TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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CORRELATION OF KNOCKING CHARACTERISTICS OF FUELS IN AN ENGINE HAVING A HEMISPHERICAL COMBUSTION CHAMBER

By A. M. Rothrock and Arnold E. Biermann
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SUMMARY

Data are presented to show the effects of inlet-air pressure, inlet-air temperature, and compression ratio on the maximum permissible performance obtained with a cylinder having a hemispherical-dome combustion chamber. The five aircraft-engine fuels used have octane numbers varying from 90 to 100 plus 2 ml of tetraethyl lead per gallon. The data were obtained on a $5\frac{1}{4}$-inch by $4\frac{3}{4}$-inch liquid-cooled engine operating at 2,500 rpm. The compression ratio was varied from 6.0 to 8.9. The inlet-air temperature was varied from 110° to 310° F. For each set of conditions, the inlet-air pressure was increased until audible knock occurred and then reduced 2 inches of mercury before data were recorded. The results for each fuel can be correlated by plotting the calculated end-gas density factor against the calculated end-gas temperature. Measurements of spark-plug electrode temperatures showed that, with two spark plugs, cutting off the switch to one spark plug lowered the electrode temperature of that plug from a value of 1,365° F to a value of 957° F. The results indicate that the surface temperatures of combustion-chamber areas which become new sources of ignition markedly increase after ignition commences.

INTRODUCTION

The N.A.C.A. has been conducting an investigation on the knocking characteristics of high-octane fuels. Results obtained from an engine with a four-valve flat-disk combustion chamber, from an engine with a four-valve pent-roof combustion chamber, and from a C.F.R. engine have been reported in references 1, 2, and 3, respectively.

Previous analyses of the problem of engine knock have shown that the most important independent variables in any one engine are the ones that control the end-gas density and temperature and the mixture ratio. The results from the previous tests showed that a certain amount of correlation exists between the knocking-characteristic curves obtained for several fuels used in different engines but that certain differences are caused by the variation in engine design.

The present report gives the data thus far obtained with a cylinder having a hemispherical-dome combustion chamber of aluminum alloy. Other cylinders tested at this laboratory for knocking characteristics have had cast-iron combustion chambers. The knocking characteristics were determined for five fuels over a range of compression ratios and inlet-air densities.

In the tests conducted at the N.A.C.A. laboratory with high antiknock fuels at high output, afterfiring from hot spark plugs has presented a serious problem except when the plugs have been water-cooled. Some information has been included in this report showing the effect of water cooling on the temperature of the spark-plug center electrode and also the difference in electrode temperatures of firing and nonfiring spark plugs.

APPARATUS AND METHODS

The aircraft-engine cylinder used during these tests had an aluminum-alloy head and jacket, with the head screwed and shrunk onto a steel barrel. This cylinder has a $5\frac{1}{4}$-inch bore and a $4\frac{3}{4}$-inch stroke, giving a displacement of 102.8 cubic inches. The combustion chamber is of the hemispherical type having two poppet valves operated through rockers by an overhead camshaft. The inlet-valve stem was sodium-cooled, and both the stem and the head of the exhaust valve were sodium-cooled. The two spark plugs in this cylinder are diametrically opposite and at an angle of approximately 45° with respect to a line between the valves. The compression ratio was changed by varying the spacer thickness under the cylinder flange.

Except where otherwise noted, the following quantities were held constant during these tests:

Valve timing -	Inlet opens	30° B.T.C.
	Inlet closes	65° A.B.C.
	Exhaust opens	66° B.B.C.
	Exhaust closes	32° A.T.C.
Spark advance (retarded for 1-percent drop in power) -		29°.
Engine speed - - - - - - - - -		2,500 rpm.
Engine cooling - - - - - - - -		ethylene glycol, outlet temperature, 250° F.
Fuel-air ratio (for maximum knock) - - - - - - - - - -		approximately 0.076.
Spark plugs - - - - - - - - - -		BG 344-S.

The fuel-air ratio was calculated from measurements of the weight of fuel and of the volume of air entering the engine. Thermocouples were used to measure the exhaust temperature, the wall temperature just above the piston travel on the inlet side, the flange temperature on the inlet side, the tip temperature of one spark-plug center electrode, and the mixture temperature. The mixture thermocouple was shielded. The calculated thermal conductivity of the spark-plug center electrode was impaired approximately 10 percent by installing the thermocouple in the electrode tip. For the tests in which the spark-plug electrode temperature was measured, the spark plug was located at the front of the engine near the exhaust valve. The outer shells of the spark plugs were water-cooled during all of the tests except the ones made to determine electrode temperatures. Peak cylinder pressures were obtained with the N.A.C.A. balanced-disk indicator. The higher values of the peak pressures correspond to the last intermittent flashes of the neon tube used with the maximum-pressure indicator; the lower values correspond to an almost steady flash of the neon tube.

The inlet air was electrically heated. Because of the excessive time lag of electric heaters, it has been found difficult to change the inlet-air temperature rapidly and to hold it at the desired value. In the present set-up, these difficulties have been overcome by means of a three-way valve; one intake port is connected to a source of air at 500° F (thermostatically controlled), and the other is arranged for inducting air at room temperature. The air temperature can be rapidly changed by adjusting this valve to admit different proportions of cold and hot air. The two air streams were mixed in a large tank before entering the engine.

The procedure used in determining the knocking limitation of a fuel was as follows: With a constant inlet-air temperature and with the maximum-knock fuel mixture, the inlet-air pressure was raised until audible knock occurred. The inlet pressure was then arbitrarily reduced 2 inches of mercury before data were taken. This procedure prevented damage to the engine from running for prolonged periods under knocking conditions and also avoided the necessity for taking data while the engine was operating under the unstable conditions that accompany knock.

The fuels tested were made up from C.F.R. S-1 and C.F.R. M-2 reference fuels with additions of tetraethyl lead ($PbEt_4$); the following five fuels were tested:

Fuel	S-1 (percent)	M-2 (percent)	Tetraethyl lead, ml per gallon
1	90	10	0
2	95	5	0
3	100	0	0
4	100	0	1.0
5	100	0	2.0

In the table and the curves, the fuels are referred to by the percentage of S-1 and the tetraethyl-lead content. Tests were conducted at compression ratios of 6.0, 7.5, and 8.9 and at five inlet-air temperatures covering the range from 110° to 310° F.

The engine-performance data were computed by the method outlined in reference 1.

RESULTS AND DISCUSSION

Knocking Characteristics

The principal test results, giving the engine performance for inlet pressures of 2 inches of mercury below the audible-knock inlet pressure, are presented in table I. As shown by the data, some of the test conditions were repeated at another time with somewhat different results; a considerable difference occurred in the specific fuel consumptions and the cylinder temperatures. Although no explanation has been found, differences in piston-ring condition or the presence of afterfiring probably accounts for some of these discrepancies.

In figure 1, the power developed with the several fuels (for inlet-air pressure for audible knock less 2 inches of mercury) is presented for the three compression ratios. Curves of the peak cylinder pressures obtained for three inlet-air temperatures and two compression ratios are shown in figure 2. The experimental values (table I) have not been placed on the curves because the points are scattered. The curves as drawn represent the general trend of the data. The pressure values given are the lower readings of the N.A.C.A. balanced-disk maximum-pressure indicator.

It was pointed out in reference 1 that whether knock takes place in an internal-combustion engine depends on the density and the temperature in the end gas. Reference 2 shows that the end-gas density approaches a maximum value expressed by

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

in which

ρ_3 gas density in knocking zone immediately preceding knock.

P_1 inlet-air pressure.

T_1 inlet-air temperature.

γ adiabatic coefficient.

c_v specific heat of mixture at constant volume.

R compression ratio of engine.

H heat content per pound of mixture.

K a constant.

It has also been shown in reference 2 that the end-gas temperature T_3 approaches a maximum value expressed by

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

An analysis of the results presented in reference 2 showed that fairly good correlation of the data from a pent-roof and a flat-disk type of combustion chamber could be obtained by simplifying the density expression to RP_1/T_1 and by using the inlet-air temperature instead of the expression for T_3. An attempt to correlate the data of the present report in a similar manner is shown in figure 3. A fairly wide spread of the data is noticed for the different compression ratios, especially for the 90- and the 95-percent S-1 fuels. In general, the 100-percent S-1 and the S-1 plus tetraethyl lead could not be used at the lowest compression ratio because of the limitations of the apparatus as regards boost.

As shown by figure 4, a somewhat better correlation of the present data is obtained by substituting $T_1 R^{\gamma-1}$ for the inlet-air temperature. The spread of the points, however, does not justify the use of these factors.

A still further improvement in the correlation of the present data is obtained by using the more exact expressions for the density factor, $K\rho_3$, and the estimated end-gas temperature, T_3. These results are plotted in figure 5. Although some scatter of the points is apparent, this scatter is, in general, less than the discrepancy between the sets of data at the same compression ratios.

In reference 2 it was noted that the coordinate RP_1/T_1 could not be used for the C.F.R. engine, and the difference between the coordinates used to correlate the data for the C.F.R. engine and for the larger engines reported in reference 1 was attributed to the difference in displacement of the engines. The present results, however, showed that, for an engine similar in size to those discussed in reference 1, the best correlation was obtained when the calculated values of $K\rho_3$ and T_3 were used as the coordinates for the knock-rating curves of the different fuels. The difference in the criteria giving the best correlation of the knock data for the engines discussed in reference 2 and for the present engine must therefore be concluded to be a result not of engine size but of the interrelation of several engine factors. As long as there are differences in engine design or until the end-gas temperature and density can be directly measured, these differences in correlating factors will probably continue and must be attributed to the engine rather than to the fuel.

Spark-Plug Electrode Temperatures

Some temperature measurements of the tip of the central electrode of one spark plug are presented in figure 6. The curves in this figure were obtained by progressively increasing the inlet pressure until knock occurred. In one instance, cutting the front-plug ignition switch caused a reduction in temperature from 1,365° to 957° F. The fact that the nonfiring spark plug was probably in the end-gas zone during knock raised its temperature very little above the normal course of the curve. The heating effect of the spark itself caused a negligible rise in electrode temperature, as determined by opening and closing the ignition switch while motoring the engine.

Water-cooling the nonfiring spark plug lowered the electrode temperature from 970° to 870° F. A slightly greater drop in the temperature of the firing spark plug would probably result from water cooling.

The information presented in figure 6 also shows what may result when overheated combustion-chamber surfaces become auxiliary sources of ignition. Once ignition starts from an overheated surface, the temperature of the surface may rise somewhat, as shown in figure 6, depending upon the location of the surface with respect to a spark plug. The reasons for this rise in the temperature of the region where ignition starts as given by Lewis and von Elbe in reference 4 may be condensed as follows: At the source of ignition, the burning gas expands at a practically constant pressure, which is the compression pressure. It is subsequently compressed to nearly its original volume by the combustion of the rest of the gas in the chamber. The work of compression exceeds the work of expansion because the compression of the gas at the source of ignition takes place at a steadily increasing pressure; whereas, the expansion took place at the lower initial pressure. As a result, the gas remote from the source of ignition loses some of its energy but the gas at the source of ignition gains energy in excess of the chemical energy released within it. The result is a temperature gradient, rising toward the source of ignition, the temperature difference of which amounts to several hundred degrees.

The data in figure 6 indicate why, under certain circumstances, preignition can lead to very rapid engine failure. Assume that, because of unequal cooling throughout the cylinder, the hottest spot in the combustion-chamber surface is in the end-gas zone. Once preignition starts in this zone, the zone is no longer the end-gas zone but becomes the first part of the charge to burn. This change of the gas surrounding the hot spot from the end-gas zone to the first part of the charge to burn can cause an increase in the surface temperature at the hot spot of as much as 400° F, as shown by figure 6. This increase in the temperature of the hot spot will advance the timing of the preignition, which will further increase the hot-spot temperature. This unstable condition will lead to earlier ignition of the charge on each successive cycle and to eventual failure of the engine. The rapidity of the engine failure, once the preignition has started, depends on the rapidity with which the foregoing actions take place.

CONCLUSIONS

The results of the present tests of five fuels in a cylinder having a hemispherical-dome combustion chamber showed that:

1. The data on knock could be correlated by plotting the calculated end-gas density factor, $K\rho_3$, against the calculated end-gas temperature, T_3.

2. The particular factors used to correlate knocking test data depend upon the engine design; until the end-gas temperature and density can be directly determined, there will be differences in the correlating factors.

3. Cutting off the ignition from one of two spark plugs lowered the electrode temperature of that plug from 1,365° to 957° F.

4. Surface temperatures of combustion-chamber areas that become new sources of ignition may increase markedly after ignition commences.

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

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2. 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.

3. Lee, Dana W.: The Effects of Engine Speed and Mixture Temperature on the Knocking Characteristics of Several Fuels. T.N. No. 767, N.A.C.A., 1940.

4. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Univ. Press (Cambridge), 1938, p. 167.

TABLE I

Fuel	Compression ratio	Inlet-air temperature (°F)	Mixture temperature (°F)	Inlet pressure (in. Hg absolute)	imep (lb/sq in.)	Indicated fuel consumption (lb/ihp/hr)	Peak pressure (low)	Peak pressure (high)	Exhaust temperature (°F)	Flange temperature (°F)	Wall temperature (°F)
90 percent S-1	6.0	[a]117	98.0	44.5	225	0.433	825	950	1,331	248	—
		[a]153	117.9	43.7	206	.453	800	1,000	1,311	202	—
		[a]204	164.8	39.7	178	.451	780	900	1,279	222	—
		[a]271	211.6	37.8	155	.462	630	800	1,270	200	—
		[a]297	244.2	36.4	141	.453	580	750	1,264	219	—
		125	95.5	46.4	226	.535	-	-	-	350	385
		173	138.3	44.5	203	.583	-	-	-	309	376
		212	171.5	42.3	180	.588	-	-	-	366	373
		257	210.0	41.4	169	.600	-	-	-	355	363
		302	246.8	38.2	149	.590	-	-	-	336	354
	7.5	118	110.1	34.2	162	.479	-	-	-	233	330
		158	132.6	31.4	141	.485	-	-	-	229	324
		204	184.7	30.4	119	.481	-	-	-	207	317
		250	198.1	29.5	107	.542	-	-	-	221	322
		300	207.8	26.8	94	.461	-	-	-	196	320
	8.9	117	96.7	27.3	123	.430	525	600	1,364	293	316
		157	126.6	26.0	117	.410	525	600	1,321	300	313
		206	161.8	24.2	95	.408	460	590	1,351	300	308
		242	176.0	22.6	78	.440	425	525	1,302	268	304
		279	192.8	21.8	73	.470	425	525	1,302	263	297
		127	98.2	24.9	118	.399	590	775	1,403	285	256
		170	139.0	23.9	105	.434	550	720	1,384	268	238
		212	169.0	22.7	94	.424	430	580	1,372	280	240
		258	208.5	21.1	79	.449	360	540	1,378	277	237
95 percent S-1	6.0	[a]121	91.3	55.6	270	.454	1,060	1,200	1,345	206	267
		[a]146	119.9	53.7	253	.460	1,050	1,250	1,314	229	258
		[a]219	176.0	50.3	217	.475	900	1,100	1,313	204	246
		[a]255	214.9	48.3	192	.492	780	950	1,307	213	240
		[a]296	251.2	45.2	175	.480	760	900	1,287	264	253
		125	95.1	49.2	239	.484	-	-	-	364	376
		173	135.0	47.9	226	.522	-	-	-	319	375
		215	175.0	46.4	202	.514	-	-	-	342	384
		256	207.0	45.2	187	.509	-	-	-	353	380
		297	241.0	39.3	159	.526	-	-	-	344	362
	7.5	116	110.1	36.4	177	.455	-	-	-	234	336
		156	128.3	33.1	149	.450	-	-	-	221	325
		197	162.2	32.3	143	.470	-	-	752	250	329
		249	196.8	30.2	117	.480	-	-	1,168	206	321
		305	216.6	29.3	103	.530	-	-	1,144	183	318
	8.9	113	92.0	28.6	132	.407	600	800	1,380	310	327
		161	129.3	27.8	124	.407	575	725	1,367	301	314
		196	148.5	25.8	105	.420	575	750	1,343	270	314
		243	173.2	24.6	90	.420	525	600	1,358	273	311
		285	198.2	22.3	81	.400	400	600	1,348	281	306
		126	101.5	27.1	133	.481	630	900	1,321	275	256
		171	134.0	27.5	134	.437	-	-	1,349	283	238
		215	171.9	25.3	107	.409	-	-	1,377	266	210
		255	197.4	23.7	94	.482	-	-	1,383	269	214
		300	225.0	21.1	73	.502	-	-	1,365	208	218
S-1	7.5	123	101.4	41.0	206	.453	-	-	1,375	231	356
		161	129.9	39.0	186	.441	-	-	1,297	229	346
		209	167.9	37.1	164	.446	-	-	1,240	245	345
		239	199.5	34.9	145	.453	-	-	1,223	228	333
		292	239.1	33.5	129	.457	-	-	1,217	190	327
	8.9	116	95.0	31.7	167	.368	800	900	1,369	314	327
		164	132.3	30.2	140	.435	775	925	1,384	307	317
		200	159.9	28.4	115	.461	600	800	1,379	292	312
		241	175.7	25.1	96	.458	475	600	1,364	277	309
		290	196.5	24.2	87	.443	425	500	1,355	275	306
		128	98.3	31.6	167	.473	-	-	1,326	301	244
		171	137.8	28.8	141	.466	-	-	1,364	290	244
		216	175.2	27.3	120	.472	-	-	1,359	276	215
		259	203.2	25.1	99	.508	-	-	1,358	274	209
		297	226.0	23.1	86	.494	-	-	1,383	269	222
S-1+1 ml $PbEt_4$	6.0	[a]292	234.1	57.5	243	.481	860	1,100	1,348	247	-
	7.5	[a]119	118.8	49.9	257	.456	-	-	-	-	-
		[a]158	112.9	49.5	233	.441	-	-	1,209	258	385
		[a]220	163.6	46.8	219	.442	-	-	1,180	160	378
		[a]250	195.8	45.9	201	.463	1,150	1,250	1,178	168	376
		[a]313	248.2	42.1	173	.446	900	1,000	1,167	173	365
	8.9	128	100.0	43.0	227	.413	-	1,250	-	288	342
		162	137.6	40.2	200	.409	-	-	-	232	341
		205	173.9	38.5	183	.406	-	-	-	273	339
		238	195.8	36.0	160	.410	850	1,050	-	312	332
		282	229.4	34.6	146	.414	750	1,050	-	303	333
S-1-2 ml $PbEt_4$	7.5	[a]115	82.6	54.3	277	.438	-	-	1,247	253	385
		[a]170	126.0	52.2	246	.445	-	-	1,195	265	397
		[a]199	156.9	51.5	237	.446	-	-	1,209	233	379
		[a]252	206.2	47.6	206	.433	1,200	1,325	1,198	162	370
		[a]291	228.4	46.0	191	.437	1,100	1,300	1,189	175	373
	8.9	122	93.0	46.6	245	.403	1,100	1,200	-	340	348
		163	136.0	42.1	214	.475	-	-	-	291	341
		204	173.2	41.0	198	.466	-	-	-	246	339
		246	200.8	40.1	178	.466	1,000	1,150	-	316	335
		283	229.7	35.7	149	.476	750	1,075	-	312	338

[a]Accompanied by afterfiring.

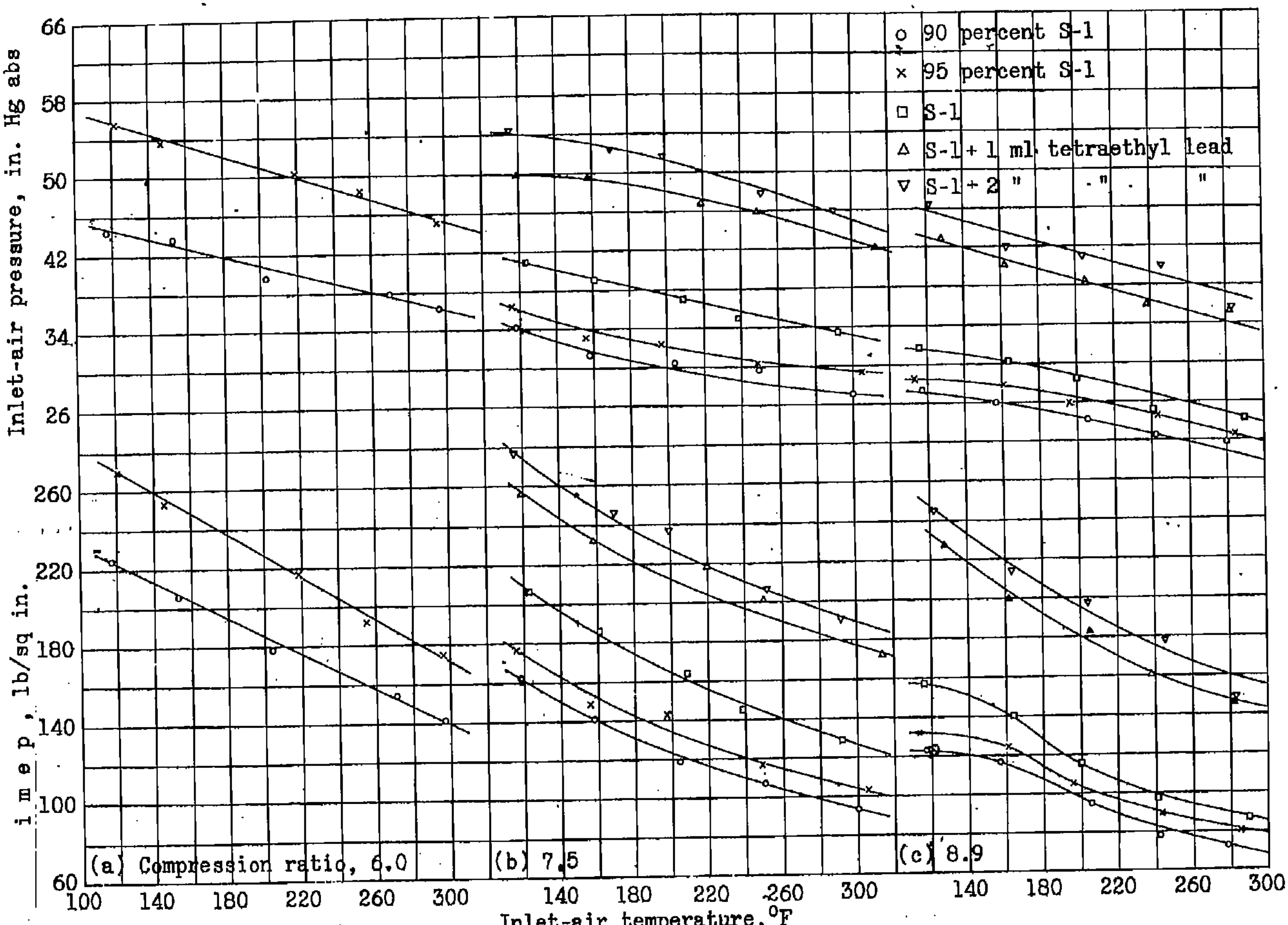


Figure 1 a to c.- Engine performance for audible-knock pressure less 2 inches of mercury.

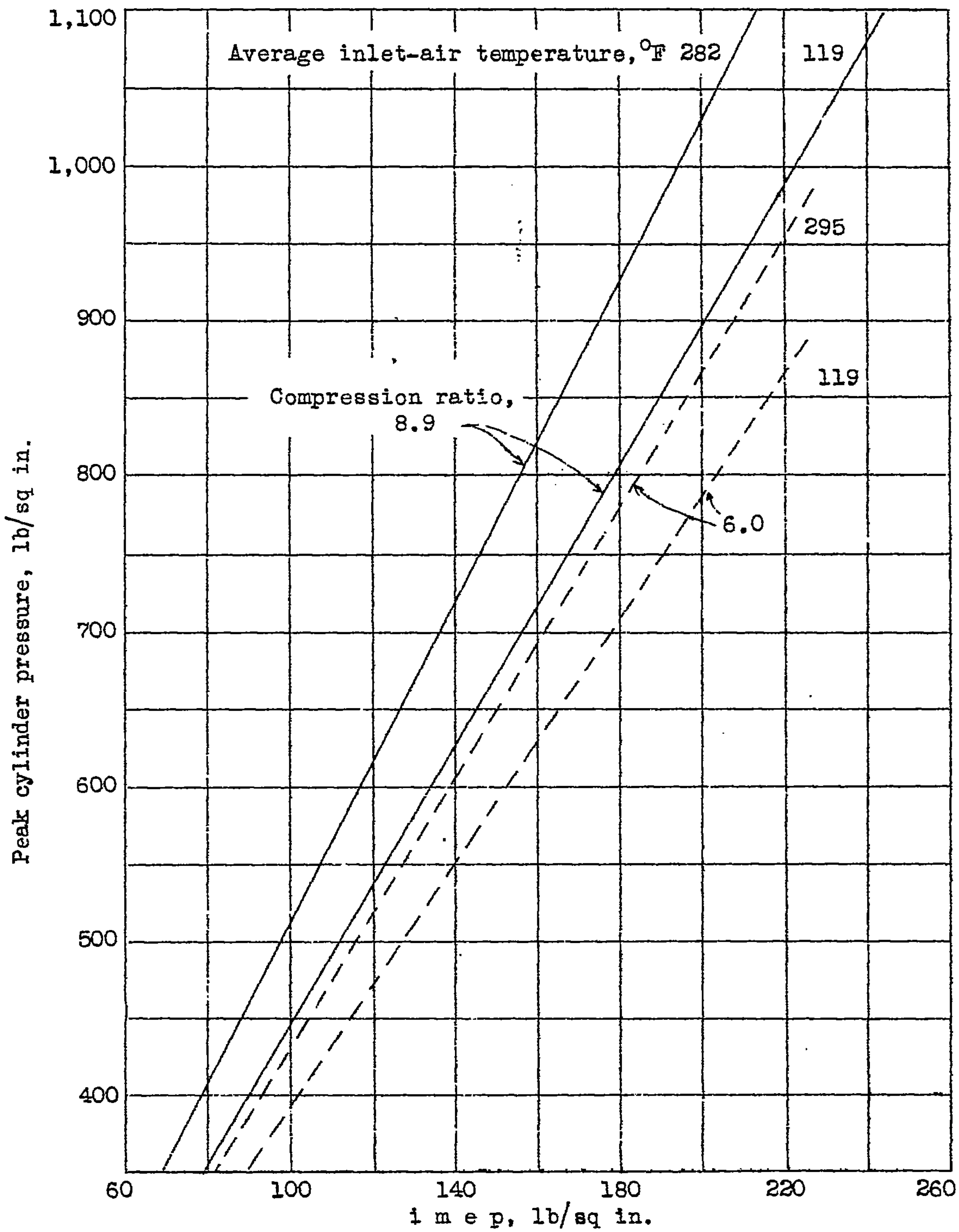
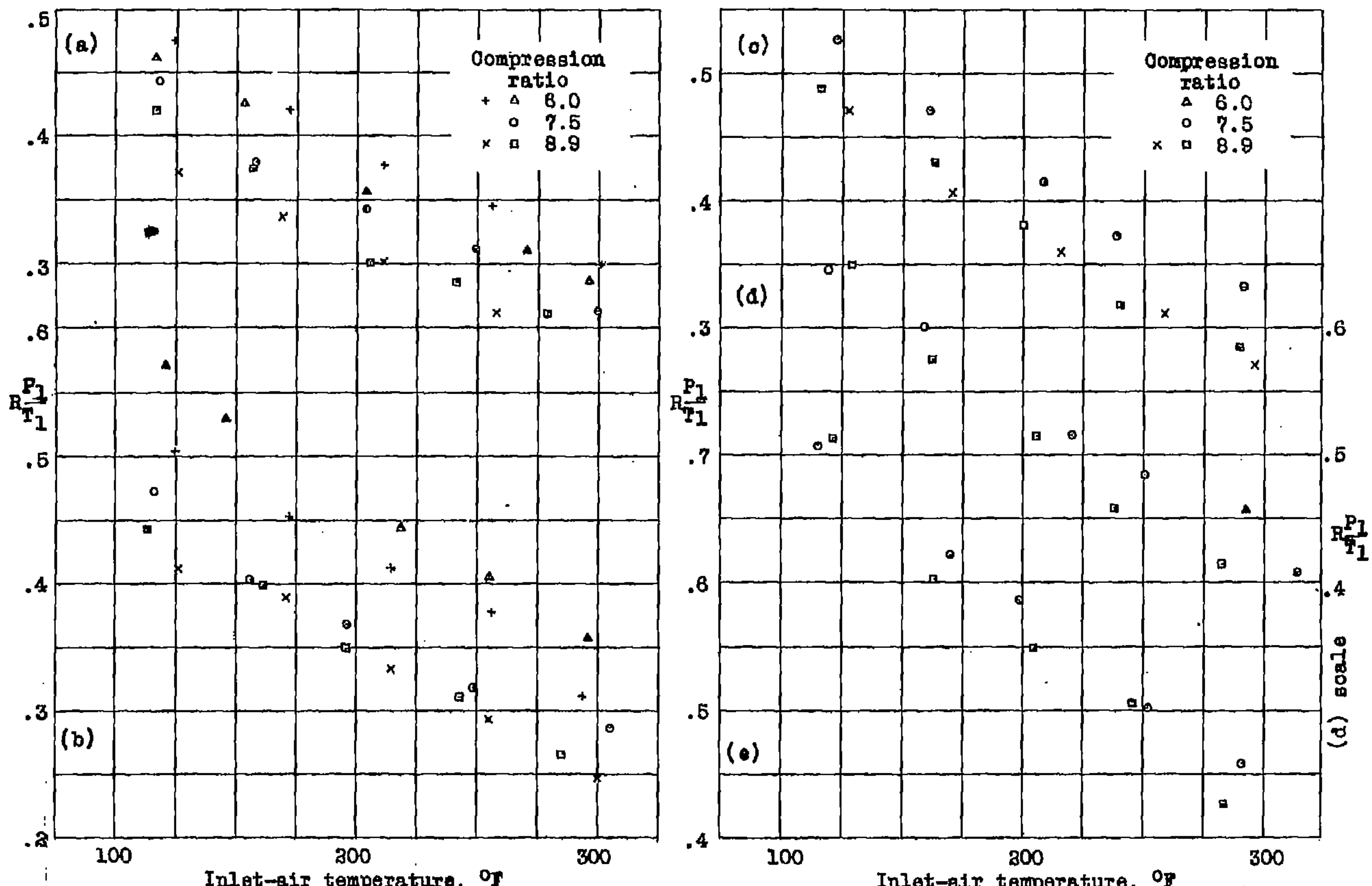
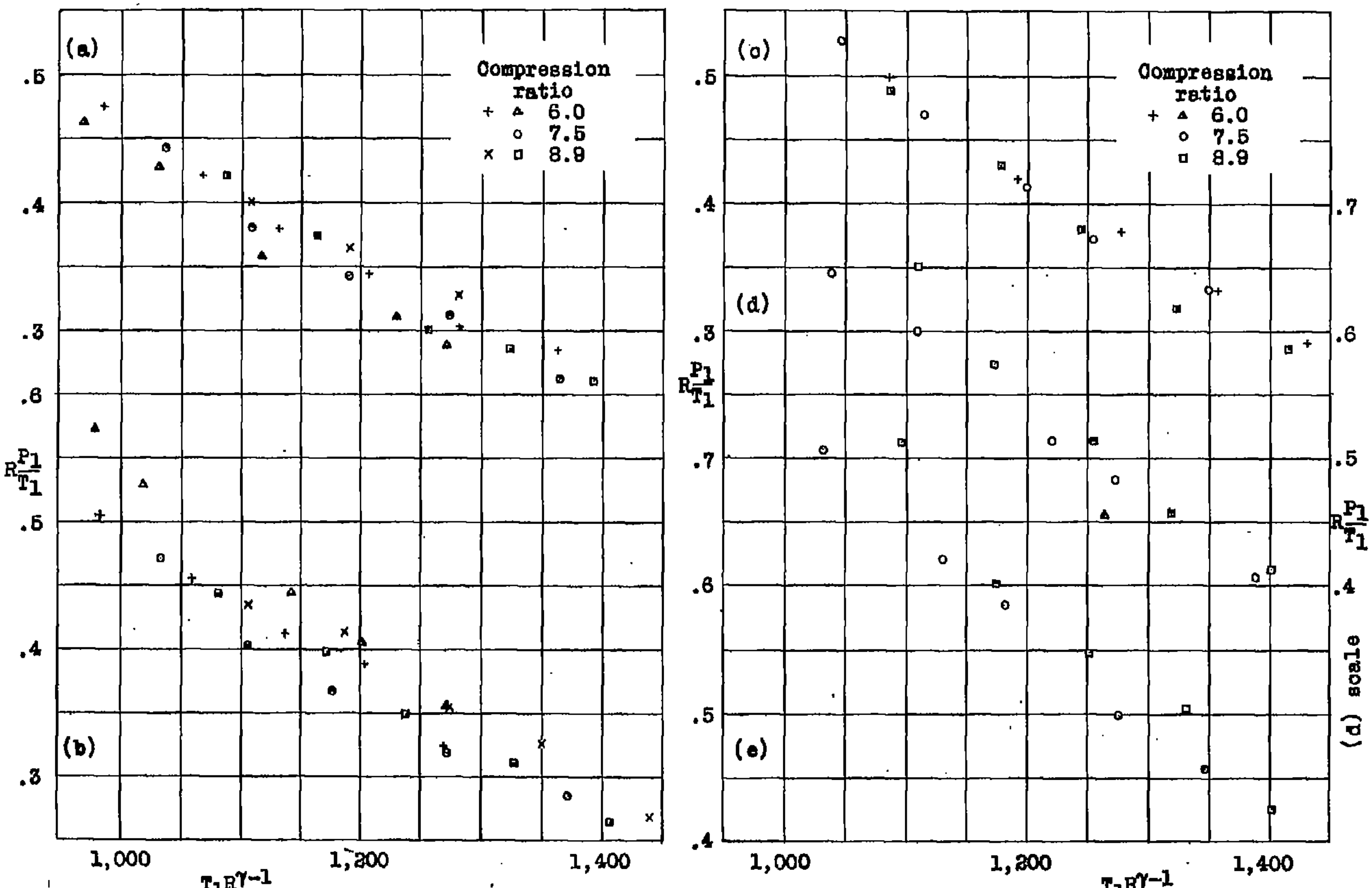


Figure 2.- Variation of maximum cylinder pressure with inlet-air temperature and compression ratio.



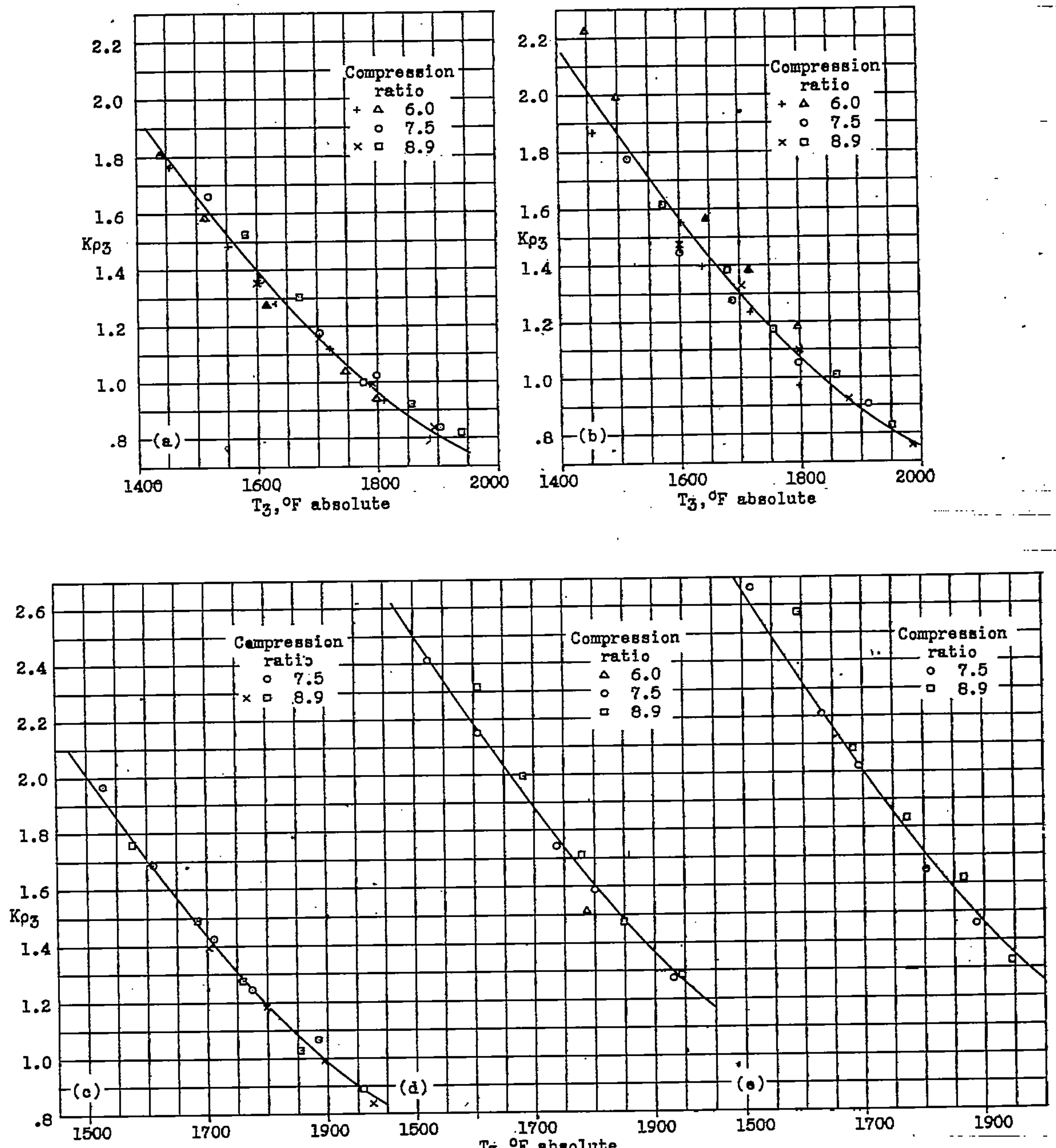
(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+3 ml tetraethyl lead.

Figure 3 a to e.- Effect of inlet-air temperature on the maximum permissible density factor, $R\frac{P_1}{T_1}$



(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+2 ml tetraethyl lead.

Figure 4 a to e.- Relationship between the temperature factor $T_1R^{\gamma-1}$ and the maximum permissible density factor, $R\frac{P_1}{T_1}$.



(a) 90 percent S-1. (b) 95 percent S-1. (c) S-1. (d) S-1+1 ml tetraethyl lead. (e) S-1+2 ml tetraethyl lead.

Figure 5 a to e.- Effect of estimated temperature T_3 of end-gas on the maximum permissible end-gas density factor, $K\rho_3$.

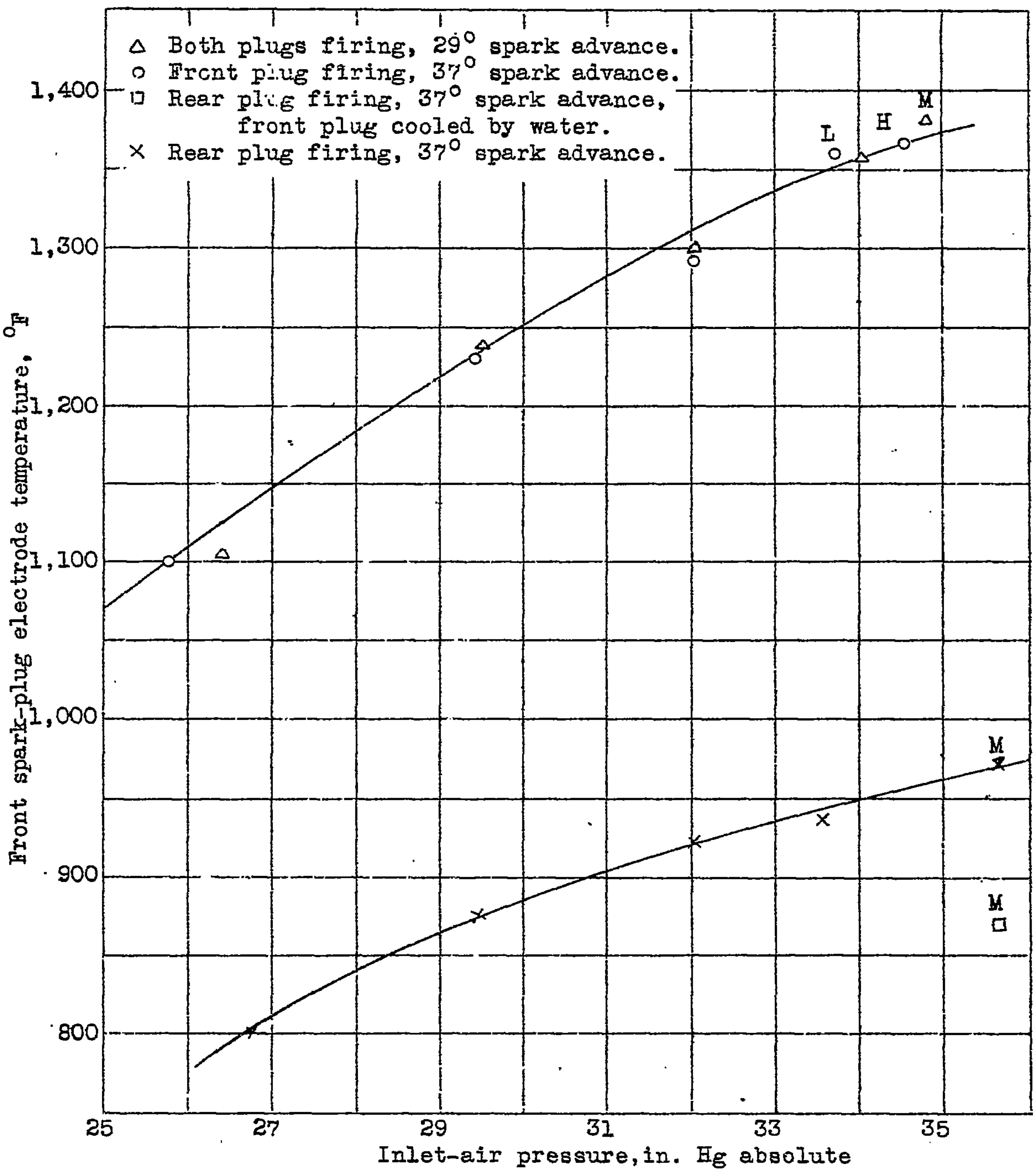


Figure 6.- Front spark-plug electrode temperatures with the plug firing and not firing and with water flowing over the plug. Compression ratio, 7.5; engine speed, 2,000 rpm; maximum-knock mixture; inlet-air temperature, 120°F; ethylene glycol temperature, 240°F; S-1 fuel; spark retarded for 99 percent maximum power. L, light pinking knock; M, medium loud knock; H, hard knock.