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ECONOMY OF INTERNALLY COOLING ONLY THE OVERHEATED
CYLINDERS OF AIRCRAFT ENGINES

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and Hugh M. Henneberry

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

ECONOMY OF INTERNALLY COOLING ONLY THE OVERHEATED

CYLINDERS OF AIRCRAFT ENGINES

By Arnold E. Biermann, George R. Miller
and Hugh M. Henneberry

SUMMARY

Cylinder-to-cylinder temperature and mixture distributions of four different aircraft engines were analyzed to determine the possible economy of automatically supplying water or additional fuel to only those cylinders having excessive temperatures. The cooling problem as distinguished from the fuel-knock problem was studied and an analysis limited to those cases in which additional cooling is ordinarily obtained by carburetor enrichment was made.

The results show that, for conditions in which overheating is reduced by enriching the mixture to the entire engine, reductions in fuel consumption from 7 to 37 percent may be obtained for cruising operation by supplying water or fuel to only the overheated cylinders. Appreciable gains in economy are also indicated for temperature-limited engines operating at rated-power fuel-air ratio and for temperature-limited engines having uniform fuel-air mixture distributions. In general, improvements in economy are found to be practically independent of the sensitivity of the coolant-metering device for sensitivities (flow response with respect to temperature change) greater than 1.5 pound per hour per °F.

INTRODUCTION

Several methods of improving temperature distribution in a radial air-cooled engine with a 3350-cubic-inch displacement have been tried. These methods include means of improving the cooling-air distribution, means of obtaining a more uniform fuel-mixture distribution, reference 1, and means of supplying internal coolants to specified cylinders in the engine.

As part of the general program of improving the temperature distribution of this engine requested by the Air Technical Service Command, Army Air Forces, an analysis to determine the advantages of supplying an internal coolant, water or additional fuel, as a function of the temperatures of the overheated aircraft-engine cylinders was made at the NACA Cleveland laboratory during the early part of 1945. The temperature and mixture distributions of the R-3350 engine and of three other radial air-cooled engines were analyzed to determine the possible economy obtained by supplying water or additional fuel to only those cylinders having excessive temperatures. The cooling problem as distinguished from the requirements imposed by fuel knock is considered and the investigation is limited to those cases in which additional cooling is ordinarily obtained by enriching the mixture to the entire engine.

METHODS OF ANALYSIS

Cylinder-to-cylinder temperature and mixture distributions of representative aircraft engines were obtained from fuel volatility flights tests conducted in 1944 by the Army Air Forces and the Coordinating Fuel Research Committee and from reference 2 and unpublished NACA data. The quantity of additional fuel required to reduce the cylinder temperatures to assumed values by supplying fuel to the entire engine was then compared with the amount of additional fuel or water required to reduce only the temperatures of the overheated cylinders.

Assumed Conditions of the Analysis

The analysis was based on the following assumptions:

1. Basic fuel-air ratios of 0.065 and 0.086 for cruising and rated power operation, respectively. (The term "basic fuel-air ratio" is defined as the fuel-air mixture metered by the carburetor as distinct from the fuel-air mixture of the individual cylinders.)
2. A thermostatically operated coolant valve for automatically supplying additional fuel or water as required by each cylinder. (The flow response of such a valve with respect to a change in temperature is referred to as "valve sensitivity" and is measured in lb/hr/°F.)
3. A carburetor having an infinitely variable mixture control. (This assumption is conservative because only two positions, automatic lean and automatic rich, are used in practice.)
4. A grade of fuel adequate to prevent fuel knock

5. Uniform charge-air distribution
6. Each cylinder enriched the same amount when temperatures are reduced by carburetor enriching
7. The power output or specific fuel consumption unchanged when water is used as a coolant
8. Constant charge-air flow conditions

Experimental Engine Data Used in the Analysis

The original conditions of engine operation from which the analysis was made are listed in the following table:

Engine	Reference	Test method	bhp	Engine speed (rpm)	Fuel-air ratio	Cooling-air pressure drop, AP (in. water)	Manifold pressure (in. Hg abs.)
I (R-1820)	AAF-CFRC flight tests	Flight (C-47)	600	1940	0.065	-----	29.2
II (R-3350)	2	Test stand	1200	2000	0.070	10.90	32.6
III (R-1830)	NACA unpublished data	Test stand	697	2250	0.070	8.00	33.9
IV (R-2800)	NACA unpublished data	Flight (B-26)	818	1794	0.064	6.38	30.9
V (R-2800)	NACA unpublished data	Flight (B-26)	1010	1996	0.086	6.93	33.1

Although the analysis was chiefly concerned with cruising conditions, one example at a rated power fuel-air ratio was desirable. Engine IV was chosen because of available data at this fuel-air ratio.

A fuel-air ratio of 0.065 representing cruising conditions was desirable for the analysis. Because the engine II and engine III data were different from this value, they were converted to a basic fuel-air ratio of 0.065 by using plots similar to figure 1. The engine IV data at a fuel-air ratio of 0.064 were not converted to a fuel-air ratio of 0.065. For simplicity, such data are referred to in the text as having a fuel-air ratio of 0.065, although they are labeled in the figures with the actual values used.

The temperature of each engine was adjusted to various temperature-limited levels by varying all cylinder temperatures equal amounts. The original curves and the final modified curves for the highest temperature-limited condition used in the calculations are presented in figures 2 to 6. The analysis was chiefly concerned with existing fuel-air ratio distribution conditions but one example of uniform cylinder-to-cylinder fuel-air ratio distribution was desirable to show the possible effect of future improvements. Engine III was selected for this purpose and figure 3 shows the existing fuel-air ratio distribution modified to uniform fuel-air ratio distribution.

Method of Obtaining Final Results

Fuel cooling. - The method used to obtain the final results is illustrated by a hypothetical three-cylinder engine. An assumed curve of carburetor fuel-air ratio plotted against cylinder temperature was drawn through the three cylinder temperatures A, B, and C for the selected carburetor setting (fig. 7(a)). The fuel-air ratio of the curves at points A, B, and C correspond to the individual cylinder fuel-air ratio at the cruising carburetor setting. The curves for each cylinder in figure 7(a) are the same shape except they are shifted by variations of fuel flow and cylinder temperature. The abscissa of figure 7(a) was converted to fuel flow and then converted to fuel flow in excess of cruising carburetor setting and plotted in figure 7(b). For continued operation, it is assumed that the engine must operate below a maximum temperature T_1 (fig. 7(b)). The difference between the highest cylinder temperature without additional fuel and the maximum allowable cylinder temperature T_1 is the initial temperature difference ΔT . Because of the temperature-flow characteristics of thermostatically operated valves, it is necessary if the cylinder temperatures are to be limited to a value of T_1 that additional fuel be added starting at a lower temperature T_2 (valve-sensitivity line, fig. 7(b)). The valve-sensitivity line represents the variation in coolant flow permitted by the control valve for a given variation in temperature and is assumed constant over the operating range.

It is evident from figure 7(b) that, if T_1 is not to be exceeded, the control valves must add X fuel to cylinder 1, Y fuel to cylinder 2, and no fuel to cylinder 3. If cooling is to be accomplished by carburetor enrichment, the carburetor must enrich each cylinder by X amount and the resulting cylinder temperatures will be A', B', and C'.

Cylinder fuel-air ratios needed to reduce the temperature of the hot cylinders to maximum allowable temperature were calculated and the respective brake specific fuel consumption values were found for both control valve and carburetor enrichment. Comparisons of the two methods of adding fuel are presented by the following expression in terms of percentage gained:

$$\left(1 - \frac{\text{av. bsfc individual valve control}}{\text{av. bsfc carburetor enriching}} \right) 100$$

An example is presented in figure 7(c) in which the initial temperature difference ΔT is considerably smaller than in figure 7(b). In this example, valve enriching is only required for cylinder 2; however, with carburetor enrichment, Z amount of fuel must be added to each cylinder because the temperature of cylinder 1 will exceed the allowable temperature T_1 upon slight enrichment of the carburetor.

Special cases, fuel cooling. - Because of the shape of the curves of additional fuel plotted against temperature, the following two conditions arise, which can cause a greater consumption of fuel with valve enrichment than would be obtained with carburetor enrichment:

1. In figure 7(d), the initial temperature T_2 for cylinder 2 is below the maximum allowable temperature T_1 but above the valve opening temperature T_2 , which causes R amount of fuel to be added to cylinder 2 with a resultant loss in economy because no enrichment is required.

2. In figure 7(b), with carburetor enrichment X amount of fuel is added to each cylinder and with valve enrichment X amount of fuel is added to cylinder 1. If the cooling conditions improve during operation, all temperatures will be lowered and the value of X will decrease. When the temperatures have reduced to the conditions represented by figure 7(d), the quantity of fuel injected into cylinder 1 is represented by S . If the pilot momentarily shuts off the additional fuel, the temperature of cylinder 1 will reduce to the value represented by point B, which is below the valve-opening temperature T_2 . The fuel consumption will be lower at point B than it was before closure of the automatic valve. A similar situation exists when carburetor enrichment is used to reduce cylinder temperatures. If the carburetor is manually controlled by the pilot and the individual injection is automatic, the carburetor control will give more economical operation because no enrichment is required under the cooling conditions.

In the foregoing example, the automatic valve can be closed by a momentary reduction of temperatures to below the valve-sensitivity line T_2 . Another method is to cut off momentarily the fuel supplied to the automatic valve. Mechanisms for closing the automatic valve to return the operation to the basic fuel-air ratio setting line are referred to hereinafter as "closing devices."

Water cooling. - The method used to determine the effects of supplying water individually to overheated cylinders as compared with carburetor enriching is quite similar to the method described for fuel. Curves of water-fuel ratio plotted against cylinder-temperature curves were converted to water flow plotted against cylinder temperature for the selected carburetor setting (fig. 7(e)).

The brake specific liquid consumption was found for each cylinder by multiplying the individual cylinder brake specific fuel consumption by

$$\left(1 + \frac{\text{water added by control valve}}{\text{fuel supplied by carburetor to cylinder}} \right)$$

These values were averaged for the engine and compared with carburetor enriching by the following expression in terms of percentage gained:

$$\left(1 - \frac{\text{av. bsfc, individual valve control}}{\text{av. bsfc, carburetor enriching}} \right) 100$$

Illustration of method using engine I data. - Figure 8(a) represents temperatures of all cylinders for engine I for fuel flows in excess of a carburetor setting of 0.065 fuel-air ratio. The temperatures at the zero abscissa are those given in figure 2. Figures 8(b) to 8(f) are similar except that all individual cylinder temperatures for each cylinder were lowered an equal amount below those taken from figure 2. An arbitrary maximum allowable rear-spark-plug-gasket temperature of 400° F and a valve sensitivity of 2 pounds per hour per °F were selected for the analysis. The method used to analyze the engine I data with water as the internal coolant is illustrated in figure 9. Cylinders 5 and 6 operate at exactly the same temperature (fig. 2). The slope of the curves when water-fuel ratio was plotted against rear-spark-plug-gasket temperature was taken from reference 3.

RESULTS AND DISCUSSION

Cruising operation with a basic fuel-air ratio of 0.065. - The improvements in economy obtained with automatic-valve enrichment as compared with carburetor enrichment are presented in figure 10 for the four engines. These data show appreciable reductions in brake

specific liquid consumptions, even with small amounts of internal cooling. The operating conditions causing negative improvements in economy are not extensive, especially if a closing device is assumed.

The results for engine I with individual cylinder enriching (fig. 10(a)) show a saving of approximately 7 percent over carburetor enriching for an initial temperature difference as low as 20° F. This saving is accomplished even though the engine had good mixture distribution and a spread in cylinder-head temperatures of only 33° F (fig. 2). The percentage change in fuel or liquid consumption becomes less as the initial temperature difference is reduced for this engine because the hottest cylinder is also a rich cylinder. This hottest cylinder is near the peak of the fuel-air and temperature curve and a small carburetor enrichment will cool it without causing the lean cylinders to rise above the maximum allowable temperature T_1 (fig. 8). Similarly, engine IV (fig. 10(d)) also shows a small saving in fuel or liquid consumption with small initial temperature differences because the hottest cylinder is a rich cylinder (fig. 5).

Figures 10(b) and 10(c) for engine II and engine III, respectively, reveal approximately 17 to 37 percent reduction in fuel consumption. Results for engine II are probably conservative because data were not available for 3 cylinders and calculations were based on 15 cylinders. The possible economies cited are the results of the wide range of head temperatures and fuel-air ratios (figs. 3 and 4). Large changes in carburetor fuel-air ratio are necessary to obtain even a small amount of cooling because, in general, the hottest cylinders are also lean cylinders. Consequently, large gains are possible for small initial temperature differences greater than zero. This fact is further explained as follows: When the average fuel-air ratio for an engine is near that for best economy, the mixture values of the various cylinders are distributed on both sides of the temperature peak. Consequently, if the mixture to the entire engine is enriched in order to lower the temperature of the cylinders at the temperature peak, the temperature of the lean cylinders will increase and a still richer mixture will be required to bring the lean cylinders over to the rich side of the temperature curve.

In general, cooling with water is somewhat more economical than cooling with fuel under the foregoing conditions (fig. 10), inasmuch as the cooling curve for water has no temperature peak. Engines that have lean cylinders with high temperatures (fig. 3) show a marked advantage of water cooling over fuel cooling for a fuel-air setting near that of best economy. Subsequent tests have shown, however, that some of the critical areas of the combustion chamber are not adequately cooled with water.

Operation with a basic fuel-air ratio of 0.086. - The reductions in fuel consumption with individual-valve enriching as compared with carburetor enriching obtained for engine IV operating with a basic carburetor setting near that for maximum power are shown in figure 11. A comparison of figures 10(d) and 11 shows that a change in the basic fuel-air ratio from 0.064 to 0.086 reduces the possible gain in economy from 31 to 17 percent.

Effect of a change in maximum allowable temperature. - The curves used to calculate figures 10 and 11 are based on a maximum allowable temperature of 400°F . The same curves, however, apply for other maximum allowable temperatures, because all cylinder-head temperatures were assumed to have the same relative spread for all cooling-air conditions.

Effect of valve sensitivity. - All calculations were made using a valve sensitivity of 2 pounds of liquid per hour per $^{\circ}\text{F}$. Figure 12, which is plotted for engine IV, shows the effect of valve sensitivity on the economy of valve enriching. (The reciprocal of valve sensitivity is used in fig. 12 for convenience of plotting.) Calculations were made in the regular manner for several valve sensitivities and three initial temperature differences to determine possible improvements over carburetor enriching. Preliminary tests indicate that practical valves will probably have sensitivities ranging from 1.5 to 3.0 (reciprocals from 0.67 to 0.33). It can be seen from figure 12 that this entire range of sensitivities results in less than a 1.5 percent difference in brake specific liquid consumption. Calculations for the other engines produced similar results.

Improvements in engines having uniform fuel-air ratio distributions. - The large cylinder-to-cylinder temperature differences existing on some engines can only be partly accounted for by unequal mixture distribution. Other factors including unequal charge and cooling-air distributions, differences in piston-ring condition and cylinder lubrication, and differences in valve and spark timing all contribute to the unequal temperature distributions experienced.

The effect of achieving a uniform fuel-air ratio distribution on the present problem has been analyzed for engine II and is shown in figure 13. The changes in cylinder temperature incurred by the assumed uniform-mixture distribution are shown in figure 3.

The correction of cylinder temperatures and fuel-air ratios to simulate uniform distribution at a basic fuel-air ratio of 0.065 reduces the maximum advantage of individual-valve enrichment to about 15 percent. The data indicate the extent to which the fuel consumption of engines having uniform fuel-air distribution but nonuniform temperature distribution can be improved by individual-cylinder enriching.

SUMMARY OF RESULTS

From the analysis of cylinder-to-cylinder temperature and mixture distributions of four radial air-cooled engines at the assumed conditions, the following remarks apply:

1. In typical air-cooled aircraft-engine installations operating under cruising conditions in which overheating is ordinarily prevented by enriching the fuel-air mixture to the entire engine, reductions in fuel consumption from 7 to 37 percent may be realized even for moderately overheated engines by adding water or fuel to only the overheated cylinders.
2. Appreciable gains in economy are indicated for temperature-limited engines operating at rated power fuel-air ratio.
3. Appreciable gains in economy are indicated for temperature-limited engines having uniform fuel-air mixture distributions.
4. In general, improvements in economy are practically independent of the sensitivity of the coolant valves for values of sensitivity greater than 1.5 pound per hour per °F.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 14, 1945.

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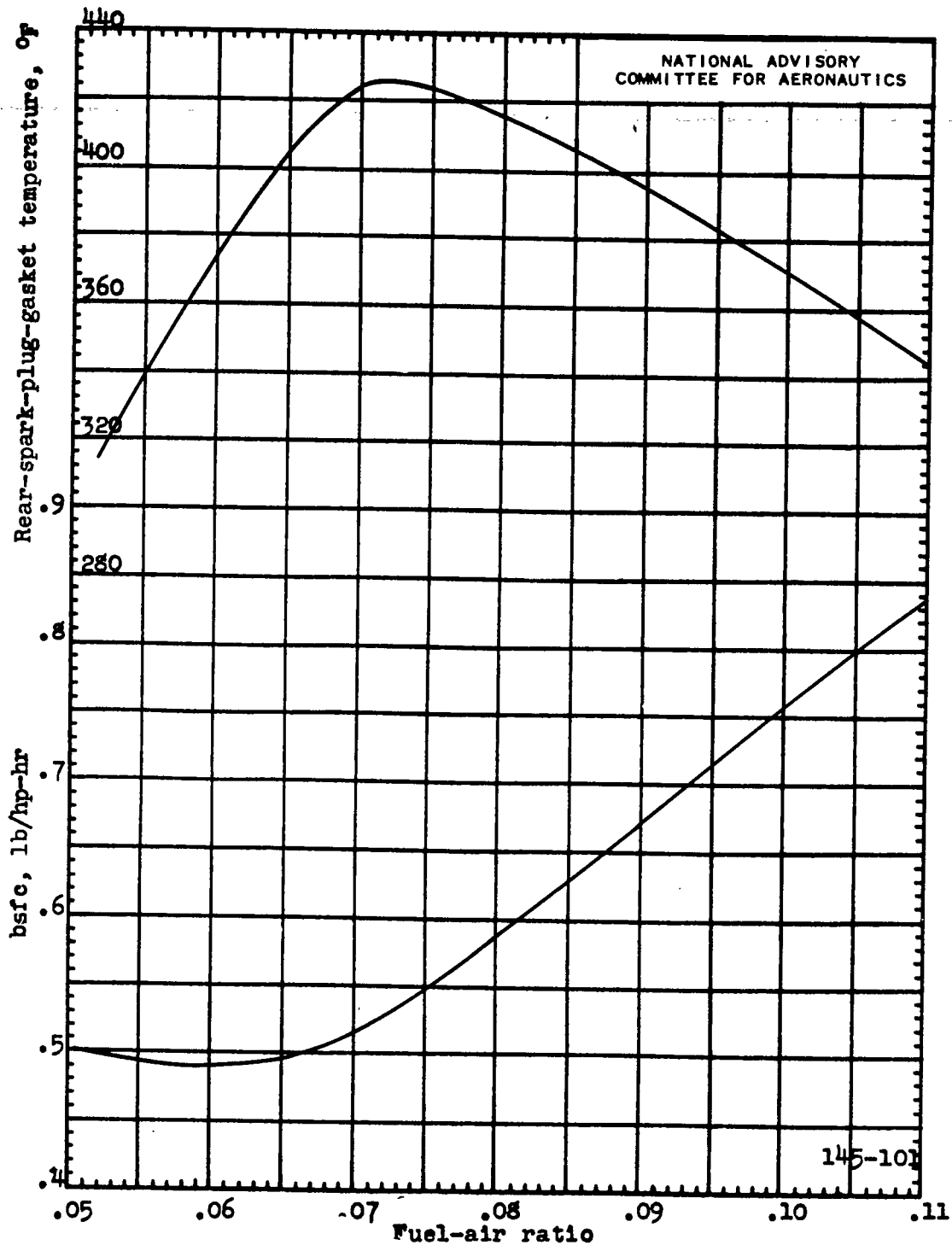


Figure 1. - Typical variation of temperature and brake specific fuel consumption with mixture strength for engine II cylinder. (From unpublished NACA data.)

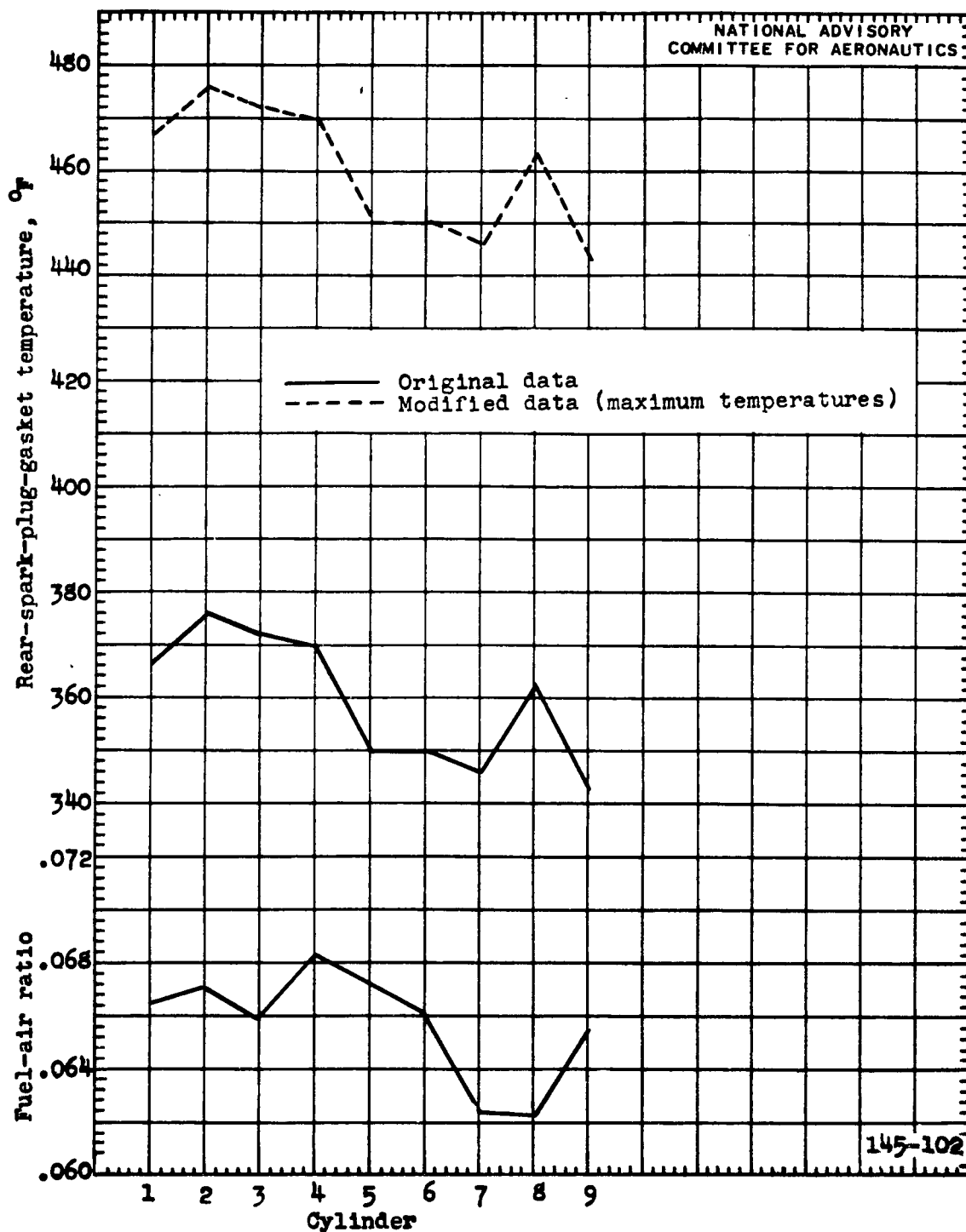


Figure 2. - Temperature and mixture distribution of engine I.
Engine speed, 1940 rpm; manifold pressure, 29.2 inches mercury absolute; average fuel-air ratio, 0.065. (Data from Army Air Forces-Coordinating Fuel Res. Committee flight tests.)

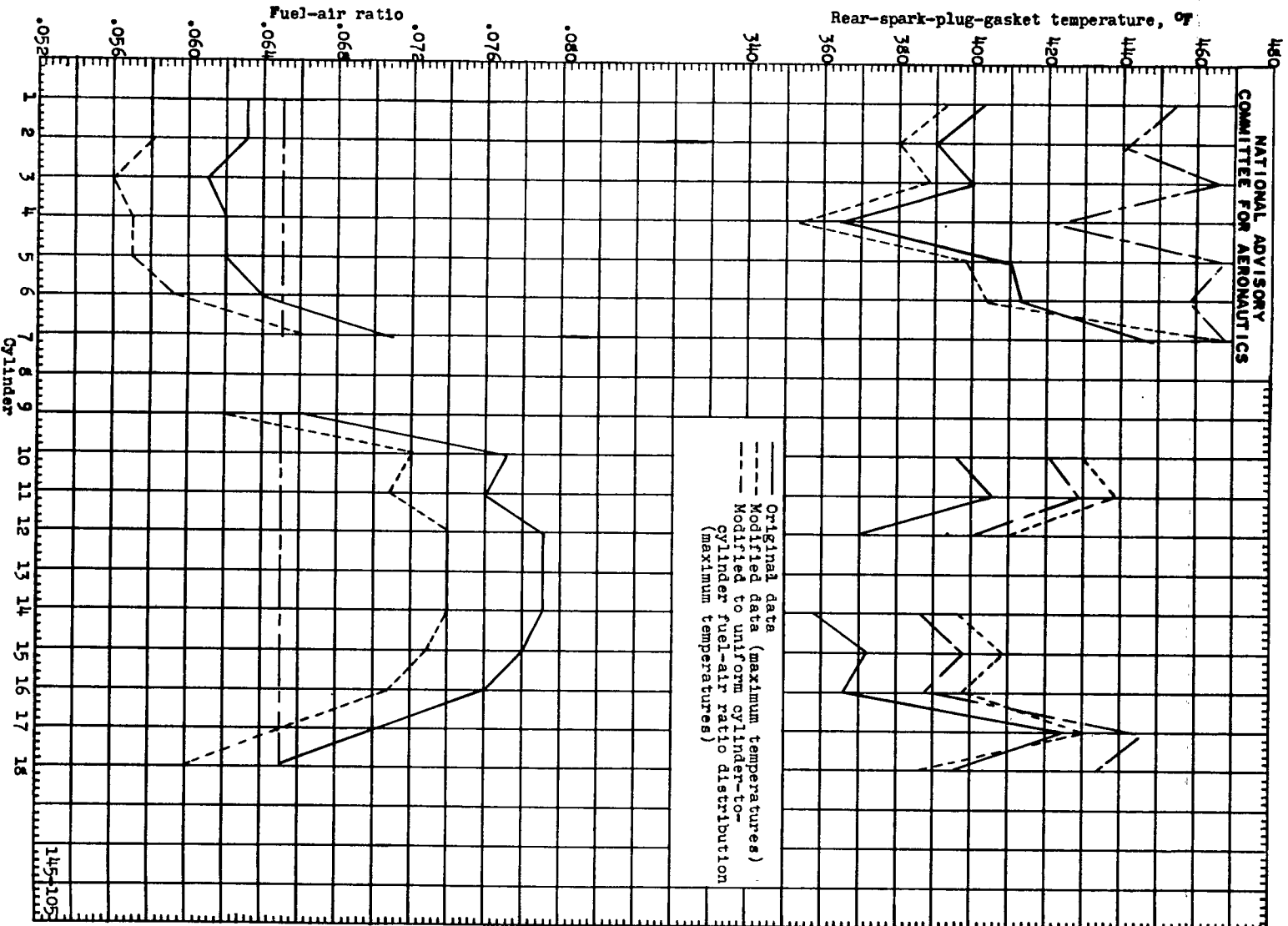


Figure 3. - Temperature and mixture distribution of engine II. Engine speed, 2000 rpm; manifold pressure, 32.6 inches mercury absolute; average fuel-air ratio: original, 0.070; modified, 0.065. (Data from reference 2.)

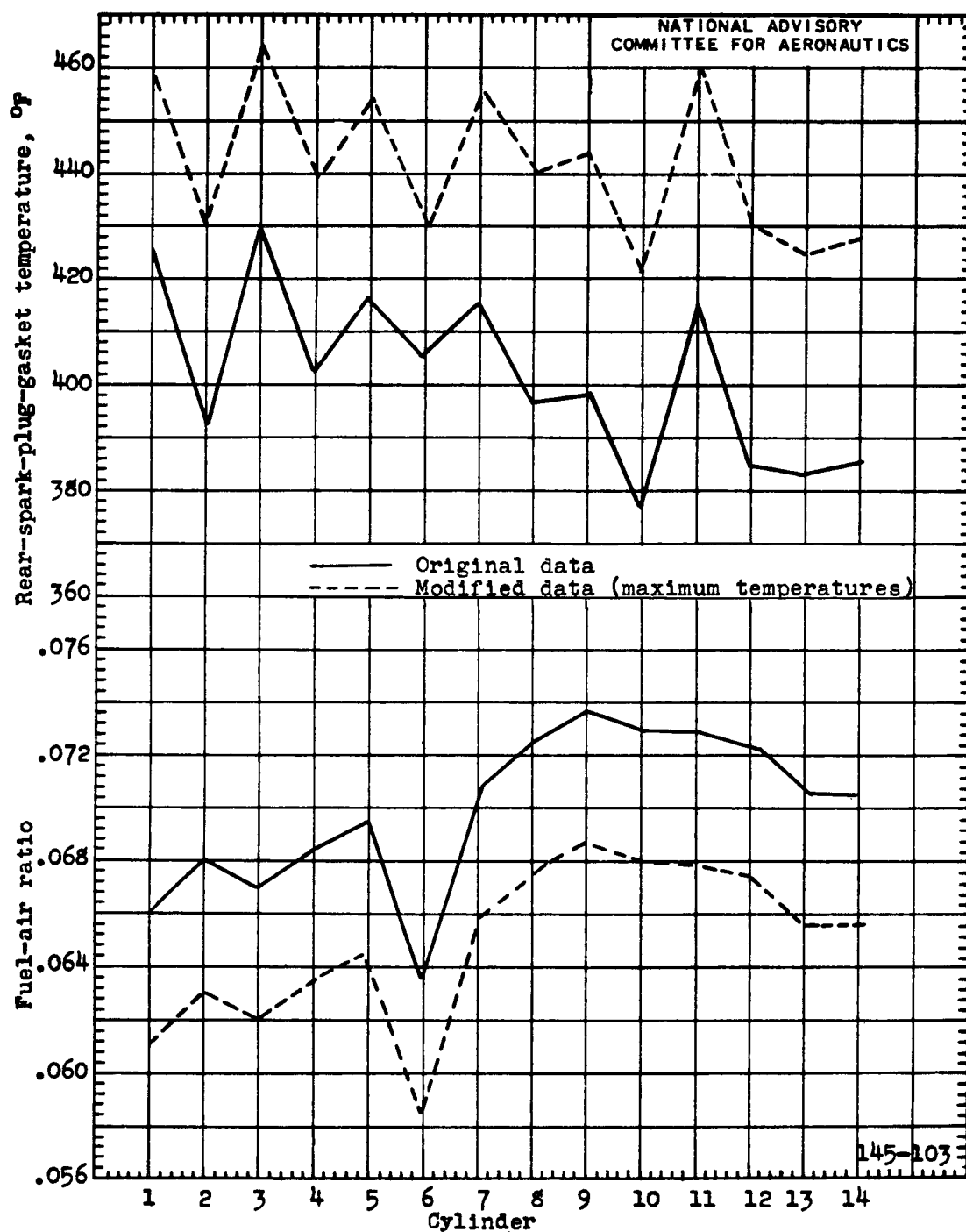


Figure 4. - Temperature and mixture distribution of engine III. Engine speed, 2250 rpm; manifold pressure, 33.9 inches mercury absolute; average fuel-air ratio: original, 0.070; modified, 0.065. (From unpublished NACA data.)

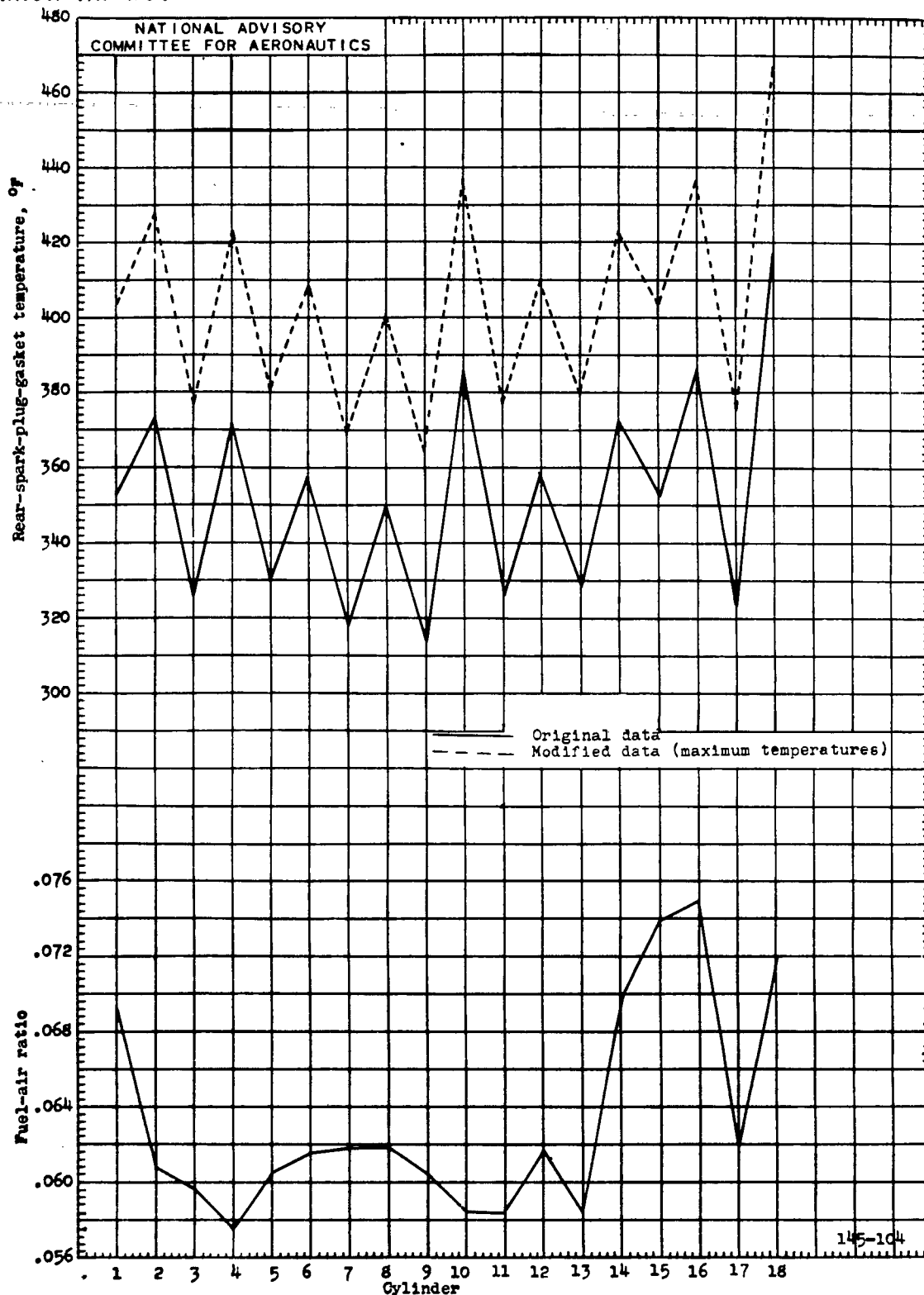


Figure 5. - Temperature and mixture distribution of engine IV. Engine speed, 1794 rpm; manifold pressure, 30.9 inches mercury absolute; average fuel-air ratio, 0.064. (From unpublished NACA data.)

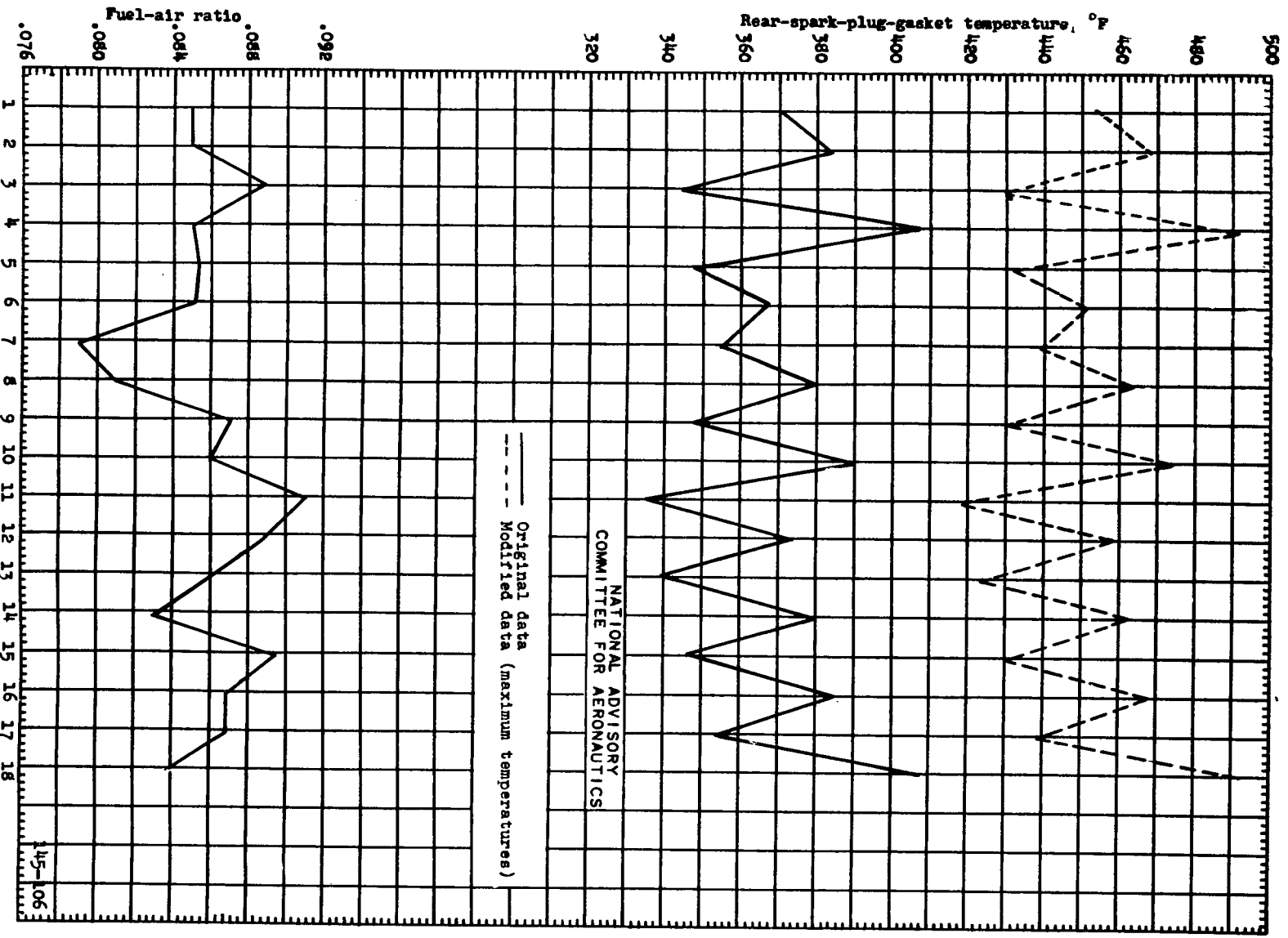


Figure 6. - Temperature and mixture distribution of engine IV. Engine speed, 1996 rpm; manifold pressure, 33.1 inches mercury absolute; average fuel-air ratio, 0.086. (From unpublished NACA data.)

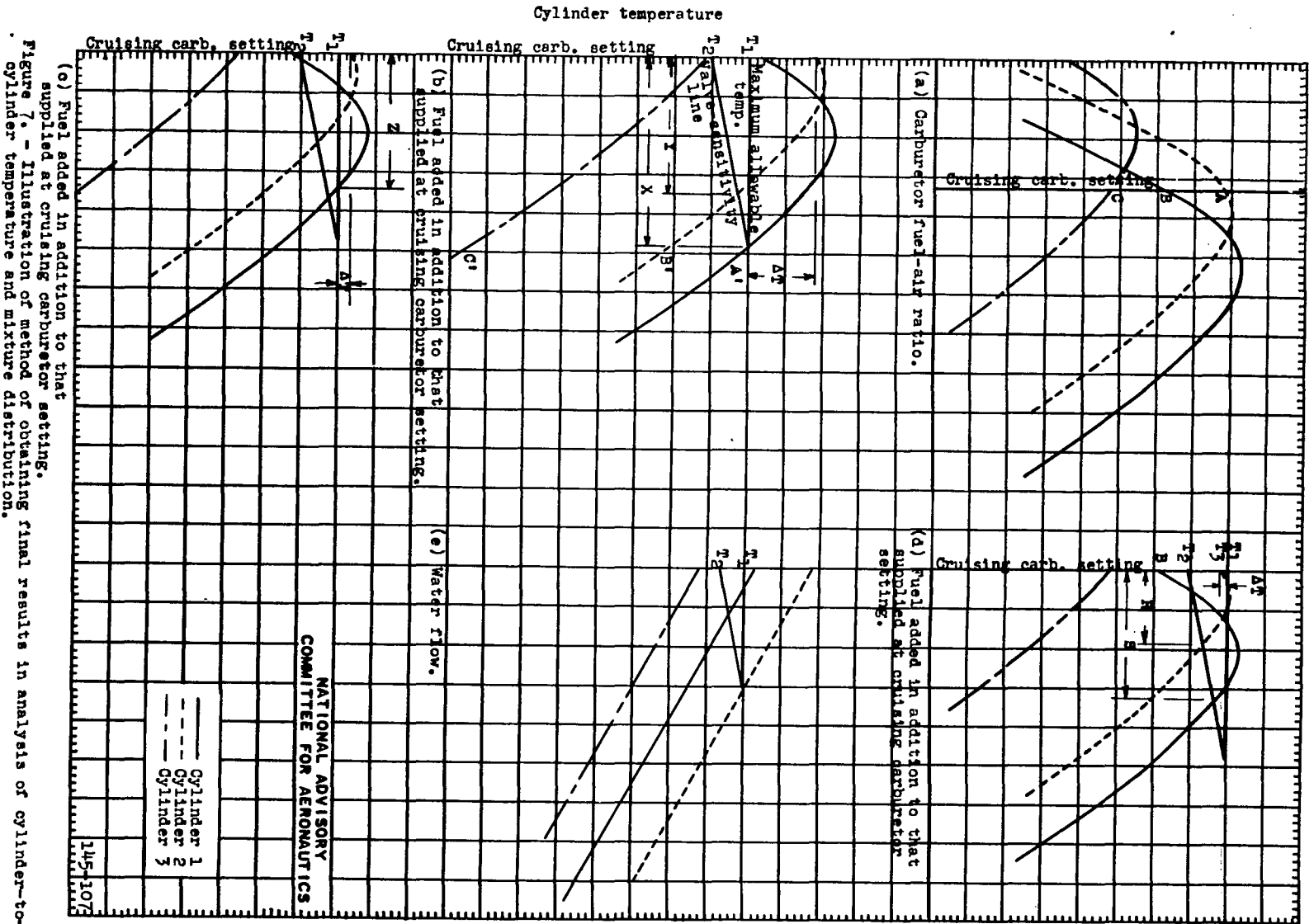


Figure 7. - Illustration of method of obtaining final results in analysis of cylinder-to-cylinder temperature and mixture distribution.

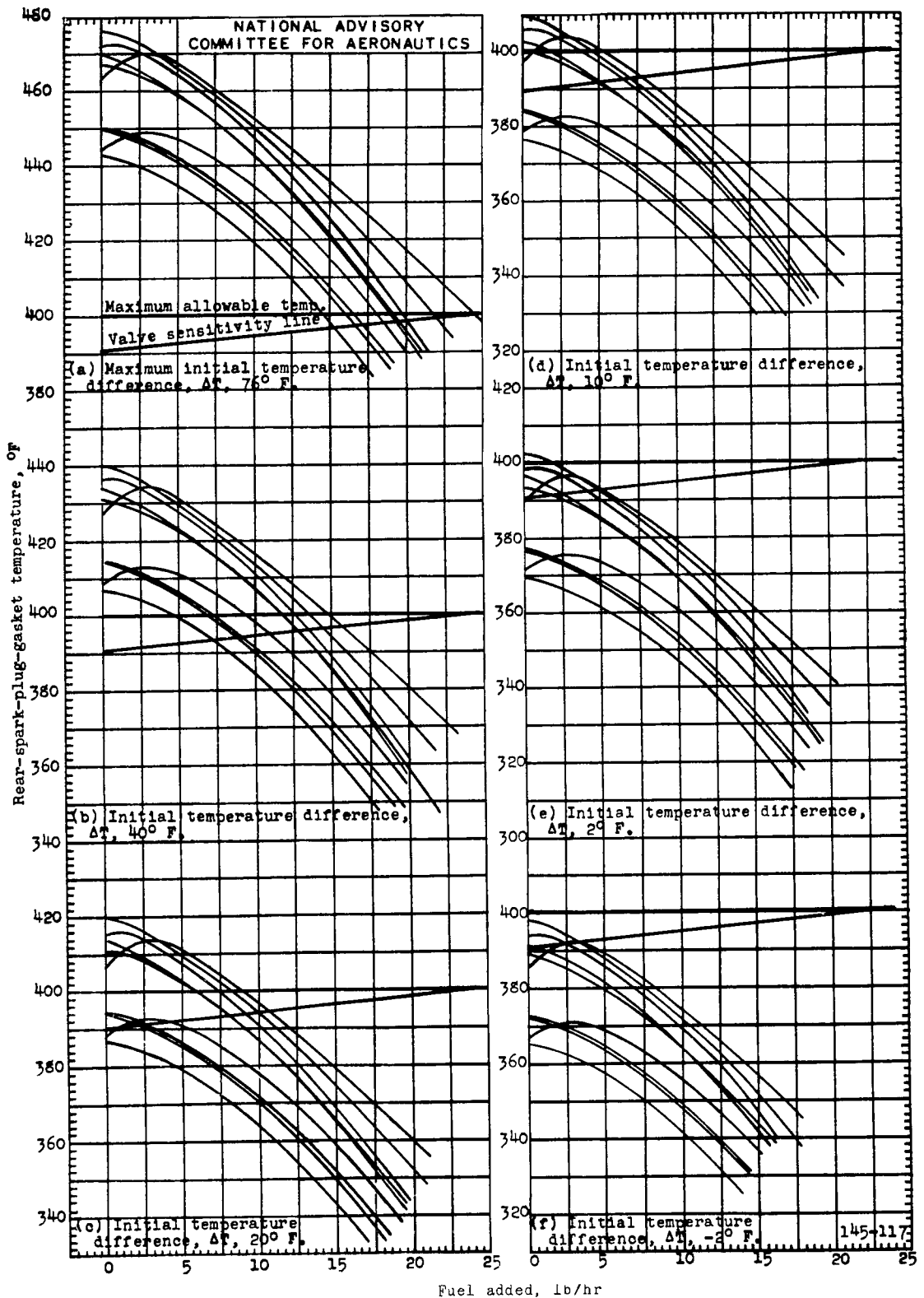


Figure 8. - Illustration of method used to determine amount of fuel to be added to mixture of each cylinder in order to limit maximum temperature. Engine I; engine speed, 1940 rpm; manifold pressure, 29.2 inches mercury absolute; carburetor fuel-air ratio, 0.085.

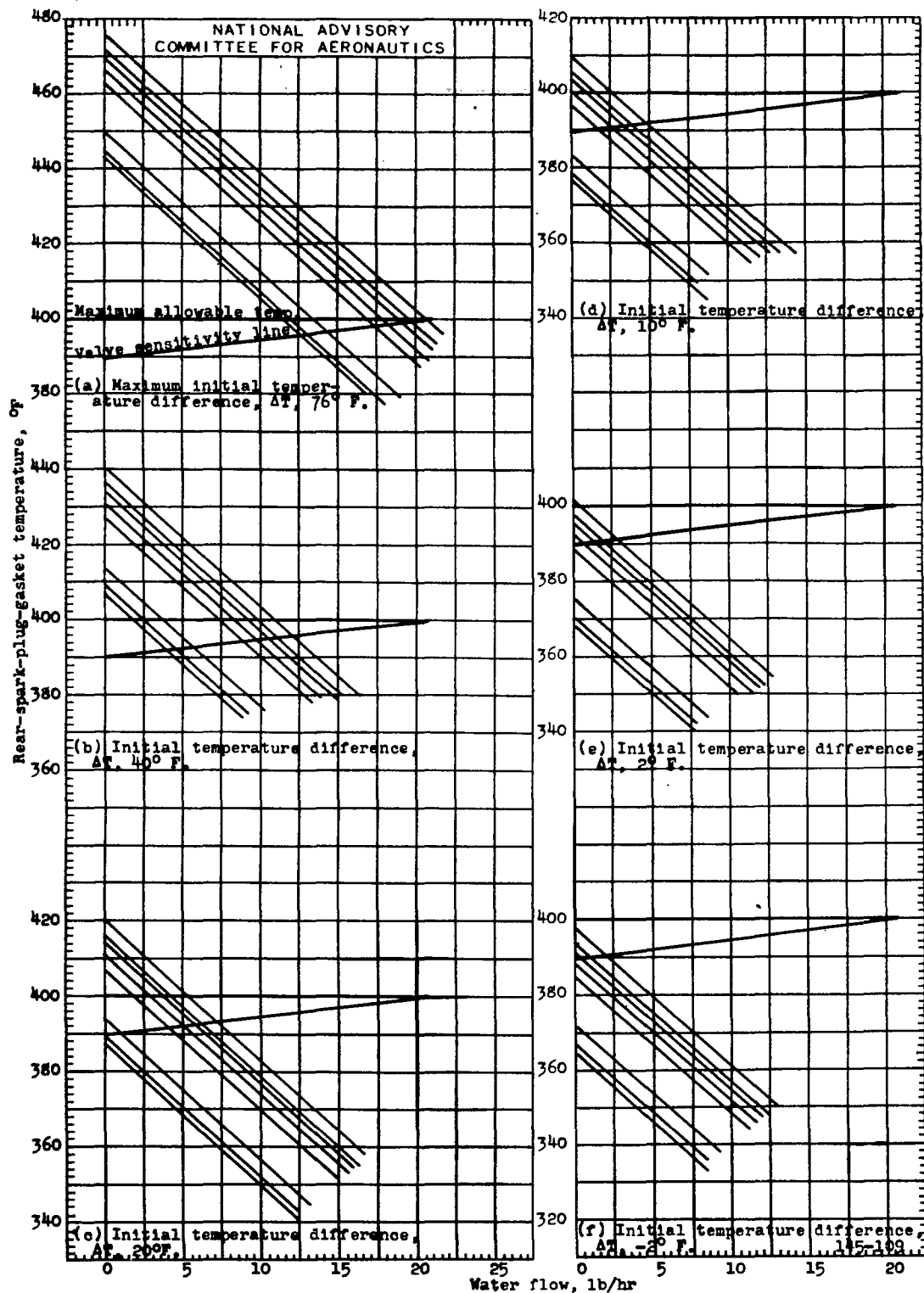
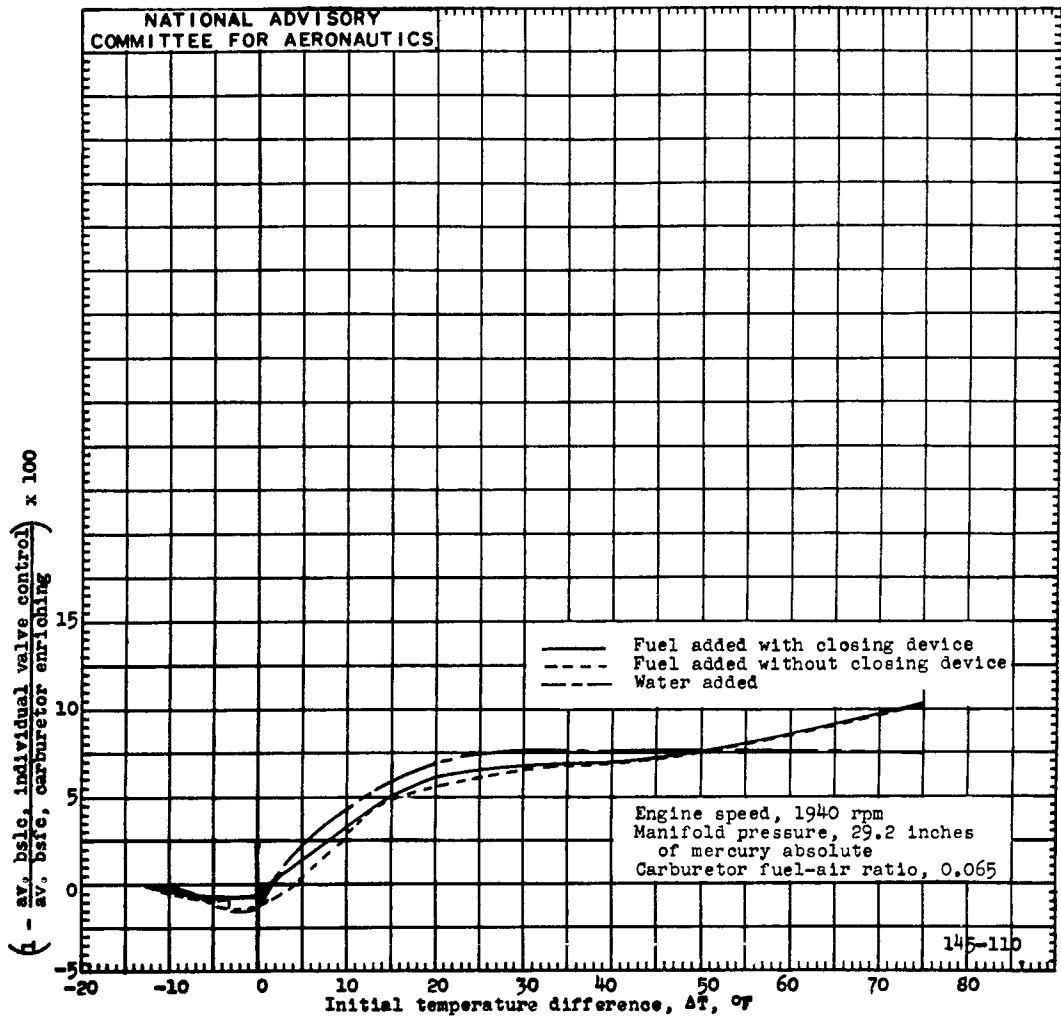
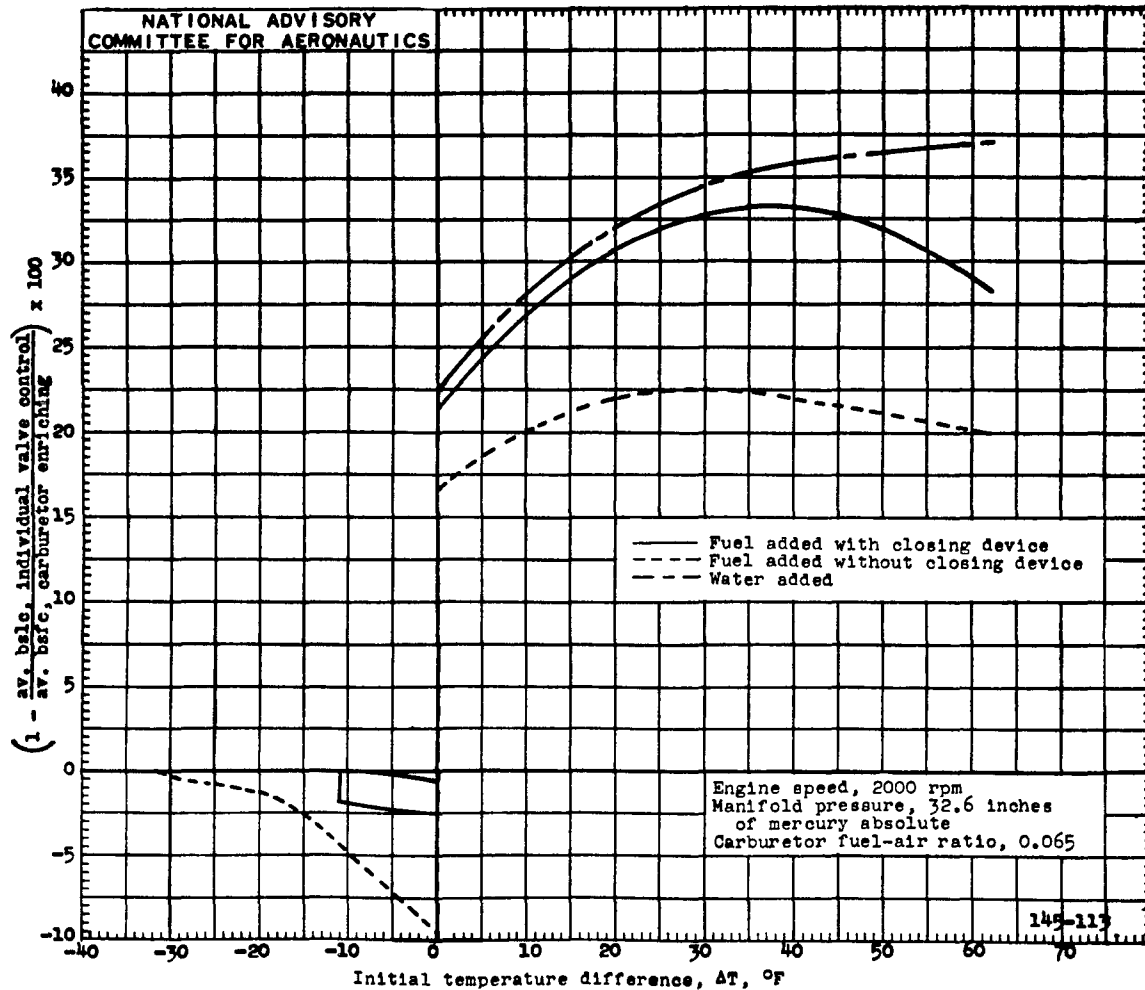


Figure 9. - Illustration of method used to determine amount of water to be added to mixture entering each cylinder in order to limit maximum temperature. Engine I; engine speed, 1940 rpm; manifold pressure, 29.2 inches mercury absolute; carburetor fuel-air ratio, 0.065.

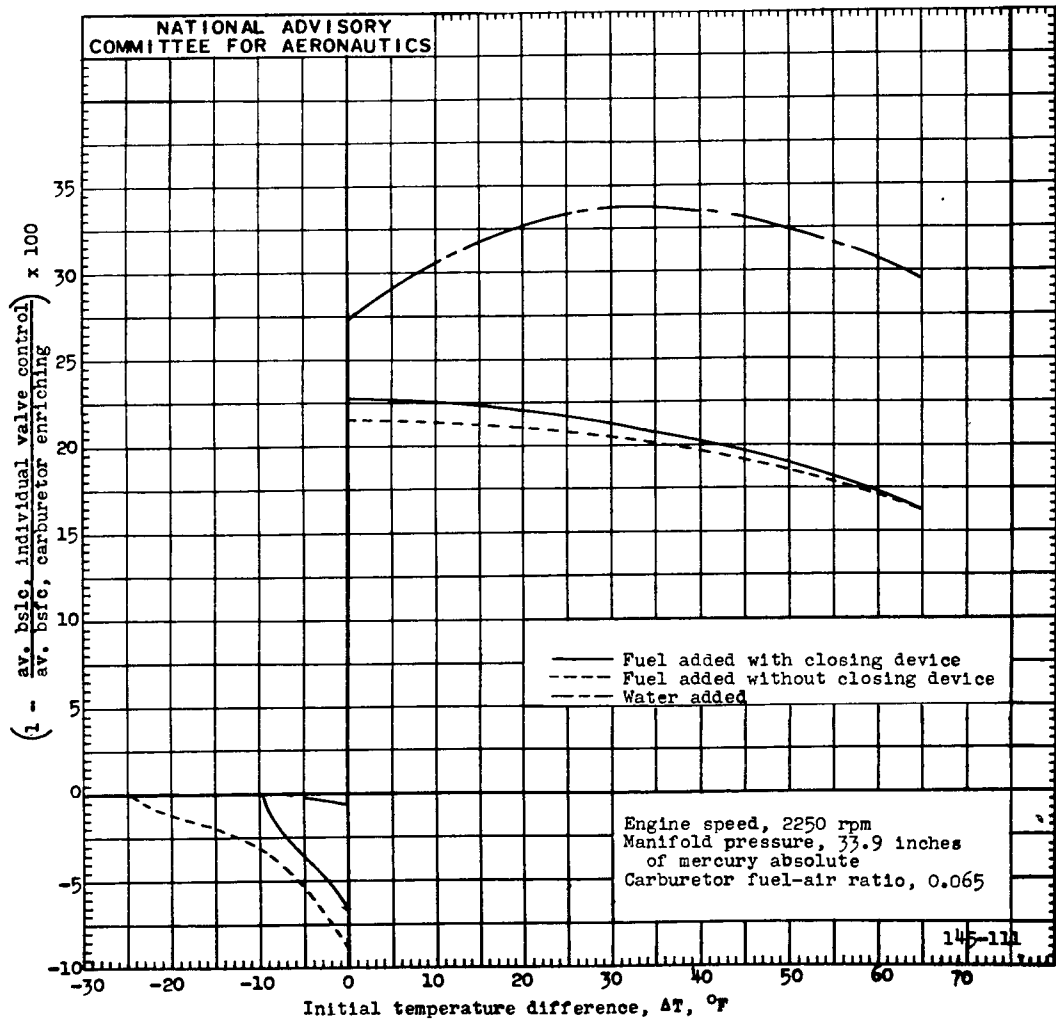


a) Engine I.
Figure 10. - Percentage change in brake specific liquid consumption obtained by automatically adding coolant to overheated cylinders as compared with adding coolant to entire engine.



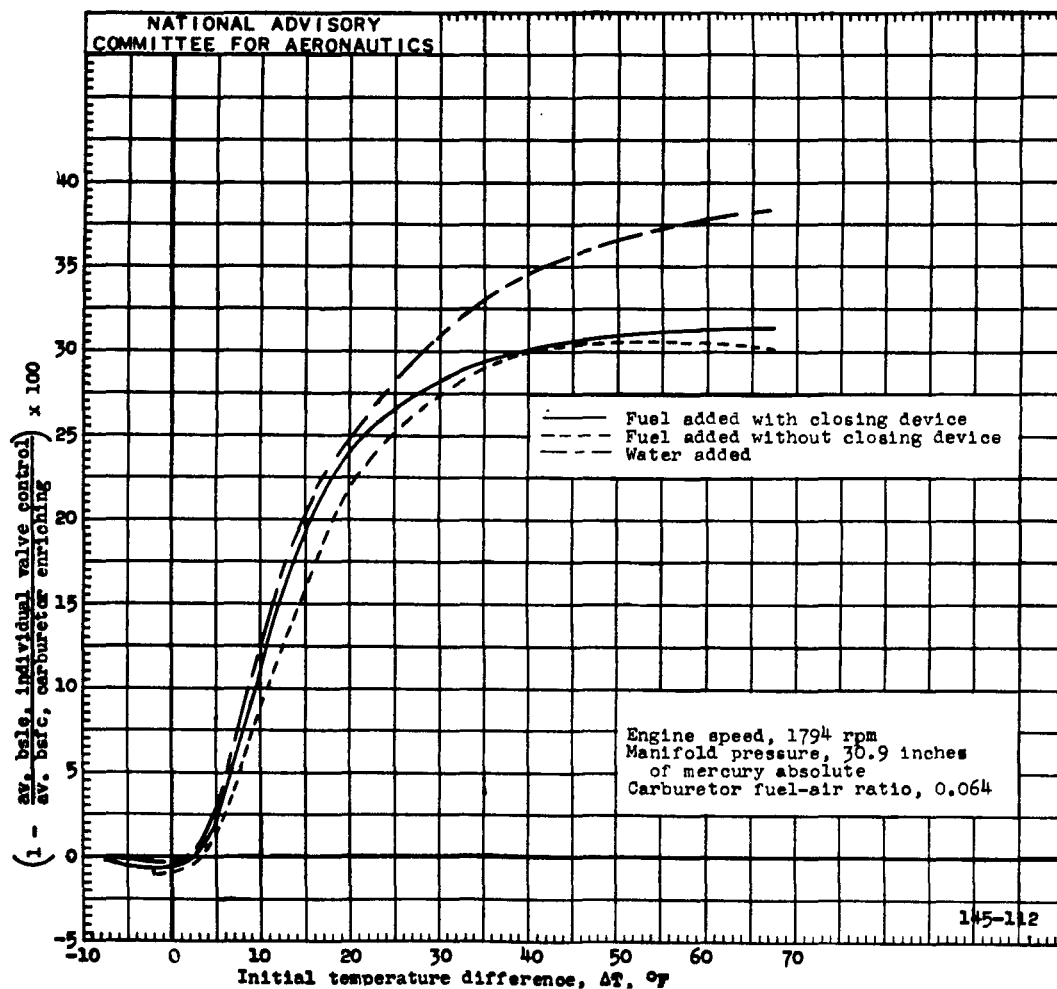
(b) Engine II.

Figure 10. - Continued. Percentage change in brake specific liquid consumption obtained by automatically adding coolant to overheated cylinders as compared with adding coolant to entire engine.



(c) Engine III.

Figure 10. - Continued. Percentage change in brake specific liquid consumption obtained by automatically adding coolant to overheated cylinders as compared with adding coolant to entire engine.



(d) Engine IV.

Figure 10. - Concluded. Percentage change in brake specific liquid consumption obtained by automatically adding coolant to overheated cylinders as compared with adding coolant to entire engine.

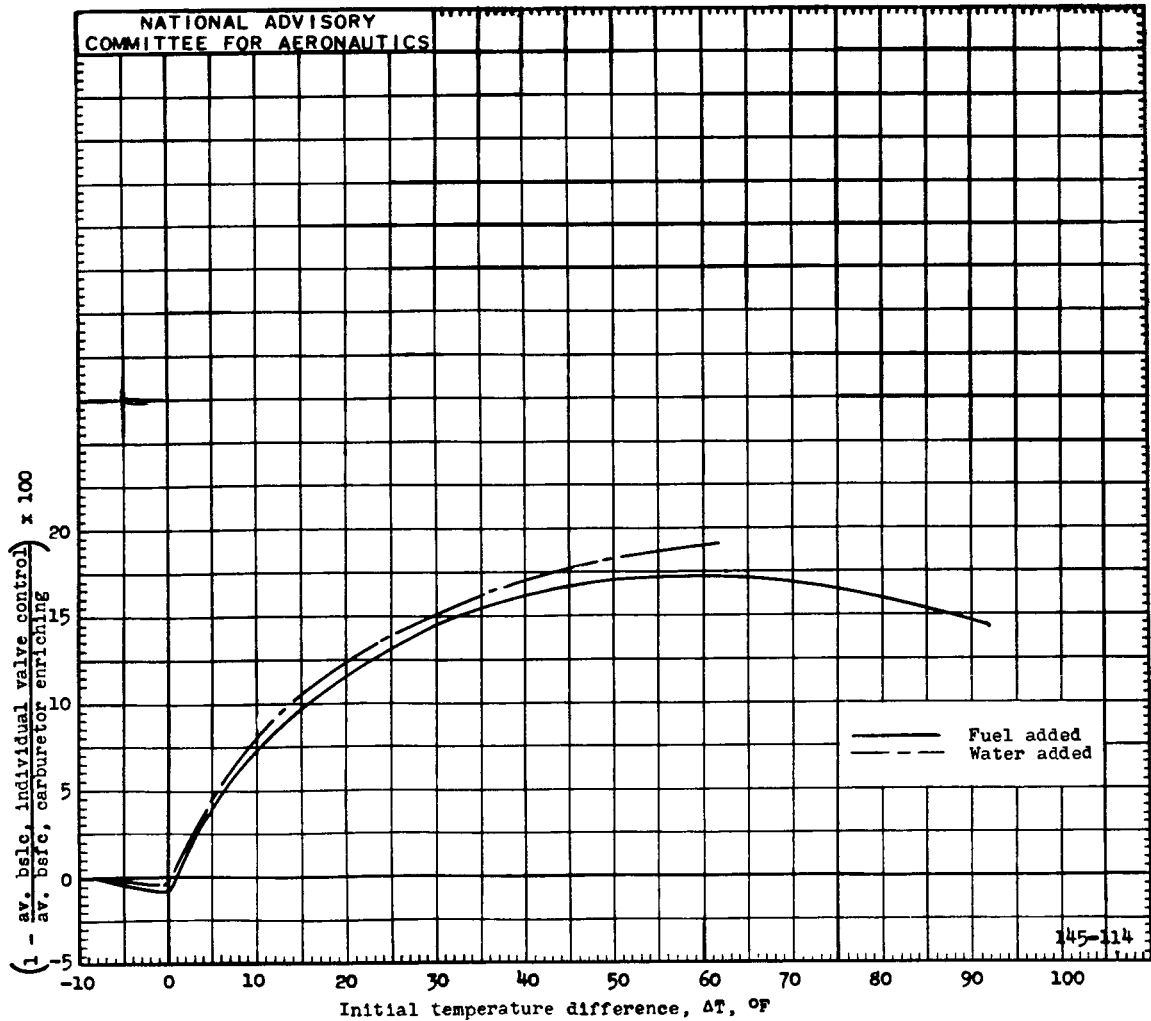


Figure 11. - Percentage change in brake specific liquid consumption obtained by automatically adding fuel or water to only the overheated cylinders as compared with adding coolant to the entire engine. Engine IV; engine speed, 1996 rpm; manifold pressure, 33.1 inches mercury absolute; carburetor fuel-air ratio, 0.086.

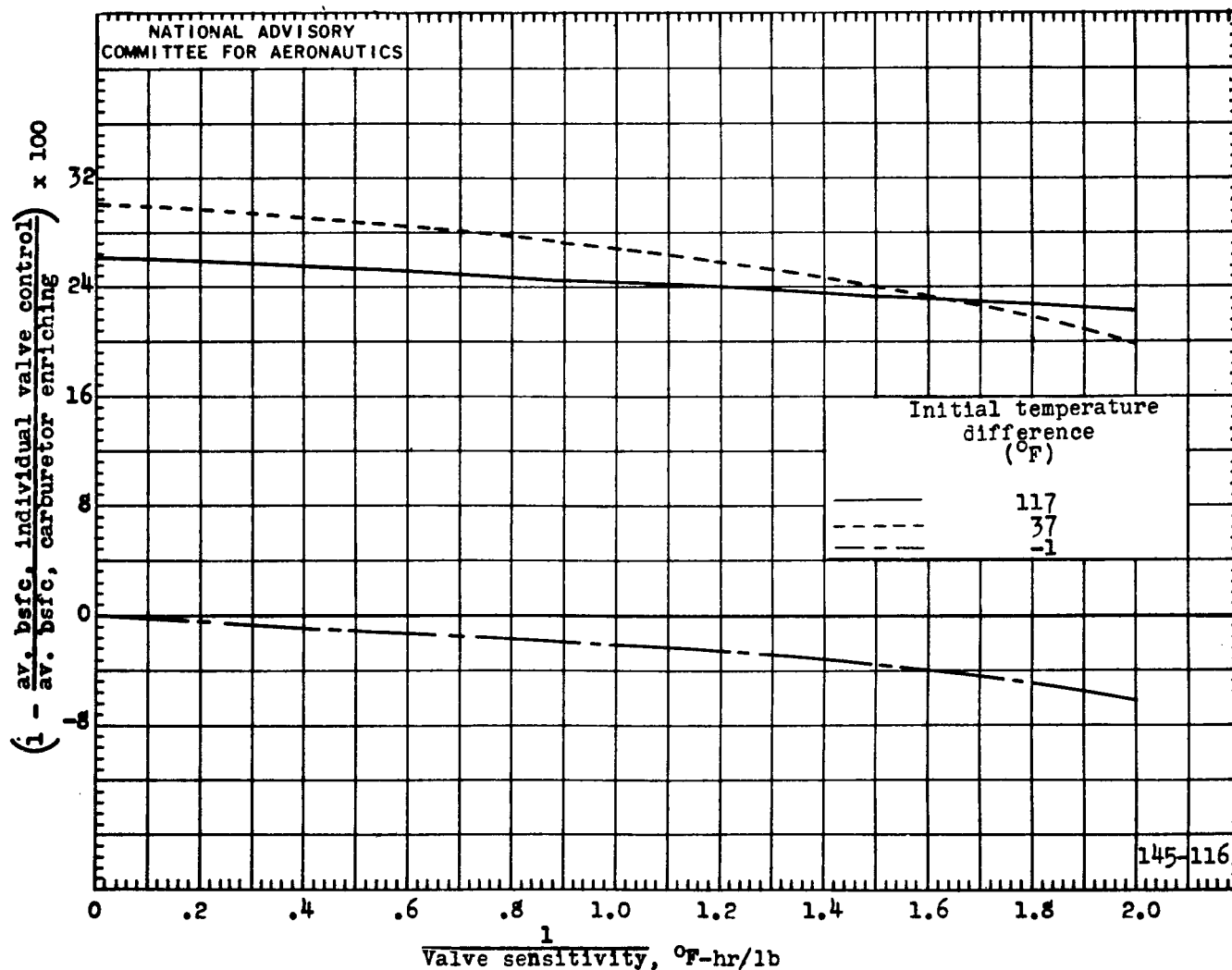


Figure 12. - Effect of valve sensitivity on percentage change in brake specific fuel consumption obtained by adding fuel to only the overheated cylinders as compared with adding fuel to the entire engine. Engine IV; engine speed, 1794 rpm; manifold pressure, 30.9 inches mercury absolute; carburetor fuel-air ratio, 0.064.

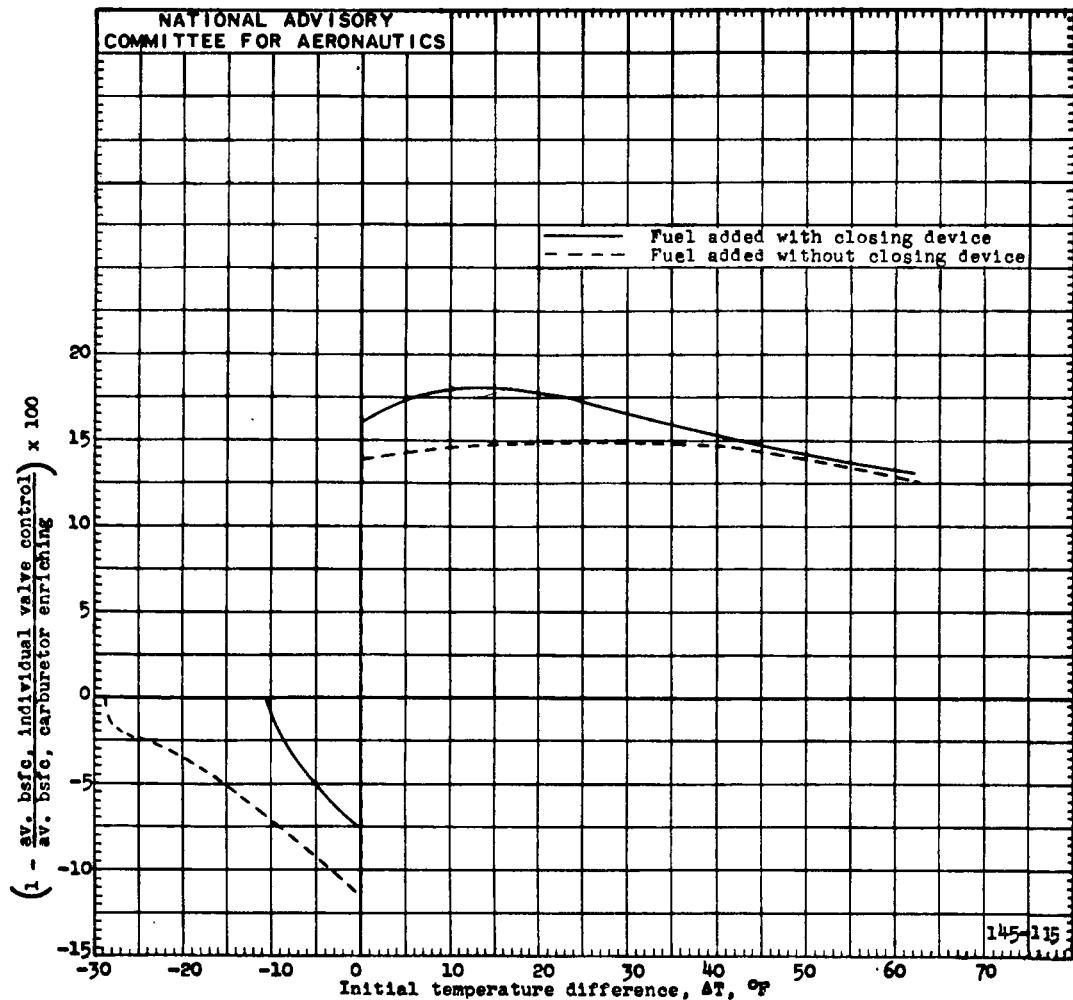


Figure 13. - Percentage change in brake specific fuel consumption obtained by automatically adding fuel to only the overheated cylinders as compared with adding fuel to the entire engine. Engine II having an assumed uniform cylinder-to-cylinder fuel-air distribution; manifold pressure, 32.6 inches mercury absolute; carburetor fuel-air ratio, 0.065.

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ABSTRACT

Temperature and mixture distribution in four radial aircraft engines were analyzed to determine possible economy obtained by internally cooling overheated cylinders. In radial engine operating at cruising speeds in which overheating is usually treated by enriching mixture throughout entire engine, reduction in fuel consumption was 7 to 37% in engines where only overheated cylinders were cooled by water or fuel. Appreciable economic gains were indicated for temperature limited engines operating at rated power fuel/air ratio or uniform fuel/air mixture distribution.

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