REPORT No. 568

THE QUIESCENT-CHAMBER TYPE COMPRESSION-IGNITION ENGINE

By H. H. Foster

SUMMARY

The performance of a single-cylinder 4-stroke-cycle compression-ignition engine having a vertical disk form of combustion chamber without air flow has been determined. The number, size, and direction of the orifices of the fuel-injection nozzles used were independently varied. A table and graphs are presented showing the performance of the engine with different nozzles; results of tests at different compression ratios, boost pressures, and coolant temperatures are also included.

The best unboosted performance was obtained at a compression ratio of 15.3 at an engine speed of 1,500 revolutions per minute, using water as a coolant. The increase in indicated mean effective pressure with boost pressure was proportional to the increase in weight of inducted air for equal air-fuel ratios and comparable maximum cylinder pressures. The engine operation was smoother with boosting.

The engine power and fuel economy obtained with a 6-orifice nozzle was equal to or better than that obtained with nozzles having any other form, number, or combination of orifices. The optimum value for the number, direction, or size of the orifices is not sharply defined. Results indicate that impingement of the fuel spray on the piston and chamber walls, although it may be detrimental to efficient combustion, may aid distribution and consequently increase the power output. Although the results do not afford a rational basis for nozzle design that can be reduced to an analytical or empirical formula, they do show that engine performance can be improved by careful design of the injection nozzle.

The large percentage of the total fuel in the relatively solid spray core injected from round-hole orifices and the short time available preclude the probability of obtaining a homogeneous mixture of the fuel and air in a quiescent combustion chamber using a multiple-orifice nozzle. The resultant inferior performance compared with that obtained from the same combustion chamber with forced air flow, despite the easy starting, easy scavenging, low mechanical losses, and freedom from knock, renders the quiescent-chamber engine unattractive for aircraft-engine use.

INTRODUCTION

In the course of the general investigation of the possibilities and limitations of the compression-ignition engine for aircraft use, the N. A. C. A. has been investigating the performance of a single-cylinder 4-stroke-cycle test engine with a vertical disk-shaped combustion chamber. This combustion chamber has been designated "quiescent" because there is evidence that any air movement which may occur in the chamber has no marked effect on the distribution of the fuel (reference 1). In order to obtain as nearly a homogeneous mixture of the fuel and air as possible, it is therefore necessary to meter and distribute the fuel to the air in the combustion chamber by means of the injection system.

Determination of the optimum distribution of the fuel to the air in this combustion chamber was undertaken in two ways. The first was the commonly used method of conducting a series of engine-performance tests and systematically varying the number, size, and direction of the orifices until the test results indicated an optimum value in any series of changes. The second method consisted in mathematically proportioning the area of each orifice to the volume of air into which the spray from this orifice would be injected. As a matter of convenience and in order to have a basis of comparison, results from the first method were used as a starting point for the second. Some of the results of nozzle investigations, started in 1927 and continued into 1933, have been published as technical notes (references 2 and 3). The purpose of this report is to summarize the nozzle investigations and to present further results obtained at different compression ratios, boost pressures, and coolant temperatures. All the data presented were obtained at the N. A. C. A. engine-research laboratories at Langley Field, Va.

APPARATUS AND METHODS

The test unit used in this work is shown in figure 1. The engine has a 5-inch bore and a 7-inch stroke and is connected to an electric dynamometer. Necessary

auxiliaries and apparatus for obtaining the performance data are shown grouped about the engine. Parts of the engine are, as far as practicable, the same as those of the N. A. C. A. universal test engine (reference 4), the main exception being the cylinder head, which has a vertical disk-shaped combustion chamber between the heads of horizontally opposed intake and exhaust valves, as shown in figure 2. Changes in compression ratio were obtained by varying the length of the removable throat-orifice ring between the combustion chamber and the cylinder while keeping the mechanical clearance between the piston crown and cylinder head at about 0.032 inch.

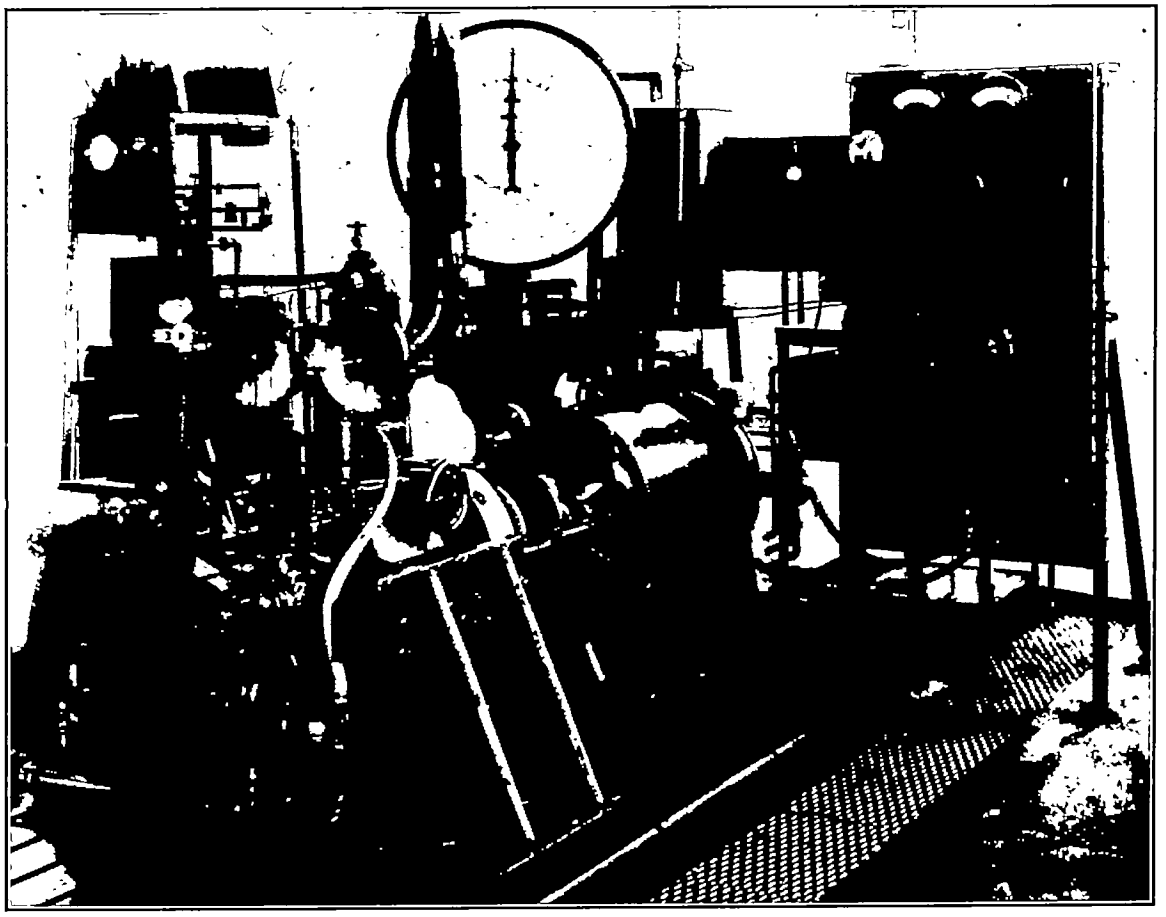


FIGURE 1.—Test engine and auxiliary equipment.

A detail drawing of the injection pump is shown in figure 3. It differs from the pump as actually used only in having micrometer screws instead of levers for controlling the position of the start-and-stop cam blocks, which control the closing and opening of the bypass valve, thus changing the time and period of injection. Shifting of the position of the control blocks, combined with the variable-velocity cam, varies the quantity and the rate of fuel discharge.

Figure 4 shows a comparison of two representative rates of injection: a low rate, in which the injection period was 27 crank degrees; and a high rate, in which the injection period was 20 crank degrees at an engine speed of 1,500 r. p. m. for full-load fuel quantity. The pump was driven from the crankshaft through a reduction gear in which there was an adjustment for changing the angular relation between the crankshaft and the pump cam. A spring-loaded automatic injection valve, set to open at 3,000 pounds per square inch, was installed in the top hole of the combustion chamber. The valve and pump were connected by a steel tube 36 inches long and of one-eighth inch inside diameter.

Figure 5 shows enlarged sections of the nozzles. The length-diameter ratio of the orifices is 2. The fuels used were conventional Diesel engine fuels described in reference 5 as fuels 1 and 2. The rate of fuel consumption was obtained by timing the consumption of 0.50 pound of fuel. Full-load fuel quantity (zero excess air), 0.000325 pound per cycle, is the fuel quantity required for a chemically correct mixture with the quantity of air inducted per cycle by this engine at a volumetric efficiency of 82 percent.

Information regarding spray penetration and spray interference in the combustion chamber was desired as an aid in nozzle design; accordingly, a full-scale

model following the outline of the disk-shaped combustion chamber was placed in the N. A. C. A. spray-photography pressure chamber and photographs of the spray formation in this chamber were obtained. The edges of the combustion-chamber shape were slightly obscured in the photographs by the pressure-chamber cover plate. Injection pressures were of the same order as those used in the full-load engine tests. The spray-chamber air density was made to approximate that of the combustion chamber at the time of injection.

Figure 6 is a schematic diagram of the air system used in this investigation. Rubber diaphragms were placed over the ends of the overhead drums to damp pulsations and to give a smooth flow of air to the engine. Motoring tests showed the optimum length of air-intake pipe for maximum charging efficiency at an engine speed of 1,500 r. p. m. to be approximately 6 feet, which determined the height of the surge tank above the engine. Air consumption was determined by timing the displacement of 80 cubic feet of air from a 100-cubic-foot gasometer by means of an electrically operated stop watch. The inlet-air temperature was maintained at 95° F. Water and oil temperatures (out) were maintained at 170° and 140° F., respectively. For the special variable-coolant temperature tests Prestone and glycerin were used.

Maximum cylinder pressures were indicated by a calibrated Bourdon spring gage connected to an N. A. C. A. disk-type check valve operated by the pressure

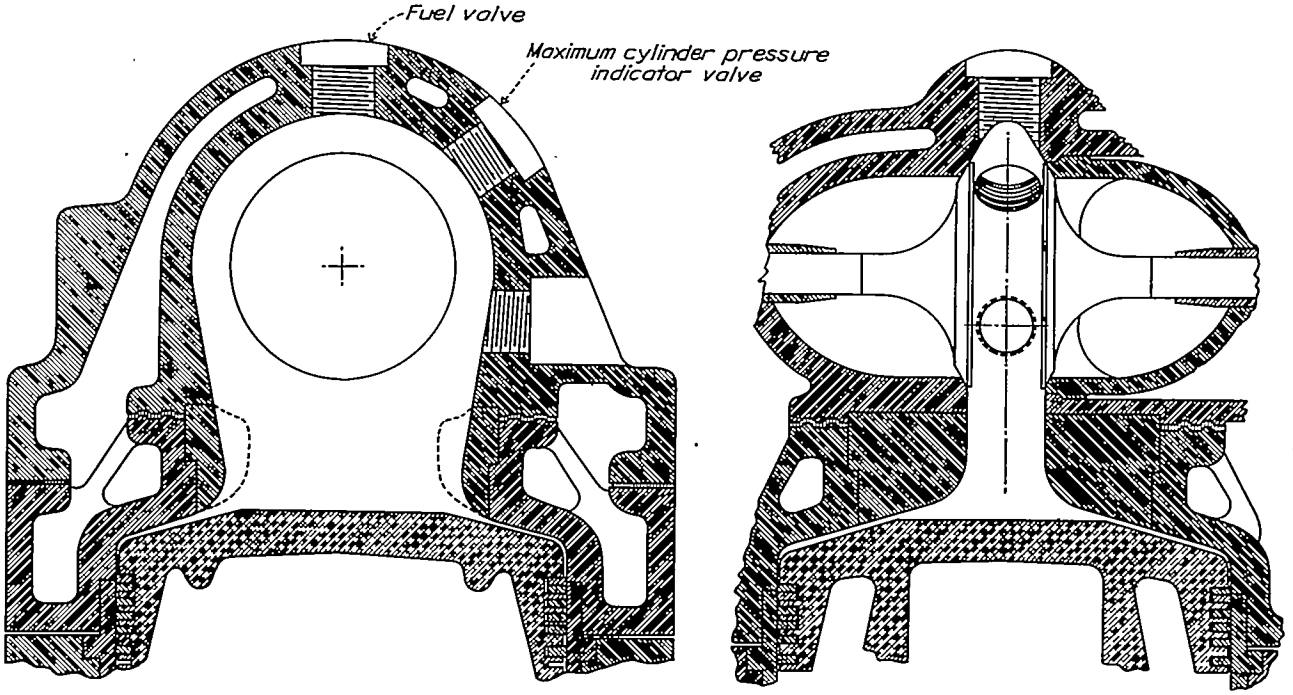


FIGURE 2.—Combustion chamber.

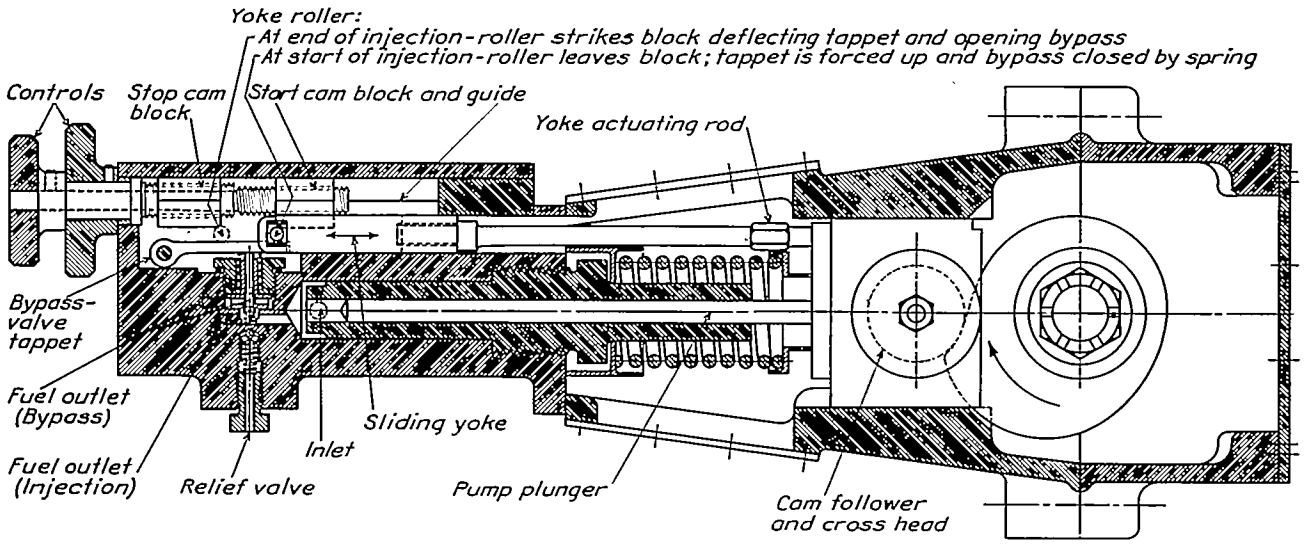


FIGURE 3.—Fuel-injection pump.

of the gases in the cylinder. This instrument, designated a "trapped-pressure" indicator, was used because it afforded an easy and reliable means of directly

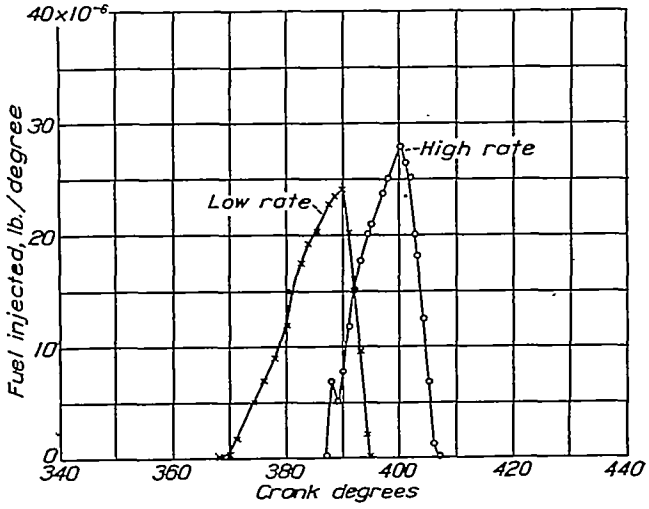


FIGURE 4.—Comparison of the injection rates used in the engine-performance tests; full load; 1,500 r. p. m.

observing the pressure readings as the engine controls were changed. Trapped-pressure readings are usually 5 to 25 pounds per square inch lower than those of the

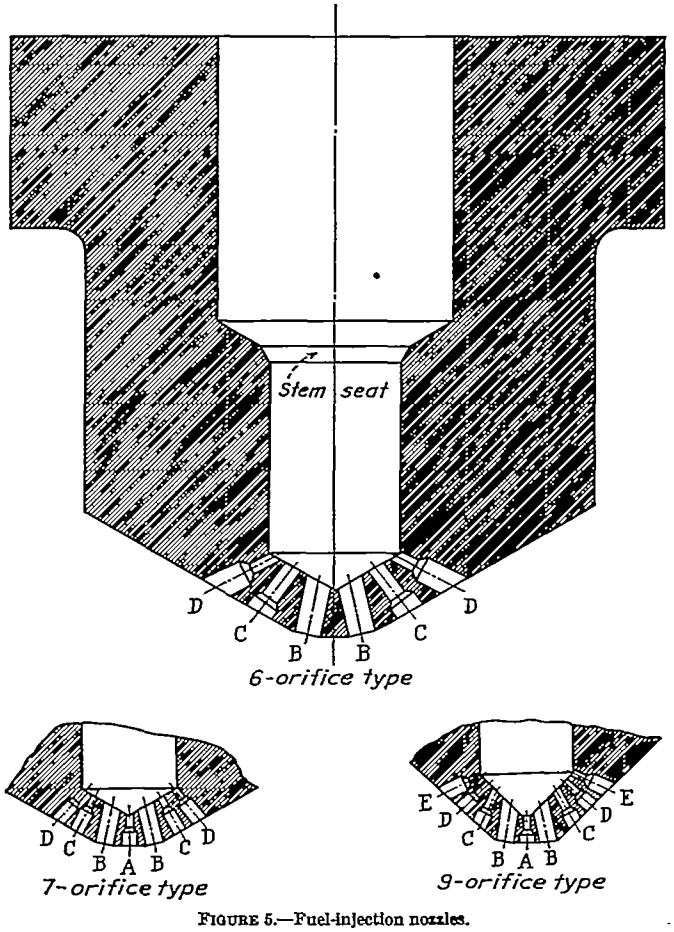
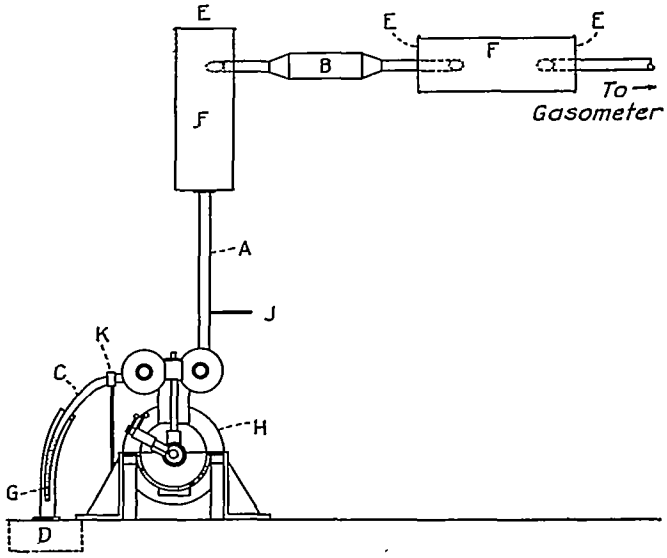


FIGURE 5.—Fuel-injection nozzles.

balanced-diaphragm type of indicator in the range of permissible rates of pressure rise. The difference in readings increases with an increase in the rate of pressure rise. Indicator cards were taken with the Farnboro electric indicator (reference 6) during the course of its remodeling.

No attempt was made to operate the engine at a particular value of maximum cylinder pressure in the early test work, inasmuch as undesirable knock was encountered before objectionable cylinder pressures were reached; instead, the fuel pump was adjusted to give the desired fuel quantity and then the timing was advanced until a faint knock was heard. Immediately after a power test the engine was motored and friction readings were obtained to which were added the brake readings in order to calculate values of indicated mean effective pressure and fuel consumption.

Engine speed was determined by a revolution counter and a stop watch, both of which were electrically



A, air duct, 5-inch diameter.
B, air heater.
C, exhaust stack, 5 feet long; 3-inch-diameter section, 2 feet 8 inches long; section 2 feet 4 inches long tapering to 1¾-inch diameter.
D, exhaust trench.
E, rubber diaphragm.
F, surge tank, 18-cubic-foot capacity.
G, tapered section, perforated.
H, test engine.
J, thermometer.
K, water sprayer.

FIGURE 6.—Diagrammatic representation of air system.

operated. The standard test speed of 1,500 r. p. m., unless otherwise noted, was used in all the tests.

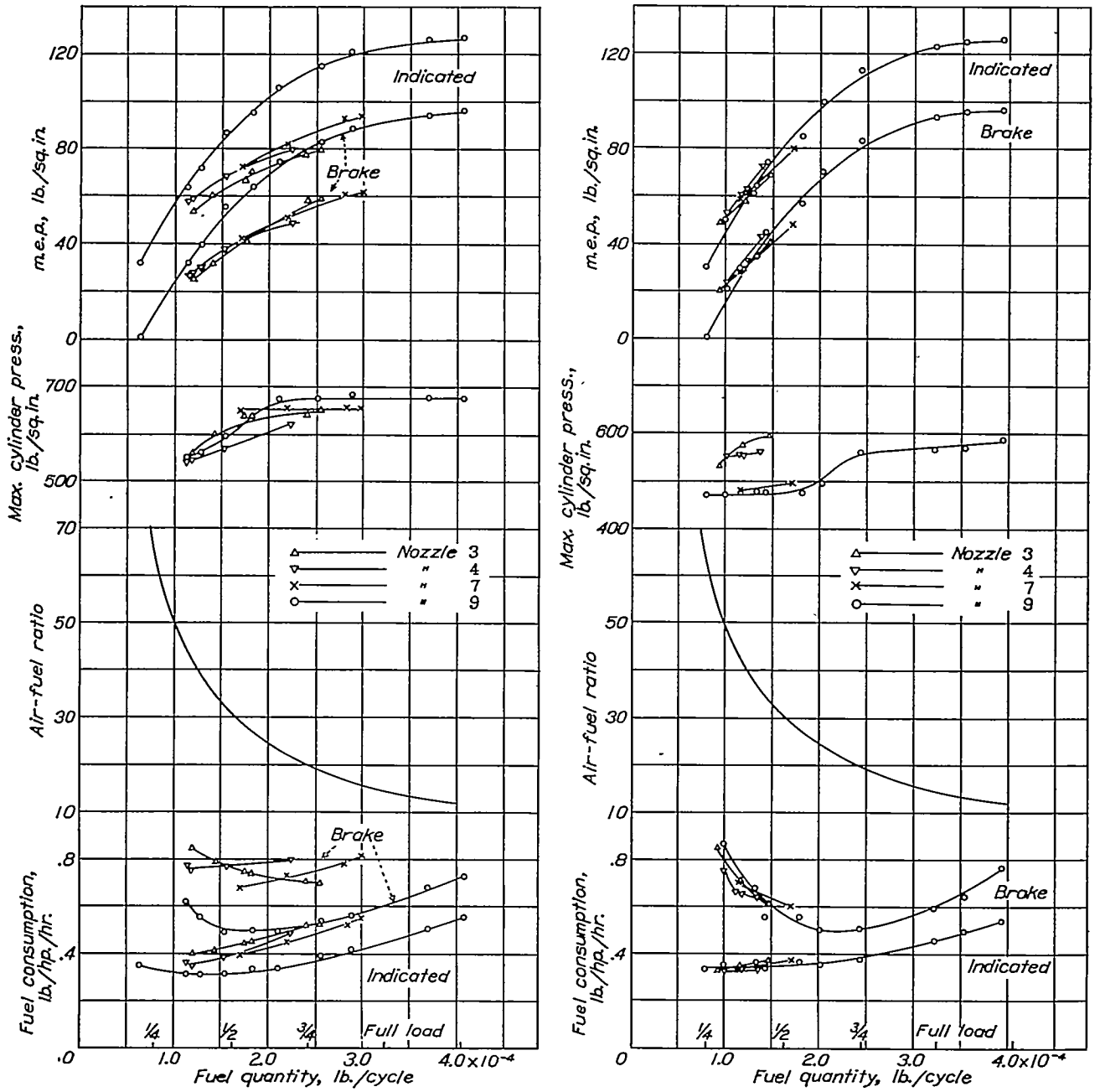
TESTS AND RESULTS

PRELIMINARY INVESTIGATION

The test results obtained on the engine with different arrangements of fuel-valve nozzles are presented in chronological order in table I, which lists the nozzles used, the number, size, and direction of their discharge orifices, and their corresponding engine performance. The nozzles are classified into different series, each of which is discussed in detail and for which variable fuel-quantity performance curves are shown.

Miscellaneous series.—The first experimental nozzles were built with the idea of injecting fuel into the

available air without impingement on either the piston crown or the combustion-chamber walls. Figure 7 shows the engine performance obtained with nozzles 3, 4, and 7 and the limited fuel-quantity range imposed by the use of the relatively small orifice areas to prevent impingement; it also shows the engine performance with both the high and low rates of injection. (See fig. 4.) The fuel-quantity range of the small-area nozzles is slightly extended by the use of a lower rate of injection and the accompanying longer injection period.



(a) Low rate of injection.

(b) High rate of injection.

FIGURE 7.—Comparison of engine performance using preliminary nozzles.

Seven-orifice series.—The design of nozzle 9, the first of the 7-orifice type having alternate large and small orifices, was based on the assumption that the sprays from the small orifices with their shorter penetration would distribute fuel to that part of the combustion chamber nearer the injection nozzle and thus give a more uniform mixture of the fuel and the air. A comparison of the performance curves for the high and low rates of injection of nozzle 9 (fig. 7) shows that they are quite similar except for the maximum cylinder pressure, which is higher for the low rate of injection. Engine operation was considerably smoother with the low rate of injection but the exhaust was smokier for the same air-fuel ratios. The high rate of injection with its shorter injection period resulted in earlier completion of combustion, a cleaner exhaust, and somewhat higher rates of pressure rise with conse-

quently rougher engine operation. The high rate of injection was adopted for all subsequent tests and fuel nozzles were developed for its use.

The engine performance obtained with nozzle 9 warranted the continuation of tests to determine the effect on engine performance of varying, first, the two main orifices that deliver fuel to the air charge in the rectangular throat and directly above the piston crown and, second, the other orifices that deliver fuel to the air in the upper part of the combustion chamber. Figure 8 shows comparative engine performance for a range of

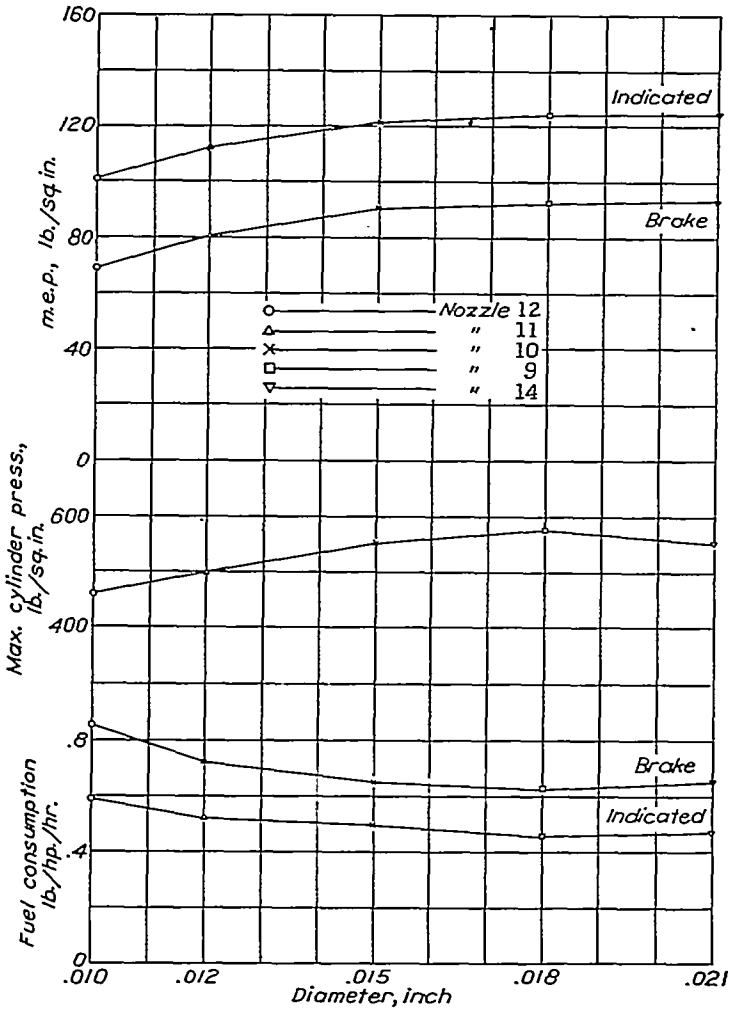


FIGURE 8.—Effect of changing the diameter of the two main orifices B on engine performance at full load.

sizes of the two main orifices B (fig. 5) from 0.010 to 0.021 inch diameter. The results show that 0.018 inch is the optimum diameter for the two main orifices of this combination.

An inspection of the carbon formation on the piston crown showed that the sprays from orifices of 0.012-inch diameter or larger impinged upon the piston crown. Inasmuch as the specific fuel consumption decreased as the B orifices were enlarged to 0.018 inch, it is concluded that impingement of a spray does not necessarily affect the combustion adversely. The larger quantity of fuel injected from the 0.018-inch orifices, compared with that injected from the 0.012-inch orifices, was apparently necessary for the utilization of the available air.

Variation in volumetric efficiency with fuel quantity is shown in figure 9. The decrease in volumetric efficiency is attributed to an increase in the quantity of residual gases in the combustion chamber and also to an increase in temperature of the combustion chamber and cylinder walls, as the fuel quantity or load is increased.

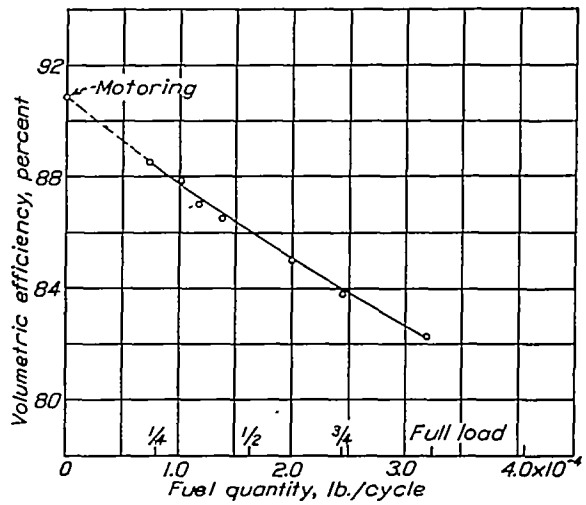


FIGURE 9.—Effect of load on volumetric efficiency.

Figure 10 shows the effect on engine performance of changing the diameters of only the outside orifices D (fig. 5), which deliver fuel to the air in the uppermost part of the combustion chamber, from 0.006 inch to 0.012 inch in 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. An increase in diameter of these two orifices from 0.010 to 0.012 inch caused a slightly smokier exhaust with no measurable change in power output. Table I shows the effect on engine performance of changing the C orifices from 0.005 inch to 0.012 inch. The difference in performance between nozzles 17 and 18 indicates that the C orifices should be considered as fillers when used in combination with the larger D orifices. This change from 0.005 to 0.012 inch decreased the power output and increased the fuel consumption. Spray photographs (see fig. 19 (b)), taken afterward, showed that the spray tips from orifices C and D were projected into the same space, which probably resulted in localized overrich mixtures of fuel and air and a consequent decrease in engine performance.

PROPORTIONAL-AREA INVESTIGATION

Nine-orifice series.—The 9-orifice series was so designed that the orifice areas were proportional to the volume of air served by each orifice. The two main 0.018-inch-diameter orifices, which were apparently a

better established optimum than the other sizes of orifice and which could be compared with previous data, were used as a beginning for the investigation. When the air volume for each orifice was computed, the air in the clearance between the piston crown and cylinder head was included in that served by the main sprays. The angular spacing of the orifices in this series was slightly closer than that used in the 7-orifice series and an additional orifice was added on each end of the line, making a total of nine in one plane. Nothing

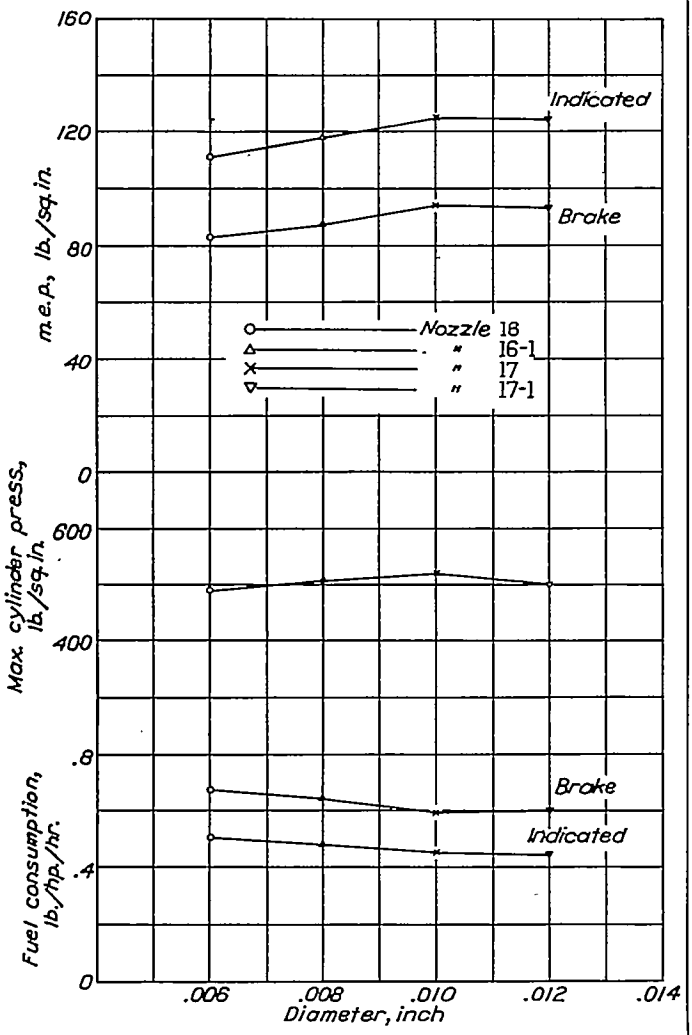


FIGURE 10.—Effect of changing the diameter of the two outside orifices D on engine performance at full load.

either in the performance data or in the spray photographs (see fig. 19(f)) indicates that these additional orifices discharged enough fuel to make any difference in performance; therefore their addition is considered an unwarranted complication.

The first nozzle of this series was built without the small center orifice A (fig. 5) (which has no place in the proportional-area arrangement) in an attempt to determine its value. The increase in engine performance (see fig. 11) showed the effect of this center orifice. The center spray of this particular orifice combination and angular spacing apparently reached air that had not been reached by the two main sprays.

Effect of number of orifices, E series.—Figure 12 gives a comparison of engine performance with one of the best 7-orifice and one of the best 9-orifice nozzles. It was decided to continue the use of the proportional-area principle but to substitute for the original angular spacing (fig. 5) one based upon the spray-photography data. The spray photographs showed that the spray cone angle for sprays under comparable conditions,

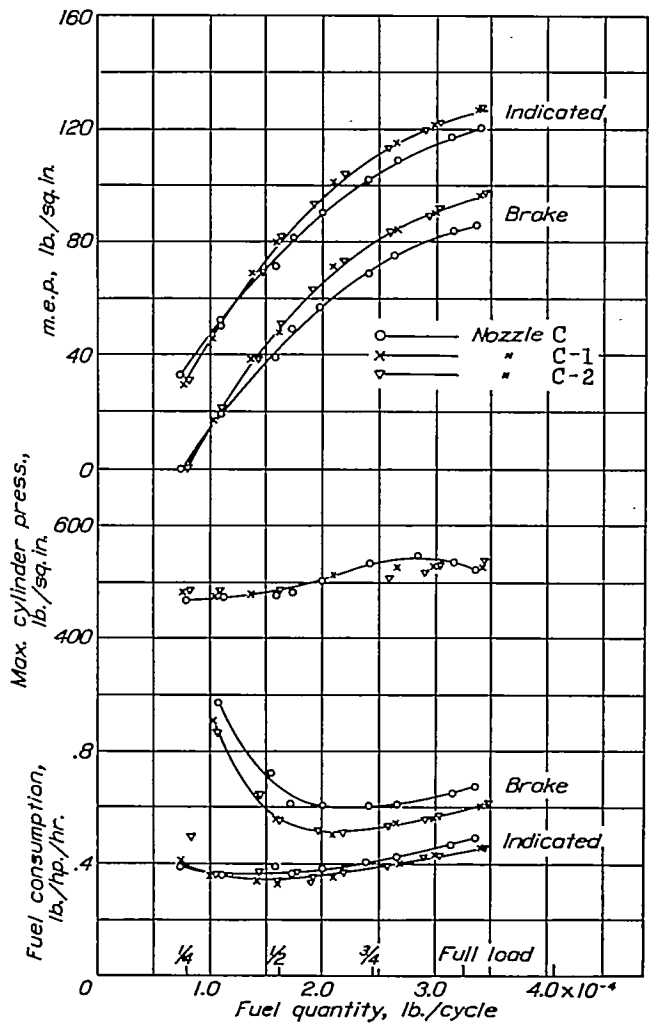


FIGURE 11.—Effect of the center orifice A on engine performance.

except for temperature, varied from 18° to 22°. Accordingly, 20° was adopted as the angular spacing of all the orifices.

In order to determine just how far it was advisable to follow the proportional-area principle, comparative performance tests were made with nozzles designed to extend the idea beyond practicable limits in the construction of nozzles for commercial engines. Before these tests were started the throat orifice connecting the cylinder and combustion chamber (fig. 2) was enlarged by increasing its width. This alteration increased the clearance volume and thereby decreased

the compression ratio from 13.6 to 12.6. It was desired to continue to use a nozzle design that would be comparable with the designs used in former tests; therefore the diameters of the two main orifices were maintained at 0.018 inch and the volume of air in the mechanical clearance space between the piston crown and the cylinder head was added to that served by the main orifices. These nozzles are designated by the letter E; the subscript denotes the number of orifices in the nozzle at the time of test. Thus this series was started with nozzle E_2, which contained only the two main orifices. The number of orifices was increased

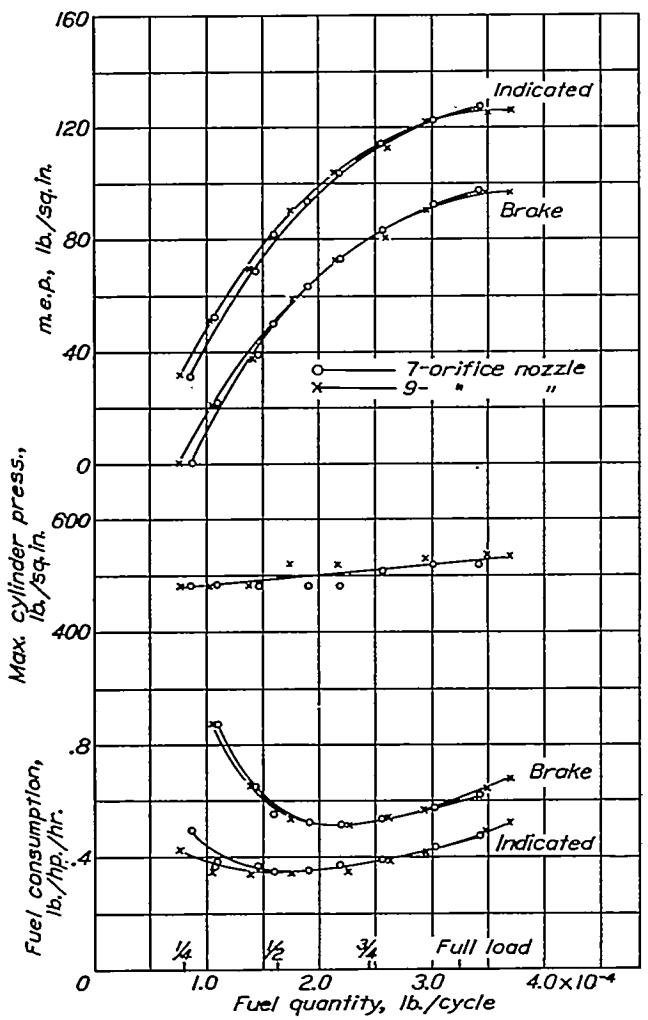


FIGURE 12.—Comparison of engine performance using one of the best 7-orifice and one of the best 9-orifice nozzles.

by increments of two and the nozzle performance tested for each increment. At the end of the series there were 6 orifices in one plane and 5 orifices in a plane on each side of the first, with angular spacing of 20° between orifices and 10° between planes. (See fig. 13.)

There is a slight deviation from the proportional-area principle in the E series after E_{12} because it was considered impracticable to use orifices smaller than 0.005-inch diameter. This deviation is not serious because the percentage of the total orifice area involved is smaller than the experimental error. The performance tests shown in figures 14 and 15 indicate that no justifiable gain would be obtained by using more than six orifices for this combustion chamber. The test points of figure 14 have been omitted to save confusion. These results simplified subsequent nozzle design.

Effect of angular spacing, F series.—There were a number of indications during these tests that the 20° angle between sprays was not the optimum. About this time the results of the work on dispersion at Pennsylvania State College were published (reference 7) and, according to the method outlined by deJuhasz the boundaries of combustion were laid out for the F_6 nozzle as shown in figure 16. If the volumes within these boundaries are assumed to be the minimum space requirements for combustion, it is evident that the sprays overlap and probably interfere with each other during combustion. An investigation was accordingly made of the effect on engine performance of varying the angle between the spray axes of the individual sprays; the corresponding orifice sizes were maintained constant.

When the series of nozzles using different angular spacing of the orifices was designed, it was again necessary to deviate from the proportional-area principle because the volume of air served by each orifice changed with the angle. The fact that the corresponding orifice sizes were maintained the same for all angles caused a departure from the proportional-area principle of about 1 percent, which was neglected as it was less than the error in the determination of performance values.

The nozzles of this series are designated by the letter F with a subscript denoting the angle between the axes of the orifices. Thus, the E_6 and the F_{20} are identical nozzles, with six orifices spaced at 20°. The performance tests of these nozzles showed very little variation, as evidenced by the curves in figure 17, but observation of the exhaust gases and the sensitiveness to controls led to a decision to standardize on an angle of 25° for further work with this combustion chamber. As a check on this decision, two 0.005-inch orifices were added to the center of the F_{29} nozzle to see if any unused air remained between the two main sprays. The resulting increase in performance, as shown in the curves of figure 18, indicated that the small filler sprays are effective when the angle between the sprays on either side is too great.

From the test results it was concluded that a nozzle having an angular spacing of 25° would give the best performance and that any increase which could be obtained by further refinements in nozzle design would not be commensurate with the complication involved in its construction. The results, however, did not show angular spacing to be very critical within the range covered in these tests, possibly because of the

small percentage of fuel in the outer part of the spray as shown by the dispersion data in reference 7.

Effect of total orifice area, H series.—In anticipation of boosting tests to be started with this cylinder head, it was considered that an increase in total orifice area should be investigated because, with more air available for combustion, it would naturally follow that more fuel should be supplied.

The nozzles of this series were designated by the letter H. The increase in the total orifice area over that of the best of the E and F series, E_6, was 24 percent, 39 percent, 15 percent, and 65 percent, for nozzles H–1, H–2, H–3, and H–4, respectively. The increase in air density for 9 inches of mercury boost pressure is about 24 percent. The corresponding orifices in nozzle H–1 were therefore increased 24 percent in area. In nozzles H–2, H–3, and H–4 the two large orifices were chosen to give successive increases in discharge area and the smaller orifices were proportionally increased.

The nozzles of this series produced but little difference in the unboosted performance (table I) or in subsequent tests with boosting. They did, however, give smoother engine operation than the nozzles of smaller area owing to localized overrich mixtures in the combustion chamber, resulting in lower rates of burning and consequently lower rates of pressure rise.

The nozzle-area requirements, then, depend not upon air density but rather upon the combustion chamber size and shape, the injection period desired, the rate of injection, the engine speed, and the capacity of the injection pump.

Correction to proportional-area design.—One of the assumptions in the application of the proportional-area principle in nozzle design is that the same discharge pressure will be acting on each orifice in a multiple-orifice nozzle. Observation of the fuel spray in the atmosphere indicated that, as the areas of the orifices were increased for greater discharge area, the flow of fuel from the large main orifices reduced the effective pressure on the other orifices and, therefore, the fuel distribution did not fulfill the requirements expected of the particular nozzle. This lack of proportion was verified by catching sprays from individual orifices in a container with a long neck (reference 8). The sum of the weights of the sprays from the individual orifices caught in this way checked within ±1 percent the weight of the sprays from all the orifices caught simultaneously under the same conditions. The areas of the orifices discharging insufficient fuel were increased until all spray discharges were in the proper ratio. A nozzle designed for a shortened combustion chamber (compression ratio 15.3) and designated K–4 was developed by this procedure and is considered the

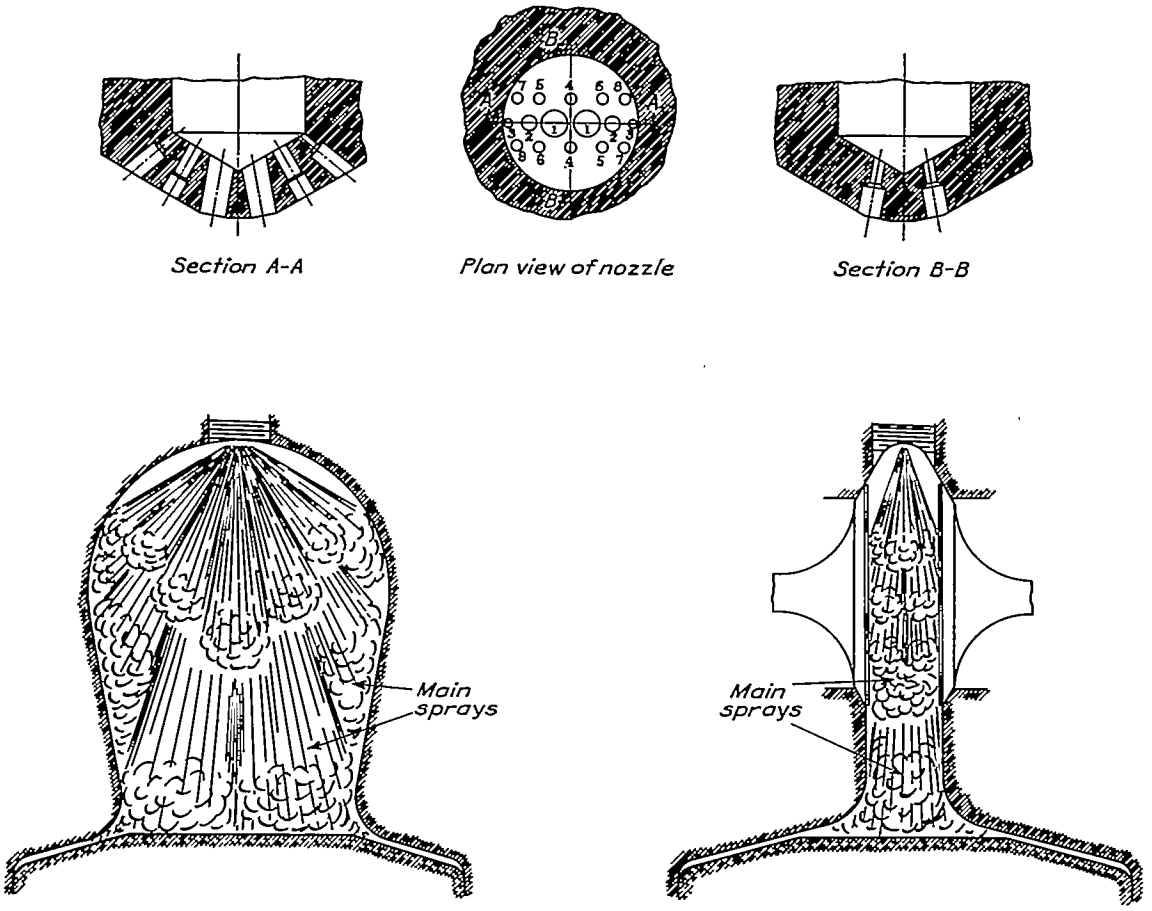


FIGURE 13.—Projected spray distribution using nozzle E_{16}.

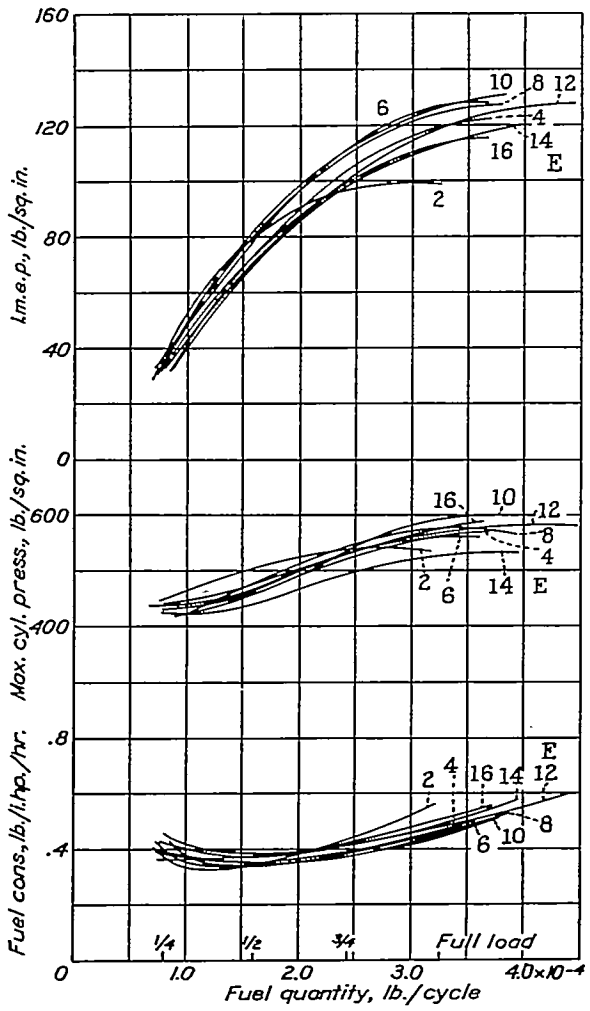


FIGURE 14.—Comparison of engine performance using injection nozzles E_2 to E_{16}, variable fuel quantity.

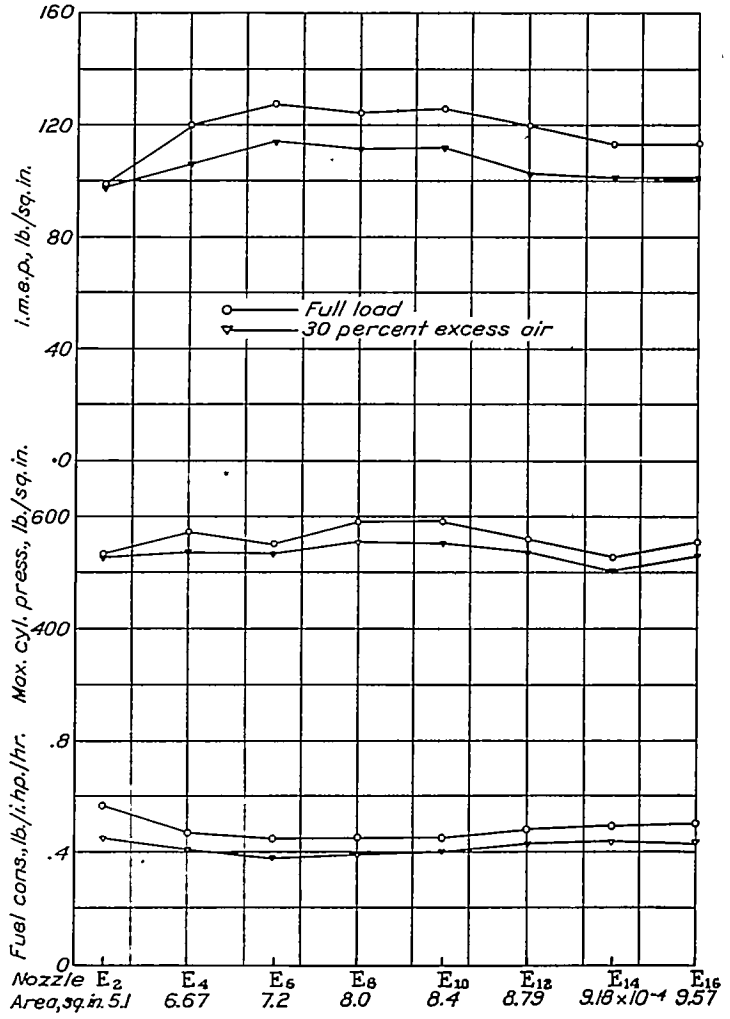


FIGURE 15.—Comparison of engine performance using injection nozzles E_2 to E_{14}.

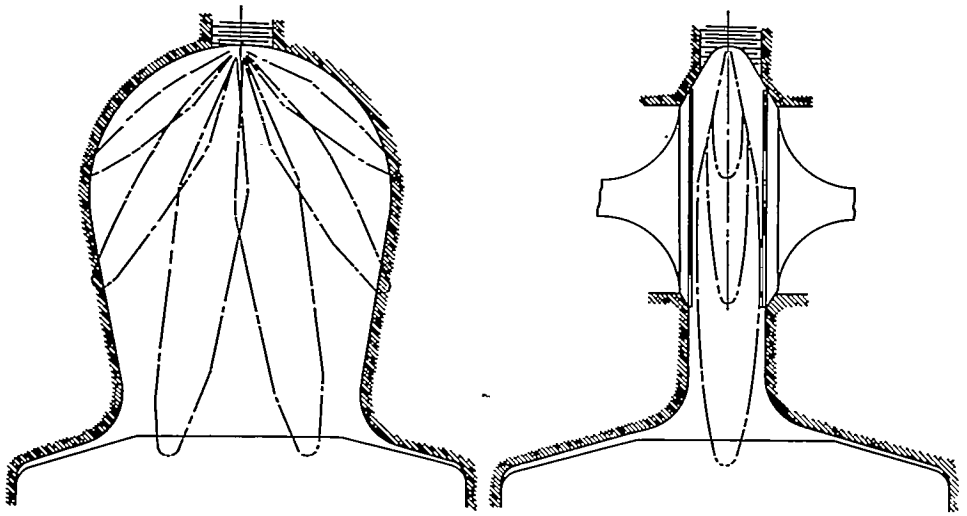


FIGURE 16.—Boundaries of combustion for nozzle E_6.

best of the development series. Knowledge gained from the tests of the preceding H-series nozzles and of the original K nozzle with its subsequent alterations aided in determining the final orifice sizes of nozzle K–4.

SPRAY PHOTOGRAPHS

The spray photographs shown in figure 19 were taken during development work with the 7- and 9-orifice series. Figures 19(a) and 19(b) show photographs of the sprays from nozzle 9 with injection pressures of 4,750 and 3,200 pounds per square inch, corresponding

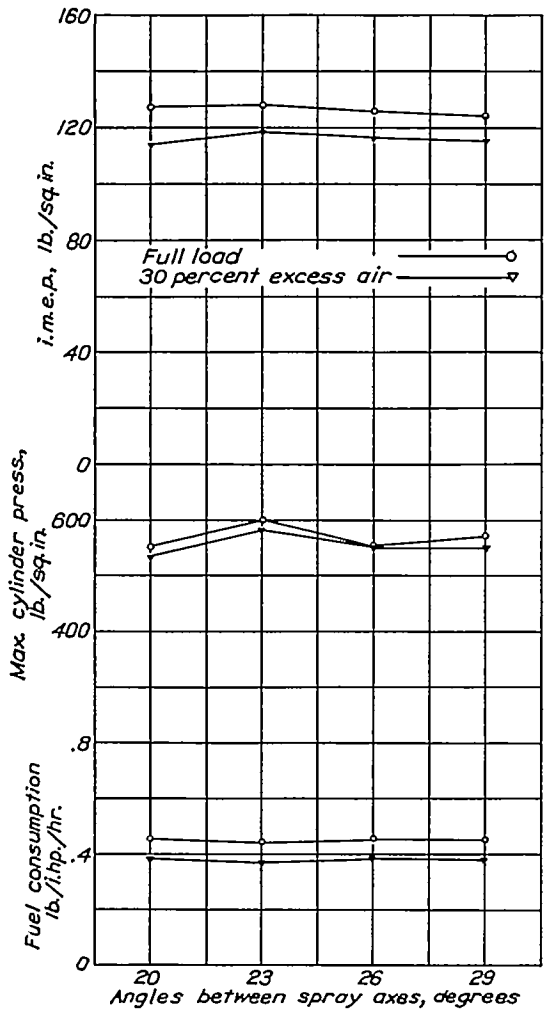


FIGURE 17.—Effect of spray spacing on engine performance, F nozzles.

to the maximum injection pressure at full load for the high and low rates of injection, respectively.

Figure 19(c) shows a photograph of the sprays from nozzle 17–1, which is similar to nozzle 9 except that the outer orifices are of 0.012-inch diameter instead of 0.008-inch. The outer sprays in this nozzle struck the sides of the chamber and were deflected downward into otherwise unreached air, thereby aiding the fuel distribution. Figure 19(d) shows spray photographs for nozzle 16–2 with 0.008-inch-diameter outer orifices.

Figure 19(e) shows photographs of sprays from nozzle 12, which had two main orifices of 0.010-inch diameter as compared with an 0.018-inch diameter for all other nozzles. Owing to the reduced orifice area, the pressure at the high injection rate was 6,800 pounds per square inch as compared with 4,750 pounds per square inch for other nozzles.

Figure 19(f) comprises photographs of sprays from the 9-orifice nozzle C–2. Lack of a more pronounced outline of the sprays may be caused by crowding these comparatively large sprays.

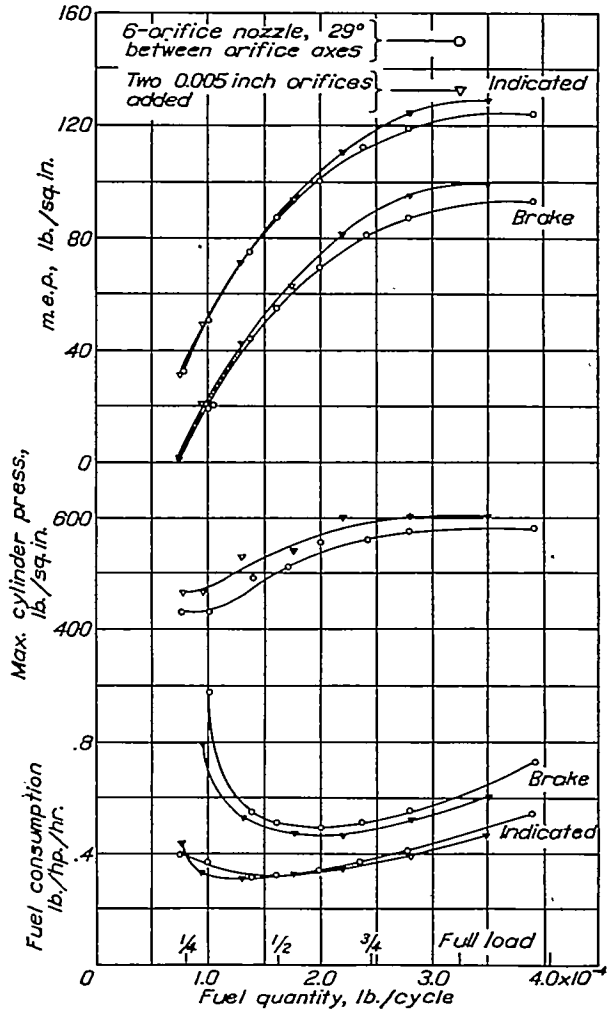


FIGURE 18.—Effect on engine performance of adding auxiliary orifices to nozzle F_{23}.

Owing to the very uneven distribution of the fuel in the sprays, visual observation of fuel injected into the air or photographs of sprays from multiple-orifice nozzles are not to be relied upon as bases for judging the fuel distribution in a combustion chamber or for estimating the relative engine performance of a particular nozzle design. This conclusion is based on the general results obtained with this quiescent combustion chamber and is borne out particularly by the E-series nozzles.

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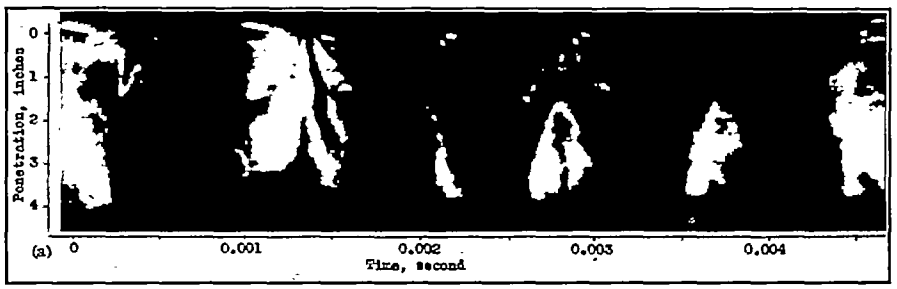
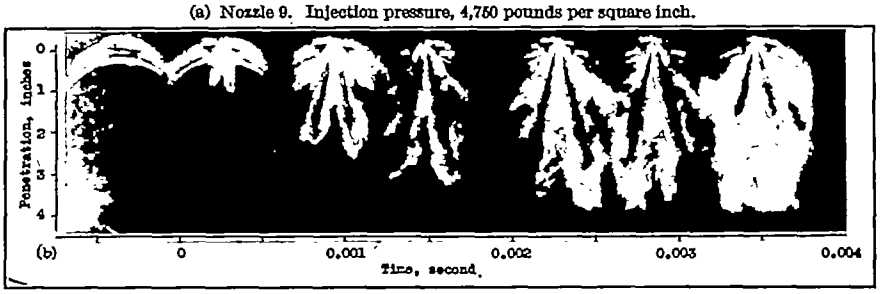
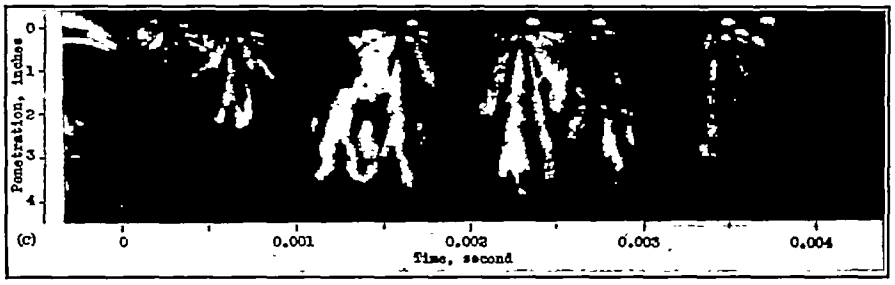


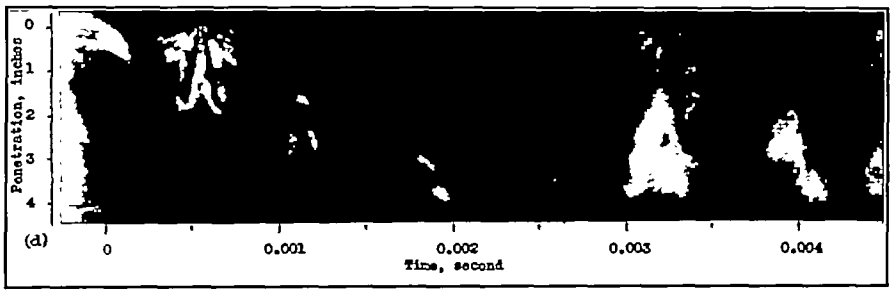
(a) Nozzle 9. Injection pressure, 4,750 pounds per square inch.



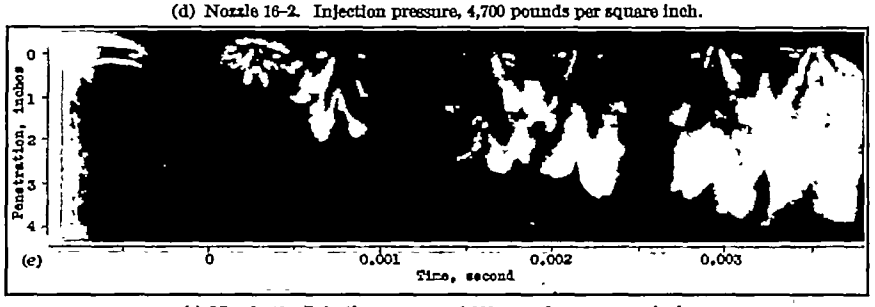
(b) Nozzle 9. Injection pressure, 3,200 pounds per square inch.



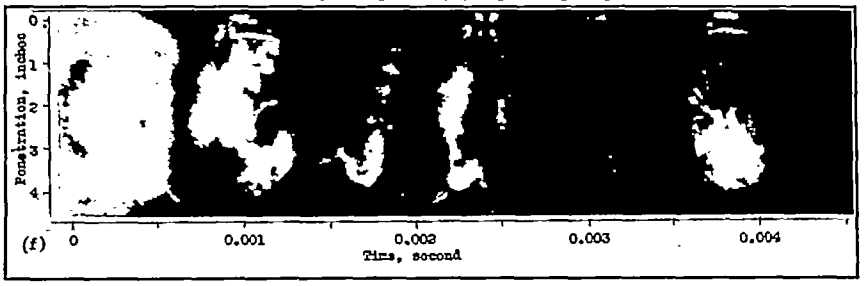
(c) Nozzle 17-1. Injection pressure, 4,700 pounds per square inch.



(d) Nozzle 16-2. Injection pressure, 4,700 pounds per square inch.



(e) Nozzle 12. Injection pressure, 6,800 pounds per square inch.



(f) Nozzle C-2. Injection pressure, 4,700 pounds per square inch.

FIGURE 19.—Photographs of fuel sprays.

MISCELLANEOUS ENGINE TEST RESULTS

Variable engine speed.—Figure 20 shows engine performance for a speed range of from 700 to about 1,700 r. p. m. for a compression ratio of 15.3 and full-load fuel quantity, using the K–4 nozzle. Operation at full load below 700 r. p. m. was not satisfactory, although the engine could be idled at 175 r. p. m. The downward trend in the indicated mean effective pressure at

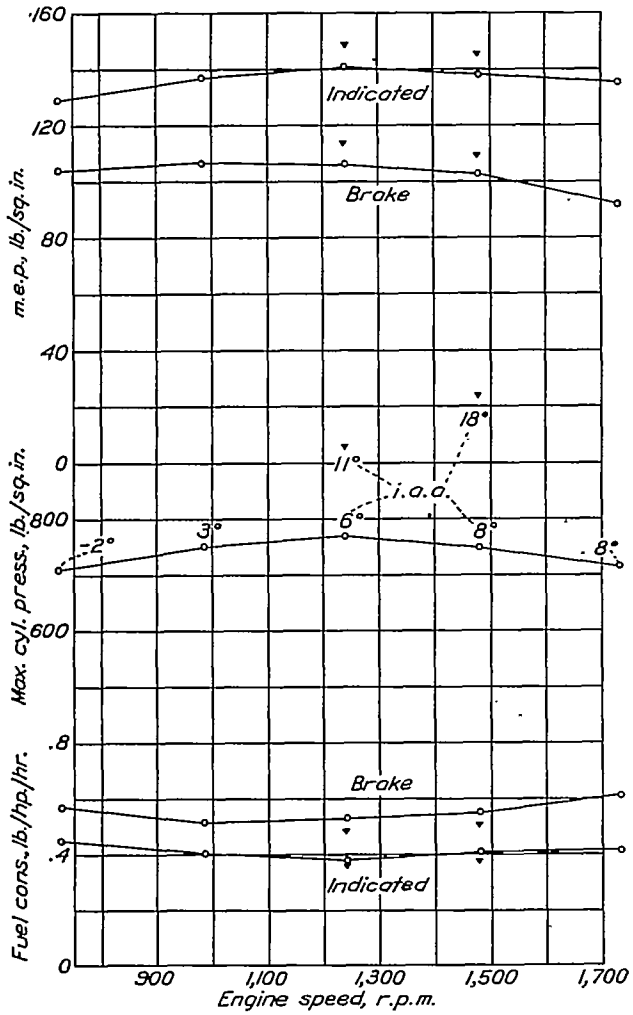


FIGURE 20.—Effect of engine speed on engine performance at full load; nozzle K–4; i. a. a., indicated.

the higher speed is caused by decreased volumetric efficiency because the valve timing was better suited to the 1,200–1,500 r. p. m. range than to the higher speed range.

The effect upon performance of increasing the injection advance angle and therefore the maximum cylinder pressure is shown for the 1,200–1,500 r. p. m. speed range. Although mechanical limitations made it inadvisable to operate the single-cylinder test engine at higher speeds, there was nothing in the fuel-system or engine-combustion characteristics to indicate that higher speeds could not be advantageously used.

Boosting.—The effect of boosting when the quiescent combustion chamber is used will be only briefly mentioned since a complete report of the boosting results with and without valve overlap has already been published (reference 8). The indicated power generally increases proportionately with the increase in weight of the inducted air charge available for combustion. This proportionality is, of course, affected by air-fuel ratio, injection-advance angle, and scavenging. Boosting, then, merely extends the performance curves and does not essentially change their characteristics.

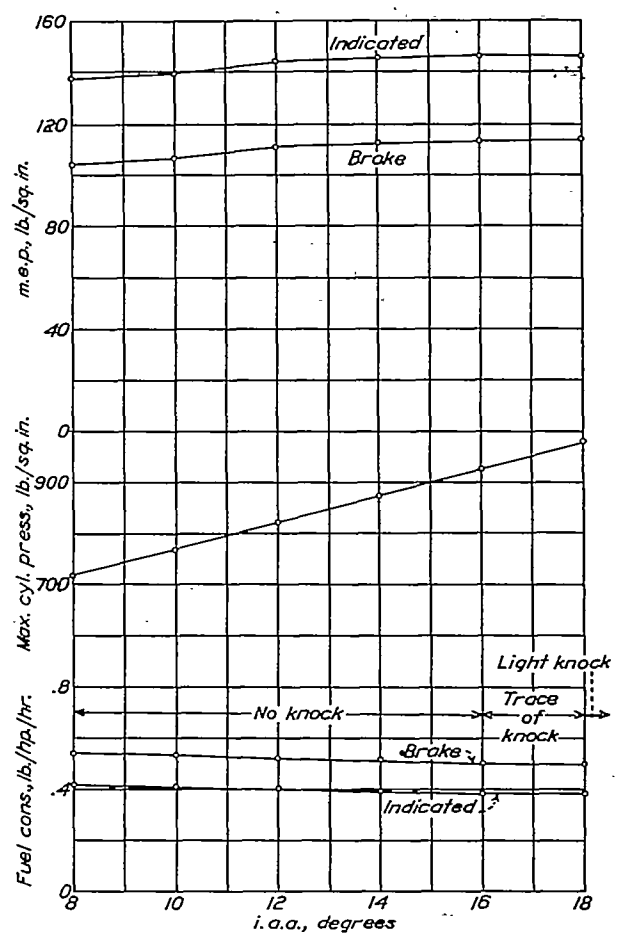


FIGURE 21.—Effect of injection advance angle on engine performance at full load; nozzle K–4.

It was found that the engine operated considerably smoother when boosted. The balanced-diaphragm maximum-cylinder-pressure indicator showed that the difference in maximum cylinder pressure between individual cycles becomes considerably less than when the engine is unboosted. This condition is again indicated by the smooth, even line and by the absence of scattered points on the indicator card.

Compression ratio.—In addition to performance tests at the adopted standard compression ratios of 13.6 and 12.6, performance tests were conducted at compression ratios of 10.6 and 15.3, which are about

the practicable limits obtainable with this cylinder head. The preliminary test results showed little difference in specific power output and fuel consumption for compression ratios of 10.6, 12.6, 13.6, and 15.3 for the same ratio of maximum cylinder pressure to compression pressure. The engine-operating characteristics, however, were found to be quite different. At a compression ratio of 10.6, starting was difficult and the ignition lag under standard test conditions was more than one-third longer than that obtained at a compression ratio of 15.3. The rate of pressure rise at the lower compression ratio as determined from indicator cards was nearly double the corresponding values obtained at a compression ratio of 15.3. Starting was easy at the higher compression ratio, the explosion pressures were more uniform, and the engine operation was considerably smoother than at the lower compression ratios.

The shortened, compact combustion chamber at the compression ratio of 15.3 simplified fuel distribution. The more homogeneous mixture of fuel and air and the shorter ignition lag permitted the use of higher cylinder pressures, which resulted in better engine performance.

Figure 21 shows the effect of injection advance angle on engine performance. This performance, with the K-4 nozzle, is the best obtained with the quiescent chamber with normal aspiration. The valve timing was changed to give a very small overlap, which probably aided in scavenging the combustion chamber and improving combustion. (See reference 8.)

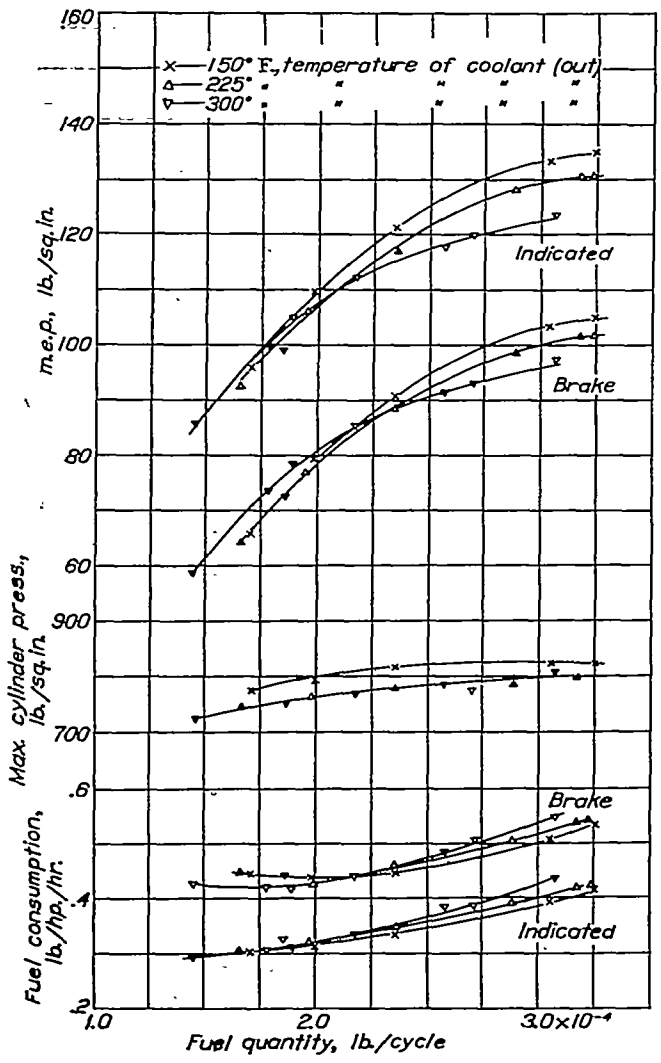


FIGURE 22.—Effect of coolant temperature on engine performance; i. a. a., 21°; nozzle H-1.

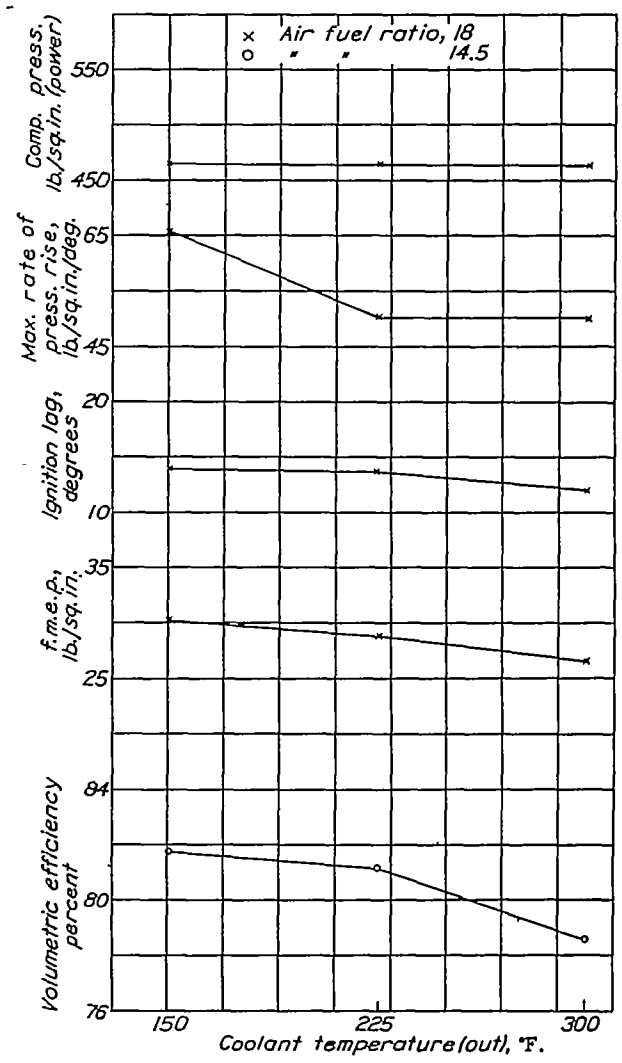


FIGURE 23.—Effect of coolant temperature on engine-operating characteristics; i. a. a., 21°; nozzle H-1.

High-temperature cooling.—Figures 22 and 23 show some of the effects on engine performance and operating characteristics of increasing the coolant temperature from 150° to 300° F. in an attempt to reduce the ignition lag. The test results and observations showed: a 4-percent decrease in volumetric efficiency, objectionable breather smoke from the hot piston at full load, difficulty in maintaining the high boiling point of the coolant due to absorption of moisture, an 8-percent

decrease in power and a corresponding increase in fuel consumption at full load, a 12-percent decrease in friction mean effective pressure, a decrease in ignition lag, a decrease in the rate of pressure rise in the cylinder, and smoother engine operation. Obviously the gain obtained from the decreased friction losses and probably lower losses to the coolant when using high-temperature cooling cannot compensate for the loss in performance occasioned by the lowered volumetric efficiency and the adverse effect on combustion. The reduction in the ignition lag resulted in a correspondingly earlier occurrence of high temperatures in the combustion chamber, which probably caused fuel from the latter part of the injection to pass through regions of high temperatures which, in turn, reduced the penetration and prevented some of the fuel from reaching sufficient air for combustion. These results and conclusions are in agreement with those of Rothrock and Waldron (reference 9) regarding the effect of engine-jacket temperature on combustion in a compression-ignition engine.

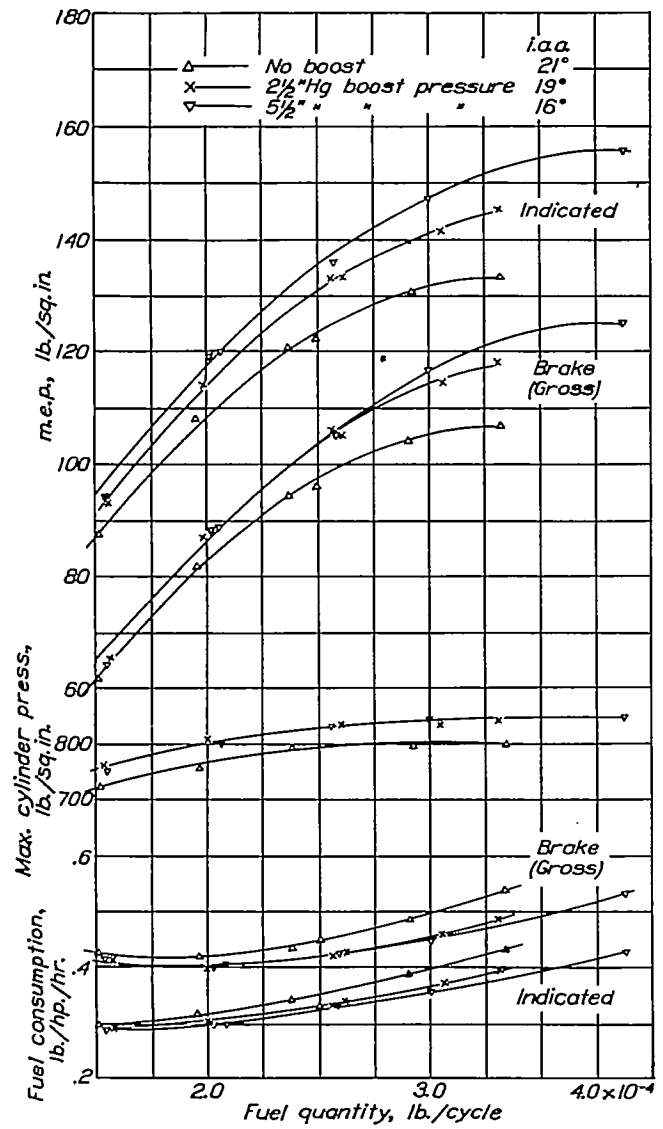


FIGURE 24.—Effect of boost pressure on engine performance at a coolant temperature of 265° F.; nozzle H-1.

Because of the high temperatures and the small volume of the coolant used, it was not practicable to investigate the heat losses to the coolant. With water as the coolant and at standard operating temperatures, however, the heat loss to the coolant was about 24 percent of the total heat of the fuel and changed little with change in load. Figures 24 and 25 show that boosting did not change the trend of the curves for the general operating characteristics or for the performance at high coolant temperatures.

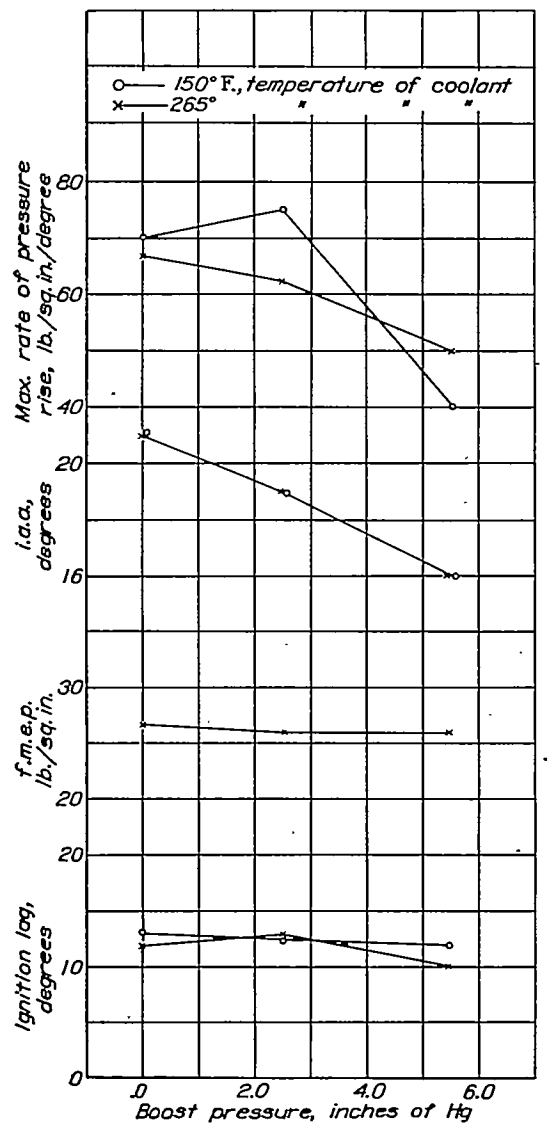


FIGURE 25.—Effect of boost pressure and coolant temperature on engine-operating characteristics; nozzle H-1.

Indicator cards.—Figure 26 shows a typical pressure-time card of the quiescent combustion-chamber engine for a compression ratio of 15.3, full-load fuel quantity and 1,500 r. p. m., with both an optimum and a retarded injection advance angle. The line cut was

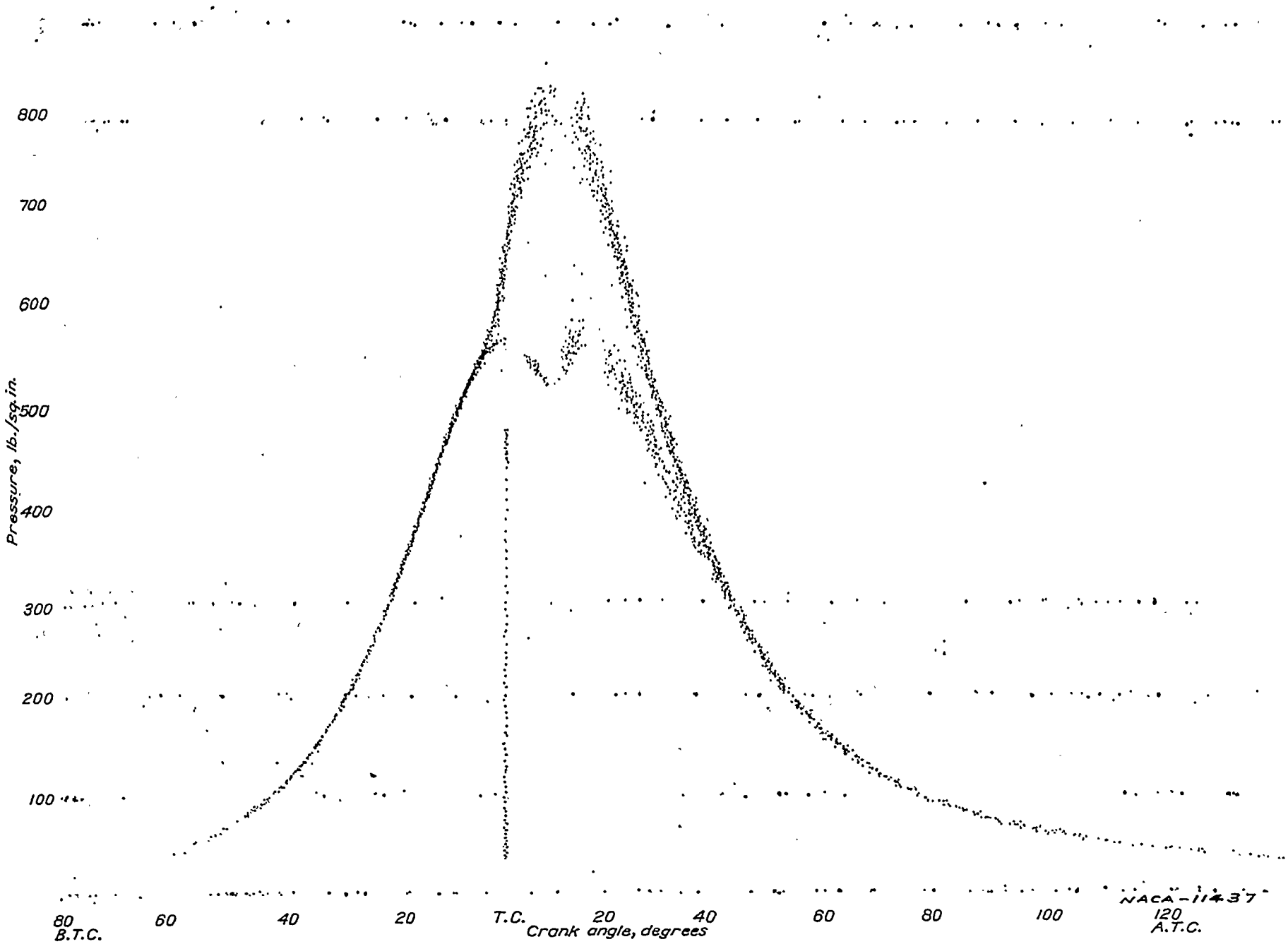


FIGURE 26.—Typical indicator card, optimum and retarded i. a. a.

made from a copy of the original card recorded directly on a special thin white paper. With the optimum injection advance angle, two general rates of pressure rise may be noted—in this case 40 and 20 pounds per square inch per degree; the breakaway occurs about 4° before top center. The earlier occurrence of the higher rate is believed to be caused by comparatively rapid and uncontrolled combustion when burning starts, owing to the ignition lag and the more favorable

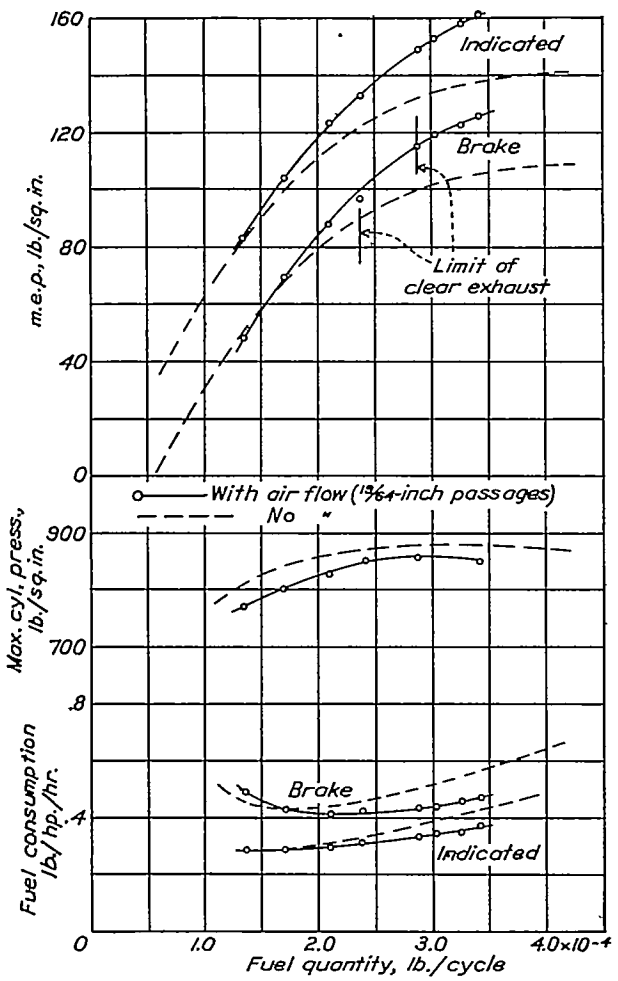


FIGURE 27.—Comparison of engine performance with and without air flow. Double-passage displacer; 1,600 r. p. m.

conditions in the combustion chamber for air and fuel mixing. Fuel injected after the burning starts reaches the remaining available air with increasing difficulty; hence there are slower burning and lower rates of pressure rise for the last part of the fuel injected. These conclusions are in agreement, generally, with those of Ricardo (reference 10) and with those regarding the behavior of this engine observed over a wide range of test conditions.

Remarks.—No trouble was experienced on account of the clogging of the small orifices in the fuel-valve nozzle. The fuel was usually centrifuged and the test runs were intermittent rather than of long duration, rarely exceeding 4 hours. The engine tests indicate that orifices smaller than 0.008-inch or larger than 0.020-inch need not be used.

A study of fuel-dispersion data (reference 11) shows the very uneven fuel distribution in the fuel spray and the large percentage of the total fuel contained in the relatively solid core of the spray; these factors are reflected in the values of specific fuel consumption, power output, and cloudy exhaust. These results show the futility of trying to obtain a truly homogeneous mixture of fuel and air in a quiescent combustion chamber with a nozzle having round-hole orifices. Random tests with two injection valves, the other two valve locations, and nozzles having other types of orifices, such as the impinging jets, the pintle, and the slit (reference 11), resulted in engine performance considerably inferior to the performance obtained with nozzles having round-hole orifices in one valve in the top location. It thus appears that the quiescent combustion chamber has inherent limitations that prevent it from attaining the high performance ultimately expected of the compression-ignition aircraft engine.

At the beginning of 1934 this quiescent chamber was converted into an air-flow chamber by the use of a displacer piston. The preliminary performance results (reference 12) were so satisfactory and so far superior to those obtained with the quiescent chamber (fig. 27) that work with the quiescent chamber has been discontinued. The air-flow type of combustion chamber apparently offers considerably greater possibilities of development than the quiescent chamber.

CONCLUSIONS

The results of these investigations indicate that:

1. 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 the orifice sizes and determining from the engine power the optimum combination. Neither method, however, is complete in itself; the use of both should yield the best results.

2. In a multiorifice fuel-injection valve nozzle for a vertical disk-type quiescent combustion chamber, there is no sharply defined optimum value for the number, direction, or size of the orifices. A 6-orifice nozzle gave power and economy equal to or better than that obtained with any other number and arrangement of orifices.

3. The rate of injection influences the rate of pressure rise in the cylinder and apparently the severity of combustion shock.

4. Although the results do not afford a rational basis of nozzle design that can be reduced to an analytical or empirical formula, they do show that engine performance can be improved by careful design of the injection nozzle.

5. There is little difference in the power output for compression ratios of 10.6, 12.6, 13.6, and 15.3. The ease of starting, the smoothness of engine operation, and the somewhat better fuel economy, however, warrant the use of the 15.3 compression ratio.

6. The use of coolant temperatures higher than can be obtained with water as the coolant results in a net decrease in performance because of their adverse effect on volumetric efficiency and combustion.

7. Boosting extends the performance curves but does not essentially alter their characteristics; however, it tends to make the engine operate more smoothly. The increase in indicated mean effective pressure is proportional to the increase in the weight of inducted air for equal air-fuel ratios and comparable maximum cylinder pressures.

8. The inferior performance compared with that obtained from the same combustion chamber with forced air flow, despite the easy starting, easy scavenging, low mechanical losses, and freedom from knock, renders the quiescent combustion chamber engine unattractive for aircraft-engine use.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *April 30, 1936.*

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TABLE I.—NOZZLE CHARACTERISTICS AND CORRESPONDING ENGINE PERFORMANCE; ENGINE SPEED, 1,500 R. P. M.

Orifice arrangement	Nozzle	Total orifice area (sq. in.)	Orifice diameter (inch)	Total orifice area (percent)	I. m. e. p.		Indicated fuel consumption		Maximum cylinder pressure (lb./sq. in.)	Full-load fuel with clear exhaust (percent)	Compression ratio
					¾ full load (lb./sq. in.)	Full load (lb./sq. in.)	¾ full load (lb./I. hp.-hr.)	Full load (lb./I. hp.-hr.)			
MISCELLANEOUS SERIES—LOW RATE OF INJECTION FOR THIS SERIES ONLY											
	3	0.00013	A=0.008 B= .006 C= .004	A=38.1 B=21.4 C=9.5	78	Orifice area too small	0.52	----------	650	----------	13.6
	4	.00014	B= .008 C= .005	B=35.9 C=14.1	80		.52	----------	650	----------	13.6
	7	.00019	A= .008 B= .007 C= .005 D= .004	A=26.4 B=20.25 C=10.3 D=6.67	87		.48	----------	650	----------	13.6

TABLE I.—NOZZLE CHARACTERISTICS AND CORRESPONDING ENGINE PERFORMANCE; ENGINE SPEED, 1,500 R. P. M.—Continued

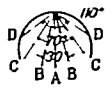
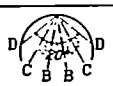
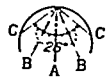
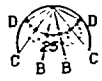
Orifice arrangement	Nozzle	Total orifice area (sq. in.)	Orifice diameter (inch)	Total orifice area (percent)	I. m. e. p.		Indicated fuel consumption		Maximum cylinder pressure (lb./sq. in.)	Full-load fuel with clear exhaust (percent)	Compression ratio
					¾ full load (lb./sq. in.)	Full load (lb./sq. in.)	¾ full load (lb./i. hp.-hr.)	Full load (lb./i. hp.-hr.)			
7-ORIFICE SERIES—HIGH RATE OF INJECTION FOR THIS AND SUBSEQUENT SERIES											
	9	0.00069	A=0.007 B=.018 C=.005 D=.008	A=5.58 B=36.8 C=2.84 D=7.25	112	124	0.380	0.460	575	66	13.6
	10	.00053	A=.007 B=.015 C=.005 D=.008	A=7.26 B=33.2 C=3.7 D=9.42	100	121	.430	.490	550	64	13.6
	11	.00041	A=.007 B=.012 C=.005 D=.008	A=9.52 B=28.0 C=4.85 D=12.3	97	112	.435	.520	500	62	13.6
	12	.00034	A=.007 B=.010 C=.005 D=.008	A=11.5 B=23.5 C=5.08 D=14.9	92	101	.460	.580	460	58	13.6
	14	.00087	A=.007 B=.021 C=.005 D=.008	A=4.43 B=30.75 C=2.25 D=5.75	106	123	.405	.465	550	66	13.6
	16	.00064	A=.007 B=.018 C=.005 D=.006	A=6.0 B=39.7 C=3.06 D=4.42	97	111	.460	.500	490	----------	13.6
	16-1	.00069	A=.007 B=.018 C=.005 D=.008	A=5.58 B=36.8 C=2.84 D=7.25	112	124	.380	.450	575	66	13.6
	16-2	.00072	A=.007 B=.018 C=.007 D=.008	A=5.18 B=35.1 C=5.32 D=6.9	110	123	.370	.455	535	68	13.6
	17	.00074	A=.007 B=.018 C=.005 D=.010	A=5.19 B=34.25 C=2.64 D=10.6	112	125	.370	.450	520	81	13.6
	17-1	.00081	A=.007 B=.018 C=.005 D=.012	A=4.75 B=31.25 C=2.42 D=23.95	112	124	.360	.445	500	71	13.6
	18	.00093	A=.007 B=.018 C=.012 D=.010	A=4.14 B=27.30 C=12.15 D=8.45	95	111	.440	.500	510	72	13.6
	18-1	.00097	A=.010 B=.018 C=.012 D=.010	A=8.10 B=26.2 C=12.65 D=8.10	95	111	.440	.500	510	72	13.6
	18-2	.00107	A=.012 B=.018 C=.012 D=.012	A=10.5 B=23.7 C=10.5 D=10.5	104	112	.400	.500	475	67	13.6
9-ORIFICE SERIES											
	C	0.00084	A B=0.018 C=.010 D=.008 E=.007	B=30.2 C=9.35 D=5.98 E=4.58	104	118	0.410	0.480	540	74	13.6
	C-1	.00088	A=.007 B=.018 C=.010 D=.008 E=.007	A=4.37 B=28.8 C=8.91 D=5.69 E=4.37	112	125	.360	.460	540	74	13.6
	C-2	.00092	A=.010 B=.018 C=.010 D=.008 E=.007	A=8.53 B=27.60 C=8.52 D=5.44 E=4.13	111	125	.380	.450	535	73	13.6
	C-3	.00078	A=.007 B=.018 C=.008 D=.007 E=.006	A=4.93 B=32.50 C=6.40 D=4.94 E=3.63	102	122	.415	.460	500	71	13.6

TABLE I.—NOZZLE CHARACTERISTICS AND CORRESPONDING ENGINE PERFORMANCE; ENGINE SPEED, 1,500 R. P. M.—Continued

Orifice arrangement	Nozzle	Total orifice area (sq. in.)	Orifice diameter (inch)	Total orifice area (percent)	I. m. e. p.		Indicated fuel consumption		Maximum cylinder pressure (lb./sq. in.)	Full-load fuel with clear exhaust (percent)	Compression ratio
					¾ full load (lb./sq. in.)	Full load (lb./sq. in.)	¾ full load (lb./I. hp.-hr.)	Full load (lb./I. hp.-hr.)			
E SERIES											
	E_2	0.00051	B = 0.018	B = 50	98	99	0.440	0.570	530	55	12.6
	E_4	.00067	B = .018 C = .010	B = 37.9 C = 11.7	104	120	.390	.470	570	73	12.6
	E_6	.00072	B = .018 C = .010 D = .006	B = 35.25 C = 10.90 D = 3.92	112	127	.380	.450	550	73	12.6
See figure 13	E_8	.00080	E_6 + two 0.007	----------	110	124	.380	.450	590	62	12.6
Do	E_{10}	.00084	E_6 + two 0.005	----------	112	126	.390	.450	590	68	12.6
Do	E_{12}	.00088	E_{10} + two 0.005	----------	104	120	.420	.480	560	65	12.6
Do	E_{14}	.00092	E_{12} + two 0.005	----------	100	113	.420	.490	530	66	12.6
Do	E_{16}	.00096	E_{14} + two 0.005	----------	100	113	.430	.500	570	71	12.6
	E_5	.00066	A = .018 B = .014 C = .008	A = 38.4 B = 23.6 C = 7.5	114	123	.370	.460	550	75	12.6
F SERIES											
	F_{20}	0.00072	B = 0.018 C = .010 D = .006	B = 35.25 C = 10.90 D = 3.92	112	127	0.380	0.450	550	73	12.6
	F_{23}	.00072	B = .018 C = .010 D = .006	B = 35.25 C = 10.90 D = 3.92	114	128	.365	.440	600	75.5	12.6
	F_{26}	.00072	B = .018 C = .010 D = .006	B = 35.25 C = 10.90 D = 3.92	114	126	.380	.450	550	80	12.6
	F_{29}	.00072	B = .018 C = .010 D = .006	B = 35.25 C = 10.90 D = 3.92	114	124	.375	.460	570	74.5	12.6
H SERIES											
	H 1	0.00089	B = 0.020 C = .011 D = .007	B = 35.10 C = 10.60 D = 4.30	119	128	0.360	0.440	600	73	12.6
	H-2	.00100	B = .022 C = .011 D = .006	B = 38.00 C = 9.50 D = 2.83	115	128	.360	.450	600	70	12.6
	H-3	.00083	B = .020 C = .010 D = .0055	B = 37.80 C = 9.42 D = 2.85	117	124	.360	.450	600	72	12.6
	H-4	.00119	B = .024 C = .012 D = .0065	B = 37.80 C = 9.45 D = 2.77	114	128	.365	.445	590	64	12.6
	K-4	.00097	B = .019 C = .014 D = .008	B = 29.1 C = 15.8 D = 5.2	123.5	136	.340	.410	880	73.7	15.3