ARR No. 4C31

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

March 1944 as
Advance Restricted Report 4C31

THE EFFECT OF COMPRESSION RATIO, COOLED EXHAUST GAS MIXED WITH INLET AIR, AND INLET-AIR TEMPERATURE ON THE KNOCK-LIMITED PERFORMANCE OF A FULL-SCALE SINGLE-CYLINDER ENGINE

By Ray E. Bolz and Roland Breitwieser

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

THE EFFECT OF COMPRESSION RATIO, COOLED EXHAUST GAS MIXED WITH INLET AIR, AND INLET-AIR TEMPERATURE ON THE KNOCK-LIMITED PERFORMANCE OF A FULL-SCALE SINGLE-CYLINDER ENGINE

By Ray E. Bolz and Roland Breitwieser

SUMMARY

Object. - To determine the effect on the knock-limited permissible power output, on the indicated specific fuel consumption, and on the cylinder temperatures (1) of exhaust-gas dilution of the inlet-air charge, (2) of inlet-air temperature without exhaust-gas dilution, and (3) of compression ratio.

Scope. - Tests were made on a Wright R-1820 G200 single-cylinder engine at an engine speed of 1600 rpm. The tests consisted of determining the maximum permissible engine performance as limited by knock under the following conditions:

1. Compression ratio (7.0 to 10.0) without exhaust-gas dilution in the intake air and at constant inlet-air temperature.

2. Compression ratio (7.0 to 10.0) with exhaust-gas dilution (0 to 20 percent by weight of intake air) and at constant inlet-air temperature.

3. Inlet-air temperature (100° F to 250° F) with no exhaust-gas dilution and at constant compression ratio.

Summary of results. - The tests showed the following results:

1. Increasing the cylinder compression ratio to 10.0 from the original value of 7.0 decreased the knock-limited indicated mean effective pressure 42 percent at a fuel-air ratio of 0.06 and 24 percent at a fuel-air ratio of 0.10. The respective decreases in the indicated specific fuel consumption for these fuel-air ratios were 8 and 10 percent.

2. Decreasing the inlet-air temperature at a compression ratio of 7.0 to 100° F from the original value of 250° F increased the

knock-limited indicated mean effective pressure 30 percent at a fuel-air ratio of 0.06 and 12 percent at a fuel-air ratio of 0.10.

3. The use of cooled exhaust gas mixed with the intake air raised the knock-free power of a conventional aircraft fuel.

4. The use of exhaust gas caused an increase in indicated specific fuel consumption both when the engine was operated at the knock-limited permissible performance and below this limit.

5. Exhaust-gas additions had a cooling effect on the engine head and cylinder. The exhaust-valve-guide temperature, however, always exhibited a tendency to increase with exhaust-gas dilution at fuel-air ratios below 0.065.

6. The use of exhaust gas mixed with the intake air at high compression ratios to obtain the same power output as the conventional low-compression-ratio engine decreased the cylinder temperatures.

7. At a compression ratio of 7.0, a 4° F decrease in the inlet-air temperature had the same average effect in raising the knock-limited performance of the engine as an addition of 1 percent exhaust gas to the inlet air.

8. Decreasing the inlet-air temperature from 250° F to 100° F had no appreciable effect on the temperatures of the cylinder head and barrel, though the knock-limited power output increased as much as 30 percent. For these conditions the exhaust-valve-guide temperature increased a maximum of 30° F at about 0.07 fuel-air ratio.

Conclusions. - From an analysis of the test results, the following conclusions were reached:

1. The use of exhaust gas as an internal coolant presents the following disadvantages from considerations of engine operation:

(a) Comparatively high percentages of exhaust gas (20 percent by weight of intake air or more) are required to produce an appreciable increase in knock-limited indicated mean effective pressure

(b) The use of exhaust gas causes a decrease in indicated thermal efficiency and requires an increase in inlet-air pressure for a given power output compared with conventional operation.

2. The advisability of the use of exhaust gas as an internal coolant for increasing the maximum permissible power output of an

aircraft engine must be judged in addition to the data presented in this paper on the difficulties to be encountered in cooling the exhaust gas and in introducing it into the incoming charge.

INTRODUCTION

In early investigations concerning the effect of exhaust-gas dilution on knock-limited performance of engines, Ricardo (reference 1) mixed cooled exhaust gas with engine intake air and found the gas to be a knock inhibitor. Sanders and Barnett (reference 2) conducted similar tests to determine the effect that engine exhaust gas mixed with engine intake air has on knock-limited performance of a CFR engine. As a result of the program in reference 2, more complete tests were run on a Wright 1820 G200 single-cylinder test engine and are reported herein. The purpose of these tests was to survey the following possibilities:

1. To use exhaust gas as an internal coolant in conjunction with the use of higher compression ratios to accomplish an increase in the thermal efficiency of engines without lowering the knock-free power output.

2. To use exhaust gas as an internal coolant in existing aircraft engines to increase take-off and cruising knock-free power outputs. Such an increase would result in lower specific engine weight and therefore in increased load-carrying capacity, speed, or climb for a given airplane.

The advantage of using exhaust gas as an internal coolant is that a continuous supply may be taken directly from the engine without the necessity of carrying additional fluid in the airplane. The obvious disadvantage is the equipment that would be necessary for cooling the engine exhaust gas prior to injection into the intake air. The term "inlet mixture" as used in this report refers to a mixture of air and exhaust gas existing in the intake system before fuel injection.

Of interest also is the experimental evaluation of the effect of inlet-air temperature and compression ratio on knock-limited engine performance as a means of comparison with the exhaust-gas results.

The experiments were conducted at Langley Memorial Aeronautical Laboratory in October and November 1942.

APPARATUS

Test engine. - The tests were made using a Wright 1820 G200 crankcase and cylinder equipped with a special high-compression piston for obtaining a compression ratio of 10.0. Compression ratios of 7.0, 8.0, and 9.0 were obtained by the use of spacers between the crankcase and cylinder flange. The compression ratio was checked by oil displacement.

Engine torque was measured with a 150-horsepower cradle dynamometer and engine speed was determined with an electric timer and revolution counter. A constant engine speed of 1600 rpm was maintained through the use of a 60-cycle neon lamp and appropriate flywheel markings.

Incipient knock was determined by a magnetostriction pickup in conjunction with an oscillograph. The engine temperatures were determined from calibrated surface thermocouples and from a potentiometer.

Cooling (fig. 1). - The engine cooling air originated from a rotary blower in series with an induction blower. The energy of relatively high-pressure air from the rotary blower was utilized to induce a large volume of low-pressure air for engine cooling. The quantity of cooling air was controlled both by the speed of the motor driving the blower and by a slide valve in the cooling-air duct. The engine was equipped with an aluminum cowling closely formed to the shape of the cylinder. No means of controlling the temperature of the cooling air supplied was available. The maximum variation of this temperature throughout the test program was ±8° F.

Combustion air (fig. 1). - Combustion air originated from the laboratory supply line; the pressure was controlled by a pressure-regulating valve. Air quantity was measured by a square-edge thin-plate orifice meter. A heater with a manually controlled bypass valve regulated the inlet-air temperature before its entry into the inlet surge tank. The surge tank was of approximately 10-cubic-foot capacity and was separated from the engine by a short inlet pipe equipped with a venturi throat and a fuel needle valve. The inlet-air thermometer was located in the outlet of the surge tank. Throughout the tests the inlet-mixture pressure and the inlet-air pressure were limited to 60 inches of mercury absolute by the heating capacity of the air-heater coils.

Exhaust gas (fig. 2). - The engine had normal exhaust through a silencer to a lower-pressure vent trough. A 1-inch pipe, which was connected to the exhaust pipe at the engine port, passed exhaust gas through 20 feet of water-jacketed cooling pipe and a water trap to an exhaust-gas compressor. Completing the exhaust-gas system was a large surge tank with a pressure-regulating valve to maintain a constant tank pressure of 90 inches of mercury absolute, a water trap, a square-edge thin-plate orifice for measuring the quantity of flowing gas, and a globe control valve. The exhaust gas was piped to the inlet-air surge tank near the inlet-pipe connection of the engine. No special provision was made for mixing the exhaust gas with the inlet air other than that provided by the turbulence in the surge tank. In all tests the quantity of exhaust gas was limited by the capacity of the exhaust-gas compressor to 20 percent of the intake air.

All orifices were installed and calibrated according to the recommendations of the A.S.M.E.

Fuel (fig. 2). - The fuel-measuring device consisted of a glass burette of 1/2-pound capacity with a photoelectric-cell timing device. Measurements of the rate of fuel flow were taken by a rotameter. An independent, gear-type fuel pump supplied low-pressure fuel (50 to 60 lb/sq in.) for continuous injection. The amount of fuel supplied to the engine was regulated by a bypass on the pump and by a manually controlled mixing valve in the inlet pipe. The fuel was injected upstream into the manifold venturi about 15 inches from the inlet port of the engine; the injection was in the form of several continuous streams of fuel from drilled orifices in the injection tube. All fuel lines were water-jacketed.

The fuel used throughout the test was Army 100-octane gasoline obtained from the Army supply station at Langley Field, Va.

TEST PROCEDURE

Equilibrium engine conditions were established and check points taken before each day's run. When the oil temperature, the inlet-air temperature, the cooling-air pressure, and the exhaust-gas-tank pressure had all attained their desired conditions, the fuel flow was regulated for rich-mixture operation. The inlet-air pressure and the corresponding differential pressure at the exhaust-gas orifice for the desired mixture were then increased by increments at the point of incipient knock. All other controls were simultaneously adjusted for constant engine conditions. The test readings were recorded after 10- to 15-minute operation at each particular point which allowed equilibrium to be established. Lean-mixture points were taken by setting the inlet-air pressure, the exhaust-gas orifice differential pressure, and the inlet-air temperature at desired values and then by increasing the fuel flow to the point of incipient knock.

The following tests were conducted to determine the effect of various factors on engine performance:

[Engine speed, 1600 rpm; cooling-air pressure drop, 6.5 in. water; oil-out temperature, 165° F to 175° F]

Spark advance (deg B.T.C.)	Inlet-mixture temperature (°F)	Inlet-air temperature (°F)	Exhaust-gas dilution (percent)	Compression ratio	Limiting condition
Effect of exhaust-gas dilution at various compression ratios					
20	250	----------	0, 10, 20	7.0 8.0 9.0 10.0	Incipient knock
Effect of spark advance					
20 25 30	250	----------	20	9.0	Incipient knock
Effect of exhaust-gas dilution at constant imep					
20	250	----------	0 10 20	7.0	imep, 162 lb/sq in.
Effect of inlet-air temperature					
20	----------	100 150 200 250	0	7.0	Incipient knock

TEST RESULTS

Effect of Compression Ratio on Maximum Permissible Engine Performance

Figure 3 presents the relation between fuel-air ratio and knock-limited performance when the engine was operated with fresh intake air and a constant spark advance of 20° B.T.C. at compression ratios of 7.0, 8.0, 9.0, and 10.0. The spark advance was retarded a few degrees from optimum for the engine operating at 1600 rpm and 7.0 compression ratio. The data of figure 3 are cross-plotted in figure 4 as constant fuel-air-ratio curves. The plotted points are not data points but are shown to illustrate the consistency of the curves.

Values of indicated specific fuel consumption for a compression ratio of 10.0 as compared with a compression ratio of 7.0 were appreciably lower. For example, the percentage decreases at fuel-air ratios of 0.06 and 0.10 are 8 and 10, respectively. (See fig. 4.) Accompanying this noticeable increase in engine efficiency at higher compression ratios, however, is a decrease in available knock-limited mean effective pressure. At a compression ratio of 10.0 compared with a compression ratio of 7.0 (fig. 4) the percentage decreases are 42 and 24 at fuel-air ratios of 0.06 and 0.10, respectively. This decrease in maximum permissible power is primarily a result of higher combustion temperature and density and, therefore, of higher end-gas temperature and density accompanying higher compression ratios. The decrease is secondarily a result of greater flame speeds at higher compression ratios with no readjustment of the spark advance to optimum at each compression ratio. (See reference 3.)

Figure 5 presents curves of constant indicated mean effective pressure showing knock-limited engine performance over the range of compression ratios from 7.0 to 10.0. The lines representing knock-limited indicated mean effective pressure over the range of fuel-air ratios from 0.065 to 0.10 show that any increase in power at the knock limit at a given compression ratio must be accomplished by an increase in fuel-air ratio. Figure 5 also shows that for any given power output the required inlet-air pressure decreased for higher compression ratios even though the fuel-air ratio increased.

Effect of Compression Ratio on Engine Temperatures

Figure 6 is a record of the temperatures of the cylinder head, the cylinder barrel, and the exhaust-valve guide corresponding to the conditions in figure 3. The visual impression presented by the curves - namely, that the cylinder head, the cylinder barrel, and the exhaust-valve-guide temperatures decrease with an increase in compression ratio - is misleading because the power output also decreased. Unpublished NACA data indicate than an increase in compression ratio at constant indicated mean effective pressures increases the temperatures of the cylinder head and decreases the temperatures of the cylinder barrel and the exhaust-valve seat and guide.

Effect of Exhaust Gas on Full-Scale Single-Cylinder Engine Performance

Figure 7 presents the relation between fuel-air ratio and the knock-limited performance when the engine was operating with fresh intake air, with 10 percent exhaust gas added to intake air, and with 20 percent exhaust gas added to intake air at compression ratios of 7.0, 8.0, 9.0, and 10.0. The exhaust-gas concentration is expressed as percentage by weight in the mixture relative to fresh air.

These exhaust-gas tests were run at a constant spark advance. The analysis of the effect of exhaust gas on the reduction of flame speed, however, led to the series of curves of figure 8. Three runs were made at a spark advance of 20°, 25°, and 30° B.T.C. using 20 percent exhaust gas at 9.0 compression ratio. The advanced spark (fig. 8) brought about a much lower indicated specific fuel consumption and also a lower knock-limited indicated mean effective pressure. This decrease in knock-limited indicated mean effective pressure indicates that peak pressures were occurring more nearly at top dead center for higher spark advances and were thus aggravating the conditions that led to knock. The results indicate that the spark advance of 30° B.T.C. was approaching the optimum value at an engine speed of 1600 rpm and a compression ratio of 9.0, when 20 percent exhaust gas was used. The relation of optimum spark advance to varying compression ratio and to varying exhaust-gas dilution, however, cannot be predicted from these data.

The effect of a 20-percent addition of exhaust gas on maximum permissible engine operation at two representative fuel-air ratios is indicated in the following table:

[All values are expressed as percentage increase of the 20-percent exhaust-gas dilution, knock-limited performance factors over the conventional 0-percent performance factors.]

Compression ratio	Increase in indicated mean effective pressure (percent)	Increase in inlet-air pressure (percent)	Increase in indicated specific fuel consumption (percent)
0.06 fuel-air ratio			
7.0	25	57	12
8.0	35	72	10
9.0	58	89	9
10.0	72	82	4
0.09 fuel-air ratio			
7.0	4	29	7
8.0	14	46	9
9.0	21	47	5
10.0	26	45	0

The following table presents the data of indicated specific fuel consumption for exhaust-gas dilutions of 0 and 20 percent at the knock limit:

Compression ratio	Indicated specific fuel consumption (lb/ihp-hr)			
	Fuel-air ratio, 0.06		Fuel-air ratio, 0.09	
	Exhaust-gas dilution (percent)		Exhaust-gas dilution (percent)	
	0	20	0	20
7.0	0.365	0.406	0.533	0.570
8.0	.360	.395	.515	.560
9.0	.340	.370	.500	.520
10.0	.335	.348	.475	.475

It is evident from this table and from figure 7 that the addition of exhaust gas noticeably increases the knock-limited indicated mean effective pressure at the higher compression ratios both on an absolute and on a percentage basis. It may also be seen that the addition of exhaust gas increases the indicated specific fuel consumption and that this increase becomes smaller at the higher compression ratios.

These phenomena may have their explanation in the fact that constant spark advance was used throughout the experiment. It has been shown (reference 3) that for higher compression ratios optimum spark advance usually decreases, other conditions being constant, whereas the addition of exhaust gas to the inlet air tends to increase the optimum spark advance. Therefore, the combination of these two opposing but unequal effects, coupled with the fact that the spark advance of 20° B.T.C. was a few degrees retarded from optimum at 7.0 compression ratio with no exhaust-gas dilution, may have produced more nearly optimum spark advance at the higher compression ratios with exhaust-gas injection and may account for the more favorable effect of these gases on engine efficiency at the higher compression ratios. According to figure 8, it is quite possible that the addition of exhaust gas may not affect the specific fuel consumption if the spark advance were set at optimum for each exhaust-gas dilution. The use of optimum spark advance, however, would reduce the effectiveness of the exhaust gas in increasing permissible power.

Figure 9 is a clear illustration of the increase in indicated specific fuel consumption with exhaust-gas addition at 7.0 compression ratio because it was taken at constant indicated mean effective pressure well below the detonation level.

The curves from a CFR engine presented in reference 1, showing the relation of indicated specific fuel consumption to fuel-air ratio for a compression ratio of 7.0, exhibit no definite increase in indicated specific fuel consumption for exhaust-gas additions of 5 and 7 percent. This fact is not necessarily contradictory to the present results, however, because the spread of the points for indicated specific fuel consumption in the CFR data is as great as the expected variation and the percentages of exhaust gas used in the CFR test were not sufficiently large to establish a definite trend.

From figure 7, a comparison can be made of the curve for 20-percent exhaust-gas dilution at a compression ratio of 10.0 with the curve for 0-percent exhaust-gas dilution at a compression ratio of 8.0. Quantitatively similar knock-limited indicated-mean-effective-pressure curves, indicating equal power outputs, are revealed. The indicated specific fuel consumption over the range of fuel-air ratios from 0.065 to 0.10, however, is lower at the 10.0 compression ratio that at the 8.0 compression ratio; the maximum difference is about 5 percent. In addition, the cylinder temperatures plotted in figures 10(b) and 10(d) are 25° F to 50° F lower at 10.0 compression ratio than at the 8.0 compression ratio. A cooling advantage as well as an efficiency advantage associated with the use of high compression ratios and exhaust-gas dilution is thus indicated. These temperature effects will be more fully discussed.

Figure 11 clearly illustrates the comparison of indicated specific fuel consumptions at various knock-limited levels by showing the relation between indicated specific fuel consumption and indicated mean effective pressure for the test conditions given in figure 7. At an indicated specific fuel consumption of 0.375, about 10 percent more power is available for the 20-percent-exhaust-gas dilution at 10.0 compression ratio than for the 0-percent dilution at 8.0 compression ratio. This advantage rapidly decreases at higher fuel-consumption operation. Contrary to the higher efficiency advantage accompanying the use of high compression ratios with exhaust-gas dilution is the fact that such a practice requires appreciably higher boost pressures for a given power output. This difference is from 3 to 5 inches of mercury in the comparison just cited. Figure 9 also clearly illustrates this fact because a 30-percent increase in inlet-air pressure is necessary, when 20-percent exhaust gas is used, in order to accomplish the same power output attained when the engine was operated with no exhaust-gas dilution and with all other conditions equal.

From these results it seems reasonable to conclude that the addition of exhaust gas at higher compression ratios offers the advantage of better fuel economy at the same power-output level that exists for aircraft engines of lower compression ratio but offers the disadvantage of appreciably higher boost pressures required for the same power output. The supercharger and aftercooling requirements are thus increased and the critical altitude attainable with a given installation is lowered.

The use of exhaust gas for increasing the power output of conventional aircraft engines with lower compression ratios may also be evaluated from the results of these tests. Figure 7, for a compression ratio of 7.0 and an exhaust-gas dilution of 20 percent, shows an increase in knock-limited indicated mean effective pressure of about 4 percent at a fuel-air ratio of 0.09, an increase of 25 percent at a fuel-air ratio of 0.06, and a further, but questionable, leaner-region power increase over the knock-limited indicated mean effective pressure available when no exhaust gas was used. In the light of present-day aircraft operation, therefore, when an exhaust-gas dilution of 20 percent and the conditions of the test illustrated in figure 7 were used, the take-off horsepower could be increased 4 percent and the engine could be operated at a lower fuel-air ratio during take-off because of the cooling effect of the exhaust-gas addition (fig. 10(a)). The cruising horsepower, however, could be increased up to 25 percent with resulting advantages of higher speed and better climb. In these cases of exhaust-gas dilution, an additional weight on the aircraft would exist because of the required exhaust-gas cooler and increased power would be required by the supercharger for any given engine output.

In general, the engine performance at higher percentages of exhaust-gas dilution was limited to a smaller range of fuel-air ratios and the knock itself became more unsteady and was audible at varying intervals during any one test. Operation was especially erratic in the lean regions and may have been caused by: (1) non-homogeneous mixing of the exhaust gas with the intake air causing varying percentages to exist within the cylinder at different strokes; (2) faulty, uneven fuel injection; or (3) a combustion characteristic associated with the gas. Because much better operation in the limiting regions of fuel-air ratio was possible with greater spark advance, point (3) was probably predominant.

Because the capacity of the compressor was limited, 20 percent is the highest recorded percentage of exhaust gas used in these tests; a few isolated points were taken at 30 percent, however, and indicated fairly smooth engine operation and fairly proportional increases in the limits of maximum permissible engine operation. These higher percentages of exhaust gas further limited the operating range of fuel-air ratio.

Effect of Exhaust Gas on Engine Temperatures

Figures 10 and 12 show engine temperatures at various points on the cylinder head and cylinder barrel as functions of fuel-air ratio. Figure 10 indicates the effect of exhaust gas on knock-limited engine temperatures for the four compression ratios tested.

An important trend is the general cooling effect that exhaust gas has on all engine temperatures with the exception of the temperature of the exhaust-valve guide. Figure 12 indicates this fact very clearly because the temperatures are those that existed for constant indicated mean effective pressure with various percentages of exhaust gas.

The temperatures at the center of the head, at the rear spark-plug bushing, at the rear middle of the cylinder barrel, and at the rear barrel above the cylinder flange are lowered by an exhaust-gas dilution of 20 percent at the 7.0 compression ratio (fig. 10(a)) even though the power output is increased. In the case of the higher compression ratios, these same temperatures tend to increase slightly above their initial exhaust-gas-dilution value of 0 percent in the region leaner than about 0.07 fuel-air ratio.

The temperature of the exhaust-valve guide for the tests with exhaust-gas dilution always increased considerably in the lean regions, as shown in figures 10 and 12. This increase is probably a direct result of the effect of exhaust gas on retarding the rate of combustion, although this statement cannot be supported by the data of the present report. For satisfactory use of exhaust gas in present aircraft engines, however, better cooling for the exhaust-valve guide would probably be necessary, although no operating troubles were experienced during this test.

Effect of Inlet-Air Temperature on the Performance of a Full-Scale Single-Cylinder Engine

Figure 13 indicates the knock-limited performance of the engine, operating with fresh-air intake and 7.0 compression ratio, for inlet-air temperatures of 100°, 150°, 200°, and 250° F. These data are cross-plotted in figure 14 as constant fuel-air-ratio curves. As in figure 4, points are shown only to indicate the consistency of the curves and are not actual data points. The increase in knock-limited indicated mean effective pressure available by reducing the inlet-air temperature from 250° F to 100° F is 30 percent at 0.06 fuel-air ratio and 12 percent at 0.10 fuel-air ratio. In addition, this increase in permissible power at the knock limit, made possible by lowering the inlet-air temperature, is accomplished with no change in indicated specific fuel consumption and with a small increase in inlet-air pressure. As a result, a comparison of figure 13 with figure 7 for a 7.0 compression ratio shows that a 4° F reduction in inlet-air temperature has the same general effect toward increasing the maximum permissible power output of the engine as a 1-percent exhaust-gas dilution and is not accompanied by any rise in indicated specific fuel consumption, as was the case in the use of exhaust gas over the range of fuel-air ratios tested. These data stress the necessity of cooling the exhaust gas to the inlet-air temperature and also serve to show the importance of aftercooling in relation to permissible engine power.

Effect of Inlet-Air Temperature on Engine Power Output

Cylinder-head, cylinder-barrel, and exhaust-valve-guide temperatures are shown in figure 15 for inlet-air temperatures of 100° F and 250° F. Even though the engine power output for the 100° F inlet-air temperature exceeded the output at 250° F inlet-air temperature by about 13 to 24 percent, the temperatures of the cylinder head and barrel remained practically unchanged. They were slightly lower in the rich region and slightly higher in the lean region. The exhaust-valve-guide temperature exhibited a more marked increase in the lean region. The maximum increase was about 30° F at a fuel-air ratio of 0.07.

DISCUSSION

The use of higher compression ratios to increase the thermal efficiency of an aircraft engine is a satisfactory procedure, but such a practice is always accompanied by a large decrease in knock-limited power output of an engine at a given fuel-air ratio. An immediate solution to this problem may lie in the use of a suitable coolant fluid taken into the cylinder with the fuel-air mixture to raise the maximum permissible performance of the high-compression-ratio engine to the level of existing engines of lower compression ratio. If this internal coolant is of such nature that it need not be carried as part of the fuel load, it may then reduce the indicated specific fuel consumption without sacrificing the weight-power ratio of the engine.

The use of exhaust gas as the internal coolant appears unsatisfactory from the results of this test for several reasons. First, the use of exhaust gas causes a decrease in thermal efficiency, partly nullifying the advantage of an engine with a higher compression ratio, and requires a very noticeable increase in inlet-air pressure for a given power output compared with an engine operating with fresh-air intake. This need for an increase in inlet-air pressure means greater supercharger and aftercooling requirements and a lower critical altitude for a given aircraft installation.

Second, the exhaust gas must enter the cylinders along with the air under inlet-pressure conditions. Therefore, if the exhaust gas is introduced into the cylinder inlet manifolds, the pressure must be obtained from the energy of the exhaust gas as it leaves the engine cylinder or the gas must be passed through the supercharger. If the first method is possible, it must be accomplished without appreciably increasing the back pressure on the engine; otherwise the power advantage accompanying the use of exhaust gas may be offset. If the exhaust gas is introduced ahead of the supercharger, a further increase in power requirements of this unit may again tend to offset the increased power output available through the use of the gas to inhibit engine knock.

Finally, the use of exhaust gas would necessitate cooling practically all of the gases from 2 of 9 cylinders, or 3 of 14 cylinders, from about 1600° F or 1800° F to the inlet-air temperature. An air-cooled heat exchanger would have to be adapted for this cooling, and calculations indicate that a large cooling surface would be necessary with a corresponding weight of 150 pounds or more for a conventional 1200-horsepower engine. It may be pointed out from reference 4, however, that the use of a heat exchanger may not cause an appreciable additional drag on the aircraft installation (at cruising speed). The design may be such as to take advantage of the "Meredith effect" in deriving thrust power from the heat energy of the exhaust gases absorbed by the air. This thrust power gained from the Meredith effect at high aircraft speeds tends to compensate for the power lost in cooling-air drag and, under some conditions of flight, may even produce a small net thrust aiding propulsion. The heat-exchanger unit, however, would always offer the disadvantage of increased installation weight and take-off drag.

The other method investigated in this project for increasing the power output of an engine is the use of low temperatures of the combustion air supplied to the engine cylinders. This practice is very effective and shows the advisability of using an aftercooler for multicylinder aircraft-engine installations. The disadvantages to this installation are again the heat-exchanger-weight limitations and the increased drag.

SUMMARY OF RESULTS

The tests showed the following results:

1. Increasing the cylinder compression ratio to 10.0 from the original value of 7.0 decreased the knock-limited indicated mean effective pressure 42 percent at a fuel-air ratio of 0.06 and 24 percent at a fuel-air ratio of 0.10. The respective decreases in the indicated specific fuel consumption for these fuel-air ratios were 8 and 10 percent.

2. Decreasing the inlet-air temperature at a compression ratio of 7.0 to 100° F from the original value of 250° F increased the knock-limited indicated mean effective pressure 30 percent at a fuel-air ratio of 0.06 and 12 percent at a fuel-air ratio of 0.10.

3. The use of cooled exhaust gas mixed with the intake air raised the knock-free power of a conventional aircraft fuel.

4. The use of exhaust gas caused an increase in indicated specific fuel consumption both when the engine was operated at the knock-limited permissible performance and below this limit.

5. Exhaust-gas additions had a cooling effect on the engine head and cylinder. The exhaust-valve-guide temperature, however, always exhibited a tendency to increase with exhaust-gas dilution at fuel-air ratios below 0.065.

6. The use of exhaust gas mixed with the intake air at high compression ratios to obtain the same power output as the conventional low-compression-ratio engine decreased the cylinder temperatures.

7. At a compression ratio of 7.0, a 4° F decrease in the inlet-air temperature had the same average effect in raising the knock-limited performance of the engine as an addition of 1 percent exhaust gas to the inlet air.

8. Decreasing the inlet-air temperature from 250° F to 100° F had no appreciable effect on the temperatures of the cylinder head and barrel, though the knock-limited power output increased as much as 30 percent. For these conditions the exhaust-valve-guide temperature increased a maximum of 30° F at about 0.07 fuel-air ratio.

CONCLUSIONS

From an analysis of the test results on a Wright R-1820 G200 engine, the following conclusions were reached:

1. The use of exhaust gas as an internal coolant presents the following disadvantages from considerations of engine operation:

(a) Comparatively high percentages of exhaust gas (20 percent by weight of intake air or more) are required to produce an appreciable increase in knock-limited indicated mean effective pressure.

(b) The use of exhaust gas causes a decrease in indicated thermal efficiency and requires an increase in inlet-air pressure for a given power output compared with conventional operation.

2. The advisability of the use of exhaust gas as an internal coolant for increasing the maximum permissible power output of an aircraft engine must be judged in addition to the data presented in this paper on the difficulties to be encountered in cooling the exhaust gas and in introducing it into the incoming charge.

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

REFERENCES

1. Ricardo, Harry R.: The Internal-Combustion Engine. Vol. II. Blackie and Son, Ltd. (Glasgow and Bombay), 1923, pp. 43-44.

2. Sanders, Newell D., and Barnett, Henry C.: Effect of Varying Percentages of Exhaust Gas on Engine Performance. NACA RB No. 3D27, April 1943.

3. Taylor, C. Fayette, and Taylor, Edward S.: The Internal Combustion Engine. International Textbook Co. (Scranton, Pa.), 1938, p. 78.

4. Meredith, F. W.: Note on the Cooling of Aircraft Engines with Special Reference to Ethylene Glycol Radiators Enclosed in Ducts. R. & M. No. 1683, British A.R.C., 1935.

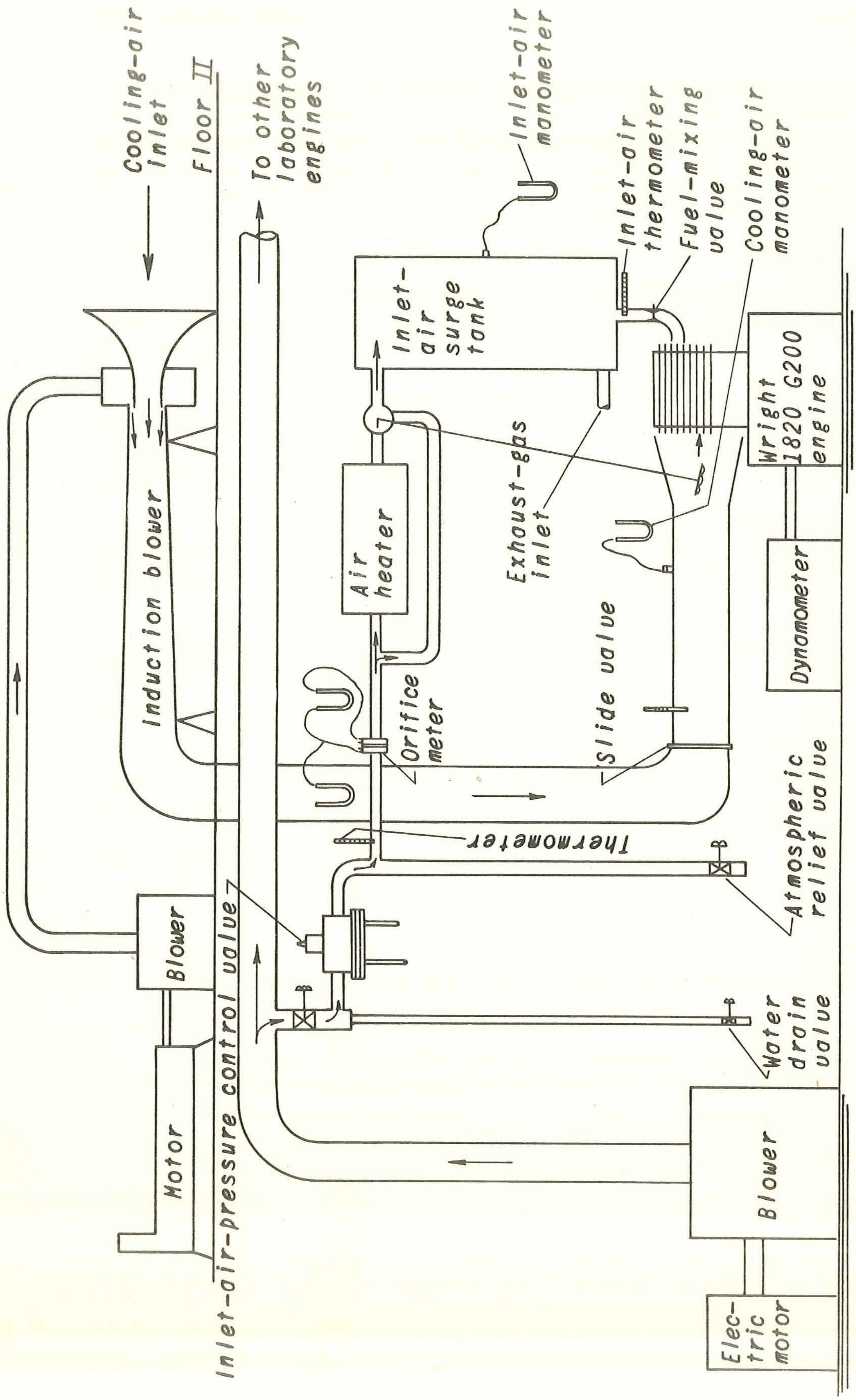

Figure 1. - Combustion-air and cooling-air apparatus.

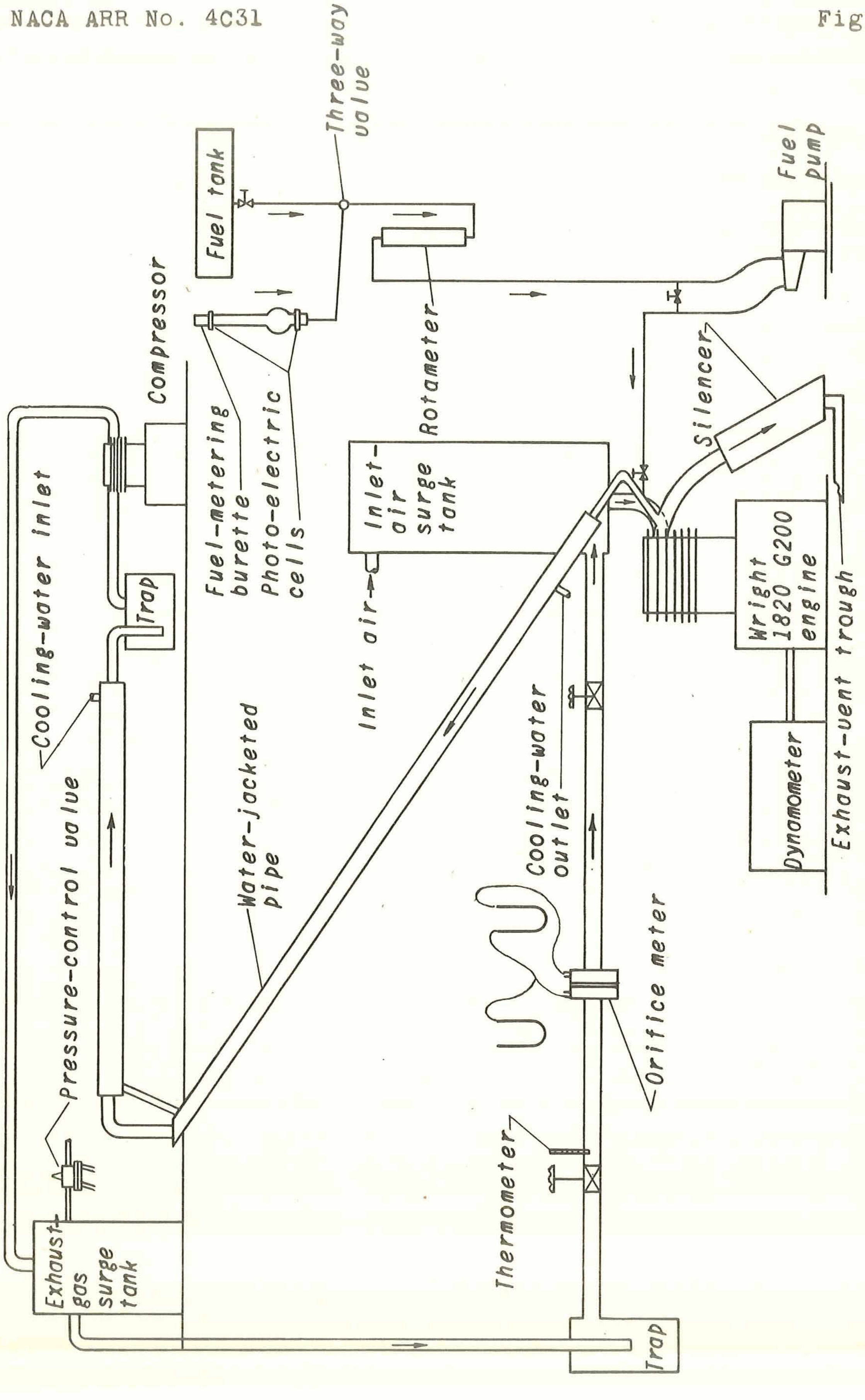

Figure 2. - Exhaust-gas and fuel apparatus.

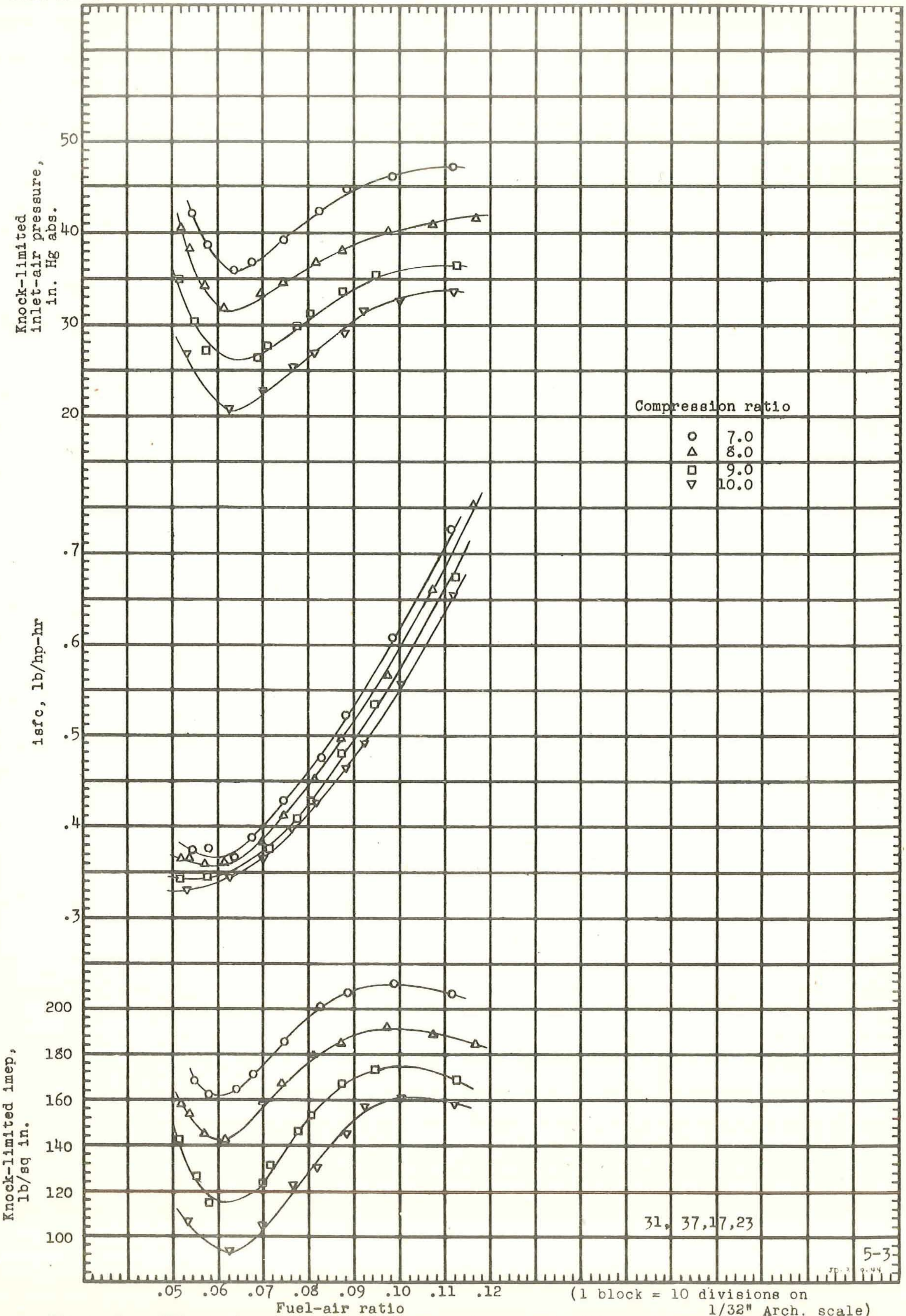

Figure 3. - Effect of compression ratio on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; oil-out temperature, 170° F; spark advance, 20° B.T.C.; engine speed, 1600 rpm; inlet-air temperature, 250° F; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane.

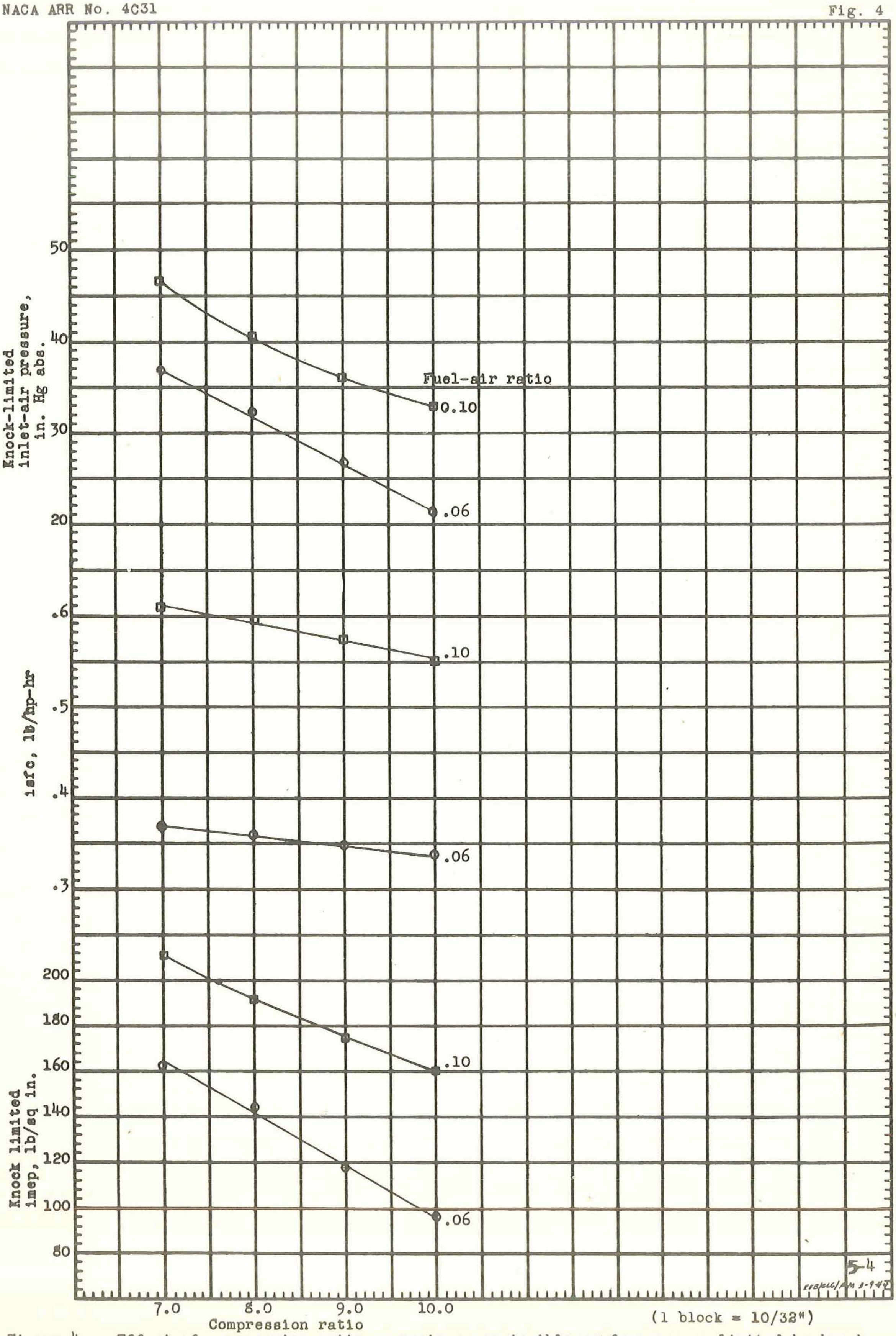

Figure 4. - Effect of compression ratio on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; oil-out temperature, 170° F; spark advance, 20° B.T.C.; engine speed, 1600 rpm; inlet-air temperature, 250° F; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane. Cross plot of data from figure 3.

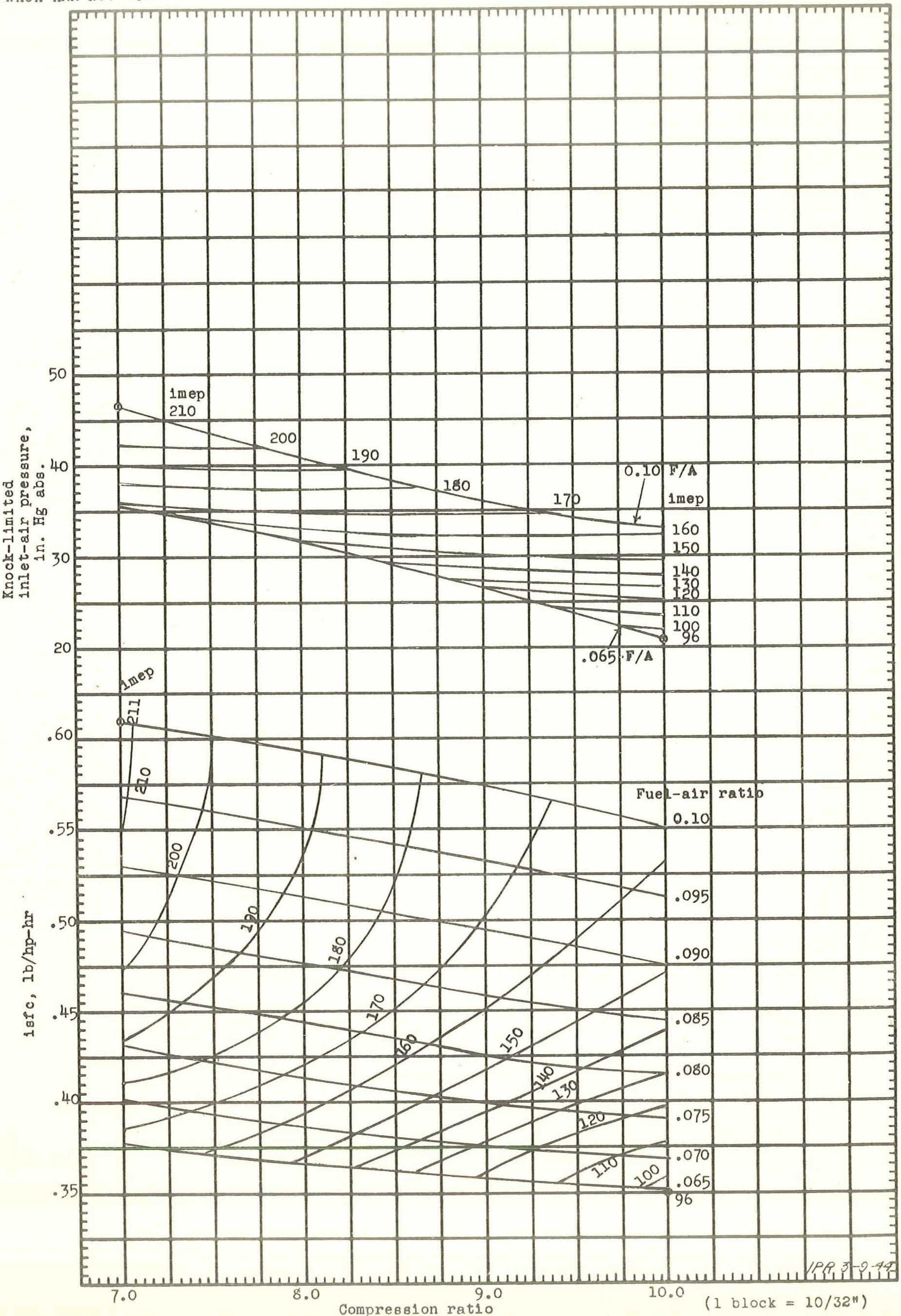

Figure 5. - Effect of compression ratio on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; oil-out temperature, 170° F; spark advance, 20° B.T.C.; engine speed, 1600 rpm; inlet-air temperature, 250° F; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane.

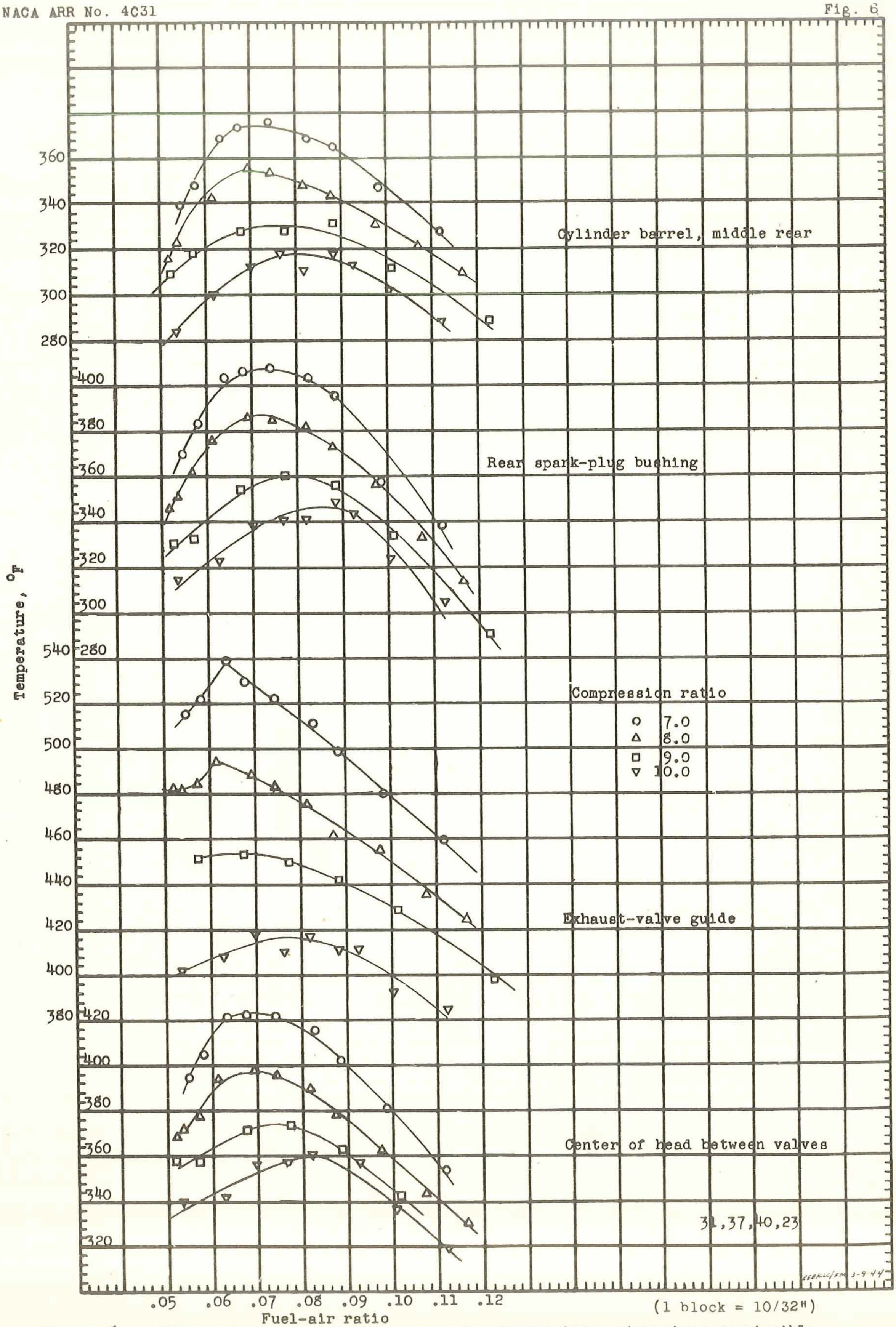

Figure 6. - Effect of compression ratio on engine temperatures at maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; oil-out temperature, 170° F; spark advance, 20° B.T.C.; engine speed, 1600 rpm; inlet-air temperature, 250° F; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane.

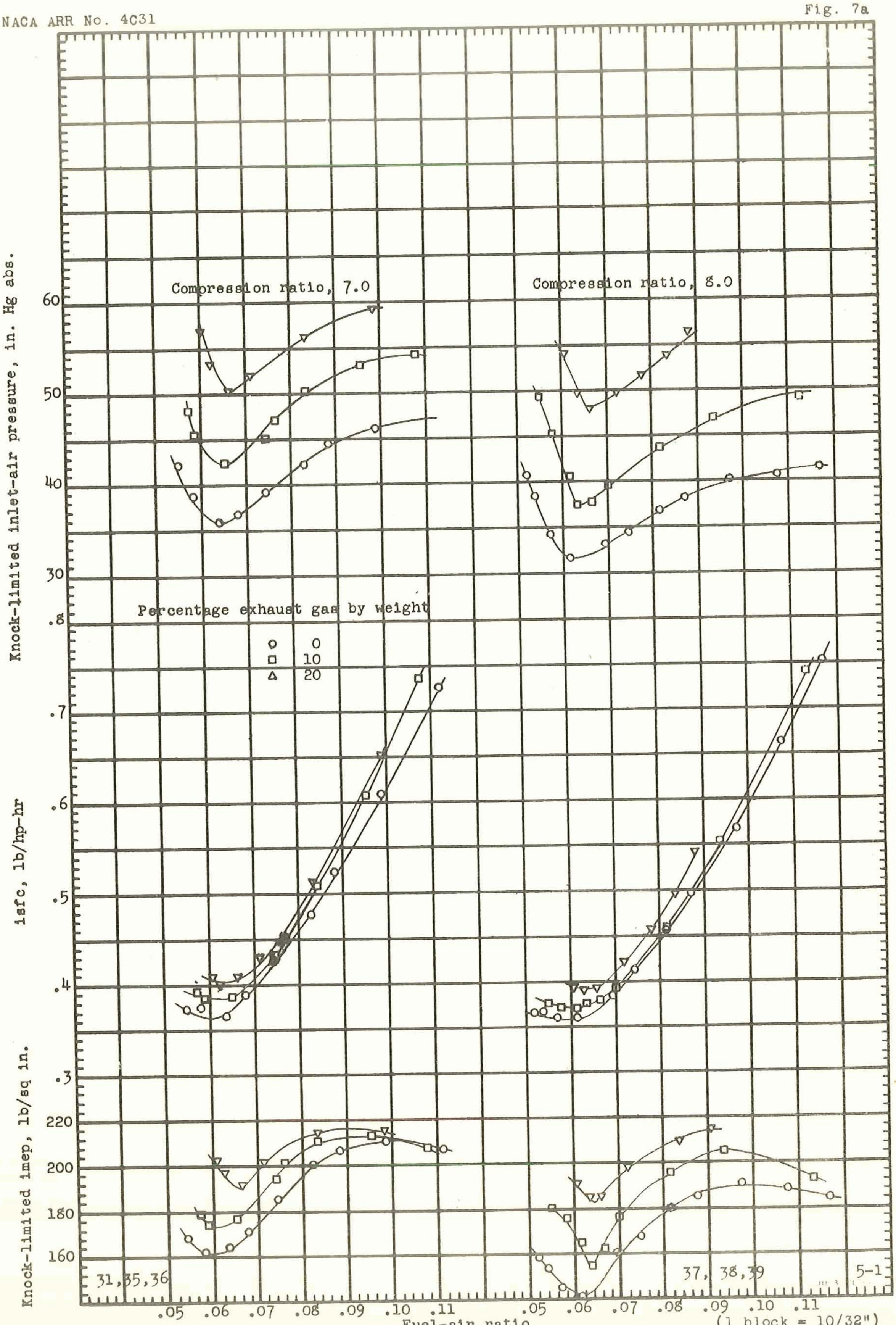

Figure 7a.- Effect of exhaust-gas dilution on maximum performance as limited by knock. Wright 1820 G200, single-cylinder test engine; air and exhaust-gas mixture, inlet temperature, 250° F; spark advance, 20° B.T.C.; oil-cut temperature, 170° F; engine speed, 1600 rpm; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane.

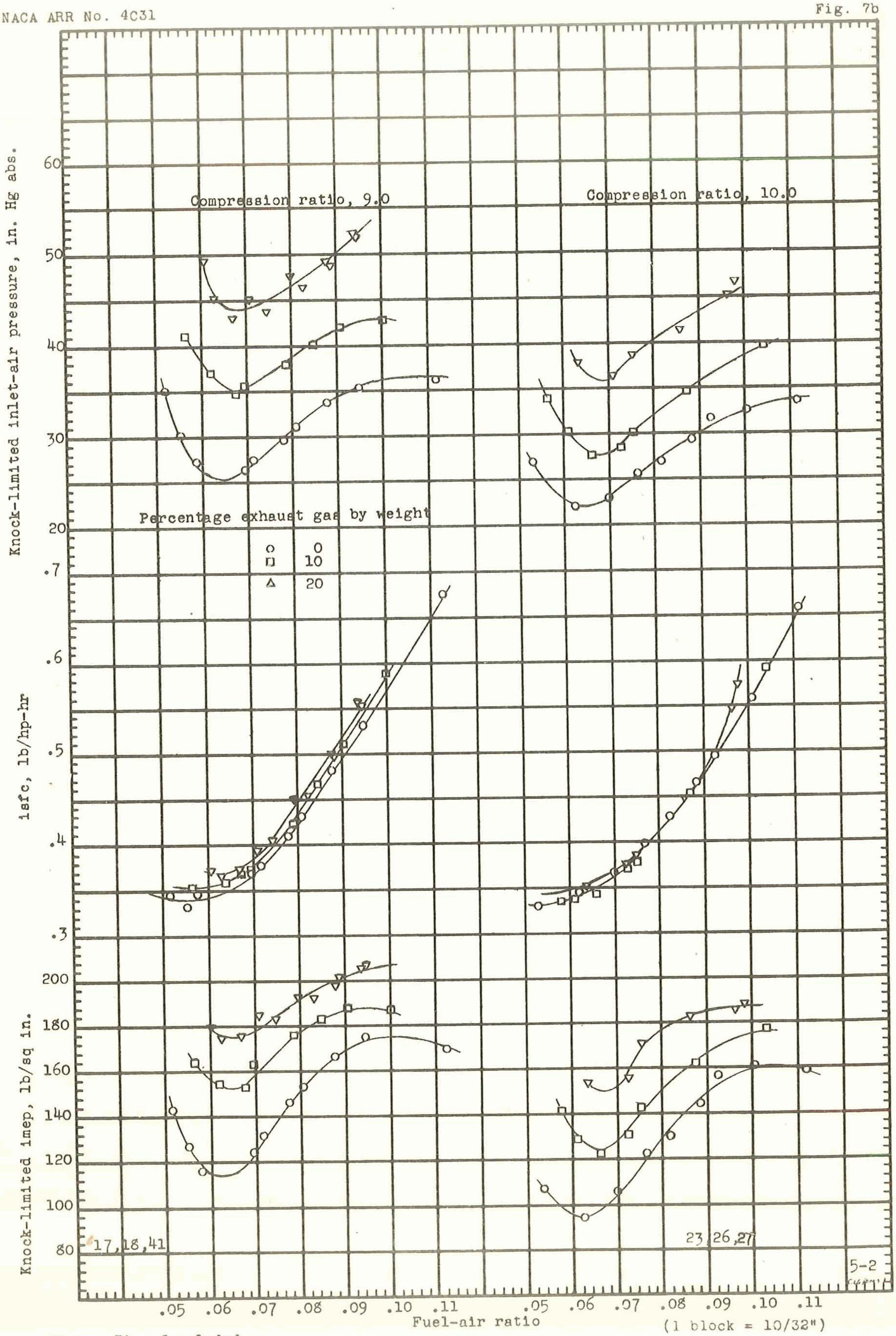

Figure 7b.- Concluded

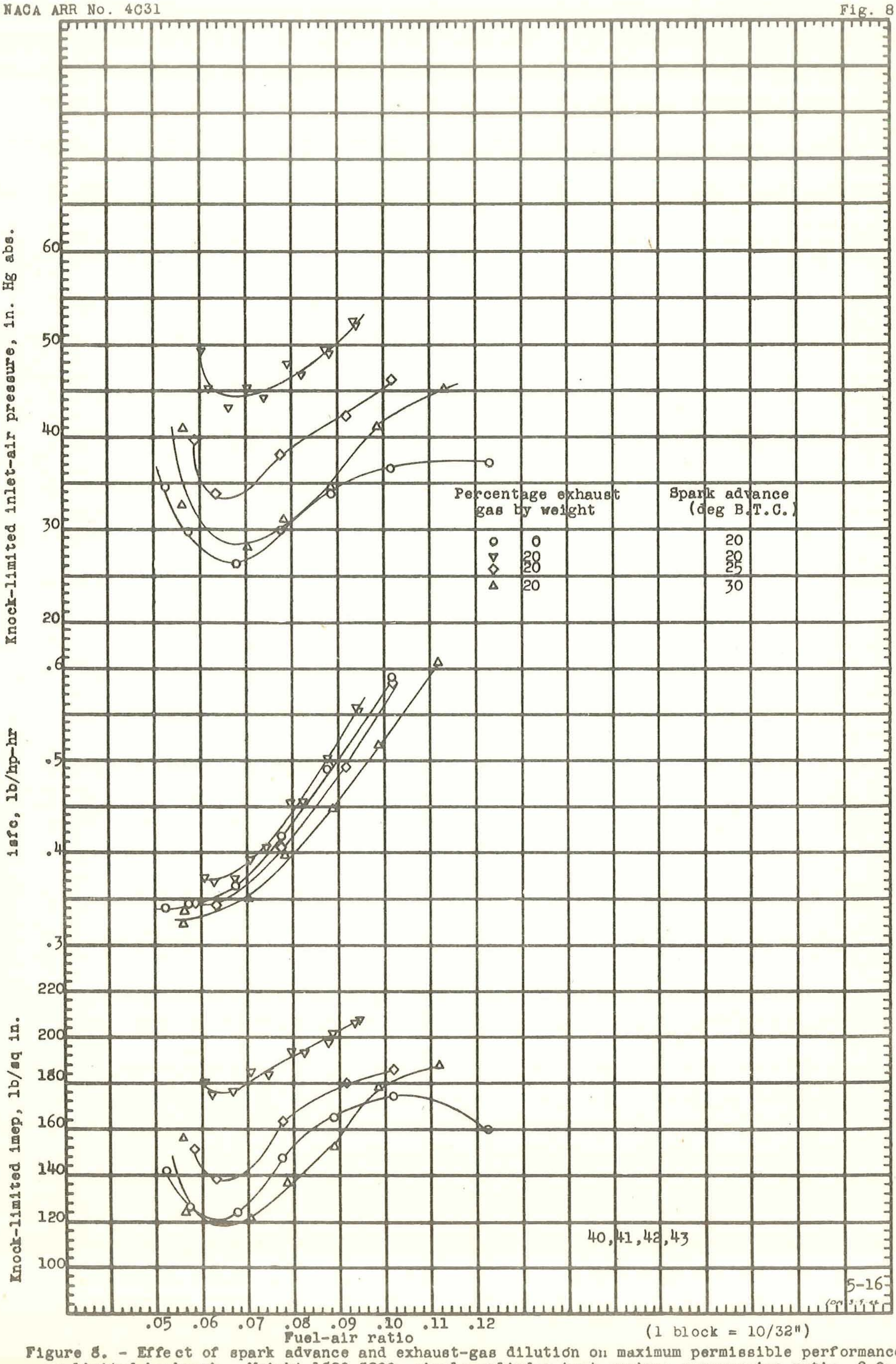

Figure 8. - Effect of spark advance and exhaust-gas dilution on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; compression ratio, 9.0; oil-out temperature, 170° F; engine speed, 1600 rpm; inlet-air and exhaust-gas temperature, 250° F; cooling-air pressure drop, 6.5 inches water; fuel, Army 100 octane.

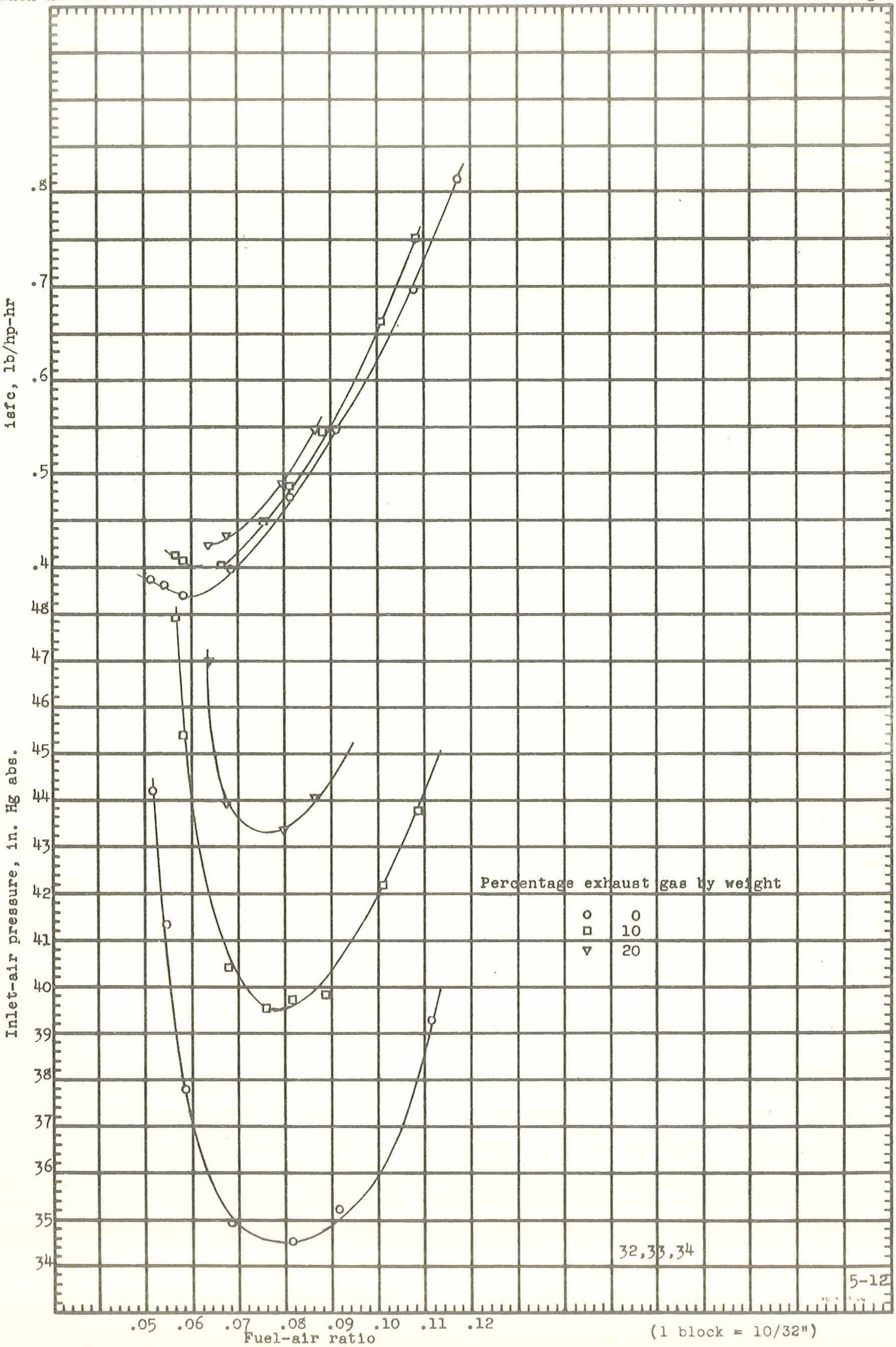

Figure 9. - Effect of exhaust-gas dilution on fuel consumption at constant indicated mean effective pressure of 162 pounds per square inch. Wright 1820 G200, single-cylinder test engine; spark advance, 20° B.T.C.; compression ratio, 7.0; oil-out temperature, 170° F; engine speed, 1600 rpm; inlet-air temperature, 250° F; cooling-air pressure drop, 6.5 inches of water; fuel, Army 100 octane.

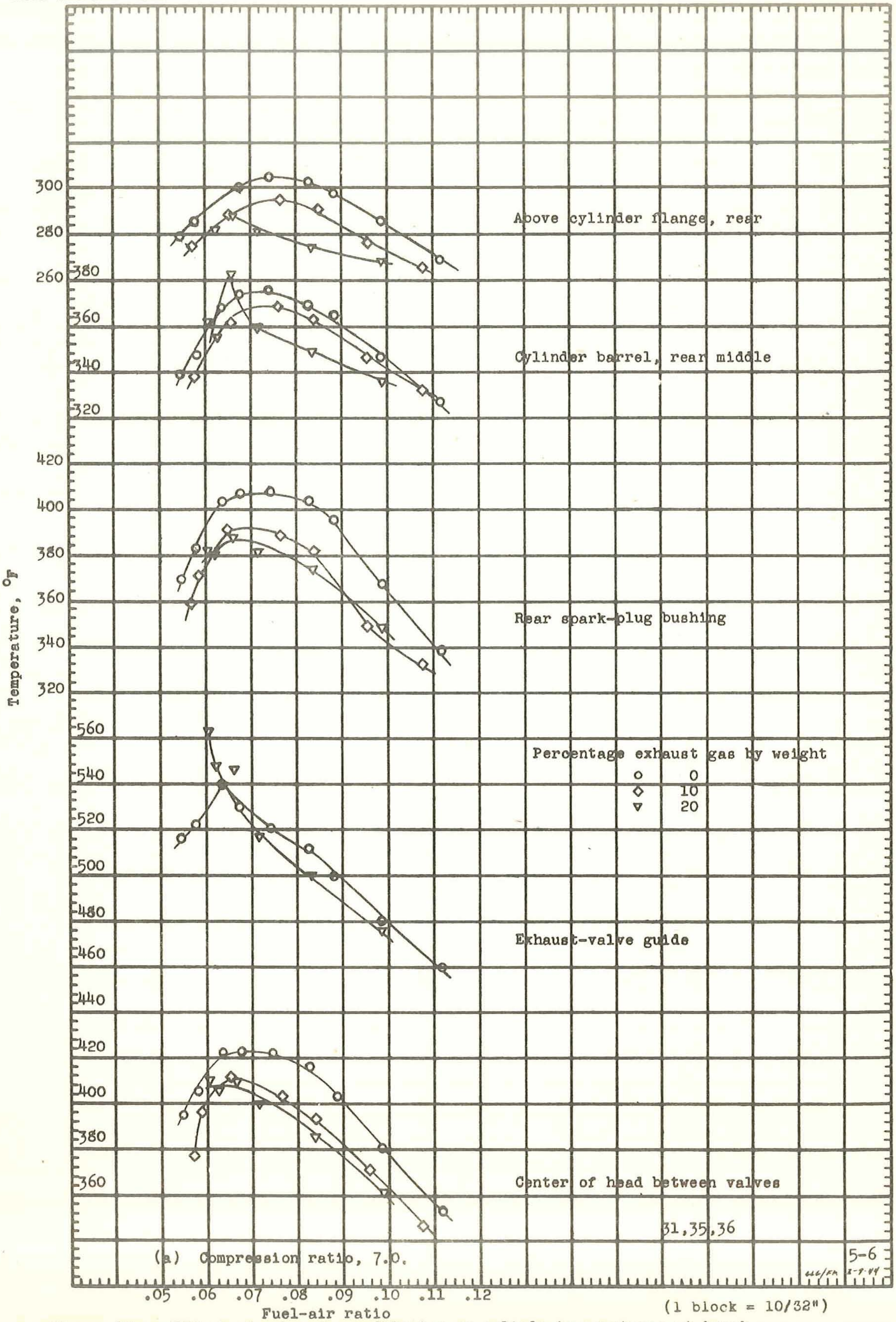

Figure 10a.- Effect of exhaust-gas dilution on cylinder temperatures at knock. Wright 1820 G200, single-cylinder test engine; spark advance, 20° B.T.C.; oil-out temperature, 170° F; engine speed, 1600 rpm; inlet-air and exhaust-gas temperature, 250° F; cooling-air pressure drop, 6.5 inches water; fuel, Army 100 octane.

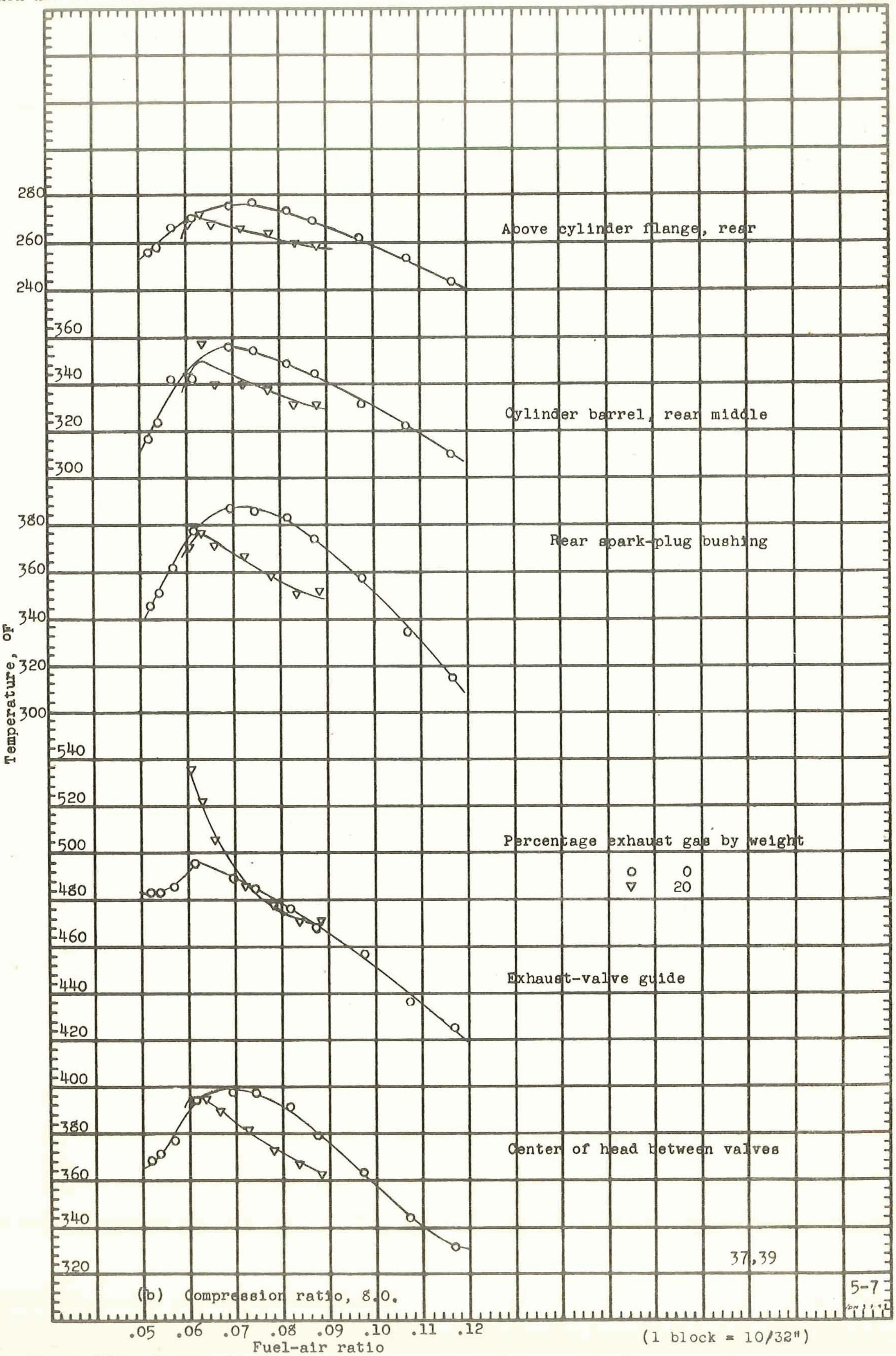

Figure 10b.- Continued.

#19

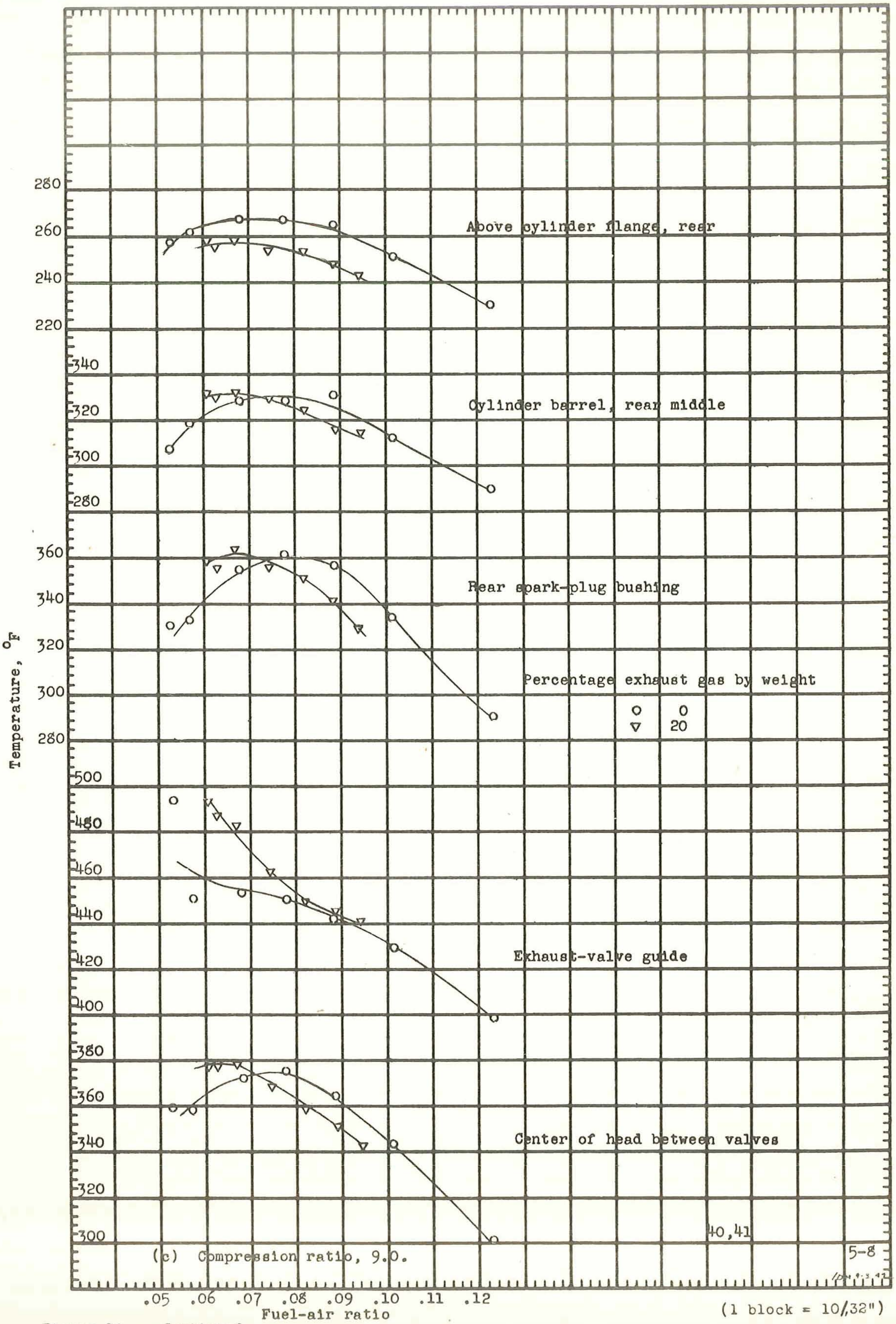

Figure 10c.- Continued.

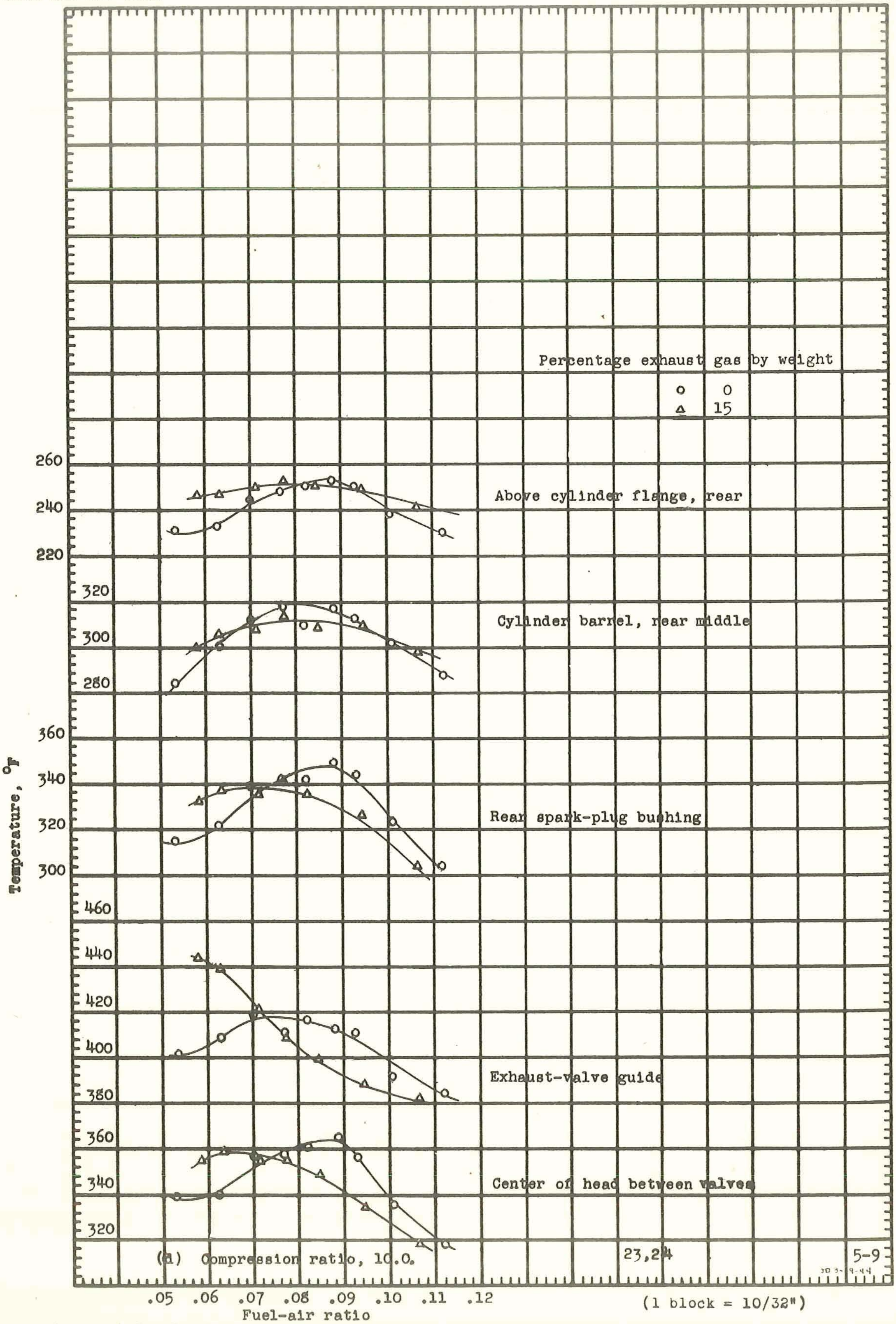

Figure 10d.- Concluded.

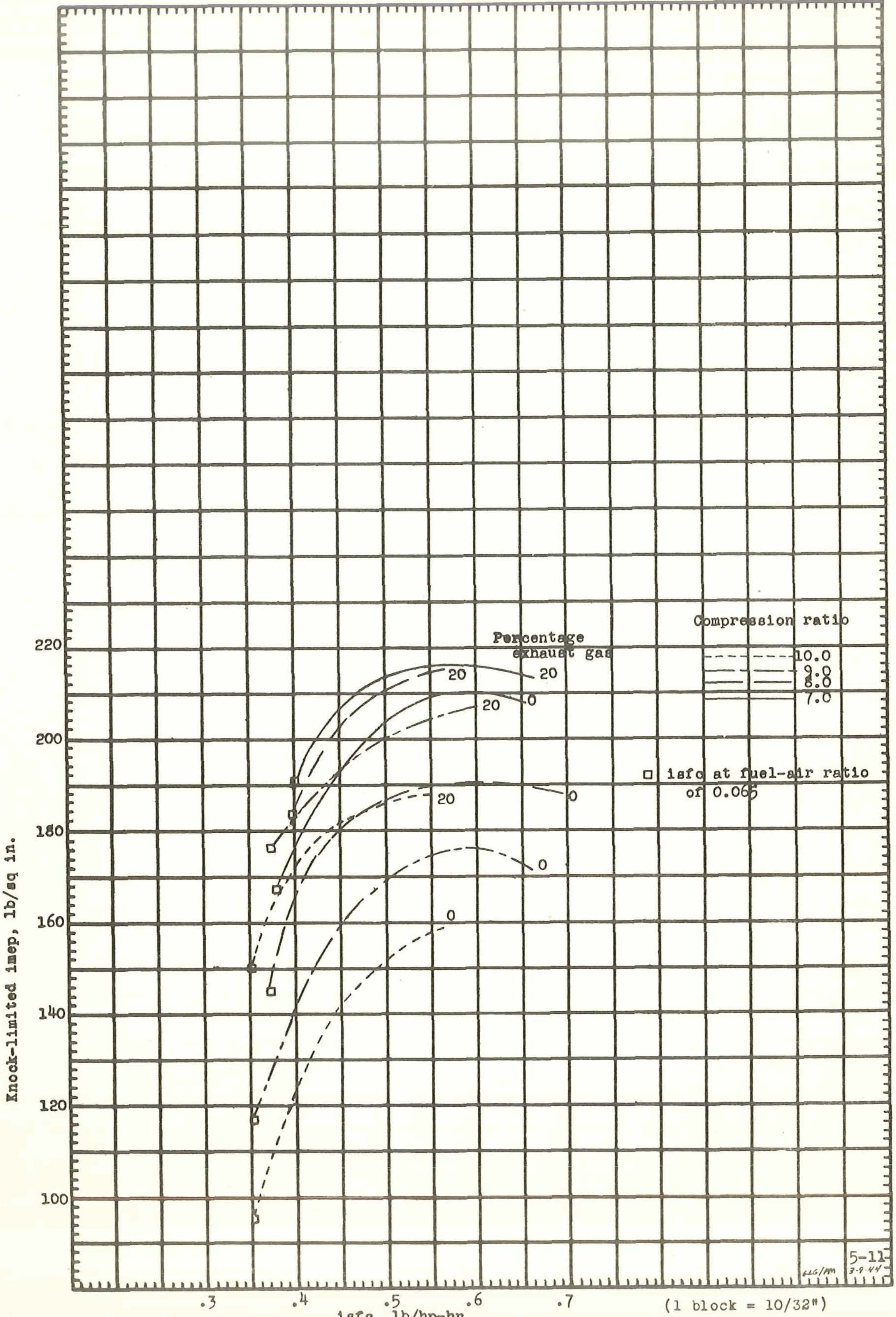

Figure 11. - Indicated specific fuel consumptions required at various knock-limited levels with exhaust-gas dilution at fuel-air ratios above 0.065. Wright 1820 G200, single-cylinder test engine; spark advance, 20° B.T.C.; oil-out temperature, 170° F; engine speed.

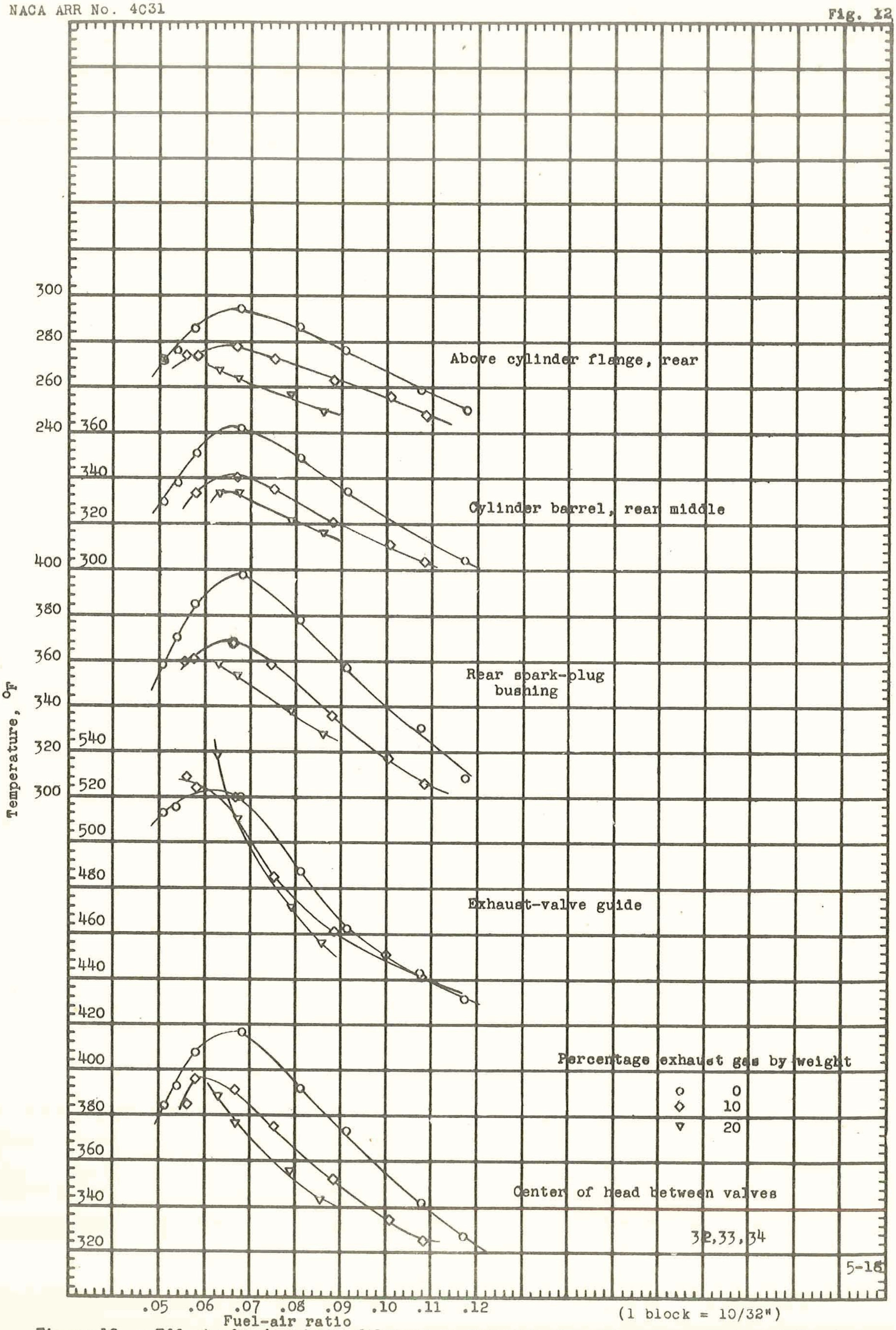

Figure 12. - Effect of exhaust-gas dilution on cylinder temperatures at constant indicated mean effective pressure of 162 pounds per square inch. Wright 1820 G200, single-cylinder test engine; spark advance, 20° B.T.C.; compression ratio, 7.0; oil-out temperature, 170° F;

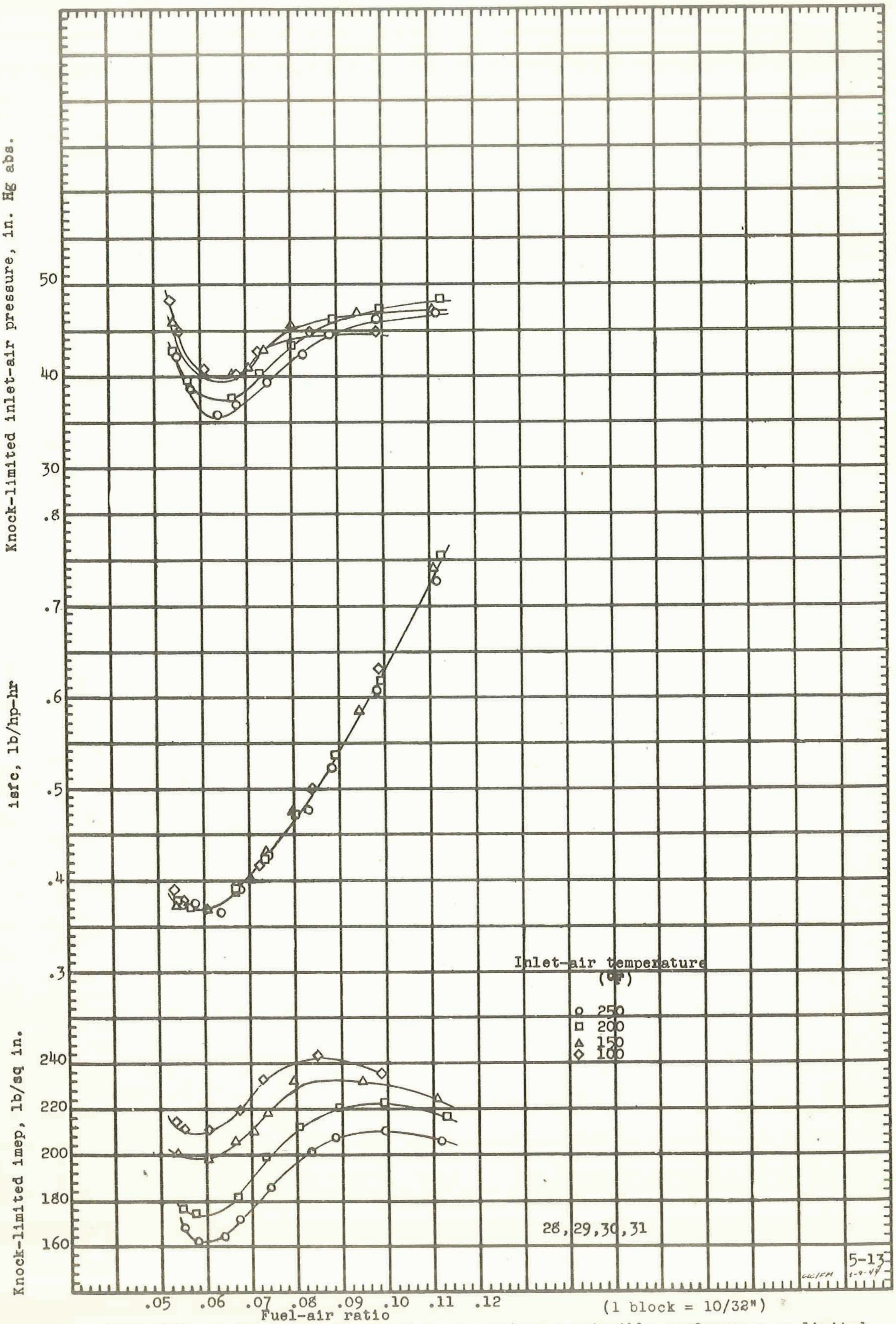

Figure 13. - Effect of inlet-air temperature on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; compression ratio, 7.0; spark advance, 20° B.T.C.; oil-cut temperature, 170° F; engine speed, 1600 rpm; cooling-air pressure drop, 6.5 inches of water; exhaust gas, 0 percent; fuel, Army 100 octane.

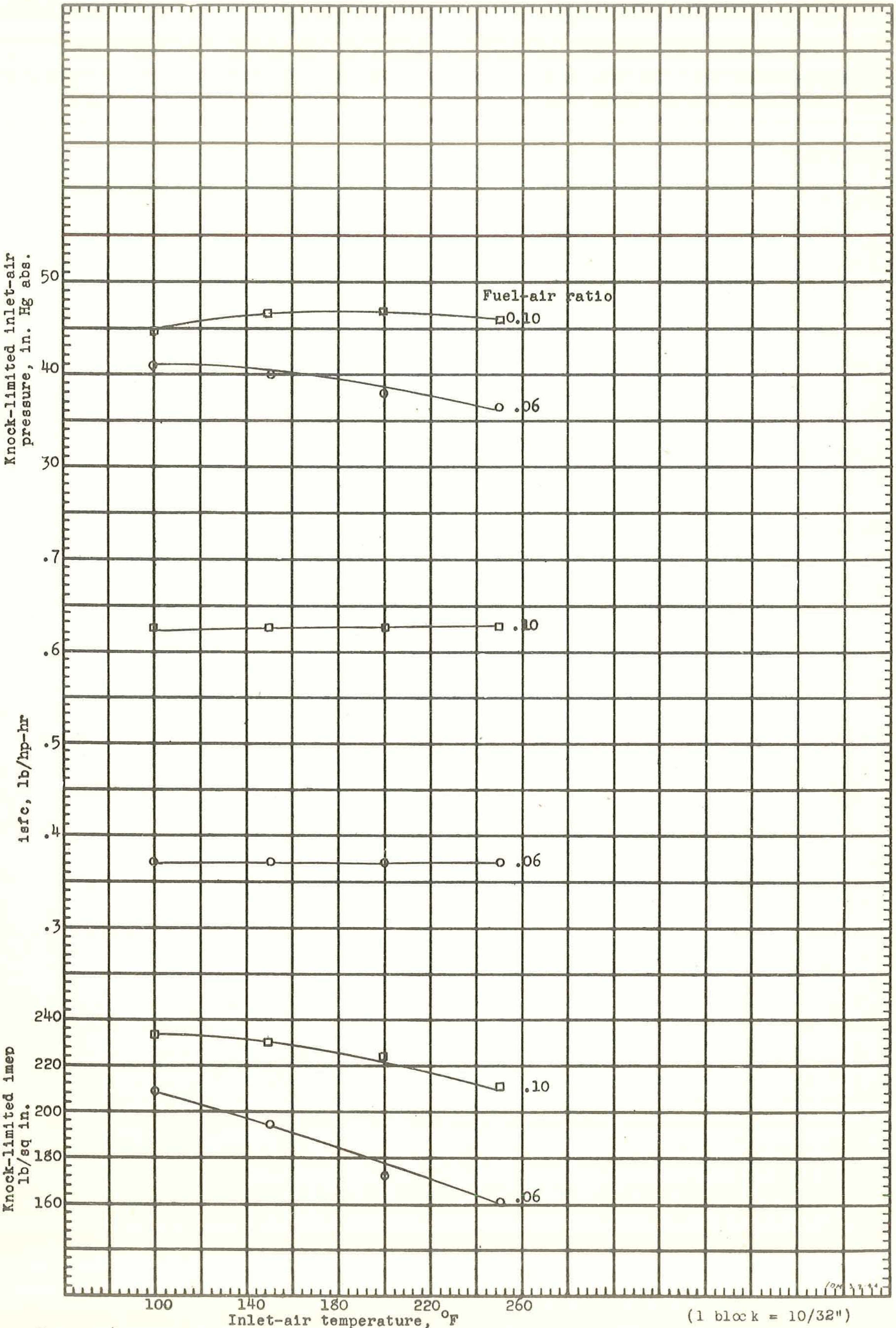

Figure 14. - Effect of inlet-air temperature on maximum permissible performance as limited by knock. Wright 1820 G200, single-cylinder test engine; compression ratio, 7.0; spark advance, 20° B.T.C.; oil-out temperature, 170° F; engine speed, 1600 rpm; cooling-air pressure drop, 6.5 inches of water; exhaust gas, 0 percent; fuel, Army 100 octane. Cross

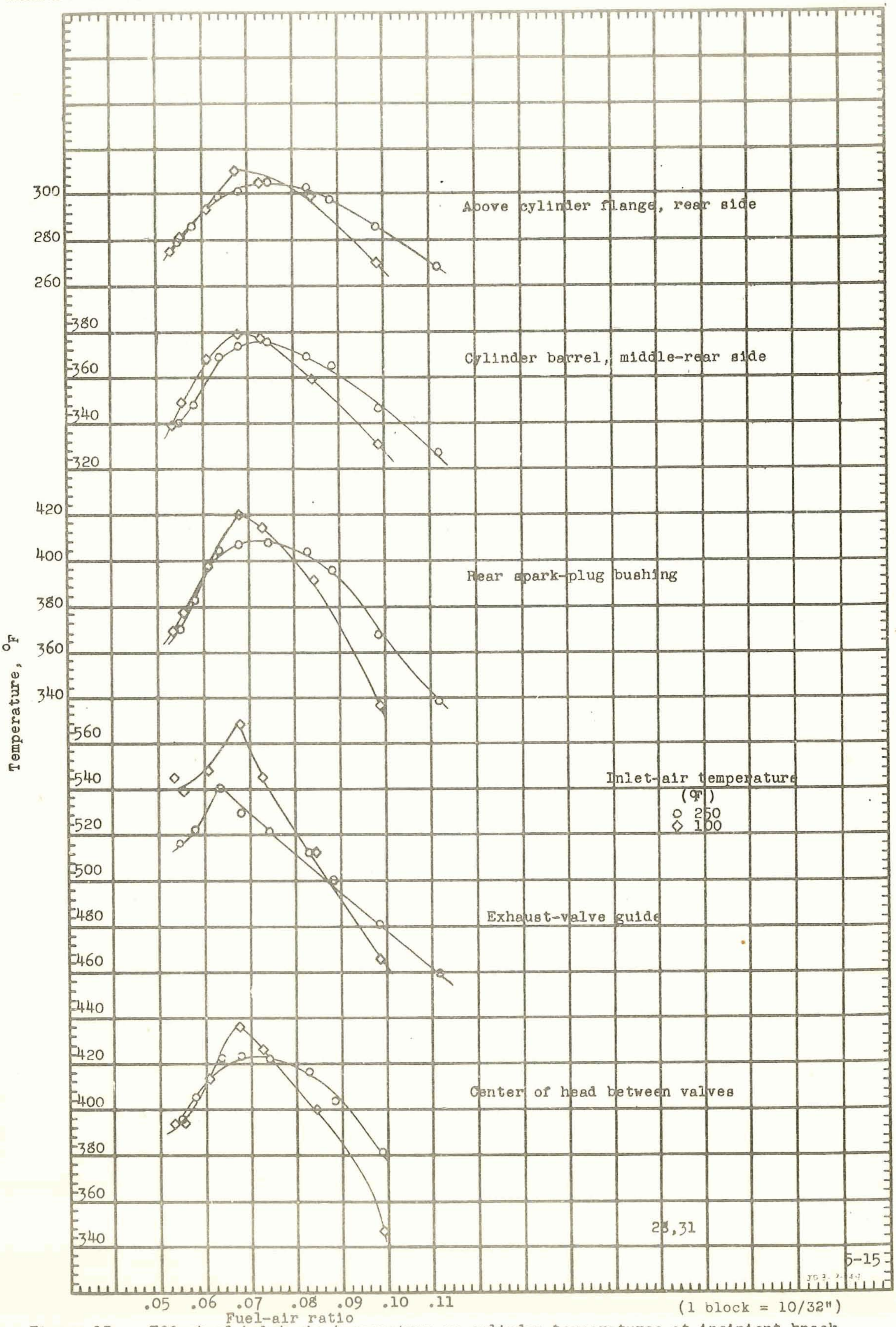

Figure 15. - Effect of inlet-air temperature on cylinder temperatures at incipient knock. Wright 1820 G200 single-cylinder test engine; spark advance, 20° B.T.C.; compression ratio, 7.0; oil-out temperature, 170° F; engine speed, 1600 rpm; cooling-air pressure drop, 6.5 inches of water; exhaust gas, 0 percent; fuel, Army 100 octane.