MR No. E5L03

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

January 1946 as
Memorandum Report E5L03

CORRELATION OF MIXTURE TEMPERATURE DATA OBTAINED FROM BARE INTAKE-MANIFOLD THERMOCOUPLES

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WASHINGTON

E-273

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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

CORRELATION OF MIXTURE-TEMPERATURE DATA OBTAINED FROM BARE INTAKE-MANIFOLD THERMOCOUPLES

By H. Jack White and Goldie L. Gammon

SUMMARY

A relatively simple equation has been found to express, with fair accuracy, variation in manifold-charge temperature with change in engine operating conditions. This equation and associated curves have been checked by multicylinder-engine data, both test stand and flight, over a wide range of operating conditions.

Average mixture temperatures, predicted by the equations of this report, agree reasonably well with results within the same range of carburetor-air temperatures from laboratories and test stands other than the NACA.

INTRODUCTION

This paper is intended to demonstrate the degree to which mixture-temperature data may be reduced to algebraic terms and correlated in terms of the several pertinent engine-operating and design variables. The information presented herein was obtained in the multicylinder-engine phase of the triptane and high-performance fuel evaluation program, requested by the Air Technical Service Command, Army Air Forces. Much of the data included herein have been presented in different form in earlier reports (references 1, 2, and 3). In reference 2, a brief analysis of the mixture-temperature correlation was made. The present report extends the correlation to several other engines and includes data obtained over a wider range of conditions.

Reduction of mixture-temperature data to an algebraic relation is of interest for several reasons. Manifold-charge temperatures are of importance in engine-cooling studies as well as in the correlation of fuel knock-limit data for both single-cylinder and multicylinder test engines. The prediction of average mixture temperature at any operating condition permits fuel knock limits to be estimated from a minimum amount of test data, thereby permitting the elimination of a great volume of experimental testing. This method of analysis furthermore lends itself to various engines and may be used to advantage in comparing different engines as to their relative severity upon fuels inasmuch as mixture temperature is such an important variable in fuel knock characteristics. Matching of multicylinder knock-test conditions by single-cylinder engines is greatly facilitated by an accurate evaluation of mixture temperatures for both.

APPARATUS AND INSTRUMENTATION

The four double-row radial air-cooled engines investigated in these tests were an R-1830-75 (engine A) installed in a four-engine bomber, an R-1830-94 (engine B) installed in a test stand and loaded by a propeller, an R-1830-94 (engine C) installed in a four-engine bomber, and an R-1830-90C (engine D) installed in a four-engine bomber.

Manifold-mixture temperatures were measured in all intake pipes by bare 24-gage iron-constantan thermocouples. These thermocouples were located equidistant (for front-row and rear-row cylinders) from the supercharger outlet. Details of the installation are shown in figure 1. Carburetor-air temperatures were obtained by thermocouples attached (fig. 2) to the carburetor screen directly over the venturis. (See appendix of reference 4.)

Other measurements necessary for the correlation of mixture temperatures were fuel-air ratio (requiring fuel flow and air flow) and engine speed. Values of fuel flow were obtained by both a rotameter and a reaction-type flowmeter for the three flight engines and by a rotameter for the test-stand engine. Air flow was determined in flight from carburetor-metering-pressure data, supplemented by air-box calibration curves, and for the test stand by a standard 6-inch flat-plate orifice installed according to A.S.M.E. recommendations in a 20-inch-diameter duct upstream of the carburetor. Engine speed was obtained from electric tachometers in all cases.

FORMULATION OF MIXTURE-TEMPERATURE EQUATION

A partial derivation of the equation used in the analysis of mixture-temperature data follows. The symbols to be used are:

T_m	manifold-mixture temperature, (°F)
T_c	carburetor-air temperature (screen thermocouple), (°F)
ΔT_s	temperature rise across supercharger, (°F)
ΔT_v	temperature drop due to fuel vaporization, (°F)
V	blower tip speed, (ft/sec)
V_1	blower tip speed, (ft/min)
J	mechanical equivalent of heat, (ft-lb(force)/Btu)
c_p	specific heat of air at constant pressure, (Btu/(lb)(°F))
g	acceleration due to gravity, (ft/sec^2)
K	constant
q_{ad}	pressure coefficient of supercharger
η	adiabatic temperature-rise ratio of supercharger
N	engine speed, (rpm)
R	impeller gear ratio
d	impeller diameter, (in.)
F/A	fuel-air ratio
L	average latent heat of aviation gasoline, (Btu/lb)
c_f	average specific heat of aviation gasoline, (Btu/(lb)(°F))

The manifold-mixture temperature is assumed equal to the sum of the carburetor-air temperature plus the temperature rise due to compression in the supercharger less the temperature drop due to fuel vaporization. In figure 3 is shown a schematic cross section through a typical air-cooled engine induction system. The arrangement of the thermocouples typifies that of the double-row radial air-cooled engines discussed herein. The trends in "dry" and "wet" charge temperatures shown at the top of this sketch are considered representative of the general variation in temperatures to be expected through an induction system of this type. Thus,

$$T_m = T_c + \Delta T_s - \Delta T_v \tag{1}$$

From a familiar equation given in a number of engineering texts

$$\Delta T_s = K \frac{V^2}{J\ c_p\ g} \tag{2}$$

If J is 778, c_p is 0.243, and g is 32.2, equation (2) becomes

$$\Delta T_s = K \frac{V^2}{6090} \tag{3}$$

The factor K in equation (3) may be evaluated in terms of the physical characteristics of the actual impeller and diffuser. Thus,

$$\Delta T_s = \frac{V^2}{6090} \frac{q_{ad}}{\eta}$$

An average ratio of 0.90 has been found experimentally to be representative of superchargers for this type of engine; therefore

$$\Delta T_s = \frac{V^2}{6090} 0.90$$

$$\Delta T_s = 1.48 \times 10^{-4}\ V^2 \tag{4}$$

However, blower tip speed $V = \dfrac{3.14\ N\ R\ d}{60 \times 12}$

For engines A, B, and C with impellers of 11.3-inch diameters and at low impeller gear ratio (7.15:1), equation (4) may be expressed

$$\Delta T_s = 1.83 \times 10^{-5}\ N^2 \tag{5}$$

at high impeller gear ratio (8.47:1) equation (5) becomes

$$\Delta T_s = 2.58 \times 10^{-5}\ N^2 \tag{6}$$

It should be pointed out that for engine D with an impeller of 11.0-inch diameter both equations (5) and (6) will be slightly different.

The temperature drop due to fuel vaporization for charge thermocouples, as installed in these engines, has been found empirically to be approximated by

$$\Delta T_v = 390\ F/A \tag{7}$$

Expression (7) differs considerably from a longer form, which may express this temperature drop more precisely as follows:

$$\Delta T_v = \frac{L}{c_p + c_f\ F/A}\ F/A$$

This expression is often shortened (by elimination of $c_f \times F/A$) to

$$\Delta T_v = \frac{L}{c_p}\ F/A$$

or approximately

$$\Delta T_v = 530\ F/A \text{ for an AN-F-28 fuel} \tag{7a}$$

Equation (7a) differs from (7) only in the magnitude of the proportionality constant. This difference may be the effect of only partial vaporization of the fuel in the intake manifolds up to the point where the thermocouples are located, as shown in figure 3. The difference between equations (7) and (7a) may also arise from the fact that the cooling effect of fuel vaporization during compression in the supercharger was not considered inasmuch as ΔT_v was assumed to take place independently of the compression process.

Finally, the general form of the equation may be written, making use of expression (4),

$$T_m = T_c + 1.48 \times 10^{-4}\ V^2 - 390\ F/A \tag{8}$$

or

$$T_m = T_c + 4.1 \times 10^{-8}\ V_1{}^2 - 390\ F/A$$

For specific application to engines A, B, and C this equation becomes

Low blower:

$$T_m = T_c + 1.83 \times 10^{-5}\ N^2 - 390\ F/A$$

High blower: (engines B and C only)

$$T_m = T_c + 2.58 \times 10^{-5} N^2 - 390 F/A$$

The curves in figure 4 are presented as a demonstration of the application of such equations. With these relations it becomes possible to determine with ease the average operating mixture temperature for a wide range of engine conditions.

RESULTS AND DISCUSSION

The equations and curves just presented have been checked by a large amount of data from the four multicylinder engines enumerated previously. The mixture-temperature data of this report cover a wide range of all engine variables except carburetor-air temperature. The variation in carburetor-air temperature is between approximately 60° and 105° F.

Data that have been utilized for this correlation are actually faired averages of a large amount of variable fuel-air-ratio runs made during the conduct of fuel knock tests with these engines. References 1, 2, and 3 present the original plots of knock data, including the variables of average mixture temperature and carburetor-air temperature through which mean curves or lines have been faired. Points plotted in this report are those obtained by cross-plotting such curves as are seen in references 1 to 3 at several fixed fuel-air ratios, ranging from 0.06 to 0.10. This procedure eliminates the small cylinder-to-cylinder spread in temperatures, which consisted of an average deviation of approximately ±1° F and a maximum deviation usually of about ±5° F. Figure 5 is included to show typical mixture-temperature distribution patterns for these engines.

The correlated mixture-temperature data for the four engines are shown in figure 6. The ranges of engine conditions are shown in the key to this figure. The scatter of these data is generally within a band of 10° F. The range in mixture temperature (from approximately 120° to 280° F) represents variation in engine conditions from 1800 rpm, low blower at 90° F carburetor-air temperature, to 2800 rpm, high blower at 100° F carburetor-air temperature.

It is of interest to compare the correlation equation determined in this report with data from outside sources. Toward this end, figure 7 is included to show the degree of similarity between this correlation and that presented in reference 5. The dashed curve (without data points) is that for a carburetor-air temperature of 100° F and a fuel-air ratio of 0.05 obtained from the equation reported herein. The difference between the two curves is seen to be approximately 2° F at the high-temperature end (280° F) and 15° F at the low-temperature end (120° F). The curve from reference 5 was found to fit the experimental data with a mean deviation of ±6.6°F. This curve can be roughly approximated by the following equation:

$$T_m = 0.7\ T_c + 3.7 \times 10^{-8}\ V_1^{\,2} - 600\ F/A + 60 \qquad (9)$$

When equation (9) is compared with equation (8) it is seen that the first two terms after the equal sign are different in magnitude but are dimensionally and exponentially alike. The chief differences to be discerned are the variation in effect of carburetor-air temperature, the magnitude of temperature drop due to fuel vaporization, and the final constant. As previously mentioned, the effect of carburetor-air temperature was not investigated over a very wide range for the tests in the present report; consequently it is not felt that this term in the equation is as certain over as wide a range of variation as are the others.

A better approximation to the correlation curve for the data from reference 5 (fig. 7) was obtained by the use of the equation

$$T_m = 0.7\ T_c + 5.9 \times 10^{-10}\ V_1^{\,2.37} - 600\ F/A + 70 \qquad (10)$$

Equation (10) fits the curve shown from reference 5 with a mean deviation of approximately ±1° F over the total range of the curve, whereas equation (9) (involving $V_1^{\,2}$) has a mean deviation of approxmately ±3° F.

SUMMARY OF RESULTS

The following results were obtained from a large amount of mixture response fuel knock data from four double-row radial air-cooled engines:

1. Average engine mixture temperatures were correlated by the general equation

$$T_m = T_c + 1.48 \times 10^{-4}\ V^2 - 390\ F/A$$

where

T_m manifold-mixture temperature, (°F)

T_c carburetor-air temperature (screen thermocouple), (°F)

V blower tip speed, (ft/sec)

F/A fuel-air ratio

2. For the engines A, B, and C, this equation can be written

Low blower:

$$T_m = T_c + 1.83 \times 10^{-5} N^2 - 390 \, F/A$$

where N is engine speed in revolutions per minute.

High blower:

$$T_m = T_c + 2.58 \times 10^{-5} N^2 - 390 \, F/A$$

3. The mixture-temperature correlation equations obtained in this work agree fairly well with the correlation data reported by an outside source.

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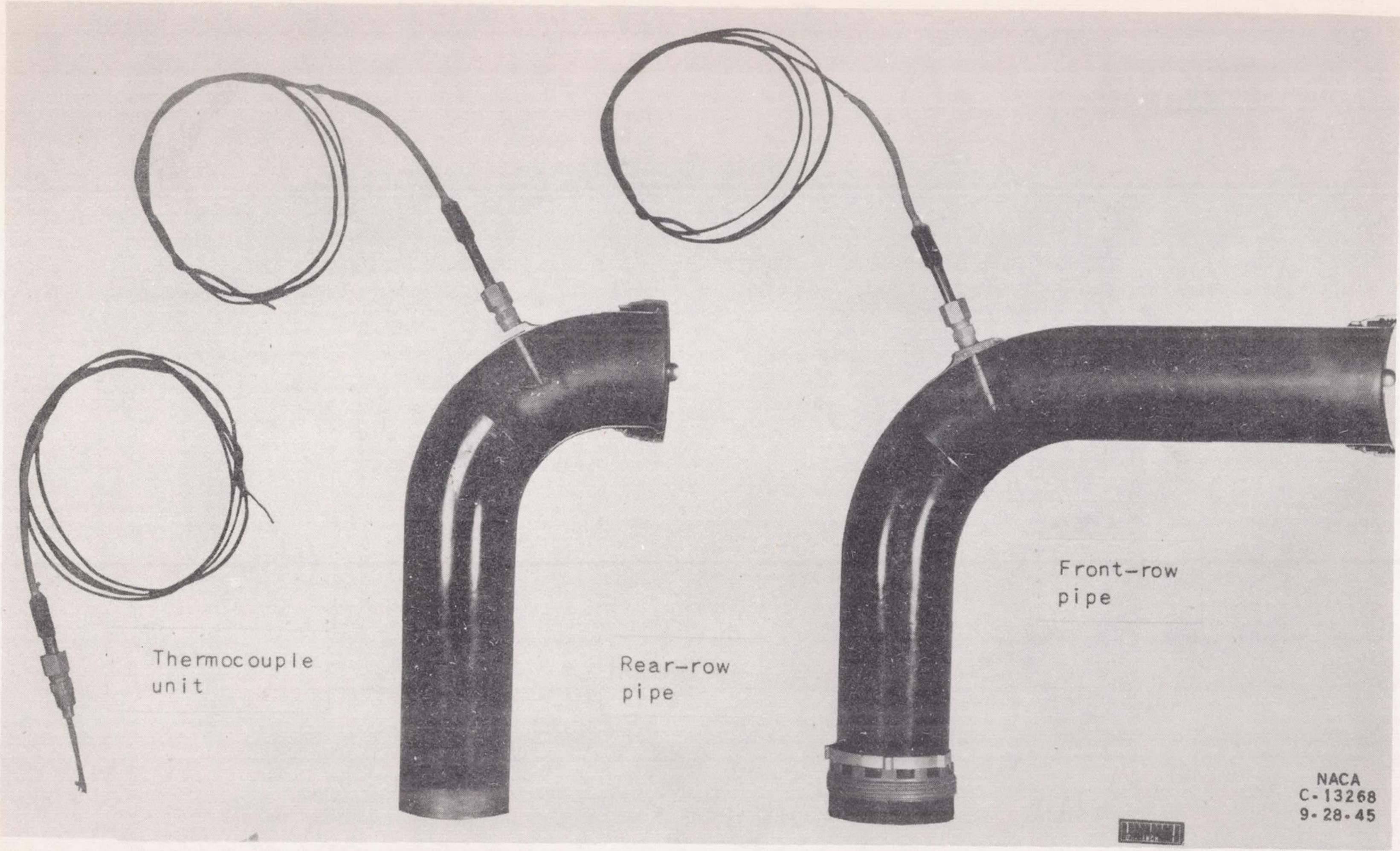

Figure 1. - Installation of mixture thermocouples in double-row radial air-cooled engine intake pipes.

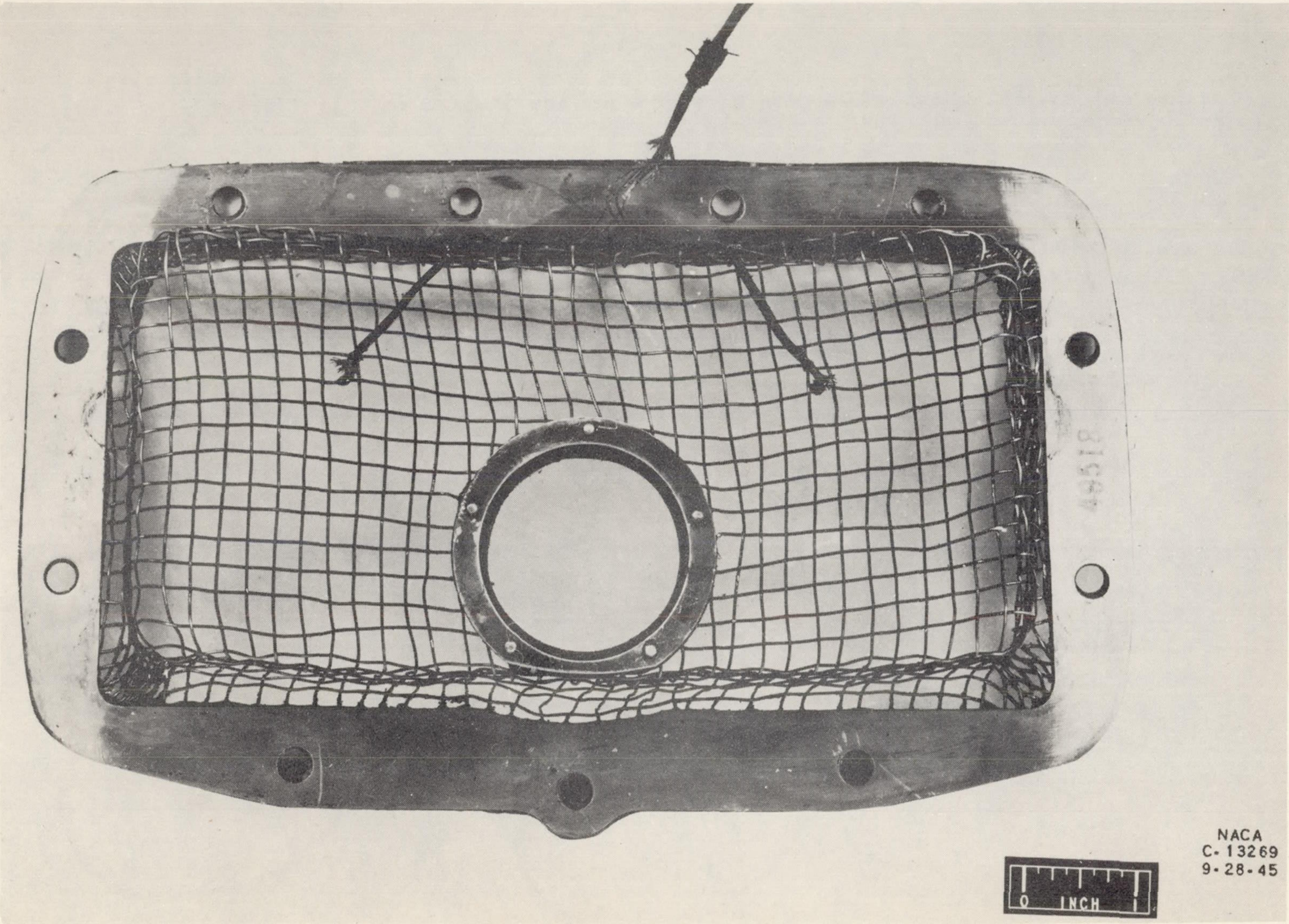

Figure 2. - Installation of dual carburetor-screen thermocouples.

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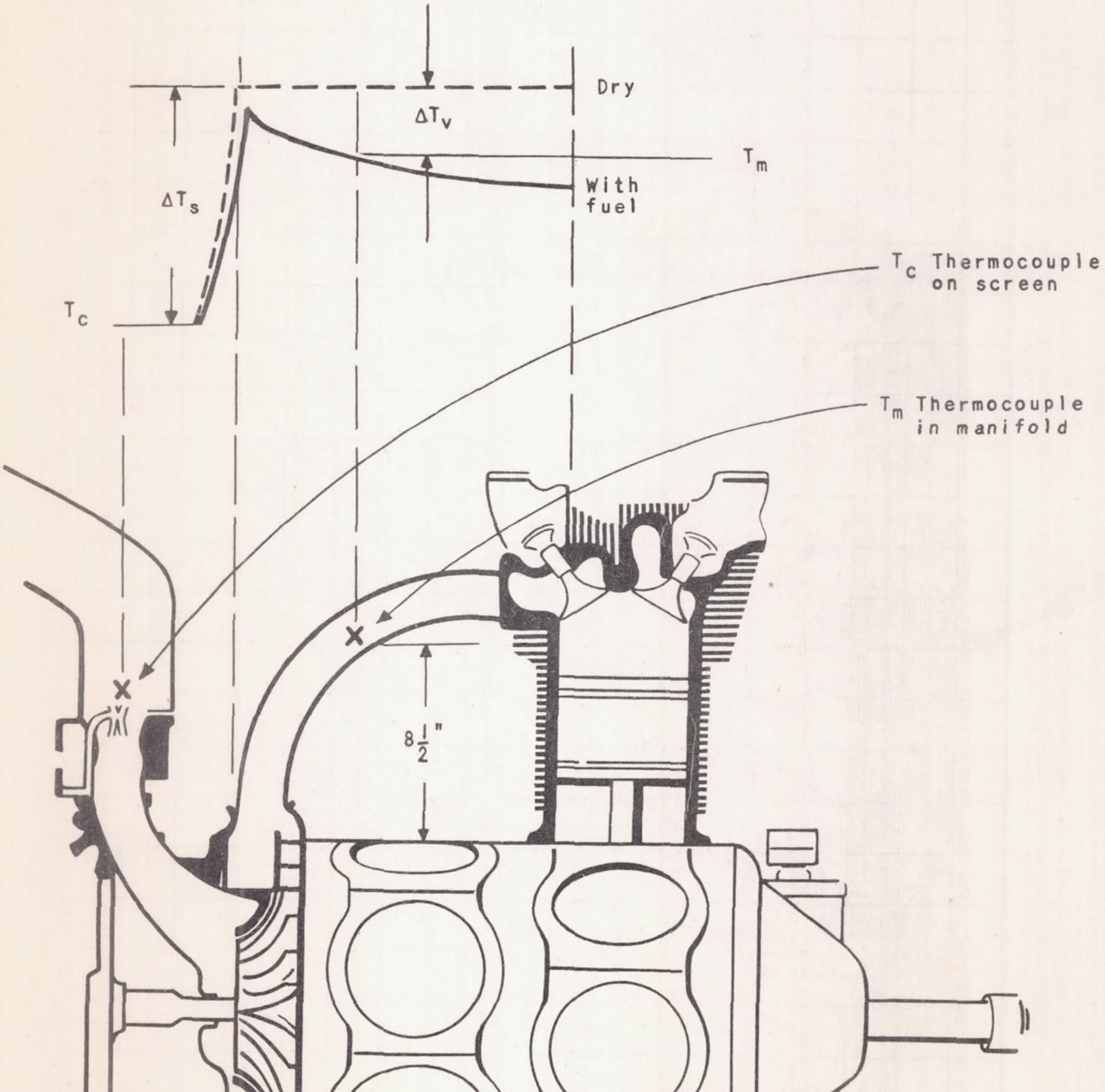

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Figure 3. - Schematic section of a typical radial-engine induction system.

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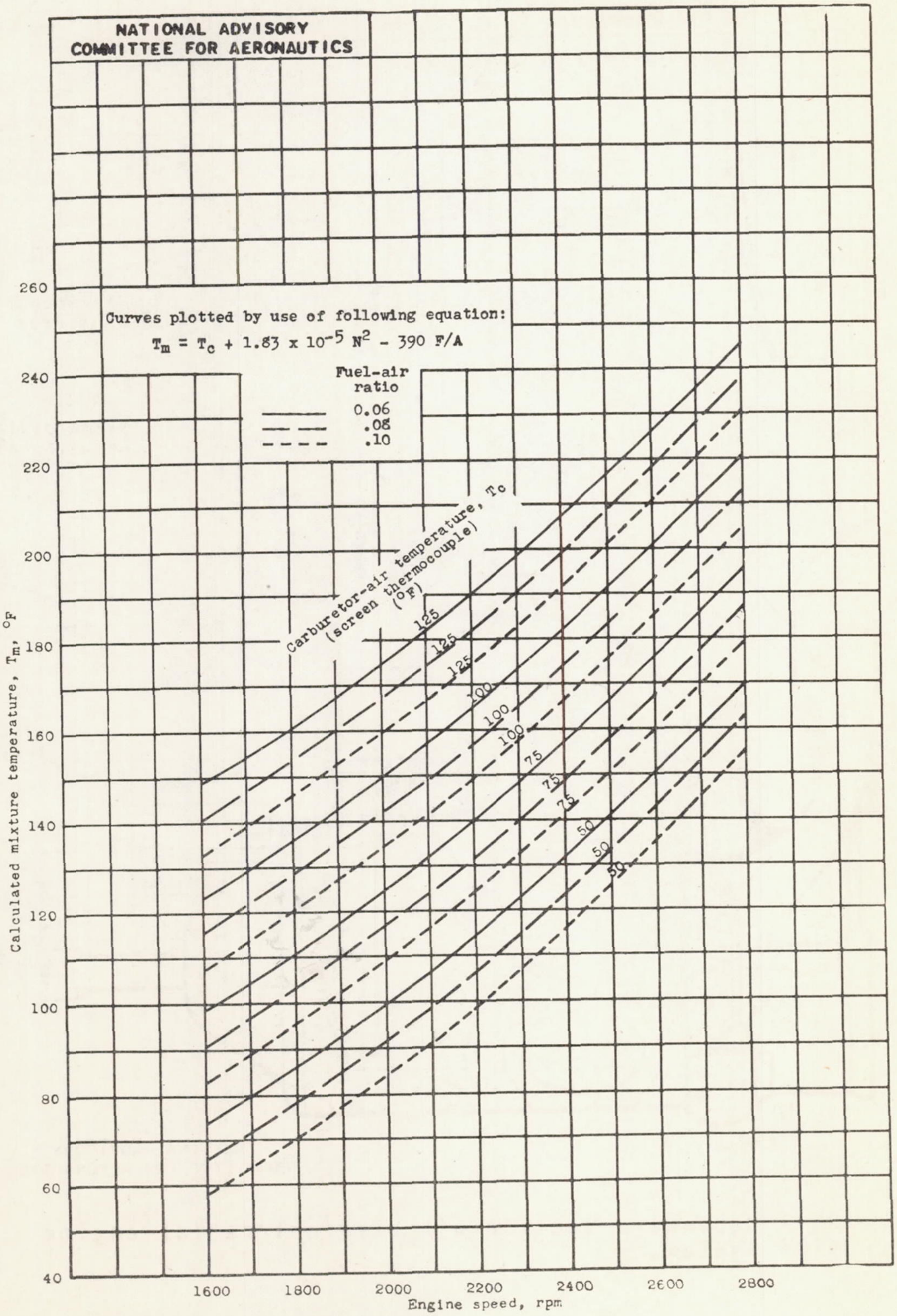

(a) Low blower (7.15:1); engines A, B, and C.

Figure 4. - Calculated relation between engine speed, carburetor-air temperature, fuel-air ratio, and mixture temperature. Impeller diameter, 11.3 inches.

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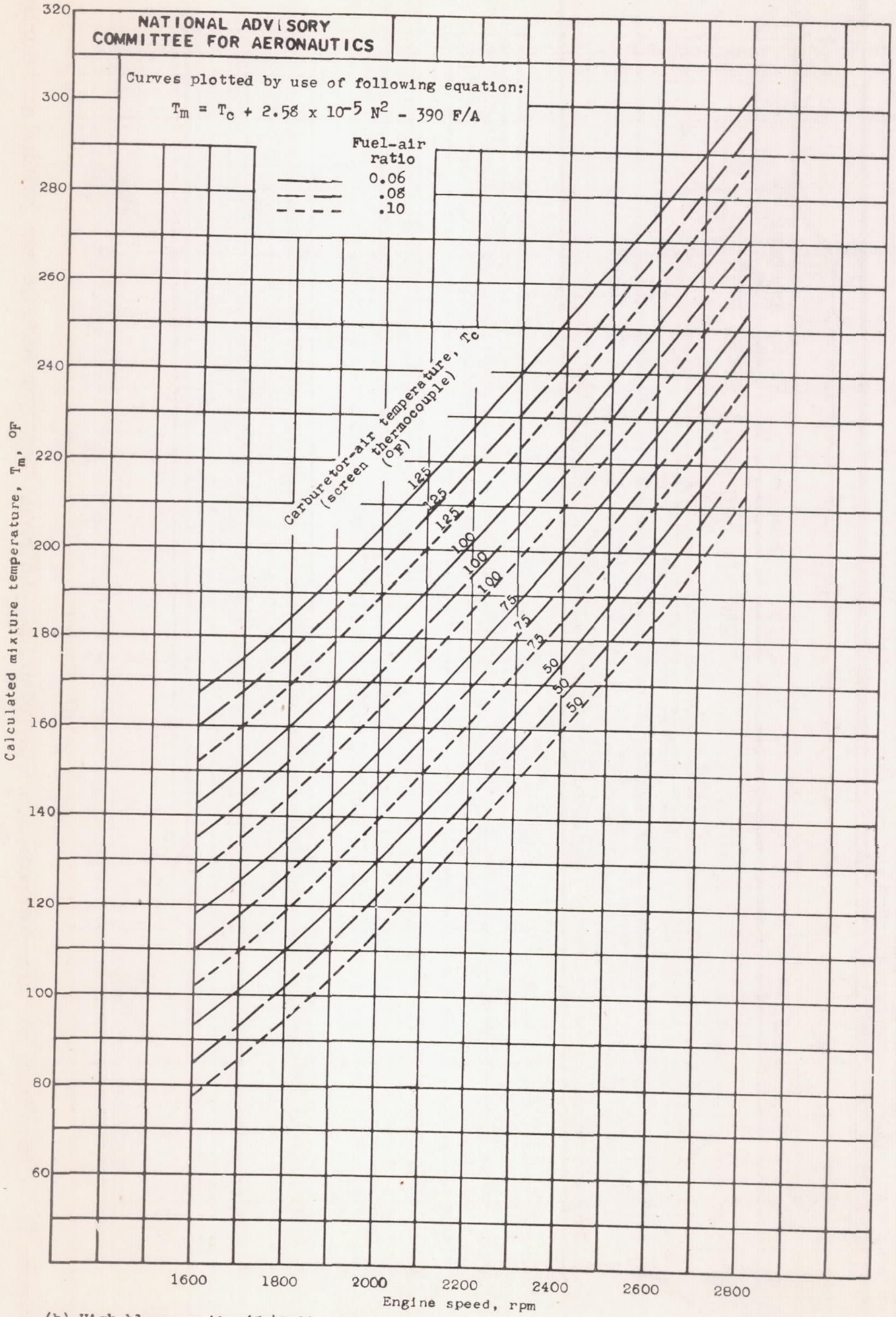

(b) High blower ratio (8.47:1); engines B and C.

Figure 4. - Concluded.

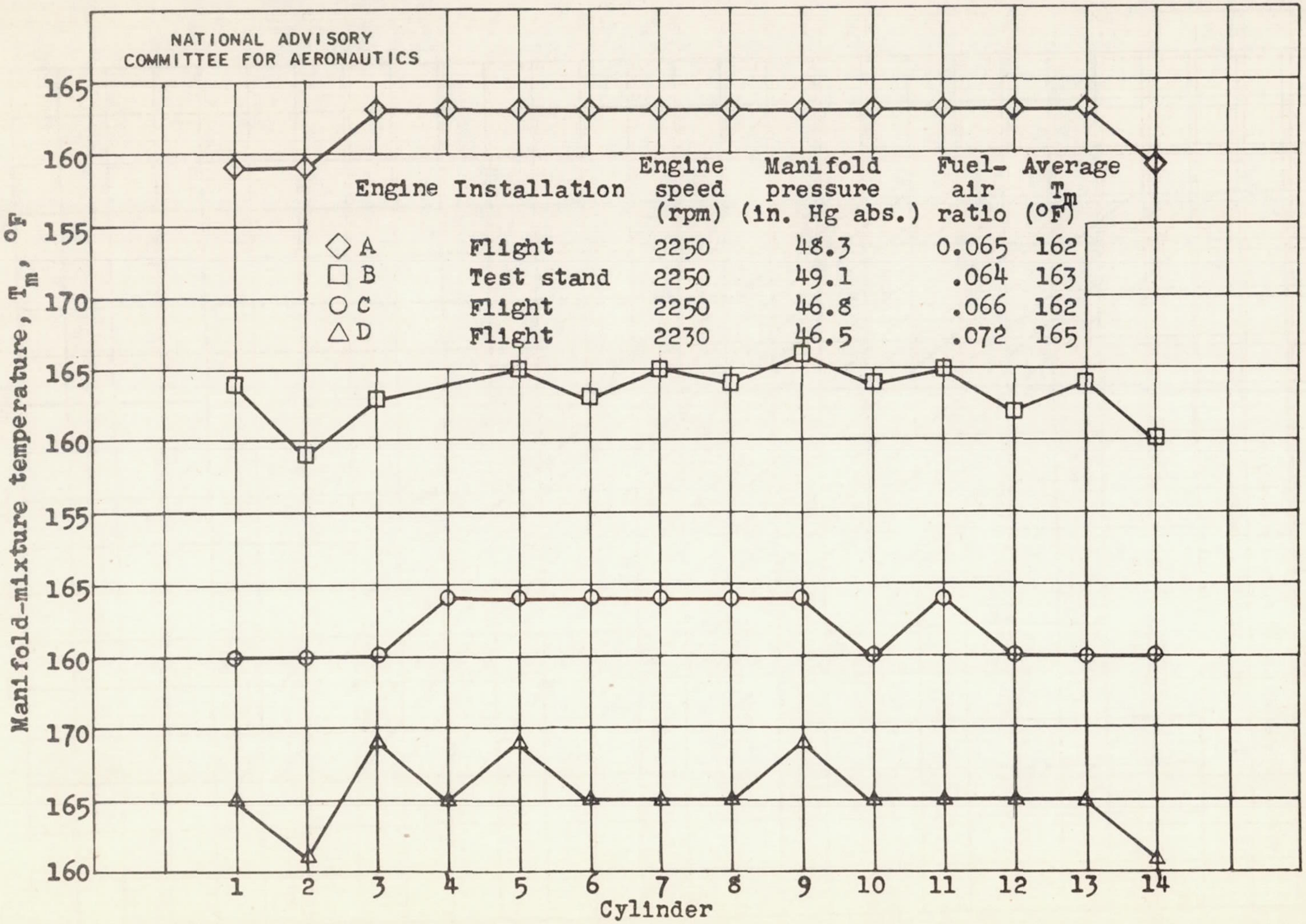

Figure 5. - Manifold mixture-temperature distribution patterns for four double-row radial air-cooled engines. Impeller gear ratio, 7.15:1.

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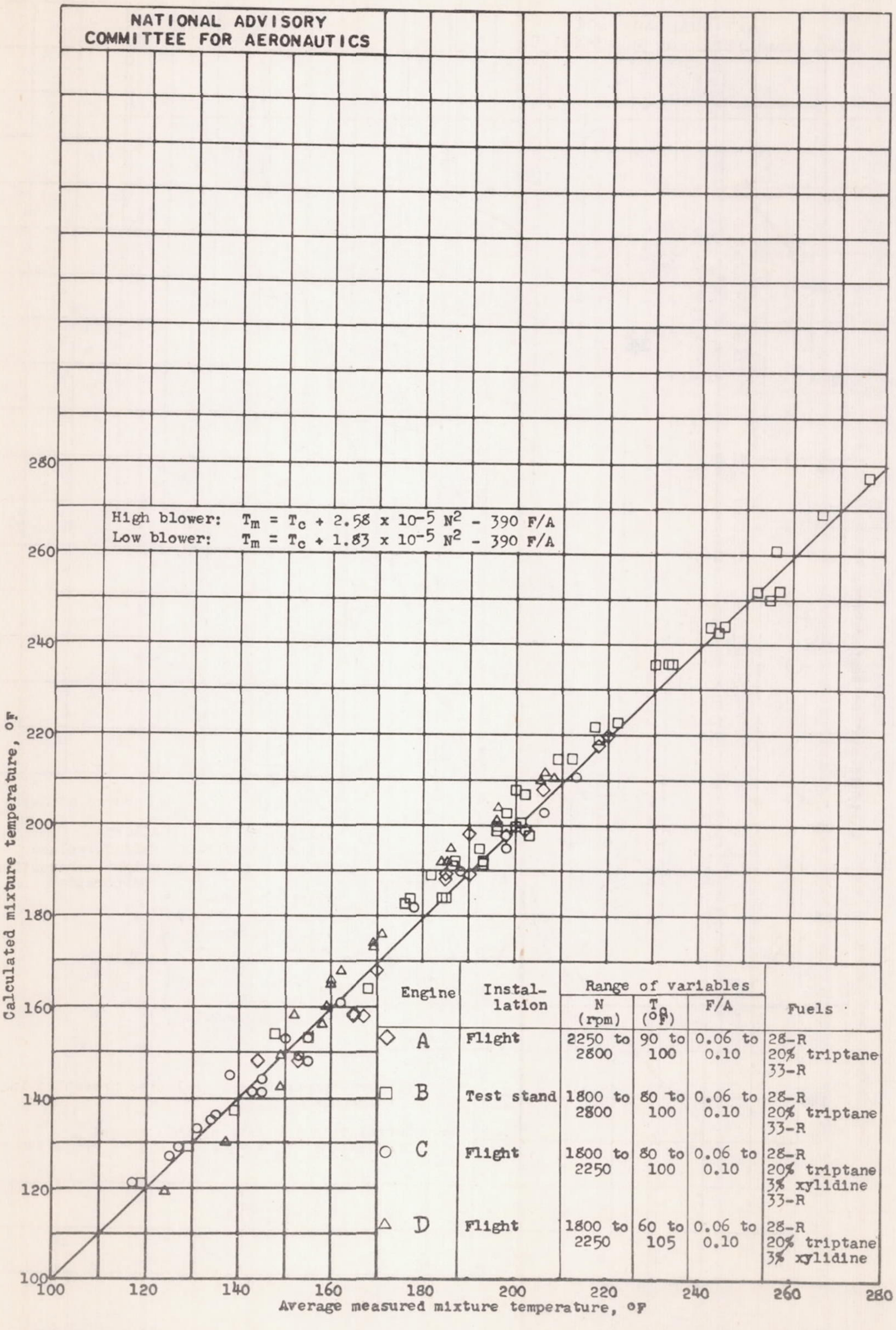

High blower: $T_m = T_c + 2.58 \times 10^{-5} N^2 - 390 F/A$

Low blower: $T_m = T_c + 1.83 \times 10^{-5} N^2 - 390 F/A$

Engine	Installation	Range of variables			Fuels
		N (rpm)	T_c (°F)	F/A	
◇ A	Flight	2250 to 2800	90 to 100	0.06 to 0.10	28-R 20% triptane 33-R
□ B	Test stand	1800 to 2800	80 to 100	0.06 to 0.10	28-R 20% triptane 33-R
○ C	Flight	1800 to 2250	80 to 100	0.06 to 0.10	28-R 20% triptane 3% xylidine 33-R
△ D	Flight	1800 to 2250	60 to 105	0.06 to 0.10	28-R 20% triptane 3% xylidine

Figure 6. - Relation between calculated and average measured mixture temperature for double-row radial air-cooled engines in flight and test-stand operation.

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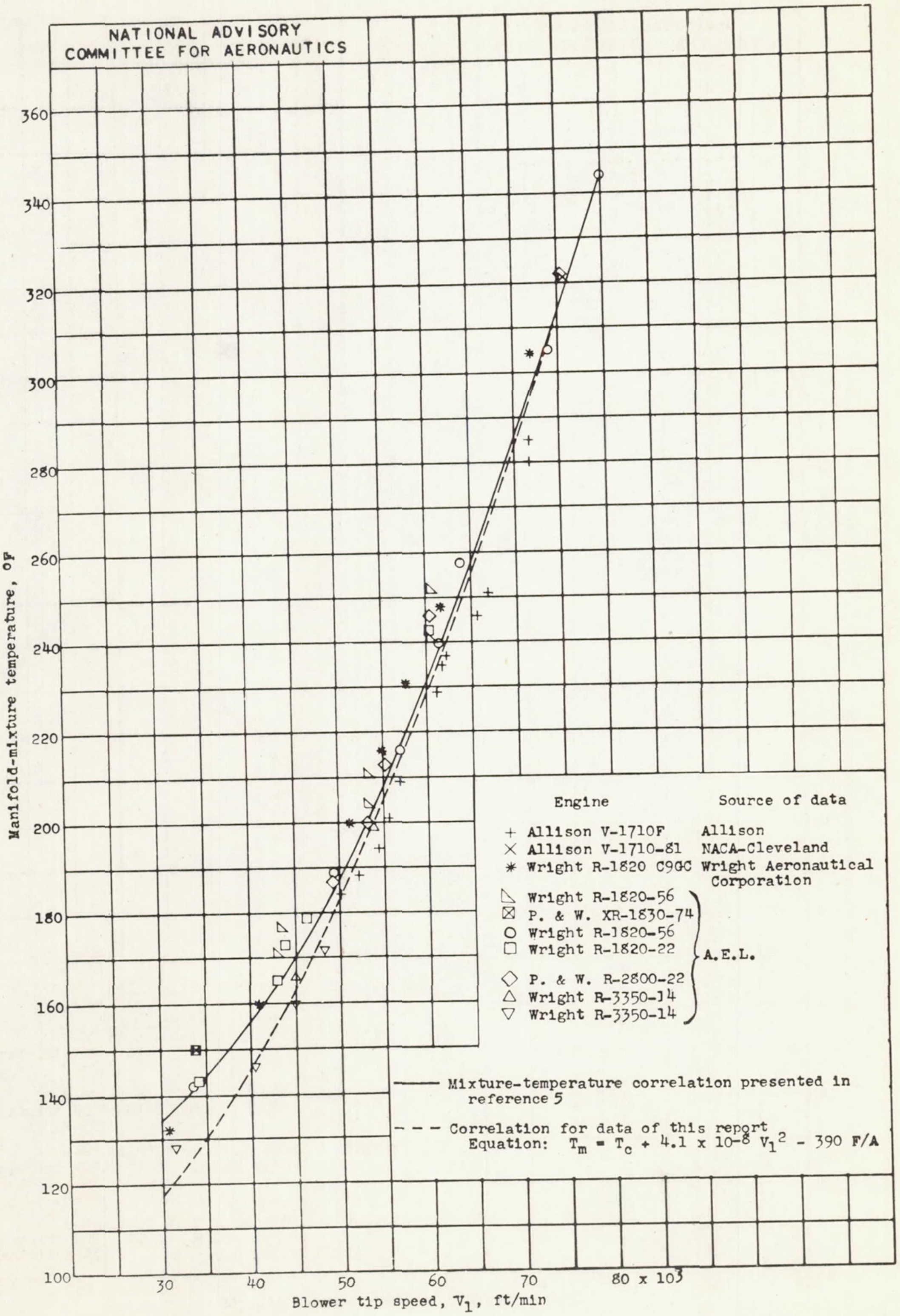

Figure 7. - Correlation of mixture-temperature data from outside sources. Carburetor-air temperature. 100° F; fuel-air ratio, 0.05. Plot obtained from plate 4 of reference 5.