TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 485

A COMPARISON OF SEVERAL METHODS OF MEASURING IGNITION LAG

IN A COMPRESSION-IGNITION ENGINE

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Washington
January 1934

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SUMMARY

    The ignition lag of a fuel oil in the combustion cham-
ber of a high-speed compression-ignition engine was meas-
ured by three different methods. The start of injection
of the fuel as observed with a Stroborama was taken as the
start of the period of ignition lag in all cases. The end
of the period of ignition lag was determined by observa-
tion of the appearance of incandescence in the combustion
chamber, by inspection of a pressure-time card for evi-
dence of pressure rise, and by analysis of the indicator
card for evidence of the combustion of a small but defi-
nite quantity of fuel.

    A comparison of the values for ignition lags obtained
by these three methods indicates that the appearance of
incandescence is later than other evidences of the start
of combustion, that visual inspection of a pressure-time
diagram gives consistent and usable values with a minimum
requirement of time and/or apparatus, and that analysis of
the indicator card is not worth while for ignition lag
alone.

INTRODUCTION

    At the present stage of the development of the high-
speed compression-ignition engine considerable attention
is being given to methods of rating fuel oils as to their
suitability for use in such engines (references 1-5). It
is generally recognized that there is a definite connection
between the ignitibility of fuel oil and its satisfactory
operation in an engine. As a measure of ignitibility the
length of the period of delay between the injection and
the ignition of the fuel has been used, but no method as
yet devised for the measurement of this period can be con-
sidered as universally satisfactory and acceptable.

Ignition lag in a compression-ignition engine is most
satisfactorily defined as the interval between the start
of injection of fuel and the point at which the pressure
in the engine cylinder measurably exceeds the compression
or expansion pressure without ignition. Ignition lag may
thus be measured in time units or it may be more convenient-
ly expressed in degrees of crankshaft rotation.

The use of ignition lag as a measure of the ignitibil-
ity of a fuel requires that the limits of the period of ig-
nition lag be so defined that there will be no doubt as to
just what part of the operating cycle is included by this
term. There seems to be a general agreement that the pe-
riod of ignition lag begins with the entrance of the first
particle of fuel into the combustion chamber. The end
point of the period of ignition lag is determined by a va-
riety of methods depending upon the equipment available in
the laboratories where the work is done and, although
there is a lack of agreement in absolute values, there is
excellent similarity in comparative values.

Some of the devices used to determine the start of
the ignition lag are an electrical contact in the combus-
tion chamber closed by the impact of the entering fuel,
mechanisms which record the rise of pressure in the injec-
tion tube or the movement of the injection valve stem,
and stroboscopic apparatus that allows a visual determina-
tion of the start of the spray with respect to the posi-
tion of some part of the test engine, usually the flywheel.

The determination of the end of the period of igni-
tion lag depends upon the investigator's conception of
what constitutes effective ignition. At this laboratory
three methods have been used at different times to detect
effective ignition taking as evidence of the start of com-
bustion (a) the appearance of incandescence in the combus-
tion chamber, (b) the occurrence of perceptible combustion
pressures on an indicator card, and (c) the determination
of the effective combustion of a small but definite fuel
quantity by analysis of the indicator card.

Previous work at this laboratory had shown that at
fixed engine-operating conditions the time at which incan-
descence first appears in the combustion chamber of a com-
pression-ignition engine is quite definite and constant.
Most of the investigators of the self-ignition temperatures
of fuels agree that some combustion occurs before inflam-
mation, but investigators who use windows in combustion

chambers of spark-ignition engines find such a close rela-
tionship between the progress of the flame front and the
rise of pressure in the cylinder that inflammation is con-
sidered to be simultaneous with the start of combustion.
If this close relationship occurs also in the compression-
ignition engine the appearance of incandescence in the
combustion chamber may be used as evidence of ignition of
the fuel.

When the indicator card is used to detect the occur-
rence of effective ignition the determination depends upon
the accuracy and sensitivity of the pressure indicator.
Effective ignition is generally considered to occur at the
point where the pressure line with combustion diverges
from the pressure line without combustion and is commonly
designated "the breakaway point." The pressure line with-
out combustion, but with operating temperatures in the cyl-
inder, is different from the motoring pressure line with
comparatively low temperatures in the cylinder. A pres-
sure diagram with the higher cylinder temperatures but
without ignition at the usual place may be obtained by op-
erating the engine with retarded injection.

Gerrish and Voss (reference 6), by considering that
combustion starts when the pressure rise has shown that a
small but definite quantity of fuel has been burned, are
able to get consistent trends from the analysis of indica-
tor cards that would give inconsistent results if the com-
bustion were assumed to start at the last point where no
burning could be detected.

The series of engine tests reported herein were made
in the N.A.C.A. Laboratory at Langley Field, Va., during
March 1932, and were used for a comparison of the three
methods outlined above for the determination of the igni-
tion lag of a fuel oil in a compression-ignition engine.

APPARATUS AND TEST PROCEDURE

This investigation was made with a single-cylinder
test engine equipped with an N.A.C.A. cylinder head no. 4
having a vertical-disk form of combustion chamber. This
engine as equipped with the special apparatus for obtain-
ing the necessary data is shown in figure 1. The appara-
tus includes the disk stroboscope (A) suspended over the
engine and driven from the exhaust camshaft of the engine

by a flexible shaft (B), the Farnboro indicator pressure
element (C) connected by wire and tube to the recording
mechanism (not shown), a quartz glass window (D) with its
reflecting mirror (E), a Stroborama projector (F) for il-
luminating the index (G) painted on the engine flywheel
and pointing to a scale (H) graduated in degrees of crank-
shaft rotation. Figure 2 shows the method by which it was
possible to observe simultaneously the incandescence in
the engine cylinder and the position of the flywheel as
illuminated by the flash of the Stroborama.

The engine-operating conditions are listed in table
I. For the tests with variable injection advance angle
the same pump control settings were used and the varia-
tion in fuel quantity with change of injection advance an-
gle was too small to affect the data as used. Pressure-
time diagrams were taken with the Farnboro indicator as
modified at this laboratory, photographic prints of the
records being used for the analysis. The recording drum
was rotated at crankshaft speed.

The start of fuel injection was determined by observ-
ing the first appearance of fuel at the tip of the injec-
tion valve nozzle by means of the Stroborama and the tim-
ing was fixed by simultaneously noting the flywheel posi-
tion. This observation was made while injecting the fuel
into the atmosphere, as previous injecting into a pres-
sure chamber had shown no variation in timing with the
density rising to 1.5 pounds per cubic foot. This deter-
mination could be reproduced within one half crankshaft
degree.

Some preliminary tests were made to determine the best
technic for obtaining the reading of the first appearance
of incandescence. After the engine had reached stabilized
operating temperatures, it was stopped and the quartz win-
dow was inserted as quickly as possible. Engine operation
was immediately resumed and the observer brought the first
part of the incandescent period into phase with the open-
ing of the slot in the stroboscope. The Stroborama flash
was synchronized with the first appearance of incandes-
cence by remote control and the position of the flywheel
noted. Any one observer could repeat observations within
1°.

Tests were made to determine whether the field of
view from the small window was so restricted that inflam-
mation might occur in any portion of the chamber and not
be visible. A fuel quantity that reduced the scale load-

ing from 22 to 21 pounds while motoring the engine was suf-
ficient to produce an unmistakable flash lasting about 35
crankshaft degrees. This fuel quantity, estimated to be
0.000005 pound per cycle, air-fuel ratio about 1,000,
should theoretically reach enough air to burn completely
within 1-1/4 inches of the nozzle. Apparently any fuel
quantity that would operate the engine would produce suf-
ficient incandescence for these tests.

Tests with increasing fuel quantity at a constant in-
jection advance angle showed that the start of incandes-
cence was well defined and constant at fuel quantities be-
tween 0.00014 and 0.00019 pound per cycle. Below this
range there was slightly more variation in the start of
incandescence and above it the window had to be cleaned
too frequently. The window could be used for more than
20 minutes at a fuel quantity of 0.00015 pound per cycle
without introducing an error due to the sooting of the
window. The absence of change in the time of the appear-
ance of incandescence over a wide range of fuel quantity
per cycle is an indication that the observation is not ma-
terially affected by the spatial distribution of the flame
and that the position of the window does not prevent the
observer from detecting incandescence in parts of the com-
bustion chamber not directly in the field of view through
the window.

The data were then procured for the comparison of the
three methods of measuring ignition lag. A fuel quantity
of approximately 0.00015 pound per cycle (air-fuel ratio
about 32) was used and the injection advance angles were
varied in 2° intervals from 16° B.T.C. to 6° A.T.C. In-
dicator cards were taken and the first appearance of in-
candescence recorded for each injection advance angle.
The pressure-time curves are shown combined in figure 3
with the start of incandescence marked on each curve. An
analysis of these curves for effective fuel burned gives
the series of curves shown in figure 4. The high-pressure
sections of four of the indicator cards are shown in fig-
ure 5. These data are considered well suited for a com-
parison of the different methods on account of the short
ignition lag and the comparatively large effect of any
variation or errors in measurement.

RESULTS AND DISCUSSION

The ignition lags as obtained from the data are listed in table II. The columns 2 to 6, inclusive, are the individual determinations by visual inspection of the indicator card of five engineers experienced in engine testing. The seventh column is an average of the five values for each injection advance angle. The eighth column lists the ignition lags obtained when the first appearance of incandescence is considered as marking the start of combustion. The last column shows the values obtained by considering that combustion has started when a small but definite amount of fuel has been effective in raising the pressure in the cylinder. No two series of values were determined by the same person. It should be noted that the ignition lags as determined by any of these methods remain virtually constant over the normal operating range and increase at both ends of this range so that the ignition lag both decreases and increases with increase in injection advance angle.

At the time this work was started it was hoped that the first appearance of incandescence would fix a comparatively definite point that would show the start of combustion in the engine cylinder, but after preliminary observations it was realized that the appearance of the visible flame is a comparatively gradual process. The time of appearance of incandescence in the combustion chamber was surprisingly late because in all cases it occurred after the pressure-time record had shown a definite pressure rise (fig. 3). Therefore, it is obvious that the appearance of incandescence is of little value in establishing the start of combustion in a compression-ignition engine because it occurs later than other evidences of the start of combustion. However, the values of the ignition lag obtained by using the appearance of incandescence as the starting point of combustion follow the same trend as the values obtained by using the start of pressure rise but with a smaller variation.

The method of measuring ignition lag by using the breakaway point or start of pressure rise as the termination of the period of lag is open to the objection that the determination may not be reproduced by different observers. A measure of the consistency in determining the breakaway point may be obtained by comparing the individual determination of the five observers with the average

of their determinations. Of the 60 values listed in table
II, 22 agree with the average, 18 are within $1/2^o$, and 16
are within 1°, leaving only 4 in excess of 1°. Two thirds
of the total determinations are within a range of 1 crank-
shaft degree and practically all are within $\pm 1^o$. Thus, it
appears that this method is sufficiently accurate and con-
sistent to give good comparative values but not necessa-
rily exact values for ignition lag. The values obtained
by this method show a greater variation than the values ob-
tained by either of the other methods.

The values for ignition lag obtained by considering
combustion as starting when a small but definite quantity
of fuel has been burned are possibly more definite than
values obtained by other methods, but in this case they
are lacking in contrast as ten consecutive values cover a
range of only 1° and therefore indicate that the ignition
lag remains virtually constant over a range of 20° of in-
jection advance angle.

A comparison of the three sets of values for ignition
lag indicates that the values obtained from direct inspec-
tion of the indicator card by experienced observers are
consistent and have the advantage of requiring no extra
apparatus and a minimum of time. The appearance of incan-
descence in the combustion chamber of a compression-igni-
tion engine is of doubtful value for determining when com-
bustion starts. The ignition lags obtained from analyses
of the indicator cards were apparently not of sufficient
value to justify the expenditure of time required by this
method. These results indicate that it will be quite dif-
ficult to have agreement in values for ignition lag be-
tween different laboratories or even between different
experimenters until apparatus and methods are standardized.

Langley Memorial Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., November 14, 1933.

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TABLE I

Test Apparatus

Engine	N.A.C.A. Universal test engine
Cylinder head	" No. 4
Fuel injection pump	" No. 7
Fuel injection valve	" No. 13

Engine Operating Conditions

Engine speed	1,500 r.p.m.
Full load fuel quantity	0.000325 lb./cycle
Fuel quantity used in tests	0.00015 "
Injection period used in tests	12° (crank)
Injection advance angle	Variable
Injection nozzle type	6 orifices in single plane
Fuel valve position	Top hole of cylinder head
Valve-opening pressure	3,000 lb./sq.in.
Compression ratio	15
Temperature cooling water (out)	170° F.
Temperature lubricating oil (out)	140° F.
Temperature fuel oil	85° F.
Temperature inlet air	65° F.
Barometer	30.26 in.Hg
Engine valve timing	$\left\{ \begin{array}{l} \text{Inlet : opens } 38^{\circ} \text{ B.T.C.} \\ \text{closes } 27^{\circ} \text{ A.B.C.} \\ \text{Exhaust: opens } 36^{\circ} \text{ B.B.C.} \\ \text{closes } 25^{\circ} \text{ A.T.C.} \end{array} \right.$

TABLE II

Ignition Lag

(All values given in degrees of crankshaft rotation
at 1,500 r.p.m. For time values multiply by 0.000111 sec.)

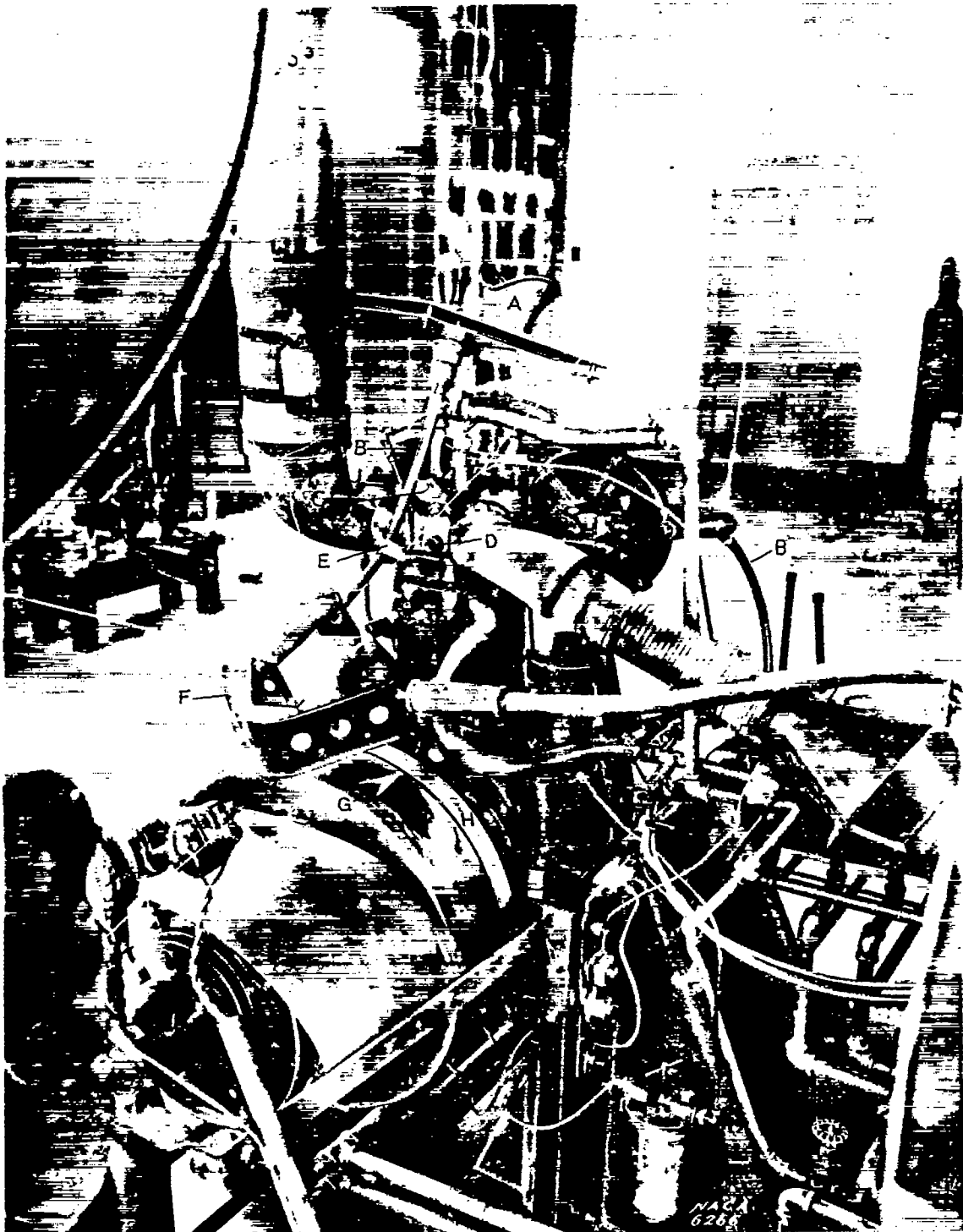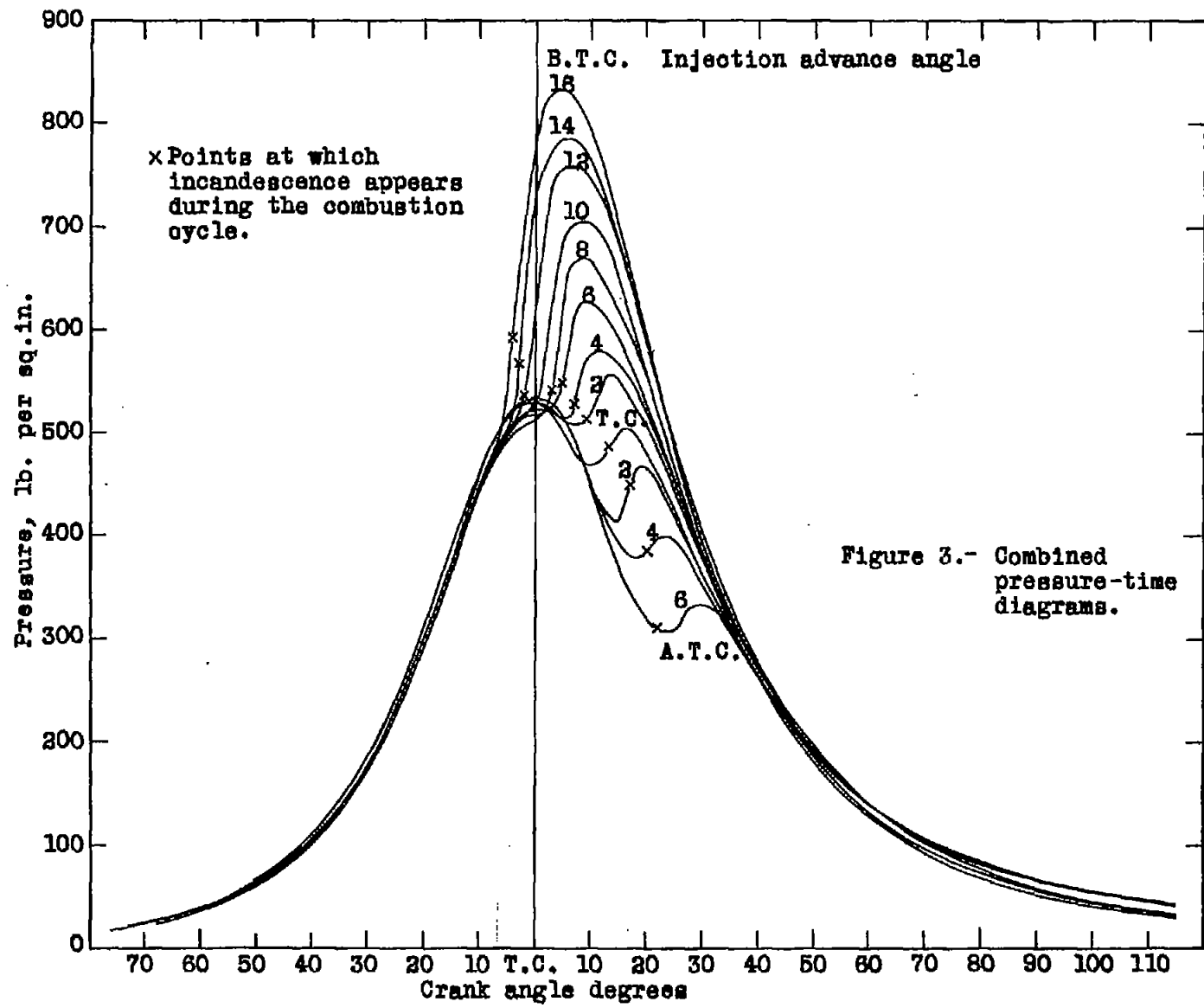| Injection advance angle	Direct observation of card Observers						Start of incan-descence	Card anal. Fuel quan. 4×10^{-6} lb.
	A	B	C	D	E	average		
A.T.C. 6	16	15	15	14	13	14+	16+	12.4
4	13	12	11	12	12	12	16	10.2
2	10	12	11	11	12	11	15+	10.5
T.C.	8+	8	7	9	8	8	13	9.7
B.T.C. 2	7	8	8	8	7	7+	11	9.7
4	8	8	7	9	8	8	11	9.9
6	8	7	7	7	6	7	11	10.1
8	8	8	8	7	7	7+	11	10.6
10	9	9	10	7+	7	8+	10	10.5
12	9	8+	9	8	9+	9	10	10.3
14	10	9	10	9	9	9	11	10.4
16	10	10	9	10	10	10	12	-

Figure 1.- Test engine with auxiliary apparatus.
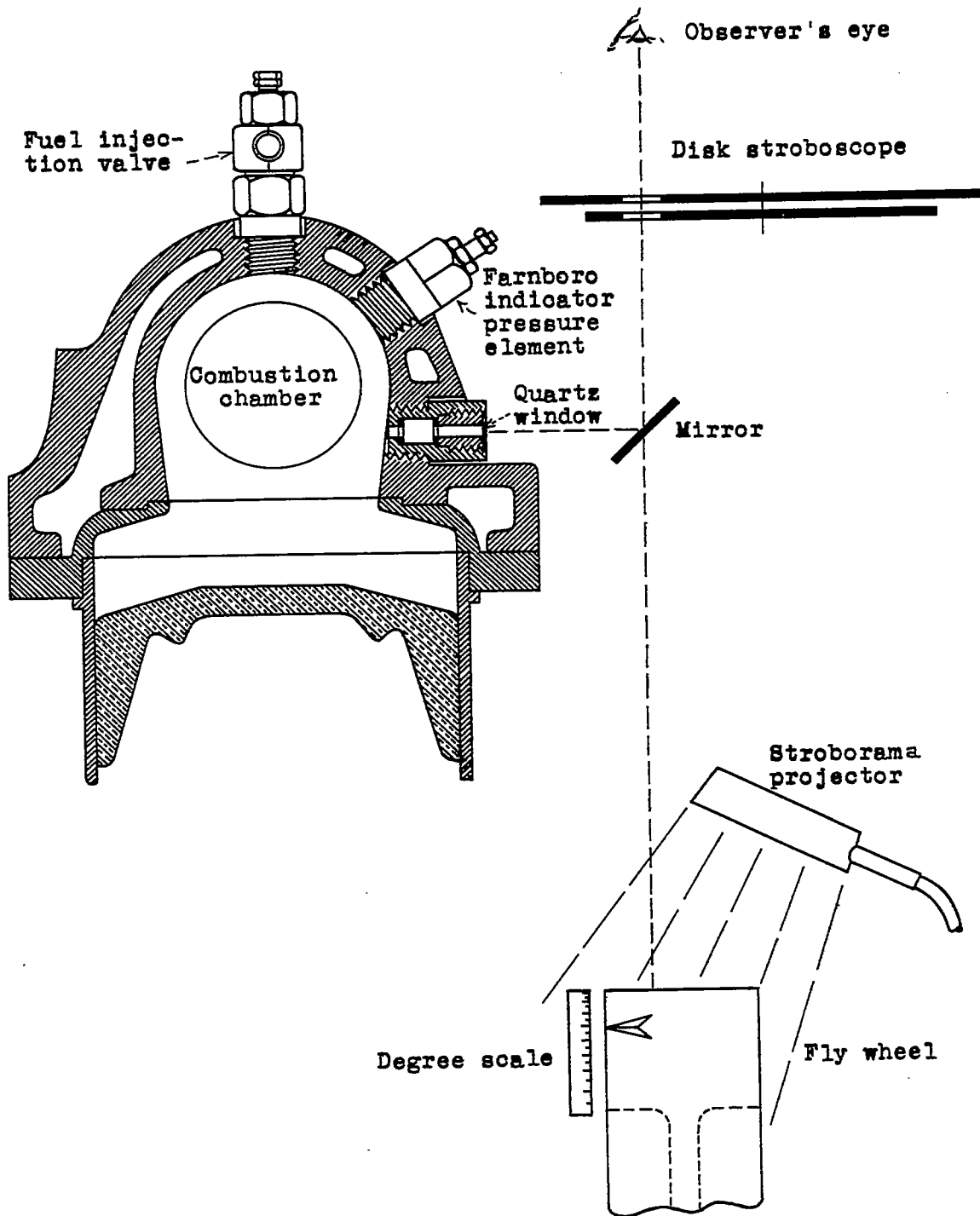
Figure 2.- Schematic diagram of relative positions of observer
and apparatus when making simultaneous observations.

Figure 3.- Combined pressure-time diagrams.

×Points at which incandescence appears during the combustion cycle.

B.T.C.   Injection advance angle

Fig. 3

+ Points at which incandescence appears during the combustion cycle.
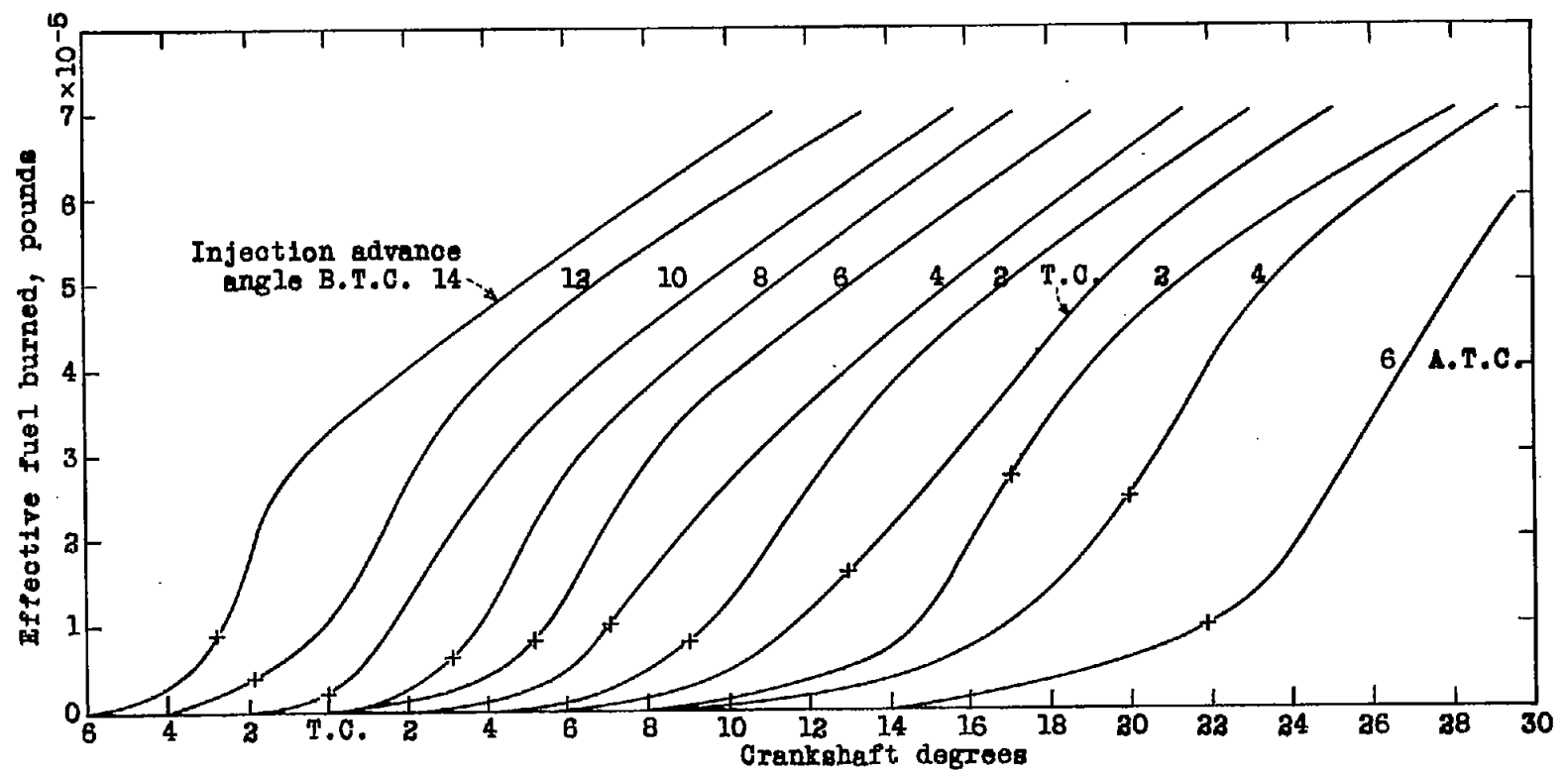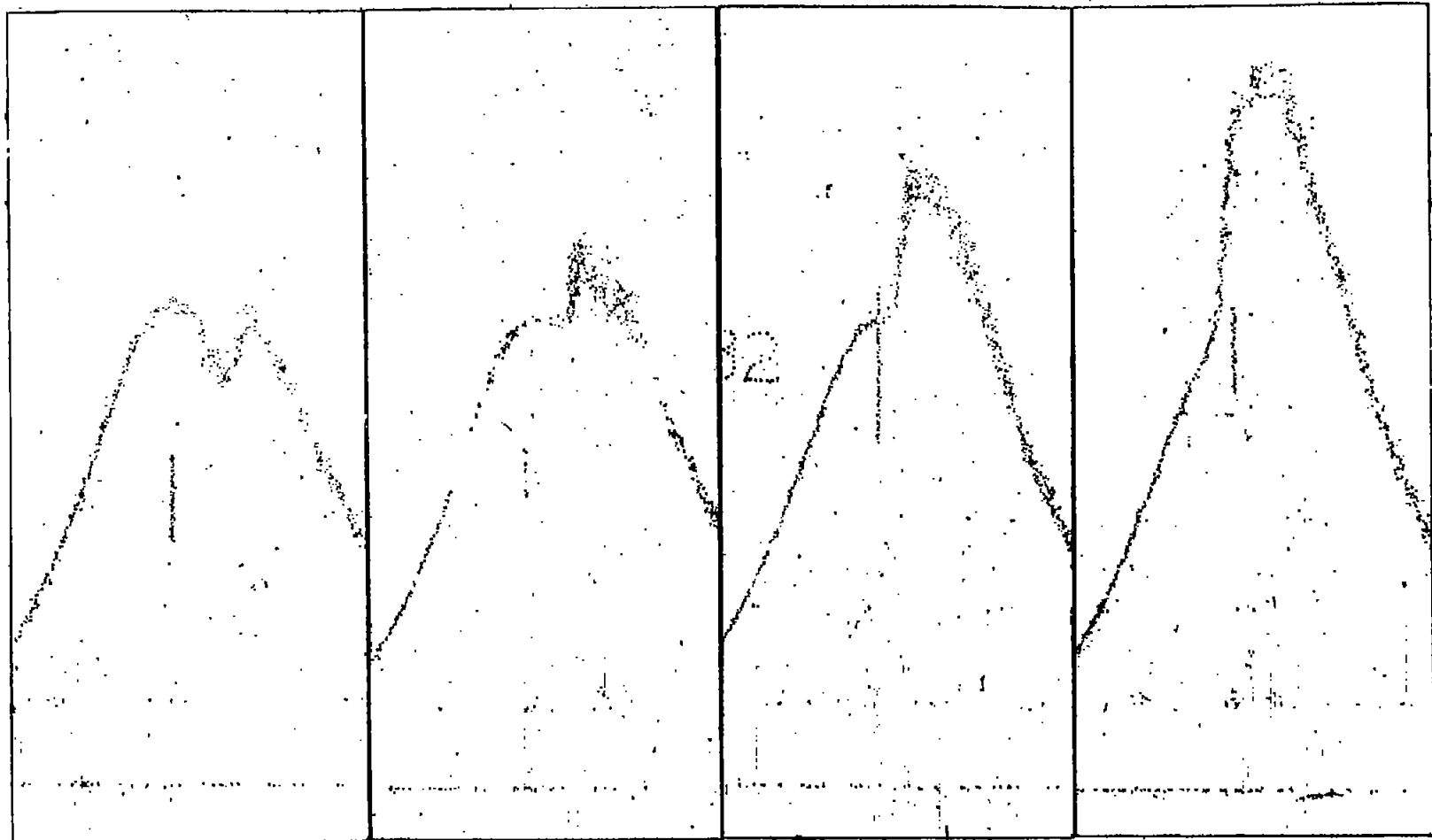

Figure 4.- Combined curves of effective fuel burned as determined by analysis of indicator cards.

Fig. 4

I.A.A.:-   T.C.   4° B.T.C.   8° B.T.C.   14° B.T.C.

Figure 5.-Typical pressure-time records × $\frac{3}{4}$.
Vertical line marks top center.

Fig. 5