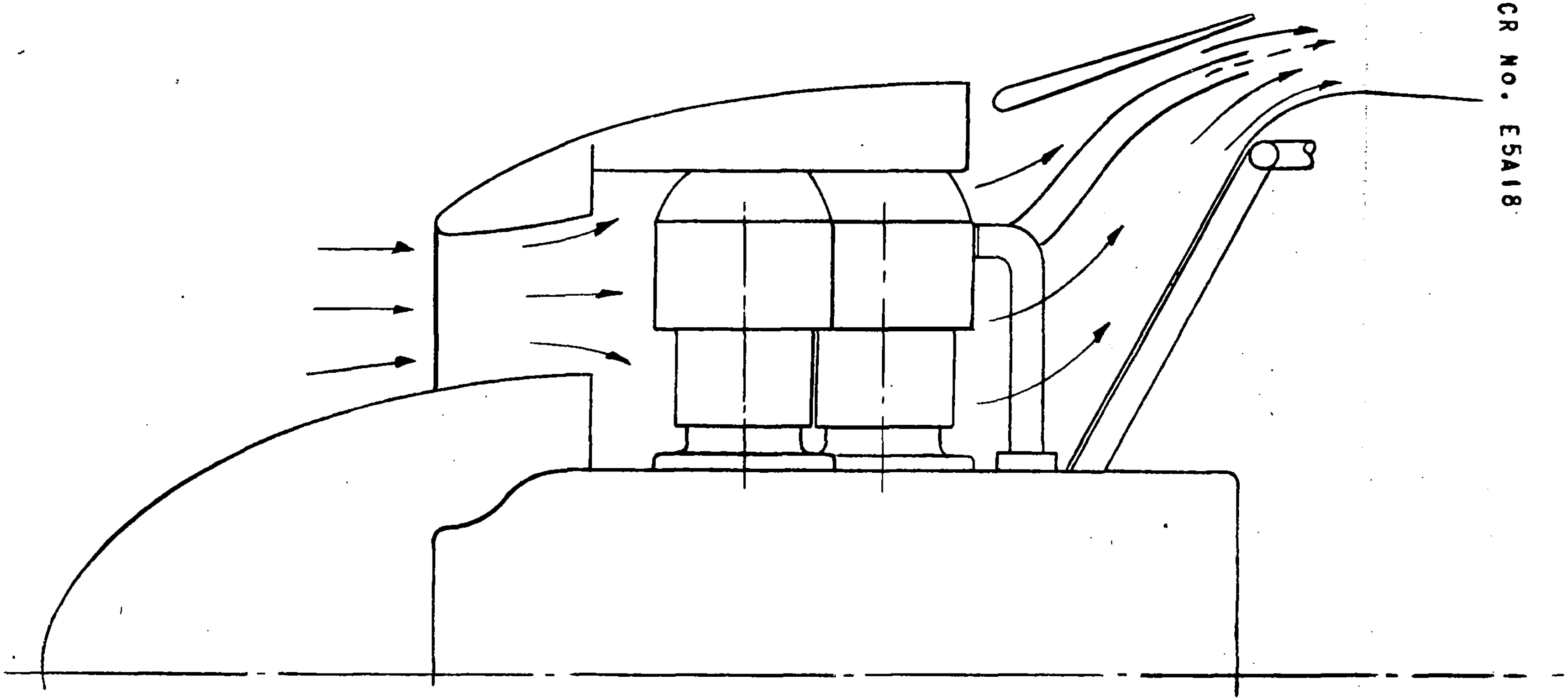

Figure 9. - Engine cooling-air flow for NACA tests.

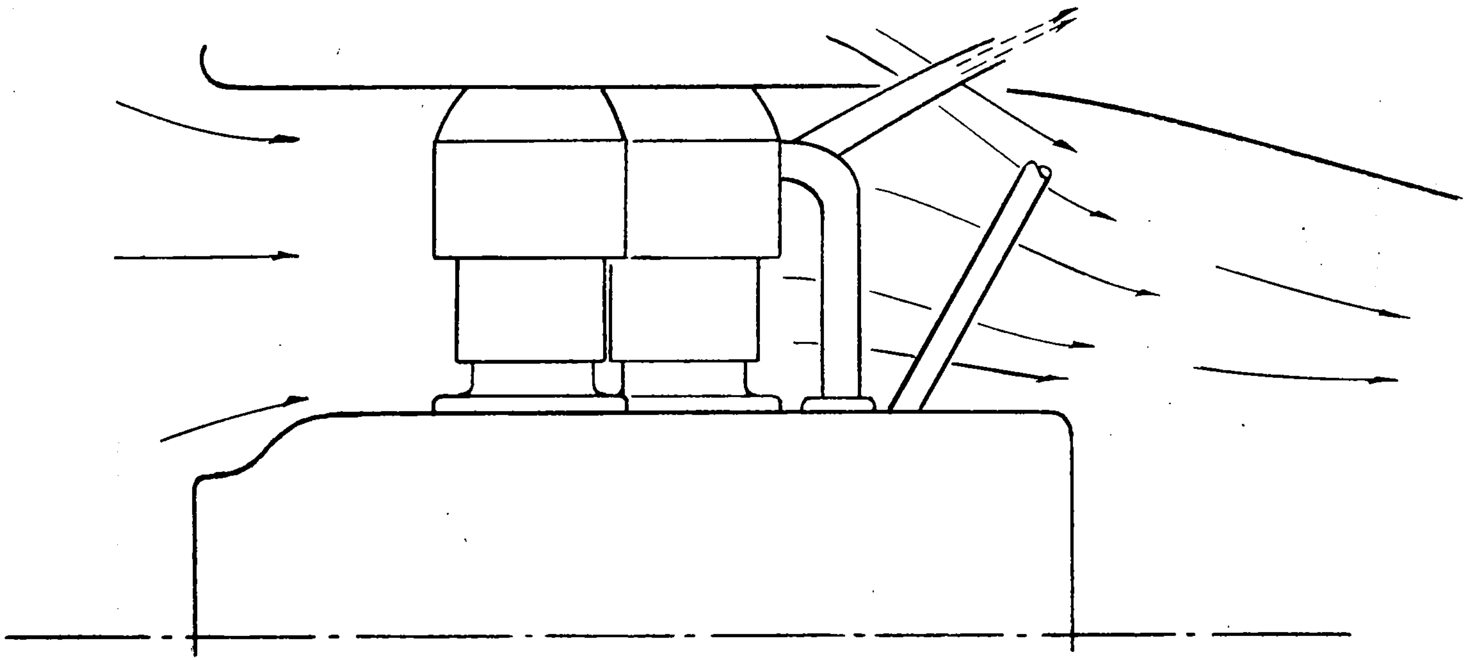

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Figure 10. - Engine cooling-air flow for Wright Aeronautical Corporation tests.

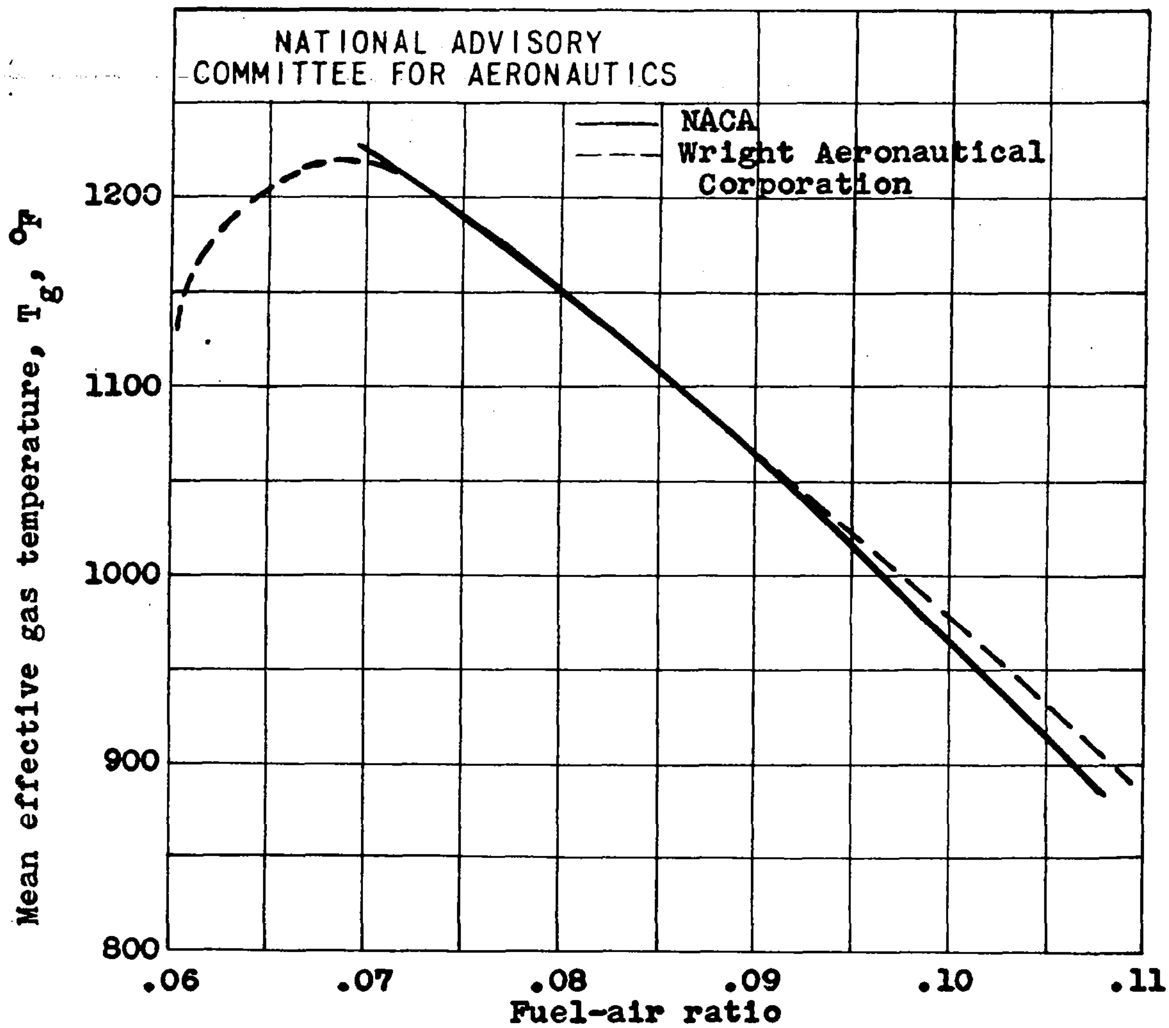

Figure 11.- Comparison of curves of mean effective gas temperature from Wright Aeronautical Corporation and NACA data.