TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 435

THE EFFECT OF CLEARANCE DISTRIBUTION ON THE PERFORMANCE

OF A COMPRESSION-IGNITION ENGINE

WITH A PRECOMBUSTION CHAMBER

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Washington
November, 1932

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## SUMMARY

The clearance distribution in a precombustion chamber
cylinder head was varied so that for a constant compression
ratio of 13.5 the spherical auxiliary chambers contained
20, 35, 50, and 70 per cent of the total clearance volume.
Each chamber was connected to the cylinder by a single cir-
cular passage, flared at both ends, and of a cross-sec-
tional area proportional to the chamber volume, thereby
giving the same calculated air-flow velocity through each
passage. Results of engine-performance tests are presented
for each of the four clearance distributions to show the
variations of power, fuel consumption, explosion pressure,
rate of pressure rise, ignition lag, heat loss to the cool-
ing water, and motoring characteristics.

For good performance the minimum auxiliary chamber
volume, with the cylinder head design used, was 35 per cent
of the total clearance volume; for larger volumes the per-
formance improves but slightly. With the auxiliary chamber
that contained 35 per cent of the clearance volume there
were obtained the lowest explosion pressures, medium rates
of pressure rise, and slightly less than the maximum power.
For all clearance distributions an increase in engine speed
decreased the ignition lag in seconds and increased the
rate of pressure rise.

## INTRODUCTION

The precombustion or auxiliary chamber with forced air
flow for mixing fuel and air is one of the general combus-
tion-chamber types used in compression-ignition engines.

When designing a precombustion-chamber cylinder head the
influences of the variations of the different elements
should be known. The precombustion-chamber position, vol-
ume, and shape, and the connecting passage area, shape, and
direction have been subject to varied design treatment.
The distribution of the clearance between the precombustion
chamber and the cylinder is one of the fundamental varia-
bles whose effect should be determined. Theoretically, the
volume of the precombustion chamber, or weight of air in it,
should control the amount of precombustion if injection is
confined to the chamber.

Experimental work on high-speed compression-ignition
engines with precombustion chambers has been done at this
laboratory by Joachim and Kemper (reference 1) and Spanogle
and Moore (reference 2).

The work presented here is an experimental investiga-
tion of the effect of clearance distribution between the
auxiliary chamber and the cylinder for the same relative
passage restriction and compression ratio. This work was
done during 1931 by the National Advisory Committee for
Aeronautics at Langley Field, Va.

APPARATUS AND METHODS

The single-cylinder test engine unit with electric dy-
namometer shown in Figure 1 was used in this series of tests.
The engine is 4-stroke-cycle, compression-ignition, of 5-
inch bore and 7-inch stroke, and has the standard Liberty
valve-actuating mechanism and valve timing. An N.A.C.A.
universal test engine base and cylinder were used which al-
lowed the compression ratio to be held constant as the
clearance distribution was changed. The fuel-injection
equipment (as in reference 2) consisted of a primary gear
pump, and a cam-operated, constant-stroke, fuel-injection
pump that delivered fuel to a spring-loaded injection valve
having a single 0.050-inch-diameter orifice. A timing mech-
anism permitted the injection advance angle to be varied.
Two types of injection-valve stems were used, a plain stem
giving a narrow spray cone and a stem with two helical
grooves of 23° angle, which gave a cone of more widely dis-
persed spray.

The auxiliary testing equipment was the same as for
the work of reference 2 except that the balanced-pressure

apparatus (reference 3) was used to measure the maximum
cylinder and chamber pressures and the improved Farnboro
indicator was used to obtain indicator cards (reference 4).
In this work, temperature measurements were made in both
the chamber and cylinder by means of a 0.020-inch un-
shielded chromel-alumel thermocouple. The hot junction of
the thermocouple, the locations of which are shown in Fig-
ure 2, extended about 1/2 inch into the combustion space.

The cylinder head (fig. 2) used for these tests is so
constructed that the two pieces forming the precombustion
chamber and connecting passage are removable without dis-
turbing other parts of the engine. By the construction and
assembly of different chamber parts and adjustment of the
compression ratio of the universal test engine, this cylin-
der head is easily adaptable to the investigation of a va-
riety of combustion-chamber forms.

In this work the combustion-chamber form was not cho-
sen to give maximum engine performance, but was designed
so that the clearance could be transferred from cylinder to
chamber with a minimum change in the shape of the combustion
space. The cylinder clearance volume (see fig. 2) was
formed between the domed cylinder head and the domed piston
crown. The auxiliary chamber clearances were spherical and
contained 20, 35, 50, and 70 per cent of the total clear-
ance for a compression ratio of 13.5. For convenience of
reference these clearance distributions will be called the
20, 35, 50, and 70 per cent chambers.

The connecting passages were circular in cross section,
of constant length/diameter ratio, and were flared at both
ends. The cross-sectional area of each of the four passages
was designed to be proportional to the auxiliary chamber
volume. The passage diameters were 23/64, 15/32, 9/16, and
43/64 inch for the 20, 35, 50, and 70 per cent chambers,
respectively. At the same engine speeds for each of the
four clearance distributions, the calculated air velocities
through the passages were the same. The passage axis passed
through the centers of the spheres and intersected the cyl-
inder axis at an angle of 45°. The air flow in each of the
four combustion chambers was directed counter to the fuel
spray.

The cooling water entered around the bottom of the cyl-
inder head. Part of the water rose and was discharged
through an outlet in the top of the head; the rest passed

around the chamber and through an outlet in the chamber
cap. Thermometers were located at the inlet to the cylinder and head and at the outlets from the cylinder, head,
and chamber cap.

The standard conditions of testing were kept constant
except when taken singly as variables. For convenience of
reference, the conditions which were considered as standard
are tabulated below.

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

Compression ratio (each clearance distribution). . . . . . . . . . . . . . . . . . . . 13.5

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

Full-load fuel quantity. . . . . . . . . . . . . 0.0003 lb.
   (12 per cent excess air)              per cycle
   (85 per cent volumetric efficiency)

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

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

Spray type . . . . . . . . . . . . . . . . Noncentrifugal

Nozzle type. . . . . . single orifice, 0.050 in. diameter

Fuel valve position . . upper chamber hole

Valve opening pressure . . 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.

The test procedure was the same for each clearance distribution. The compression ratio was checked and the following motoring data taken. The f.m.e.p. was computed from the scale reading taken while the dynamometer was motoring the engine. Compression pressures were obtained from both cylinder and chamber over a speed range of 600 to 1,800 r.p.m. with both the balanced-diaphragm maximum pressure indicator and the Farnboro indicator equipment. A double indicator card at 1,500 r.p.m. was obtained by taking the chamber and cylinder records on the same sheet of paper. Motoring temperature readings at 1,500 r.p.m. were taken in the chamber and cylinder for all chamber sizes tested.

Power-test data were obtained of b.m.e.p., explosion pressures in chamber and cylinder, fuel consumptions, and heat losses to cooling water. Thermocouple temperatures were obtained for each chamber and cylinder at standard conditions and also at 900 and 1,200 r.p.m. for the 50 per cent chamber and cylinder. These data were taken at the standard fuel quantity over a range of speeds from 600 to 1,800 r.p.m. Indicator cards were also taken from the chamber and cylinder during these variable-speed tests. From the indicator cards the ignition lags and rates of pressure rise were measured. The ignition lag is considered in this report as the time in seconds from the start of injection of fuel as observed with a Stroborama to the beginning of pressure rise due to combustion as shown by inspection of the indicator card. At standard fuel quantity and engine speed, performance tests were made to determine the effect of injection characteristics. Valve-opening pressures of 2,000 and 5,000 pounds per square inch were used. With standard conditions a test was made to determine the effect of using a centrifugal spray. A test was also made at standard conditions using the noncentrifugal spray in the lower hole of the chamber cap. In addition to the tests made at full load, similar data were obtained for each clearance distribution at half load, 1,500 r.p.m. Also at 1,500 r.p.m., the fuel quantity at the start of exhaust flame was obtained for each clearance distribution by slowly increasing the load until a trace of flame appeared in the exhaust.

More detailed combustion and heat-loss data were obtained from the 50 per cent chamber because it had been used previously for a series of tests. During the testing, the barometric pressure varied from 29.49 to 30.40 inches

of mercury; the engine power data, however, were not cor-
rected to standard pressure and temperature.

For all tests the general engine-operating character-
istics were noted. Secondary tests were made to determine
the starting and idling characteristics. The starting tests
were made in the following manner: with the engine cold
(about 70° F.) it was given two revolutions with the dyna-
mometer. If it did not start during three such attempts,
it was motored at speeds starting at 300 r.p.m. and increas-
ing until the minimum starting speed was reached. These
tests were repeated with the engine immediately after nor-
mal power operation. The engine was tested for slow speed
operation by determining whether or not it would idle at
300 r.p.m.

## TEST RESULTS AND DISCUSSION

Starting and idling.- The starting characteristics of
the engine changed with each of the different chambers em-
ployed. None of the chambers gave starting on two revolu-
tions of the crankshaft when cold; but starting was possi-
ble with all four of the chambers immediately after normal
power operation. The minimum starting speed (compression
pressure, 390 pounds per square inch) of the 20 and 70 per
cent chambers when cold was 300 r.p.m.; those of the 35 and
50 per cent chambers were 800 and 600 r.p.m., respectively.
The cold starting speed when using the centrifugal spray in
the 50 per cent chamber was 700 r.p.m.

The idling characteristics were the same for all the
chambers, idling at 300 r.p.m. being obtainable, though un-
steady.

Miss to knock range.- The injection advance angle
range from misfiring to allowable knocking was negligibly
affected by clearance distribution when operating at stan-
dard test conditions. With the fuel valve in the lower hole
of the 20 per cent auxiliary chamber the operating range in-
creased from 12° to 27°, but the power decreased and the
smoke and flame of the exhaust increased. The standard in-
jection advance angle of 7° at 1,500 r.p.m. gave a start of
pressure rise which varied from T.C. to 3° A.T.C. for all
clearance distributions, as determined by inspection of in-
dicator cards.

Table I, which follows, presents further notes on the
engine-operating characteristics.

TABLE I

## GENERAL OPERATING CHARACTERISTICS

| Operating characteristics | 20 per cent chamber | 35 per cent chamber | 50 per cent chamber | 70 per cent chamber |
|---|---|---|---|---|
| Comb. knock | Dull Regular | Slight Irregular | Hard Irregular | Harder Irregular |
| Cyclic variation in max. explosion press. | Cham. 300 lb./sq.in. Cyl. 100 lb./sq.in. | Cham. 200 lb./sq.in. Cyl. 100 lb./sq.in. | Cham. 140 lb./sq.in. Cyl. 130 lb./sq.in. | Cham. 90 lb./sq.in. Cyl. 140 lb./sq.in. |
| Injection range, miss to allowable knock | $12^o$ | $8^o$ | $10^o$ | $10^o$ |
| Carbon deposits | Cham. – much Cyl. – little | Cham. soot and "cake" Cyl. – soot | Cham. – soot Cyl. – soot | Cham. – soft soot Cyl. – soft soot |
| Centrifugal spray compared to noncentrifugal spray | Knock and performance slightly worse | Knock and performance worse | Knock and performance worse | Knock and performance slightly better |
| Lower fuel valve position compared to upper position | Performance worse I.A.A. range 27$^o$ | No change | Performance worse | Performance worse |
| Optimum v.o.p. | 3,500 lb./sq.in. Best | 5,000 lb./sq.in. Slightly better | 5,000 lb./sq.in. Slightly better | 3,500 lb./sq.in. Slightly better |

Effect of clearance distribution on engine performance.-
Figures 3 and 4 show that for the design of precombustion
chambers used in these tests, the minimum volume in the aux-
iliary chamber for good performance is about 35 per cent of
the total clearance volume. The inferior performance with
the 20 per cent chamber can not be attributed to the non-
centrifugal spray depositing fuel on the walls, because the
centrifugal spray which had insufficient penetration to hit
the walls gave slightly worse performance. More power was
obtained with the larger chambers, because of the greater
quantity of air ready for initial combustion. The air in
the cylinder, being distributed over the piston crown, can
not be effectively reached by the unburned gases issuing
from the chamber and therefore does not materially assist
the combustion process.

The connecting passage size evidently throttles the
passage of burning gases during combustion more than it
does the passage of air during compression. This result is
indicated by the chamber explosion pressure being higher
than the cylinder pressure with the small chambers. For the
larger chambers with correspondingly larger passages the
chamber explosion pressures are more nearly equal to the
cylinder pressures. If the proportion of air in the auxil-
iary chamber alone were controlling the explosion pressure,
the smaller chambers should have the lower pressures be-
cause theoretically there would be insufficient air for gen-
erating high combustion pressures.

Effect of clearance distribution on combustion charac-
teristics.- Figure 5 shows that clearance distribution does
not have an appreciable effect on ignition lag. This re-
sult may be expected, as the conditions of temperature,
pressure, and flow velocity were held constant during the
tests. The figure shows that the difference between the
time of start of pressure rise in the chamber and in the
cylinder is very small.

For all clearance distributions the pressure rises are
straight lines (see figs. 6a and 6b) and of such high rates
that it is impossible to measure them accurately; the nu-
merical values are therefore only approximations. The trend,
as the percentage distribution increases, is for the auxil-
iary chamber rate to decrease and for the cylinder rate to
increase and then decrease. The larger chambers containing
more air should give a faster rate of pressure rise because
the fuel and air mixture would have more nearly the correct

proportions for complete combustion. As the opposite oc-
curs, it indicates that the passage size is influencing the
rate of pressure rise, the larger passages of the larger
chambers allowing the gases to pass more freely into the
cylinder.

The temperatures indicated by the thermocouples in the
chamber and cylinder were indicative of the relative tem-
peratures. The indicated combustion temperatures of the
cylinder were nearly the same for all combustion chambers
showing that clearance distribution had no effect on the
cylinder combustion. The combustion temperature of the
chamber increases with increasing chamber size because of
the greater amount of air in the chamber available for com-
bustion.

The improvement in exhaust conditions which occurs
with increase of chamber proportions is caused by more air
being available for initial mixing in the auxiliary cham-
ber. Decrease in the rate of improvement with increase of
clearance distribution in the auxiliary chamber above 35
per cent is due to the combination of spray shape and air
flow as used in these combustion-chamber forms. This com-
bination allows a maximum of approximately 35 per cent of
the fuel to be mixed with air for efficient combustion.
The remaining fuel is consumed either very late or not at
all.

Effect of clearance distribution on heat loss to cool-
ing water.- Figure 7a shows that increase in chamber volume
causes the total heat loss to the cooling water to increase
from 20.5 to 28.5 per cent. This increase is due to the
higher combustion temperatures in the chamber and also to
an increase of approximately 10 per cent in the total com-
bustion chamber surface area. It should be noted that the
total heat loss for this auxiliary chamber type of engine
is less than that usually accepted for spark-ignition en-
gines. The amount of heat loss from the chamber cap in-
creases with chamber volume and surface, whereas the amount
of heat loss from the head decreases. As more combustion
occurs in the chamber with increased volume, the cylinder
heat loss decreases. The similarity in shape of the "cham-
ber cap + head" curve (fig. 7a) to the b.m.e.p. curve of
Figure 3 should also be noted. As the b.m.e.p. increases
the percentage heat loss to the cylinder head increases and
the percentage loss to the cylinder decreases. These re-
sults indicate that the clearance distribution of the 20

per cent chamber causes late inefficient burning in the cylinder. The chamber cap and head together lose more heat than the cylinder because of the higher temperatures and longer time available for heat transfer.

Figure 7b shows that for the 50 per cent chamber the percentage heat losses to the cooling water are but slightly influenced by injection advance angle or engine speed, but are influenced to a greater degree by fuel quantity.

Effect of clearance distribution on motoring characteristics.- Figure 8 shows that the motoring characteristics remain nearly constant as the clearance distribution varies. Because less air is moved through the passage for the smaller chambers, the f.m.e.p. should be less; the decrease in f.m.e.p., however, is slight. Therefore, the work of moving the air into the chambers is but a negligible part of the total friction loss. The maximum indicated compression pressures are higher in the chambers than in the cylinder, as was previously reported for the same type of combustion chamber. (Reference 2.) The variation in compression pressure between the four chambers is probably due to experimental error although the upward trend of the cylinder pressure curve is possibly caused by the increase in the effective cylinder compression ratio as the chamber proportion increases. The indicated air temperature of the chamber is higher than that of the cylinder, possibly because the chamber air is heated by friction on being forced through the passage or because the thermocouple is partly shielded from the inlet air.

Thirty-five per cent chamber. - The 35 per cent chamber in which the weight of air would be less than 35 per cent due to throttling of the air by the throat, approaches the clearance distribution which would give the partial combustion required by the precombustion principle. There is only enough air in the chamber to allow 35 per cent of the fuel to burn in the chamber and to expel the remaining fuel into the cylinder. The test results show that for this chamber volume there is some combustion control as indicated by the low explosion pressures.

The combustion knock is slight and the rates of pressure rise as determined from the indicator cards are comparatively low and nearly the same for the chamber and cylinder. The heat loss to the cooling water is also small, being only 21 per cent of the total heat input. Comparing

the above characteristics with those of the other chamber
sizes tested, it can therefore be seen that the 35 per cent
chamber distribution gives the best combustion control with
a minimum sacrifice in power.

Effect of speed on mean effective pressures, fuel con-
sumption, explosion pressure, and motoring characteristics
(all chambers). - Figure 9 shows the general effect of en-
gine speed and air-flow velocity on m.e.p. and fuel con-
sumption. The effect is nearly the same for all the cham-
bers with the optimum speed varying from 800 to 1,200 r.p.m.
The larger chambers, because of a more intimate mixture of
a larger quantity of fuel and air, developed the most power
and the best fuel economy. It is believed that the great
difference shown by the curves for the 20 per cent chamber
was caused by insufficient air in the small chamber.

The explosion pressures of all chambers (fig. 10) in-
crease with speed because of the better mixing of fuel and
air and resultant faster burning. As the engine speed in-
creases the air-flow velocity increases and the fuel-spray
dispersion increases slightly, thereby promoting better
mixing. The 20 per cent chamber with small passage area
confines the pressure to the chamber, giving the high cham-
ber and low cylinder pressures as shown.

Figure 11 shows that the variation between the f.m.e.p.
of the different chambers is negligible. The compression
pressure peaks at approximately 1,500 r.p.m. because of the
induction system characteristics. The pressure differences
between chamber and cylinder vary but little for the dif-
ferent clearance distributions and indicate that the re-
strictions of the passages to the compression of the air
are nearly constant.

Effect of speed on combustion characteristics (50 per
cent chamber).- Figure 12 shows that engine speed has
marked effects on the combustion characteristics of the 50
per cent chamber. Cards from the other three combustion
chambers gave trends similar to those shown in Figure 12.
As the engine speed increases the velocity of air flow in
the passage increases and the mixing of fuel and air in the
chamber is more complete with more rapid combustion and
higher rates of pressure rise. The successive engine cy-
cles varied as the engine sound clearly indicated, so that
the points on the Farnboro indicator cards are widely dis-
persed, especially at the pressure peaks. The rates of

pressure rise obtained are the maximum, since only the lead-
ing points are taken. Apparently the rate of pressure rise
and knock do not vary together, because the rates of pres-
sure rise are less at the lower speeds and the combustion
knock audibility remained constant.

The point of start of pressure rise is dependent upon
the injection advance angle which is the earliest permitted
by allowable knock intensity. The start of pressure rise
varies from approximately 10° A.T.C. at 600 r.p.m. to 2°
A.T.C. at 1,800 r.p.m. The ignition lag measured in sec-
onds is reduced one-half by an increase in engine speed
from 600 to 1,200 r.p.m., primarily because of the better
fuel and air mixing caused by higher velocity of air flow.

The combustion temperatures as measured by thermocou-
ples in the chamber and cylinder show an increase in tem-
perature with speed. It is believed that this trend towards
higher temperatures at increased speed is due to better com-
bustion caused by the increased velocity of air flow with
speed. This observation can not be definitely stated be-
cause of the lack of sensitiveness of the thermocouples used
in this work.

Motoring indicator card. - Figure 13 shows a double
indicator card taken at 1,500 r.p.m. when using the 50 per
cent chamber assembly. The differences between the cards
from the four clearance distributions are small. Below an
engine speed of 1,000 r.p.m. the difference between the
chamber and cylinder cards was less than the dispersion of
the points on the Farnboro indicator record. In Figure 13
the maximum pressure difference thus indicated is 35 pounds
per square inch at 1,500 r.p.m. The maximum pressure dif-
ference, in favor of the cylinder, occurs at approximately
20° B.T.C. The indicator cards are too indistinct at the
tops to give any information as to the manner in which the
chamber pressure finally rises higher than the cylinder
pressure.

## CONCLUSIONS

The results of this investigation show that for the de-
sign of combustion chamber used in these tests, the minimum
auxiliary chamber volume for good performance is 35 per cent
of the total clearance volume; for greater percentages, the

improvement in performance is slight.  This size of precombustion chamber is advantageous because, compared to the other sizes, it has the lowest explosion pressures, medium rates of pressure rise, and least combustion knock.

The variation in precombustion chamber volume as the clearance distribution was varied had a negligible effect on f.m.e.p., compression pressures, and relative compression temperatures.  However, this change in auxiliary chamber size with the resulting change in the total surface exposed to the gases of combustion does affect the heat losses to the cooling water and causes them to vary with the size of the precombustion chamber.

Variation of clearance distribution only for a fixed ratio of precombustion chamber volume to connecting passage area does not exercise sufficient control over combustion or eliminate combustion knock.

Langley Memorial Aeronautical Laboratory,
     National Advisory Committee for Aeronautics,
          Langley Field, Va., October 26, 1932.

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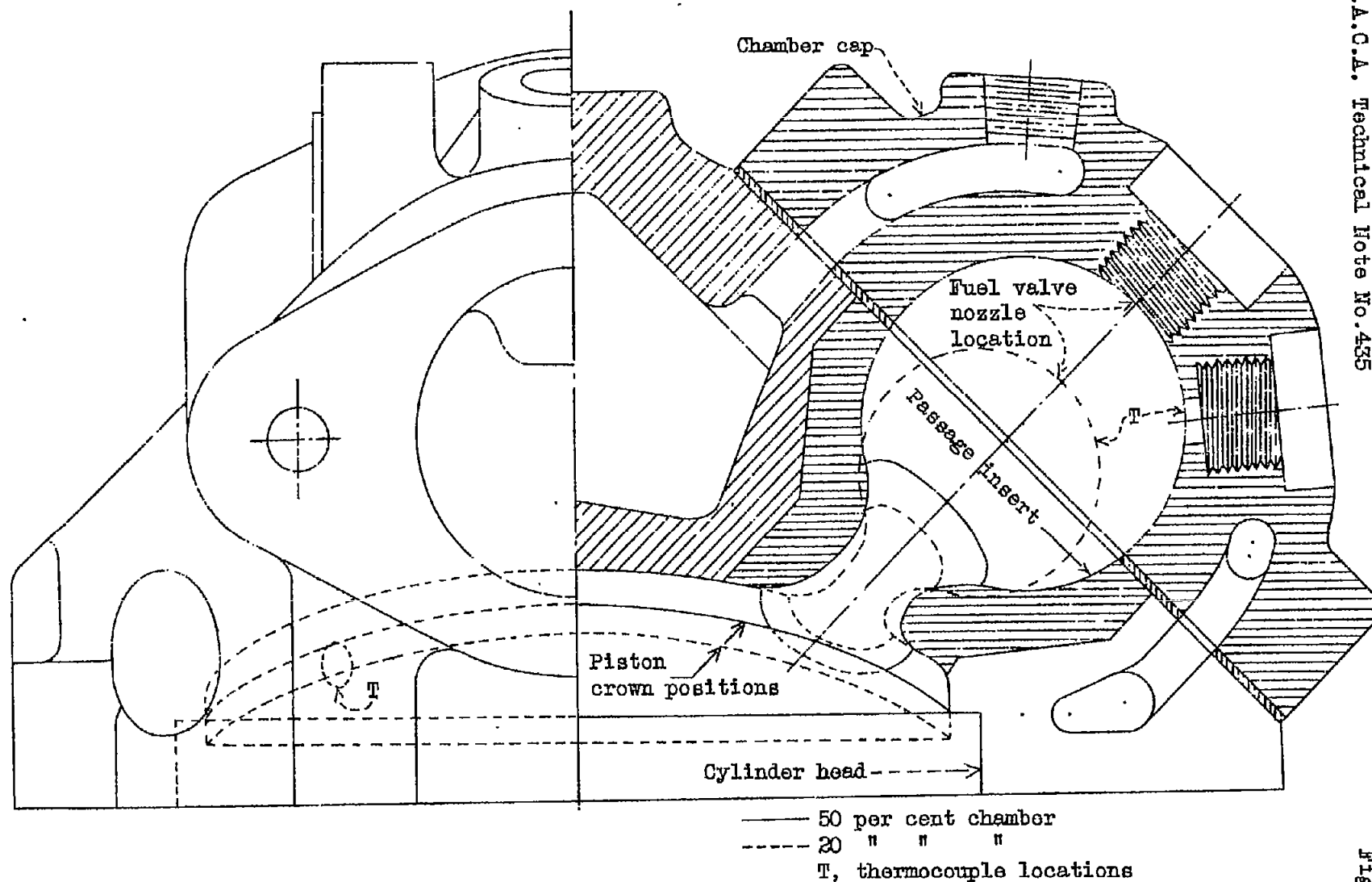
Fig.1

Fig.1

Chamber cap

Fuel valve
nozzle
location

Passage insert

T

Piston
crown positions

T

Cylinder head

———— 50 per cent chamber
----- 20 " " "
T, thermocouple locations
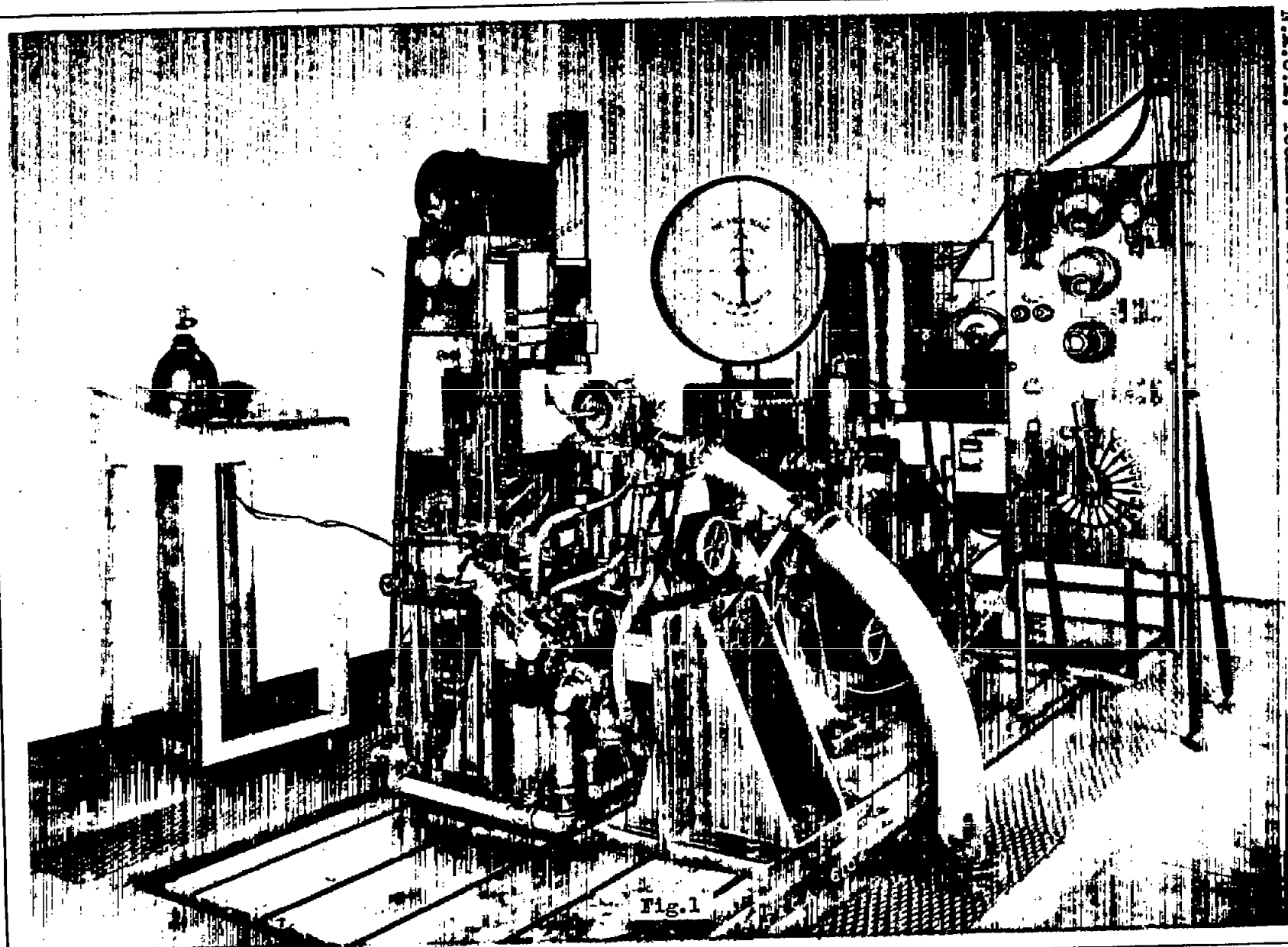
Fig.2  Cylinder-head design, showing removable
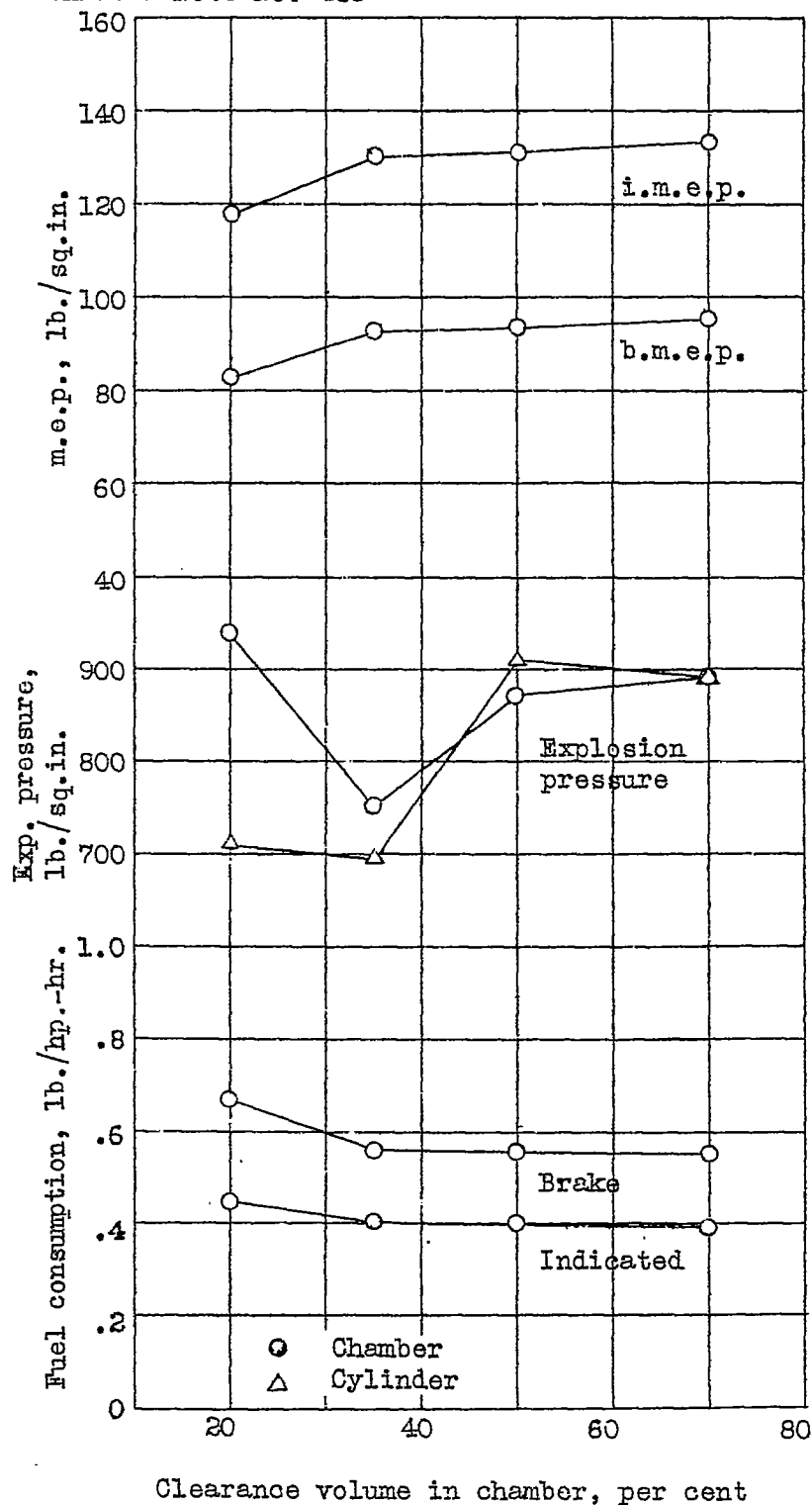insert and two chamber outlines.

Fig.2

Fig. 3  Effect of clearance distribution on engine performance at
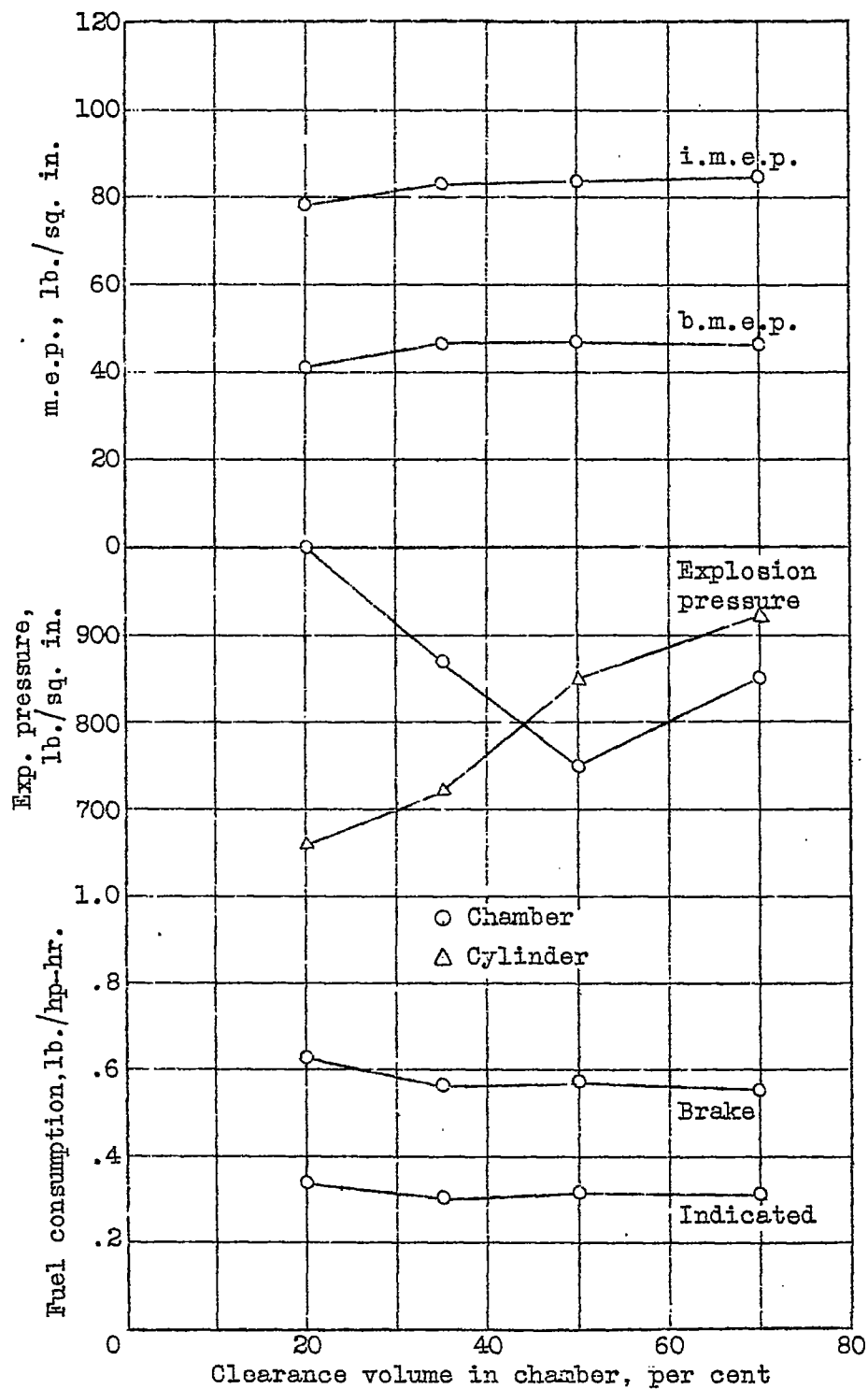0.0003 lb. fuel/cycle, 12 percent excess air.
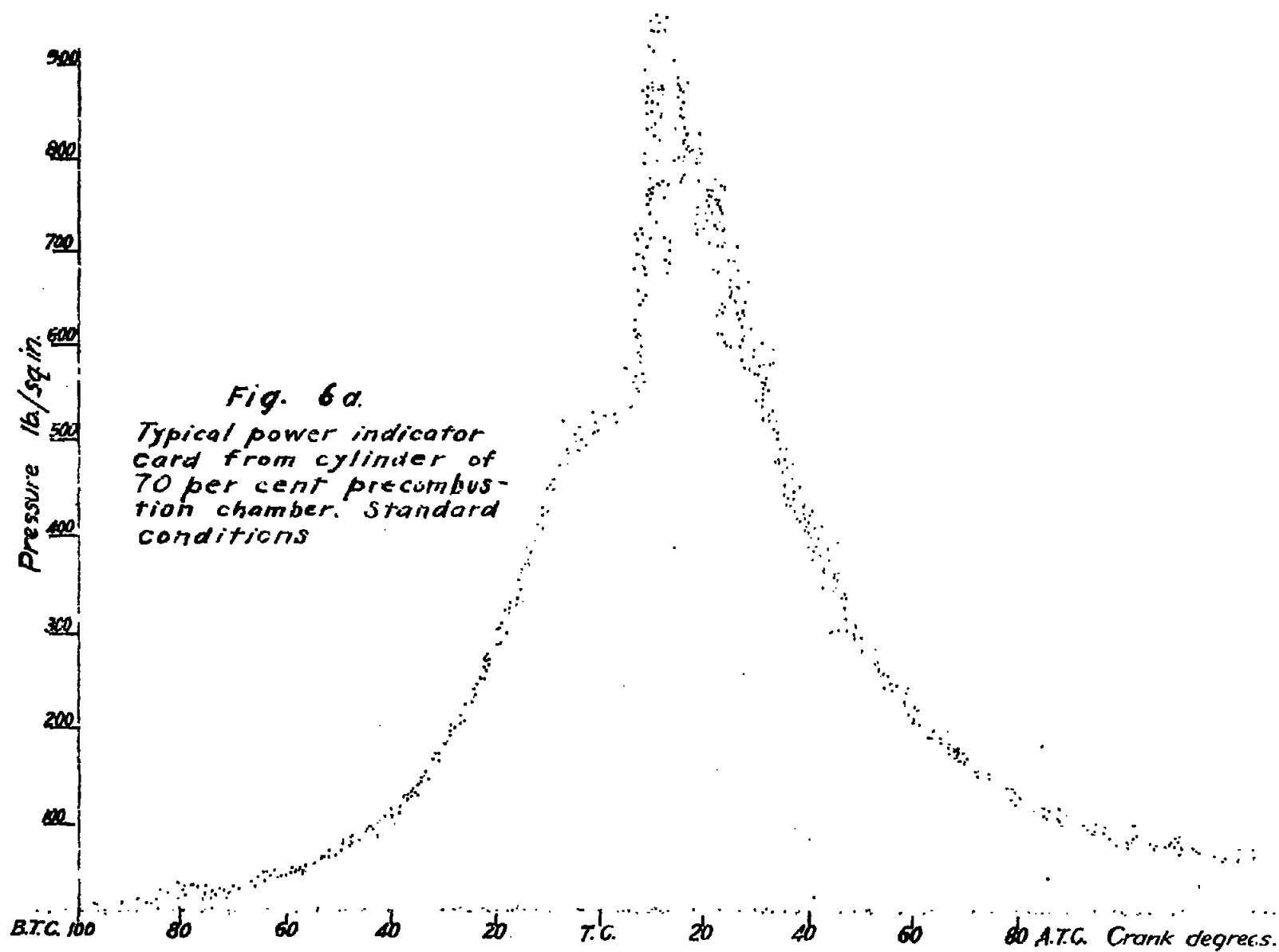
Fig.4  Effect of clearance distribution on engine performance at
       0.00015 lb. fuel/cycle, 54 per cent excess air.
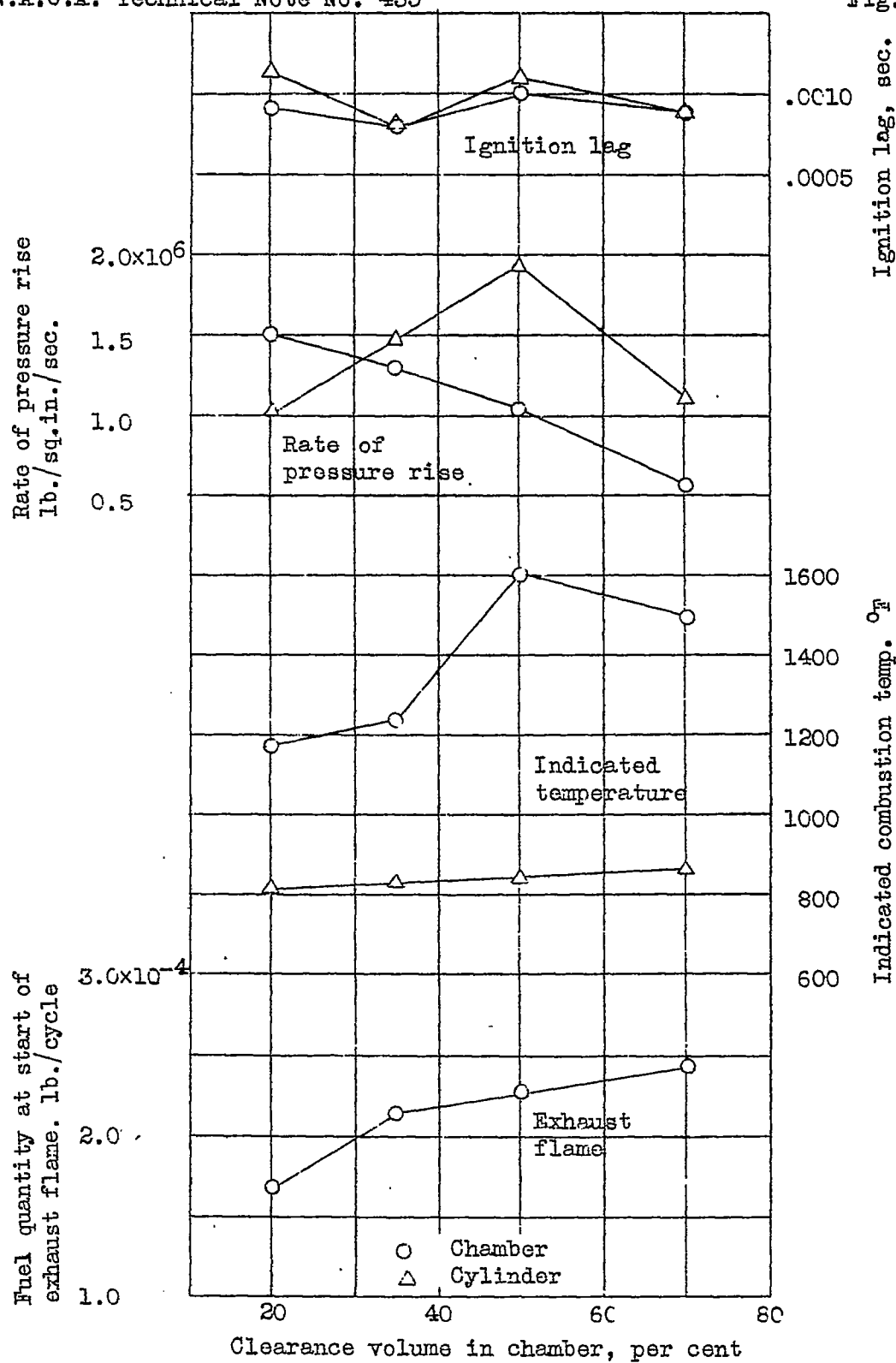
Fig. 5  Effect of clearance distribution on combustion
characteristics

Fig. 6a.
Typical power indicator
card from cylinder of
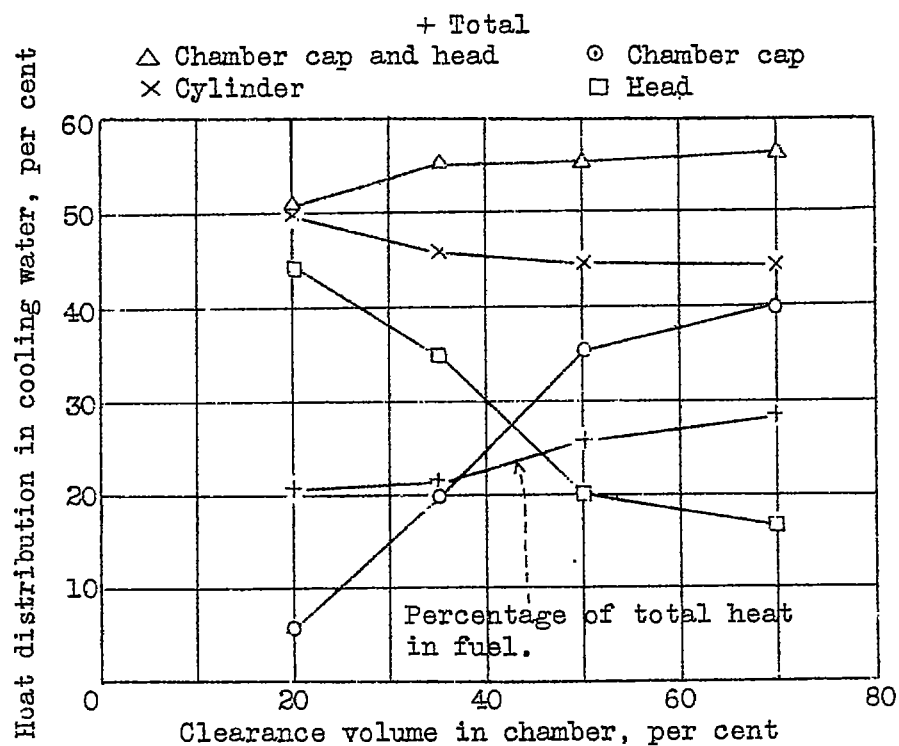70 per cent precombus-
tion chamber. Standard
conditions
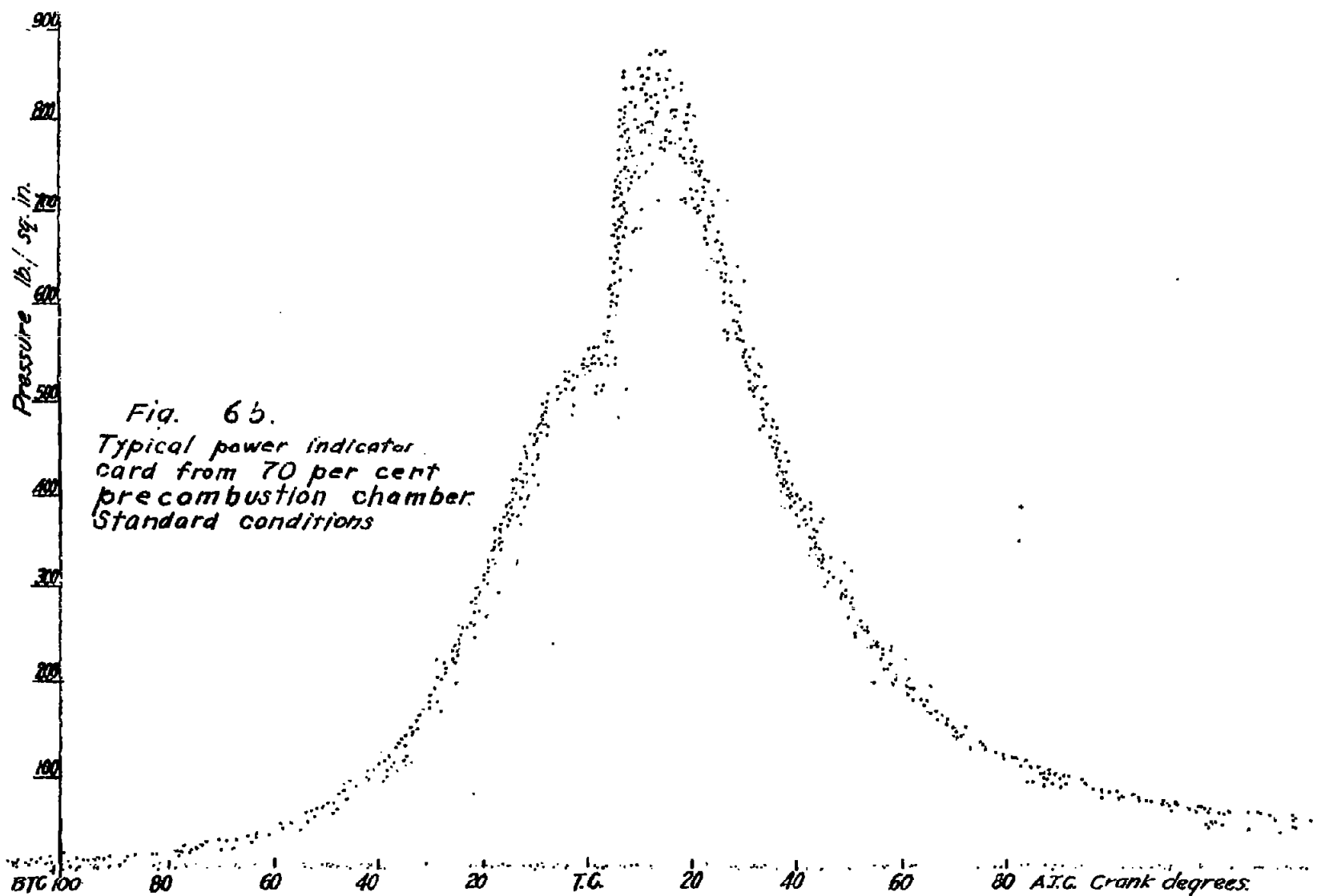
Fig. 6 b.
Typical power indicator
card from 70 per cent
precombustion chamber.
Standard conditions

Pressure lb./ sq. in.

900
800
700
600
500
400
300
200
100

BTC 100    80    60    40    20    T.C.    20    40    60    80 A.T.C. Crank degrees.

+ Total
△ Chamber cap and head          ⊙ Chamber cap
✕ Cylinder                      □ Head

Fig.7a  Effect of clearance distribution on heat loss to cooling water.
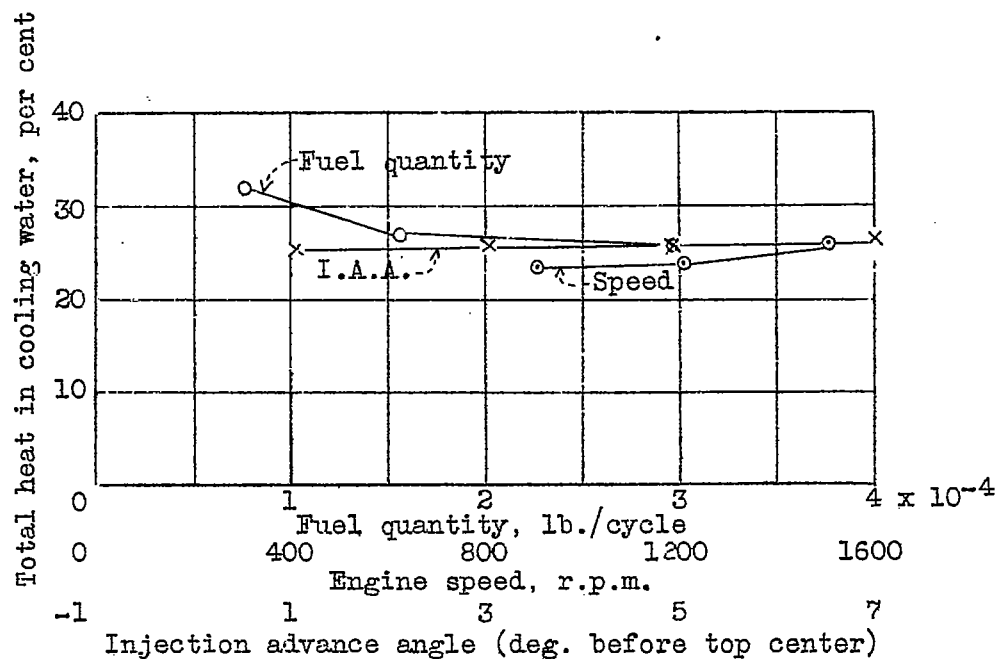
Fig.7b  Effect of operating conditions on heat loss to cooling water,
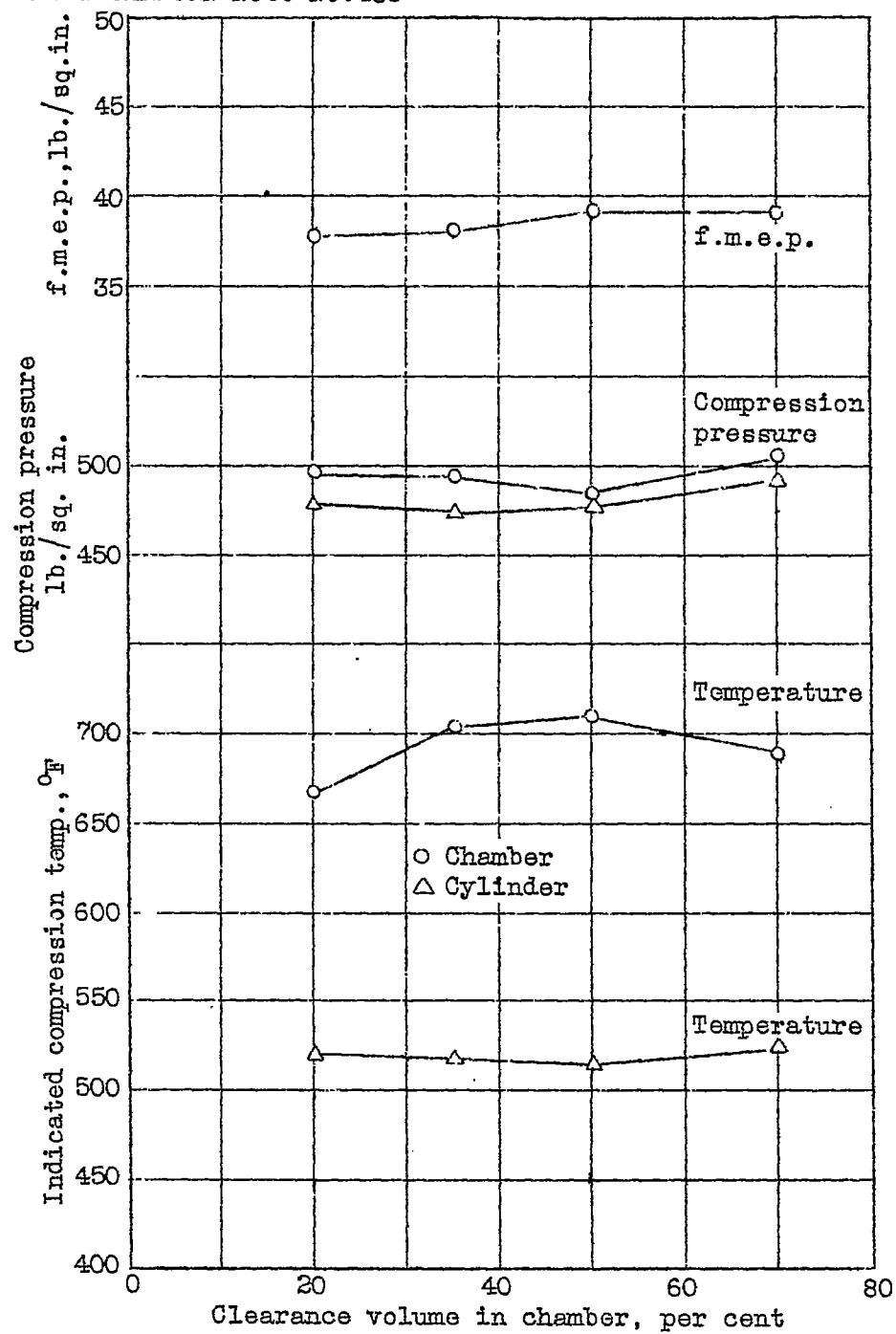        50 per cent chamber.

Fig.8



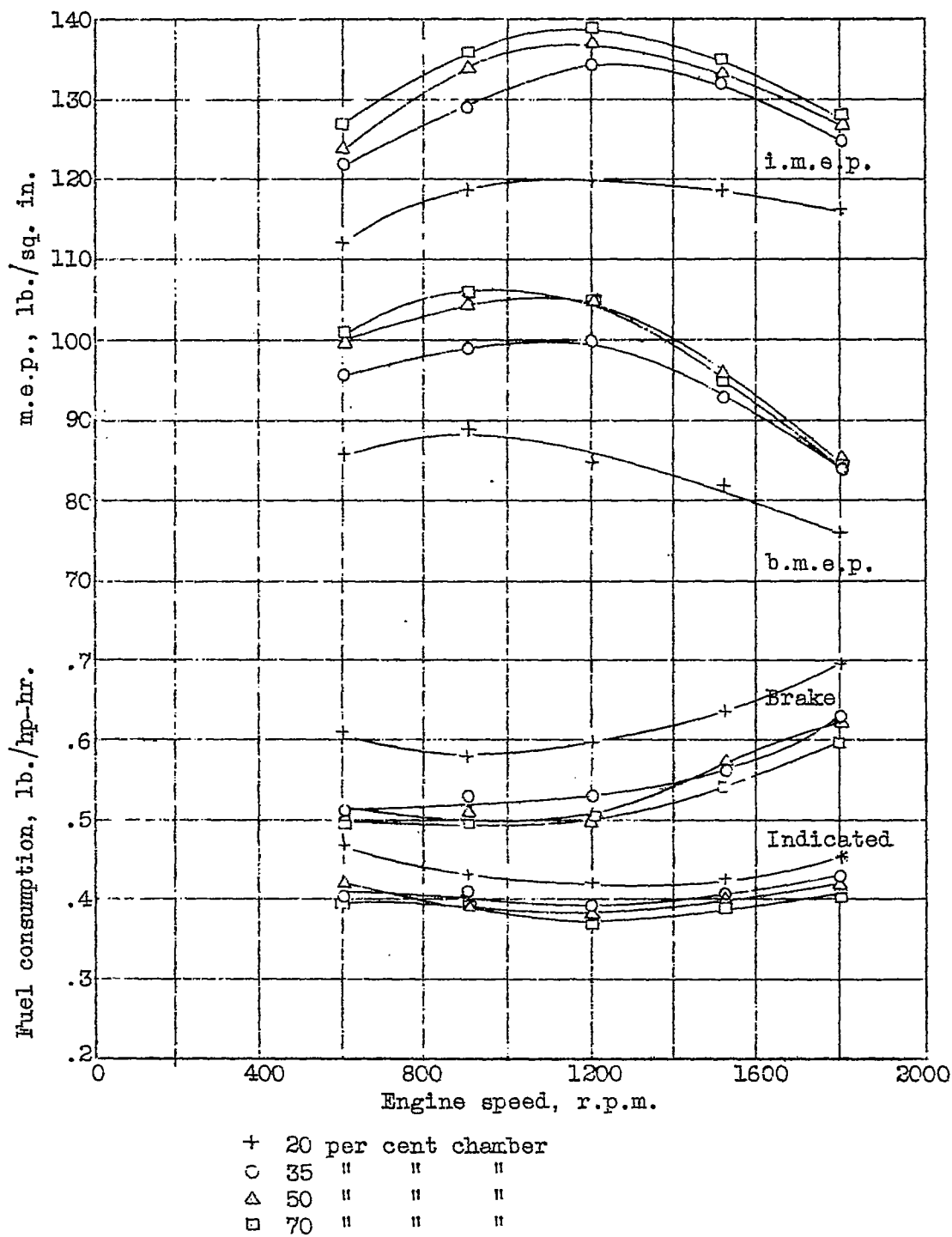Fig.8  Effect of clearance distribution on motoring characteristics.

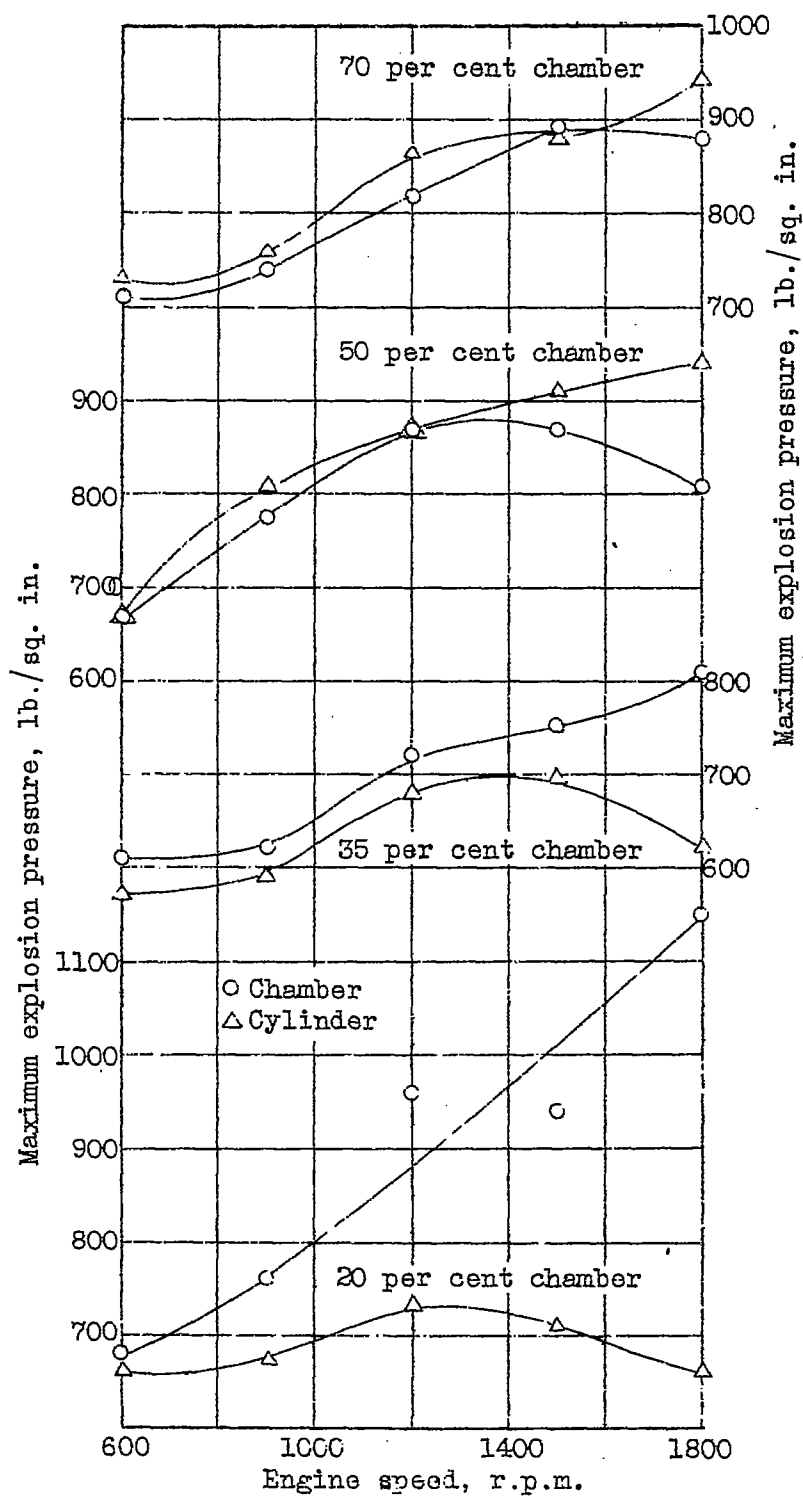Fig.9  Effect of speed on mean effective pressures and fuel consumption.

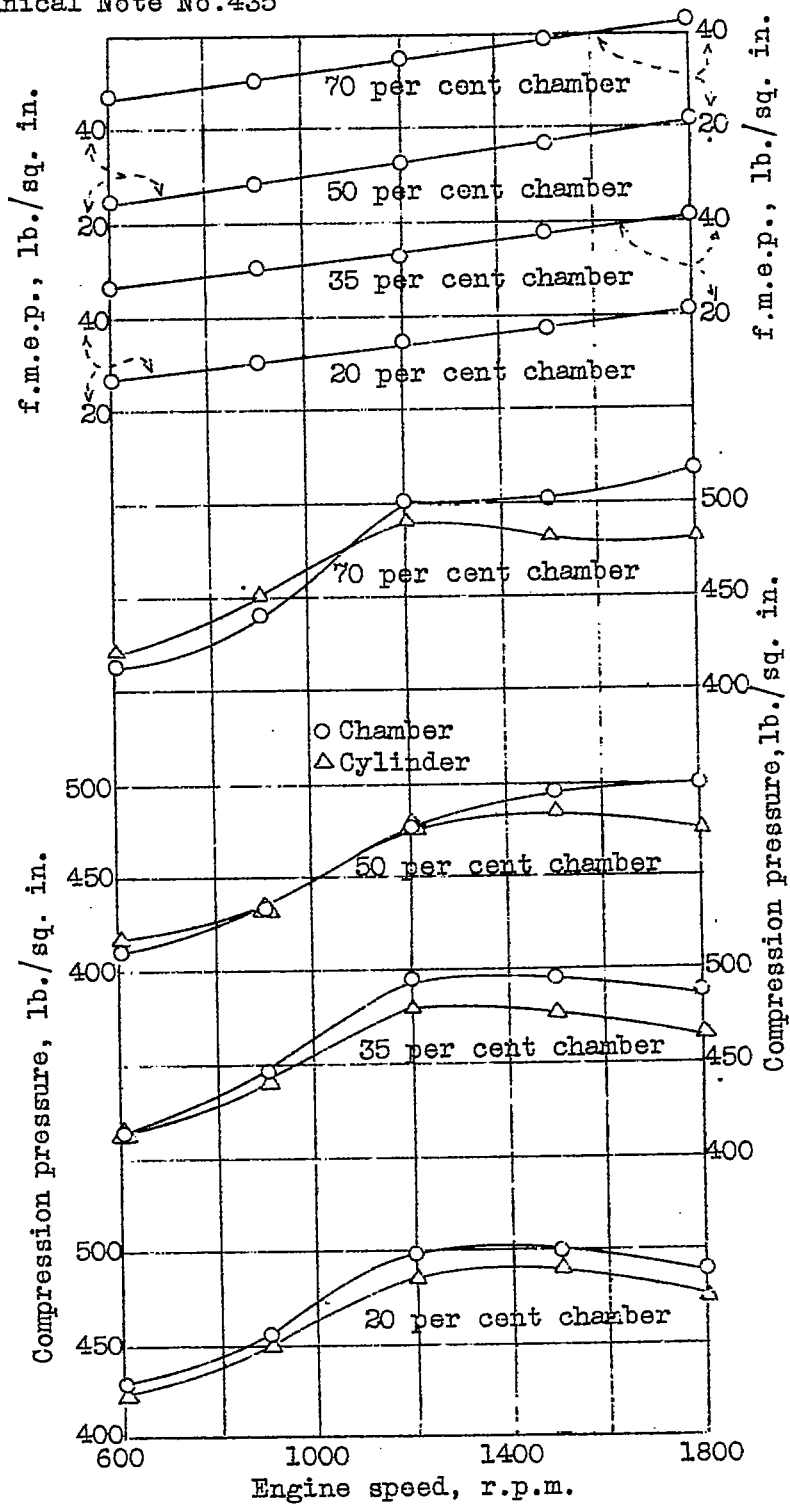Fig.10　Effect of speed on maximum explosion pressure.

Fig.11   Effect of speed on compression pressure and friction mean
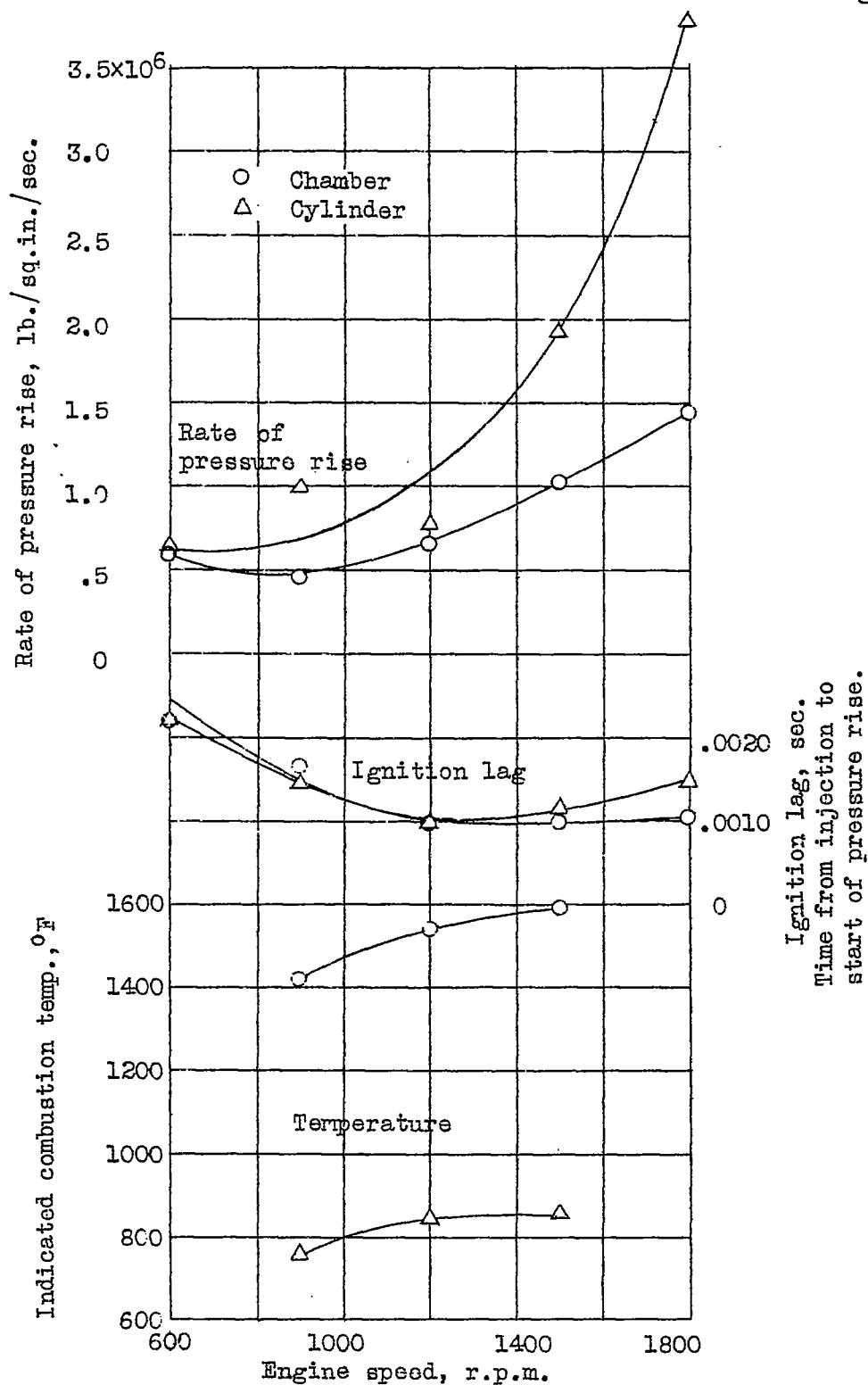         effective pressure.

Fig. 12  Effect of speed on combustion characteristics,
          50 per cent chamber.

Fig. 13.

Motoring double-indicator
card from chamber
and cylinder, 50 per
cent chamber, 1500 r.p.m.

Cylinder

Chamber

Pressure lb/sq.in.

500

400

300

200

100

B.T.C. 100    80    60    40    20    T.C.    20    40    60    80  A.T.C. Crank degrees

Fig. 13.