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No. 707

COMPRESSION-IGNITION ENGINE PERFORMANCE WITH UNDOPED AND DOPED FUEL OILS AND ALCOHOL MIXTURES

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SUMMARY

Several fuel oils, doped fuel oils, and mixtures of alcohol and fuel oil were tested in a high-speed, single-cylinder, compression-ignition engine to determine power output, fuel consumption, and ignition and combustion characteristics.

Fuel oils or doped fuel oils of high cetane number had shorter ignition lags, lower rates of pressure rise, and gave smoother engine operation than fuel oils or doped fuel oils of low cetane number. Higher engine rotative speeds and boost pressures resulted in smoother engine operation and permitted the use of fuel oils of relatively low cetane number. Although the addition of a dope to a fuel oil decreased the ignition lag and the rate of pressure rise, the ensuing rate of combustion was somewhat slower than for the undoped fuel oil so that the effectiveness of combustion was practically unchanged.

Alcohol used as an auxiliary fuel, either as a mixture or by separate injection, increased the rates of pressure rise and induced roughness. In general, the power output decreased as the proportion of alcohol increased and, below maximum power, varied with the heating value of the total fuel charge.

INTRODUCTION

Most published experimental investigations of fuels for compression-ignition engines have been principally concerned with ignition characteristics while engine power and economy were given but slight consideration (references 1, 2, 3, and 4). In order to improve the ignitibility of fuel oils, various compounds have been added for the specific purpose of reducing the ignition lag (reference 5).

The possibility has been suggested that fuel dopes might be added or superior fuels obtained which will enable a greater part of the fuel charge to be burned during the early part of the expansion stroke. French reports (references 6 and 7) indicate that the use of ethyl alcohol as an auxiliary fuel appreciably improved the engine power and the ignition characteristics and decreased the rate of pressure rise and the maximum cylinder pressure.

The purpose of the work presented in this report was to determine the ignition, the combustion, and the engine-performance characteristics of several fuel oils, to determine the effect of adding fuel dopes, and to test the value of alcohol and gasoline as auxiliary fuels. The results have been accumulated from tests of new fuels as they became available. Some of the fuel dopes submitted by private investigators were considered to be ignition and combustion accelerators. Many of the fuels were examined by the U.S. Naval Engineering Experiment Station at Annapolis, Md., to determine their physical-chemical properties and, especially, their cetane numbers. The engine tests reported herein were made by the N.A.C.A. during 1936, 1937, and 1938.

FUELS

The fuels tested are readily classified into three distinct groups:

1. Fuel oils.

2. Doped fuel oils.

3. Auxiliary fuels.

Table I shows the properties of the fuels of groups 1 and 2 as determined by the Naval Engineering Experiment Station. For the determination of the cetane number, the constant-ignition-lag method and the modified magnetic pick-up method (references 1 and 2) were used on a compression-ignition conversion unit of the C.F.R. engine with the turbulent-type combustion chamber.

Fuel oils.- Fuel 1 is the laboratory fuel oil used by the N.A.C.A. for routine engine tests. It is a distillate from a Pennsylvania or equivalent crude oil. (This fuel is similar to fuel 2 of reference 8.)

Fuel 2 is U.S. Navy M-306, specified for aircraft compression-ignition engines.

Fuel 3 is a commercial marine fuel oil sold on the Atlantic seaboard of the United States.

Fuel 4 is U.S. Navy 7-0-2C, specified for general use in submarines and small boats.

Fuel 5 is No. 3 furnace oil purchased for boiler heating.

Doped fuel oils.- Fuel 6 was obtained by adding 1 percent of ethyl nitrate to the No. 3 furnace oil.

Fuel 7 was obtained by adding 2.5 percent of iso-amyl nitrate to the laboratory fuel oil (i.e., to fuel 1).

Fuel 8 (properties not given in table) was obtained by adding 4 percent of tetranitromethane to the laboratory fuel oil.

Auxiliary fuels.- Fuel 9 (see table I) was a mixture of laboratory fuel oil and 25 percent by volume of 87 octane gasoline (U.S. Army Specification No. 2-92, Grade 87).

Fuel 10 (properties not given in table) was laboratory fuel oil and commercial ethyl alcohol of 92 percent purity by weight. Alcohol was used in proportions of 10, 25, 40, and 80 percent by volume of the total fuel charge when the total charge was mixed by constant agitation and injected from a single valve. When the main and the auxiliary fuels were injected separately from two valves, equal weights of alcohol and fuel oil were used. Recent information had indicated this proportion to be the best from considerations of power.

FUEL-INJECTION SYSTEMS

For the fuel oils, the doped fuel oils, and the gasoline-fuel oil mixture, only one fuel-injection pump and one valve were used. The pump was cam operated and had a constant plunger displacement with constant start and variable cut-off of injection. Figure 1 shows the arrangement of the fuel-spray axes and the combustion chamber used. For a fuel quantity of 0.00035 pound per cycle injected at 2,000 r.p.m. engine speed, the injection period was 22 crank degrees as determined by observations with a stroborama, a stroboscope of the electrical-discharge type.

This fuel-injection system was also used when the alcohol and the fuel oil were mixed before injection. Owing to immiscibility of the alcohol and the fuel oil, constant agitation by a small high-speed gear pump was required to maintain a uniform mixture in the fuel tank. The uniformity of the mixture injected into the engine was checked by catching samples of the mixture in a bottle as it was injected by the fuel valve into the air. The specific gravity of the samples indicated that the mixture was within ±1 percent of the desired proportions.

For the engine tests in which the alcohol and the fuel oil were separately injected, two separate fuel-injection pumps and valves were used; each pump had an independent timing device. Figure 2 shows the arrangement of the axes of the two fuel sprays. The arrangement of the alcohol spray was chosen to give a reasonably uniform distribution throughout the combustion chamber without consideration of the interference of the fuel-oil and the alcohol sprays.

TEST ENGINE AND TESTS

The displacer-piston combustion chamber and the fuel-oil spray arrangement used in these tests (see fig. 1) have been completely described in references 9 and 10. The more important parts of the test unit and standard test conditions were as follows:

Engine....................	Single-cylinder, 4-stroke-cycle, 5-inch bore by 7-inch stroke, (137.5 cu. in. displacement).
Engine speed.............	2,000 r.p.m.
Compression ratio.........	14.5.
Valve timing..............	Inlet opens 27° B.T.C. Inlet closes 28° A.B.C. Exhaust opens 66° B.B.C. Exhaust closes 41° A.T.C.

Operating temperatures...	Water (out), 170° F.; lubricating oil (out), 165° F.
Fuel-injection valves....	N.A.C.A. automatic, spring-loaded to 3,500 pounds per square inch opening pressure.
Full-load fuel quantity..	Fuel-air ratio = 0.069.
Power measurement and absorption............	Electric dynamometer unit.
Air- and fuel-consumption measurements..........	Gasometer with synchronized electrically operated stop watches and revolution counters.
Indicator................	Modified Farnboro for indicator cards.
Maximum cylinder-pressure measurement..........	Trapped-pressure valve and pressure gage; indicator card for balanced pressures.

For each fuel oil, doped fuel, or auxiliary fuel, engine-performance tests were made at 2,000 r.p.m. for various fuel quantities to determine the power and the fuel consumption. The maximum cylinder pressure, the ignition lag, and the rate of pressure rise were determined from indicator cards. The injection advance angle was held constant at 12.0° before top center for the determination of ignition lag at 2,000 r.p.m. With a 5- by 6-inch cylinder and other equipment as before, supplementary tests were made with a fuel of low cetane number (furnace oil) at engine speeds from 1,000 to 2,400 r.p.m. and for boost pressures from 0 to 20 inches of mercury at 2,000 r.p.m.

Indicator cards for the laboratory fuel, the laboratory fuel plus 2.5 percent iso-amyl nitrate, the No. 3 furnace oil, and the No. 3 furnace oil plus 1 percent ethyl nitrate were analyzed to determine the total amounts of effective fuel burned during various crank angles of the expansion stroke. By "effective fuel burned" is meant the combustion of the quantity of fuel required to produce the change in enthalpy (total heat) recorded on the indicator diagrams; the term does not include the fuel dissipated as heat losses.

RESULTS AND DISCUSSION

Fuel Oils

The indicator card of figure 3 is typical for the undoped fuel oils (group 1) used in each particular test. The card shows not only the pressure-time record for the standard injection advance angle but also the retarded-injection record required to determine the break-away from the compression line at the start of burning. Figure 3 can be considered a reference card because the fuel was the standard laboratory fuel oil and has a reasonably high cetane number, 62. The break-away on all of the cards is a gradual change in slope except for No. 3 furnace oil (fig. 4). For the No. 3 furnace oil, the break-away is much more abrupt. All of the cards in this group except that for the furnace oil show two distinct rates of pressure rise. The first rate (and the only rate for the furnace oil) is attributed to the rapid burning of the fuel accumulated during the ignition lag. The second, slower rate occurs up to the time of cut-off of injection. On the indicator card for No. 3 furnace oil, a definite reduction in compression pressure occurs at top center, owing to the fuel vaporization and the cooling of the air charge.

The different combustion characteristics of the several fuels are shown in table II, which gives detailed numerical results obtained from an analysis of the indicator cards. For constant injection advance angles, the ignition lag decreased with increasing cetane number by as much as 50 percent. The maximum ignition lag, 12.5°, was for the No. 3 furnace oil having a cetane number of 29.9, and the minimum lag, 8.0°, was for the commercial marine fuel oil having a cetane number of 58.0. Injection of the laboratory or the commercial marine fuel oil could be retarded to 12° after top center before misfiring occurred; injection of the furnace oil, however, could be retarded only to top center. Rates of pressure rise follow very nearly the variations of ignition lag; i.e., longer lags cause higher rates of pressure rise owing to greater accumulations of fuel at the time of ignition. Although the maximum cylinder pressure did not change greatly, the highest value occurred with the fuel of lowest cetane number (No. 3 furnace oil), as did the roughest running and the harshest combustion sound. Ignition lag, then, is the factor controlling rates of pressure rise, maximum cylinder pressure, and combustion sound for a given rate of injection.

No engine-performance curves are presented for the several fuel oils because the mean effective pressures and the fuel consumptions were the same for each fuel. The mean effective pressures and the fuel consumptions shown later (fig. 10) for undoped laboratory fuel oil are typical of each of the fuel oils being discussed. The various fuel oils with the same injection advance angles but with different ignition lags gave identical power outputs and fuel consumptions within the limits of experimental accuracy. Fuel oils of low cetane number, however, gave higher balanced cylinder pressures than fuel oils of high cetane number. Table I shows that the maximum difference in heating values of the fuel-oil group is 3 percent, No. 3 furnace oil having the lowest and laboratory fuel oil having the highest values. The low heating value, however, did not reduce the power because more of the fuel burned in the early part of the expansion stroke (as will be seen later) to give a more effective combustion cycle. The differences in the exhaust conditions were negligible for all the fuel oils. It is certain that, of the fuel oils tested, the fuel of highest cetane number did not give a higher mean effective pressure or a lower fuel consumption but did give smoother engine operation.

Engine operation with the No. 3 furnace oil being too rough to be acceptable, tests were made with a 5-inch by 6-inch cylinder under conditions intended to make the operation smoother. It was believed that the rate of pressure rise per degree and the roughness could be reduced by increasing the engine speed. As the engine speed was increased from 1,000 to 2,400 r.p.m. (fig. 5), the angular rate of pressure rise tended to decrease and the extreme roughness decreased to a slight roughness. Increasing the engine speed not only increases the angular velocity but also increases forced air-flow velocity in the combustion chamber. It is this increase in mixing air-flow velocity that decreases the ignition lag and increases the absolute rate of pressure rise. In a combustion chamber that uses forced air flow to mix the fuel and the air, the increased angular and air-flow velocities work against each other as the engine speed is increased; higher air-flow velocities tend to cause faster fuel mixing and burning and greater absolute rates of pressure rise, while the higher angular velocity causes a lower rate of pressure rise per degree. In a quiescent type of combustion chamber, the effect of the higher angular velocity should predominate causing the rate of pressure rise per degree to decrease as the engine speed increases.

The results of previous tests (reference 10) have shown that smoother engine operation resulted from increased inlet-air pressure because the ignition lag and the rate of pressure rise were decreased. The decrease in ignition lag is caused by the increased heat per unit volume and the greater rate of heat transfer rather than by the higher temperature of the compressed air.

Tests made at full-load fuel quantity with the No. 3 furnace oil over a range of boost pressures to 20 inches of mercury gave the results shown in figure 6; i.e., the engine operation changed from very rough to slightly rough. As was expected, the ignition lag and the rate of pressure rise decreased although, at boost pressures greater than 10 inches of mercury, the rate of pressure rise slightly increased, possibly because of too much injection advance, as borne out by the relatively high (reference 10) ratio of explosion pressure to compression pressure. In general, the results indicate that higher engine rotative speeds and boost pressures improve smoothness of engine operation and permit the use of fuel oils of relatively low cetane number.

The rates of pressure rise shown in figures 5 and 6 are unusually high. Such values are generally associated with loud knock and extremely rough engine operation. As noted on the figures, roughness was encountered but not destructive conditions.

The decrease in roughness at the higher speeds, despite the higher absolute rates of pressure rise shown, may be accounted for by the fact that there is considerably less acceleration of the pressure-rise rate and that the duration of the peak pressure is shorter.

Doped Fuel Oils

The indicator cards shown in figures 7, 8, and 9 were obtained for the doped fuel oils. Apparently the addition of dope caused the break-away to become more gradual and smooth. (See figs. 4 and 7.) When the break-away occurred very early, as with the doped laboratory fuel (fig. 9), the pressure rise was practically an extension of the compression curve so that the pressure-rise curve and the compression curve had a common slope. It is also worthy of note that the retarded-injection cards indicate more of a tendency to constant-pressure combustion when dope is added.

Table II includes the ignition and the combustion qualities of the doped fuel oils. The addition of 1 percent of ethyl nitrate to the No. 3 furnace oil increased the cetane number from 29.9 to 47.7. The ignition lag and the rate of pressure rise decreased 13 and 23 percent, respectively; the resulting operation was quite satisfactory. The ignition qualities of the laboratory fuel oil were good even without the addition of a dope. The addition of 2.5 percent of iso-amyl nitrate to the laboratory fuel oil increased the cetane number from 62.5 to 88.1. The ignition lag and the rate of pressure rise were decreased 23.5 and 46.5 percent, respectively. The smoothness of operation was further improved and the break-away became very gradual (fig. 8). One dope of unknown composition that was submitted for test by a private investigator had practically no effect on the ignition qualities or on the engine performance when added to the laboratory fuel oil in proportions of 1 and 2 percent. Another private investigator submitted tetranitromethane as a fuel-oil dope; a 4-percent addition to the laboratory fuel oil decreased the ignition lag and the rate of pressure rise by 23 and 35 percent, respectively.

Of the four fuel dopes tested, three failed to influence either the mean effective pressure or the fuel consumption. That is, although the added dope produced earlier ignition, it apparently produced neither earlier nor more complete combustion of the fuel charge. The addition of 4 percent of tetranitromethane, however, improved the brake mean effective pressure and the corresponding fuel consumption 3 percent. (See fig. 10.) The addition of 1 or 2 percent of the dope had practically no effect. The increase in maximum cylinder pressure of about 25 pounds per square inch for the doped fuel was insufficient to cause the difference shown in performance. The investigator who submitted the tetranitromethane stated that the addition of 4 percent would be too expensive to be commercially practicable.

Comparison of Ignition Characteristics

Figure 11 gives a summary of the data on ignition lag and rate of pressure rise from table II plotted against cetane number. The curves are straight lines and the slopes have the values that would be expected from a variation in cetane number. The points for the commercial marine fuel oil and for the gasoline-fuel oil mixture are farthest from the straight line. The variation of the ignition lag of the marine fuel oil is equivalent to only 1°, which is almost within the precision of the tests. The point for the gasoline-fuel oil mixture is off the curve because maximum rate of pressure rise is not necessarily a function of cetane number.

The fuel-oil dopes were expected to act as combustion accelerators; that is, the dope would not only reduce the ignition lag of a given fuel but would also cause more fuel to burn in the early part of the expansion stroke. The effectiveness of combustion would be improved by decreasing late burning and the power output should be increased for a given fuel consumption. Engine tests of the fuels containing accelerators, however, showed little if any increase in power although the ignition lags did decrease.

The results of the several combustion analyses are shown in figure 12; the curves show that the ignition lags are decreased by the fuel dopes, as was previously determined directly from the indicator cards. In spite of the different times at which ignition occurs, the variations in the total amounts of fuel burned (or the variations in effectiveness of combustion) are small during the cycle. When the curves are shifted so that they all rise from the origin, the rates of burning of the doped fuel oils are seen to be slower than those for the undoped fuel oils; that is, the rate of burning for several degrees after ignition is slower for the doped fuel oils. The fuel oil with the longest ignition lag, No. 3 furnace oil, gave the fastest rate of burning at all crank angles. For all the undoped and the doped fuel oils, the combustion continues late in the cycle and, at large loads, is conducive to a smoky exhaust.

Gasoline as Auxiliary Fuel

It was thought that a mixture of 25 percent gasoline and 75 percent fuel oil (see table I and fig. 13) would evaporate faster than fuel oil alone and that more of the total fuel charge would burn earlier than for undoped fuels. The fuel oil was expected to ignite first, owing to its lower ignition temperature, but the gasoline was expected to evaporate more quickly than the fuel oil and to produce better combustion during the early part of the expansion stroke. The cetane number of the mixture was 42.4, however, compared with 62.5 for the fuel oil alone and the ignition lag in the engine was increased 17-1/2 percent, possibly owing to the cooling action of the rapidly evaporating gasoline. The rate of pressure rise decreased 14 percent, the maximum cylinder pressure decreased 4 percent, and the combustion sound, unexpectedly, became very low.

The addition of 25 percent gasoline to fuel oil greatly increased the fire hazard because, as table I shows, it decreased the flash point from 236° F. to below 80° F.

The engine-performance test of the gasoline-fuel oil mixture showed that the mean effective pressure was 3 percent lower than for fuel oil alone and that the fuel consumption increased. As the heating value of the fuel mixture was the same as for a like weight of fuel oil, the effect of the gasoline must have been to cause slower rather than faster burning with a consequent decrease in power.

Mixed Injection of Alcohol and Fuel Oil

From the indicator cards, of which figure 14 is representative, the addition of alcohol is seen to have increased the ignition lag by as much as 88 percent for the 40-percent alcohol mixture. The cause of this large increase may have been the cooling of the fuel and the air charge by evaporation of the alcohol. As usual with increased ignition lags, the rate of pressure rise (fig. 15), the maximum cylinder pressure, and the roughness increased with increased percentages of alcohol until roughness became intolerable. A mixture of 80 percent alcohol and 20 percent fuel oil could not be ignited at a compression ratio of 14.5. The spontaneous ignition temperature of fuel oil is about 500° F. and that of alcohol is about 1,025° F. (reference 11). The high ignition temperature required by alcohol and the excessive cooling of the fuel and air mixture by evaporation of the large percentage of alcohol must have been responsible for suppressing ignition.

Engine power decreased and fuel consumption increased (fig. 16) as the proportion of alcohol was increased, especially for mixtures with more than 25 percent alcohol. The heating value was 19,900 B.t.u. per pound for the fuel oil and 11,700 B.t.u. per pound for the 90 percent pure alcohol so that power comparisons are more fairly made on a basis of equal heat input. On this basis (fig. 15), the use of alcohol was more favorable; for conditions of no excess air, the power remained practically constant with variations in the percentage of alcohol. Of course, more total weight of fuel oil and alcohol is required, a factor which alone precludes the use of alcohol in compression-ignition engines for aircraft.

Separate Injection of Alcohol and Fuel Oil

The addition of a small charge of alcohol to the fuel-oil charge considerably lowered the sound of combustion. At the start of exhaust haze, a small added charge of alcohol slightly increased the power and the exhaust became a white smoke. For the 50 percent alcohol and 50 percent fuel oil mixture by weight, the engine operation was always rough. When the alcohol was injected either 15° before the fuel oil or leading the fuel oil by 293°, as during the intake stroke, the engine operation was rough and unsteady and the fuel-oil injection advance angle became critical. Injection of the alcohol 15° after the fuel oil caused the exhaust to become a white smoke without influencing power (fig. 17).

Simultaneous injection of fuel oil from both fuel valves (fig. 2) gave lower brake mean effective pressures (fig. 17) than injection of the same fuel quantity from one fuel valve (fig. 1) doubtless because overrich regions occurred at the zones of spray interference. For the simultaneous injection of fuel oil and alcohol, a similar interference occurred and combustion was probably adversely influenced. Comparison of performance, however, is considered indicative. In the study of figure 17, it should be remembered that the air charge is sufficient to require but 0.00034 pound of fuel oil for complete combustion. At all except very large fuel quantities, the power is lower for the half-alcohol and half-fuel-oil charge because of the lower heating value of the alcohol of given charge weight.

It was believed that injection of alcohol on the intake stroke might increase the volumetric efficiency by cooling of the incoming-air charge. Volumetric efficiency tests showed that the air charge was slightly less, possibly because the air flow into the cylinder was obstructed by the fuel spray and possibly because the alcohol evaporated quickly from the hot chamber walls to help fill the cylinder. The very early injection of the alcohol did give more time for vaporization and mixing with the air charge and was advantageous, as evidenced by the fact that the maximum power was higher by 4 percent than for any other condition of injection.

CONCLUSIONS

1. Fuel oils of high cetane number gave no more power than fuel oils of low cetane number but had less ignition lag, lower rates of pressure rise, and smoother engine operation over a complete load range at 2,000 r.p.m.

2. Increased engine speeds and boost pressures resulted in smoother engine operation and permitted the use of fuel oils of low cetane number.

3. Fuel dopes decreased ignition lags and rates of pressure rise and increased smoothness of engine operation. The addition of 4 percent tetranitromethane increased engine power by less than 3 percent.

4. Fuel dopes improved neither the completeness nor the effectiveness of combustion.

5. Alcohol as an auxiliary fuel, in general, decreased power as the proportion of alcohol increased. Any increases in power obtained by double injection did not exceed 4 percent and were obtained at the expense of increased fuel consumption. Alcohol increased the igntion lag, the rate of pressure rise, and the roughness of operation.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 23, 1939.

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TABLE I - PHYSICAL AND CHEMICAL PROPERTIES OF UNDOPED AND DOPED FUEL OILS

Fuel	Specific gravity (60/60° F.)	A. P. I. gravity (deg.)	Flash point, closed cup (°F.)	Cloud point (°F.)	Pour point (°F.)	Saybolt Universal viscosity (sec.) At 32° F.	At 100° F.	Total sulfur (percent)	Heat value, calorimeter gross (B. t. u. per lb.)
1: Laboratory	0.833	38.37	236	28	25	93	44	0.04	19,909
2: Navy M-306 (aircraft standard)	.824	40.22	166	-	-20	-	33	.11	19,790
3: Commercial marine	.843	36.35	182	14	15	61	38	.30	19,578
4: Navy 7-0-20 (submarine standard)	.852	34.58	188	12	10	65	39	.26	19,660
5: No. 3 furnace oil	.877	29.85	162	Indistinct	-65	58	38	.18	19,315
6: No. 3 furnace oil + 1 percent ethyl nitrate	.875	30.21	125	-10	-25	57	38	.20	19,257
7: Laboratory + 2.5 percent iso-amyl nitrate	.834	38.16	145	28	25	86	43	.10	19,696
8: Laboratory + 4 percent tetranitromethane	-	-	-	-	-	-	-	-	-
9: Laboratory + 25 percent 87 octane gasoline	.799	45.60	Below 80	8	10	42	35	.12	19,775
10: Laboratory + 10, 25, and 40 percent alcohol	—	—	-	—	—	—	—	—	—

Fuel	Spontaneous ignition temperature (°F.)	Aniline point (°F.)	Diesel index number	Cetane number	Distillation characteristics First drop (°F.)	10 cc. (°F.)	50 cc. (°F.)	90 cc. (°F.)	End point (°F.)	Recovered (percent)
1: Laboratory	-	186.3	71.5	62.5	529	546	575	622	672	98.4
2: Navy M-306 (aircraft standard)	-	154.0	61.7	59.9	384	414	466	551	597	98.0
3: Commercial marine	490	160.9	58.5	58.0	408	453	525	619	673	98.4
4: Navy 7-020 (submarine standard)	495	156.7	54.2	49.2	421	475	533	600	661	98.7
5: No. 3 furnace oil	575	126.2	37.7	29.9	375	438	497	581	640	98.7
6: No. 3 furnace oil - 1 percent ethyl nitrate	495	130.4	39.4	47.7	212	442	504	590	647	98.3
7: Laboratory + 2.5 percent iso-amyl nitrate	485	183.2	69.9	88.1	188	545	575	622	660	98.0
8: Laboratory + 4 percent tetranitromethane	-	-	-	-	-	-	-	-	-	-
9: Laboratory + 25 percent 87 octane gasoline	730	170.8	77.9	42.4	135	182	560	617	658	97.8
10: Laboratory + 10, 25, and 40 percent alcohol	—	—	—	—	—	—	—	—	—	—

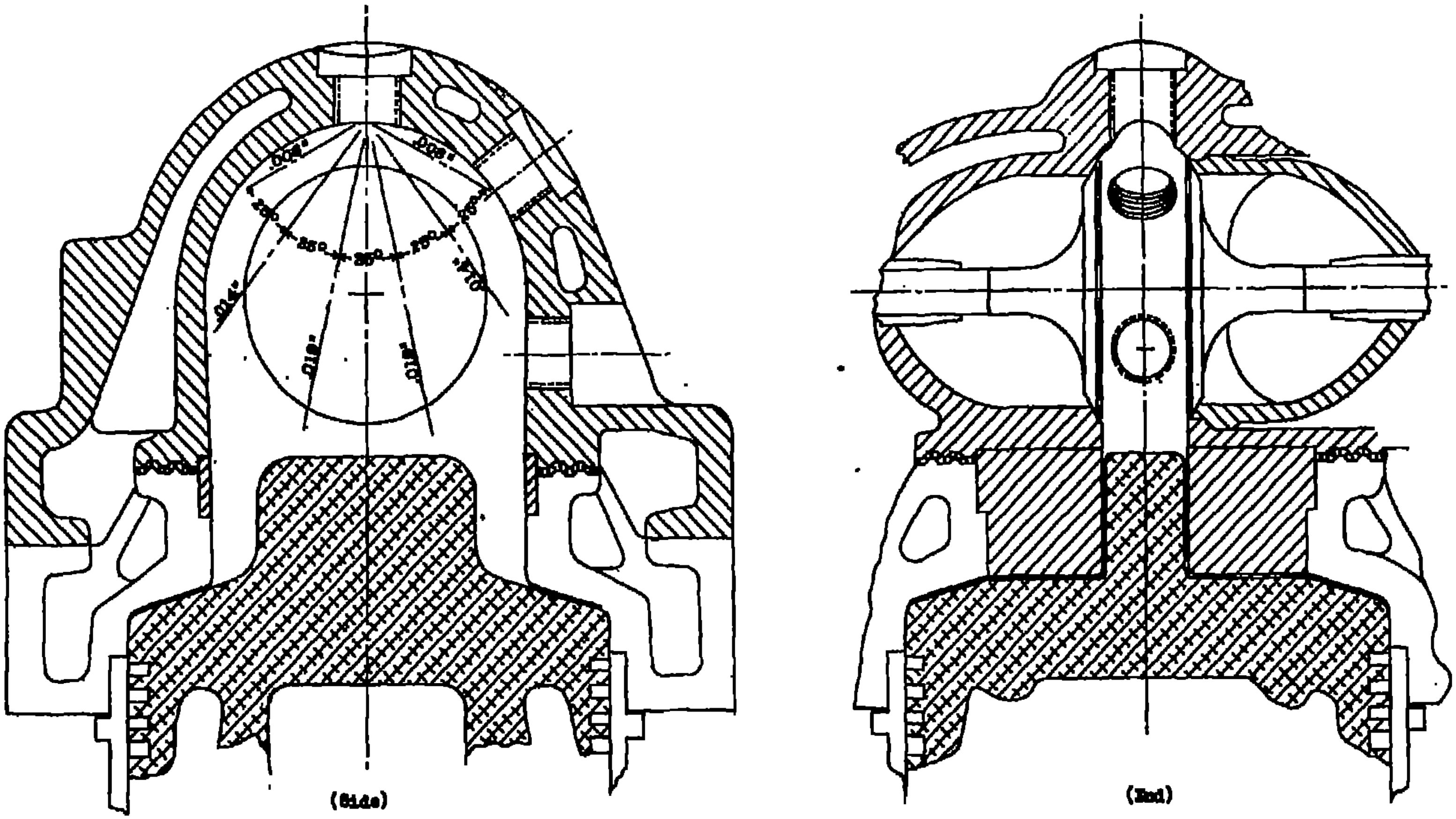

Figure 1 - Fuel-spray axes and combustion chamber

Relative fuel-spray lengths at T.C. for an i.a.a. of 10° B.T.C.; orifice diameters indicated.

TABLE II - IGNITION AND COMBUSTION PERFORMANCE OF UNDOPED AND DOPED FUELS

Fuel	Cetane number	Figure	Injection advance angle (crank deg.)	Ignition lag		Maximum cylinder pressure (lb./sq. in.)		Maximum rate of pressure rise	
				(deg.)	(sec.)	Trapped	Balanced	(lb./sq. in./deg.)	(lb./sq.in./sec.)
1: Laboratory	62.5	3	12.0	8.5	0.00071	890	980	43	520,000
2: Navy N-306 (aircraft standard)	59.9	-	12.0	9.0	.00075	890	935	51	612,000
3: Commercial marine	58.0	-	12.0	8.0	.00067	900	930	40	480,000
4: Navy 7-O-20 (submarine standard)	49.2	-	12.0	9.5	.00079	875	930	50	600,000
5: No. 3 furnace oil	29.9	4	12.0	12.5	.00104	870	1,050	70	840,000
6: No. 3 furnace oil + 1 percent ethyl nitrate	47.7	7	12.0	10.0	.00083	900	960	54	650,000
7: Laboratory + 2.5 percent isoamyl nitrate	88.1	8	12.0	6.5	.00054	910	950	23	276,000
8: Laboratory +4 percent tetranitromethane	-	9	12.0	6.5	.00054	950	950	28	336,000
9: Laboratory + 25 percent 87 octane gasoline	42.4	11	12.0	10.0	.00083	815	875	37	444,000
10. Laboratory + 40 percent alcohol	-	14	12.0	16.0	.00133	875	1,000	97	1,163,000

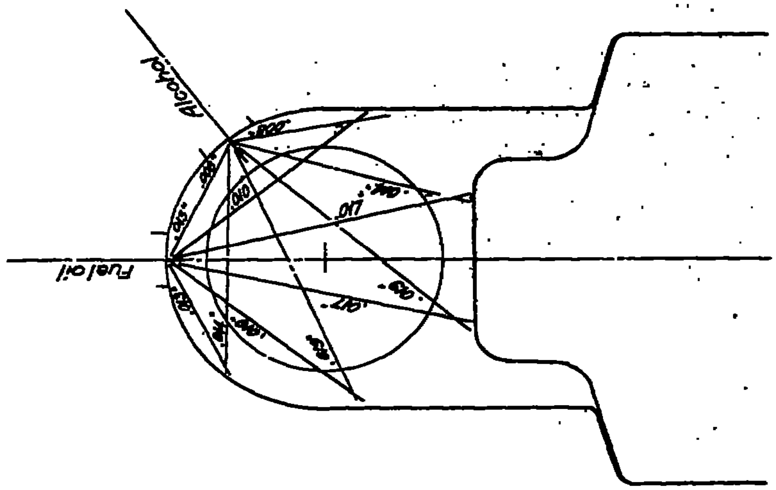

Figure 2.- Fuel-spray arrangement for separate injection of fuel oil and alcohol. Angles between adjacent sprays 25° for both nozzles. Orifice diameters indicated

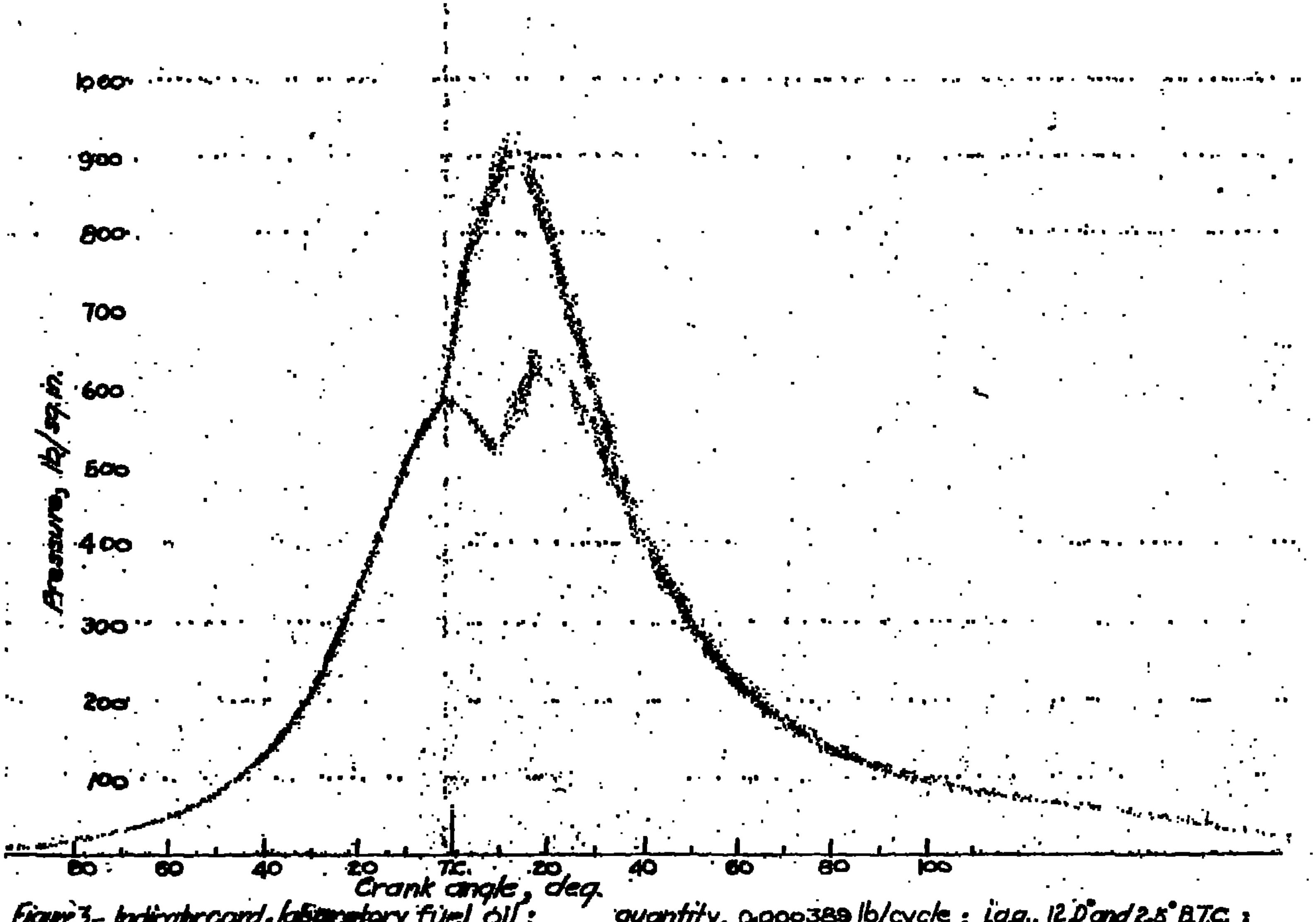

Figure 3.- Indicator card, laboratory fuel oil; quantity, 0.000389 lb/cycle; i.a.a., 12.0° and 2.5° B.T.C.; ignition lag, 8.5°; maximum rate of pressure rise, 43 lb/sq.in./deg.

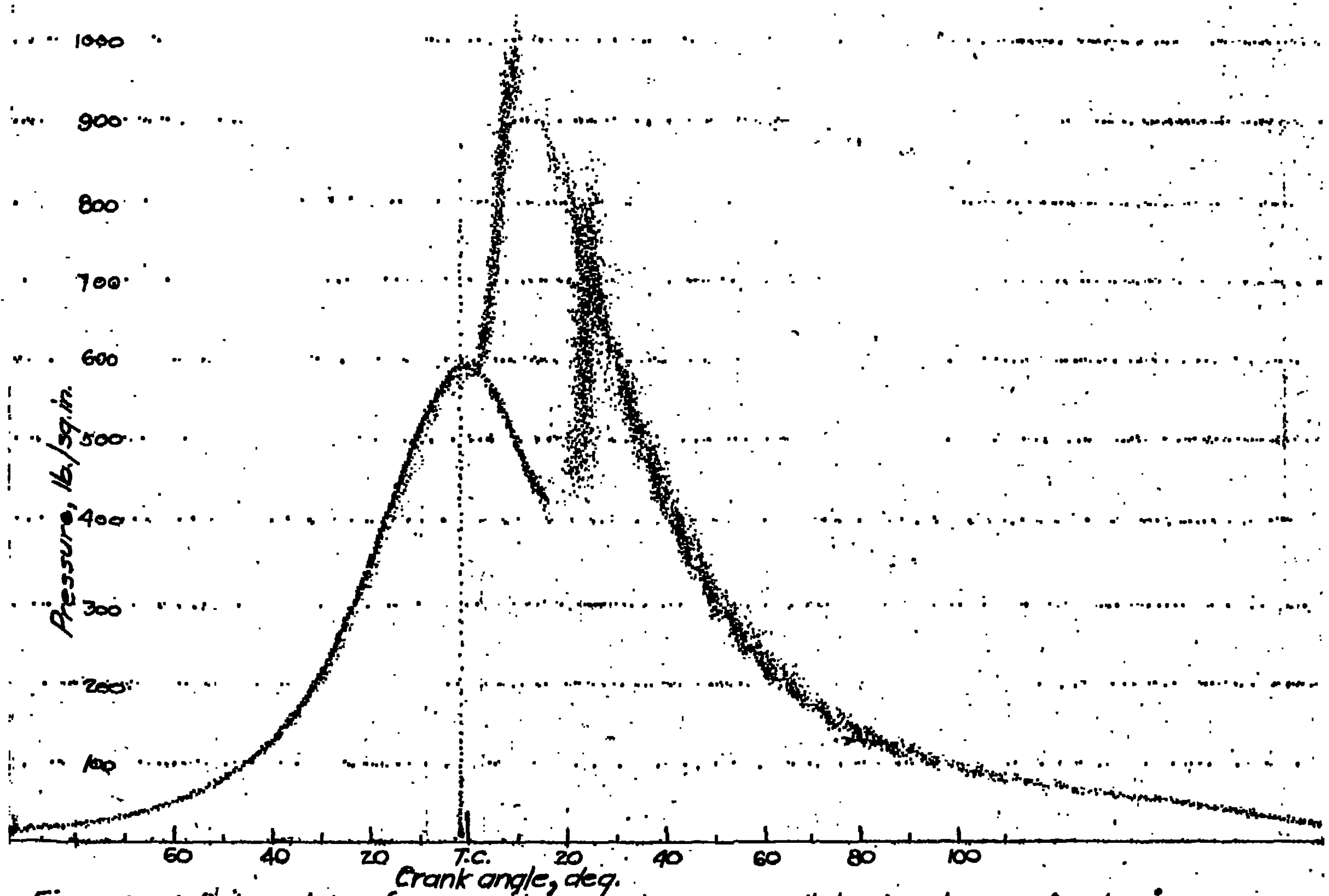

Figure 4.- Indicator card, No. 3. furnace oil; quantity, 0.000366 lb./cycle; i.a.a. 12.0° and 2.5°; ignition lag, 11.5°; maximum rate of pressure rise, 70 lb/sq.in/deg.

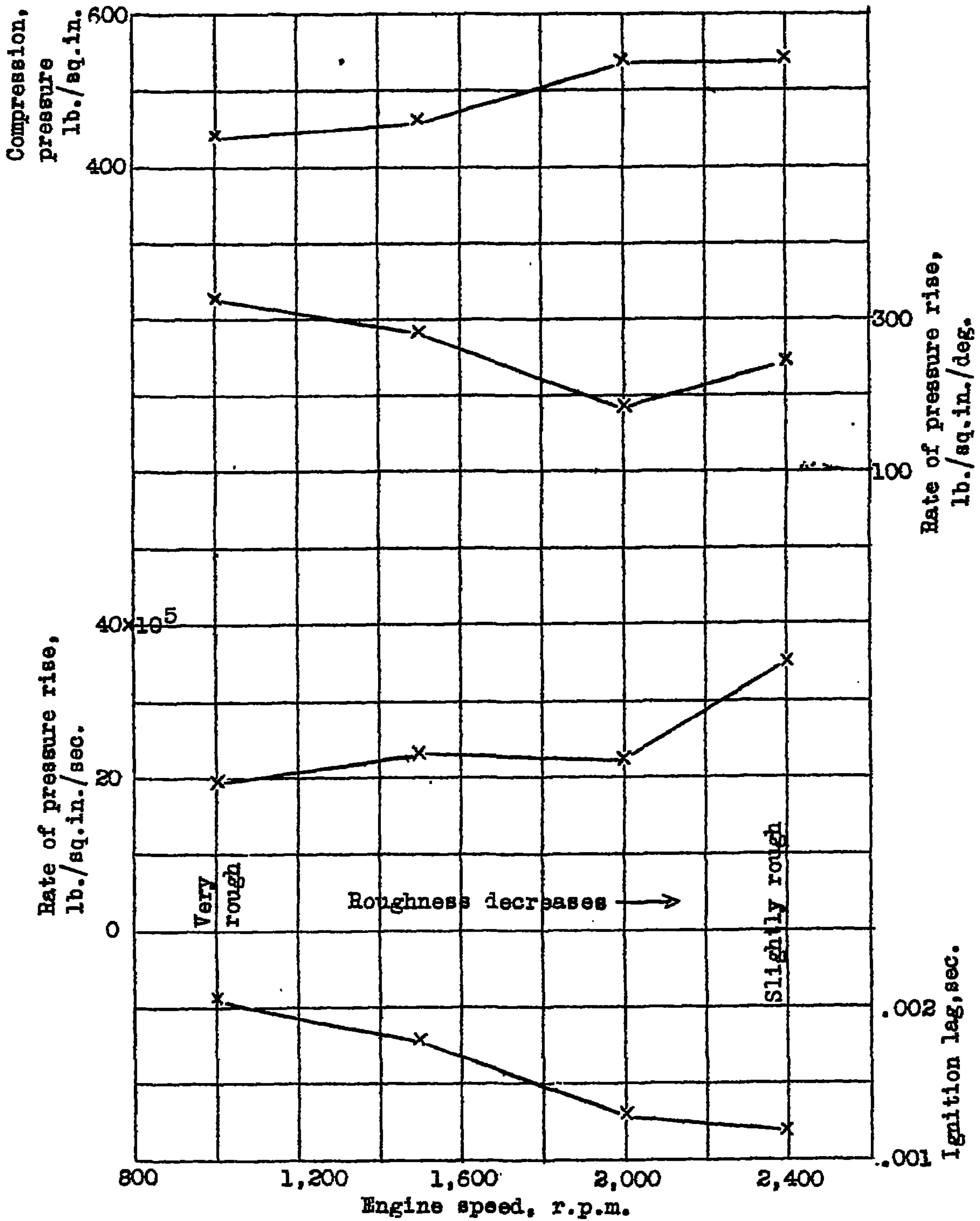

Figure 5.- Effect of engine speed on combustion characteristics. 5-by 6-inch test engine; No.3 furnace oil.

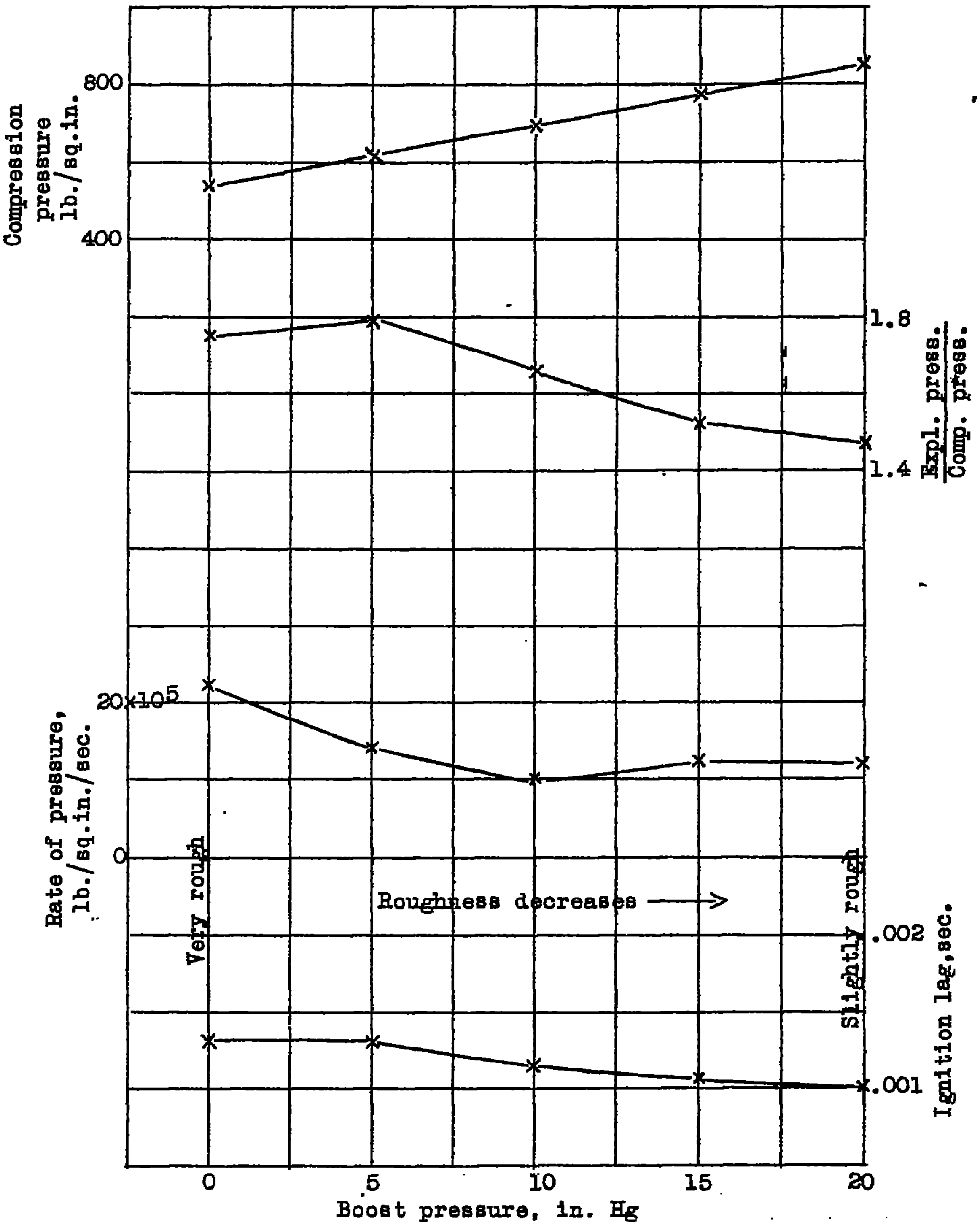

Figure 6.- Effect of boost pressure on combustion characteristics. 5-by 6-inch test engine; engine speed, 2,000 r.p.m.; i.a.a., 12°; No.3 furnace oil; air-fuel ratio, 14.5.

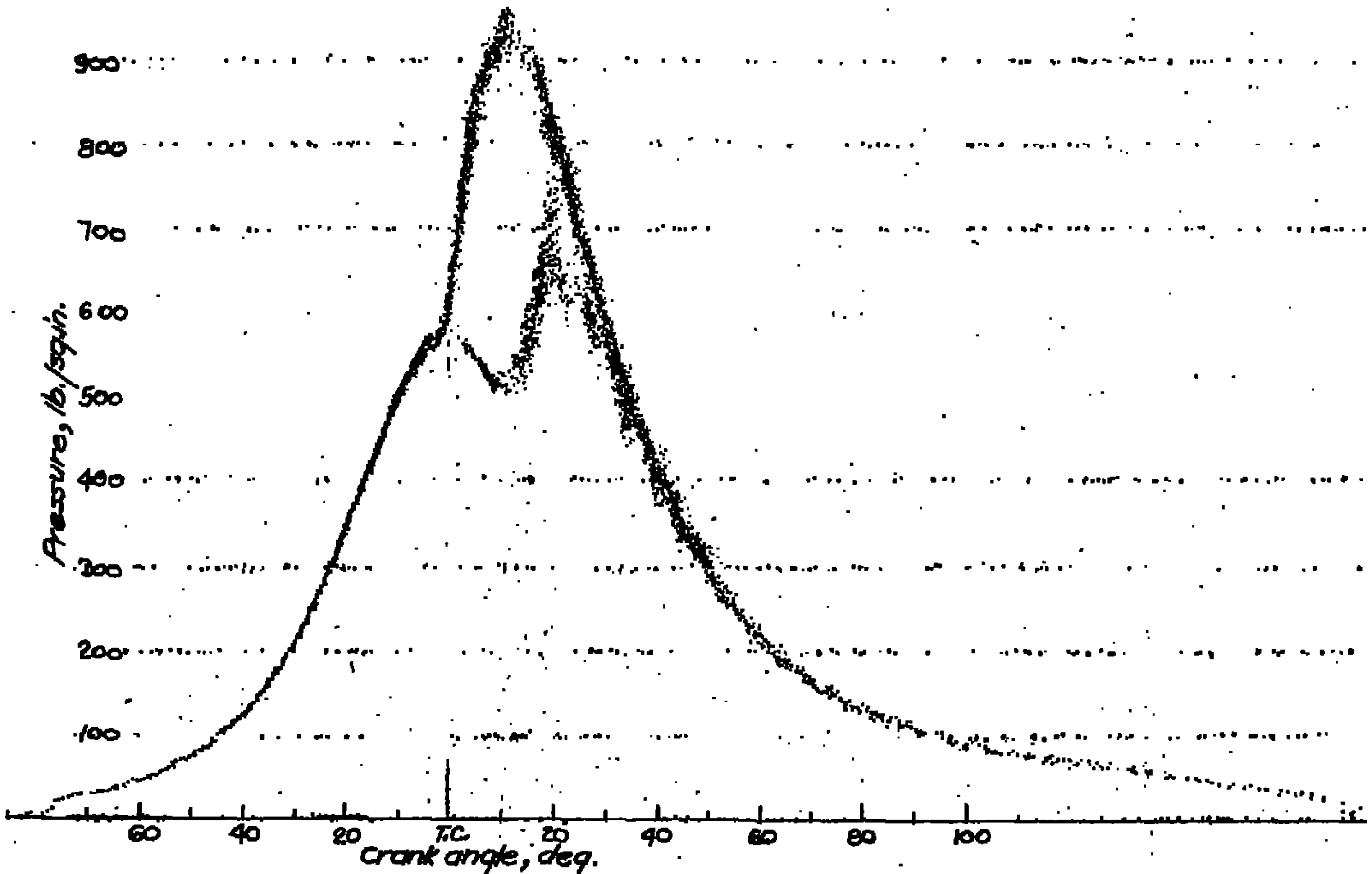

Figure 7.- Indicator card, No.3 furnace oil + 1 percent ethyl nitrate; quantity, 0.00037 lb./cycle; i.a.a., 12.0° and 2.5°; ignition lag, 10°; maximum rate of pressure rise, 54 lb./sq.in./deg.

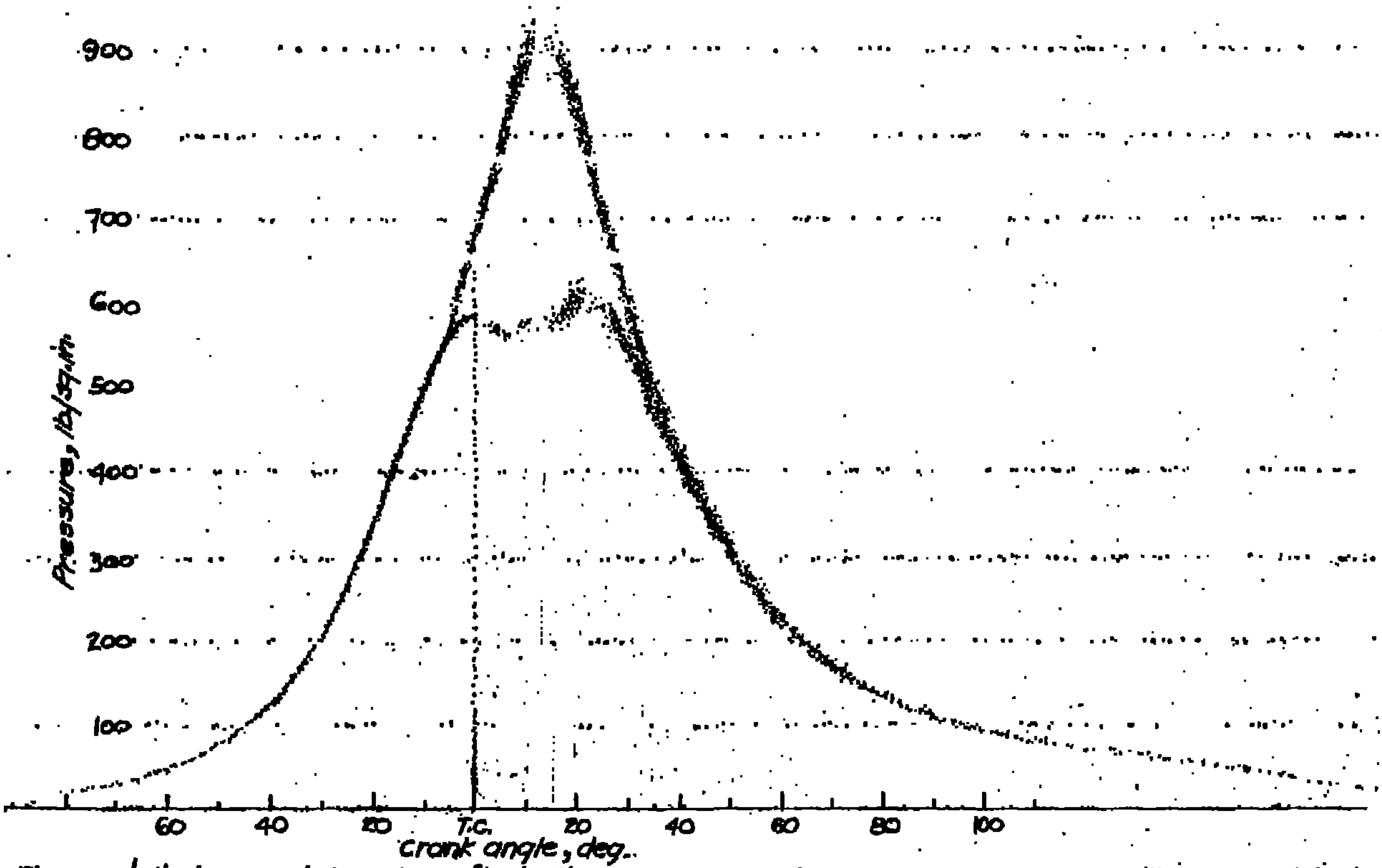

Figure 8.- Indicator card, laboratory fuel oil + 2.5 percent iso-amyl nitrate; quantity, 0.000376 lb/cycle; i.a.a., 12.0° and 2.5°; ignition lag, 6.5°; maximum rate of pressure rise, 23 lb./sq.in./deg.

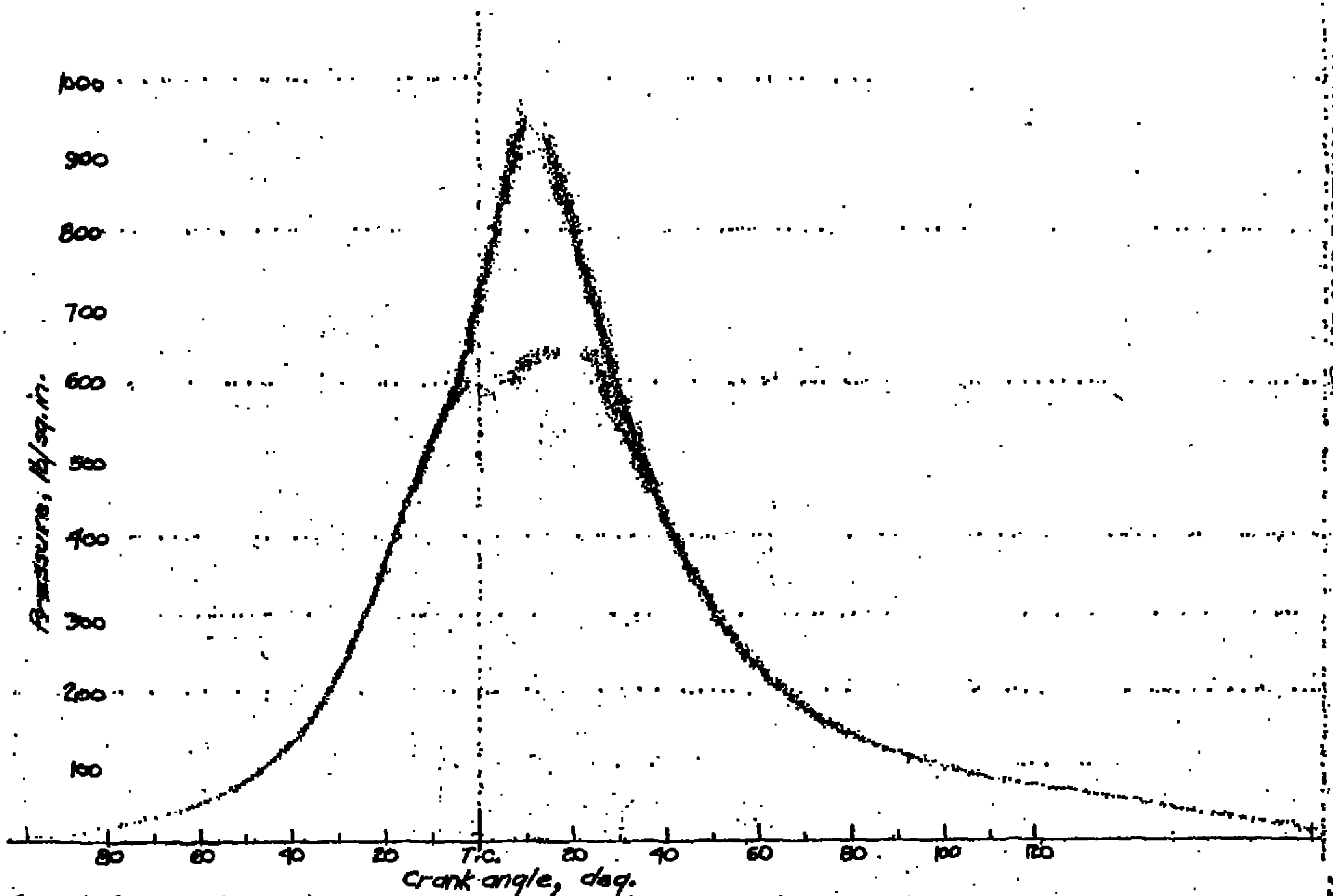

Figure 9.- Indicator card, laboratory fuel oil + 4 percent tetranitromethane; quantity, 0.00039 lb/cycle; i.a.a., 12.0° and 4.5°; ignition lag, 6.5°; maximum rate of pressure rise, [illegible] lb/sq in./deg.

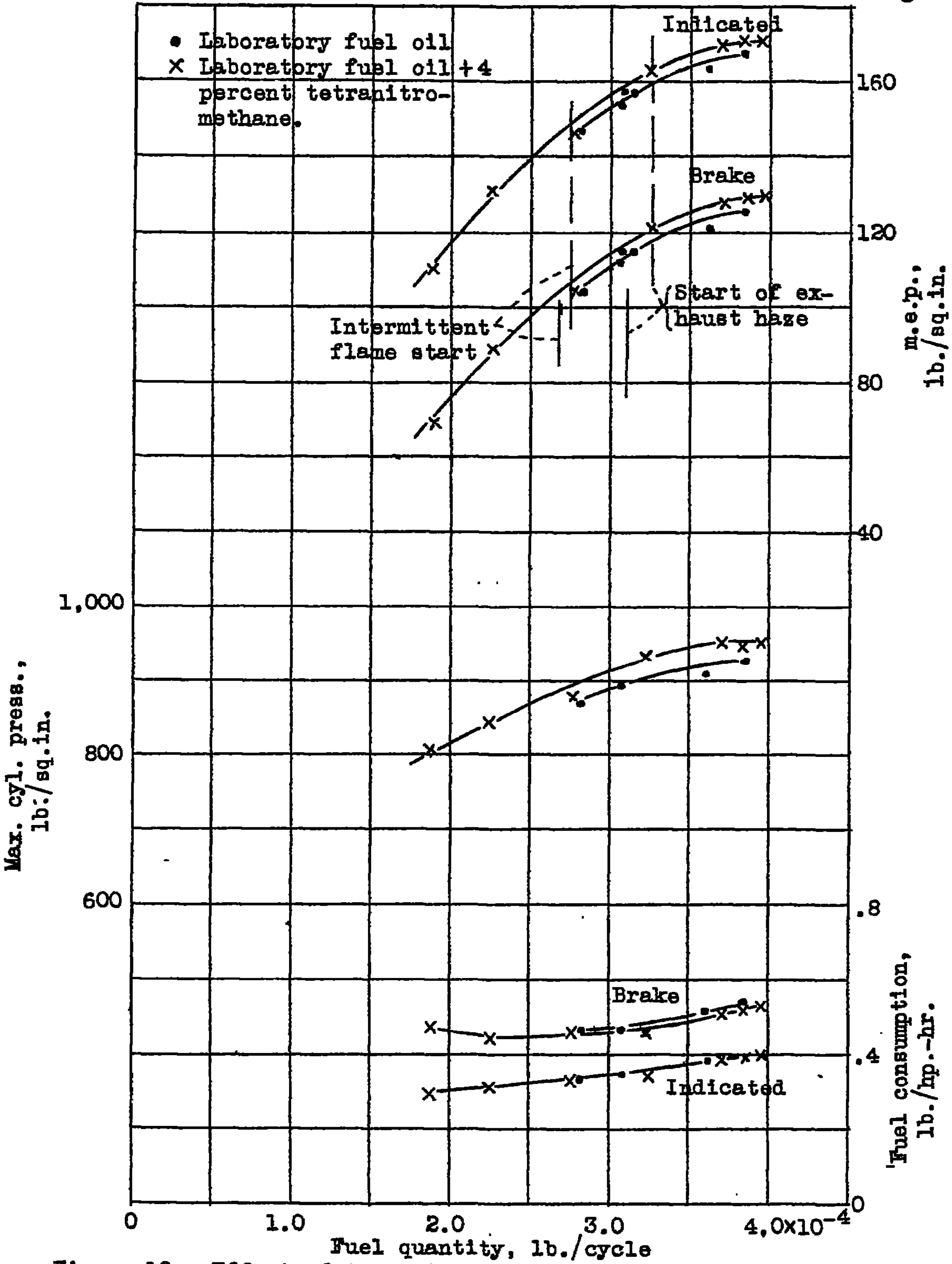

Figure 10.- Effect of tetranitromethane on engine performance. Constant i.a.a., 12°.

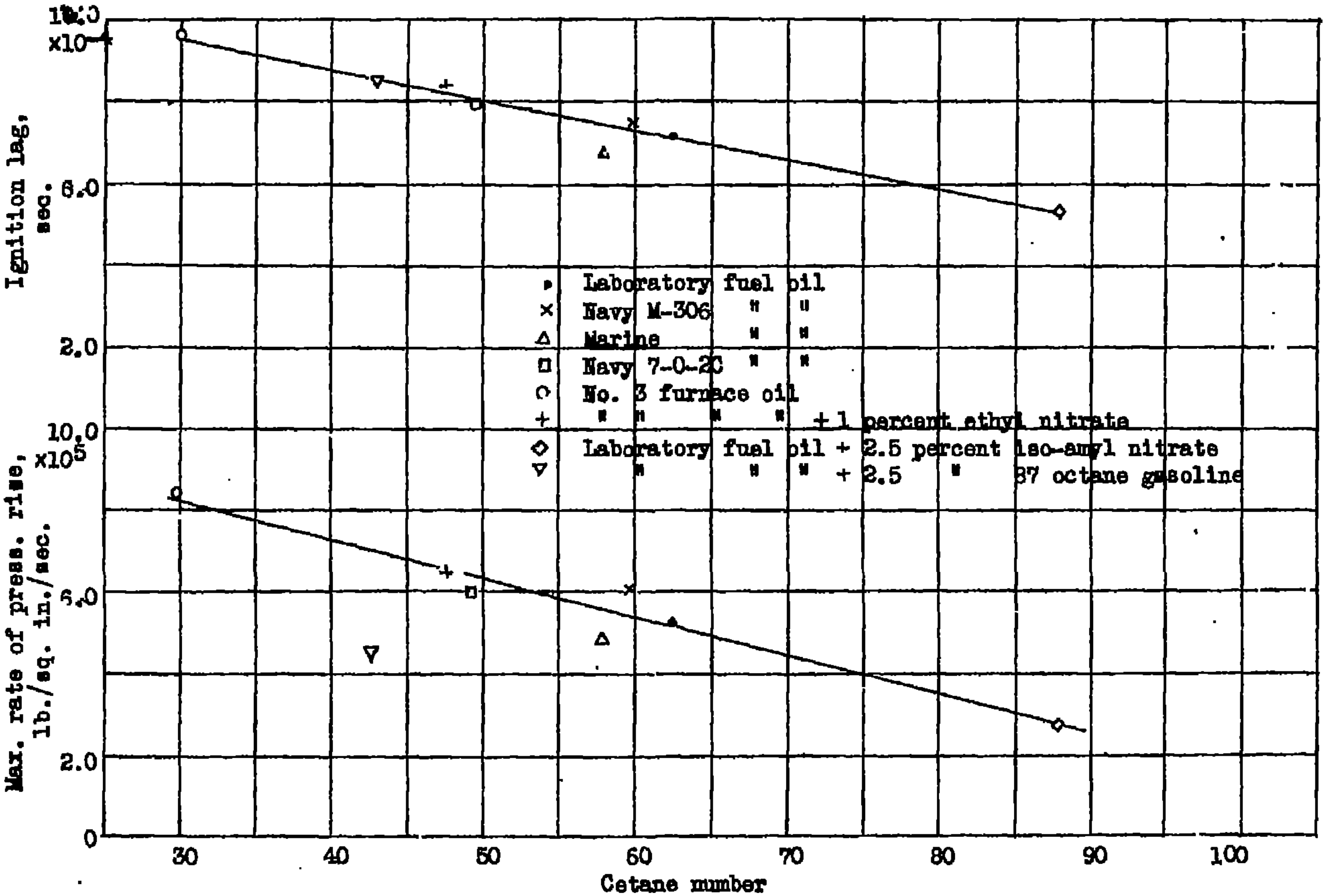

Figure 11.- Cetane number from C.F.R. engine against indicator-card data from high-speed test engine.

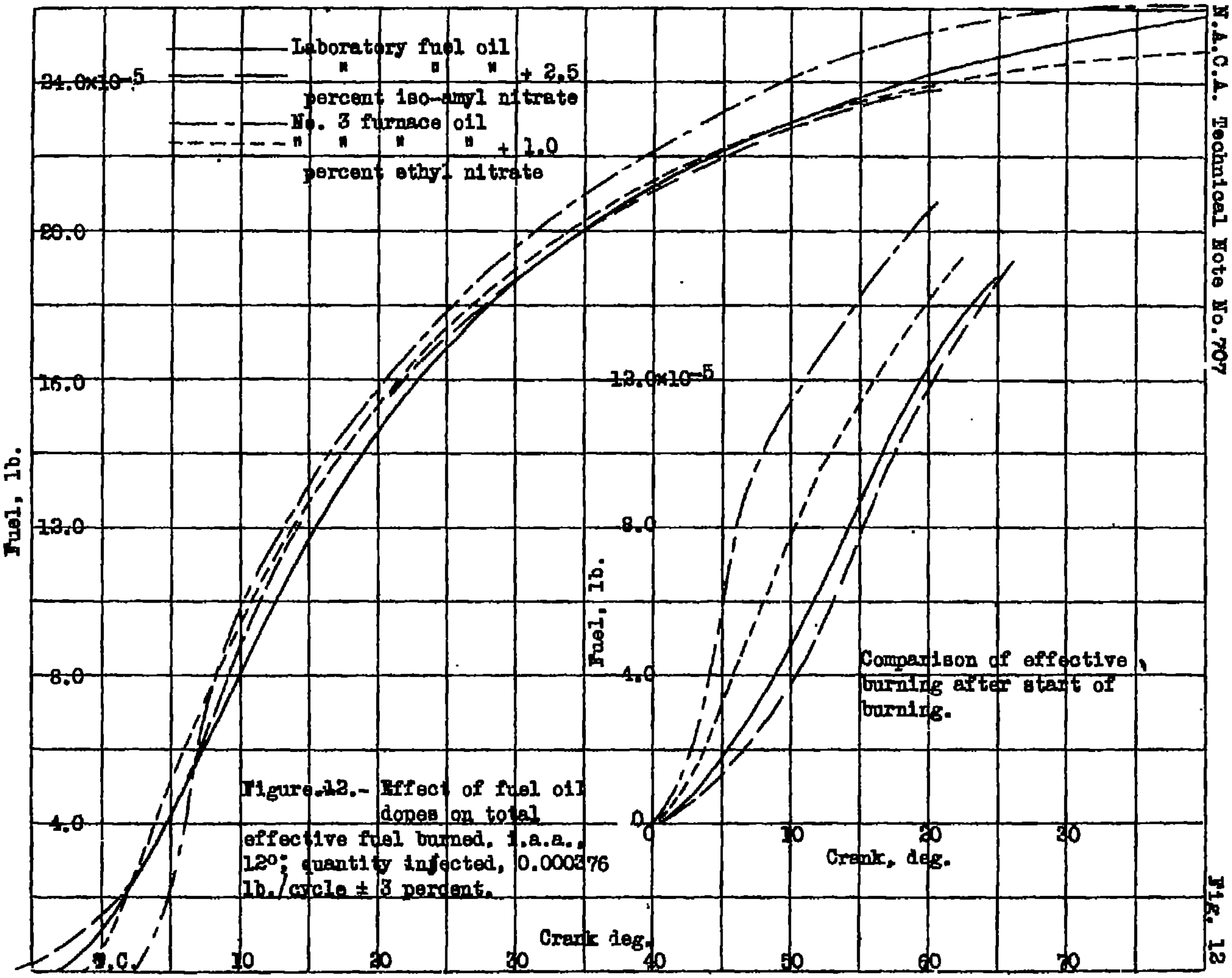

Figure 12.- Effect of fuel oil dopes on total effective fuel burned. i.a.a., 12°; quantity injected, 0.000276 lb./cycle ± 3 percent.

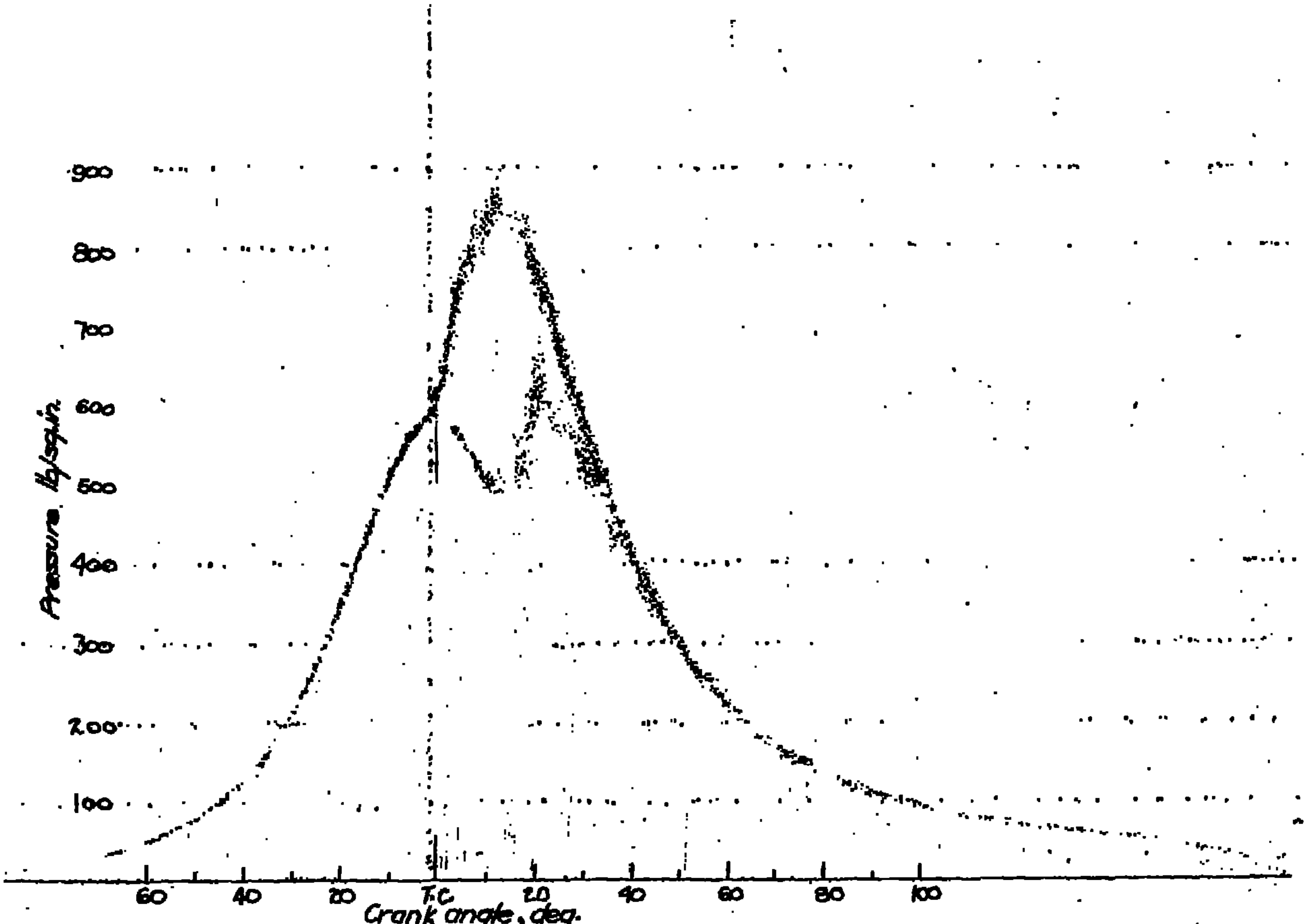

Figure 13.-Indicator card, laboratory fuel oil + 25 percent 87 octane gasoline; quantity, 0.000373 lb/cycle; i.a.a., 12.0° and 2.5°; ignition lag, 10°; maximum rate of pressure rise, 57 lb/sq.in./deg.

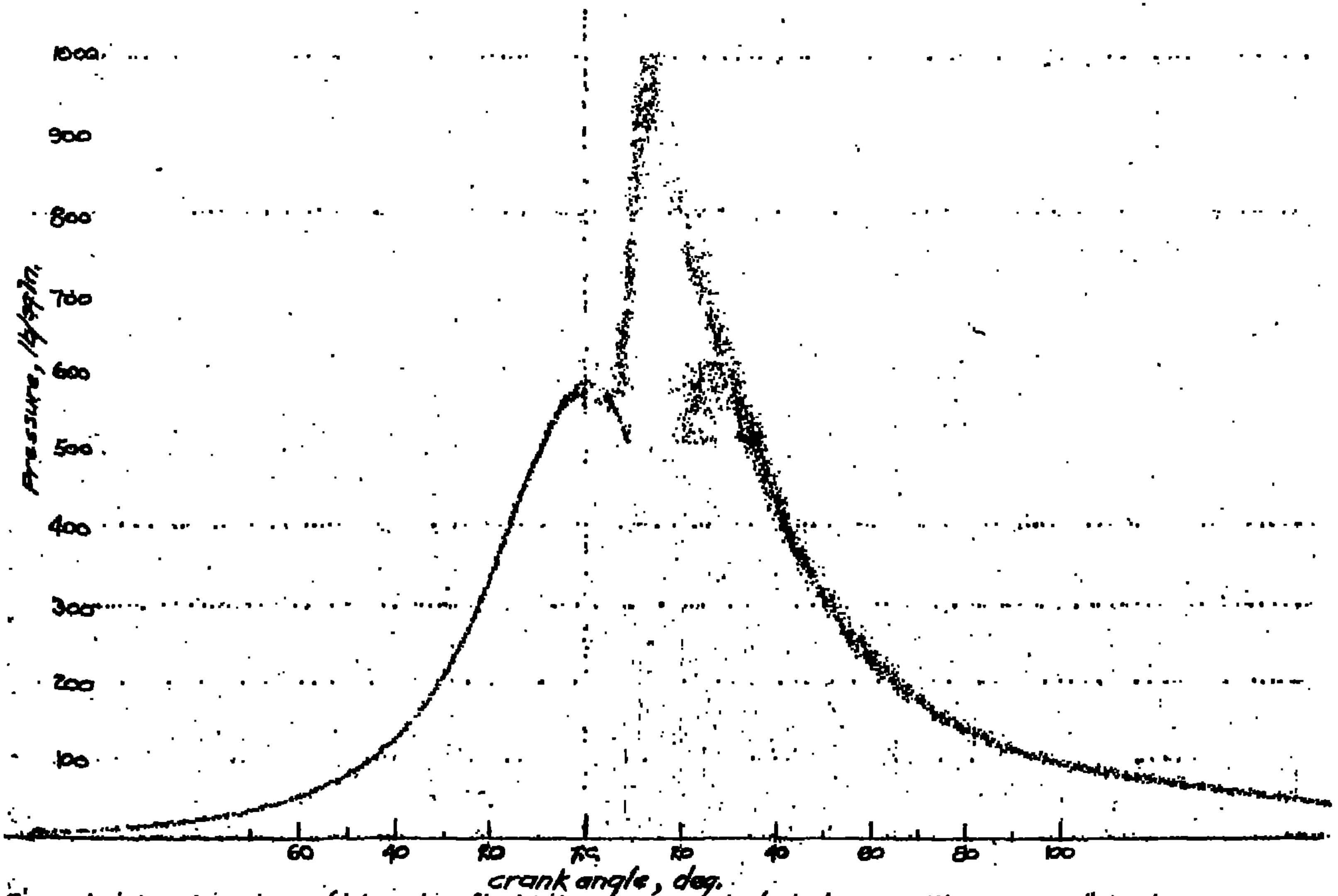

Figure 14.- Indicator card, mixture of laboratory fuel oil + 40 percent alcohol; quantity, 0.000365 lb./cycle, i.a.a., 12° and 4°; ignition lag, 16°; maximum rate of pressure rise, 97 lb./sq.in./deg.

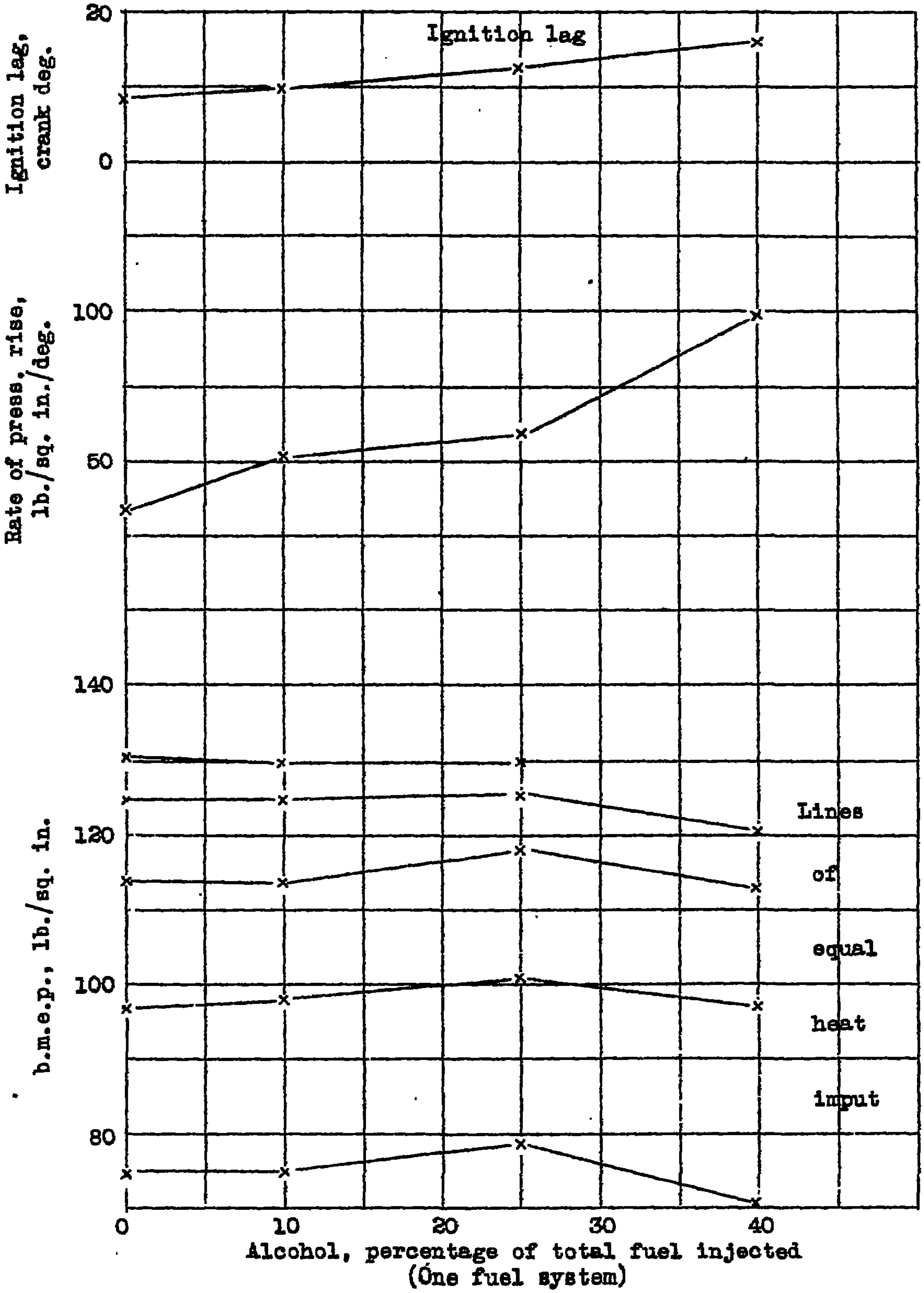

Figure 15.- Effect of alcohol-fuel oil mixtures on several engine performance factors.

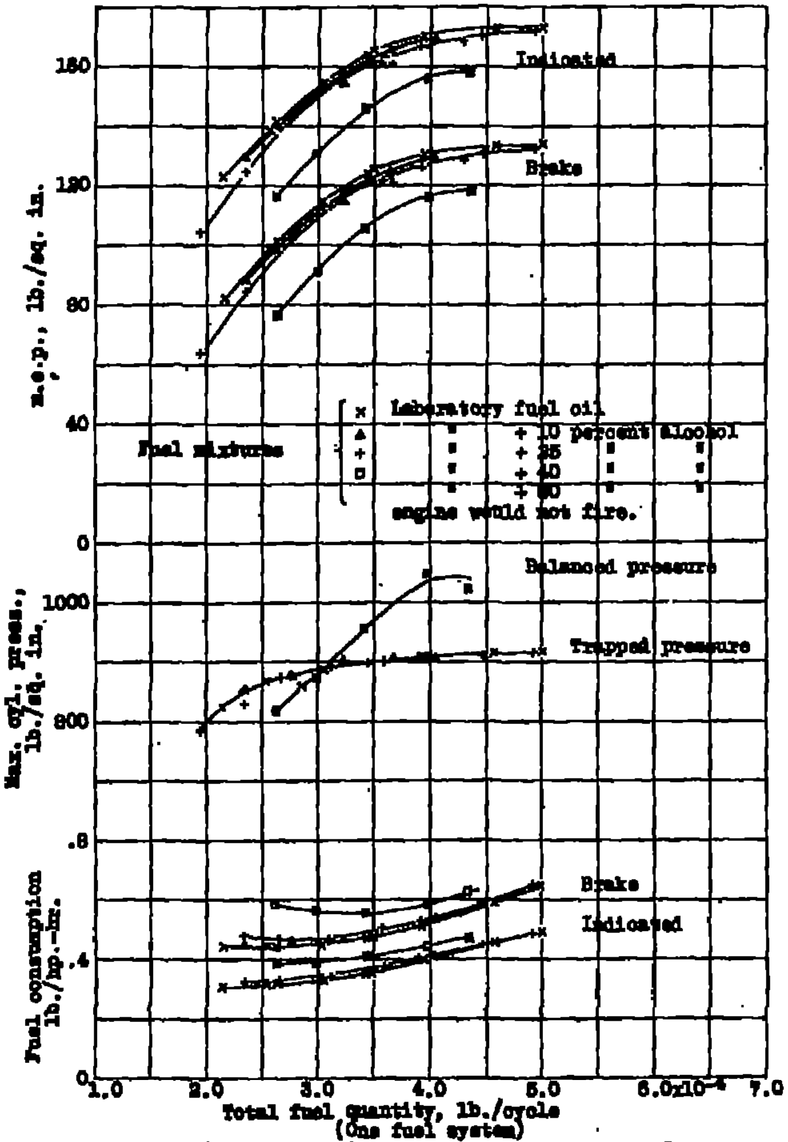

Figure 16.- Effect of alcohol-fuel oil mixtures on engine performance.

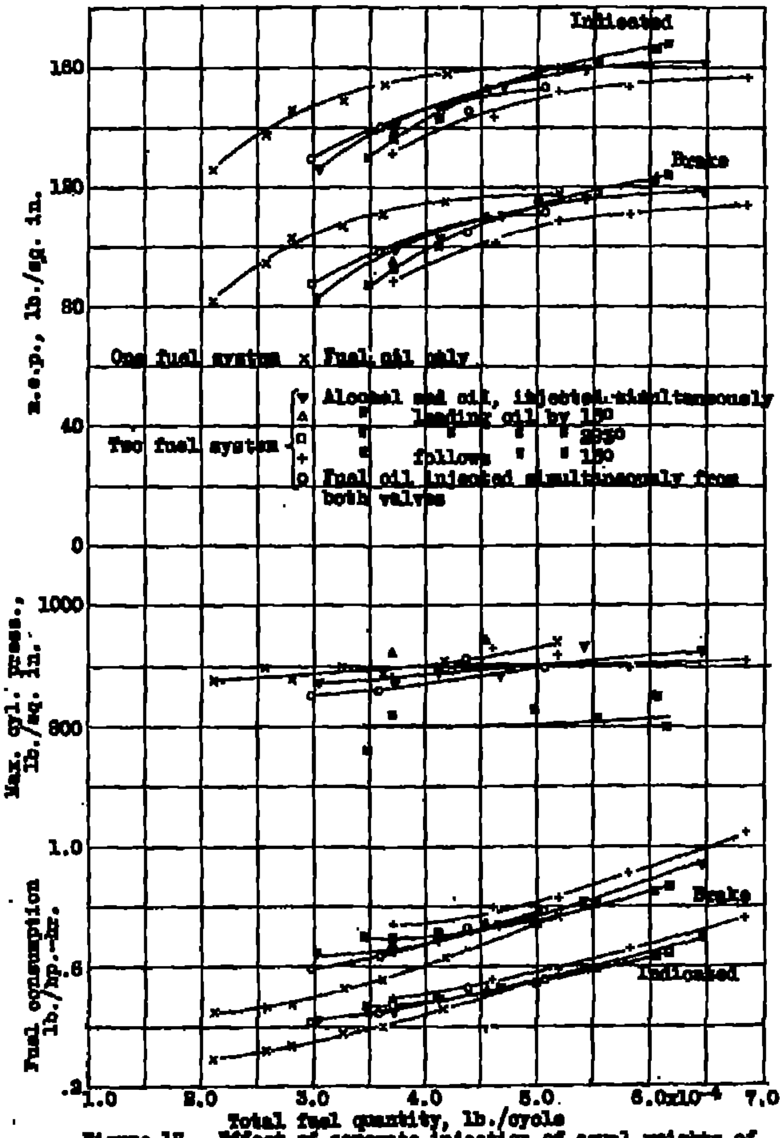

Figure 17.- Effect of separate injection of equal weights of fuel oil and alcohol on engine performance.