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JUL 19 1940

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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 767

THE EFFECTS OF ENGINE SPEED AND MIXTURE TEMPERATURE ON THE KNOCKING CHARACTERISTICS OF SEVERAL FUELS

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Washington
July 1940

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THE EFFECTS OF ENGINE SPEED AND MIXTURE TEMPERATURE ON THE KNOCKING CHARACTERISTICS OF SEVERAL FUELS

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SUMMARY

Six 100-octane and two 87-octane aviation engine fuels were tested in a modified C.F.R. variable-compression engine at 1,500, 2,000, and 2,500 rpm. The mixture temperature was raised from 50° to 300° F in approximately 50° steps and, at each temperature, the compression ratio was adjusted to give incipient knock as shown by a cathode-ray indicator. The results are presented in tabular form.

The results are analyzed on the assumption that the conditions which determine whether a given fuel will knock are the maximum values of density and temperature reached by the burning gases. A maximum permissible density factor, proportional to the maximum density of the burning gases just prior to incipient knock, and the temperature of the gases at that time were computed for each of the test conditions. Values of the density factor were plotted against the corresponding end-gas temperatures for the three engine speeds and also against engine speed for several end-gas temperatures.

The maximum permissible density factor varied only slightly with engine speed but decreased rapidly with an increase in the end-gas temperature. The effect of changing the mixture temperature was different for fuels of different types. The results emphasize the desirability of determining the antiknock values of fuels over a wide range of engine and intake-air conditions rather than at a single set of conditions.

INTRODUCTION

A method of expressing the relative maximum power-output possibilities of aviation engine fuels for a wide range of engine operating conditions has been developed

by Rothrock and Biermann. The method is described in reference 1 and is illustrated with data from several single-cylinder test engines using different types of fuel. Because the maximum performance that may be obtained with most aviation fuels depends on their knocking characteristics, the conditions affecting knock are used as the basis of comparison. The assumption is made that the conditions which determine whether a given fuel will knock are the maximum density and temperature reached by the burning gases. It would be extremely difficult to determine these conditions directly. Rothrock and Biermann therefore developed equations with which the gas density and temperature resulting in incipient knock could be estimated from certain engine and inlet-air conditions. The conditions most likely to affect the density and the temperature of the gases were concluded to be:

(a) Compression ratio.

(b) Inlet-air pressure.

(c) Inlet-air temperature.

(d) Spark advance.

(e) Fuel-air ratio.

(f) Combustion-chamber size and shape.

(g) Wall temperature of combustion chamber and cylinder.

(h) Engine speed.

The object of the tests described in this report was to determine the effects of engine speed and mixture temperature on the knocking characteristics of several aviation engine fuels of different types, using the method presented in reference 1, and thereby to check further the usefulness of the method.

Some of the listed engine and inlet-air conditions must be kept constant in any one test program if the number of tests is to be held to a reasonable limit. Conditions (f) and (g) were rendered constant for these tests by using only one test engine which, furthermore, had evaporative cooling. Condition (e) was kept constant by always using the fuel-air ratio that gave maximum engine power.

One set of tests was made with the spark advance set for maximum power in each case and another set of tests was made with a constant spark-advance setting. The inlet-air pressure was atmospheric in every case and so was practically constant. For each fuel, the remaining variables were therefore inlet-air temperature, engine speed, and compression ratio.

With each fuel at each engine speed and at each mixture temperature, the compression ratio was raised until incipient knock began. The test results are presented in tabular form. A maximum permissible density factor, proportional to the density of the burning gases in the end zone just prior to incipient knock, and the temperature of the gases at that time were computed for each test condition. The computed results are presented as curves.

The tests were conducted during 1938 at the Langley Field laboratories of the National Advisory Committee for Aeronautics.

APPARATUS

The engine used was a standard C.F.R. variable-compression single-cylinder fuel-rating unit of 3-1/4-inch bore and 4-1/2-inch stroke with the following modifications: Instead of being belt-connected to a constant-speed electric motor, it was direct-connected to a cradle-type electric dynamometer; a high-speed crankcase made possible the conduction of tests at any speed up to 3,000 rpm; the three-bowl adjustable-level carburetor was replaced by an automobile-type downdraft carburetor in which the fuel supply to the main jet was manually controlled by a needle valve and all the other jets were blocked off. Unshrouded sodium-cooled valves were used for both intake and exhaust.

Electric heating units in a surge tank controlled the temperature of the air supplied to the carburetor. The readings of a mercury-in-glass thermometer installed in the intake manifold between the carburetor and the engine were used as indications of the temperature of the gasoline-air mixture.

A photograph of the engine used is shown in figure 1. The electric air heater is above the engine and the cathode-ray oscillograph used as a knock indicator is in the lower right-hand corner. The engine is shown equipped with a

manifold fuel-injection system. For the present tests, however, it was equipped with a carburetor.

The ignition system was modified to operate from the 230-volt direct-current line to which the dynamometer was connected. (See fig. 2.) Ordinary incandescent electric lamps were used to reduce the voltage for the primary circuit and, as the direct-current line was not grounded at the generator, both breaker points were insulated from the ground to guard against accidents due to stray grounds. This arrangement eliminated the necessity for a battery or a magneto. An aviation spark plug (BG-3B2) was used. The spark timing was manually controlled. The variation in spark timing was about ±0.5 crank degree at 2,500 rpm.

A piezoelectric crystal pick-up, installed in the opening ordinarily occupied by the bouncing pin, and a cathode-ray oscillograph enabled the operator to keep a close check on the rate of combustion. No bouncing pin was used in these tests. Incipient knock could be detected by the appearance of a high-frequency vibration in the pressure-time diagram on the oscillograph screen at engine conditions less severe than those required to produce audible knock. A more sensitive indication of this incipient knock was obtained by inserting the single-differentiating filter circuit shown in figure 3 between the oscillograph and its amplifier. The screen then showed the rate of change of pressure with frequencies of the order of the engine speed largely suppressed but with the knocking frequencies unaffected, and a higher amplification could therefore be used.

Distilled water was used in the evaporative-type cooling system, and a continuous indication of the fuel-air ratio was given by an Englehard fuel-air ratio meter.

FUELS

One of the fuels was the standard C.F.R. S-1 reference fuel, a technical grade of iso-octane with an octane rating of almost 100. Three other fuels were blends of S-1 and M-1 (a reference fuel having an octane number of about 18) with enough tetraethyl lead added to raise the octane number to 100, as determined by the Army method. The proportions of S-1, M-1, and tetraethyl lead in these fuels were established by the Matériel Division at Wright Field

and are given on the appropriate figures of this report. Ethyl fluid was used in the fuels in the proportion of 1.53 ml of fluid for 1 ml of tetraethyl lead.

Two other fuels rated at 100 octane by the Army method were tested. These fuels were obtained from Wright Field and were designated PPF-566 and PPF-580. Fuel PPF-566 was a toluene blend and fuel PPF-580 was an isopropyl ether blend.

The final two fuels were obtained from an aircraft-engine manufacturer and were designated N-87 and X-87. Both fuels had been tested by the C.F.R. motor method (A.S.T.M.) and had been given a rating of 87 octane number. The N-87 fuel was described as being a "conventional" aviation gasoline; the X-87 fuel was termed "unconventional" and the manufacturer stated that it seemed to be superior in octane number to N-87 when used in an aviation engine at high specific output.

PRELIMINARY TESTS

Preliminary tests made with each fuel at various compression ratios, fuel-air ratios, and spark-advance angles showed that the greatest engine power was always obtained at an indicated fuel-air ratio of about 0.077; this value was therefore selected as standard for all performance tests.

The spark-advance angle for maximum power with atmospheric intake-air density, hereinafter called the optimum spark-advance angle, always decreased as the compression ratio was increased. Optimum spark-advance angles were determined for the S-1 fuel with 1.5 ml of tetraethyl lead per gallon added to prevent knocking, and these values were used for the performance tests at optimum spark-advance angles with the blends of S-1 and M-1 fuels and also for the tests with the two fuels of 87 octane number. Separate determinations of the optimum spark-advance angle for the PPF-566 and PPF-580 fuels were made because these two fuels contained compounds whose chemical natures were radically different from those of the S-1 and the M-1 fuels. Because the supply of PPF-580 and PPF-566 fuels was limited, the optimum spark-advance angle was determined at only two or three compression ratios and a straight-line relation was assumed to exist between the optimum angle

and the compression ratio. During the performance tests, a much higher compression ratio for incipient knock was obtained than had been anticipated; extrapolation of the optimum spark-advance-angle curves was therefore necessary. Again a straight-line relation was assumed.

The values of the optimum spark-advance angle were determined at a mixture temperature of 200° F. Tests indicated that the variation in optimum angle with mixture temperature was too small to be considered in this investigation.

PERFORMANCE TESTS

Each of the eight fuels was tested at engine speeds of 1,500, 2,000, and 2,500 rpm and at mixture temperatures from about 50° or 100° F to about 300° F in approximately 50° steps. All tests were made at full throttle and with atmospheric intake pressure. At each test condition, the spark-advance angle was continuously adjusted for maximum power as the compression ratio was varied until incipient knock was indicated on the oscillograph screen. The ignition switch was then momentarily opened to check for autoignition. In no case did autoignition occur. In addition to the tests with optimum spark-advance angles, the six 100-octane fuels were tested with a fixed spark-advance angle of 30°.

No control nor measurement of atmospheric humidity was attempted. Although it was recognized that humidity variations have small effects on knock, the magnitude of those effects was considered to be negligible in comparison with the larger effects being studied. (See reference 1.)

The test results are presented in table I. In order to make the table more concise, the mixture-temperature readings for the three engine speeds and the two spark settings have been averaged. The maximum deviation of any reading from the average was 9°.

With most of the fuels, the maximum permissible compression ratio increased with increasing engine speed except at the highest mixture temperature (300° F), at which there was a slight decrease. The fuel containing 79 percent S-1, however, when tested at a constant spark-advance angle of 30°, and the N-87 fuel at the optimum spark-advance angle had increasing maximum permissible compression ratios with increasing engine speed at all mixture tem-

peratures. The PPF-566 fuel, on the other hand, had a decrease at all temperatures.

In nearly every case the maximum permissible compression ratio decreased markedly as the mixture temperature was increased. The decrease in compression ratio was greater with the optimum than with the constant spark-advance angle. In most cases, the maximum permissible compression ratio was greater for the 30° spark advance than for the optimum spark-advance angle.

Values of the maximum permissible compression ratio greater than 8 for the PPF-580 fuel and 10 for the PPF-566 fuel with optimum spark-advance angle are questionable because of the necessity of extrapolating the curves in figure 4. Comparison with the other data in table I indicates that these questionable compression ratios are probably too high.

ANALYSIS

The results of the performance tests were analyzed by the method presented in reference 1, in which the following equations are given for a density factor that is proportional to the maximum gas density at the end of normal combustion and for the maximum gas temperature at that time:

$$K\rho_3 = \frac{RP_1}{T_1}\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}} \tag{1a}$$

$$T_3 = T_1 R^{\gamma-1}\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{2a}$$

in which

ρ_3 maximum gas density at end of normal combustion.

T_3 maximum absolute gas temperature at end of normal combustion.

R compression ratio.

P_1 absolute inlet-air pressure.

T_1 absolute inlet-air temperature.

H heat content per pound of mixture.

c_v specific heat of mixture at constant volume.

γ adiabatic coefficient.

K constant.

In equation (1a), RP_1/T_1 represents the gas density at the end of the compression stroke and the expression $\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}}$ represents the further compression of the gas in the end zone during the combustion period. Similarly, in equation (2a), $T_1 R^{\gamma-1}$ represents the compression temperature and the expression $\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}}$ represents the temperature increase in the end gas caused by the compression in this zone during the combustion. Subscripts 1 and 3 refer to definite stages in the preparation and the burning of the fuel charge, 1 being the beginning of the compression stroke and 3 being the completion of combustion.

If now the values of R, P_1, and T_1 used in the equations are those causing incipient knock, the values of $K\rho_3$ and T_3 will refer to the density and the temperature of the gases in the knocking zone just before incipient knock occurs. The following analysis consists in the computation and the study of these two factors.

No account was taken in reference 1 of changes in the temperature and the pressure of the air during its passage through the carburetor and the intake passages and in the cylinder during the intake stroke. Many changes may take place. The pressure may be increased by ramming action or decreased by throttling at the valves. The temperature may be increased by turbulence and will be decreased by

vaporization of the fuel. Heat exchanges between the mixture and the combustion-chamber walls during the intake stroke are also important. In this analysis, some of these changes will be considered.

Neither the pressure nor the temperature of the air at the beginning of the compression stroke can be conveniently determined in routine engine tests, but the weight of air consumed per cycle can be measured by a suitable flowmeter, such as a calibrated thin-plate orifice. Unfortunately, such data were not obtained at the time each test was made. As the best substitute available for such data, the results of some air-consumption tests made at the conclusion of the test program will be used.

The engine was operated at the same fuel-air ratio, speeds, and mixture temperatures as for the maximum-compression-ratio tests and the air consumption per cycle was measured with a gasometer and an electrically operated engine revolution counter. The results are presented in figure 5 in the form of density correction factors F, which are simply the ratios of the volume of the air at atmospheric density actually consumed per cycle to the engine displacement. The presence of the large air heater and the long intake pipe apparently resulted in a ramming action at an engine speed of 2,000 rpm. The curves have been extrapolated from a mixture temperature of 100° F to 50° F. Compression ratio 6 was the only compression ratio used. Other tests made on this engine at a mixture temperature of 50° F have indicated that increasing the compression ratio from 6 to 11 results in a decrease in the density correction factor of about 0.030 at 1,500 rpm, 0.015 at 2,000 rpm, and practically 0 at 2,500 rpm. No corrections for the effects of compression ratio on the density correction factor, however, were attempted.

The gas density at the beginning of the compression stroke can now be estimated by multiplying the density of the air entering the heater by the proper density correction factor F; equation (1a) then becomes

$$K\rho_3 = \frac{RP_o}{T_o} F \left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}} \qquad (1b)$$

in which the subscript o refers to the state of the air at atmospheric conditions.

No further changes in the equations have been made but mixture temperatures rather than air temperatures were used for T_1.

The density correction factors eliminate the effects of changes in the engine speed and the mixture temperature on the mixture density at the beginning of the compression stroke and thus reveal the true effects of engine speed and mixture temperature on the knocking tendencies of the fuels.

Some of the data presented in reference 1 were plotted as RP_1/T_1 against T_1. Justification for the use of these simplified forms of equations (1a) and (2a) was found in the fact that the results of tests made over a wide range of inlet-air pressures, temperatures, and compression ratios could be represented as a single curve for any one fuel. The fact that the present tests were conducted at constant inlet-air pressure made it impossible to determine whether the simplified coordinates could be used in this report. Some data from supercharging tests on a C.F.R. engine by Boerlage and given in table VI of reference 1 indicate that the simpler forms should not be used for test results from a C.F.R. engine.

Values of $K\rho_3$ and T_3 were therefore computed from equations (1b) and (2a) for each of the test conditions by substituting in the equations the values of R, P_0, T_0, and T_1 from the test data, the values of the density correction factor from figure 5, and the following assumed values for the other factors: 1,160 Btu per pound of mixture for H; 0.25 Btu per pound per degree Fahrenheit for c_v; and 1.29 for γ. Pressure was expressed in inches of mercury and temperature in degrees Fahrenheit, both absolute.

The values of the maximum permissible density factor $K\rho_3$ were plotted against the end-gas temperature T_3. The results of the tests with the six 100-octane fuels are shown in figure 6 for the optimum spark-advance angle and, in figure 7, for the spark-advance angle of 30°. (The supply of the toluene blend was exhausted before tests could be completed at 1,500 and 2,500 rpm with optimum spark-advance angle.) Although all six fuels have the same octane rating as determined by the Army method, marked differences in the fuels are shown from the severity of the operating conditions at which incipient knock occurred. The toluene blend, which withstood the most se-

vere conditions, was best; the isopropyl ether blend was next; and the four fuels containing S-1, M-1, and tetraethyl lead were lowest and fairly well grouped.

The maximum permissible density factor decreased rapidly with increasing end-gas temperature for all the fuels. The rate of change was greatest with the toluene blend, followed by the isopropyl ether blend and the S-1 reference fuel. The slope of the curves for the three blends of S-1, M-1, and tetraethyl lead were about the same and slightly less than for the S-1 fuel alone.

The effect of engine speed on the maximum permissible density factor is more clearly shown in figures 8 and 9, which are cross plots of the curves in figures 6 and 7 at three values of the end-gas temperature. The cross plots show a slight increase in the maximum permissible density factor with increasing engine speed for most of the fuels at the lowest value of the end-gas temperature. As the end-gas temperature increases, the slopes of the curves decrease and even become negative in some cases.

Changes in the end-gas temperature are primarily a result of changes in the mixture temperature; the three groups of curves in figure 8 and 9 may therefore be considered to represent low, medium, and high mixture temperatures. The fact that the slopes of the curves change with changes in the end-gas (or mixture) temperature suggests that the effect of engine speed on the maximum permissible density factor may be a result of changes in the amount and the direction of heat transfer between the engine and the mixture during the intake and compression strokes rather than a result of any effect of time on the knock itself. At low mixture temperatures, for example, the mixture will absorb heat from the engine and the amount absorbed will decrease as the engine speed increases. The compression ratio required to produce incipient knock will therefore increase and the computed value of the maximum permissible density factor will be greater.

The computed values of $K\rho_3$ plotted against T_3 for the two 87-octane fuels are shown in figure 10. Tests were made only at the optimum spark-advance angle for these fuels. It is especially significant that the maximum permissible density factors for the two fuels are nearly equal at the highest values of the end-gas temperature because the data for these points were obtained at a mixture temperature of about 300° F, the temperature used in the

rating method which established them as 87-octane fuels. Figure 10 shows that these two fuels have equal antiknock properties only at a mixture temperature of about 300° F. At lower mixture temperatures, the X-87 fuel will have a higher antiknock rating at all speeds and, at higher mixture temperatures, the N-87 fuel will probably have the higher antiknock rating.

CONCLUSIONS

1. There were indications that the commonly observed effects of engine speed on the knocking characteristics of fuels are due more to changes in the temperature and the density of the mixture during the intake stroke than to any effect of time on knock itself.

2. For all the fuels tested, increasing the mixture temperature resulted in a marked decrease in the compression ratio required to produce incipient knock. The rate of change, however, was much greater with some of the fuels than it was with others.

3. The test results emphasize the desirability of determining the antiknock values of fuels over a wide range of engine and intake-air conditions rather than at a single set of conditions.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 2, 1940.

REFERENCE

1. Rothrock, A. M., and Biermann, Arnold E.: The Knocking Characteristics of Fuels in Relation to Maximum Permissible Performance of Aircraft Engines. T.R. No. 655, N.A.C.A., 1939.

TABLE I

EFFECTS OF ENGINE SPEED AND MIXTURE TEMPERATURE ON THE MAXIMUM PERMISSIBLE COMPRESSION RATIO

Fuel	Average mixture temperature	Compression ratio for incipient knock					
		With optimum spark advance			With constant spark advance (30°)		
	(°F)	1500 rpm	2000 rpm	2500 rpm	1500 rpm	2000 rpm	2500 rpm
100-percent S-1	48	—	—	—	8.90	9.30	10.10
	103	8.30	8.65	9.20	9.15	9.45	9.90
	152	8.02	8.20	8.35	9.15	9.50	9.80
	200	7.70	7.67	7.52	8.70	9.10	9.20
	250	7.35	7.12	6.82	8.70	8.70	8.70
	303	6.87	6.62	6.22	8.10	8.00	8.00
90-percent S-1 +10-percent M-1 +1.0 ml tetraethyl lead per gallon	50	—	—	—	7.90	8.20	8.90
	104	7.71	8.12	8.75	8.05	8.30	8.60
	151	7.54	8.28	8.75	8.00	8.45	8.80
	199	7.42	8.01	8.08	7.90	8.20	8.45
	253	7.24	7.61	7.57	7.45	7.65	7.65
	300	7.04	7.27	6.62	7.45	7.65	7.30
85-percent S-1 +15-percent M-1 +2.0 ml tetraethyl lead per gallon	53	—	—	—	8.50	8.90	9.80
	103	7.82	8.14	8.60	8.50	8.91	9.50
	152	7.81	8.16	8.53	8.50	8.80	9.30
	205	7.63	7.87	8.07	8.45	8.80	8.90
	252	7.45	7.82	7.60	8.10	8.70	8.50
	297	7.14	6.97	6.64	8.05	8.60	8.05
79-percent S-1 +21-percent M-1 +4.0 ml tetraethyl lead per gallon	64	—	—	—	8.75	8.75	9.95
	102	8.41	8.50	9.33	8.70	8.90	9.55
	151	8.22	8.54	9.06	8.40	9.10	9.80
	199	7.68	8.38	8.18	8.25	8.70	9.30
	250	7.83	8.16	7.80	8.05	8.70	8.80
	302	7.28	7.13	6.99	8.00	8.60	8.25
PPF-580 (isopropyl ether blend)	43	10.40	10.00	11.25	10.10	10.40	11.00
	108	10.80	9.80	10.40	10.30	10.10	10.40
	153	10.20	9.30	9.80	10.00	9.90	9.80
	198	9.50	8.50	9.00	9.30	9.35	9.20
	257	8.60	8.10	7.55	8.60	8.90	8.55
	305	8.10	7.00	7.00	8.30	8.00	8.00
PPF-566 (toluene blend)	52	—	12.15	—	13.00	12.15	11.65
	101	—	11.05	—	11.80	11.30	11.25
	151	—	10.80	—	11.35	10.95	10.40
	200	—	9.65	—	9.90	10.00	10.00
	245	—	8.70	—	9.70	9.20	8.90
	300	—	7.50	—	8.50	7.90	8.00
N-87	101	6.25	6.50	7.02	—	—	—
	150	6.50	6.40	6.72	—	—	—
	198	5.85	6.10	6.25	—	—	—
	250	5.85	5.70	5.90	—	—	—
	302	5.40	5.65	5.75	—	—	—
X-87	101	7.55	7.87	8.65	—	—	—
	149	7.05	7.35	7.95	—	—	—
	200	7.00	6.85	6.85	—	—	—
	250	5.97	6.20	6.18	—	—	—
	299	5.80	5.90	5.70	—	—	—

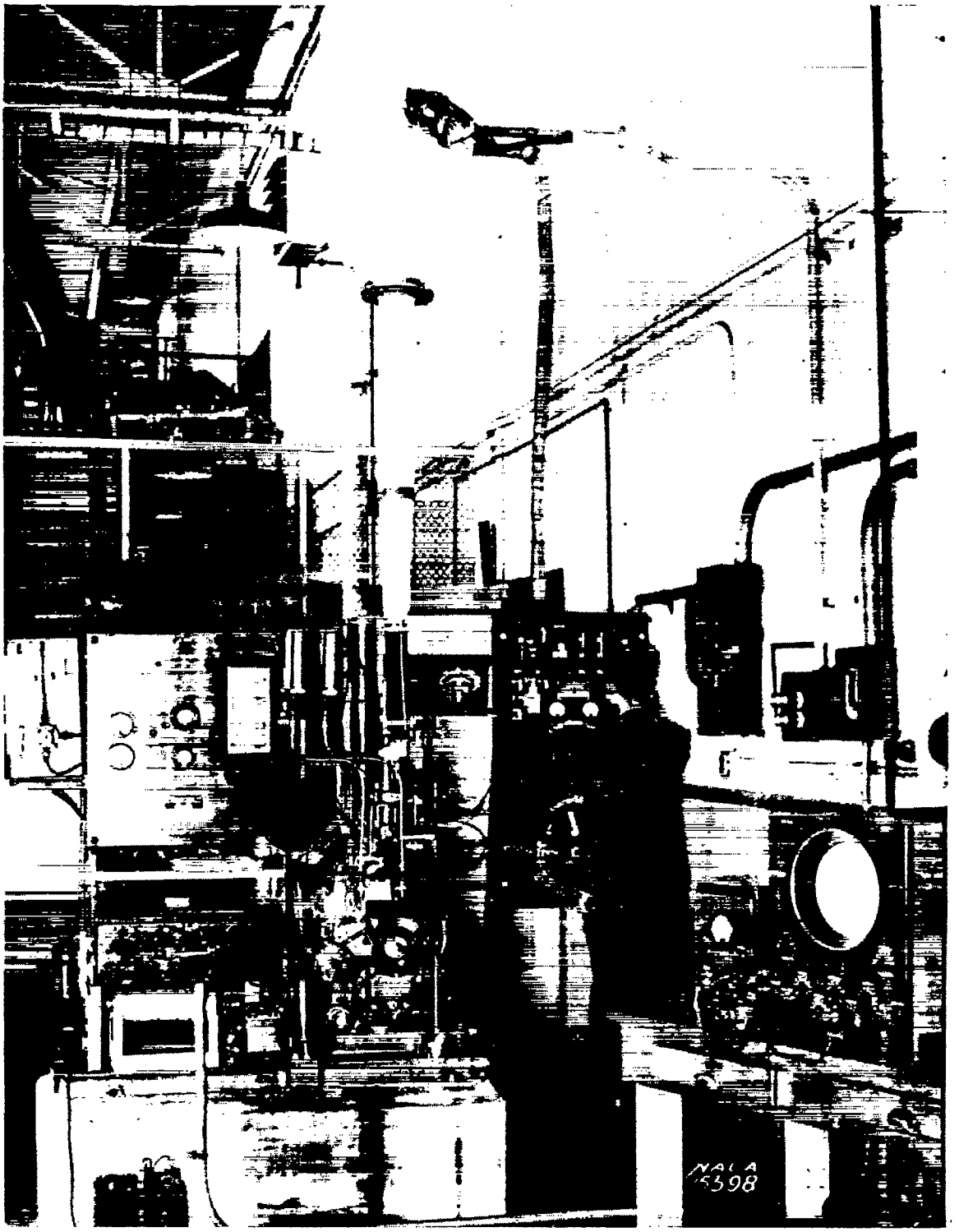

Figure 1.- General view of test equipment.

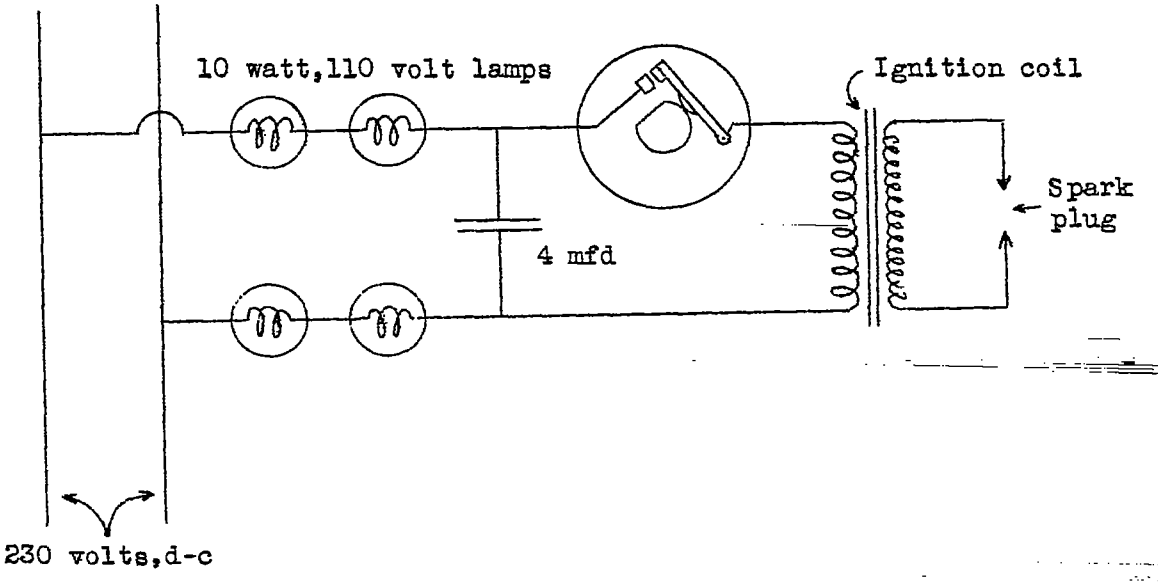

Figure 2.- Diagram of spark-ignition circuit.

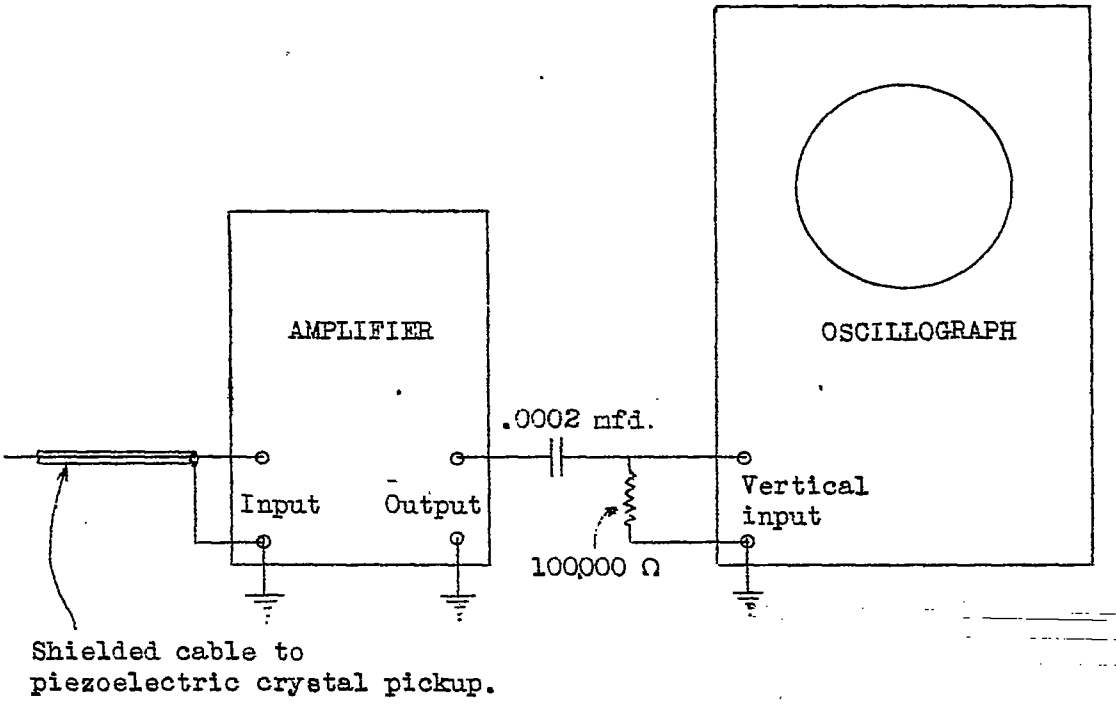

Figure 3.- Installation of cathode-ray oscillograph for indication of incipient knock.

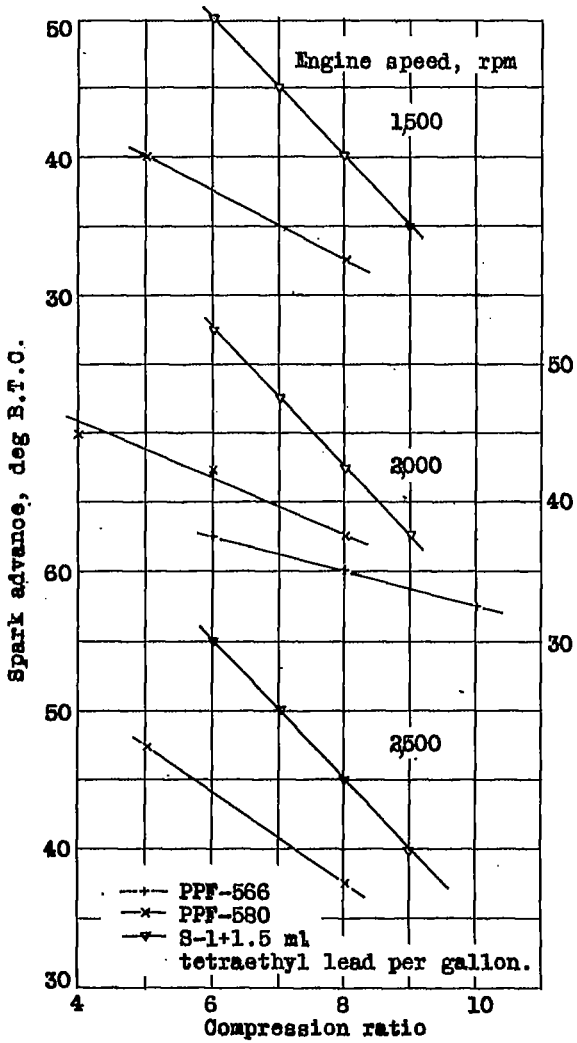

Figure 4.- Effects of engine speed and compression ratio on the spark advance for maximum power at atmospheric inlet pressure.

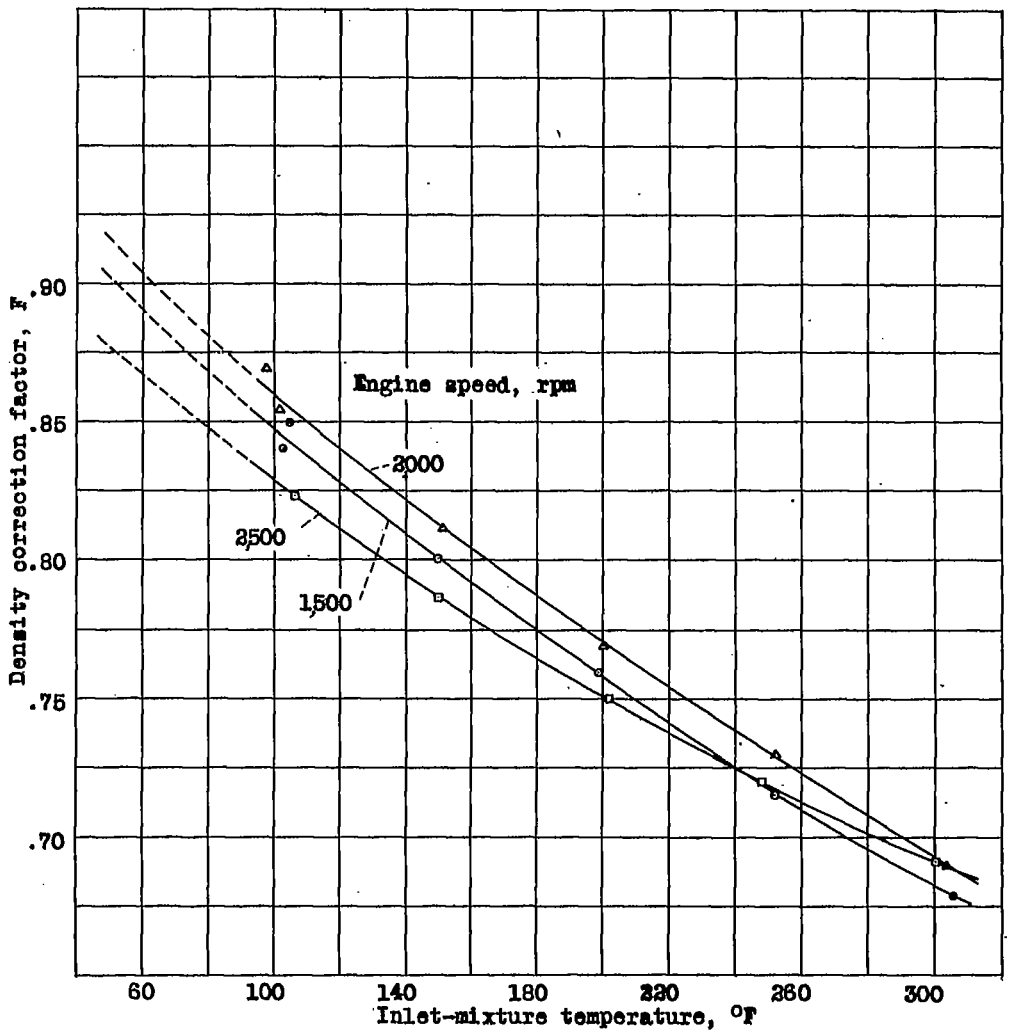

Figure 5.- Effect of engine speed and mixture temperature on the density correction factor.
Fuel-air ratio, 0.077; compression ratio, 6.

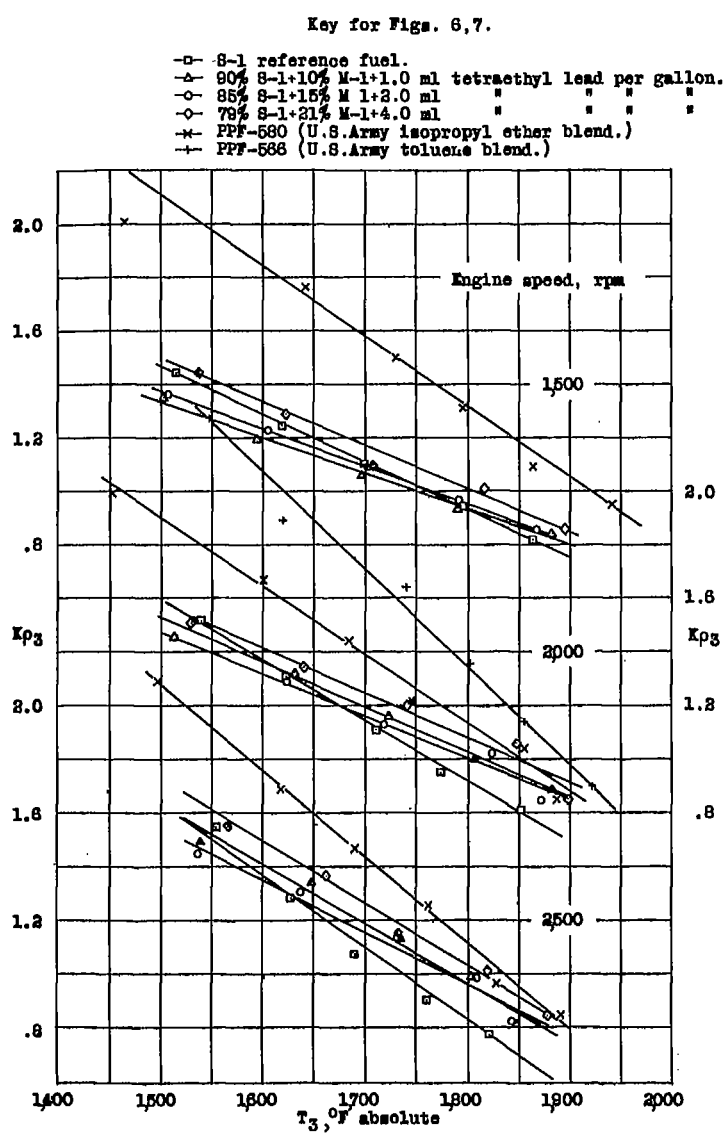

Figure 6.- Effect of computed end-gas temperature on the maximum permissible density factor. Optimum spark-advance angle.

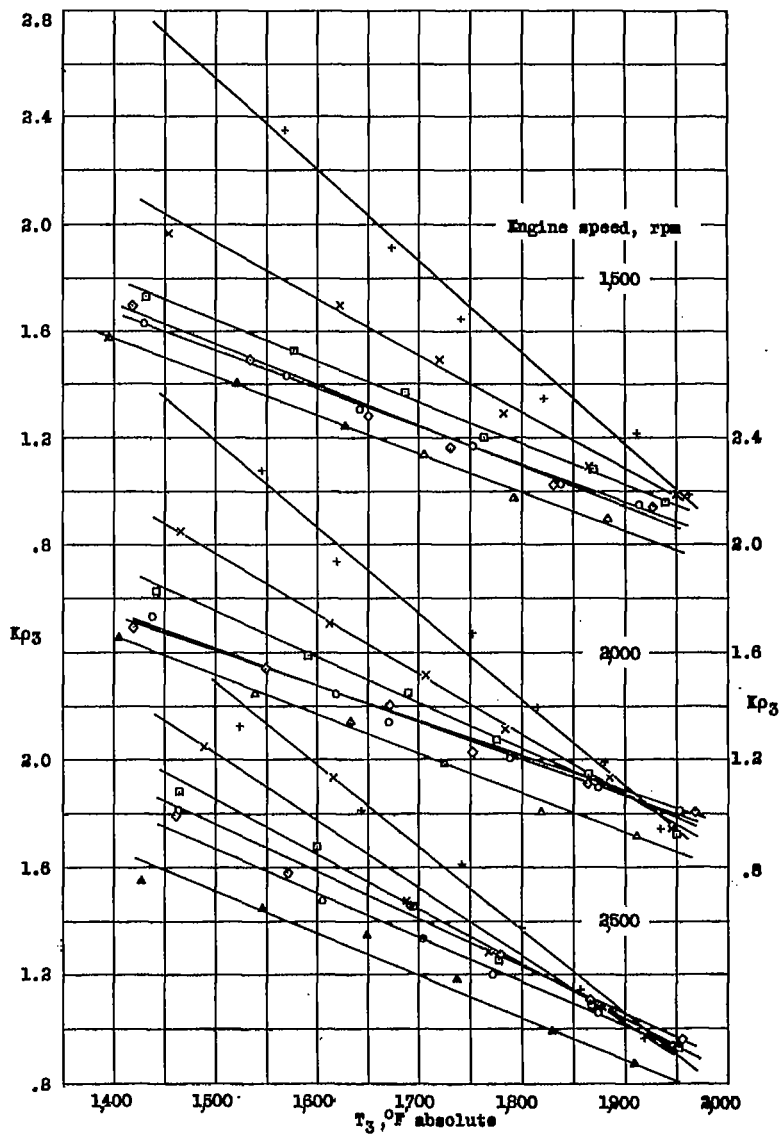

Figure 7.- Effect of computed end-gas temperature on the maximum permissible density factor. Spark-advance angle, 30°.

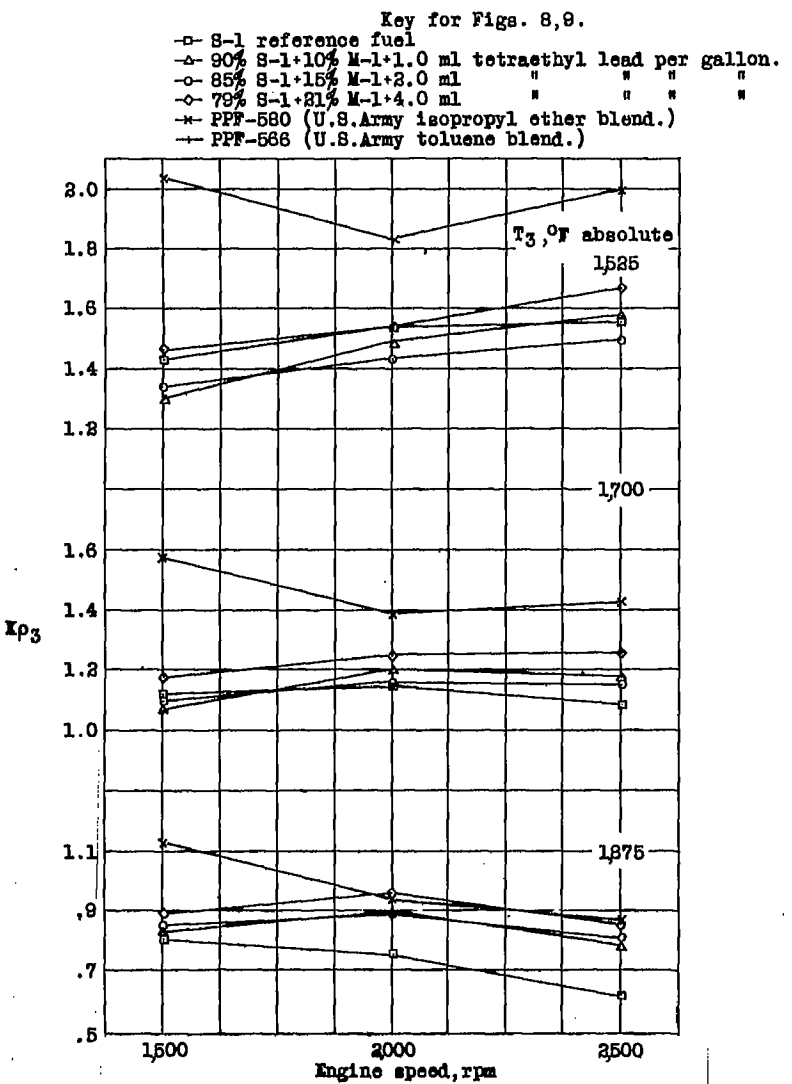

Figure 8.- Effect of engine speed on the maximum permissible density factor. Optimum spark-advance angle.

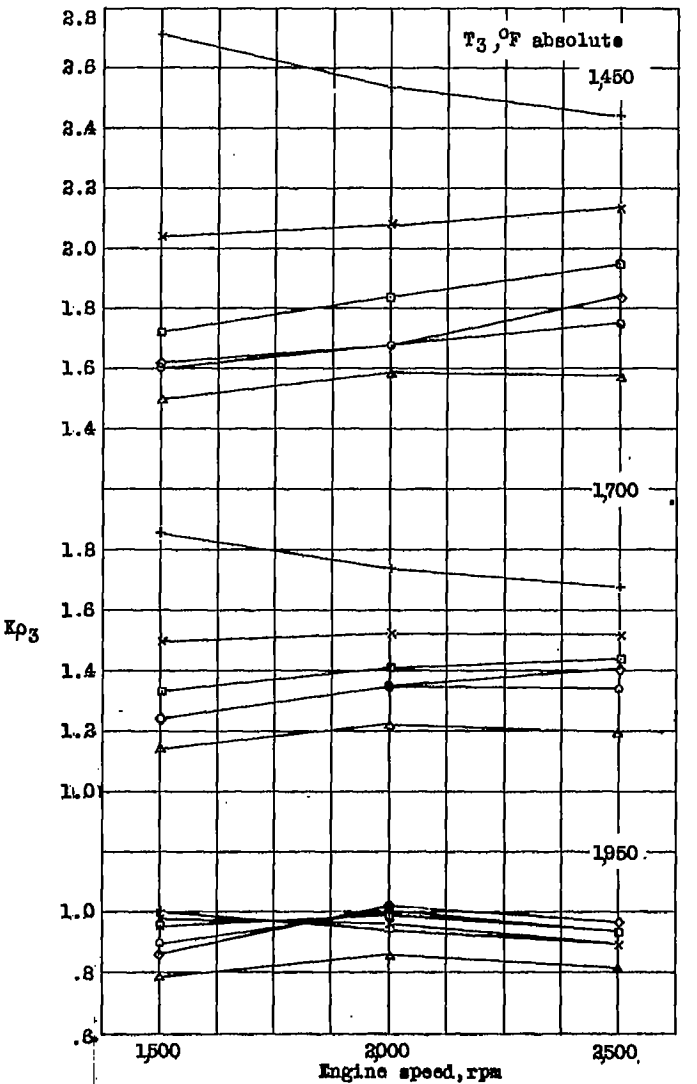

Figure 9.- Effect of engine speed on the maximum permissible density factor. Spark-advance angle, 30°.

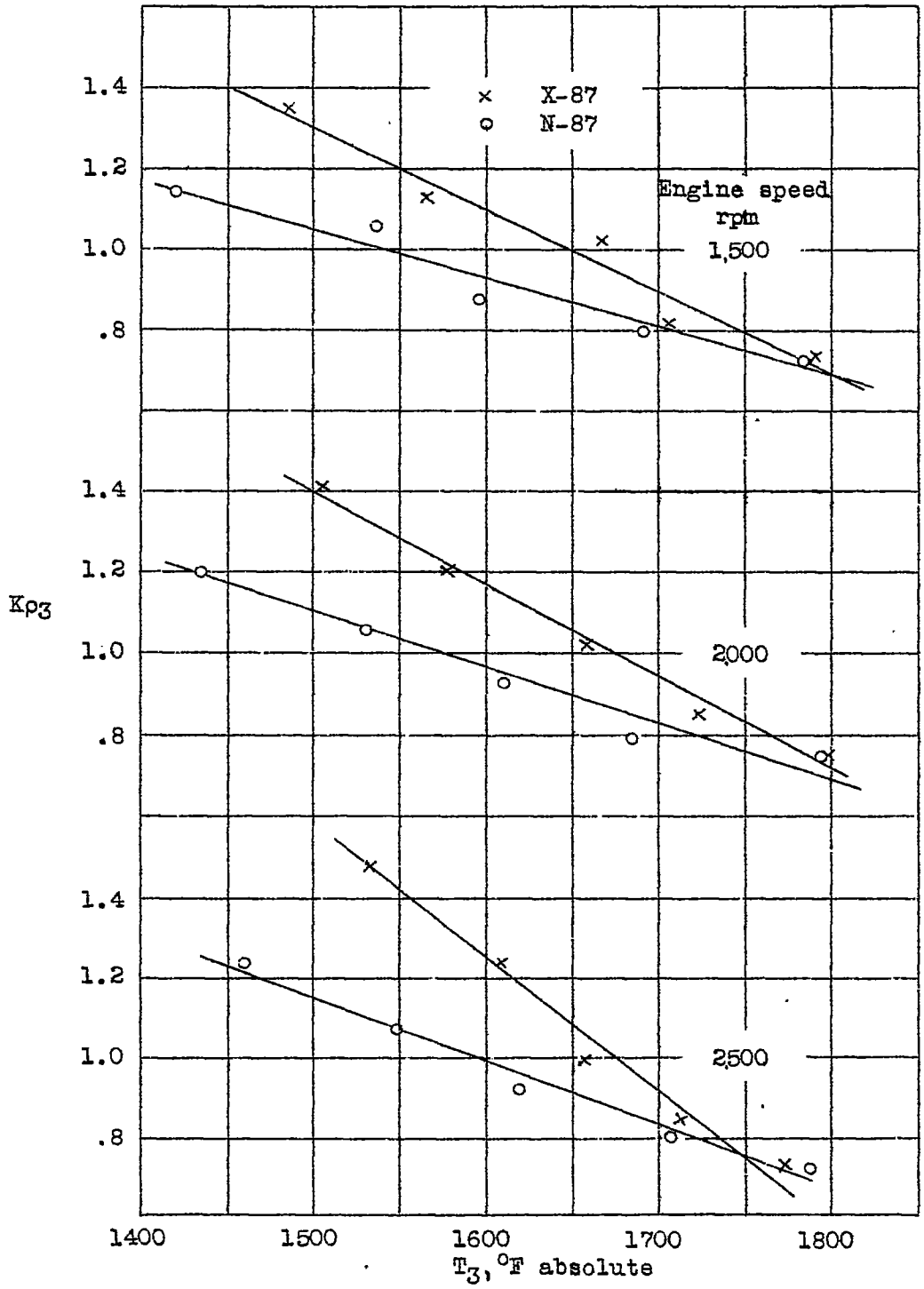

Figure 10.- Effect of computed end-gas temperature on the maximum permissible density factor. Optimum spark-advance angle.