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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PERFORMANCE OF A HIGH-SPEED COMPRESSION-IGNITION ENGINE USING MULTIPLE ORIFICE FUEL INJECTION NOZZLES

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40

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Summary

This report presents test results obtained at the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics during an investigation to determine the relative performance of a single-cylinder, high-speed, compression-ignition engine when using fuel injection valve nozzles with different numbers, sizes, and directions of round orifices. A spring-loaded, automatic injection valve was used, centrally located at the top of a vertical disk-type combustion chamber formed between horizontally opposed inlet and exhaust valves of a 5-inch by 7-inch engine.

A series of fuel injection valve nozzles with different arrangements of round orifices were tested, starting with orifices so small that impingement on the combustion chamber walls was impossible and increasing beyond the start of impingement. From these data two main jets of 0.018-inch diameter were decided upon and the other jets varied in number, size, and direction. A nozzle was tested with the area of the orifices proportional to the volume of air to be served by the jets using the

two 0.018-inch orifices as a basis.

A table and curves are presented showing the performance of the engine with different nozzles. Indicator cards and spray photographs are included. The test results are discussed, and some probable reasons given for the variation in performance with different nozzles on a basis of spray distribution. Conclusions are drawn as to the possible application of these results to the design of fuel injection valve nozzles for use with a combustion chamber having a low rate of air flow.

Introduction

The information available on the performance characteristics of high-speed, compression-ignition engines has usually been published as results of tests of particular engines, and these results have been judged entirely on a basis of brake horsepower and specific fuel consumption. Much more detailed information is necessary for a foundation upon which to base further development so that the inherent advantages of this type of engine may be generally used in aerial transportation.

The fundamental problem of the compression-ignition engine is the bringing of all the fuel into contact with sufficient air for its combustion. The particular problem of the lightweight, airless injection engine at high speeds is to obtain, in the short time available, a complete mixing and burning of a fuel charge large enough to unite with all the inducted air.

The two general means of effecting this mixture are the motion of the fuel and the motion of the air, and both are effective to a certain extent in every combustion chamber. The degree of utilization of these motions varies from the combustion chamber depending almost entirely on air flow to that which has such a low rate of air flow that the motion of the fuel is but slightly different from that in quiescent air of the same density.

The use of air flow usually entails a loss in mechanical efficiency as well as an additional heat loss to the coolant and at the present time not enough is known about persistent air flow during injection to utilize this means to its best advantage. Since the induced air flow changes its velocity with engine speed, it can be utilized over only a limited range of speeds.

Therefore, it seemed desirable to investigate the possibility of obtaining the requisite mixture of fuel and air by injecting the fuel through a combination of round orifices in a nozzle, so that it would be properly distributed throughout the air in a combustion chamber. It is impossible to eliminate air flow entirely, but in the combustion chamber used in this investigation the rate appears to be so low that there is no evidence of its influencing the distribution of the fuel.

Both Ricardo (Reference 1) and Hesselamn (Reference 2) have used multiple orifice nozzles and have published results obtained with different combustion chambers. Taylor (Reference 3) reports excellent performance in his work with multiple orifice nozzles at the Royal Aircraft Establishment. The National Advisory Committee for Aeronautics has published a report by Gardiner (Reference 4) on an attempt to make the compression space conform somewhat to the shape of the spray.

This present report includes data from tests made while attacking the problem of distribution in two different ways. The first was the commonly used method of conducting a series of engine performance tests and systematically varying the number, direction, and size of the orifices until the test results indicated an optimum value in any series of changes. The second method consisted in mathematically proportioning the discharge of each orifice to the volume of air to be served by the spray from this orifice. As a matter of convenience and to have a basis of comparison, results from the first method were used as a starting point for the second. Neither method alone is entirely satisfactory, as yet, for a basis of nozzle design and the work along this line is by no means complete. However, the results attained are being published at this time to show the possibilities of improving engine performance through the design of fuel injection valve nozzles.

Apparatus and Methods

The engine performance tests in this report were made on an N.A.C.A. Universal test engine (Reference 5) with a special head (Fig. 1), in which the combustion chamber was formed between the heads of horizontally opposed intake and exhaust valves. The cylinder head, fuel injection apparatus, and piston were designed for research purposes by the staff of the National Advisory Committee for Aeronautics. The shape of the combustion chamber and the locations of the injection valve and maximum cylinder pressure indicator are shown in Figure 2. The clearance between the piston crown and cylinder head was between 0.030 inch and 0.040 inch at top center. Figure 3 shows a longitudinal section of the fuel injection valve, and Figure 4 shows an enlarged section of the fuel injection valve nozzle.

The fuel used was a good grade of Diesel engine oil having a specific gravity of 0.847 and a Saybolt viscosity of 41 seconds at 80°F. This oil was delivered to a cam-actuated injection pump by a primary gear pump at a pressure of about 135 pounds per square inch. The injection pump was connected to the injection valve by a seamless steel tube 1/8 inch inside diameter 36 inches long. A valve opening pressure of 3000 pounds per square inch was used throughout the tests. The pump cam was shaped so that the velocity of the plunger increased during its stroke, and by means of an adjustable cam block control of the by-pass valve, injection could be timed to occur at various portions of the pump stroke, thus taking advantage of the varying velocity of the plunger to obtain different rates of fuel displacement. The injection period indicated by the oscilloscope varied from 37 to 55 crank degrees (Reference 6). The cam was driven from the crank shaft through an adjustable 2 : 1 reduction gear which allowed the angular relation between the cam and the crank shaft to be changed.

A 50-75 horsepower electric dynamometer was used to absorb the engine power and to motor the engine for starting and for the friction runs immediately after power runs. The indicated horsepower was taken as the sum of the brake and the friction horsepowers.

The engine speed was determined by a revolution counter and stop watch, both of which were electrically operated. Fuel consumption was obtained by timing the displacement of 0.5 pound of fuel. Air consumption was determined by an electrically operated stop watch which timed the displacement of 80 cubic feet of air from a gasometer.

Except for one test at speeds from 400 to 2000 r.p.m., all tests were conducted at engine speeds of 1500 r.p.m. The compression ratio was 13.6 to 1. Water and oil temperatures (out) were maintained at 170° and 140°F., respectively. The inlet air temperature was held constant at 95°F. during the tests. Test results as presented are corrected to dry air and to a barometric pressure of 29.92 inches Hg.

Compression pressures and maximum cylinder pressures were indicated by a calibrated Bourdon spring gauge connected to an N.A.C.A. disk-type indicator valve which was operated by the pressure of the gases in the combustion chamber (Reference 7). This apparatus could not be depended upon to follow the higher rates of pressure rise, so the indicated maximum cylinder pressures could not be used as a standard for setting the injection advance. Instead, the pump was adjusted to give the desired fuel quantity and rate of injection, and then the timing was advanced until a faint knock was heard.

Full load fuel quantity, 0.000345 pound per cycle as shown on the performance curves, is that quantity of fuel which will be completely burned, assuming perfect combustion, with the amount of air inducted per stroke at 87.5 per cent volumetric efficiency. Tests made just before publication indicate that this value may be too high for full load operation as shown by the curve in Figure 5. However, no changes have been made in the performance data because they are used only comparatively and any alteration on this basis would be favorable to the engine.

Indicator cars were taken with the Dobbie-McInnes electric indicator in the course of its remodeling at the Langley Memorial Aeronautical Laboratory (Reference 8). Performance is discussed on the indicated basis, because of the low mechanical efficiency of the single-cylinder test engine.

Photographs of the fuel sprays were taken with the N.A.C.A. Spray Photography Equipment (Reference 9). A full scale model following the outline of the disk-shaped combustion chamber was placed in the spray photography pressure chamber (Fig. 6), so that a picture could be obtained of the spray distribution in the combustion chamber for each nozzle. The edges of the combustion chamber shape were slightly obscured in the photographs by the pressure-chamber cover plate. The injection pressures were of the same order as those used in the engine tests at full load. The spray chamber air density corresponded to that in a combustion chamber at a compression ratio of 13.6 : 1.

The orifices were measured either on a dividing engine or with plug gauges. The length of the orifice was made twice the diameter by counterboring when necessary.

Test Results and Discussion

The test results are presented in the form of curves and a chart (Fig. 11) which lists the nozzles and gives dimensions of orifices and the performance obtained. The results presented may be considered average and are readily reproducible.

The first experimental nozzles were built with the idea of preventing any impingement on either the piston or the combustion chamber walls. Figure 7 gives the engine performance with some of these nozzles. The limited performance of nozzles Nos. 3, 4, and 7 was due to the inability to inject more fuel through these nozzles even with excessively high injection pressures, because of insufficient flow area through the orifices. Figures 7 and 8 show the results when using high and low rates of injection, respectively. It may be seen that the performance covers a a greater range of fuel quantity when the low rate of injection is used. It should be noted that only with nozzle No. 9 of this group having an orifice area of 0.00069 square inch could full load fuel be obtained.

The design of nozzle No. 9, the first of the seven-orifice type having alternate large and small orifices, was based on the assumption that the sprays from the small orifices with their shorter penetration distribute fuel to that part of the combustion chamber nearer the injection nozzle. The value of these filler sprays as an aid to distribution may be realized when it is considered that the spray as shown in a photograph does not contain a uniformly dispersed quantity of fuel, but that it contains a relatively dense core, most of which eventually travels almost to the spray tip.

The engine performance obtained using No. 9 nozzle warranted the continuation of tests, and a definite program was started to determine the effect on engine performance of varying, first, the two main orifices which deliver fuel oil to that portion of the air charge in the rectangular orifice directly above the piston crown and, second, the other orifices which deliver fuel to the air in the upper part of the combustion chamber. Figure

9 shows the engine performance results at full load for a range of sizes for the two main orifices B from 0.010-inch to 0.021-inch diameter (Fig. 4). The part of the injection pump cam giving the highest rate of injection was used in obtaining this performance. It may be seen from the curves that the 0.018-inch orifices may be considered the optimum diameter for the two main orifices. The results show that the i.m.e.p. increased from 101 to 125 pounds per square inch, with an increase in orifice diameter from 0.010 inch to 0.018 inch. The corresponding fuel consumption decreased from 0.586 to 0.468 pound per i.hp per hour. A further increase in main orifice diameter from 0.018 inch to 0.021 inch resulted in a slight decrease in power. This indicates that orifices larger than 0.018 inch supplied more fuel than could be burned efficiently by the air in that part of the combustion chamber served by these jets.

Inspection of the carbon formation on the crown of the piston showed that all the sprays from orifices of 0.012 inch or larger actually impinged upon the piston crown. Since the specific fuel consumption decreased as these B orifices were enlarged to 0.018 inch, it may be said that impingement of a spray does not necessarily mean that it is not available for combustion after impingement, or that oil particles making contact with a wall will cling to it and not ignite. It is true that these sprays were striking high temperature walls, but later experiments showed that the same was true of sprays impinging upon cooler sections of the combustion chamber walls. The 0.018-inch orifices discharged a larger quantity of fuel than the 0.012-inch orifices, and this extra quantity of fuel seemed to be necessary for the utilization of the air available for these sprays.

Figure 10 shows the effect on engine performance of changing only the two outside orifices D (Fig. 4), which deliver fuel to the air charge in the uppermost part of the combustion chamber, from 0.006 inch to 0.012 inch for nozzles having two 0.018-inch diameter main orifices. From the results, 0.010 inch appears to be the optimum diameter for the outside orifices. At full load the i.m.e.p. increased from 114 to 126 pounds per square inch, for an increase in orifice diameter from 0.006 inch to 0.010 inch. The corresponding fuel consumption decreased from 0.50 to 0.475 pound per i.hp per hour. An increase in diameter of these two orifices from 0.010 inch to 0.012 inch caused a slightly smokier exhaust with approximately 1 per cent increase in power output. This indicated that the 0.010-inch orifices supplied the proper proportion of fuel for the air available in the part of the combustion chamber served by these jets.

The chart (Fig. 11) shows the effect on engine performance of changing the orifices C from 0.005 inch to 0.012 inch. This is shown as the difference between nozzles Nos. 17 and 18, and indicates that the C orifices should be considered as filler orifices when used in combination with the larger D orifices.

This change decreased the i.m.e.p. from 126 to 116 pounds per square inch, and increased the fuel consumption from 0.48 to 0.52 pound per i.hp per hour due to a less uniform distribution of the fuel. Spray photographs taken some months after the engine tests showed that this was probably due to both spray tips being projected into the same space by different paths. The photographs show that the oil spray is reflected from the wall of the combustion chamber, but the engine data do not indicate that the spray is absorbed by the carbon on the wall, or that the comparatively cool wall causes any condensation of the spray.

Figure 12 shows a comparison of performance with the series of nozzles designed so that the area of the orifice would be proportional to the volume of air it served. The basis of this proportion was taken as the relation between the area of the two main 0.018-inch orifices and the air included in their spray angle plus the air in the clearance space about the piston crown. The first nozzle of this series was tested without the filler orifice A. The addition of an 0.007-inch filler orifice increased the i.m.e.p. from 122 to 130 pounds per square inch, and decreased the fuel consumption from 0.49 to 0.46 pound per i.hp per hour. Enlarging this filler orifice to 0.010 inch slightly increased the mean pressure.

This nozzle with nine orifices (Fig. 13) gave such a slight increase that it was questionable whether this increase was worth the added complication of two extra orifices. In this particular nozzle the outer E orifices were crowded into the corner so that less area was exposed to the impact of the oil and, therefore, there was less discharge through them than would be expected. This was suspected at the time of the engine tests and subsequently confirmed by the spray photographs. A very small amount of spray is visible from these outer orifices in photographs taken both with the dummy combustion chamber in place and without it.

From the test results it is apparent that the small filler spray was an important factor in securing good fuel distribution with resultant higher power and better fuel economy. The filler spray supplied fuel to air in which there seemed to be very little fuel remaining from the passage of the main sprays through it, although the spray photographs show some spray in this space.

Figure 14 shows typical engine performance curves for a constant speed of 1500 r.p.m., a variable fuel quantity, a constant injection advance angle of 45°, and a low rate of injection. The points marked with circles were obtained by increasing the injection advance angle in increments of 2°, and they show that the large increase in maximum cylinder pressure was out of proportion to the increase in mean effective pressure gained in this way. A comparison of these curves with those of Figure 15 for a higher rate of injection shows that they are somewhat similar, but the cylinder pressures are higher for the lower rate of injection. Figure 16 shows engine performance results for a range of injection advance angles.

Figure 17 shows the effect of speed on general engine performance with full load fuel from 400 to 2000 r.p.m. and a low rate of injection. Four hundred r.p.m. was the lower limit for consistent operation with full load fuel, although the engine would idle at 175 r.p.m. The consistently low specific fuel consumption from 800 to 1800 r.p.m. shows the desirable characteristic of constant fuel consumption over a range of speed. This also indicates uniform combustion efficiency and, therefore, absence of any effects of air flow. This absence of effective air flow agrees with the results of Rothrock's and Beardsley's investigation (Reference 10) of the effect of air flow on sprays in an apparatus simulating the conditions encountered in the passage between the combustion chamber and the cylinder of this engine.

In Figures 14 and 17 are shown, for comparison, brake performance curves for a multicylinder engine with an assumed efficiency of 85 per cent, as calculated from the data secured on the single-cylinder test engine whose efficiency is about 75 per cent.

Figures 18, 19, and 20 show pressure-volume cards plotted from pressure-time cards taken with the modified "Farnboro" indicator. A complete analysis has not been made of these cards, but they are included to show the variations in the cycle with changes in the injection advance angle and in the rate of injection. In Figure 19 the injection advance angle had been increased 5° over that in Figure 18. Figure 20 shows a card taken with a low rate of injection and a large injection advance angle.

Figures 21 and 22 show pictures of the sprays from nozzle No. 9, with injection pressures of 4750 pounds per square inch and 3200 pounds per square inch which correspond to the maximum injection pressure at full load for the high and low rates of injection, respectively.

Figure 23 shows a picture of the sprays from nozzle No. 17-1 which had outer orifices of 0.012-inch diameter. It may be seen that the outer sprays in nozzle No. 17-1 struck the side of the chamber and were deflected downward into otherwise unreached air, thereby aiding the fuel distribution. Figure 24 shows spray pictures for nozzle No. 16-2 which had outer orifices of 0.008-inch diameter.

Figure 25 shows pictures of sprays from nozzle No. 12 which had two main orifices of 0.010 inch as compared to 0.018 inch for all other nozzles. Due to the reduced orifice area, the injection pressure at the high rate of injection was 6800 pounds per square inch as compared with 4750 pounds per square inch for other nozzles.

Figure 26 shows pictures of sprays from the nine-orifice nozzle No. C-2. Lack of a more pronounced outline of the sprays may be attributed to overlapping caused by crowding of these comparatively large sprays.

Conclusions

The results of this investigation show that to obtain efficient combustion in a cylinder head with low rates of air flow during the injection of the fuel, it is necessary to proportion and direct the fuel sprays so that the fuel is distributed as uniformly as possible throughout the air.

The engine performance obtained by proportioning the areas of the orifices to the volumes of air to be served by each orifice was approximately the same as that obtained by varying all orifice sizes and determining from the engine power the optimum combination.

The mathematical method is considerably less expensive in time and material than the experimental method. However, neither is complete in itself, and both can be aided considerably by the study of spray photographs.

The engine test results indicate that impingement of the fuel spray on the piston and chamber walls is not necessarily detrimental to combustion, but may be an aid to distribution. Small filler jets are important aids to distribution. Fitting visible spray outlines to combustion chamber contours does not insure a perfect mixture, because of the varying density of the fuel in the visible spray.

Although engine performance is the ultimate standard by which the value of any particular combination of orifices must be determined, the performance of the engine is not to be entirely relied upon to indicate the worth of any combination for development purposes. The same performance values may be attained by different combinations, one of which may be the optimum of a particular means of improvement, while the other might be merely an intermediate point along a line that leads to possibilities of even better performance.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 28, 1930.

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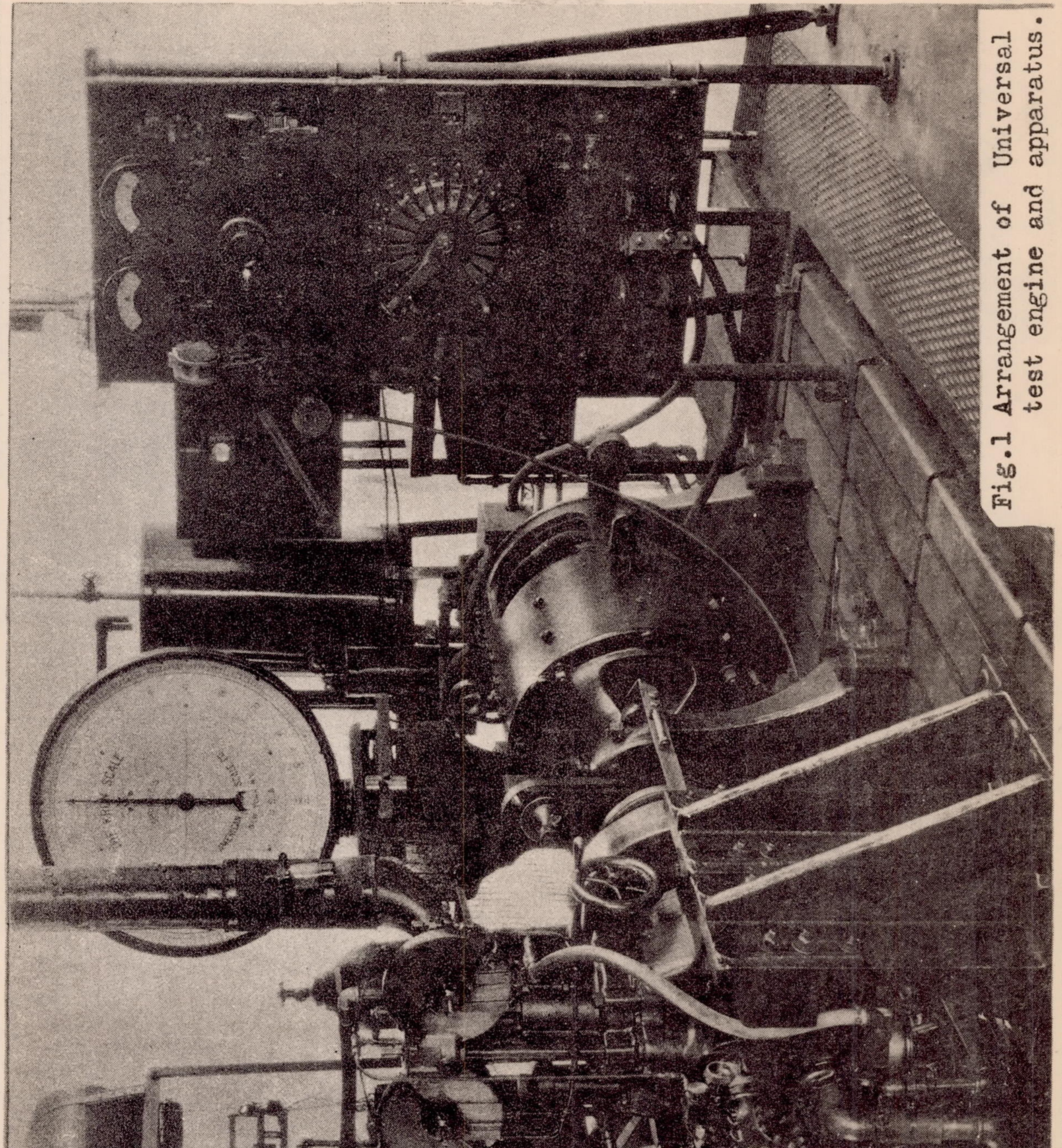

Fig.1 Arrangement of Universal test engine and apparatus.

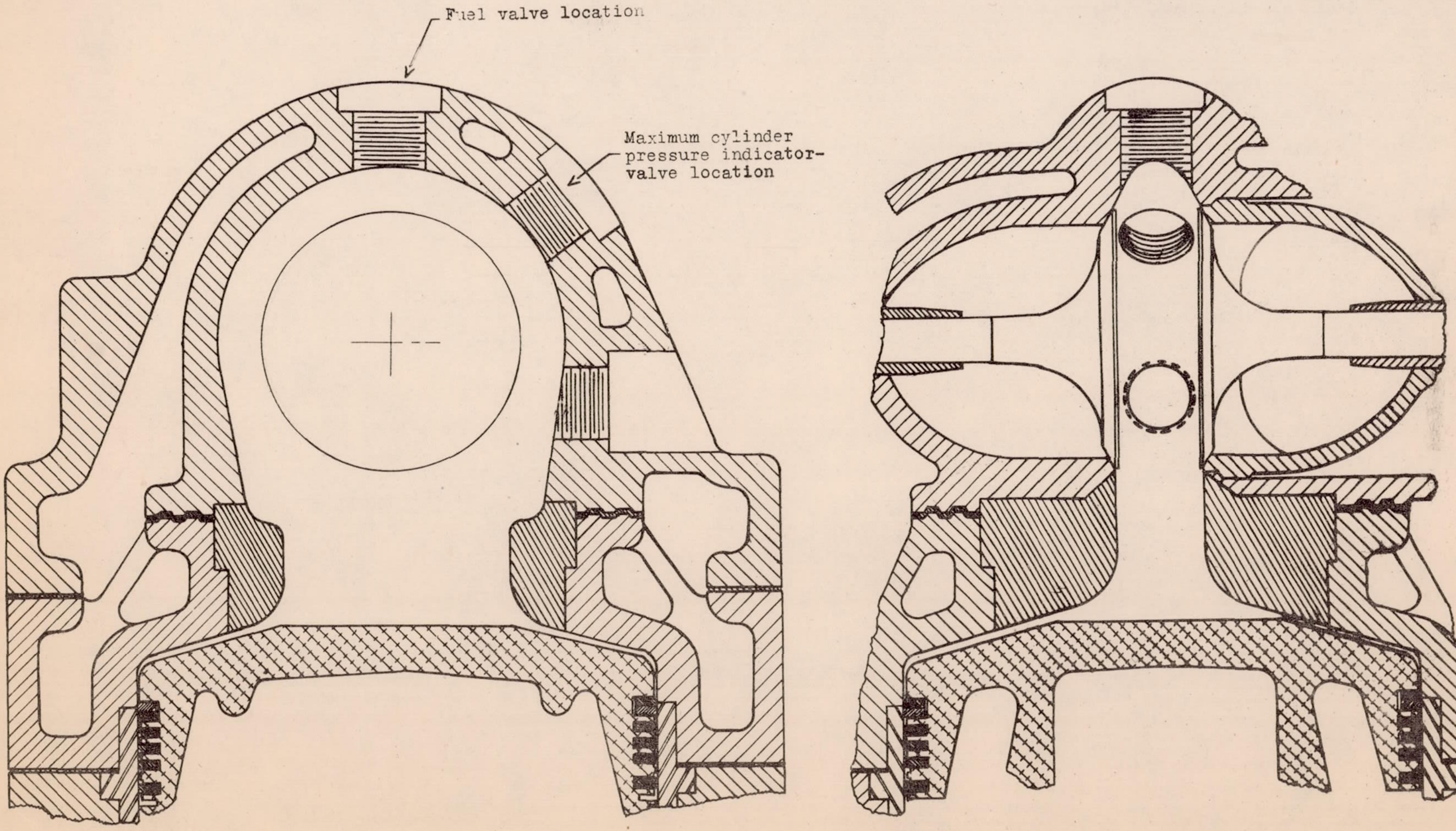

Fig.2 Combustion chamber.

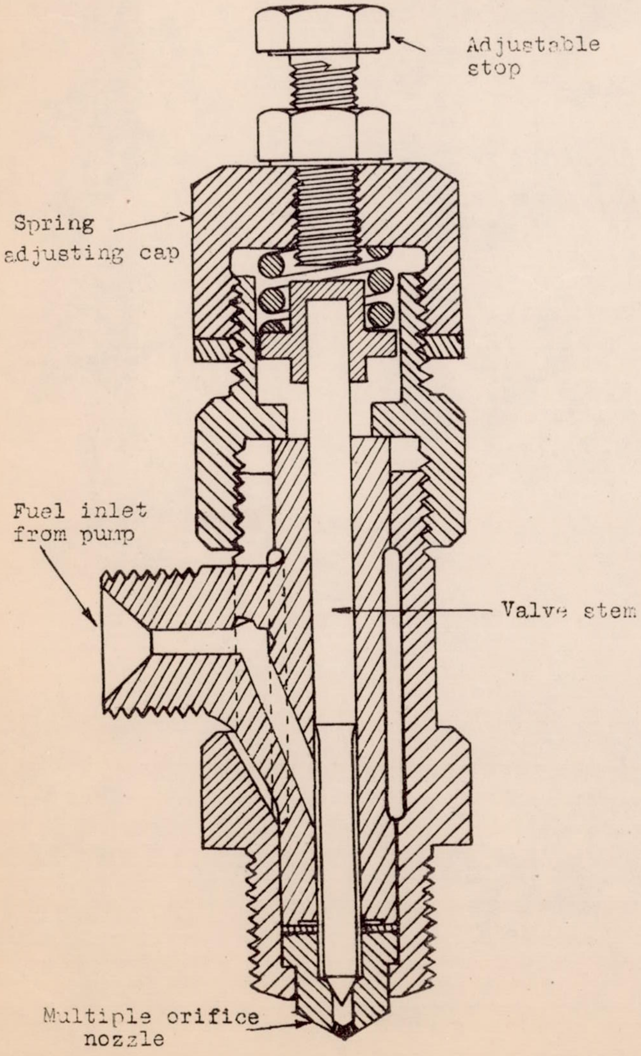

Fig.3 Fuel injection valve

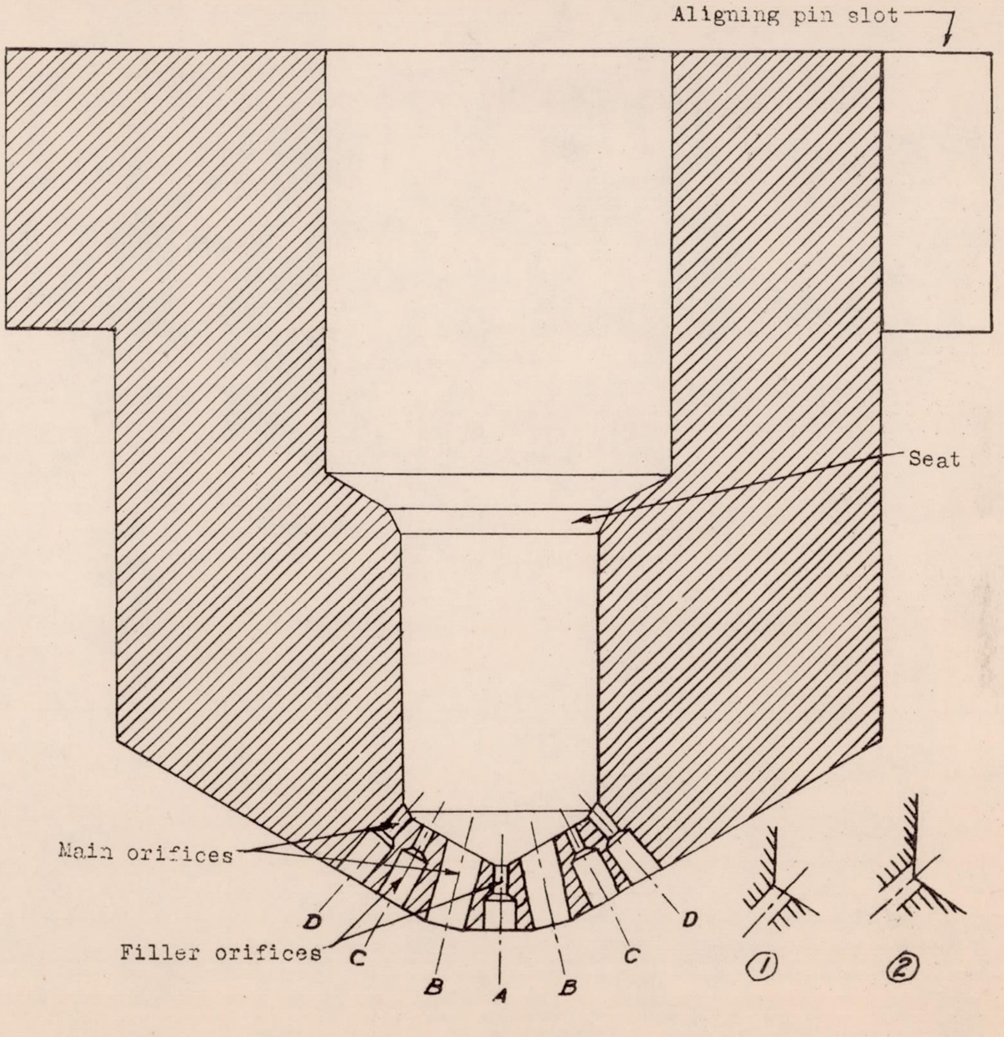

Fig.4 Multiple orifice fuel injection nozzle. (7 orifice type.) Nozzles 9 - 14 inclusive have corner orifices as in postion 1. All thereafter have corner orifices as in 2.

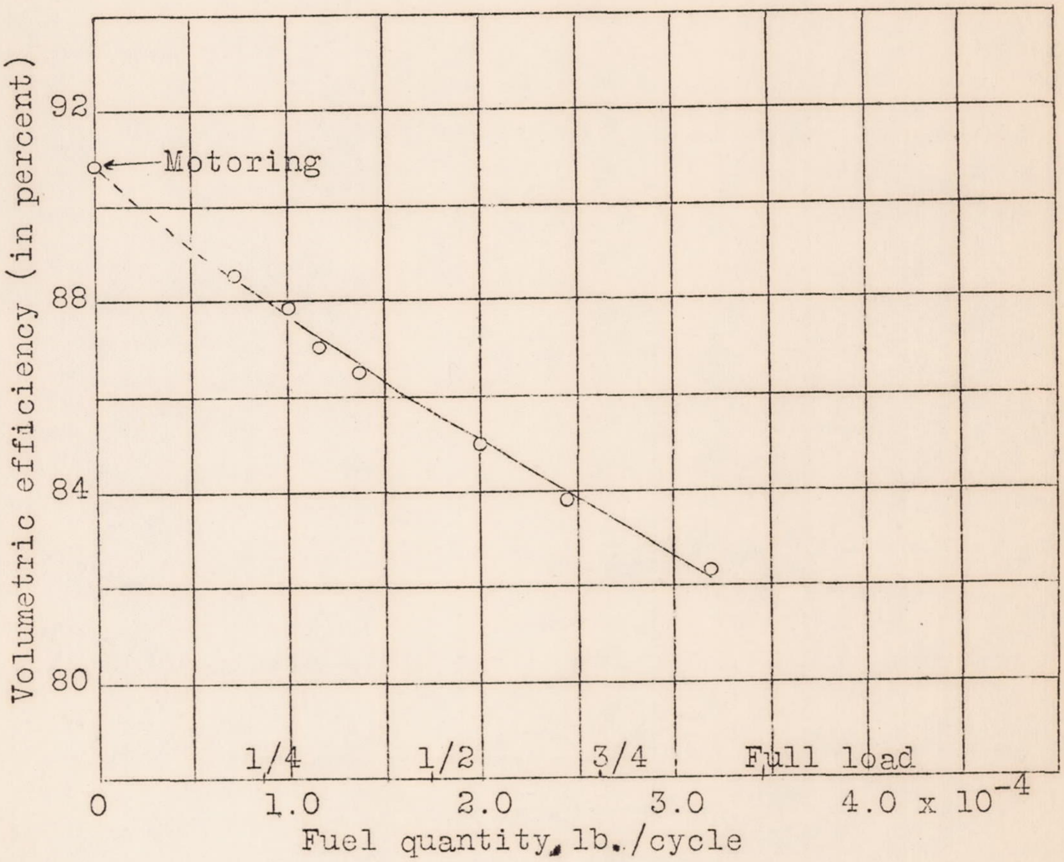

Fig.5 Effect of load on volumetric efficiency.

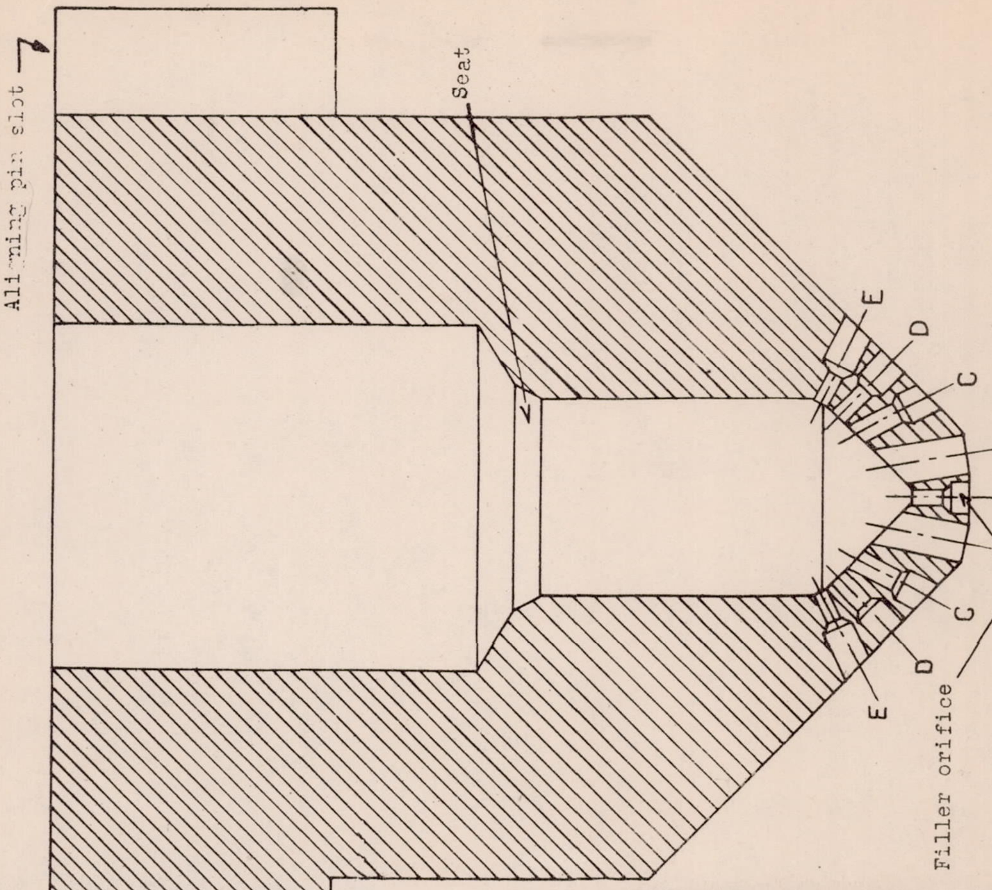

Fig.13 Multiple orifice fuel injection nozzle. (9 orifice type.)

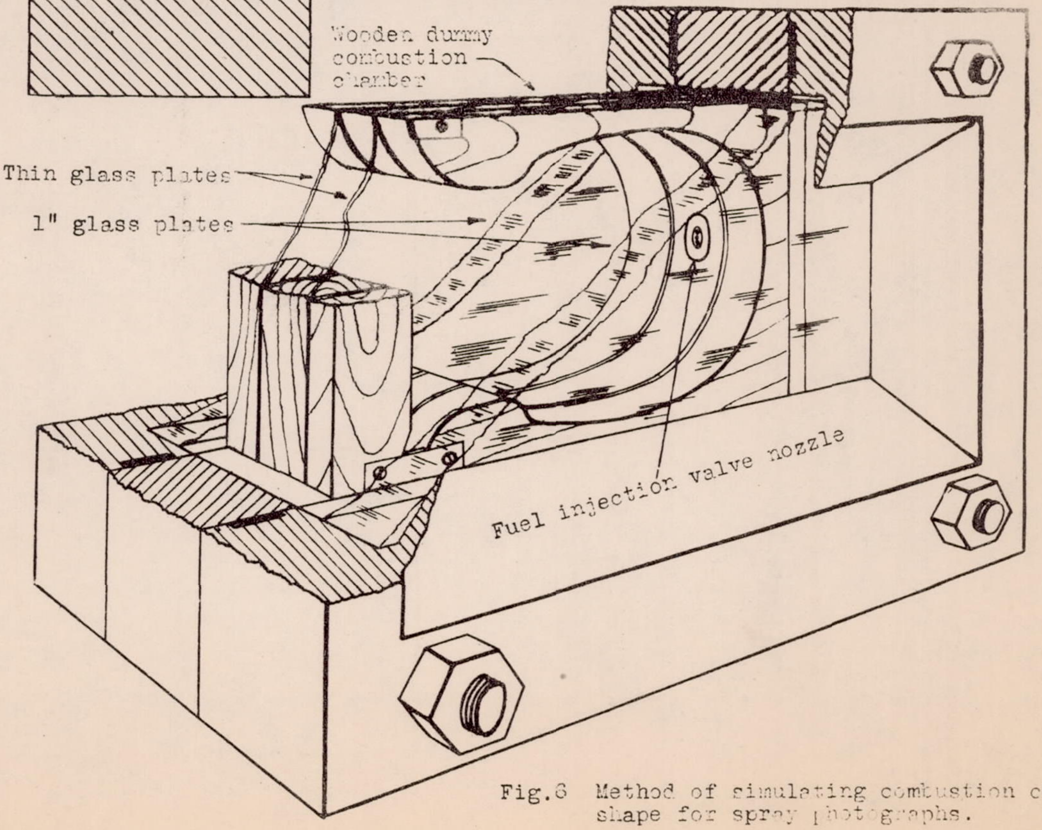

Fig.6 Method of simulating combustion chamber shape for spray photographs.

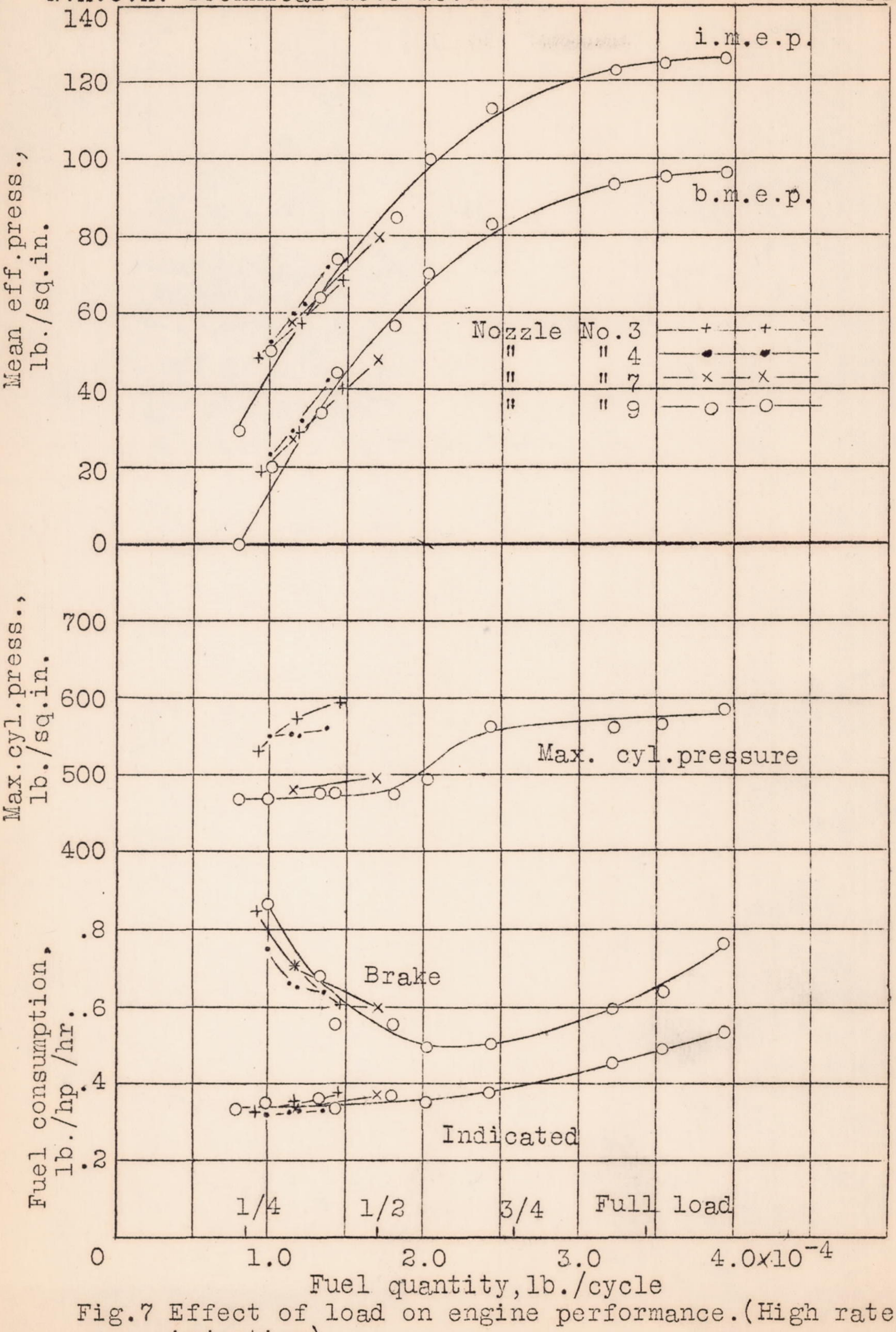

Fig.7 Effect of load on engine performance. (High rate of injection)

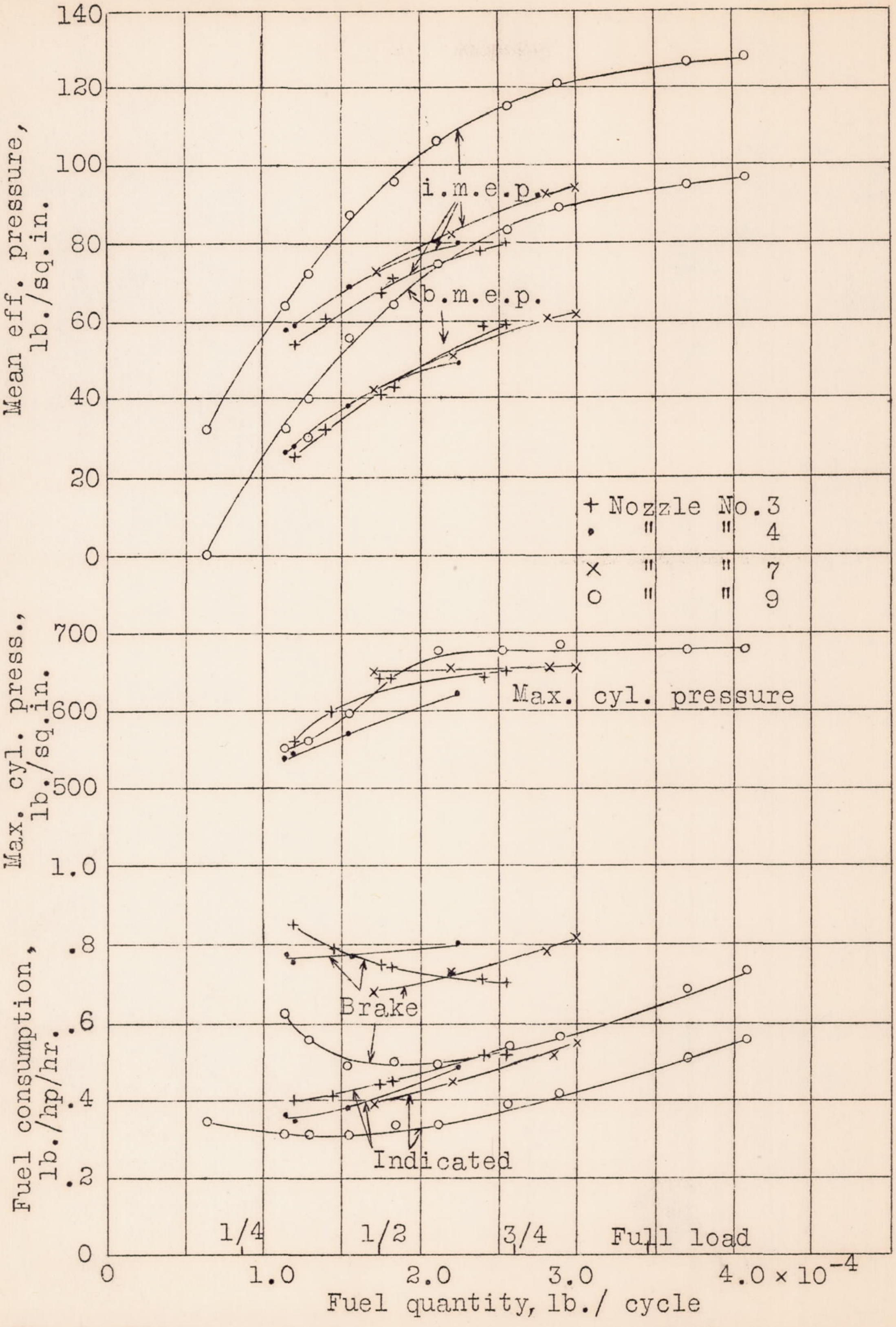

Fig.8 Effect of load on engine performance (low rate of injection)

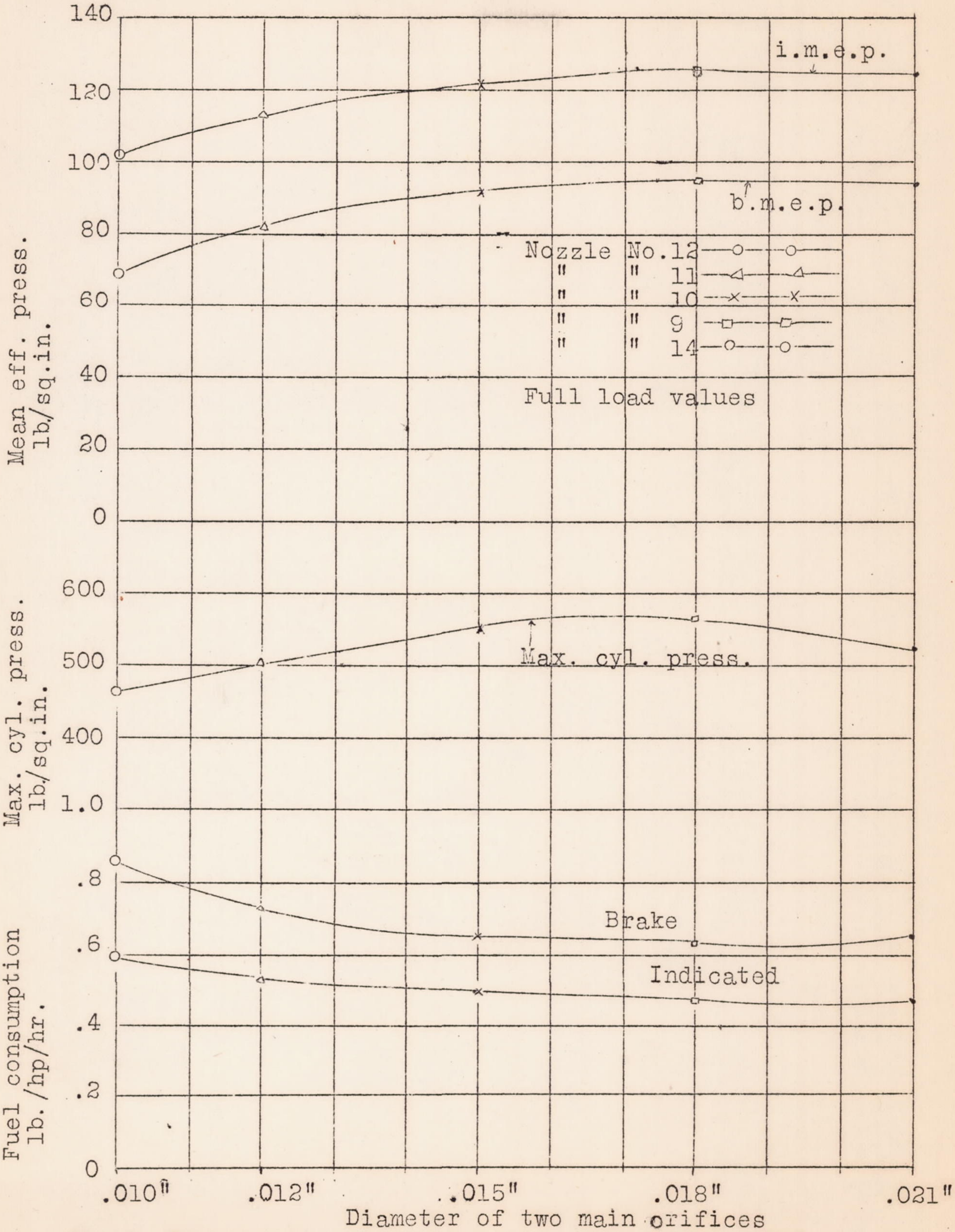

Fig.9 Effect of changing the two main orifices "B" on engine preformance.

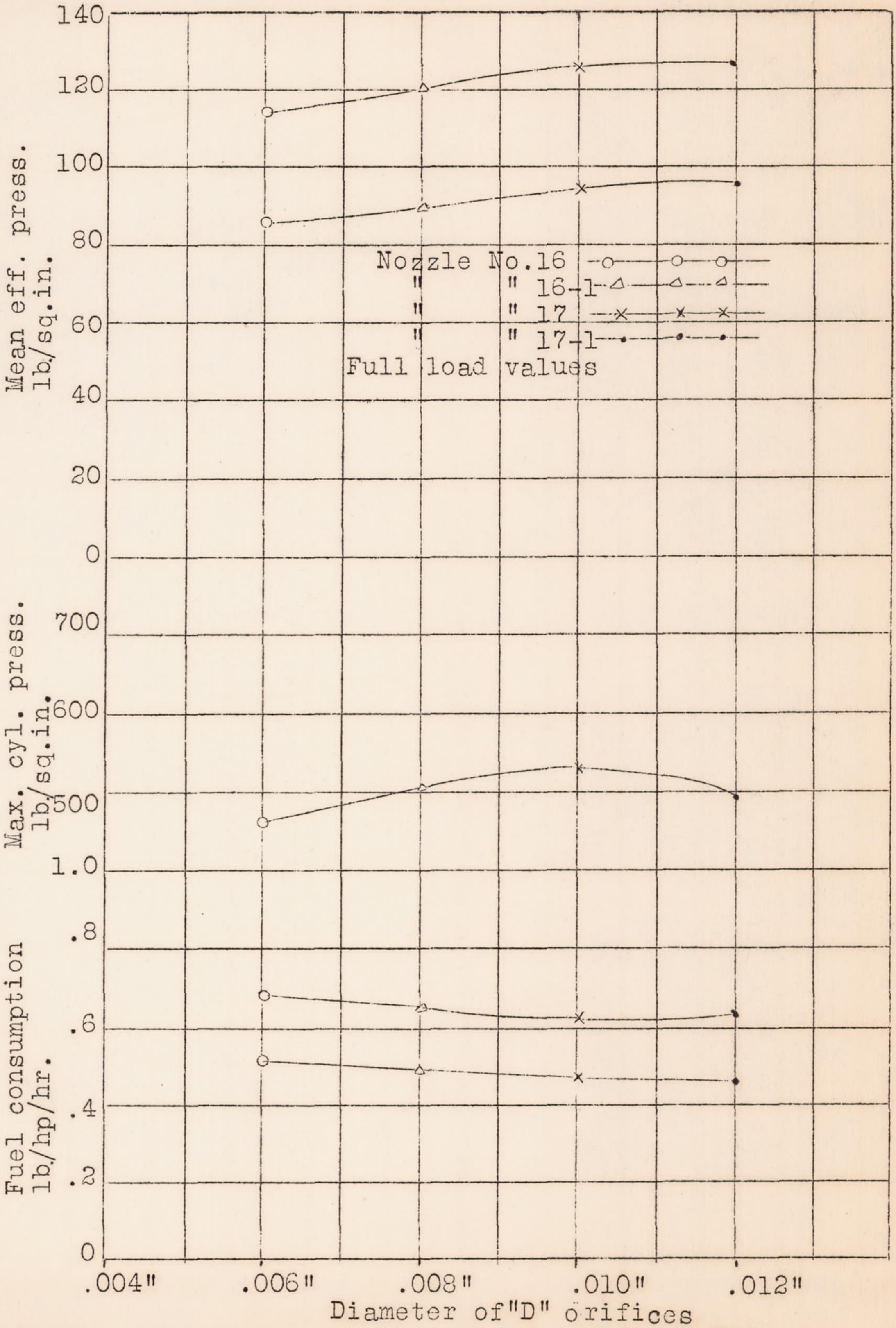

Fig.10 Effect of changing the two outside orifices "D" on engine performance.

DESCRIPTION OF FUEL VALVE NOZZLES AND SOME TEST RESULTS FOR FULL LOAD FUEL AT 1500 R.P.M.

NOZZLE Nº	ORIFICES A	B	C	D	E	TOTAL ORIFICE AREA SQ. IN.	I.M.E.P. LBS/IN²		I.F.C. LBS/I.H.P./Hr.		MAX. PRESS. CYL. (Gage Rdgs)	INJ.	%FULL LOAD TORQUE WITH CLEAR EXHAUST	%FULL LOAD FUEL WITH CLEAR EXHAUST
MISCELLANEOUS GROUP														
3	1-008	2-.006	2-.004			.00013	70		.38		575	7700	ORIFICE AREA TOO SMALL	
4		2-.008	2-.005			.00014	72		.33		540	7700		
7	1-008	2-.007	2-.005	2-.004		.00019	81		.37		480	7500		
7 ORIFICE GROUP														
							$\frac{3}{4}$ TORQUE	FULL LOAD TORQUE	$\frac{3}{4}$ TORQUE	FULL LOAD TORQUE				
9	1-007	2-.018	2-.005	2-.008		.00069	100	125	.351	.47	565	4800	84	68
10	"	2-.015	"	"		.00054	98	121	.355	.49	550	5700	87	71
11	"	2-.012	"	"		.00041	92	113	.41	.53	500	6300	75	62
12	"	2-.010	"	"		.00034	86	101	.40	.59	460	6600	77	58
14	"	2-.021	"	"		.00089	101	124	.406	.46	520	4700	58	60
16	"	2-.018	"	2-.006		.00064	93	114	.43	.50	470	4850	78	73
16-1	"	"	"	2-.008		.00069	98	122	.40	.48	500	4800	83	75
16-2	"	"	2-.007	"		.00072	101	125	.36	.47	500	4600	87	77
17	"	"	2-.005	2-.010		.00074	104	126	.34	.475	540	5000	88	78
17-1	"	"	"	2-.012		.00081	104	127	.34	.46	495	4800	86	76
18	"	"	2-.012	2-.010		.00093	93	116	.43	.52	485	4875	73	67
18-1	1-.010	"	"	"		.00097	93	116	.43	.52	495	4650	72	67
18-2	1-.012	2-.018	2-.012	2-.012		.00107	94	114	.35	.52	470	4600	72	55
9-ORIFICE GROUP														
C		2-.018	2-.010	2-.008	2-.007	.00084	99	122	.39	.49	520	4700	75	64
C-1	1-.007	"	"	"	"	.00088	105	130	.34	.46	530	4150	87	77
C-2	1-.010	"	"	"	"	.00092	106	131	.36	.45	510	4750	80	70
C-3	1-.007	"	2-.008	2-.007	2-.006	.00078	103	128	.40	.46	480	5800	67	64

Fig.11

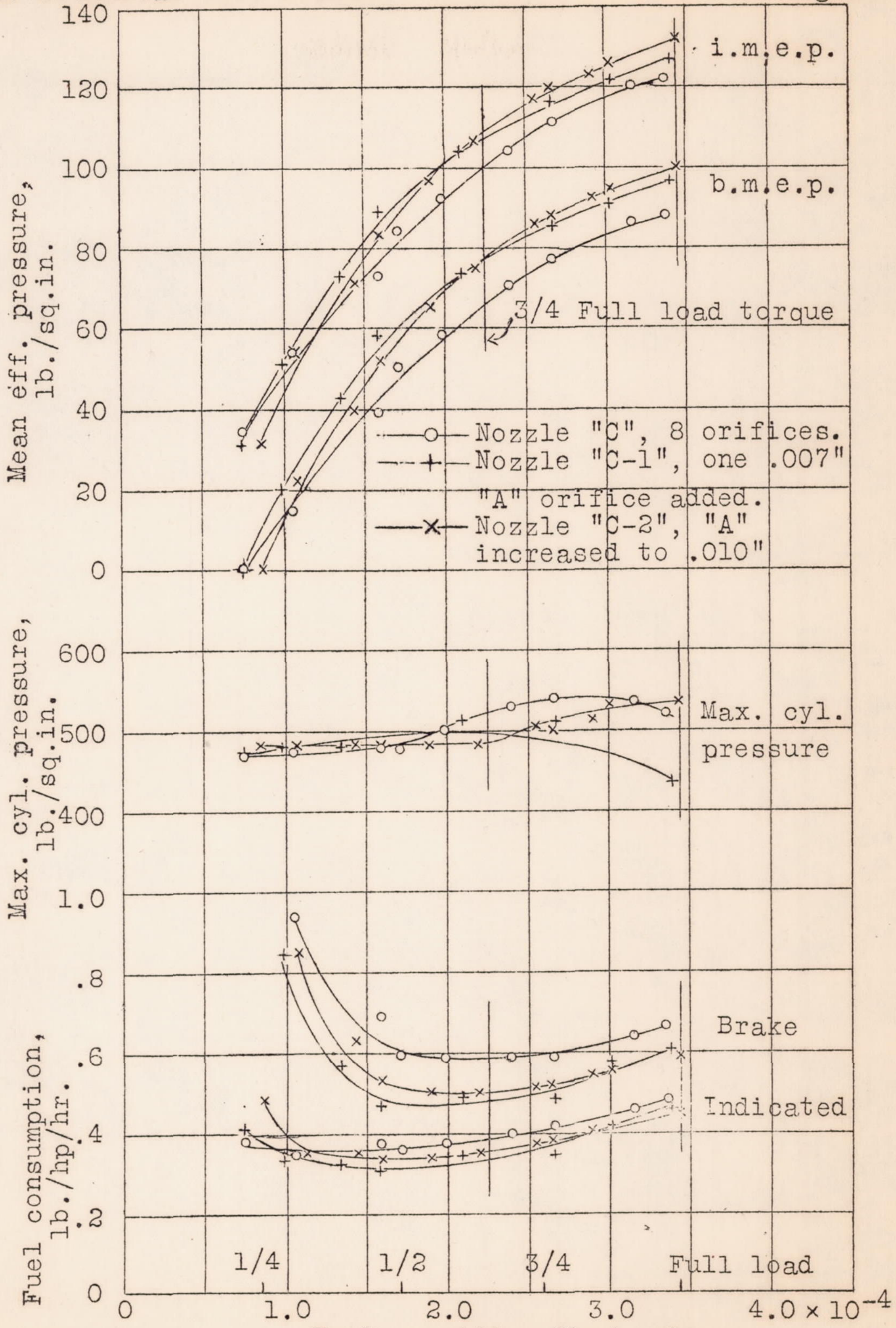

Fig.12 Effect of the center filler orifice "A" on engine performance.

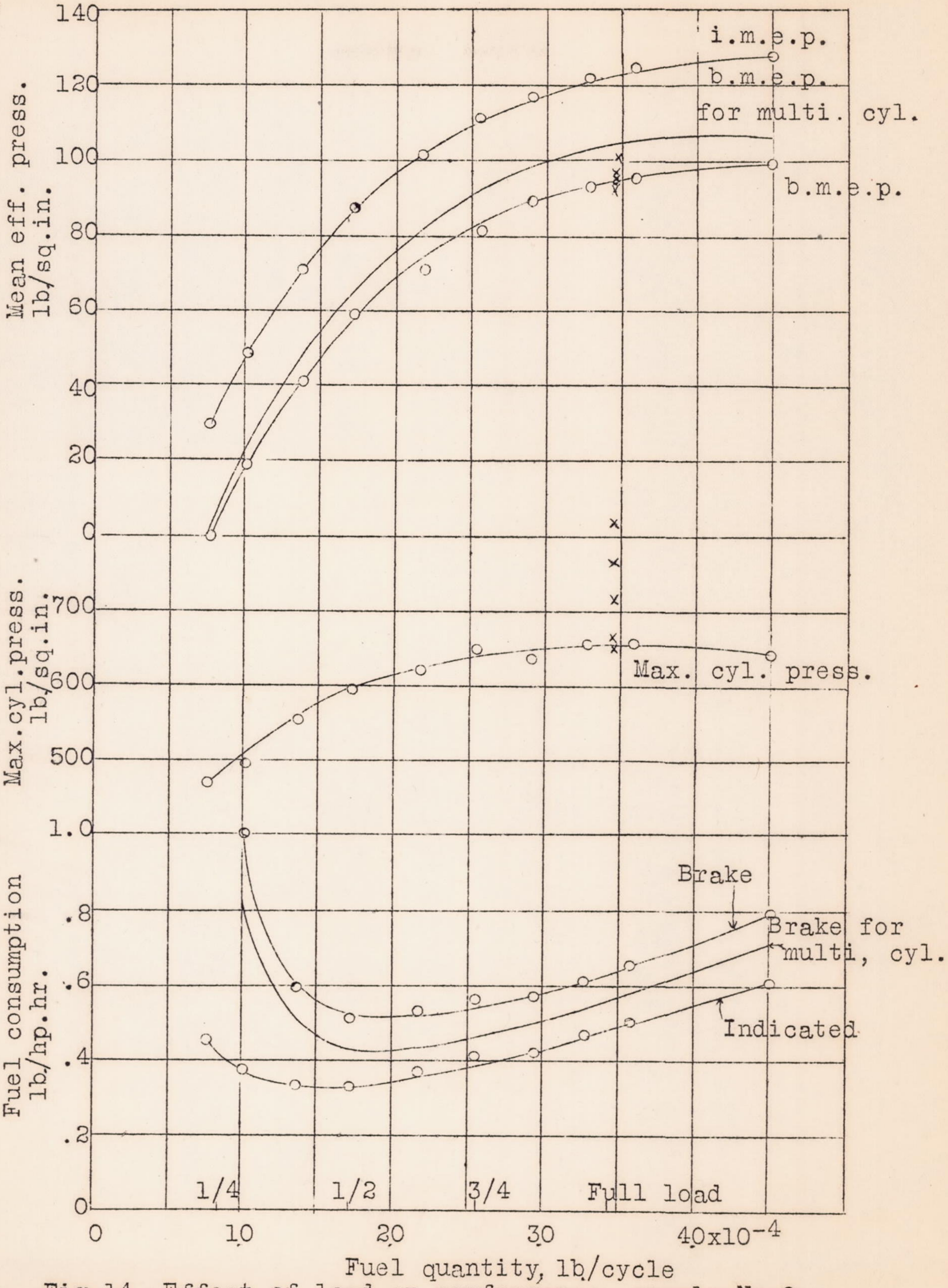

Fig.14 Effect of load on performance, nozzle No.9 (low rate of injection).

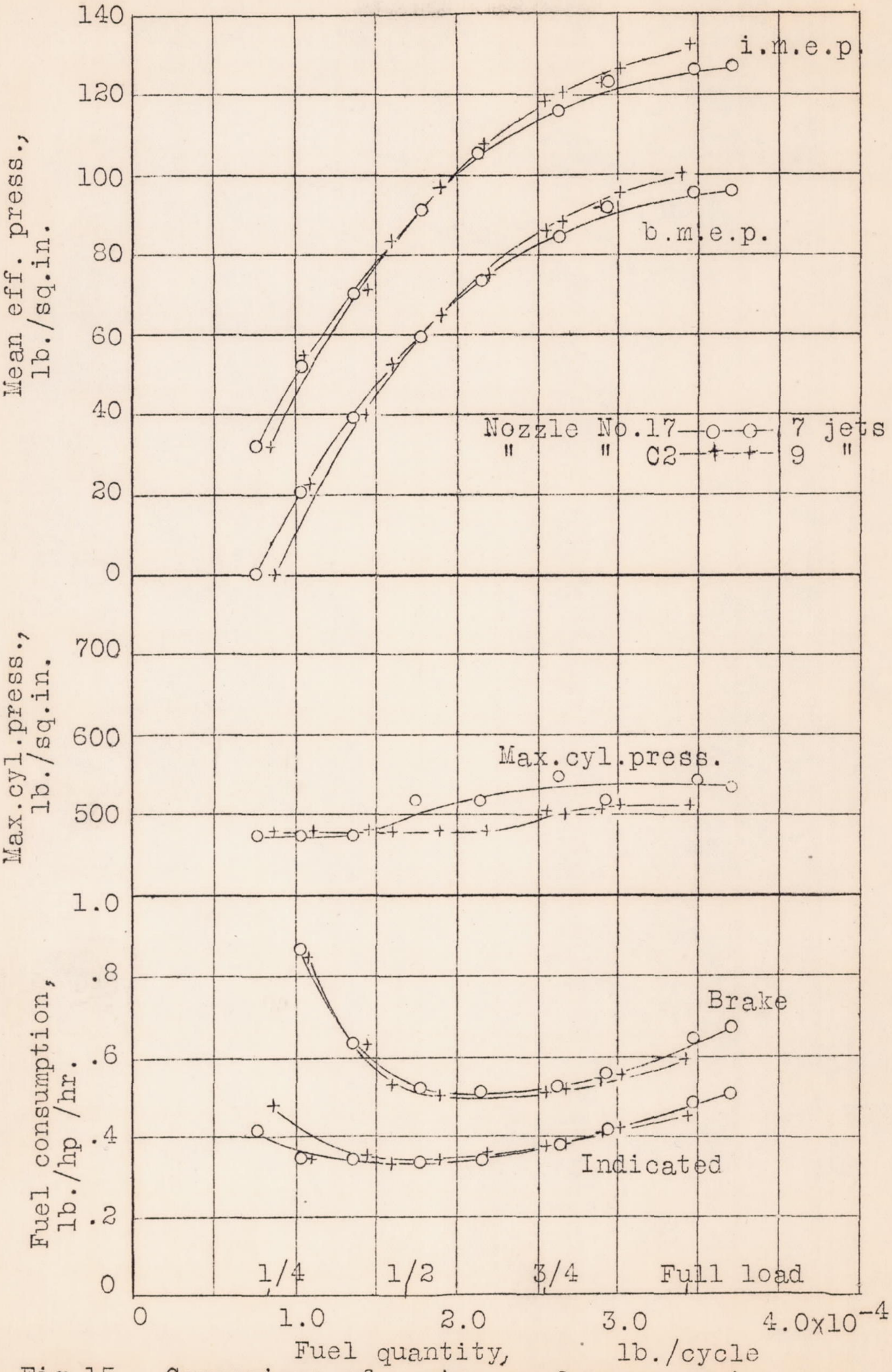

Fig.15 Comparison of engine performance using a 7 and a 9 orifice nozzle. (High rate of injection).

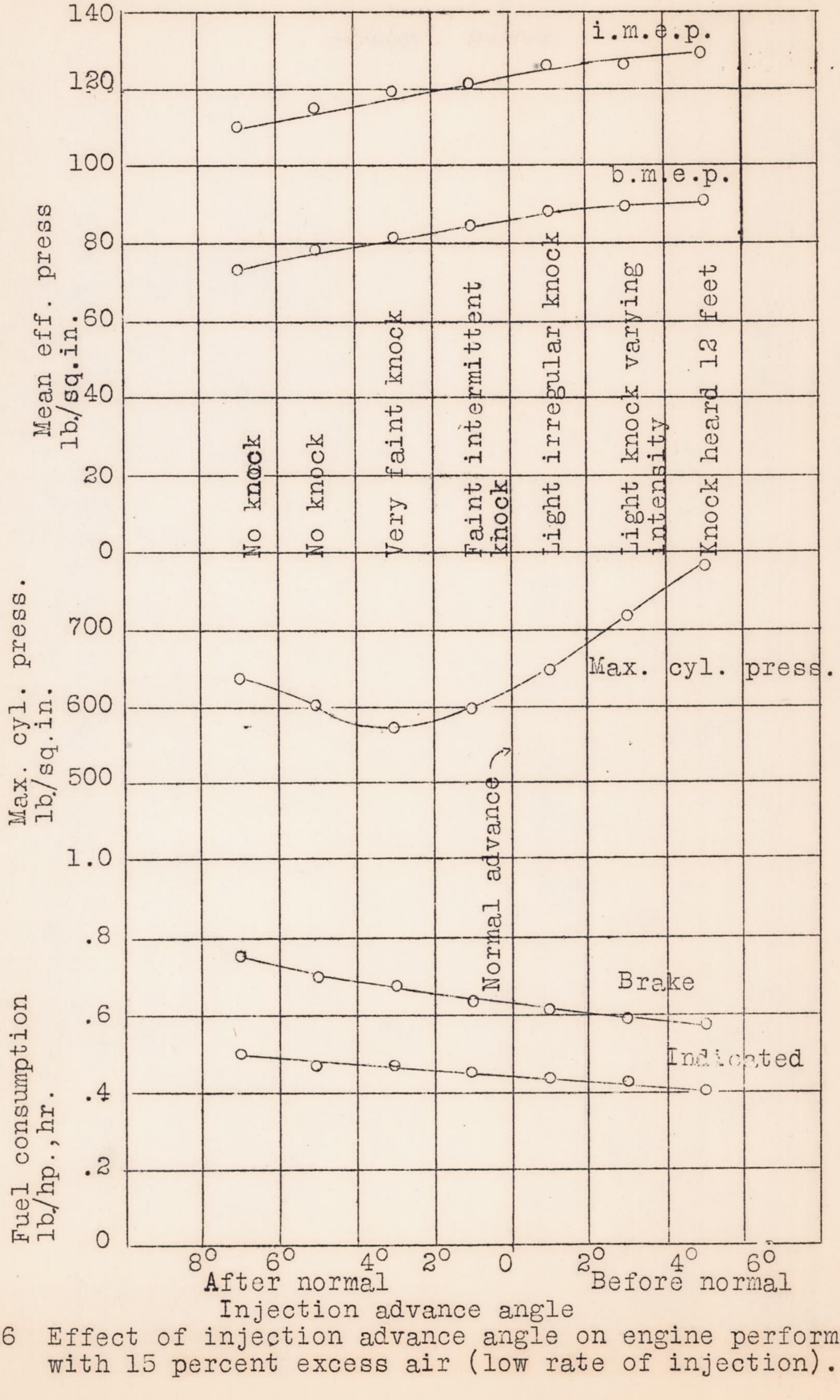

Fig.16 Effect of injection advance angle on engine performance, with 15 percent excess air (low rate of injection).

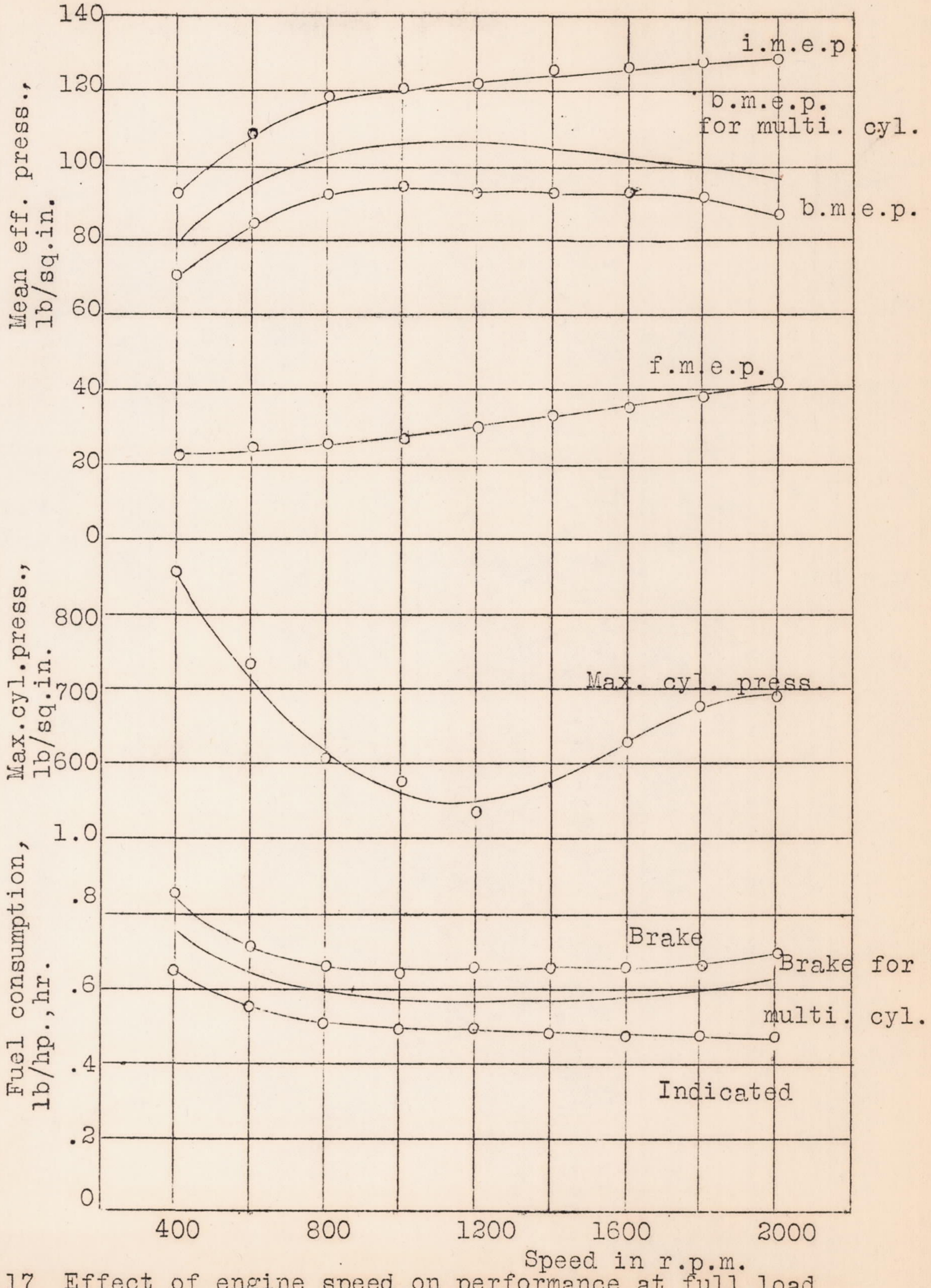

Fig.17 Effect of engine speed on performance at full load (nozzle No.9), (low rate of injection).

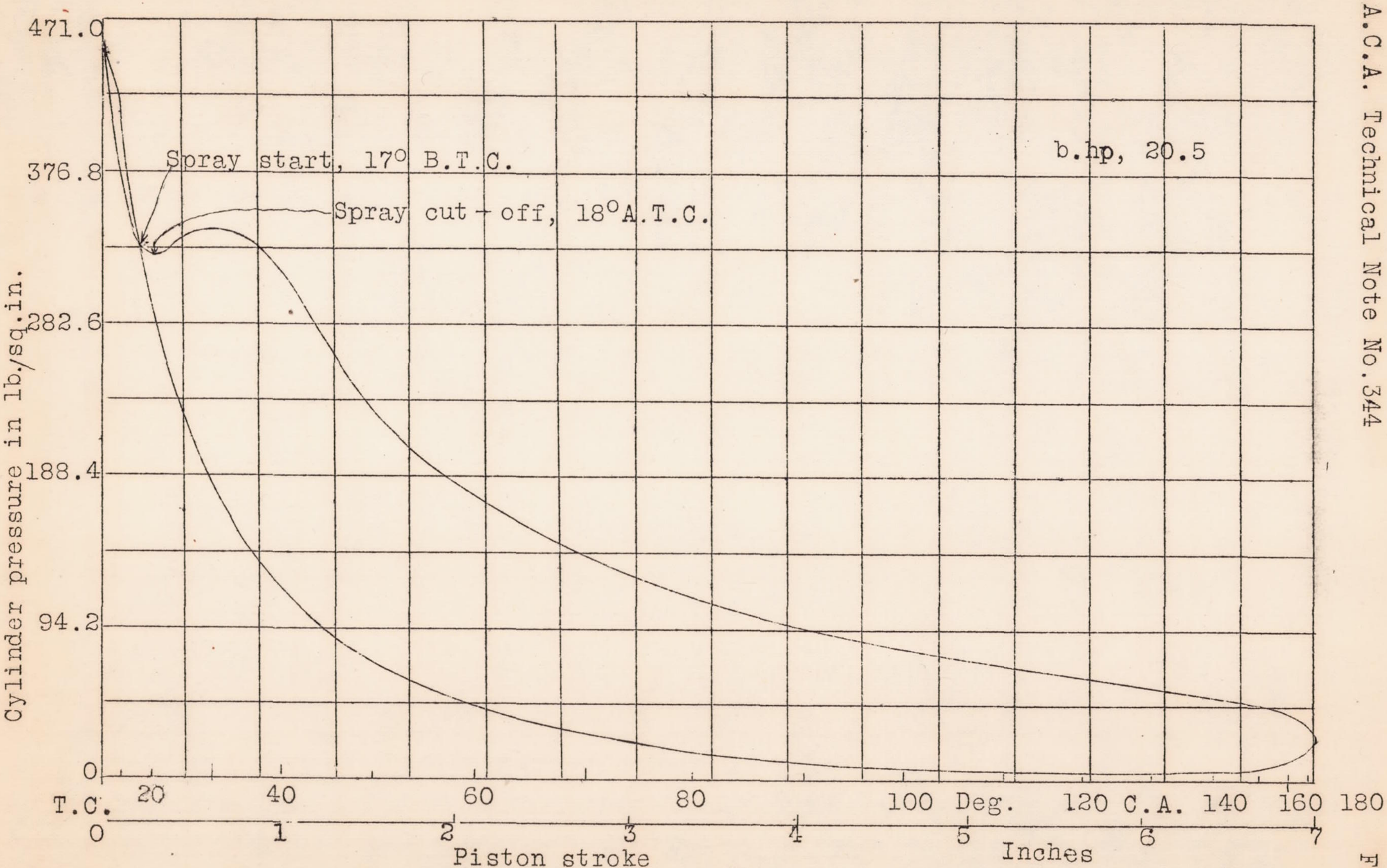

Fig.18 High - rate card (advance angle 17°).

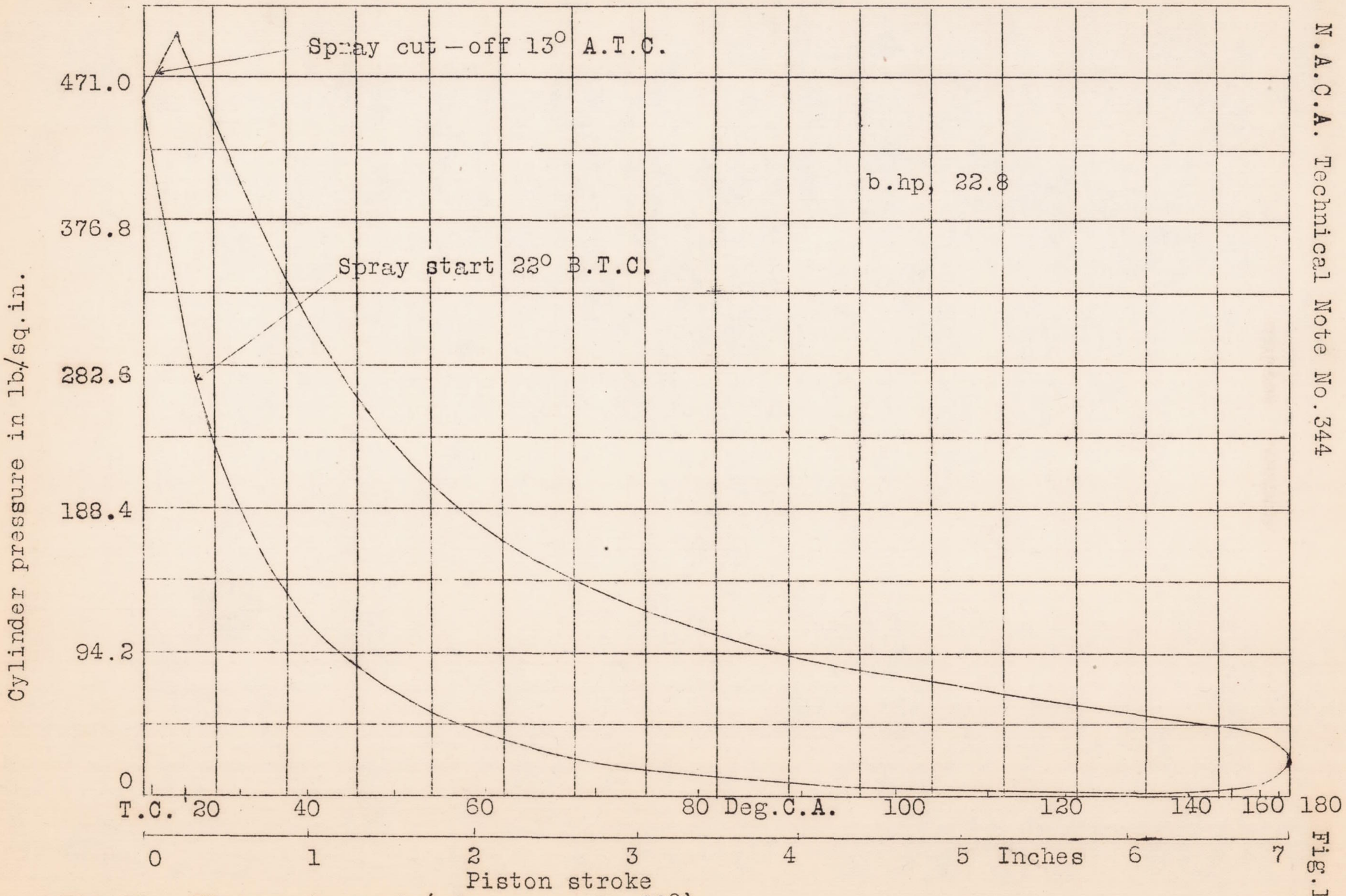

Fig.19 High-rate card (advance angle 22°).

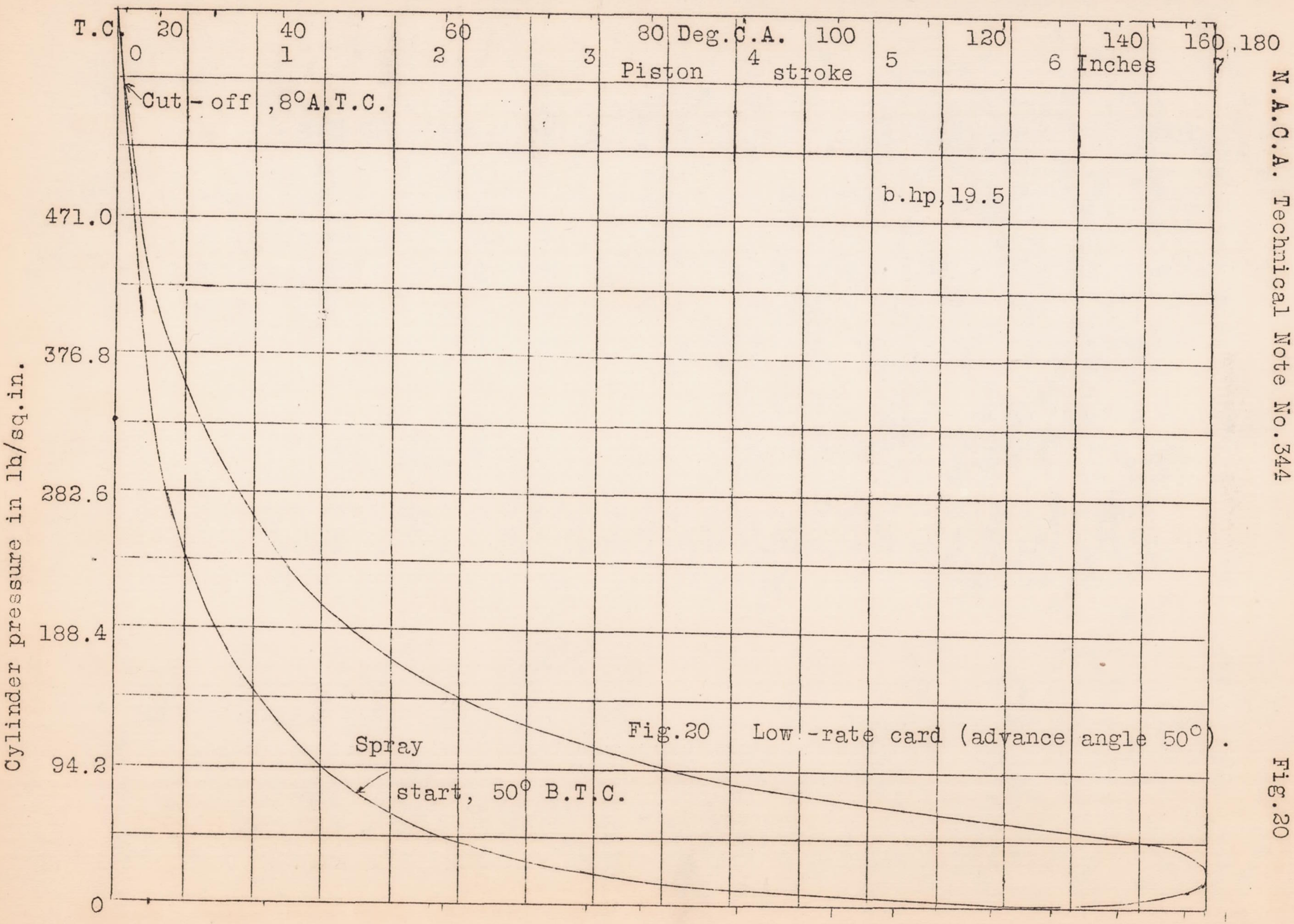

Fig.20 Low-rate card (advance angle 50°).

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Fig.21 Nozzle No.9, injection pressure 4750 lb. per sq.in.

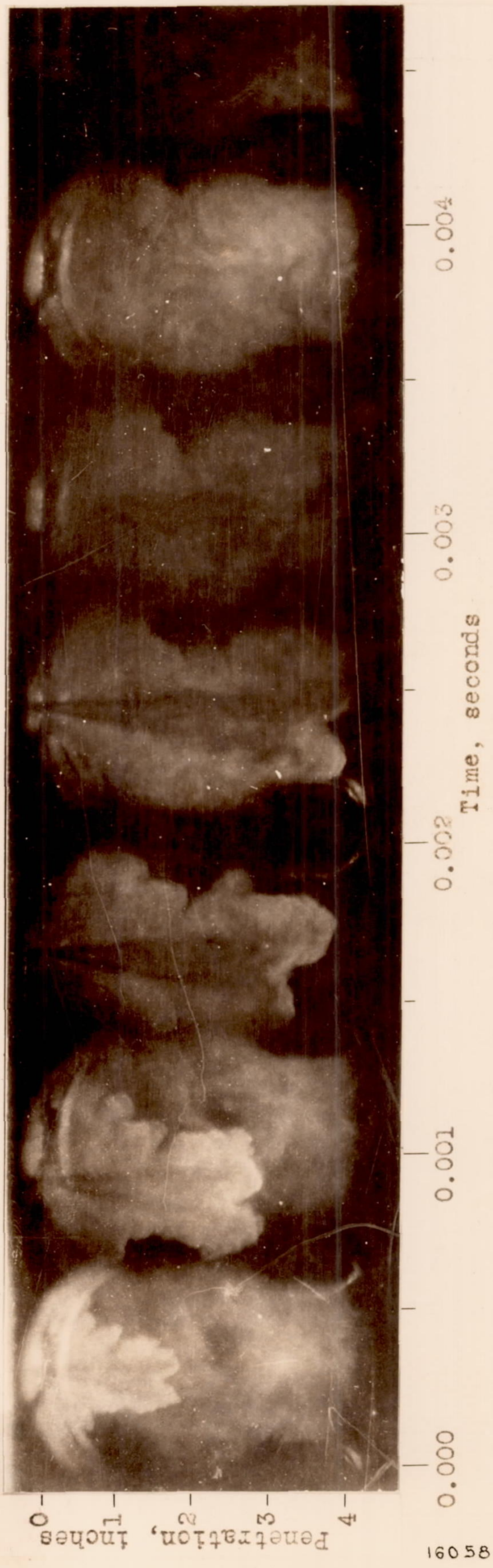

Fig.26 Nozzle No.C-2, injection pressure 4700 lb. per sq.in.

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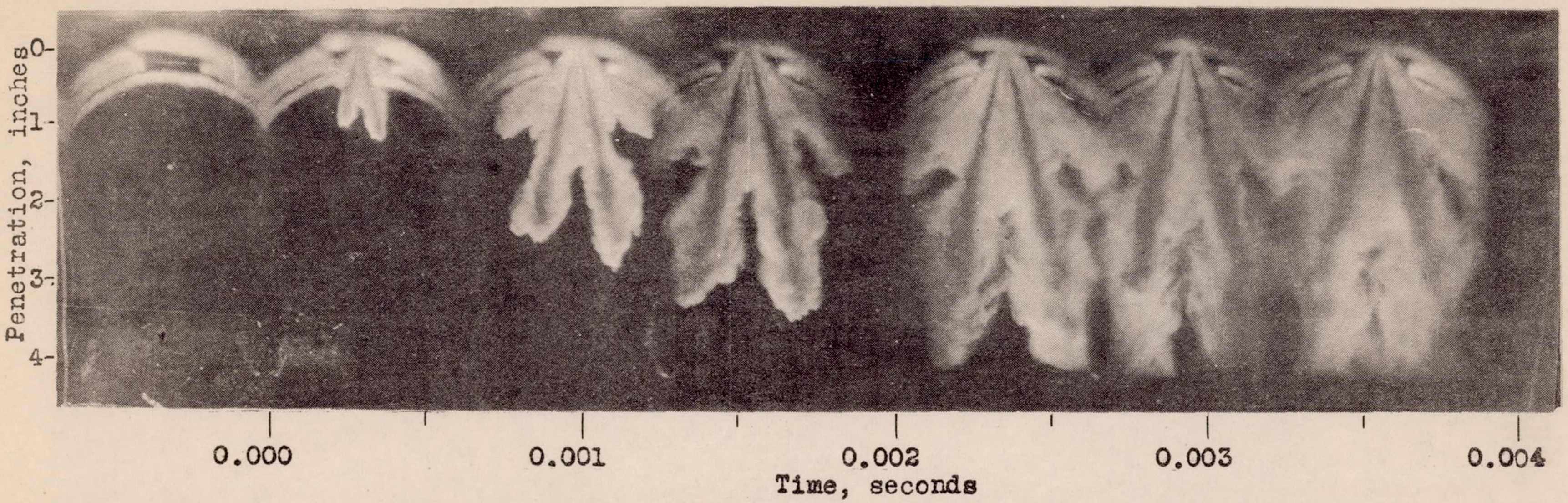

Fig.22 Nozzle No.9, injection pressure 3200 lb. per sq.in.

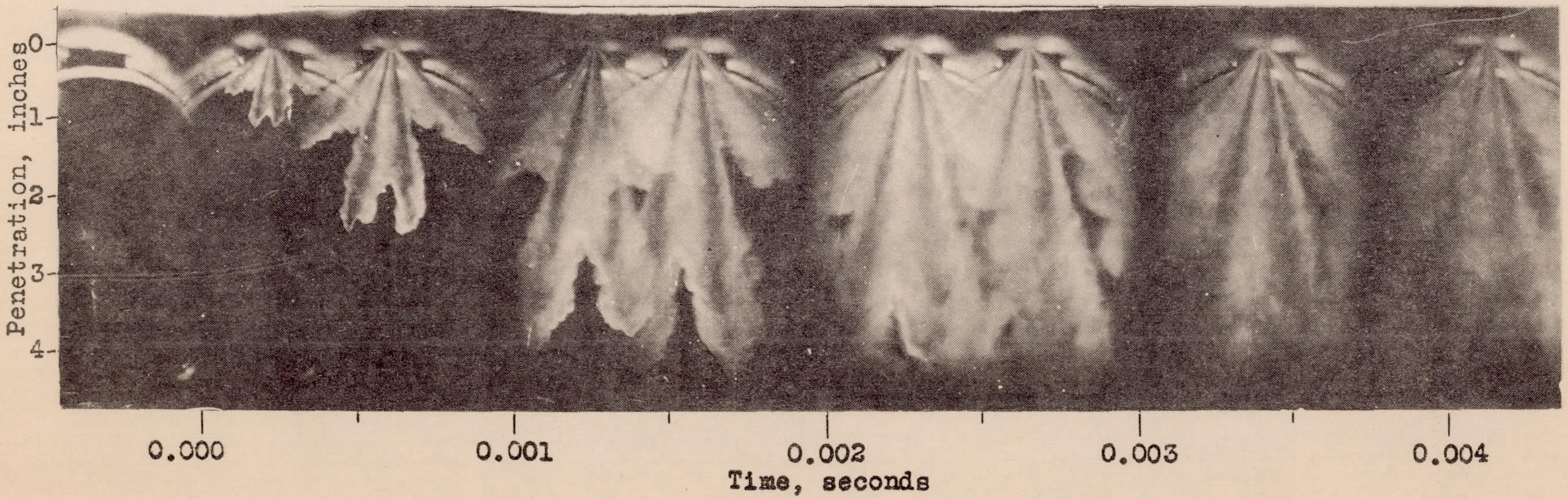

Fig.23 Nozzle No.17-1, injection pressure 4700 lb. per sq.in.

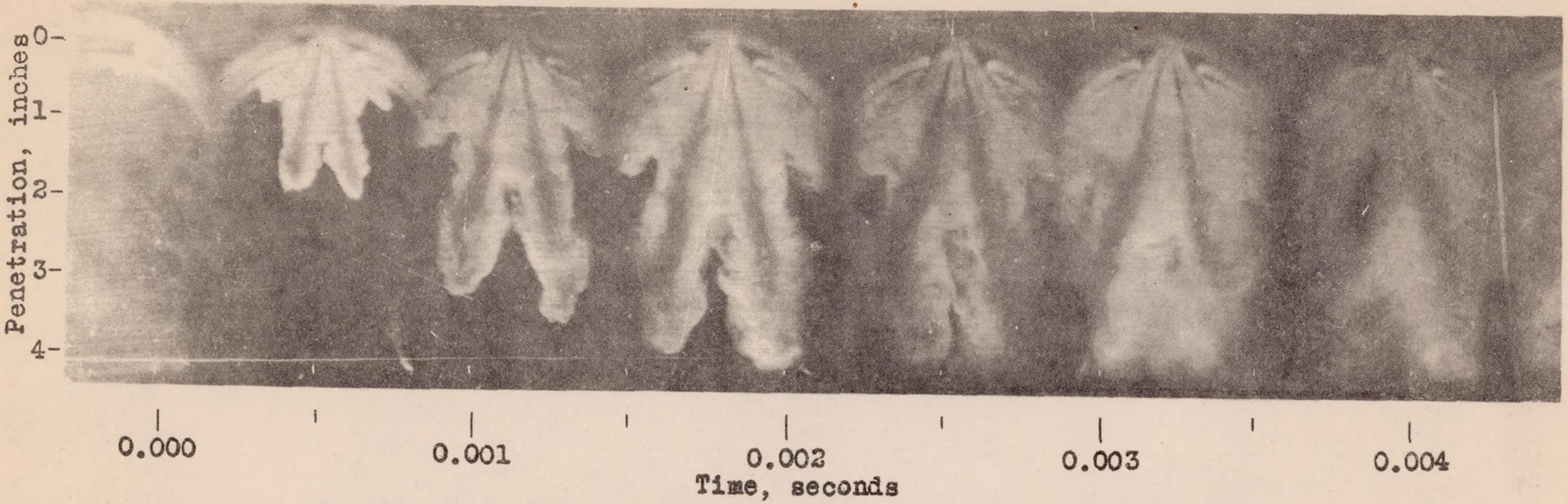

Fig.24 Nozzle No.16-2,injection pressure 4700 lb. per sq.in.

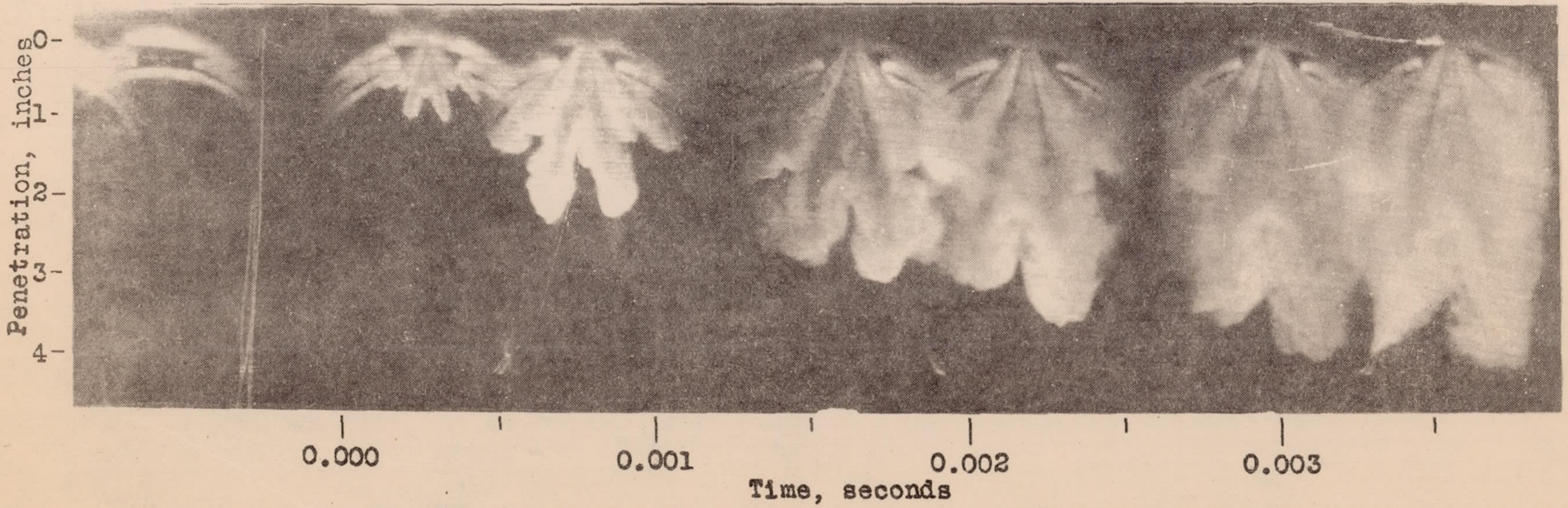

Fig.25 Nozzle No.12,injection pressure 6800 lb. per sq.in.