TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 436

THE EFFECT OF CONNECTING-PASSAGE DIAMETER ON THE PERFORMANCE OF A COMPRESSION-IGNITION ENGINE WITH A PRECOMBUSTION CHAMBER

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SUMMARY

The diameter of the passage connecting the precombustion chamber with the cylinder was varied through a range from 3/16 inch to 1-1/16 inches. The auxiliary chamber contained 50 per cent of the total clearance of the 5 by 7 inch cylinder at a compression ratio of 13.5.

Results of motoring tests are presented showing the effect of passage diameter on chamber and cylinder compression pressures, maximum pressure differences, and f.m.e.p. over a speed range from 300 to 1,750 r.p.m.

Results of engine-performance tests are presented which show the effect of passage diameter on m.e.p., explosion pressures, specific fuel consumption, and rates of pressure rise for a range of engine speeds from 500 to 1,500 r.p.m.

The cylinder compression pressure, the maximum pressure difference, and the f.m.e.p. decreased rapidly as the passage diameter increased to 29/64 inch, whereas further increase in passage diameter effected only a slight change. The most suitable passage diameter for good engine performance and operating characteristics was 29/64 inch. Passage diameter became less critical with decrease in engine speed; therefore, the design should be based on maximum operating speed. Optimum performance and satisfactory combustion control could not be obtained by means of any single diameter of the connecting passage.

INTRODUCTION

The precombustion-chamber type of cylinder head employs forced air flow to mix air with fuel in the auxiliary chamber. Combustion later expels part of the burning mixture into the cylinder where combustion continues. The completeness and control of mixing and combustion depend upon a number of factors which for convenience may be divided into two groups: first, chamber position, clearance distribution, and clearance shape; second, the connecting-passage area, shape, and direction. Several of these factors have been investigated theoretically (see bibliography) but there has been little engine investigation. The effect of clearance distribution on motoring characteristics and engine performance has been experimentally investigated at this laboratory and reported in reference 1.

The work presented herein is an investigation of the effect of passage area on the motoring characteristics and the engine performance for a constant clearance distribution. Motoring and engine-performance tests were made for a series of passage diameters between 3/16 inch and 1-1/16 inches. The investigation was undertaken because the passage area is of importance both in determining the airflow velocity into the auxiliary chamber and in controlling the flow of the burning mixture into the cylinder.

This work was done during 1932 in the power plants laboratory of the National Advisory Committee for Aeronautics at Langley Field, Va.

APPARATUS AND METHODS

The cylinder head (fig. 1) used for the tests herein reported was the same as that used in reference 1. In the present work, the auxiliary-chamber volume was chosen as in previous work (references 2 and 3) at 50 per cent of the total clearance and was held constant while the diameter of the connecting passage was varied. A connecting passage which was considered too small for practical operation was selected and progressively enlarged. (See Table I.) For the same engine speeds, the air flow velocities should be in the inverse ratios of the areas if the flow coefficients of the passages remained constant.

As in former tests, the passage used was circular in cross section. This shape was retained because, when using a circular passage, there is a minimum change in clearance shape as the area of the passage is increased. However, there was a change in the passage length/diameter ratio and radius of flare for each passage diameter tested. The length/diameter ratio varied from approximately 3.3 to 0.6 and the radius of flare varied from 11/32 to 17/32 inch. The compression ratio also varied from 13.2 to 13.7 because the precombustion chamber used was designed to give the standard compression ratio of 13.5 when using a 9/16-inch diameter connecting passage as in previous work. The effect of these variations on engine performance was considered to be negligible.

The test equipment (fig. 2) and general test methods used in these tests were the same as those of reference 1, except as specifically noted in this report. The only change in the standard test conditions is in the consideration of full-load fuel quantity, which in this report is 0.000325 pound per cycle, or that quantity of fuel which will be completely burned, assuming perfect combustion, with the amount of air inducted per cycle at 82.5 per cent volumetric efficiency. Previous publications have used both fuel quantity per cycle and load fraction as reference scales so there should be no difficulty in the correlation of this work with that already reported.

For convenience of reference, the standard test conditions are tabulated below:

Engine . . . . single cylinder, 5 by 7 in.

Engine speed . . . . 1,500 r.p.m.

Fuel . . . . Diesel engine fuel, 0.847 specific gravity, 41 seconds Saybolt Universal viscosity at 80° F.

Full-load fuel quantity . . . . . . 0.000325 lb. per cycle.

Injection period (at 1,500 r.p.m.) . . . 20° crankshaft.

Injection advance angle (at 1,500 r.p.m.) . . . . 7°.

Spray type . . . . noncentrifugal.

Nozzle type . . . . single orifice, 0.050-inch diameter.

Fuel valve position . . . . upper chamber hole.

Valve opening pressure (automatic) . 3,500 lb. per sq.in.

Fuel temperature . . . . 80° F.

Engine lubricating oil temperature (out) . . . . 140° F.

Cooling water temperature (out) . . . . 170° F.

Temperature of inlet air . . . . 95° F.

In general, the test program for each passage diameter was the same, although more extensive motoring tests were made on the smaller passages. In these tests the average compression temperature and the compression pressure were measured and indicator cards were obtained from both chamber and cylinder for speeds ranging from 300 to 1,740 r.p.m. The f.m.e.p. was computed from the dynamometer scale reading at each speed.

The power data obtained were b.m.e.p. explosion pressure in chamber and cylinder, and fuel consumption for five of the passages tested. These data were obtained at standard conditions and at speeds of 500, 1,000, and 1,500 r.p.m. The I.A.A. at these speeds were 1°, 3°, and 7° B.T.C., respectively. Indicator cards were also taken from the chamber and cylinder for standard conditions at each of the three speeds. The ignition lag was computed from these cards and is considered as the time in fractions of a second from the start of injection of the fuel as determined with the Stroborama to the beginning of pressure rise due to combustion as shown by inspection of the cards. The heat loss to the cooling water was determined only for the standard conditions. None of these data could be taken from the first two or the last passage on the test program because they created too severe conditions of combustion. For each test speed the injection advance angle was held constant throughout the series of passage diameters tested. This angle was, or closely approximated, the optimum for each passage as determined by the investigation of the I.A.A. range from misfiring to maximum allowable knock. Supplementary power tests, at the maximum allowable advance angle, were also made while testing the large passages. The point of maximum advance angle was determined by an experienced engine operator and is based on his judgment of the greatest permissible combustion shock.

During all tests, the operating characteristics such as combustion sound, idling, and starting characteristics were recorded. The combustion sound was judged by the same operator for all tests. Comparative idling characteristics were noted while observing the engine operation for at least one minute at 300 r.p.m. or at the lowest speed possible without changing of the injection-pump controls. The starting tests were made in the following manner: First, with the engine cold (about 70° F.) the crankshaft was given two revolutions. If it did not start in three such attempts, it was motored at speeds starting at 300 r.p.m. and increasing until the minimum starting speed was reached. The same procedure was followed with the engine immediately after normal power operation.

TEST RESULTS AND DISCUSSION

General operating characteristics.- The operating characteristics of the engine changed as the diameter of the connecting passage was varied. (See Table I.) The starting tests showed that with the small passages a slightly smaller fuel quantity and injection advance angle were required to effect starting. None of the passages allowed starting on two revolutions of the crankshaft when cold, whereas all of the passages did when hot. The minimum cold starting speed for all passages was 700 r.p.m. regardless of injection advance angle or fuel quantity. The engine could be idled at 300 r.p.m. with very little attention when operating with the small passage diameters. However, as the passage diameter was increased, there was an increasing tendency for the engine to hunt at idling speeds and by the time the largest passage was reached, constant manipulation of the pump control was required to maintain a speed of 300 r.p.m.

TABLE I

GENERAL OPERATING CHARACTERISTICS

Passage diameter inches	Passage area sq.in.	Idling	Injection range - miss to allowable knock	Cyclic variation of maximum explosion pressure lb. per sq.in.		Combustion sound (intensity and regularity)	Carbon deposits	
				Chamber	Cylinder		Chamber	Cylinder
* 3/16	0.028	good	40°		small	quiet - regular	none	light
*17/64	.055	"	20°		"	" "	"	"
* 3/8	.110	"	12°		80	light knock - regular		
29/64	.161	"	12°	100	100	medium knock - regular		
17/32	.222	"	11°	120	120	hard knock - regular	Increasing carbon	Increasing carbon
21/32	.338	fair	12°	100	160	dull knock - irregular		
3/4	.442	poor	12°	120	130	dull knock - irregular		
*1-1/16	.887	bad	16°			light knock - irregular		

*Engine operation would not permit complete tests to be made.

The combustion characteristics of the engine also varied as the diameter of the connecting passage was increased. The combustion sound at full-load fuel quantity for the two smallest passages was very unusual and will be termed a "whistle" for want of a better term. For the 3/8-inch diameter passage, the whistle was no longer audible and instead a light knock could be detected. As the passage diameter was increased to 17/32 inch the knock increased; however, with further increase in passage diameter the knock became less intense. The pressure indicator showed that the variation in maximum explosion pressure for successive cycles was negligible for the smaller passages, but increased to an appreciable amount as the passage diameter was increased.

The effect of passage diameter on combustion at full-load fuel quantity was particularly evidenced by the change in the appearance of the exhaust. With small passage diameters the exhaust showed some flame and a little smoke, whereas with large passage diameters the flame and smoke increased considerably and caused increased heating of the exhaust valve and manifold.

Effect of passage diameter on motoring characteristics.- The motoring characteristics shown in Figure 3 indicate that the more effective passage diameters are less than 29/64 inch. The large effect on f.m.e.p. in this range is mostly due to passage throttling losses (see figs. 7a, b, and c and 8a and b) because the mechanical and induction losses remain nearly constant. For the larger passages the passage loss is too small to affect the f.m.e.p. The pressure difference between chamber and cylinder is greater with the smaller passages than with the larger ones, which approach the integral combustion chamber condition and show little pressure difference. However, the larger passages with less throttling result in a chamber pressure higher than the cylinder pressure, as has been previously reported but not explained. These unusual pressure conditions may be related to the likewise unusual temperature conditions (see fig. 3) of higher chamber than cylinder compression temperature. There are several possibilities to explain these temperature conditions. The chamber thermocouple is protected from the cold air which enters the cylinder and which probably cools the cylinder thermocouple and the chamber air may be heated by friction and by contact in passing through the passage.

Figure 4 shows data which were obtained from indicator cards and which are pertinent to an understanding of the air flow between cylinder and chamber. These data show that the more effective range of passage diameters is less than 29/64 inch. For the larger diameters the values were too small to be accurately determined and therefore were not plotted.

The pressure difference between cylinder and chamber causes an air flow whose velocity, below the critical pressure, should vary with the square root of the pressure difference. The position of maximum pressure difference should be the position of maximum velocity of flow. The maximum velocity of flow and position of the flow, in both phase and period, should be used to distribute the fuel spray.

The pressure and phase data at 1,000 and 500 r.p.m. (fig. 4) for the larger passages were of such small magnitude that they could not be measured. It should be noted that as the engine speed decreases, the pressure difference decreases, and the position of maximum pressure difference occurs earlier in the compression stroke.

Figures 5 and 6 show that the compression pressures and f.m.e.p. depend on the passage diameter and engine speed. At the lower engine speeds none of the passages have sufficient restriction to affect either the maximum compression pressure or the pressure difference between the cylinder and the chamber. With increase in engine speed, however, the smaller passages have excessive throttling and the maximum chamber pressure increases and then decreases. For the larger passages and higher speeds, the chamber pressure is higher than the cylinder pressure. The f.m.e.p., due to smaller throttling losses, decreases nonuniformly with increase of passage diameter. The smaller passage diameters and the higher engine speeds have the greatest effect upon the throttling losses because both cause extremely high velocities of air flow through the passage, the generation of which requires energy.

From the motoring results it is apparent that the passage diameter exerts a large influence on the motoring characteristics, the effect of which is magnified by engine speed. In the design of an engine of given piston displacement the optimum relation should be obtained between the passage diameter and engine speed. At the maximum engine speed the passage should be such as to give an air-flow velocity sufficient to mix the fuel and air with a relatively small f.m.e.p. loss.

Effect of passage diameter on motoring indicator cards.- Figures 7a, b, and c and 8a and b show motoring cards with chamber and cylinder records taken on the same card and with the same top center positions. For the smaller passage diameters the cards are noticeably unsymmetrical about the T.C. lines. The lack of symmetry of the chamber card is due to throttling, both on compression and expansion, by the small passages, which displaces the peak pressure after T.C. and causes the chamber to hold its pressure late in the expansion stroke. Slow speeds alter this asymmetry somewhat, because a longer time is available for the air flow to equalize the pressures. The cylinder peak pressure occurs slightly before T.C. because the cylinder air is throttled into the chamber when the piston slows down shortly before T.C.

These double indicator cards (see figs. 7a, b, and c) show the effect of passage throttling on f.m.e.p. losses. During compression and owing to passage restriction, the piston must work against a high cylinder pressure which slowly generates a much lower chamber pressure. After top center is passed, the high cylinder pressure does work to move the piston; also, during the first part of the stroke, the cylinder pressure continues to increase the chamber pressure. When the cylinder pressure becomes less than the chamber pressure, the chamber air is throttled and prevented from returning its energy to the piston. A large f.m.e.p. loss is shown in the card area below the chamber pressure expansion line and above the cylinder pressure expansion line. As the passage diameter was increased and the pressure differences became less, the two records overlapped and became indistinct. Therefore, cards are not presented for the larger passages or at speeds of 1,000 and 500 r.p.m.

Immediately after the pressure peaks of some of the indicator cards there is a scarcity of points owing to inability of the indicator to operate with the required rapidity.

Effect of passage diameter on engine performance.- Figures 9, 10, and 11 show that, for the clearance shape used in these tests, a connecting passage of the type tested and approximately 29/64 inch in diameter will give virtually optimum performance over the speed range investigated. Because the air-flow velocity through the passage depends on engine speed, the consistent performance over a wide speed range is surprising and indicates that the longer time available for the preparation of the mixture at low speeds compensates for the lower velocity of the air through the passage and makes good performance with satisfactory engine operating conditions possible over a wide speed range. In this instance, the criterions for good engine operating conditions are moderate cylinder pressures, rates of pressure rise, and combustion sound.

In the selection of the optimum passage diameter, maximum engine speed is the determining factor because a passage which gives optimum performance at low speeds may give destructive pressures at high speeds. The excessive pressures are due to better combustion caused by increased velocity of the air at higher engine speeds with the resulting better mixing of the fuel and air. At 1,500 r.p.m., extremely high pressures were evident in the chamber while the smallest passage was being tested. Repeated attempts were made, without success, to measure the pressure in the chamber. Several types of pressure-measuring instruments available at the laboratory were used, but the life of each was too short to obtain a single reading. The failures were apparently caused by a combination of pressure and temperature, for in all cases the indicating element of the instrument was badly distorted by the pressure with evidence of excessive heating.

Although the combustion is evidently better at high speed and small passage diameters, the performance is not the optimum, owing to the excessive throttling of the small passages. These two factors, throttling and combustion, are more nearly balanced at 1,000 r.p.m. and 500 r.p.m., and the resulting performance curves at these speeds are quite flat. Therefore, in the design of a precombustion chamber this lack of sensitivity at low engine speeds is advantageous because an optimum passage size for the maximum engine speed can be selected and the performance at lower speeds will not be adversely affected.

Figure 9 shows that at 1,500 r.p.m. in both chamber and cylinder there is an increase in ignition lag and a decrease in the rate of pressure rise as the passage diameter is increased.

The increase in ignition lag found in the tests on passage sizes ranging from 3/8 inch to 17/32 inch diameter was accompanied by an increase in combustion knock; however, for the two larger passages the ignition lag increased slightly but the combustion knock became less intense. In the opinion of some investigators, combustion knock is caused by a high rate of pressure rise. The results of these tests do not confirm this belief because passages giving the highest rates of pressure rise gave the quietest engine operation.

The tests of the two larger passages showed a slight decrease in rate of pressure rise with a corresponding decrease in combustion knock, but the magnitude of the change is slight in comparison with that observed for the smaller passages.

The conclusions drawn from the results of these tests are that combustion knock is much more dependent upon ignition lag than upon rate of pressure rise and that rate of pressure rise may decrease with an increase in ignition lag. The tests made at 1,000 and 500 r.p.m. (figs. 10 and 11), owing to the lesser velocities of air flow at these speeds, do not show trends as sharply defined as those shown at 1,500 r.p.m. At each speed, the I.A.A. and rate of fuel injection was held constant for the series of passage diameters tested; therefore the effect of passage diameter on ignition lag and rate of pressure rise is evidently caused by the decrease in air velocity as the passage diameter was increased.

The curves show that some combustion control can be obtained by means of small passage diameters because the rates of pressure rise are higher in the chamber than in the cylinder when operating with the 3/8-inch diameter passage. The equivalent data could not be obtained from either of the two smaller passages because, after short power runs, the crown of the piston was dangerously eroded by the impingement of the concentrated jet of burning gases issuing from the small passage. However, small passages do effect good mixture control and minimize the effects of irregularities of the fuel-injection system, such as small variations in the start of injection. This effect is shown, when operating at small passage diameters, by the small cyclic variations in cylinder explosion pressure as measured with the balanced-diaphragm pressure indicator.

It should be noted that only in the case of the smaller passage diameters at high speed does the explosion pressure in the chamber exceed that in the cylinder. This relation of chamber pressure to cylinder pressure indicates that the larger passage sizes offer no appreciable resistance to the flow of gases from the chamber to the cylinder.

The ignition lag curves show that there is some difference between the times of start of pressure rise in the chamber and in the cylinder, but this must be very small, for even though the rate of pressure rise is only slightly higher in the cylinder, the pressure builds up and the maximum becomes greater than that in the chamber. When the cylinder pressure exceeds the chamber pressure, the direction of the flow of gases through the passage is reversed, but although the differential pressure, as shown by the figures, is small, there is insufficient time available for the pressures to become equalized except in the case of the large passages.

The combustion process slows down with increased passage diameter and the rates of pressure rise and maximum pressures in the chamber and cylinder become more nearly equal. The slower combustion is evidently due to the mixture of air and fuel becoming less complete as the passage size is increased and air-flow velocity decreased. This observation is substantiated not only by the curves but by the fact that the exhaust valve and manifold, due to the slower burning mixture, ran hotter as the passage size was increased. This condition became so severe that the 1-1/16-inch diameter passage could not be completely tested due to excessive heating of these parts.

The supplementary tests made at maximum allowable advance angle are represented on the curve sheets by the points that do not fall on the curves. These runs were made because it was found that the explosion pressures were decreasing with an increase in passage diameter and it was considered advisable to determine if the best performance could be equaled by advancing the injection and thereby raising the explosion pressures. The results of these tests at maximum allowable advance angle show that although the maximum explosion pressures were increased by about 150 pounds per square inch, the performance was only slightly improved. The combustion knock under these conditions was much worse than with any passage under standard conditions.

The scope of these tests did not include obtaining complete heat-loss data; however, measurements were made of the heat losses to the cooling water. It can be seen from Figure 12 that, with the exception of the heat loss from the head, the trend of the curves indicate that the coolant losses decrease with increase in passage diameter. This decrease in the total heat loss as well as the decrease in the heat loss from the chamber cap and cylinder, may be caused by less scrubbing of the walls as the velocity of the gases through the connecting passage is decreased, or it may be the result of a greater quantity of heat being lost to the exhaust as combustion is slowed down.

Power cards.- Figure 13 is drawn from typical indicator cards obtained during these tests. Cards were taken from the chamber and cylinder for each passage tested, but only the cards for the two passage diameters nearest the optimum are presented. These indicator cards show the pressure rises to be straight lines. The pressure lines on the power cards shown are drawn through a mean of the Farnboro points so the rates of pressure rise as determined from these cards would be average. The data plotted in the engine performance curves, however, are the maximum rates of pressure rise for any cycle.

CONCLUSIONS

The motoring tests made for each passage showed that the f.m.e.p., owing to throttling losses, was excessive when a connecting-passage diameter of less than 29/64 inch was employed; however, for a passage diameter equal to 29/64 inch, the f.m.e.p. was allowable and further increase in passage area effected only a slight decrease.

The power tests showed that, for the design of combustion chamber used in this investigation, the 29/64-inch diameter connecting passage was the most suitable for good operating characteristics and optimum performance. From the consideration of maximum power there was very little difference between this passage and the 17/32-inch diameter passage. The fuel economy and combustion sound of the former were sufficiently better, however, to warrant the selection of the smaller passage.

In the design of a precombustion-type cylinder head, the diameter of the connecting passage should be selected for optimum performance at the maximum engine operating speed. This can be done because the test results show that as the speed is decreased, the diameter of the connecting passage becomes less critical and optimum performance obtains over a wide range of passage diameters.

It is impossible to attain both maximum performance and satisfactory combustion control by means of any single size of circular connecting passage because losses due to throttling of flow tend to nullify the good mixing properties of high air velocities through small passages. The optimum performance is obtained when a favorable balance is reached between these two factors.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 9, 1932.

REFERENCES

1. Moore, C. S., and Collins, J. H., jr.: The Effect of Clearance Distribution on the Performance of a Compression-Ignition Engine with a Precombustion Chamber. T.N. No. 435, N.A.C.A., 1932.

2. Joachim, William F., and Kemper, Carlton: The Performance of Several Combustion Chambers Designed for Aircraft Oil Engines. T.R. No. 282, N.A.C.A., 1928.

3. Spanogle, J. A., and Moore, C. S.: Performance of a Compression-Ignition Engine with a Precombustion Chamber Having High-Velocity Air Flow. T.N. No. 396, N.A.C.A., 1931.

BIBLIOGRAPHY

Mehlig, H.: The Size of the Precombustion Chamber and Its Effect on the Working Method of Precombustion Chamber Diesel Engines. Auto. tech. Zeitschr., Vol. 32, Nov. 20, 1929, pp. 723-725.

Neumann, K.: Diesel-Engine Investigations. Ignition Chamber Engines. T.M. No. 589, N.A.C.A., 1930.

Ruehle, H.: The Pressure in the Compression-Ignition Engine. Z. f. tech. Physik, Vol. 10, 1929, pp. 465-472.

Schlaefke, K.: Phenomena During Compression Stroke of Precombustion Diesel Engines. V.D.I., Vol. 75, No. 33, 1931, pp. 1043-1046.

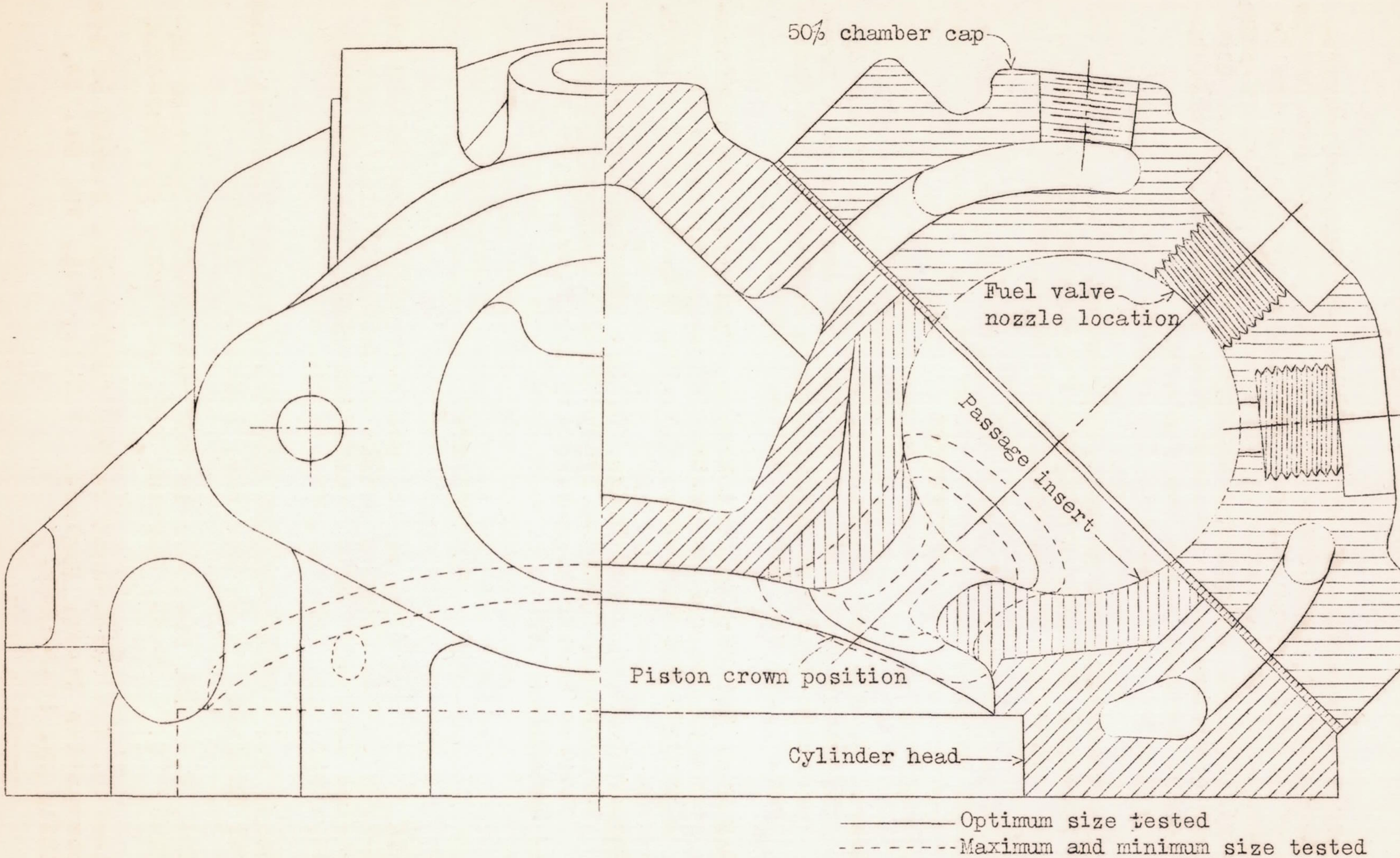

Fig.1 N.A.C.A. cylinder head design No.7 , showing removable insert and three passage outlines.

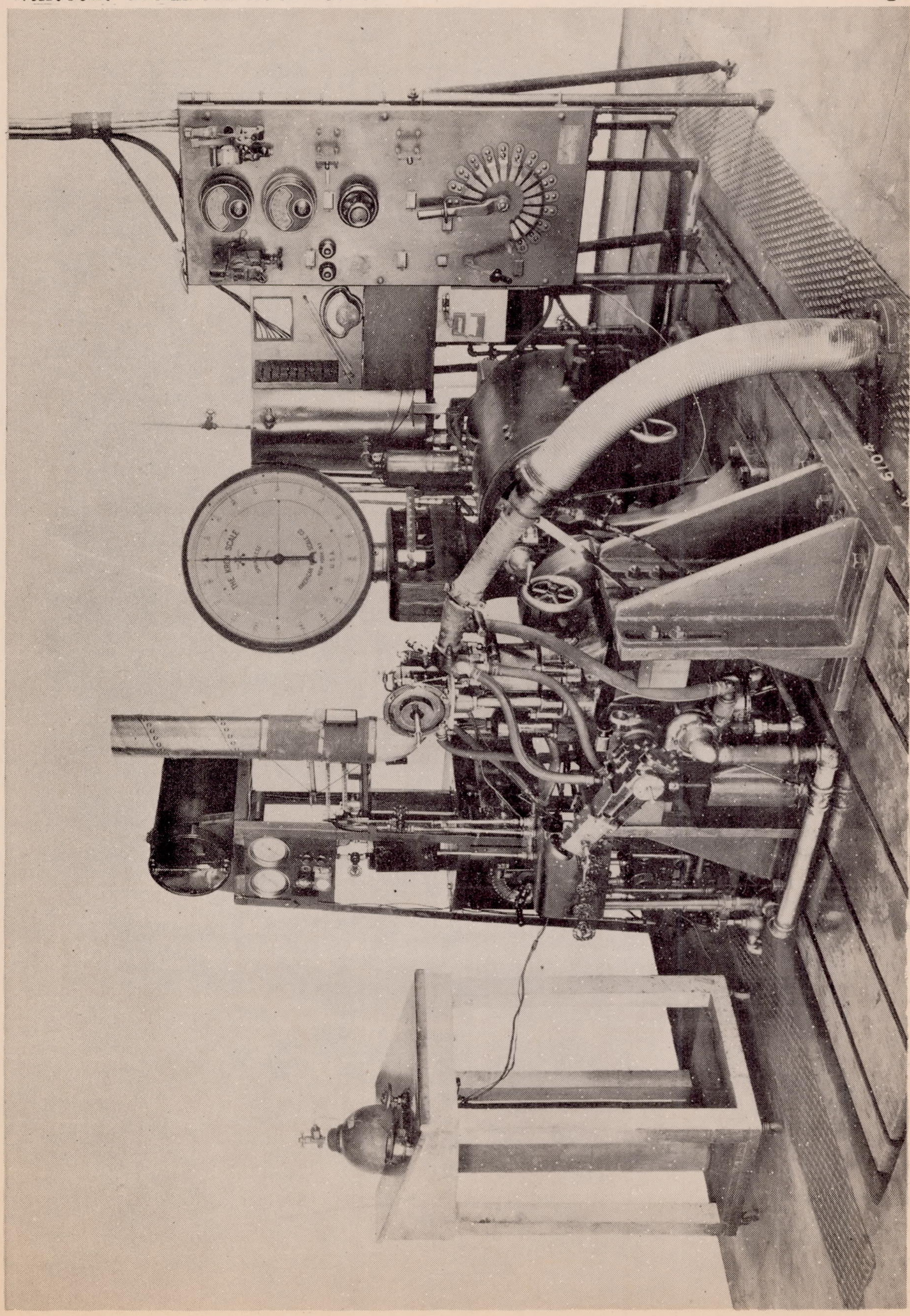

Fig.2 Single-cylinder research engine and testing equipment.

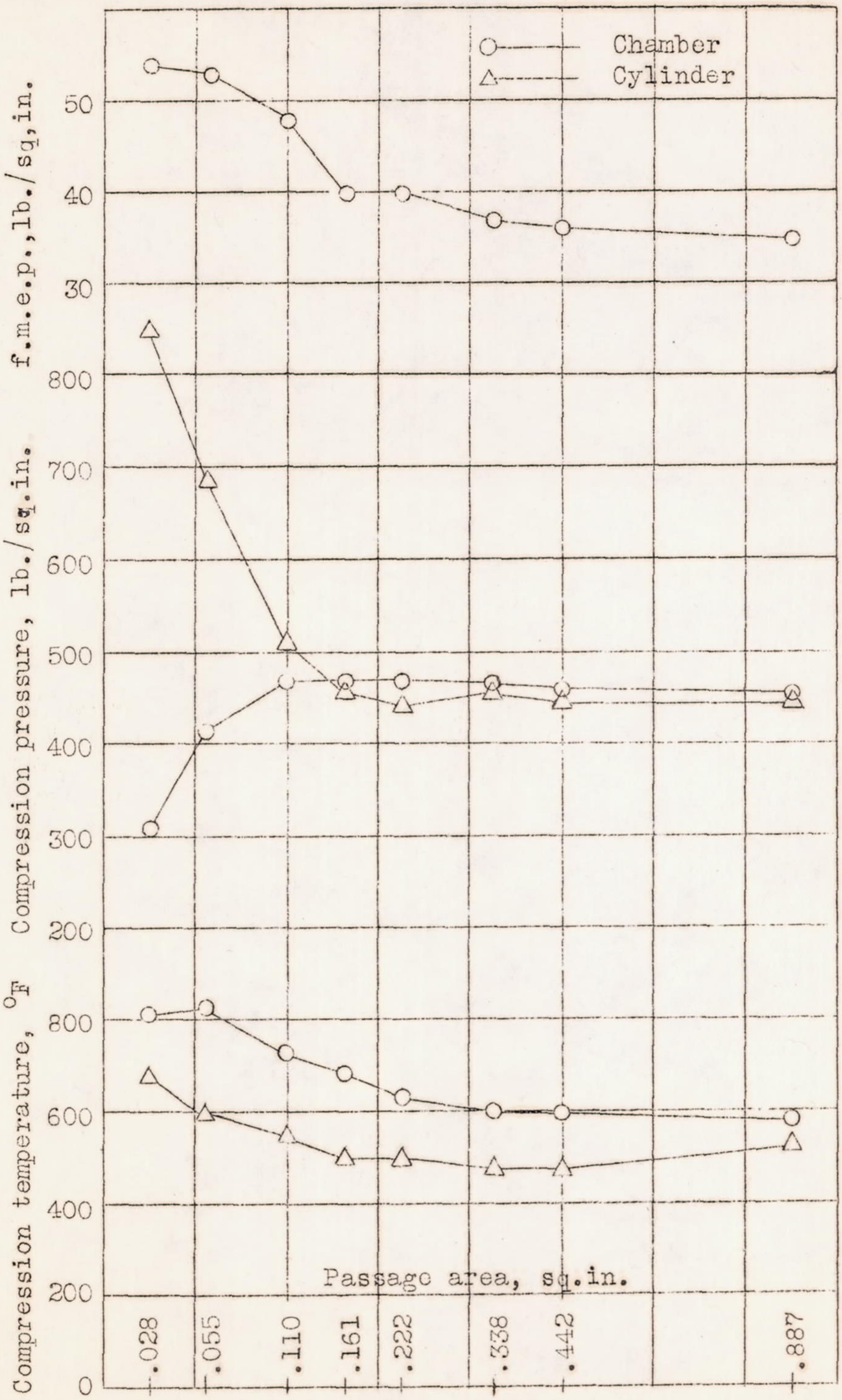

Fig. 3 Effect of passage diameter on motoring characteristics, 1500 r.p.m.

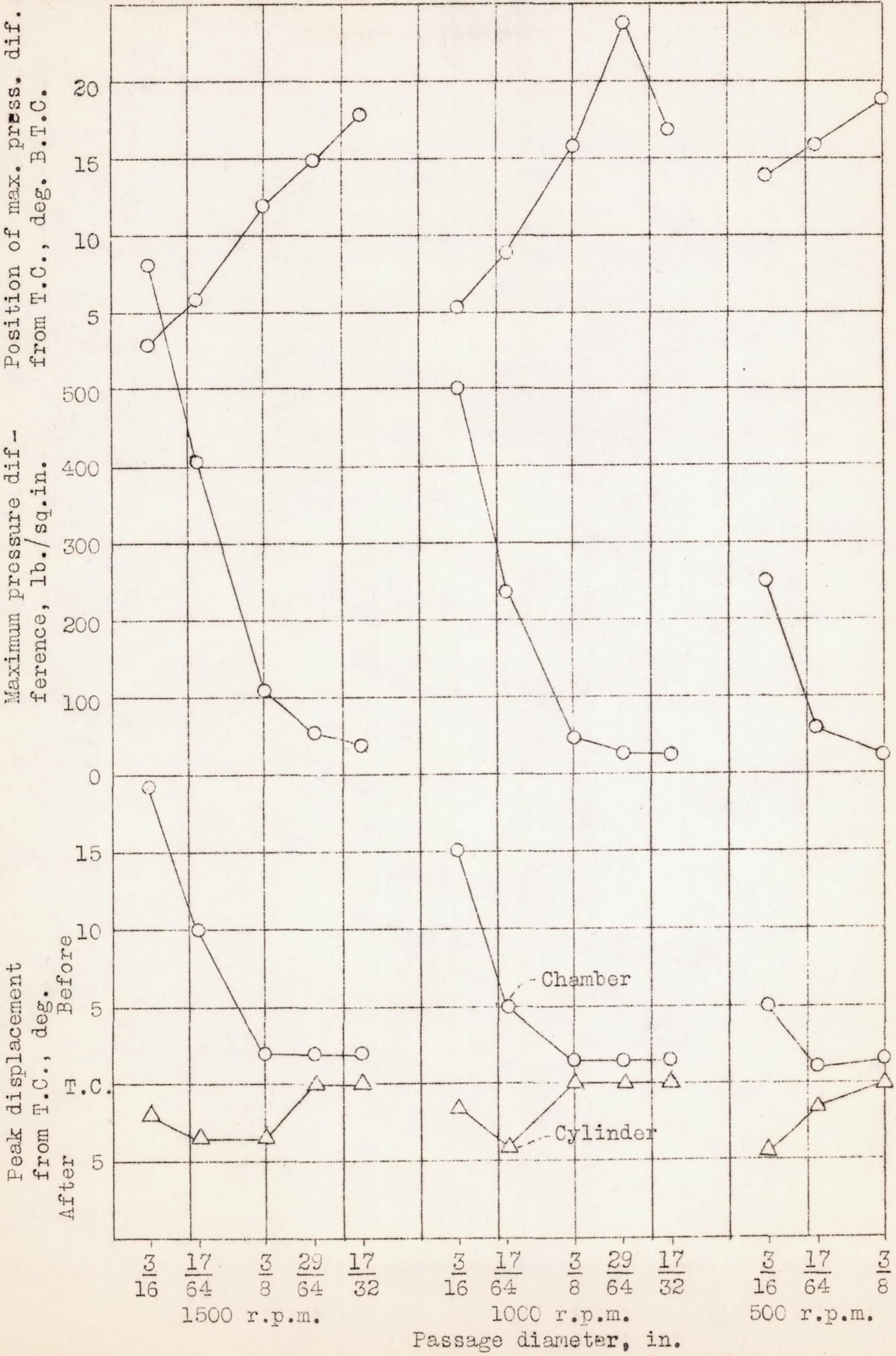

Fig. 4 Effect of passage diameter on motoring indicator-card characteristics.

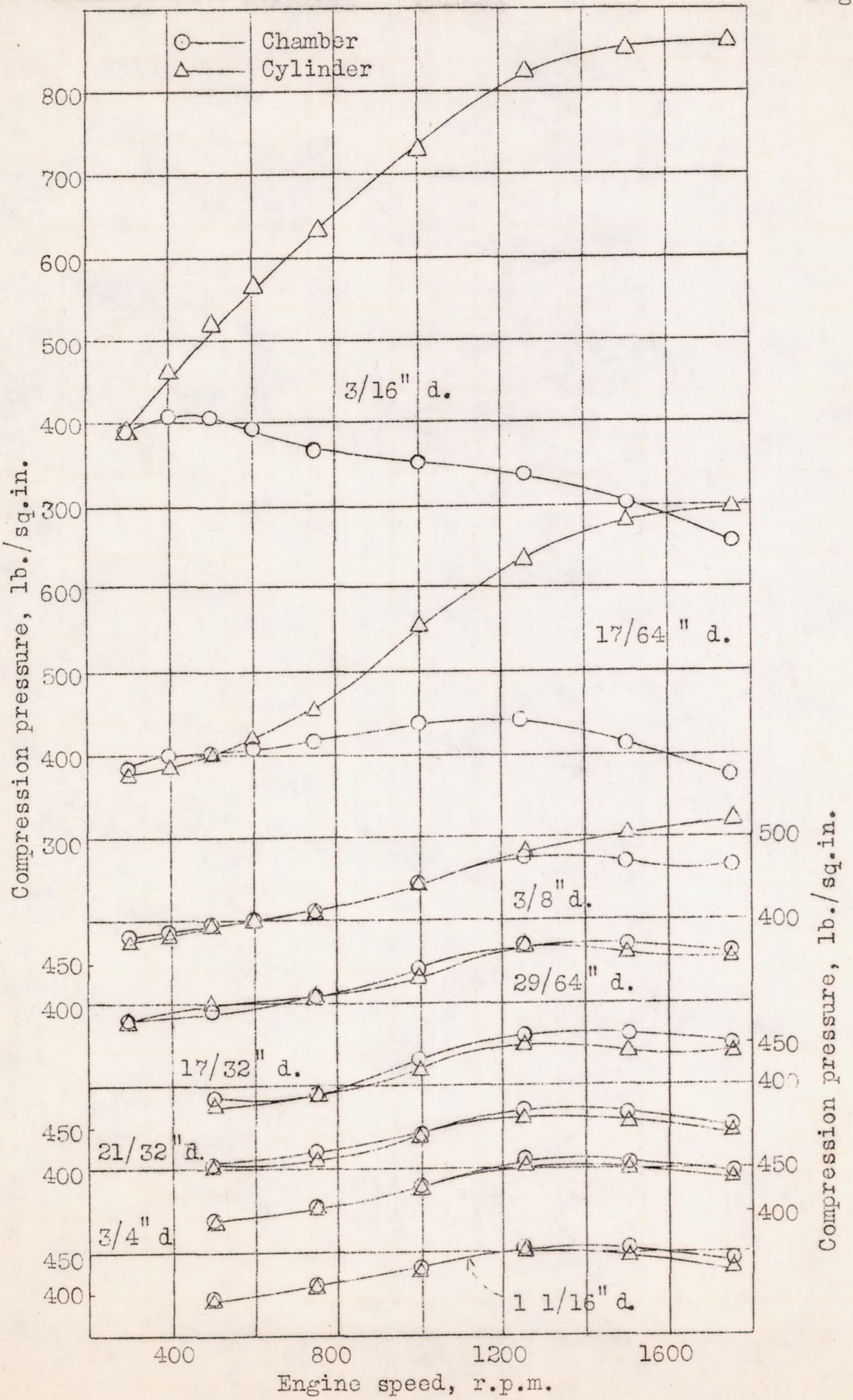

Fig. 5 Effect of engine speed on compression pressure.

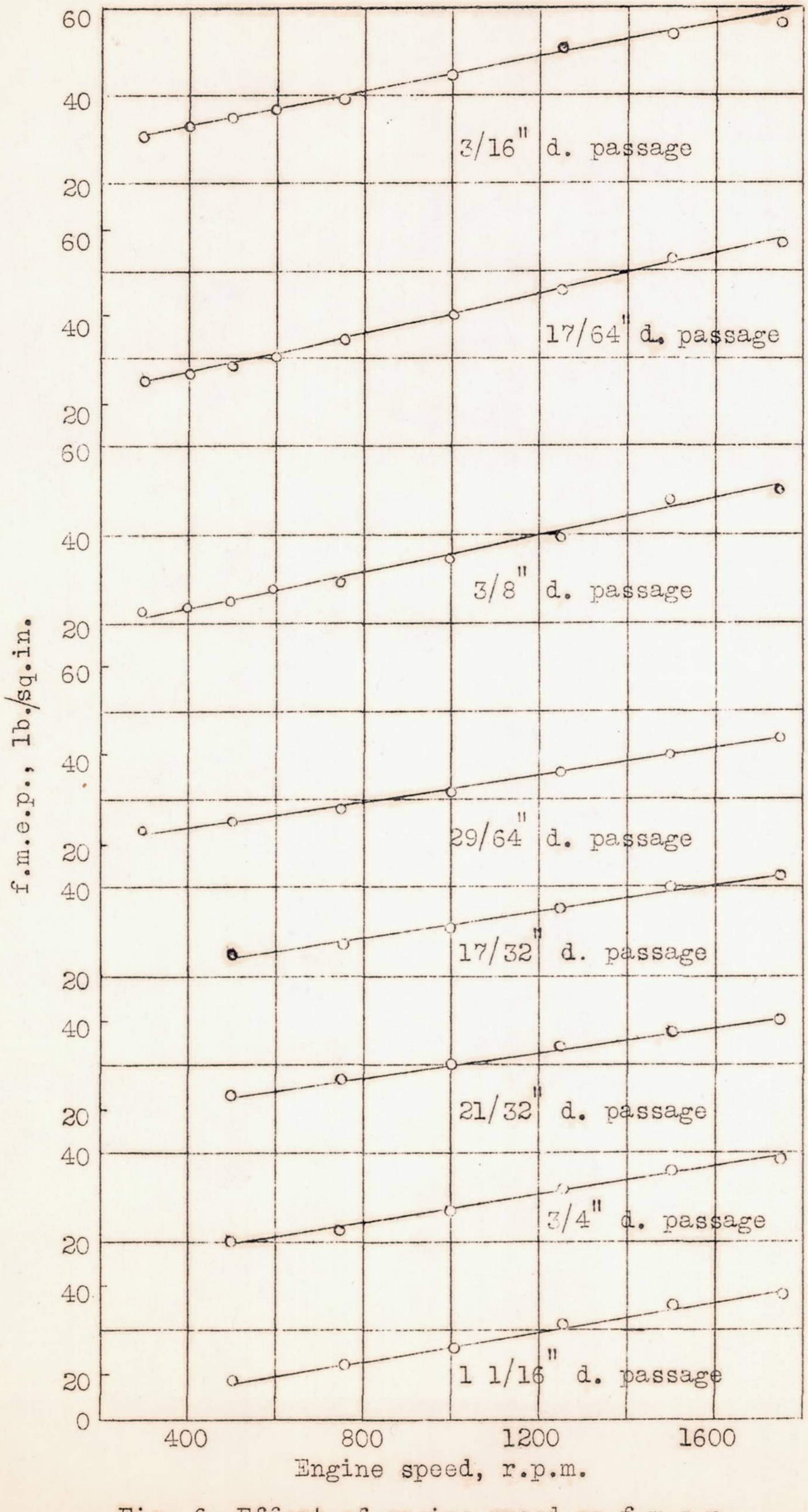

Fig. 6 Effect of engine speed on f.m.e.p.

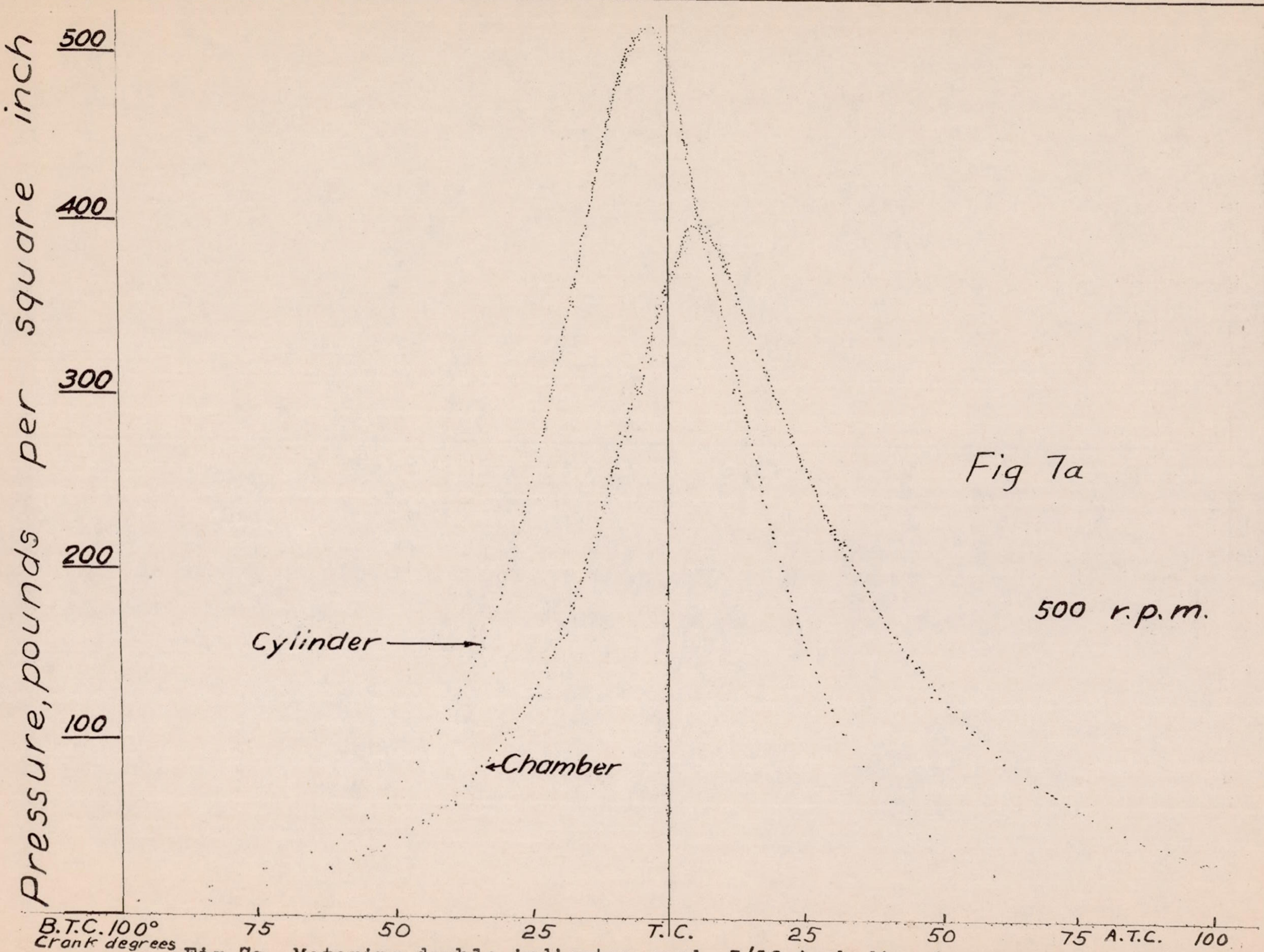

Fig.7a Motoring double indicator card, 3/16 inch diameter passage.

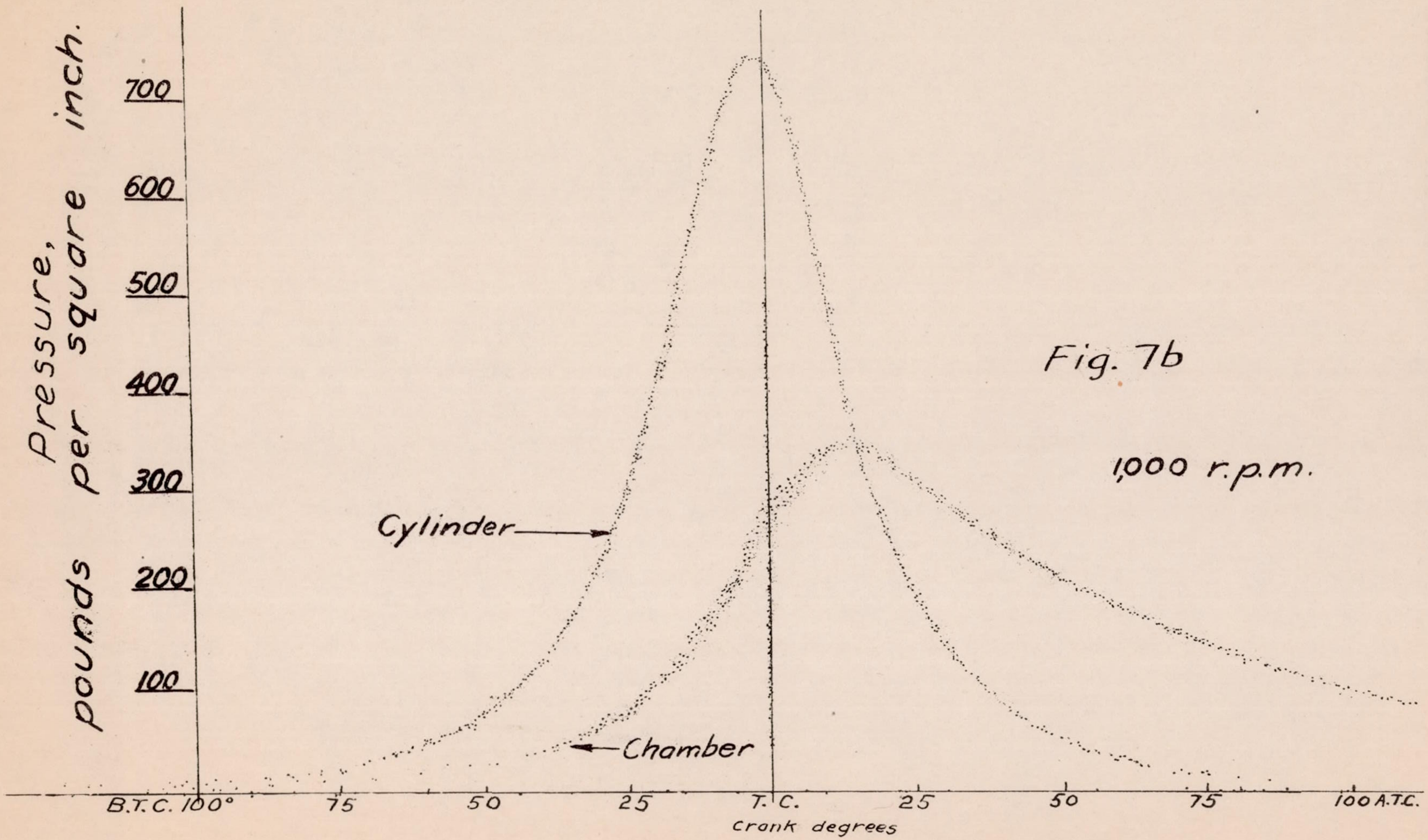

Fig.7b Motoring double indicator card, 3/16 inch diameter passage.

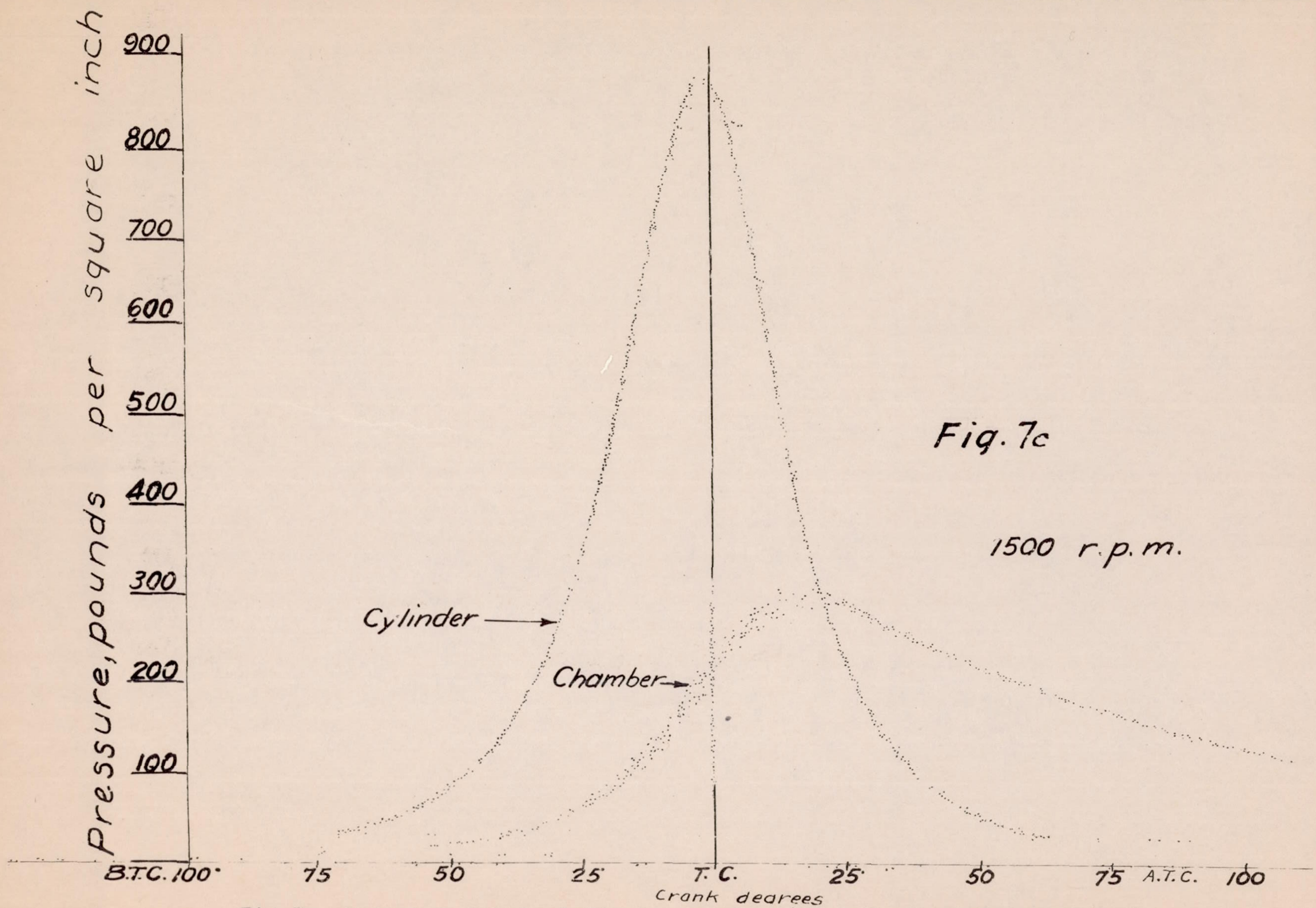

Fig.7c Motoring double indicator card, 3/16 inch diameter passage.

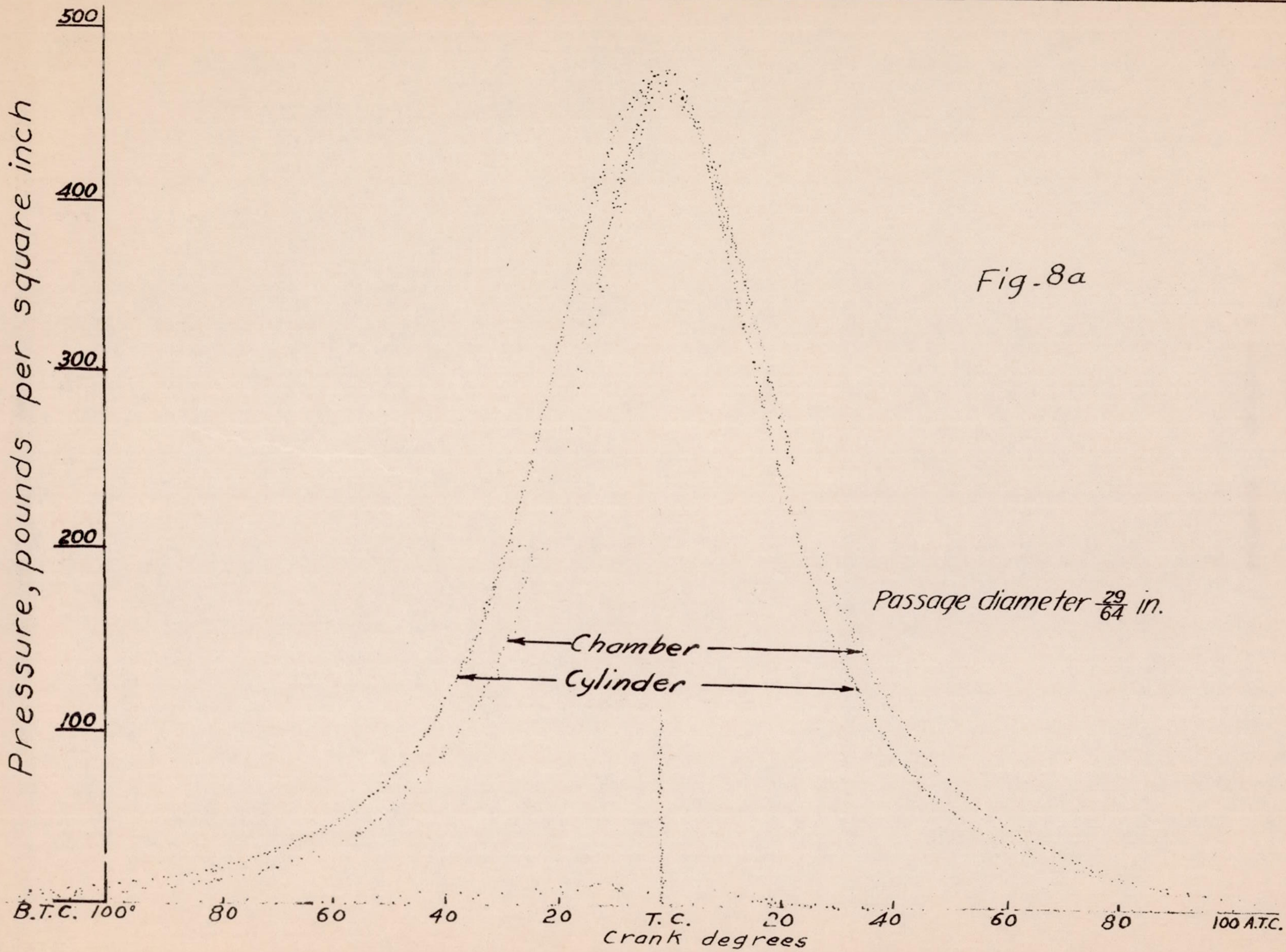

Fig.8a Motoring double indicator card, 1500 r.p.m.

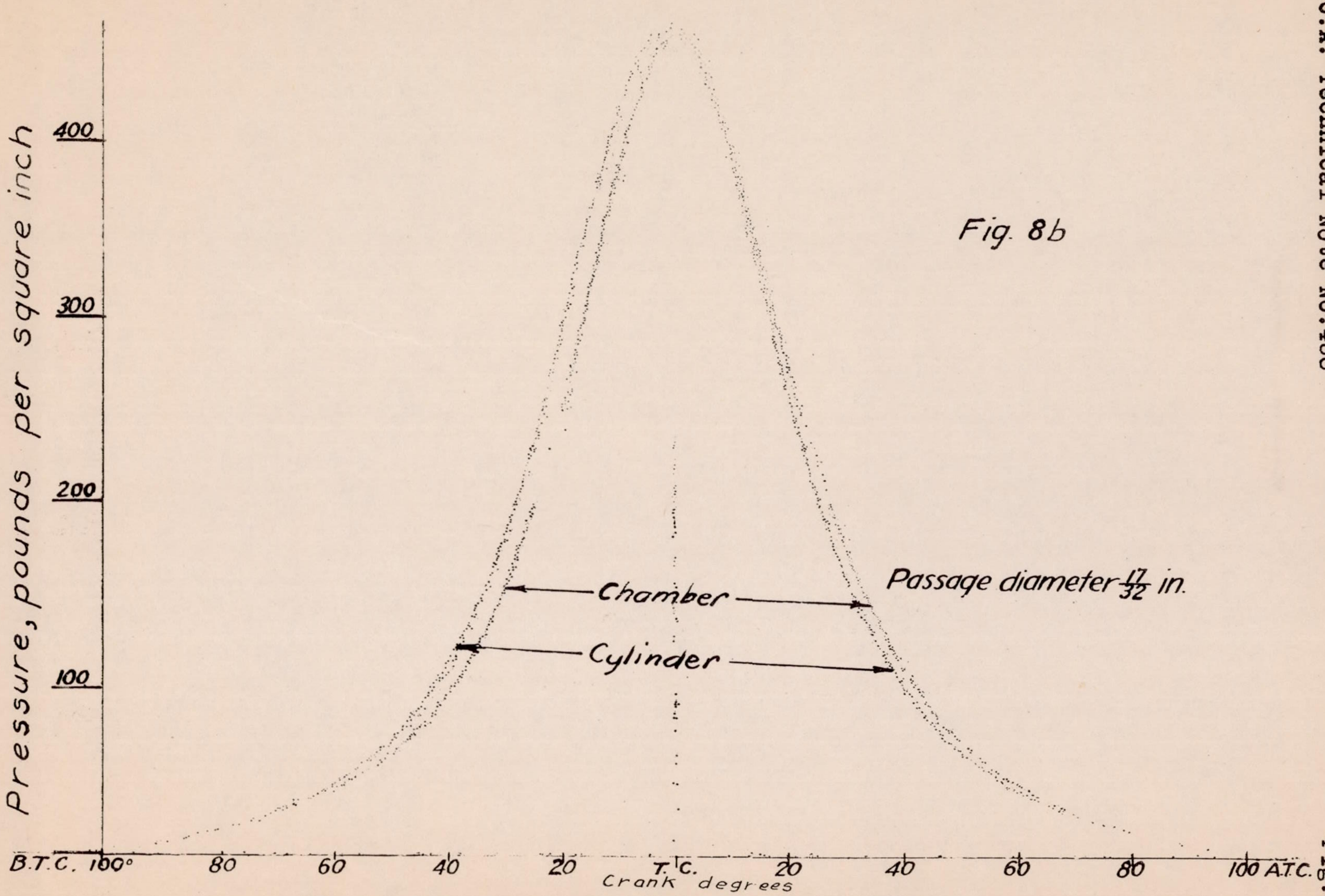

Fig.8b Motoring double indicator card, 1500 r.p.m.

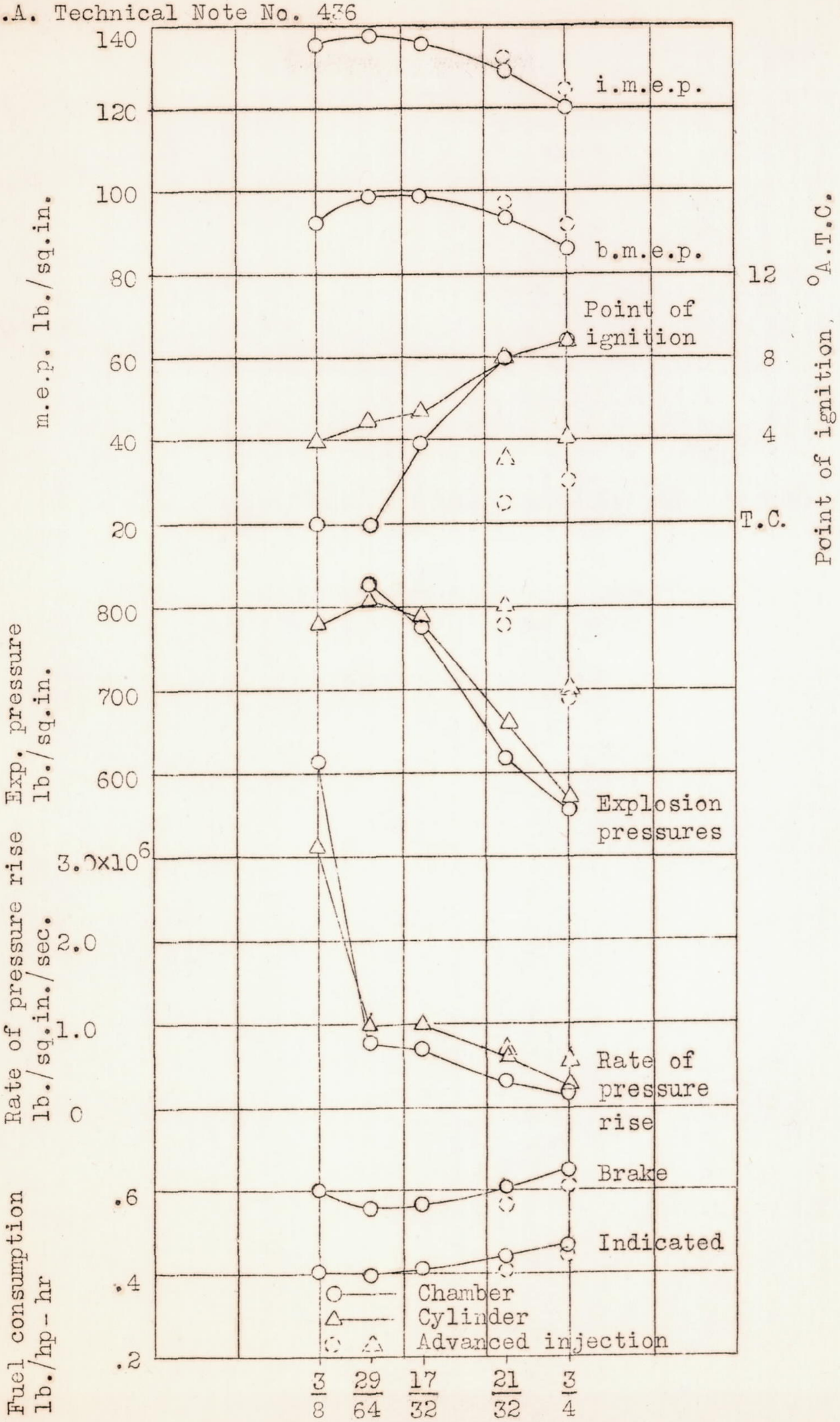

Fig. 9 Effect of passage diameter on engine performance at 0.000325 lb. fuel per cycle, no excess air, 1500 r.p.m.

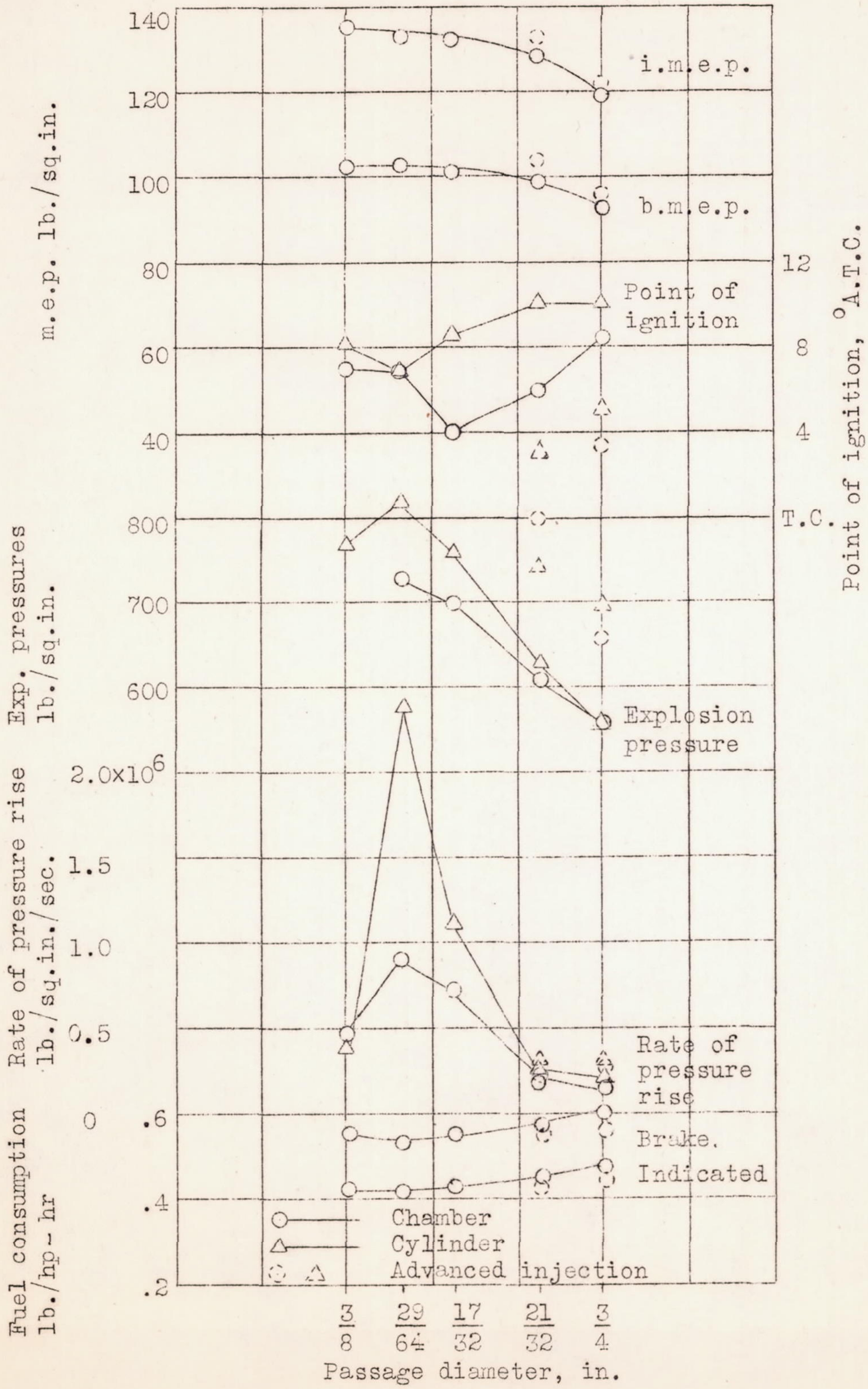

Fig. 10 Effect of passage diameter on engine performance at 0.000325 lb. fuel per cycle, no excess air, 1000 r.p.m.

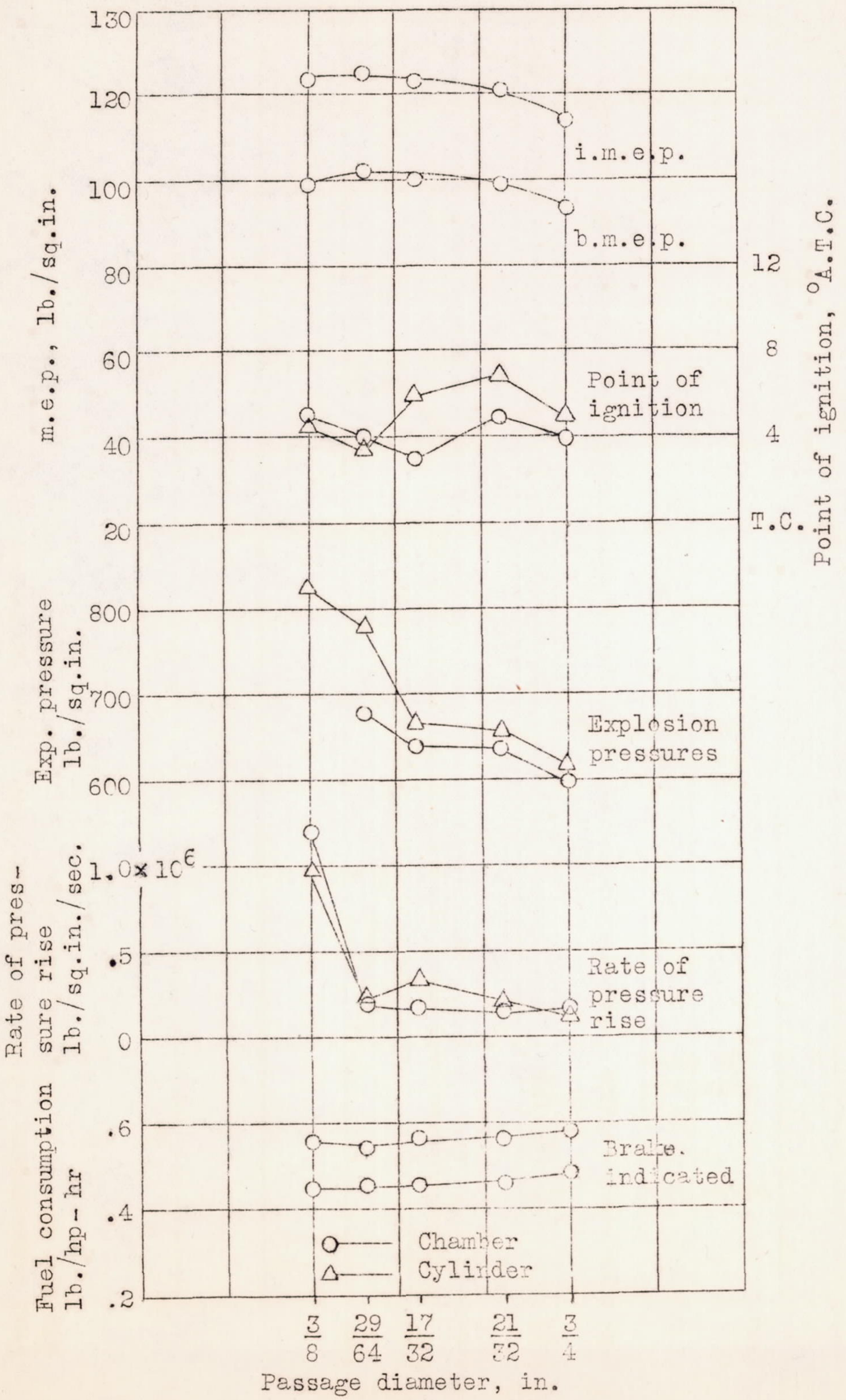

Fig. 11 Effect of passage diameter on engine performance at 0.000325 lb. fuel per cycle, no excess air, 500 r.p.m.

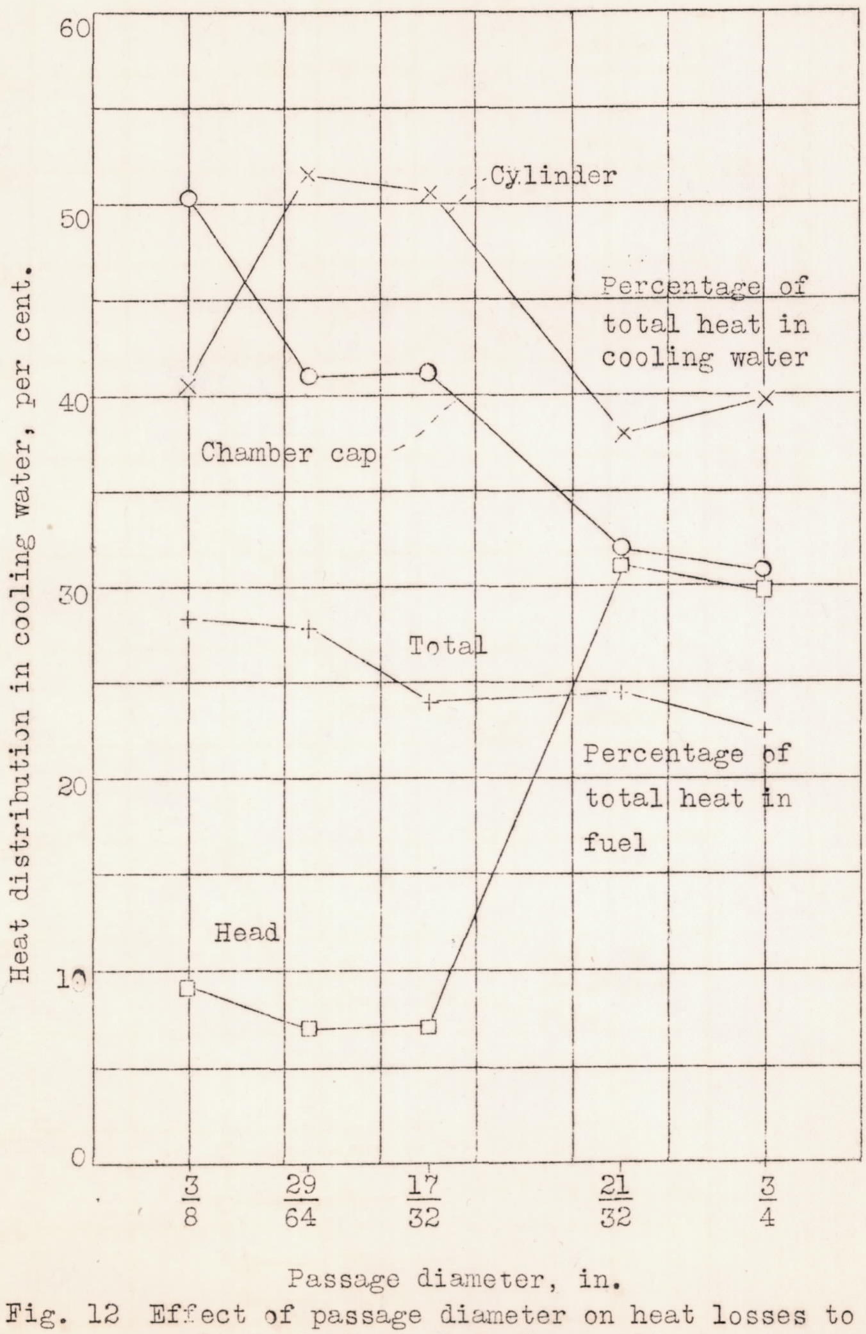

Fig. 12 Effect of passage diameter on heat losses to coolant. Full-load fuel quantity 1500 r.p.m.

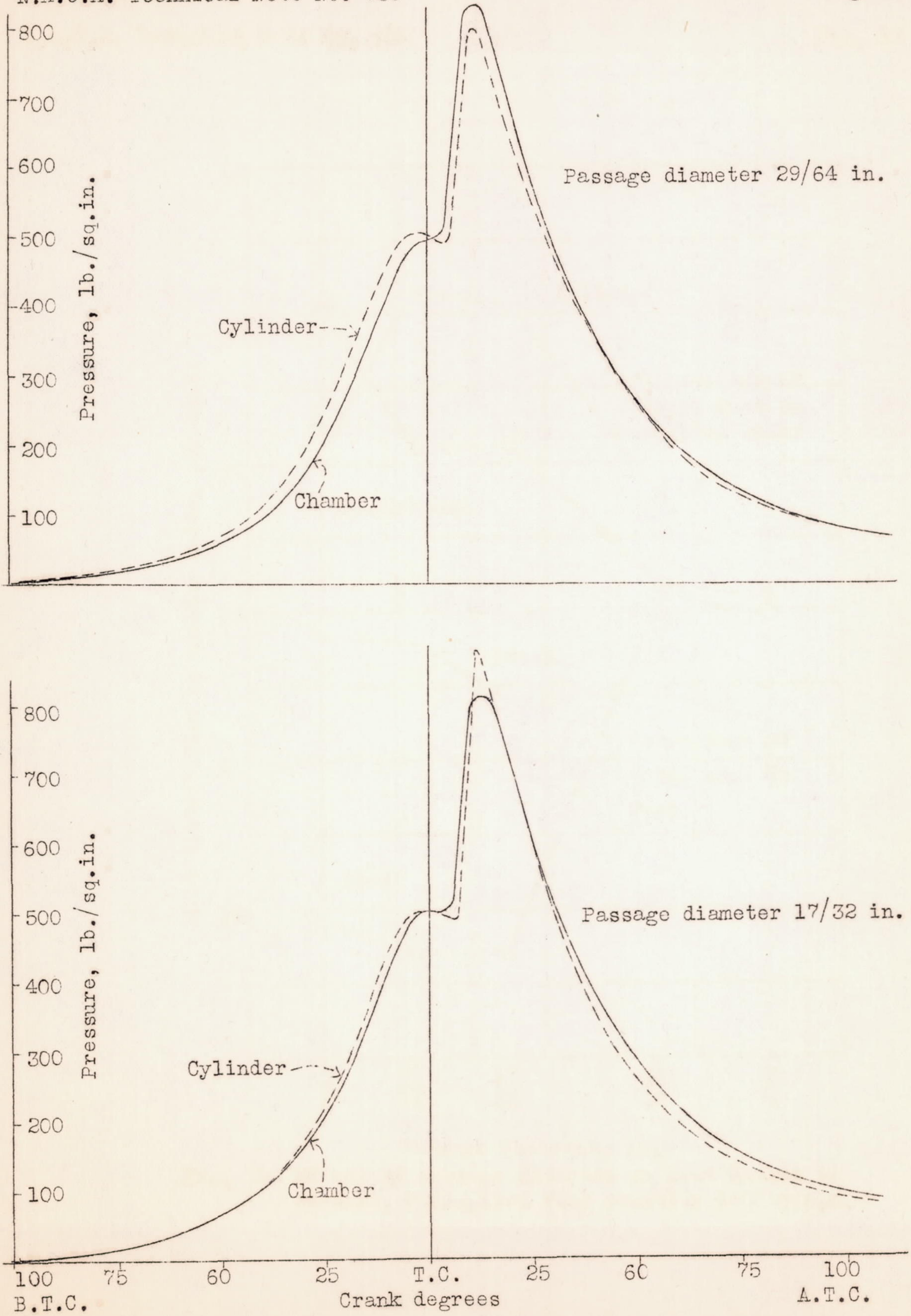

Fig. 13 Power indicator cards, 1500 r.p.m.