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TECHNICAL NOTES

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PERFORMANCE OF A COMPRESSION-IGNITION ENGINE WITH A PRECOMBUSTION CHAMBER HAVING HIGH-VELOCITY AIR FLOW

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Summary

This report presents the results of performance tests made with a single-cylinder, four-stroke-cycle, compression-ignition engine. These tests were made on a precombustion-chamber type of cylinder head designed to have high air velocity and tangential air flow in both the chamber and cylinder. A pear-shaped and a spherical precombustion chamber, both containing one-half the clearance volume at a compression ratio of 14.2:1, were used. The chamber was connected to the cylinder by a single round passage, flared at both ends and having an orifice diameter of 9/16 inch. A cam-operated fuel-injection pump supplied fuel to an automatic spring-loaded injection valve. The fuel was injected from a single round-hole orifice into the precombustion chamber.

The performance characteristics were investigated for variable load and engine speed, type of fuel spray, valve-opening pressure, injection period and, for the spherical chamber, position of the injection spray relative to the air flow. The pressure variations between the pear-shaped precombustion chamber and the cylinder for motoring and full-load conditions were determined with a Farnboro electric indicator.

The combustion chamber designs tested gave good mixing of a single compact fuel spray with the air, but did not control the ensuing combustion sufficiently. Relative to each other, the velocity of air flow was too high, the spray dispersion by injection too great, and the metering effect of the cylinder-head passage insufficient. The correct relation of these factors is of utmost importance as regards engine performance.

Introduction

The general problem in the development of a fuel-injection engine for aircraft is to obtain in an engine cylinder complete and controlled combustion at high engine speeds. A prime requirement for power and combustion efficiency is that the fuel charge be thoroughly mixed with the air. The ensuing combustion must be so controlled that it occurs early in the power stroke, but without excessive cylinder pressures or detonation. These objectives cannot be attained without the correct design of the combustion chamber and the use of the relatively best fuel spray. The necessary characteristics of the fuel spray are determined by the design of the combustion chamber.

Combustion chambers are classified by the shape of the clearance space as two distinct types: the integral type in which the clearance volume contains no restricting passages, and the auxiliary-chamber type in which the clearance volume contains one or more restricting passages. In the integral type, the mixing of fuel and air may be solely by the injection sprays penetrating to all the air in the clearance space. It may be assisted by air movement such as residual or forced air flow relative to the fuel particles. The combustion is controlled by the distribution of the fuel particles as injected and by the rate of fuel injection. (See references 1 and 2.)

In the auxiliary-chamber type of combustion chamber, the means of controlling the mixing and combustion of fuel and air are more numerous.

The auxiliary chamber may function as an air reservoir to meter the air to the combustion in the cylinder, or it may serve as an antechamber in which the fuel charge is prepared for combustion before passing into the cylinder. The antechamber becomes the usual precombustion chamber if combustion starts and is partly completed in it. The size of the chamber and the connecting passages are designed to meter and direct the partly burned, over-rich mixture into the cylinder in such proportion and at such a time that combustion will be completed and cylinder pressures be controlled. This type shows inherent mechanical and thermal losses resulting from the forcing of air and burning gases through restricting passages.

However, a desirable feature of the auxiliary-chamber type of clearance distribution is that it permits the use of a simple, low-pressure fuel spray.

Various shapes of auxiliary chambers, restricting passages, distributions of clearance, and velocities and directions of air flow have been tried in experimental and commercial combustion chambers. However, few if any of these employed high-velocity air flow as a means of mixing the fuel and air while allowing the restricting passage to control the combustion.

The value and characteristics of the precombustion type for high-speed engine performance were investigated by Joachim and Kemper (reference 3) using the N.A.C.A. No. 3 cylinder head designed to give a high velocity of air flow in the precombustion chamber on the compression stroke and of gas flow in the cylinder on the expansion stroke.

Continuing the work of Joachim and Kemper, some minor development work was done in which both the cylinder-head passage and the injection system were altered. Previously the cylinder end of the 9/16 inch passage had been flared to direct the burning gases over one-half the piston crown (reference 3); then the chamber end of the passage was flared to be tangential to the sphere. A slight decrease in f.m.e.p. and a corresponding increase in b.m.e.p. resulted. The injection-valve nozzle was extended $1\frac{1}{2}$ inches into the chamber and a single orifice of 0.025-inch diameter directed the spray at the center of the bulb-to-cylinder passage. Easier starting, slower and more regular idling resulted with a slight increase in maximum power. To reduce the ignition lag, to control combustion, and to reduce the rate of pressure rise, auxiliary orifices having diameters of 0.010 inch were directed into a section of the chamber which had less air flow than the passage. The effect on the combustion was negligible and the difficulties encountered in the injection system were large. To remedy excessive dribbling of fuel trapped in the line when the valve stem seated, a fuel pump was substituted in which a by-pass valve released the fuel pressure and controlled the injection cut-off. Although this gave a sharp cut-off of the fuel spray, the extended fuel valve offered too much restriction to fuel flow and required injection pressures greater than 8,000 pounds per square inch to obtain the injection of 0.0003 pound of fuel early enough in the engine cycle to prevent late, inefficient burning. The mechanical operation of the long valve stem was poor; sticking and slow action accentuated the dribble. The work with the extended fuel valve was discontinued and a simpler valve with a single round-hole orifice nozzle was used.

Making use of the above-mentioned minor alterations, the same cylinder head was used in making the performance tests presented here. The purpose of the tests was, as before, to determine the power performance possibilities and combustion characteristics of a precombustion-chamber-type cylinder head in which a high velocity air flow is used to mix the fuel with the air.

This report presents engine test results of the cylinder head both for a pear-shaped and a spherical precombustion chamber. The engine performance was determined for variations of engine load, speed, type of fuel spray, injection period, injection-valve-opening pressure, and relation of injection spray position to air flow. This work was done by the National Advisory Committee for Aeronautics, at Langley Field, Va.

Apparatus and Methods

The single-cylinder engine-testing unit shown in Figure 1 was used for these performance tests. The engine is four-stroke-cycle, fuel-injection, compression-ignition, of 5-inch bore and 7-inch stroke, and has standard Liberty valves, valve-actuating mechanism, and connecting rod. The piston had a domed crown of the same curvature as the cylinder head. The forms of combustion chambers tested (N.A.C.A. No. 3 with two shapes of precombustion chamber) are shown in Figure 2. Substituting a hemispherical shape of chamber cap for the conical one gives the spherical form. The standard cylinder head for these tests was the form with the conical cap. Both ends of the 9/16-inch-throat-diameter connecting passage are flared.

The fuel-injection system consisted of a primary gear pump, a cam-operated fuel-injection pump, and a spring-loaded automatic fuel-injection valve. (See fig. 3.) The Diesel fuel oil, of 0.847 specific gravity and a viscosity of 41 Saybolt seconds (Universal) at 80° F., was delivered by the primary gear pump at 125 pounds per square inch pressure to the injection pump. The injection pump was of the constant-stroke type and the plunger was driven at a constant acceleration by a cam mounted on an extension of the engine crankshaft. The extension consisted of a speed reduction and timing mechanism which operated the pump at camshaft speed and allowed the injection advance angle to be varied while the engine was running by changing the angular relation of the fuel cam with respect to the crankshaft. The quantity of fuel injected was controlled by varying the duration of the closure of a by-pass valve in the pump. The automatic fuel-injection valve was opened by the pressure of fuel oil acting on a differential area of the stem. Two single-orifice nozzles of the same type (fig. 3) were used, the standard nozzle having a 0.050-inch diameter orifice and one other nozzle designed to have its orifice diameter enlarged as desired. Two valve stems were used. The standard plain stem gave the noncentrifugal, highly penetrative spray cone of Figure 4 and the other - a stem having two helical grooves of 23° helix angle - gave the more dispersed centrifugal spray of low penetration shown in Figure 5. The photographs show the large difference in dispersion and penetration in still air for the two stems used. The photographs were obtained with the N.A.C.A. spray photography equipment (reference 4) for conditions corresponding to those of the engine performance tests; i.e., injection pressures equal to those of full-load fuel quantity, and a spray chamber air density equal to that in the combustion chamber of the engine with the piston at top center.

Figure 1 shows the equipment for measuring the several variables of engine performance. The fuel input was measured by timing electrically the consumption of one-half pound of fuel oil during the same interval that a synchronized revolution counter recorded the number of engine revolutions. The air consumption was determined by a Venturi meter, previously calibrated by a gasometer. The engine was connected to a 50- to 75-horsepower electric dynamometer which served to motor the engine for starting and friction runs, and to absorb the power developed by the engine. The engine power was calculated from the torque indicated by the dynamometer scales and the revolution counter. The maximum cylinder pressures were indicated by the N.A.C.A. trapped-pressure indicator. (See reference 5.) The Farnboro indicator, before being improved (reference 6), was used to obtain indicator cards. The injection periods and injection advance angles were determined from observations with the oscilloscope. (See reference 7.)

Several conditions were kept constant during these engine tests. The compression ratio was 14.2:1 and at the standard engine speed of 1,500 r.p.m. the compression pressure was 500 pounds per square inch. The distribution of clearance between the cylinder and auxiliary chamber was in the ratio of 1:1 for both forms of precombustion chamber used. The standard chamber shape, however, was the one with the conical cap. (Fig. 2.) The standard valve-opening pressure was 3,500 pounds per square inch. The full-load fuel quantity was taken as in the previously reported tests; i.e., 0.0003 pound per cycle. This is the amount of fuel that would give 12 per cent excess air in the cylinder at a volumetric efficiency of 85 per cent. The single 0.050-inch-diameter orifice nozzle was taken as standard. The injection system, when using this nozzle, gave an injection period of 35 crank degrees as determined with the oscilloscope for full-load fuel. The standard cylinder pressure as given by the trapped method at full-load fuel quantity was 750 pounds per square inch and was maintained by varying the injection advance angle. The outlet temperature of the cooling water was 170° F., that of the lubricating oil, 140° F., and the temperature of the inducted air, 95° F.

To obtain the data here presented a series of engine performance tests was made with the cylinder head as shown in Figure 2. The following variables were changed one at a time; fuel quantity, type of fuel spray (i.e., centrifugal or noncentrifugal), engine speed, valve-opening pressure, and injection period. All other variables were kept constant. The variation in injection period was obtained by enlarging the orifice of one of the two single-orifice nozzles from 0.020 inch to 0.060 inch in diameter, maintaining, however, a length-diameter ratio of 2.5. For all other tests the nozzle having the single 0.050-inch-diameter orifice was used because, with the fuel pump and valve available, this size gave the shortest injection period and the most power. Indicator cards were taken from the chamber and cylinder for motoring and full load power conditions at 1,500 r.p.m. The approximate direction of air flow in the auxiliary chamber was determined by motoring the engine while thin copper strips extended into the chamber from the gasket separating the head from the chamber cap. The direction of bending indicated the direction of air flow. These indications were confirmed by streaks of carbon left inside the previously cleaned and polished chamber after motoring the engine. As these tests indicated that the air flowing into the chamber was directed toward the apex of the cone and that its energy was largely dissipated there, the chamber was made spherical (fig. 2), the purpose being to aid the formation of a rotating sphere of air in the chamber and to conserve its energy. A series of full-load fuel quantity power runs at 1,500 r.p.m. was made with the spherical chamber while the position of the injection spray was varied relative to the air flow. This variation was accomplished by placing the injection valve in the side hole of the cap and by rotating the cap successively into each of the ten possible positions.

The data obtained from the tests have been computed and plotted, and are presented as curves of engine performance and as indicator cards. The indicated horsepower was taken as the sum of the brake and friction horsepowers, the friction power being that required by the dynamometer to motor the engine immediately after the power run.

In the discussions that follow, reference is made to engine detonation. By detonation is meant the metallic sound present during combustion which is associated with detonation in carburetor engines. This condition was present irregularly in the engine operation of these tests and indicated incipient detonation.

Test Results and Discussion

Effect of load on engine performance, noncentrifugal spray.- Figure 6 gives the engine performance of the standard cylinder-head form with conical cap (fig. 2), as affected by fuel quantity for the plain, noncentrifugal spray of Figure 4 and by an injection advance angle of 26°. The power is much improved over that previously obtained from this head (reference 3); the slope of the m.e.p. curves decreases more slowly. The i.m.e.p. at full load has increased from 119 to 134 pounds per square inch at a mechanical efficiency of 70.8 per cent. The maximum cylinder pressure curve attains a maximum at the same fuel quantity at which the m.e.p. curves deviate from a straight line. At this point the combustion sound was slightly metallic and irregular and passed through its maximum loudness. As the cylinder pressure remains nearly constant above one-half load it is indicated that the auxiliary chamber and connecting passage control combustion somewhat. The improvement in combustion is indicated by clear exhaust at 22 per cent excess air and by the decreased fuel consumption 0.43 to 0.39 pound per indicated horsepower per hour at full load with 12 per cent excess air. The excess air was determined from experimental data. For the same conditions but on the basis of brake performance, the fuel consumption was decreased from 0.71 to 0.56 pound per horsepower per hour. The capacity of the engine for overload is shown since the i.m.e.p. increased to 141 pounds per square inch. The improved performance was due mostly to the shorter injection period and to a more penetrating fuel spray, but it was aided by the flaring of the chamber end of the chamber-to-cylinder passage and by the improved mechanical efficiency of the engine. The shorter injection period gave time for the fuel to be better mixed with the air and to burn more efficiently.

Effect of load on engine performance, centrifugal spray.- The effect of load on engine performance when using the centrifugal injection spray is seen in Figure 7. This spray gave more detonation than the noncentrifugal injection spray and the test was run at a reduced injection advance angle and cylinder pressure. The injection advance angle was reduced to 23° B.T.C. at which condition the sound of the engine compared to that of the test for Figure 6, although the cylinder pressure was but 650 pounds per square inch. This retardation accounts for the poorer performance as presented. One test, made by advancing the injection to 26° B.T.C., as in the work of Figure 6, at a maximum cylinder pressure of 750 pounds per square inch and at full-load fuel quantity gave results equal to those of the noncentrifugal injection spray. At low loads the effect of the injection advance angle on cylinder pressure and power was negligible. The centrifugal spray does not give more power but does give more detonation because the centrifugal spray has greater dispersion.

Effect of speed on engine performance.- Figure 8 shows the effect of engine speed on the performance at full-load fuel quantity and 750 pounds per square inch cylinder pressure. Although the intensity of the fuel-mixing air flow should vary directly with the engine speed, the power does not vary with the engine speed. The indicated performance is little affected from 900 to 1,800 r.p.m., although the velocity of air flow should be about doubled. The power required to cause the air flow, however, causes a decrease of b.m.e.p. from 103 to 88 pounds per square inch, the i.m.e.p. remaining constant. The best operating speed for this particular head is about 900 r.p.m., at which speed the i.m.e.p. is still at a maximum and the f.m.e.p. has decreased from 40 to 27 pounds per square inch. The points at 1,200 r.p.m. are low because the injection advance angle was below normal. Although the cylinder pressure was kept constant the injection angle was advanced but half as fast as the engine speed. The velocity of the fuel-mixing air flow, however, increased with the engine speed so that the more complete fuel and air mixing would increase the rate of combustion. Furthermore, from observations with the oscilloscope it was seen that with increase in speed the injection spray became more widely dispersed and the start of the spray more faint.

The engine was started when cold by motoring at 600 r.p.m., but when warm from previous running it could be started by two revolutions of the crankshaft. It could be idled at 250 r.p.m., could be readily accelerated at the highest speed attempted, and would run steadily at all conditions of load from 600 to 1,800 r.p.m.

Effect of valve-opening pressure on engine performance.- The salient advantage of the precombustion-chamber type of cylinder head is shown in Figure 9, the data for which were obtained by varying the valve-opening pressure. As the valve-opening pressure is varied, the characteristics of the spray change; but the engine performance is seen to be little affected, a decrease in valve-opening pressure from 6,000 to 1,500 pounds per square inch causing only a slight improvement in engine performance. The maximum injection pressure decreased from 8,000 to 3,000 pounds per square inch, while the apparent injection period varied from 35° to 40°, a change which in itself should have decreased the performance. At the lower pressures the dispersion and penetration are decreased, but the characteristic of the head (i.e., high-velocity air flow) mixes the fuel with the air to maintain the engine performance constant. At none of the injection pressures did the fuel spray penetrate the 2-9/16 inch length of the chamber to deposit carbon opposite the valve position. The air flow reduced the penetration for, if in still air, the penetration and time would have been sufficient for the spray to hit the chamber walls.

Effect of injection period on engine performance.- The effect of the length of the injection period on engine performance is shown in Figure 10. Although the oscilloscope gives no definite information as to the rate of fuel discharge, it was clearly seen that the discharge during the first 10° was very small. The engine performance results indicate that to obtain maximum fuel economy and power the injection period must be shortened, even shorter than in the results presented. The shortening of the injection period gives better mixing, as the fuel is injected nearer the time of highest velocity air flow and, as the clearer exhaust and lower fuel consumption both indicate, late inefficient combustion is reduced. The combustion control by the precombustion chamber is indicated by the cylinder pressure reaching a maximum at a period of 35° to 40° - the power, however, continuing to increase. The orifice diameter and injection pressures are given on Figure 10 to show their relation to the injection period. The investigation of injection-period effect was not continued, because further increasing the orifice diameter lengthened rather than shortened the injection period. This lengthening was due to insufficient stem lift which caused throttling at the stem seat.

Effect on engine performance of injection position in the spherical chamber.- The direction of air flow in the auxiliary chamber and the effect of fuel-spray position relative to this air flow on the engine performance are shown in Figure 11. The air leaves the passage and rotates as a sphere about the axis indicated, with the greatest intensity of flow being at points 7 and 2 and the least intensity being at the axis ends, points 9 and 4. With the fuel spray in similar positions in the pear-shaped and spherical chambers, the engine performances are equal except that the combustion is with more incipient detonation for the spherical chamber. This increased detonation is apparently caused by the changed relation of the fuel spray to the higher velocity air flow. As the injection characteristics are the same as when the conical chamber cap is used, the ignition must be later and be actually retarded until more fuel is ready to burn. The retardation is probably caused by the air flow sweeping the faint spray start onto the walls or separating the fuel particles too widely. A faint deposition of carbon to leeward of the valve positions was seen after each power run.

The position of most power and most regular combustion with least combustion shock was the No. 2 position. The spray travel was perpendicular to the axis of the air whirl; i.e., the spray met first the lower velocity of air and then the higher. The reverse of these conditions, position No. 7, gave the least power and most irregular combustion sound. Apparently the air velocity given by the 9/16 inch diameter passage was too high for the fuel-spray characteristics used, as indicated by the increase in power and decrease in detonation when the spray position passed from the greatest to the least velocity air flow. The fuel spray penetrated the distance of 2-3/16 inches across the spherical chamber in each of these tests and opposite the valve positions carbon deposits were left. The carbon deposits were slightly displaced in the direction of the air flow. In the tests which left the largest carbon deposits the performance, including the exhaust conditions, was the best.

<u>Indicator cards - Motoring</u>.- The motoring indicator cards of Figures 12 and 13 from the standard cylinder head, although made while driving the indicator drum at crankshaft speed and using as large a pressure scale as the indicator would permit, do not show any appreciable pressure lag between the cylinder and the precombustion chamber during the compression stroke. The absence of any pressure lag indication may be due either to a passage restriction insufficient to cause a pressure lag in the chamber or to the inability of the indicator cards to show the small pressure lag. For the indicator cards as obtained, the compression curves are practically identical until a pressure of 400 pounds per square inch is reached, above which the chamber pressure leads and rises higher by 15 pounds per square inch than the cylinder pressure. The expansion curves are identical below 450 pounds per square inch. This compression-pressure difference was consistently recorded and was further investigated with the trapped-pressure method. The trapped-pressure valve placed in the cylinder and in the two chamber cap holes gave chamber pressure readings consistently higher by 20 pounds per square inch than in the cylinder, thus checking the indicator cards within the limits of allowable errors. The higher pressure in the chamber is contrary to what could be expected from air passing through a restricting passage into a chamber and no conclusive explanation is presented at this time. Attention is directed, however, to the different conditions of the compressed air in the cylinder and in the chamber; the air is compressed in the cylinder with-

out appreciable flow, but the air forced through the passage continues its motion inside the chamber. Thus the pressure-indicating unit in the cylinder is actuated by comparatively still air whereas the unit in the chamber is actuated by air rotating at high velocity. A comparison of the motoring and power cards shows that the compression pressure of the motoring cards is less than that of the power cards, as the motoring cards, although taken at standard engine-operating temperatures, were not taken immediately after a power run when the combustion chamber walls were hot.

Indicator cards - Power.- The power indicator cards from the standard cylinder head are neither complete enough nor of sufficient accuracy for quantitative analysis. They are noteworthy, however, for the indications of start and rate of pressure rise. The start of pressure rise is late for both chamber and cylinder, an approximate ignition lag being 35° crank angle. For the chamber, however, the start is 2° earlier than for the cylinder, showing that the precombustion-chamber principle is in operation. When the injection time was advanced to obtain ignition at T.C., the detonation was excessive and power was increased but little. Even with the late ignition, the indicator recorded occasional pressures of 900 pounds per square inch (the trapped pressure of 750 pounds per square inch being only an average). The cause of the occasional high pressures and detonations was the irregularity of ±2° in the injection advance angle. This irregularity was noticed while watching the spray with the oscilloscope.

Determinations of rate of pressure rise from the indicator cards are affected by the variation between the engine cycles. A small error in measuring the slope of the rise affects the numerical value greatly. The values are indicative, however, of the high rates obtainable in this type of head. The maximum rates of pressure rise in the precombustion chamber and in the cylinder are 1,030,000 pounds per square inch per second and 1,530,000 pounds per square inch per second, respectively. The lower rate in the chamber is due to the overrich mixture there. The mixture in the cylinder is more nearly in optimum proportions of fuel and air and burns faster. On the basis of present-day carburetor-engine practice (reference 8) the rate of pressure rise obtained will allow an engine speed of approximately 4,000 r.p.m.

The combustion sound for nearly all operating conditions was intermittently metallic at one-half load, dull at lower speeds, and sharper as the speed increased. The lessened spray dispersion at a valve-opening pressure of 1,500 pounds per square inch, the injection into lower velocity air flow, and the increase in the amount of fuel above one-half load decreased the detonative tendency and also the cylinder pressure.

This combustion chamber design is sensitive to injection advance angle above one-half load, for if the angle were changed by five crank degrees the combustion would vary from missing to steady detonation. This detonative tendency is caused by excessive air flow and, relatively, too much dispersion of fuel spray; ignition occurs when most of the fuel is injected and thoroughly prepared for combustion. The cylinder-head passage lacks sufficient restriction to meter the gas flow and control the combustion.

Conclusions

These results indicate that this cylinder head, for both forms of precombustion chamber, is capable of giving rapid mixing and combustion even when using a single compact, low-pressure injection spray from a large round-hole orifice nozzle. The same power and less combustion shock are given by a noncentrifugal as by a centrifugal spray having greater dispersion of fuel particles.

The engine performance improves as the injection period is decreased, indicating that the maximum power will be given by a period shorter than used in these tests.

The relation between air velocity and fuel-spray position and dispersion influences the performance of the precombustion-chamber-type engine. In these tests the air-flow velocity was too high for the fuel-spray dispersion. The mixture of fuel and air was slow to ignite but burned rapidly.

A high injection pressure is unnecessary. In fact, a decrease in injection pressure, which decreased the spray dispersion and penetration, caused a slight increase in engine performance. Similarly a decrease in engine speed with the consequent decrease in air-flow velocity affected the indicated performance but slightly. However, the brake performance was affected because the mechanical efficiency varied inversely as the engine speed.

With the clearance distribution used the combustion was not controlled by the cylinder-head passage, and any further reduction in passage area would have increased the already too high air-flow velocity. Small differences in the injection advance angle of successive cycles gave intermittent detonation. The rates of pressure rise obtained indicate, on the basis of carburetor engine performance, that this head is capable of operating an engine at approximately 4,000 r.p.m.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 3, 1931.

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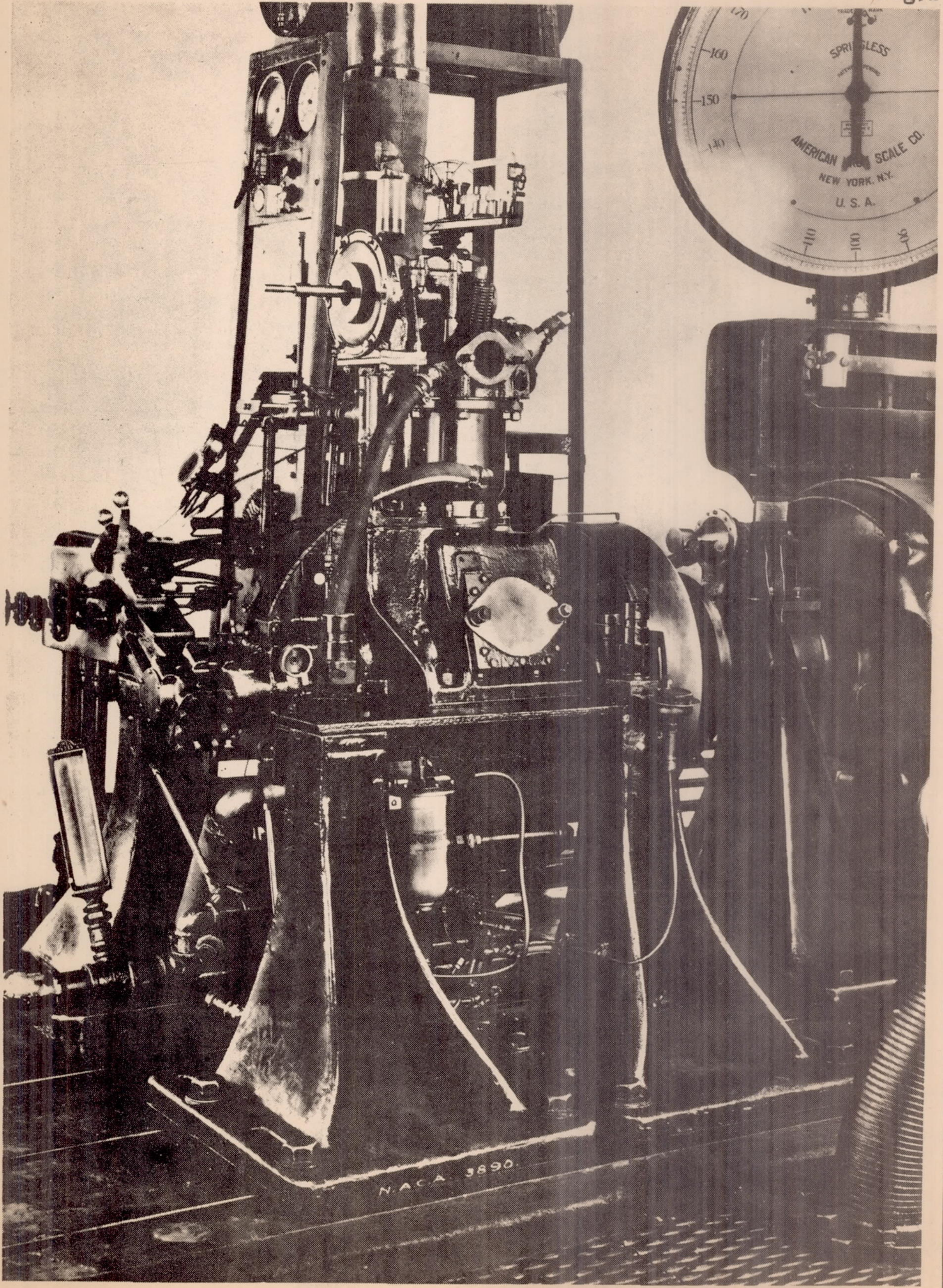

Fig.1 Single-cylinder research engine and testing equipment.

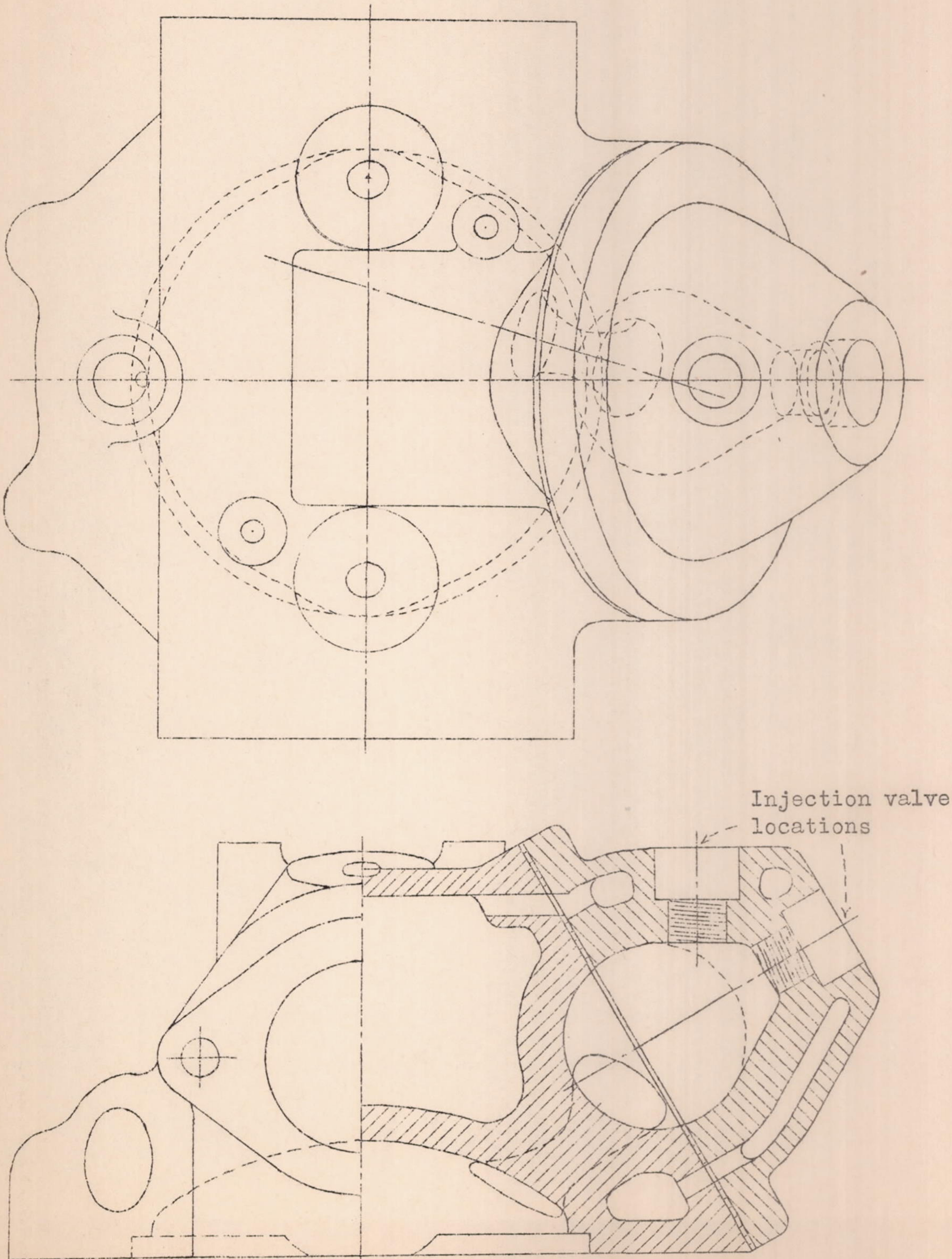

Fig. 2 N.A.C.A. cylinder-head design No. 3 showing pear-shaped and spherical (dotted) chamber forms. Passage throat diameter 9/16 inch.

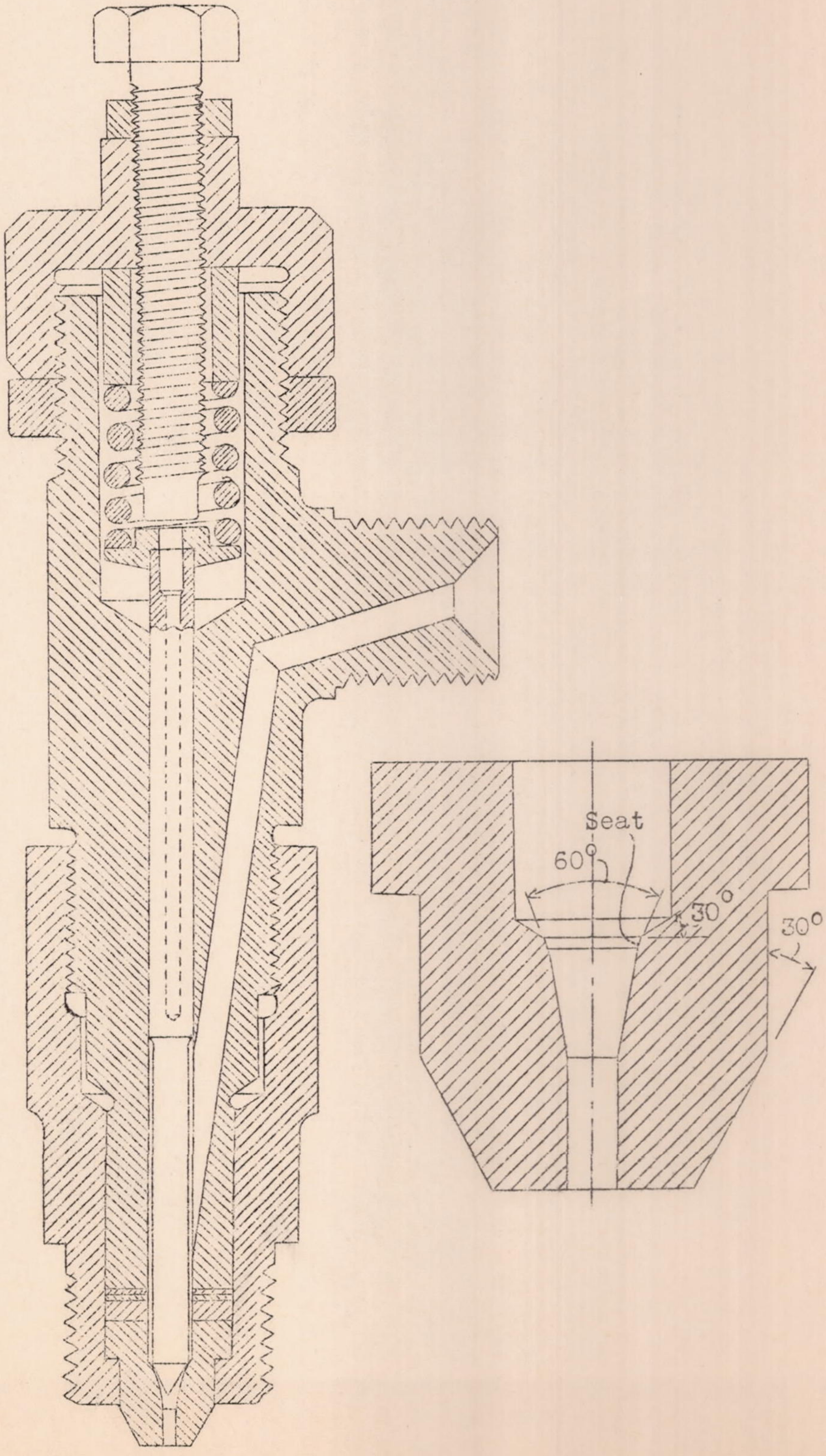

Fig.3 Automatic fuel-injection valve and single-orifice nozzle. Orifice diameter 0.050 in.

Types of injection spray used in tests. Orifice diameter, 0.050 in., air density, 1.11 pounds per cubic foot, corresponding to compression ratio of 14.2 : 1.

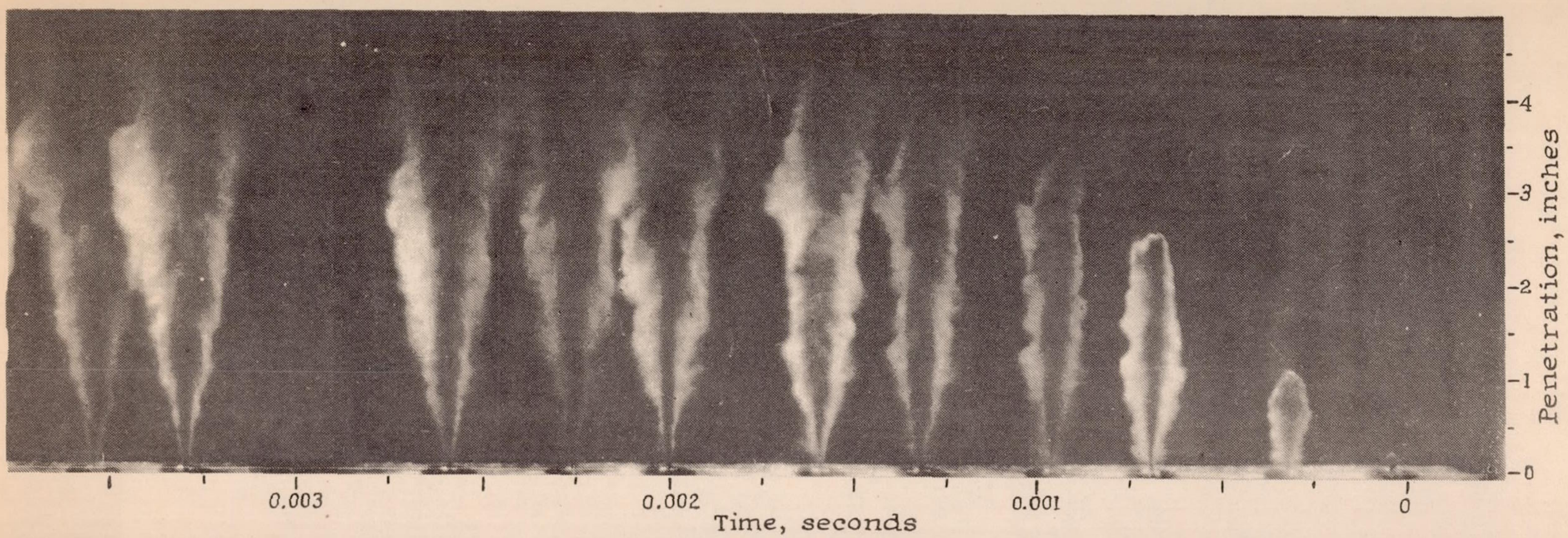

Fig.4 Noncentrifugal spray. Injection pressure, 4100 pounds per square inch gauge.

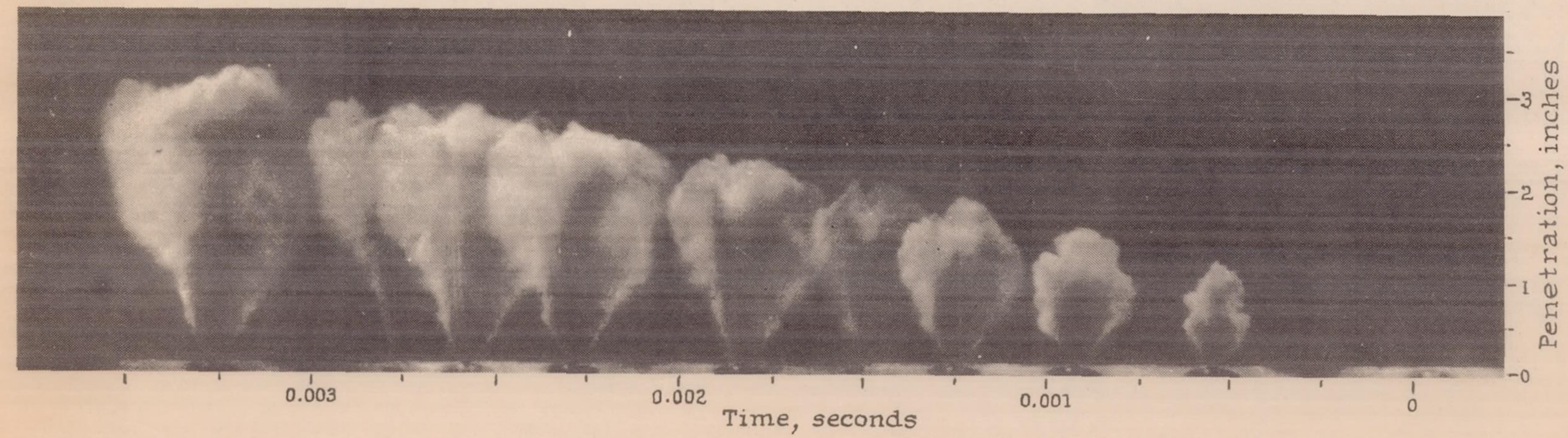

Fig.5 Centrifugal spray. Helix angle 23°, injection pressure 4700 lbs. per square inch gauge.

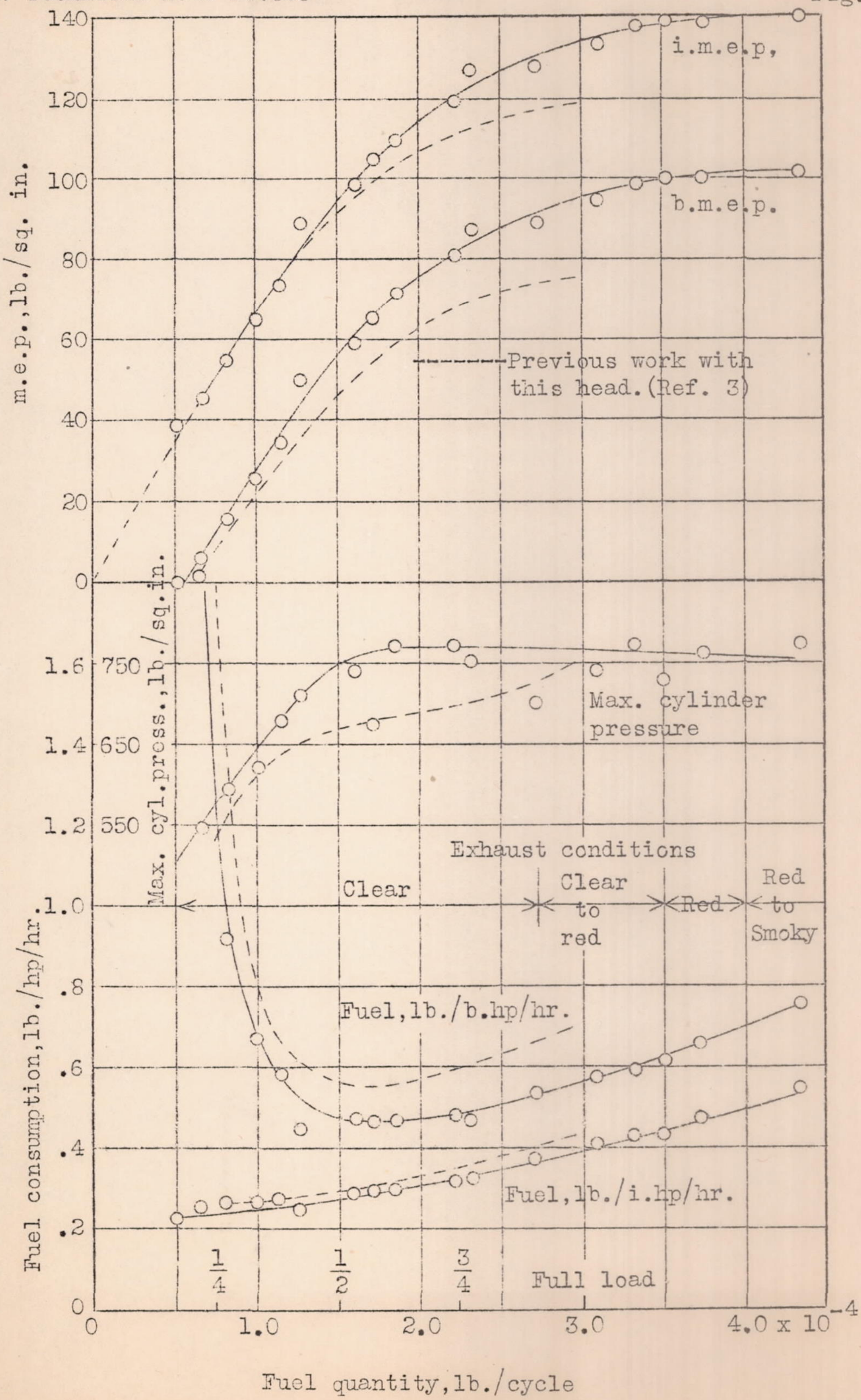

Fig.6 Effect of load on engine performance.

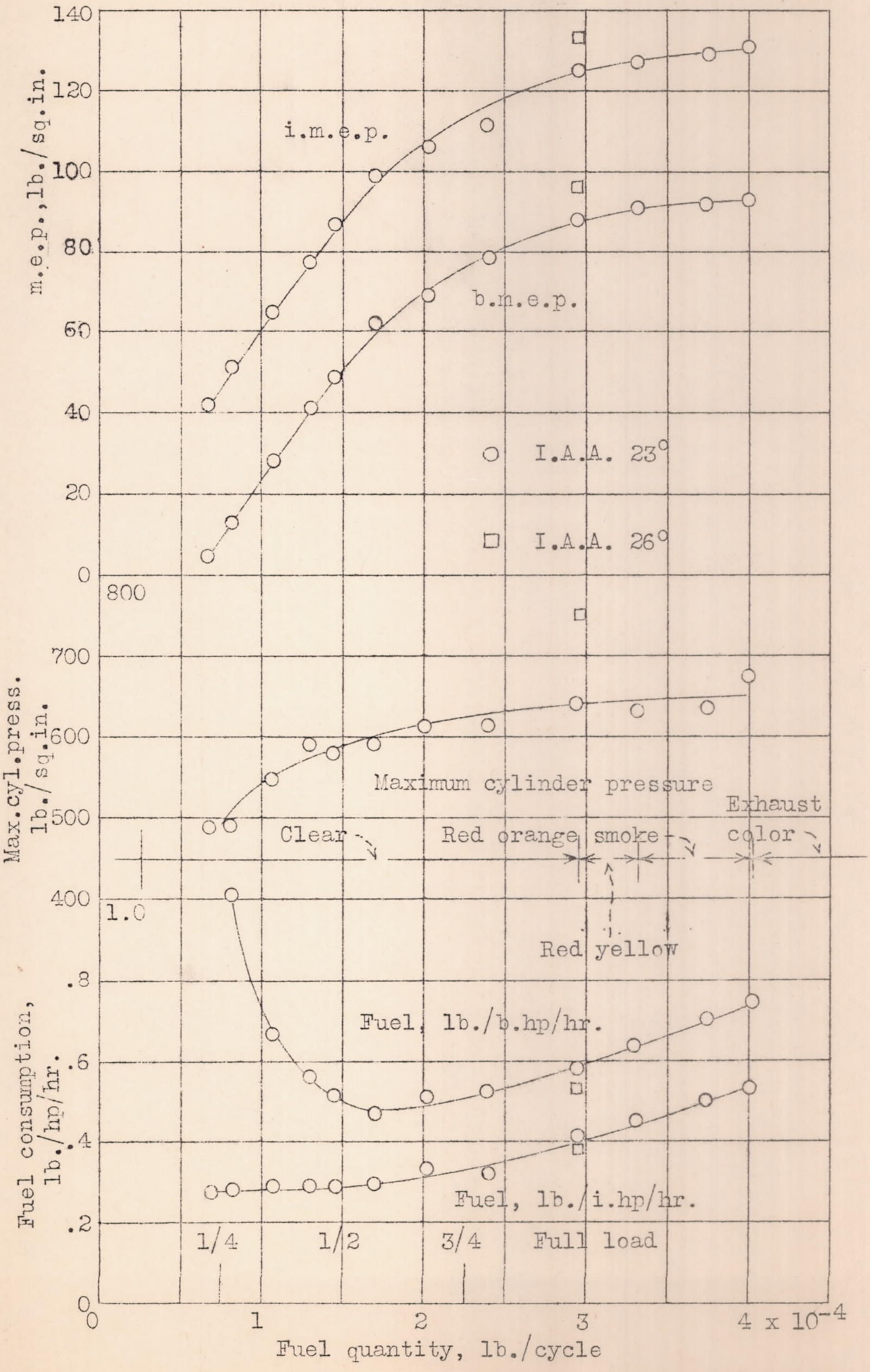

Fig. 7 Effect of load on engine performance (centrifugal spray).

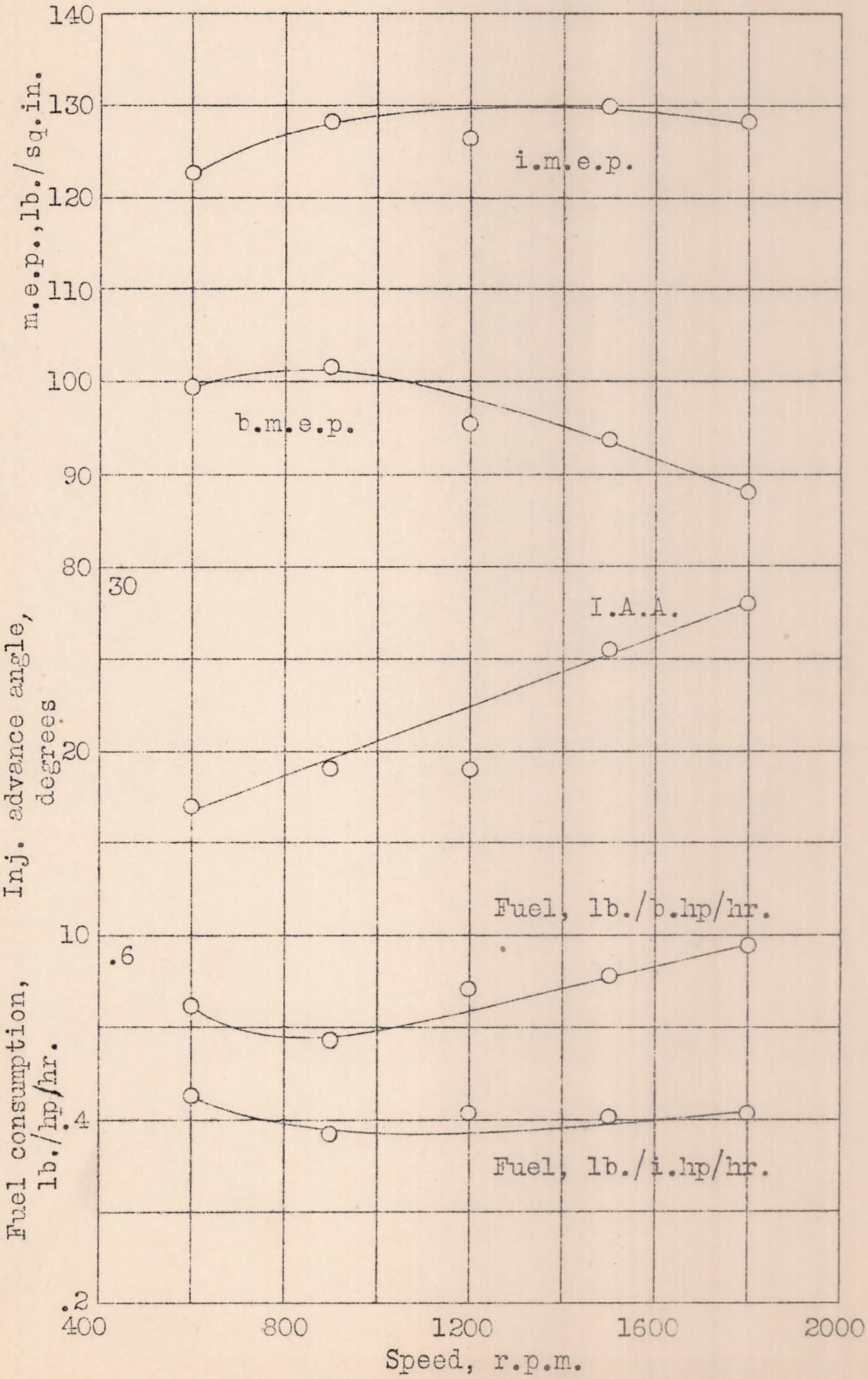

Fig. 8 Effect of speed on engine performance.

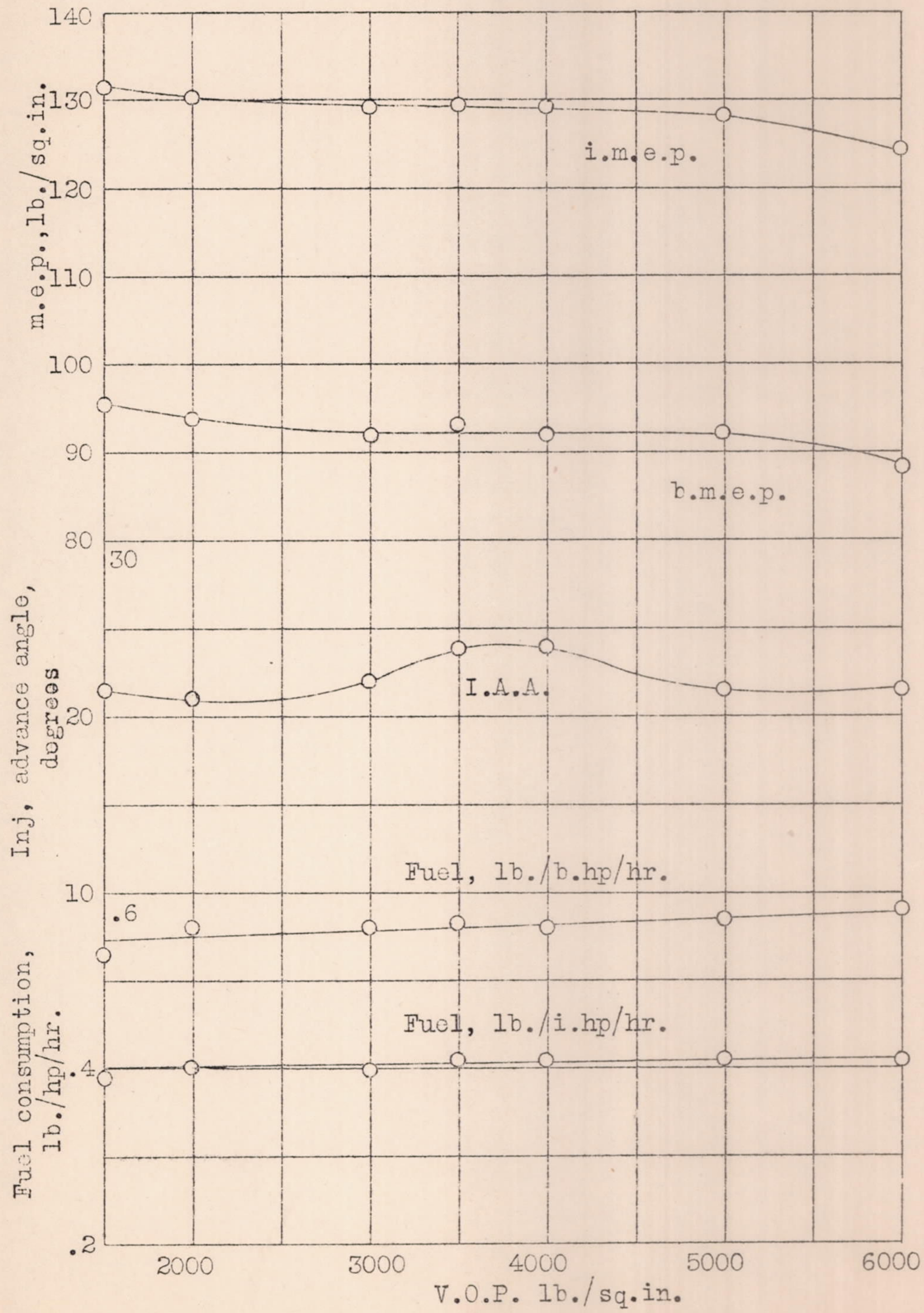

Fig. 9 Effect of valve-opening pressure on engine performance

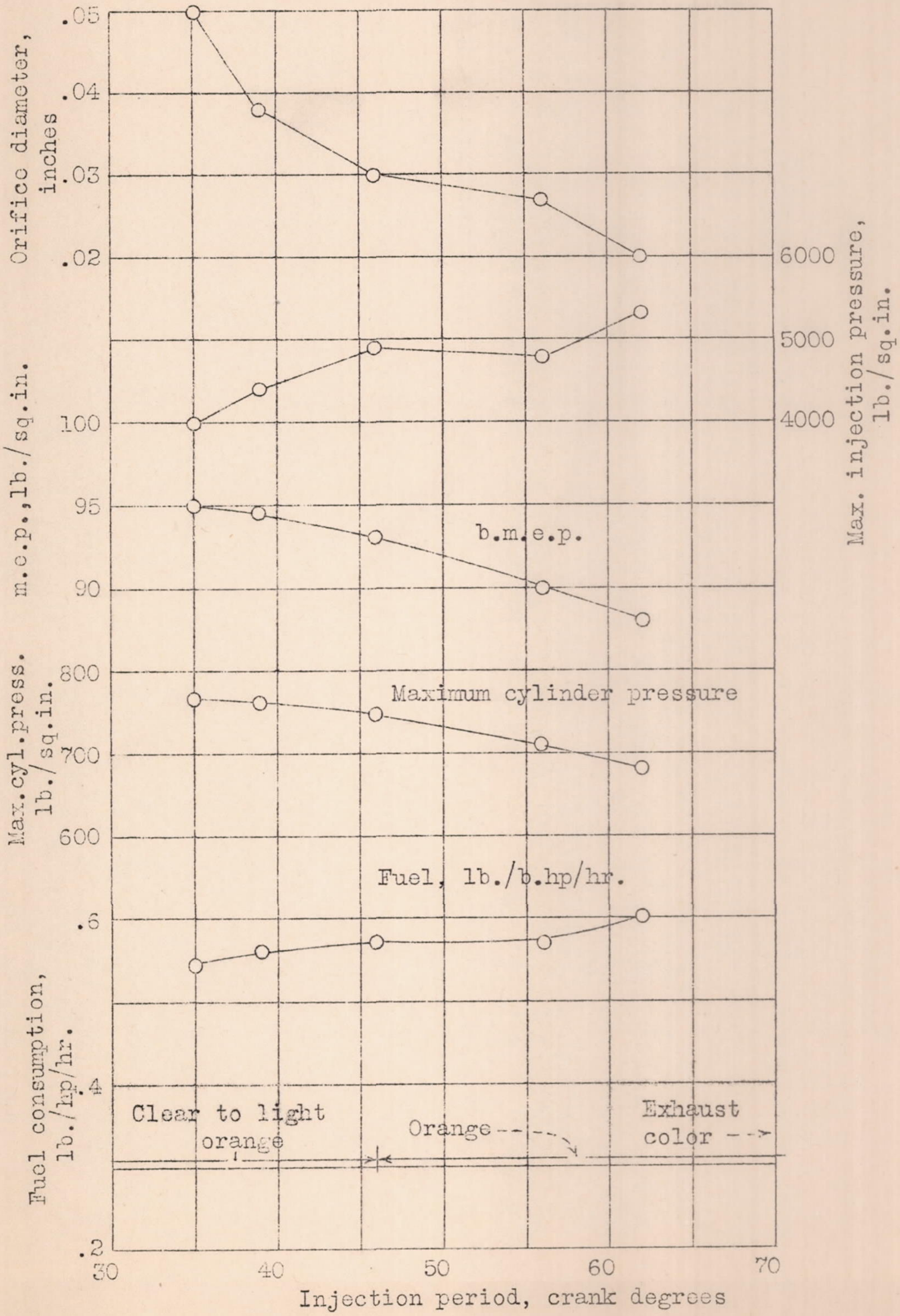

Fig. 10 Effect of injection period on engine performance

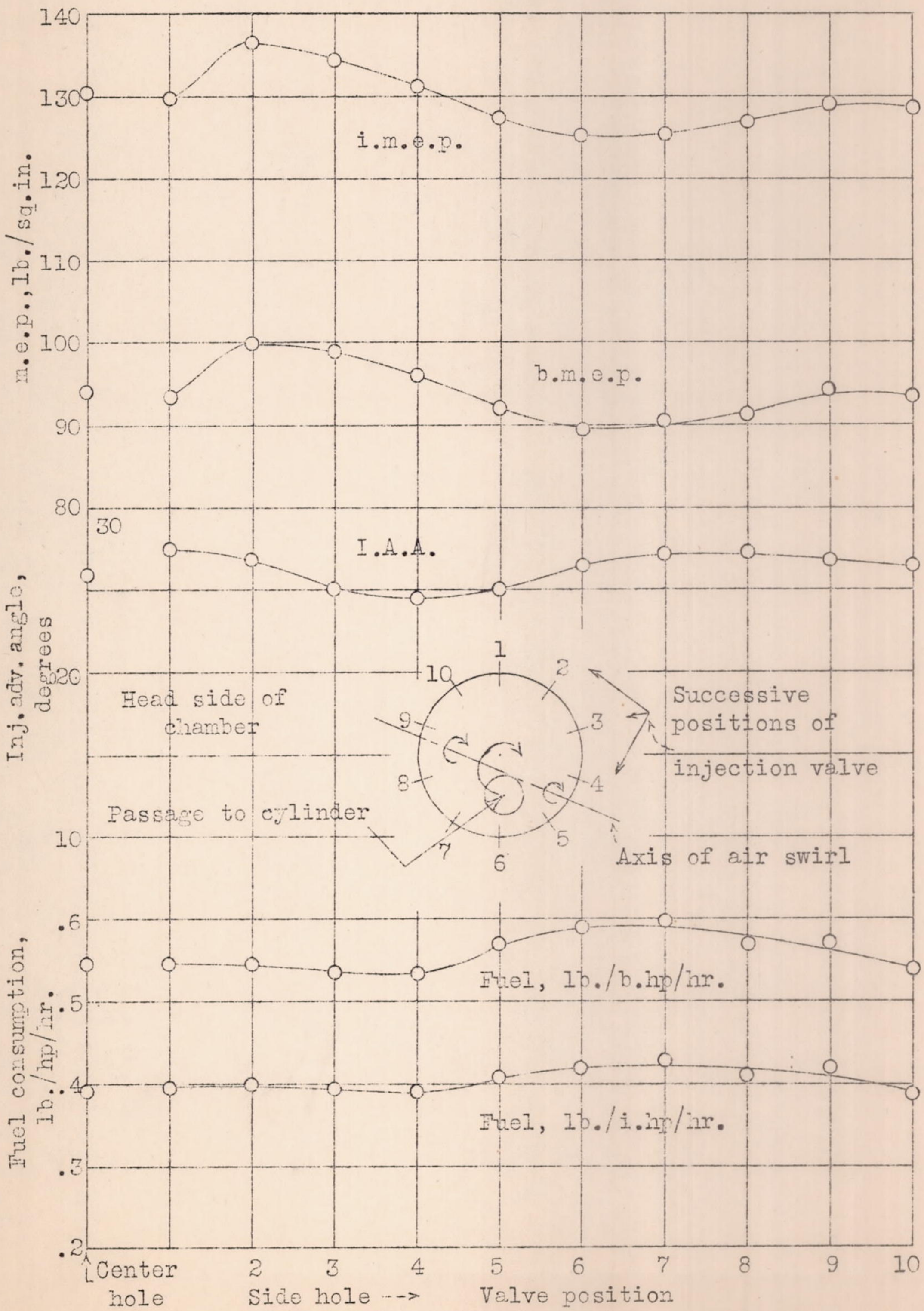

Fig. 11 Effect of injection position on engine performance (spherical chamber). 1500 r.p.m.

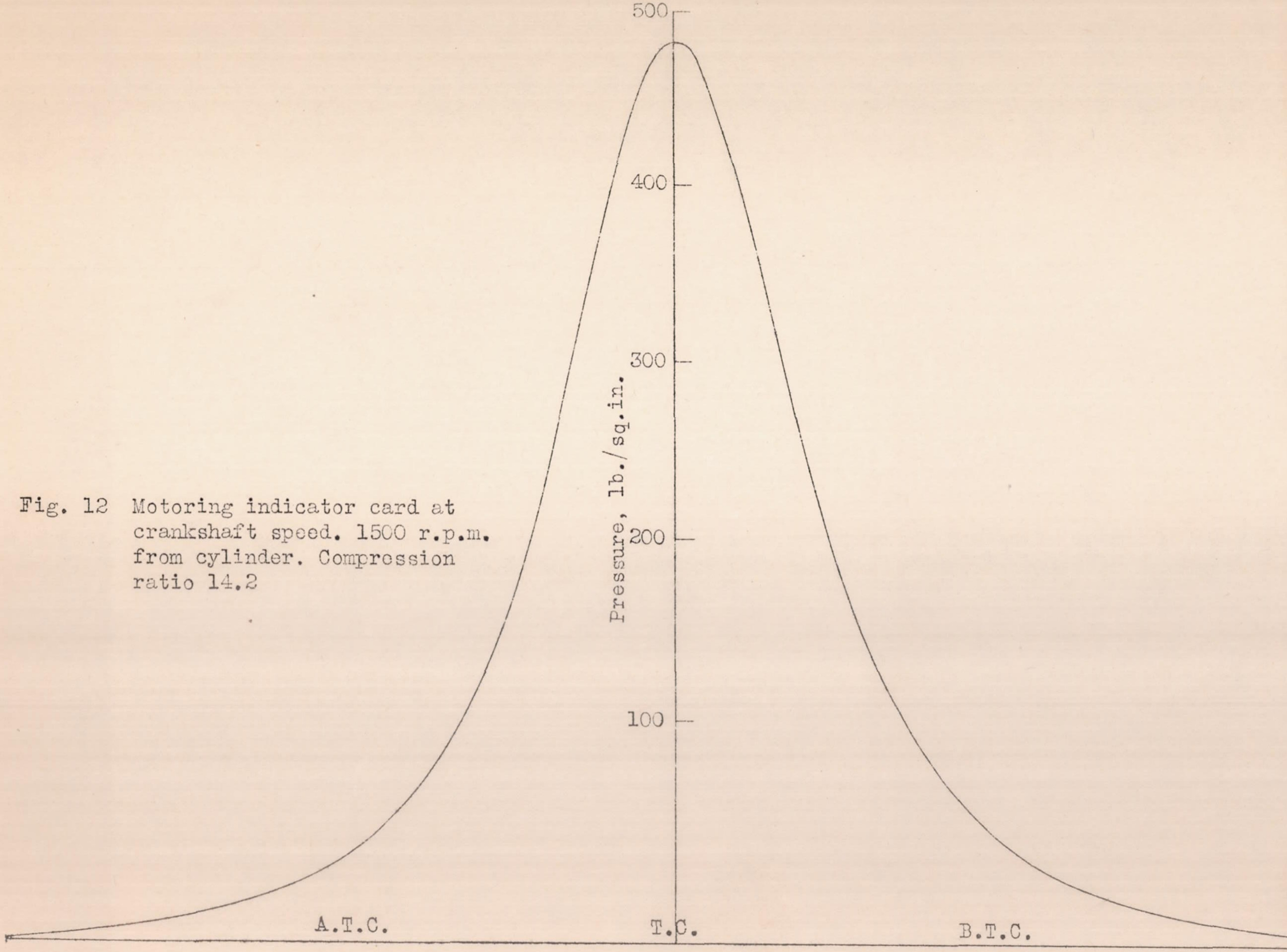

Fig. 12 Motoring indicator card at crankshaft speed. 1500 r.p.m. from cylinder. Compression ratio 14.2

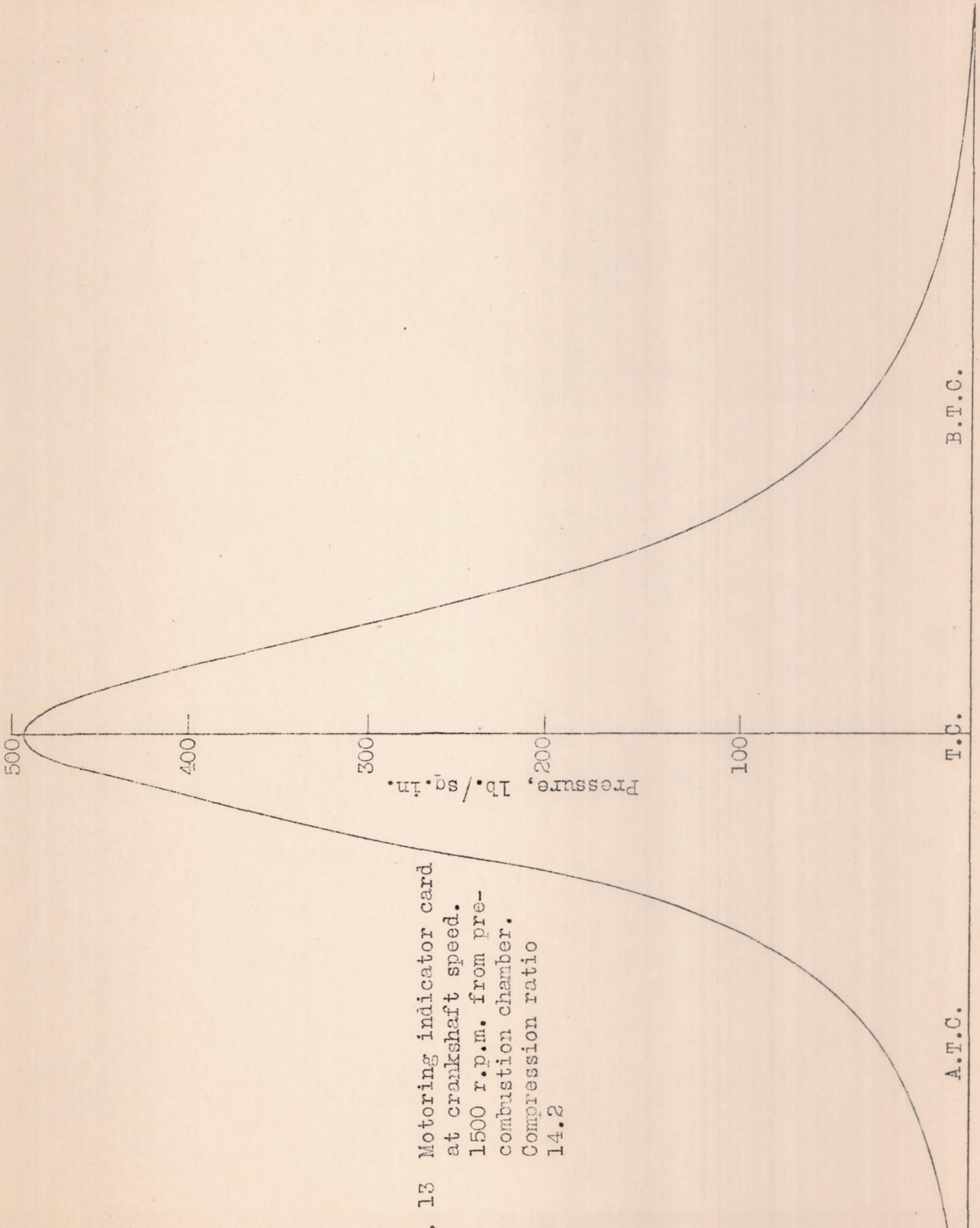

Fig. 13 Motoring indicator card at crankshaft speed. 1500 r.p.m. from pre-combustion chamber. Compression ratio 14.2

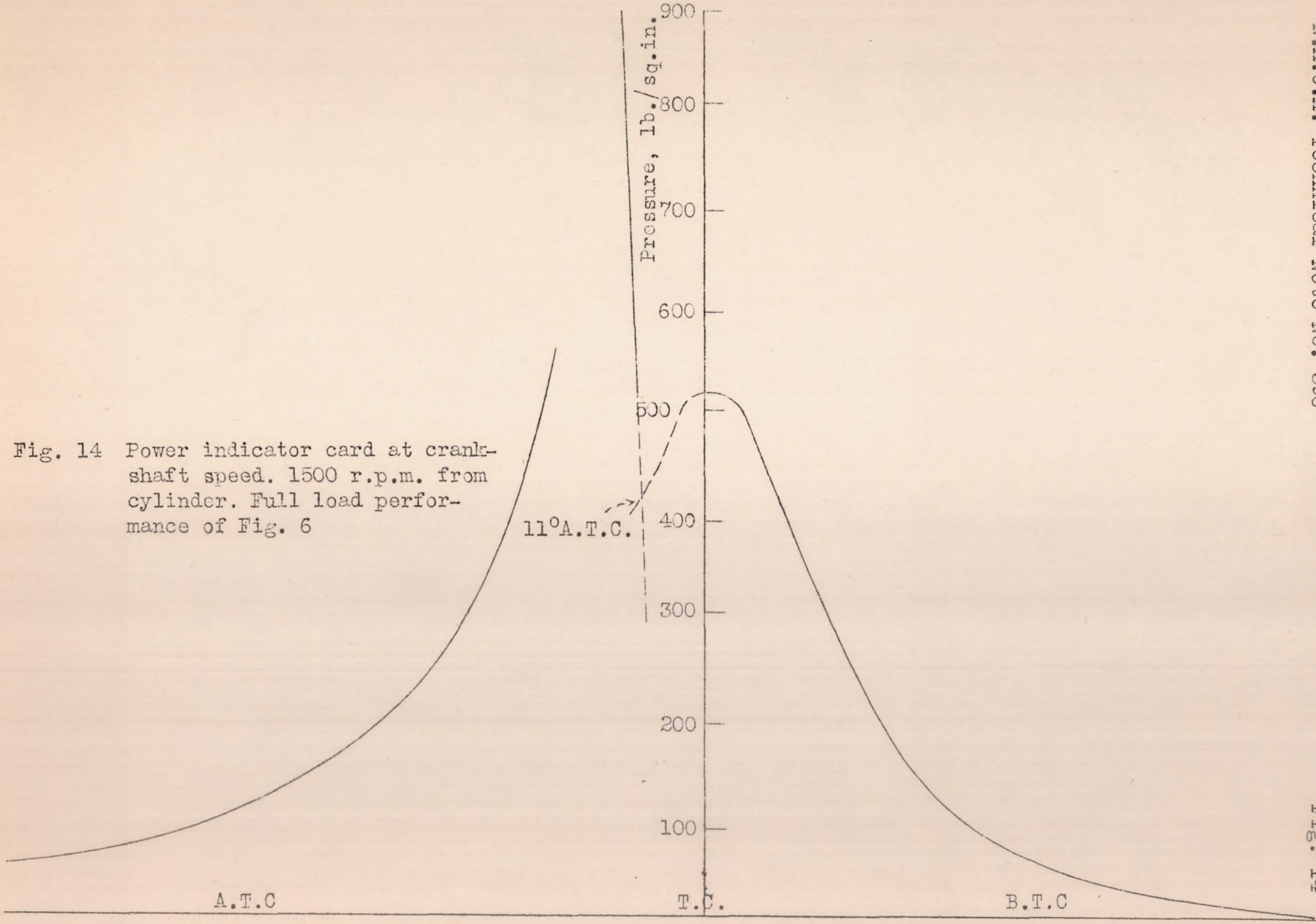

Fig. 14 Power indicator card at crankshaft speed. 1500 r.p.m. from cylinder. Full load performance of Fig. 6

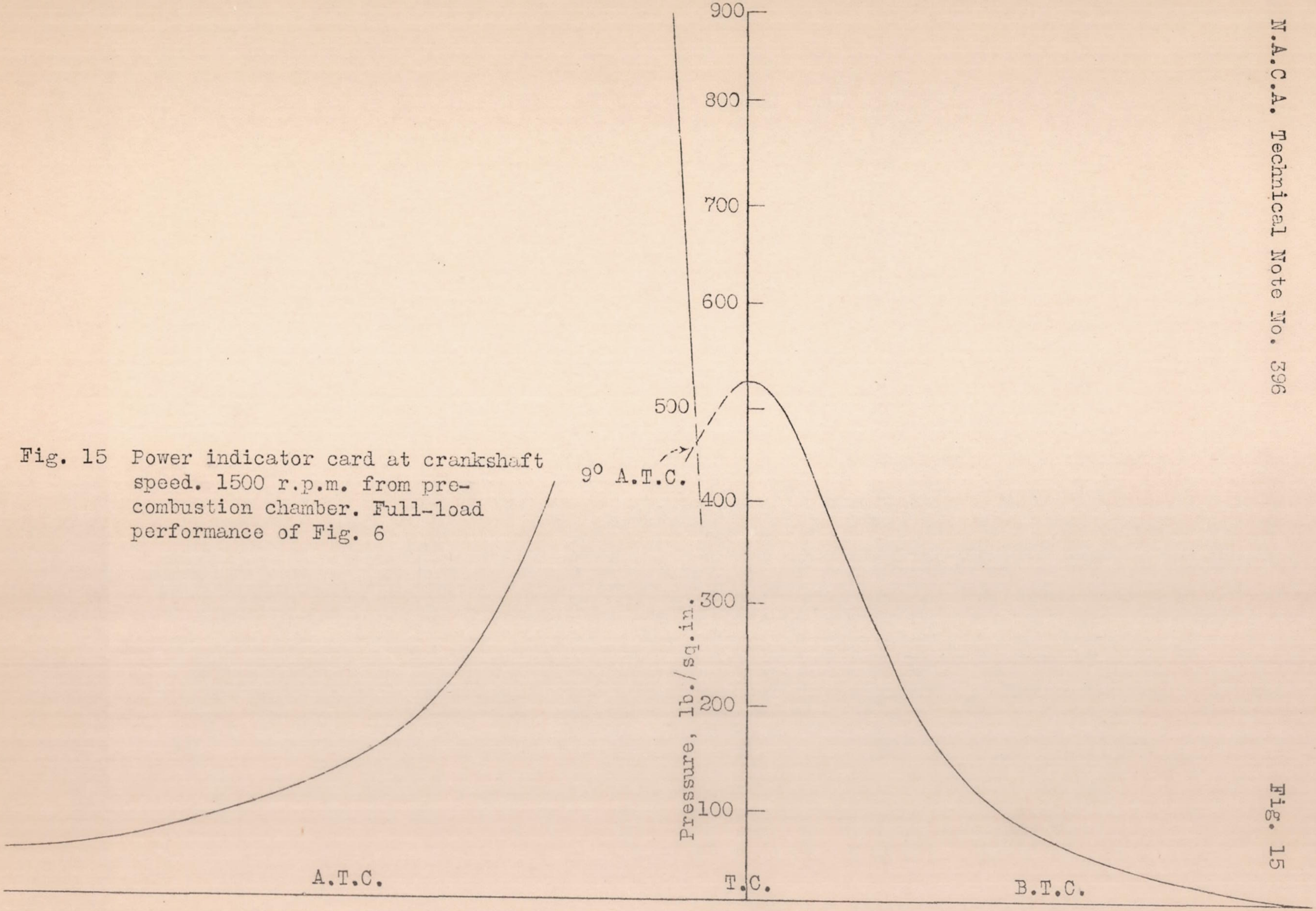

Fig. 15 Power indicator card at crankshaft speed. 1500 r.p.m. from pre-combustion chamber. Full-load performance of Fig. 6