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THE ADVANTAGES OF UNIFORM FUEL DISTRIBUTION FOR AIR-COOLED ENGINES FROM CONSIDERATIONS OF COOLING REQUIREMENTS AND FUEL ECONOMY

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INTRODUCTION

The temperatures of the individual cylinders of multicylinder engines usually deviate considerably from the mean temperature for the entire engine. This temperature deviation is objectionable because the cooling requirement of the entire engine, determined by the necessity of cooling the hottest cylinder, often becomes much greater than the cooling requirement sufficient for the average cylinder. The requirement of large cooling-pressure drops is always undesirable from drag considerations and, for certain flight conditions, may render engine operation impossible if the required pressure exceeds the pressure available.

The purpose of this report is to show by analysis of existing data, pending direct experimental determination, the extent to which nonuniform distribution of fuel to the cylinders of a multicylinder engine can produce temperature deviation and the benefits to be anticipated from attainment of uniform fuel distribution. It is not to be inferred that variation of fuel distribution to the cylinders is entirely responsible for dissymmetry of the temperature pattern, but experimental investigations lead to the conviction that this variation is an important factor.

ANALYSIS AND DISCUSSION

The Cause of Variation in Cylinder-Head Temperature with Fuel-Air Ratio

The highest combustion temperatures and correspondingly the highest cylinder-head temperatures occur at fuel-air ratios of about 0.065 to 0.07, near to the theoretically correct combining proportions of fuel and air, as shown in figure 1. The reasons for lower temperatures at other fuel-air ratios are based on the characteristics of fuel and air consumption shown in figure 2. At fuel-air ratios less than 0.07, the excess air, shown by the dashed curve of figure 2, reduces the cylinder temperature by internal cooling. At fuel-air ratios greater than 0.07, excess fuel is supplied as shown by the solid line in figure 2 and the cylinder is internally cooled by the fuel. The exact mechanism by which cooling due to excess fuel is accomplished is a subject beyond the scope of this report. This mechanism involves changes in both the heat evolution and the thermal properties of the working substance as well as the cooling due to simple refrigeration. At very rich and very lean mixtures the combustion is impaired, and the excess amounts of fuel and air required to maintain constant power produce additional cooling.

Temperature Deviations Due to Nonuniform Fuel Distribution and Their Relation to Pressure Drop

The effect, upon the head temperature of a cylinder, of variation in the ratio of fuel to air in that cylinder is shown in figure 3 for three modern radial air-cooled engines at sea-level Army summer-air conditions. These curves are intended to show, for several typical power conditions, the effect that could be produced on individual cylinder-head temperatures by nonuniformities in fuel distribution.

The curves of figure 3 have been constructed from cooling correlation curves of the type shown in reference 1. For each power condition shown, a cooling-air pressure drop has been chosen which, with uniform fuel distribution and as nearly as possible at the rated fuel-air ratio, provides the head temperature limit (rear-spark-plug boss) specified. The head temperature at other fuel-air ratios has been calculated on the assumptions that the charge-air flow and the cooling-air flow are undisturbed and that the fuel-air ratio to the cylinder in question is changed as a result of a change in only the fuel flow. In order to facilitate comparison, the curves have been extended over the entire range of fuel-air ratios, although it should be realized that actual engine operation in all parts of this range is not possible at all powers. The peaks of the curves may have been slightly flattened by the use of multicylinder-engine data instead of single-cylinder-engine data.

The significance of these temperature variations is shown for sea-level conditions in terms of cooling-air pressure drop by figure 4. These curves show the pressure drop required to maintain at the specified limits the head temperature of the cylinder experiencing the changes in fuel flow.

Specific Fuel Consumption

An inspection of the curve of brake specific fuel consumption of figure 2 discloses the relation of the brake specific fuel consumption to deviations in fuel distribution. Because of the practically linear relation of specific fuel consumption to fuel-air ratio in the rich-mixture range, the effect on specific fuel consumption of nonuniformities of fuel-air ratio is compensating, and the better economy of the cylinders receiving the leaner mixtures offsets the poorer economy of the cylinders receiving the richer mixtures, with little net change in over-all economy. In the range of leaner mixtures, where the relation of specific fuel consumption to fuel-air ratio is nonlinear, nonuniformities of distribution are not compensating, and the economy of the engine is impaired by poor distribution.

Altitude Effects

The temperature deviations caused by nonuniform distribution of fuel, as directly derived from cooling correlation curves, increase slightly with altitude. The cylinder-head temperature at fuel-air ratios resulting from nonuniform fuel distribution is plotted for engine A as a function of altitude for normal power in figure 5(a) and for cruising power in figure 5(b). The head temperature of cylinders at the specified fuel-air ratio is maintained at the specified limit over the altitude range by suitable adjustment of the cooling-air flow.

The change in cooling-air flow required to overcome these temperature deviations likewise increases with altitude. Because of the decrease in density the effect of nonuniform distribution of fuel on the pressure-drop requirement increases with altitude. This effect is shown for two representative power conditions in figure 6.

At sea level the power required to pump cooling air across the engine is small compared to the engine output and the cooling-power variation with fuel-air ratio, although considerable, is usually unimportant. The cooling-air pumping power $Q\Delta p$, the product of the cooling-air volume flow Q and the pressure drop Δp, of engine A for cruising at sea-level conditions is shown by the solid line of figure 7 as a function of fuel-air ratio. The larger pressure drops at higher altitudes, in conjunction with the greater volumes of cooling air, greatly increase the power required for pumping the cooling air. This effect is shown by the dashed line of figure 7. For the altitude calculations, sea-level conditions of carburetor and exhaust pressures, representative of a turbosupercharger installation, were assumed.

At high altitudes the cooling power is no longer unimportant, particularly when the available pressure drop is limited, as in the cruising condition. The internal drag horsepower associated with cooling varies from the pumping power as a minimum to twice this value for a system requiring the entire available pressure drop to force air across the engine. The variation in internal drag power may, as a consequence, be considerably greater than the variation of the pumping power $Q\Delta p$ as shown by the upper curve of figure 8. This curve, also for an altitude of 30,000 feet, has been constructed on the assumption that, at a fuel-air ratio of 0.07, the pressure drop across the engine is equal to the maximum pressure drop available.

Benefits of Uniform Fuel Distribution

The advantages to be realized from uniform fuel distribution are important for two principal reasons. When an engine is so operated that optimum conditions prevail for the average cylinders, nonuniformity of fuel distribution causes deviation from the optimum in the other cylinders to the detriment of engine cooling, fuel consumption, or both. What is even more important is that (because of the close proximity of the optimum conditions to the engine operating limits) without uniform distribution, operation of an engine with some of the cylinders at optimum conditions may be rendered impossible by knocking or misfiring in the other cylinders.

In the high-power range the temperature of the hottest cylinder is often 50° F above the mean, which if attributed entirely to nonuniform distribution of fuel, is found in figure 3(a) for normal rated power to correspond to a fuel-air ratio of 0.082 instead of 0.095. Reference to figure 4(a) shows that the pressure drop required to cool a cylinder at normal power and at a fuel-air ratio of 0.082 is 8.2 inches of water instead of the 4.7 inches of water required for the average cylinders. The benefit of uniform distribution would then be a 42-percent reduction in required cooling-air pressure drop.

When sufficient pressure drop is available, it may be desirable for high-power operation to accept the pressure-drop penalty at a leaner mixture in order to improve the economy. Operation at this condition is possible only if the fuel distribution is very nearly uniform because of the danger of knocking in cylinders at lean mixtures.

In the cruise range for certain types of engines such as engine A, the benefits of uniform distribution are striking. Present cruise-power operation appears to be at a fuel-air ratio of 0.07, close to the peak of the pressure-drop curve (fig. 4(a)) and to the right of the point of minimum specific fuel consumption (fig. 2). For sea-level cruising operation the use of a fuel-air ratio of 0.06 with very nearly uniform distribution offers a probable 30-percent reduction in cooling pressure drop and a 5-percent reduction in brake specific fuel consumption together with the reduced internal drag due to the decreased flow of cooling air. Without uniform distribution, operation at very lean mixtures is neither profitable nor possible.

The importance of uniform fuel distribution in altitude cruising is shown by figure 9, which shows cooled-power specific fuel consumption, here defined as

$$\frac{\text{Fuel consumption}}{\text{Brake horsepower} - \left[\dfrac{\text{internal cooling-air drag horsepower}}{\text{propeller efficiency } (= 0.8)}\right]}$$

plotted against fuel-air ratio. The internal cooling-air drag horsepower in this equation is that shown by the solid line of figure 8. The net cooled-power specific fuel consumption is reduced from 0.62 to 0.50 pound per horsepower-hour in reducing the fuel-air ratio from 0.07 to 0.06, which is a 20 percent reduction in fuel consumption.

CONCLUSIONS

1. The pressure drop required for a typical engine developing rated power at a fuel-air ratio of 0.095 with a temperature difference of 50° F between the hottest and the average cylinder may be almost twice the pressure drop required to cool an engine with uniform cylinder temperatures.

2. An economic reduction in fuel-air ratio in cruise made possible by uniform fuel-air mixture may be accompanied by as much as a 30-percent reduction in required cooling-air pressure drop for some aircraft engines.

3. The reduction in fuel-air ratio in cruise made possible by attainment of a uniform fuel-air mixture and consequent reduction of cooling drag would effect a desirable reduction in fuel consumption. At 30,000 feet altitude the reduction of fuel consumption may be as much as 20 percent.

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REFERENCE

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

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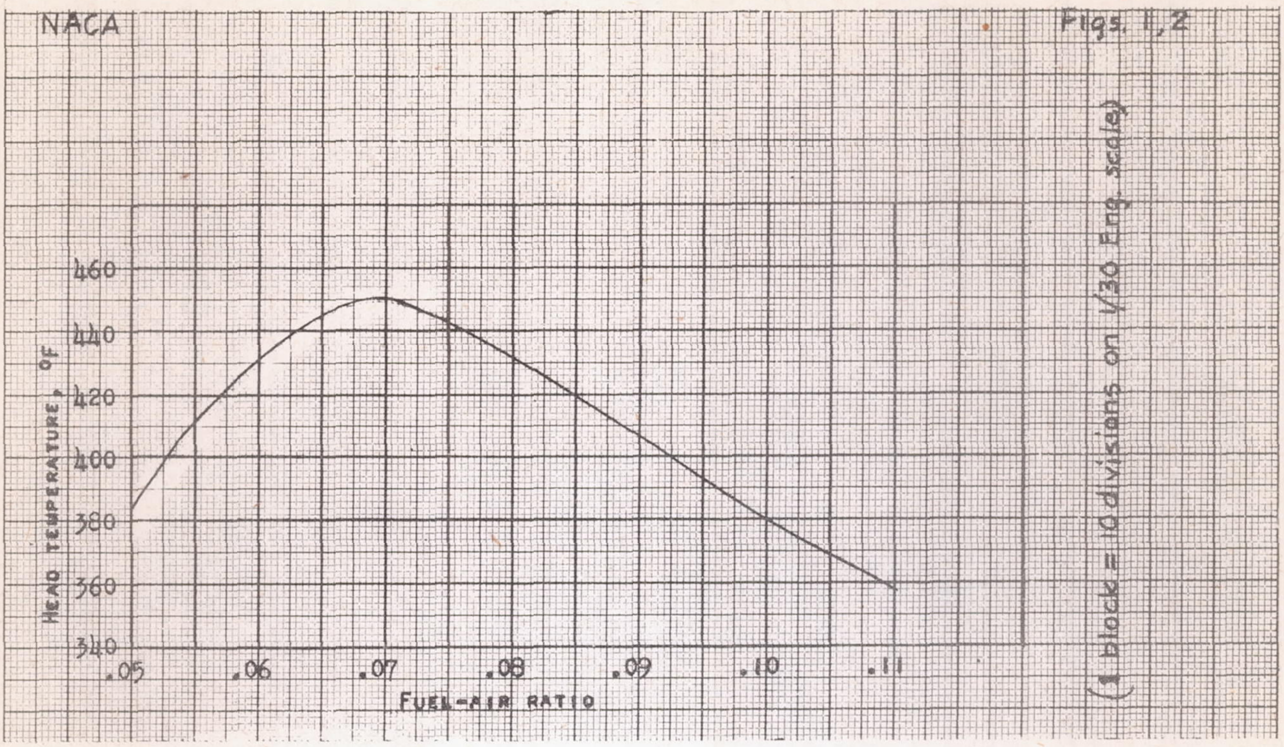


Figure 1.- The variation in head temperature with fuel-air ratio of a cylinder operating at constant power and cooling-air flow.

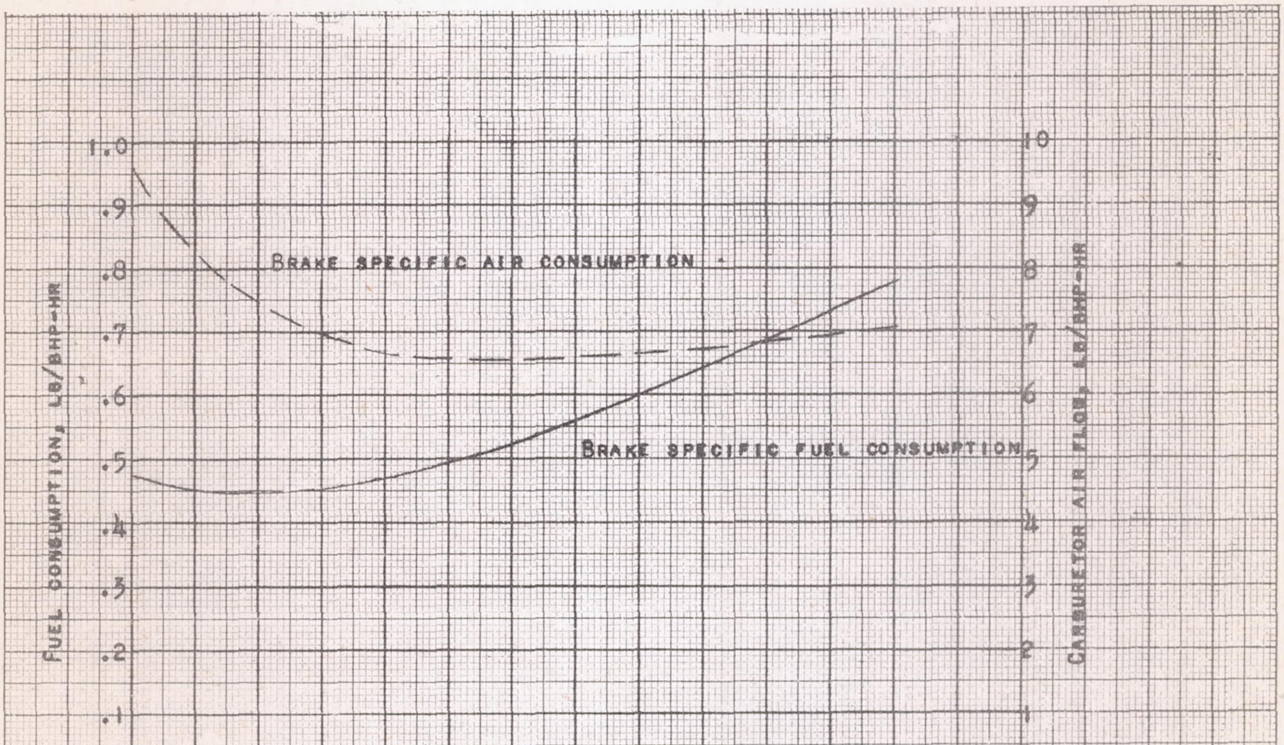
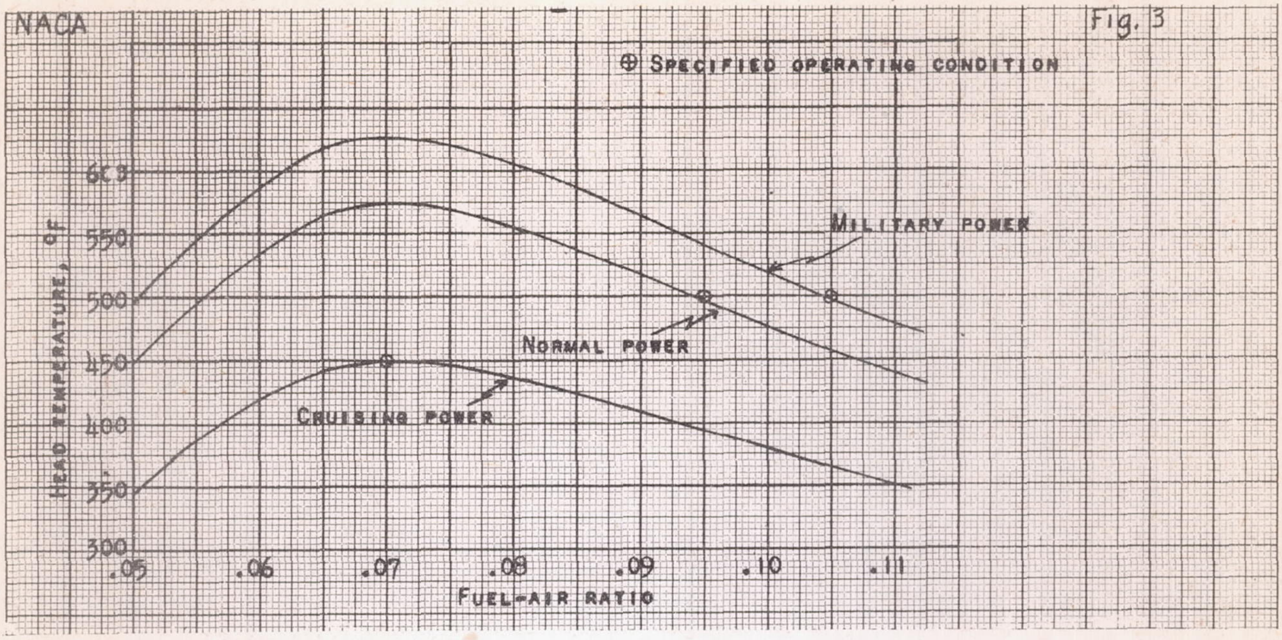
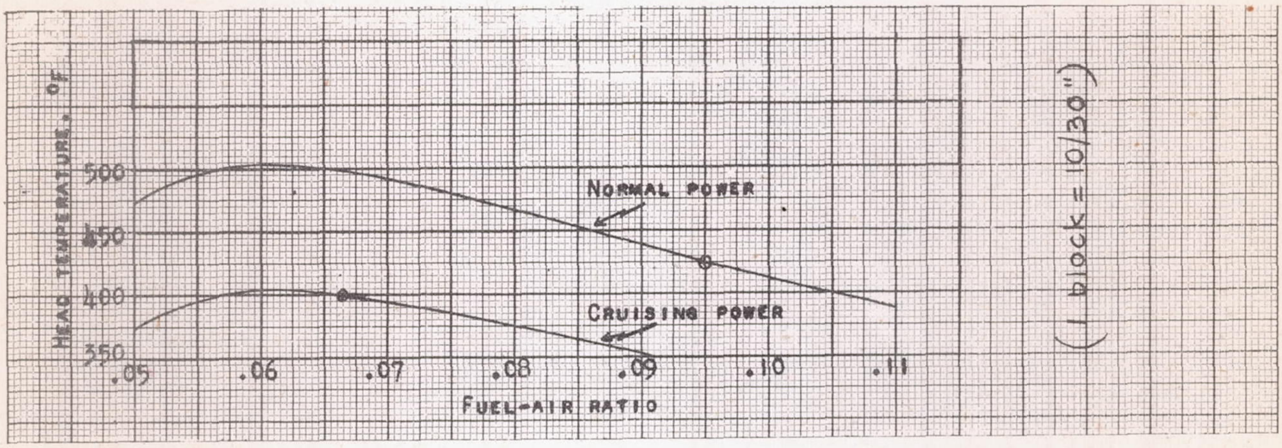


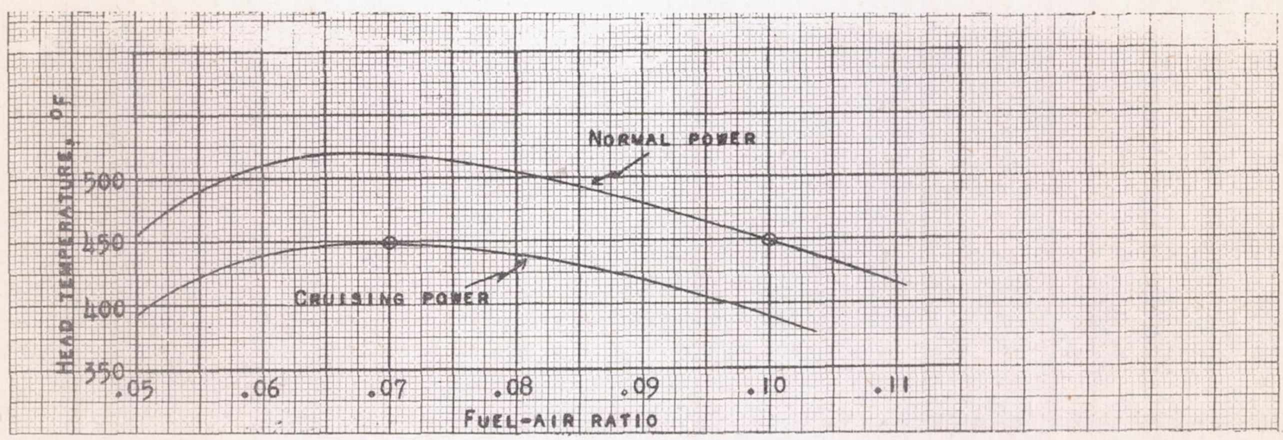
Figure 2.- Brake specific fuel and air consumption variation with fuel-air ratio for engine A, cruising power.



(a) Engine A.



(b) Engine B.



(c) Engine C.

Figure 3.- The relation between cylinder-head temperature and individual cylinder fuel-air ratio.

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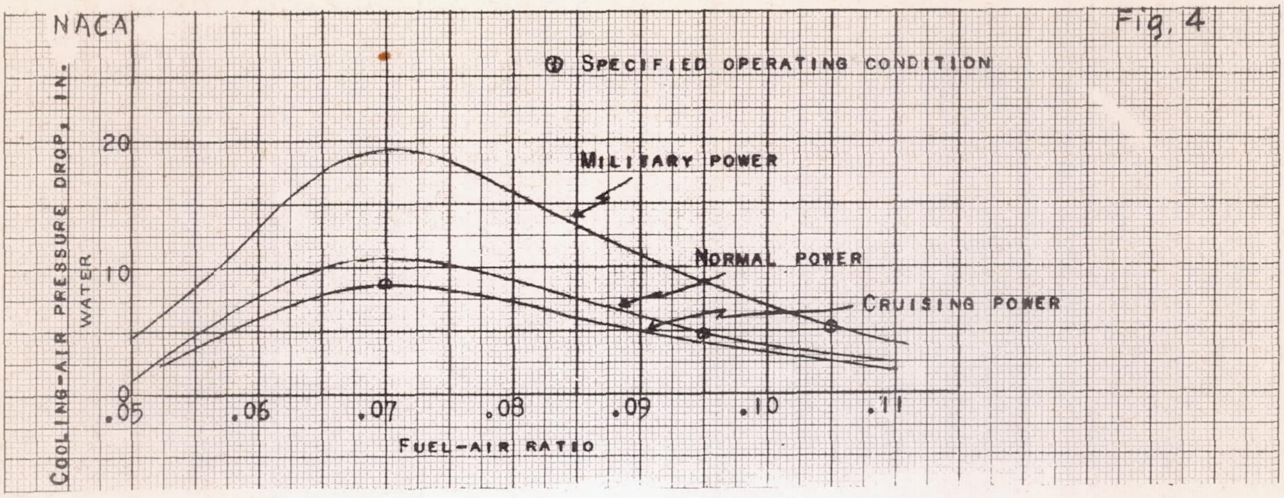
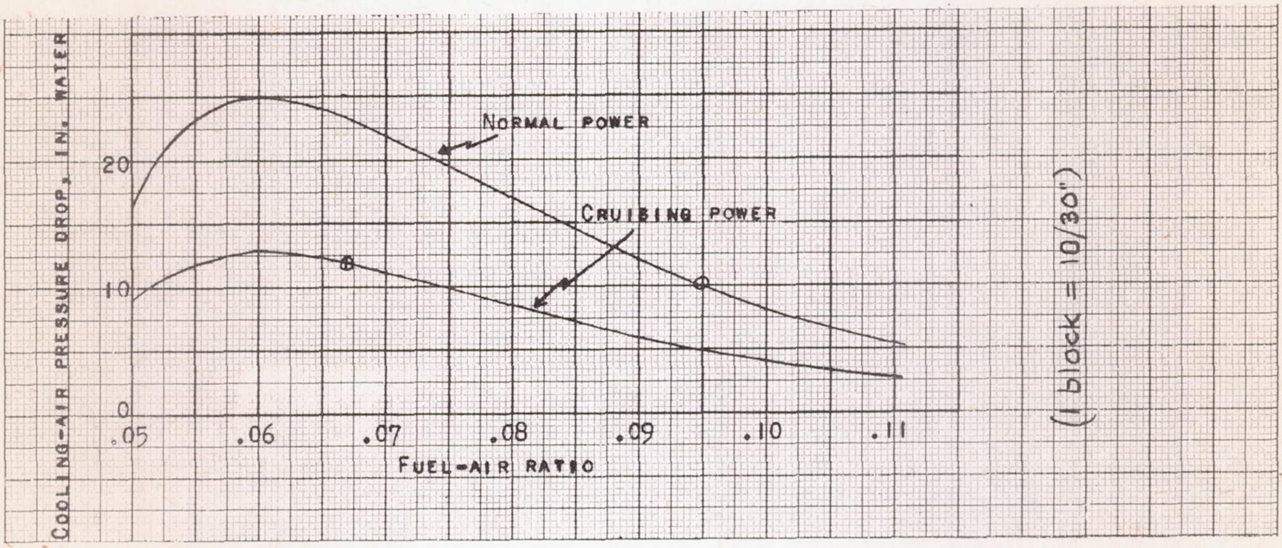
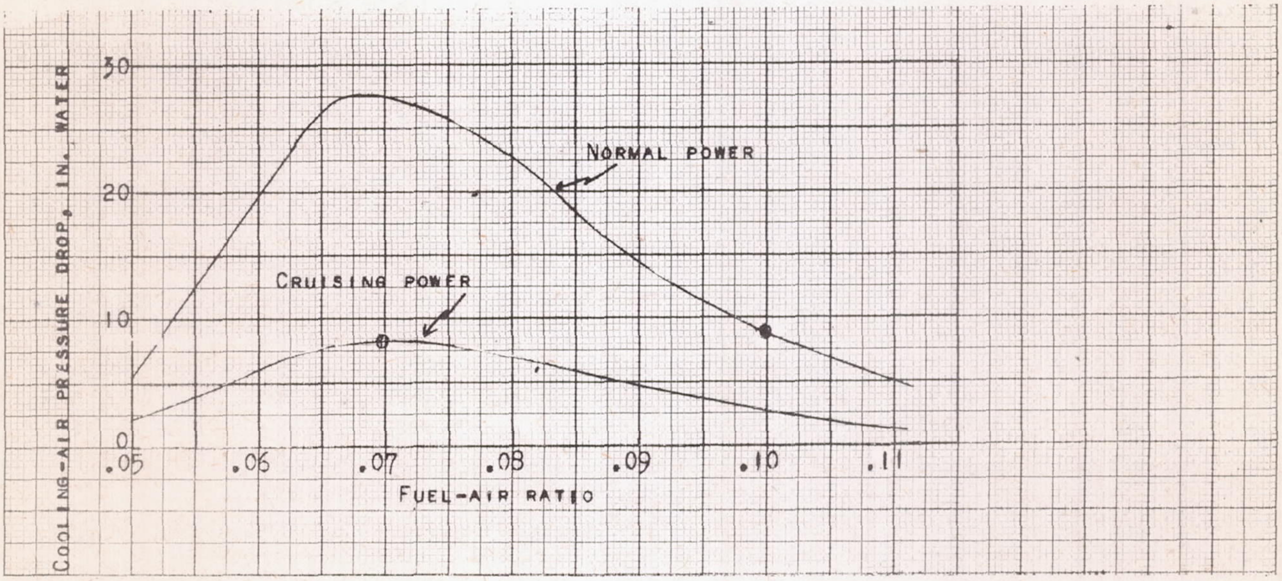


(a) Engine A.



(b) Engine B.



(c) Engine C.

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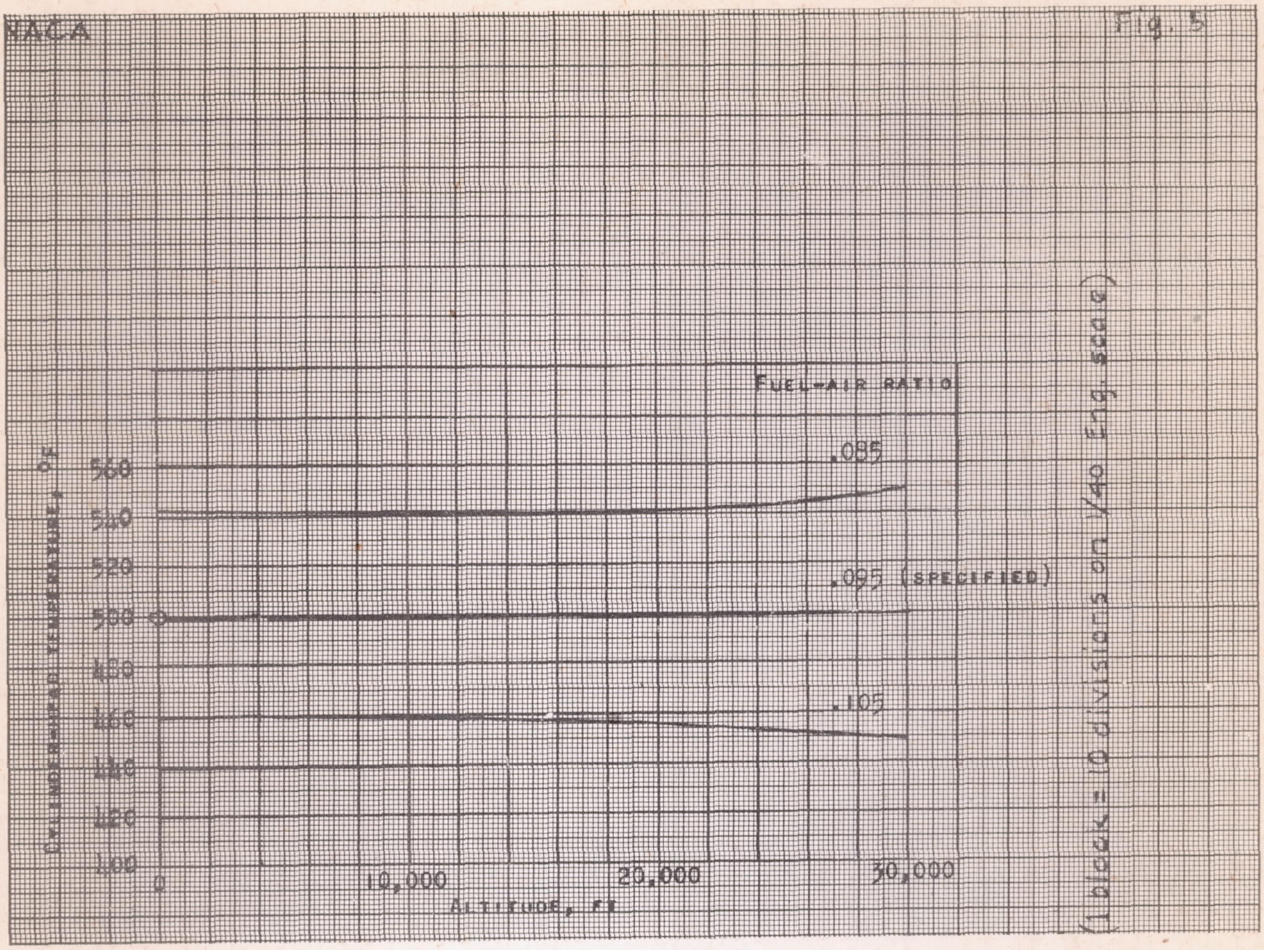
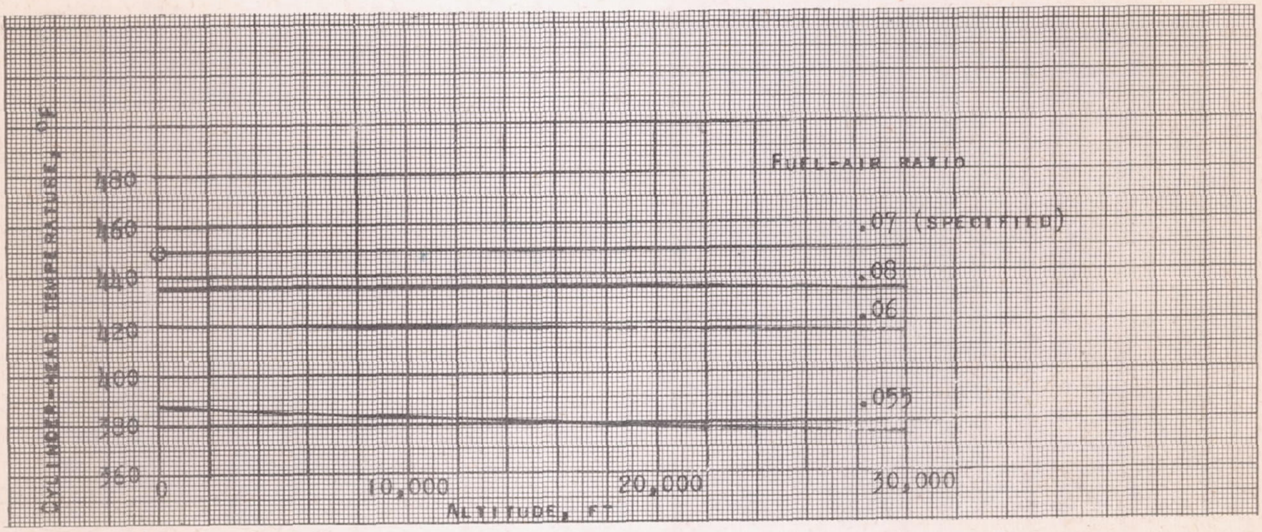


(a) Normal power, engine A.



(b) Cruising power, engine A.

Figure 5.- The variation with altitude of the effect of maldistribution of fuel on cylinder-head temperature. Pressure drop varies with altitude to maintain specified temperature limit at specified fuel-air ratio.

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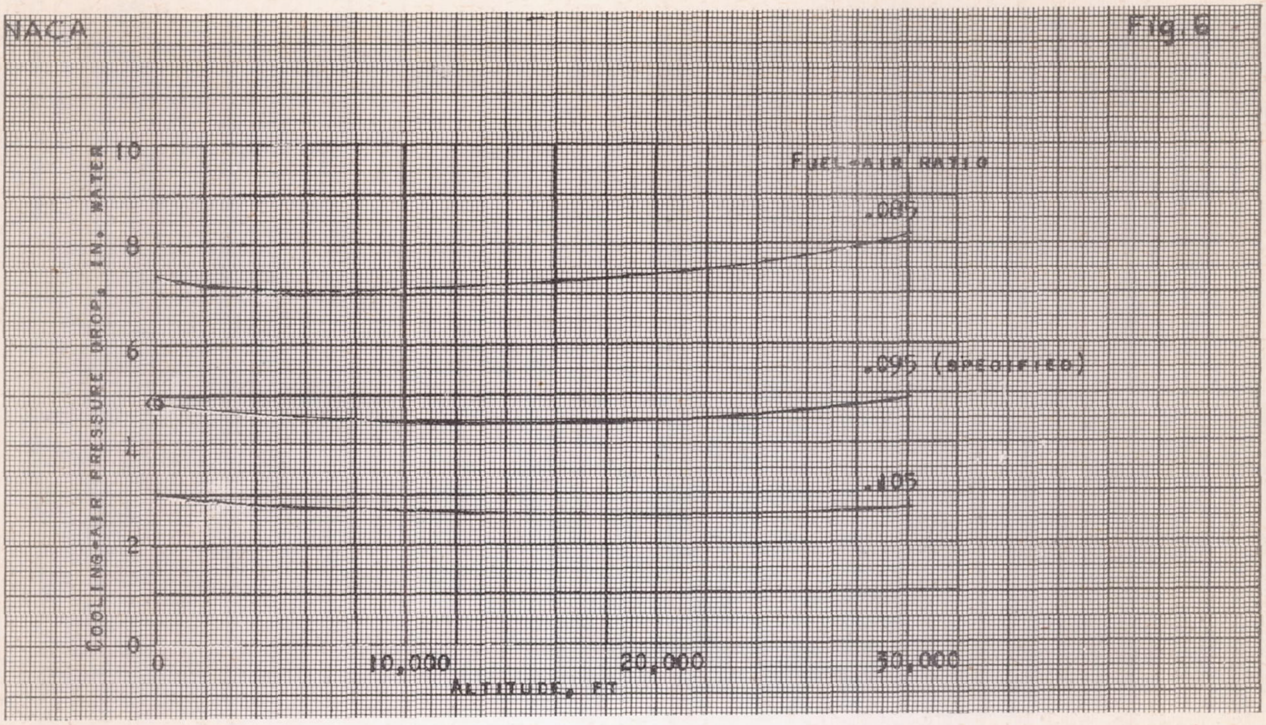
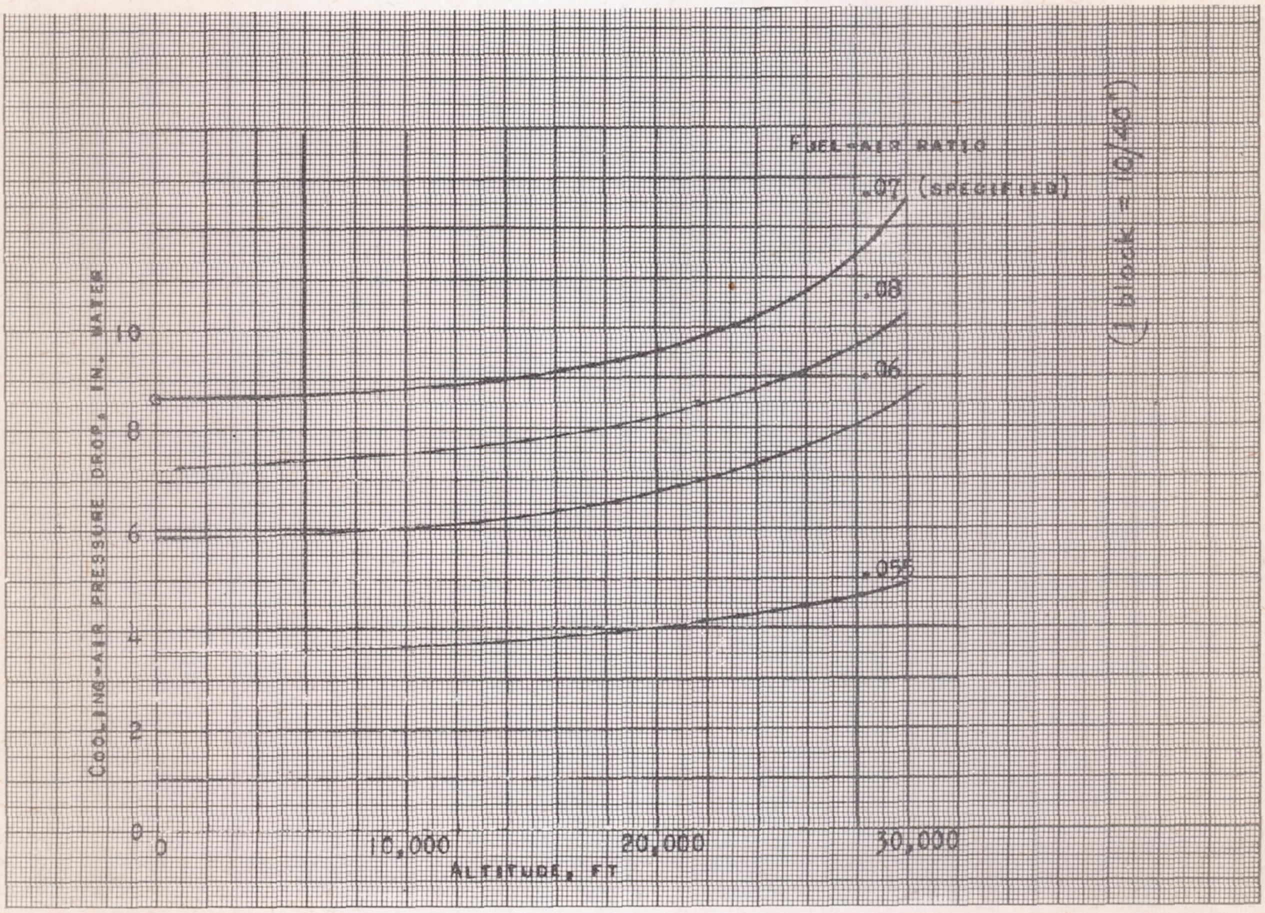


(a) Normal power, engine A; head-temperature limit, 500° F.



(b) Cruising power, engine A; head-temperature limit, 450° F.

Figure 6.- The variation with altitude of the effect of maldistribution of fuel on cooling-air pressure drop required to meet specified temperature limits.

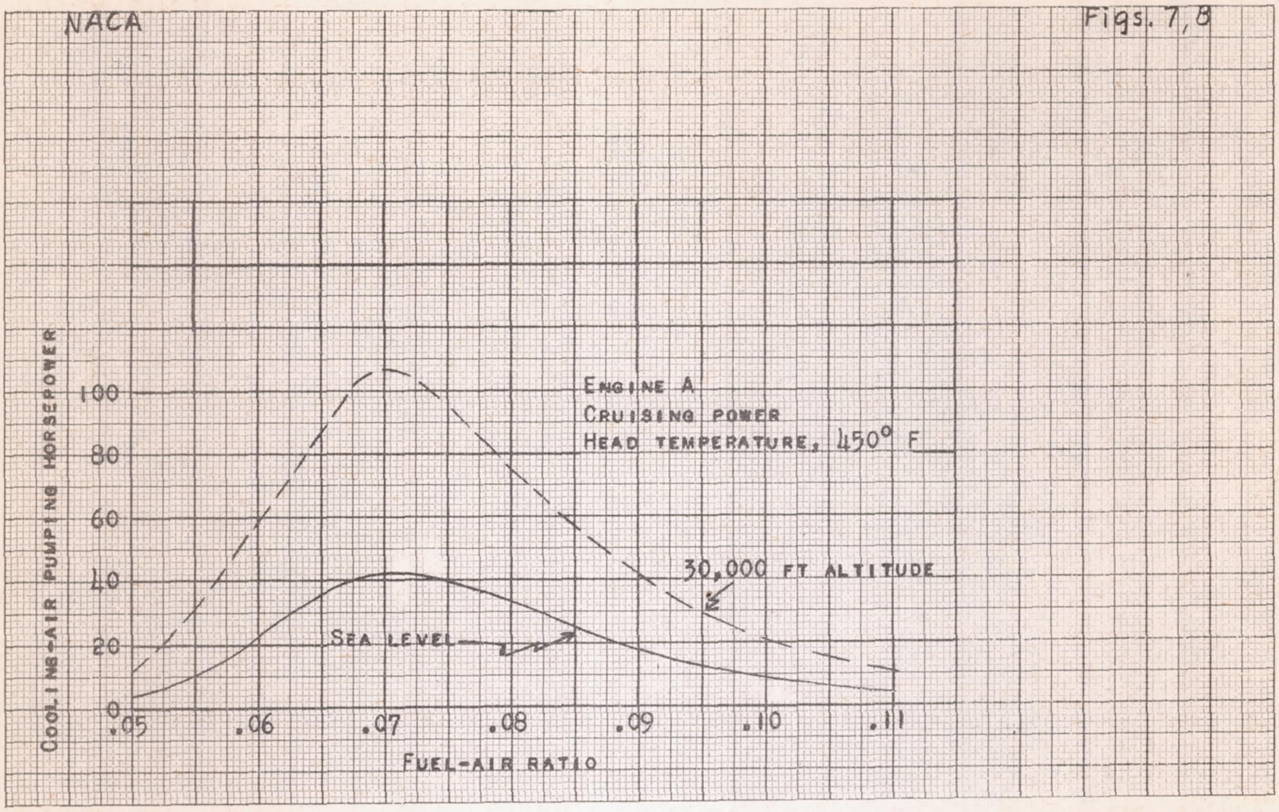


Figure 7.- Variation of cooling-air pumping power with fuel-air ratio.

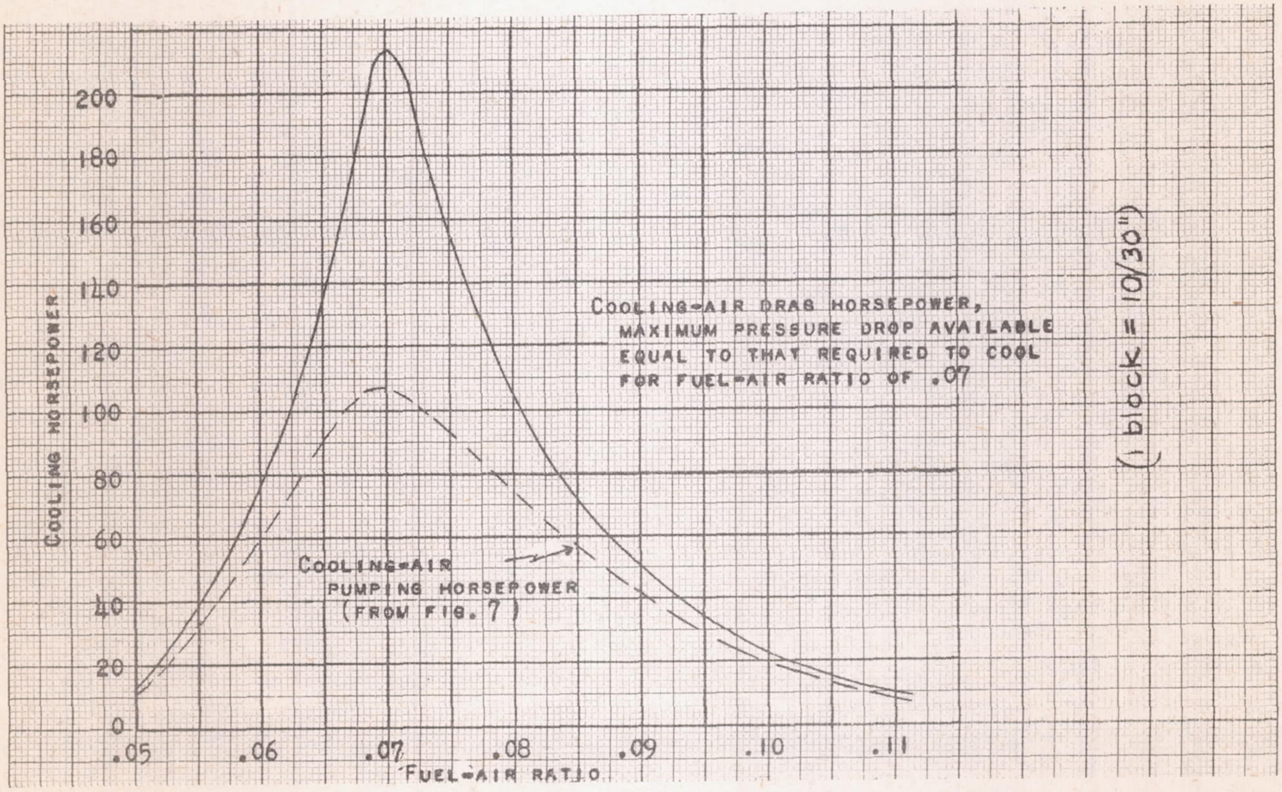


Figure 8.- Comparison of cooling-air pumping power and maximum possible cooling-air drag horsepower. Engine A, cruising power at 30,000 feet; head temperature, 450° F.

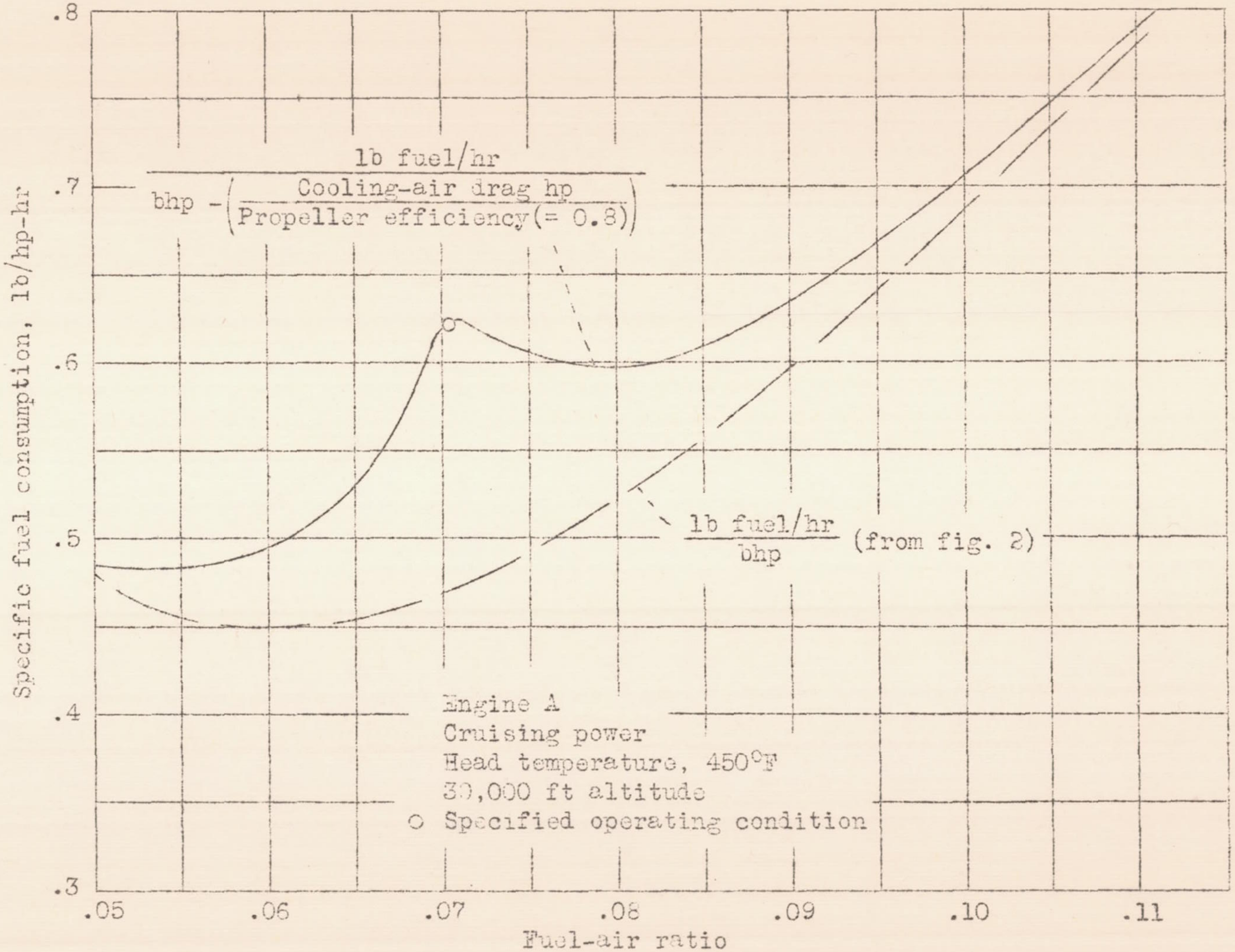


Figure 9.- Effect of fuel-air ratio on fuel consumption per net cooled horsepower.