# REPORT No. 785

## PREKNOCK VIBRATIONS IN A SPARK-IGNITION ENGINE CYLINDER AS REVEALED BY HIGH-SPEED PHOTOGRAPHY

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### SUMMARY

*The high-speed photographic investigation of the mechanics of spark-ignition engine knock recorded in three previous reports has been extended with use of the NACA high-speed camera and combustion apparatus with a piezoelectric pressure pickup in the combustion chamber. The motion pictures of knocking combustion were taken at the rate of 40,000 frames per second.*

*Existence of the preknock vibrations in the engine cylinder suggested in Report No. 727 has been definitely proved and the vibrations have been analyzed both in the high-speed motion pictures and the pressure traces. Data are also included to show that the preknock vibrations do not progressively build up to cause knock. The effect of tetraethyl lead on the preknock vibrations has been studied and results of the tests are presented.*

*Photographs are presented which in some cases clearly show evidence of autoignition in the end zone a considerable length of time before knock occurs.*

### INTRODUCTION

The NACA high-speed camera, development of which was completed late in 1938, has been used since then in the study of combustion in the cylinder of a spark-ignition engine. This camera takes photographs at the rate of 40,000 frames per second. Since the early part of 1939 the camera has been used principally in the study of the details of the knocking reaction.

Results of the studies of knock with the NACA high-speed camera have been presented in references 1, 2, and 3. When the earliest photographs of knocking combustion were projected as motion pictures, an extremely violent explosion was observed in the vicinity of the end zone, that is, in the vicinity of the last portion of the charge to be ignited by the flame fronts. This explosion took place in a period of only 25 to 100 microseconds. When the photographs of knocking combustion were examined frame by frame, as prints on photographic paper, the first frame involved in the explosion was found to have a characteristic blurred appearance within some portion of its area. This characteristic blur was shown in reference 3 to coincide in time with the beginning of the violent pressure fluctuations on the pressure-time record. These fluctuations have long been recognized as being associated with knock. The blur has consequently been regarded by the authors as the first indication of knock to be seen in the photographs.

In references 1, 2, and 3 it has been shown that, at least in some cases, a reaction having the appearance of autoignition takes place in the end zone an appreciable time before knock occurs. This preknock end-zone reaction precedes knock by a much smaller time interval than the preknock end-zone reaction found by Withrow and Rassweiler (reference 4) and is therefore either a different reaction or a later and accelerated stage of the same reaction. In some cases the preknock end-zone reaction shown in references 1, 2, and 3 caused the end zone to become indistinguishable in the photographs from regions through which flame fronts had already passed. (See frame M–10, fig. 5, reference 1, or frame G–11, fig. 7, reference 2.) In reference 3, prints of a motion picture are presented in which the first visible knocking blur and the last visible end zone are at different locations in the combustion chamber. These facts led Miller and Olsen (reference 3) to conclude that knock apparently originates only within a portion of the charge that has already been ignited, the ignition having been caused either by autoignition or by passage of the flame front.

In reference 2 Miller concluded, from a study of pressure-time records obtained with the NACA optical indicator and the NACA combustion apparatus, that pressure waves of small amplitude occurred in the combustion chamber in some cases before the knocking reaction occurred. He suggested that these preknock pressure waves might be progressively built up by some reaction which was accelerated in the high-pressure regions and decelerated in the low-pressure regions of the waves and that the rate of this same reaction might eventually reach such a magnitude as to result in knock. Draper (reference 5) had previously reported the existence of pressure waves in the cylinder charge before knock became audible.

The object of the investigation reported herein is to clarify and supplement, as far as possible, the information previously obtained from high-speed photographs and pressure-time records concerning preknock reactions.

For a further study of the preknock vibrations mentioned in reference 2, it was desirable to find a method of measuring the effect of the vibrations on the travel of the flame fronts as seen in the high-speed photographs. The method consisted in carefully measuring the flame areas and the end-zone areas on each frame of the high-speed motion pictures and plotting the results in such a manner as to show the effect of the preknock vibrations on flame-front positions. The validity of the results, of course, must depend entirely on the correctness of the conclusion that the characteristic knocking blur in the high-speed photographs coincides in time with the beginning of violent pressure fluctuations on the pressure-time record, as shown in reference 3.

In addition to the investigation of the preknock vibrations, attempts were made to find fuels, or fuels with additives, which under suitable engine operating conditions would produce a more definite appearance of autoignition in the high-speed photographs than has been previously shown.

The data were obtained in 1942 and 1943 at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., and at the Aircraft Engine Research Laboratory at Cleveland, Ohio.

## APPARATUS AND PROCEDURE

**Combustion apparatus.**—All photographs included in this report were taken with the NACA high-speed camera in conjunction with the NACA combustion apparatus and auxiliary equipment. Design details of the NACA high-speed camera, which takes photographs at the rate of 40,000 per second, have not yet been released. The combustion apparatus is an engine of 5-inch bore and 7-inch stroke, driven at test speed by a direct-connected electric motor. Principal design features include: four-stroke cycle, fuel injection, spark ignition, overhead valves, pent-roof piston, and a glass window in the combustion chamber. A diagrammatic sketch of the apparatus is given in figure 1.

**Engine operating conditions.**—As in previous projects using the combustion apparatus, the engine was fired for only one cycle in every run and was driven by the electric motor the rest of the time. Complete data for the run were obtained during this single power cycle. For all the pictures taken during the present investigation, the fuel-injection valve was placed in opening H in the cylinder head. (See fig. 1.) For pictures showing combustion of the charge with four spark plugs, the plugs were placed in openings J, F, G, and E. The plug at J was omitted for runs using only three plugs; for pictures using only one spark plug, the plug in opening G was used.

During the entire investigation, the following engine conditions were held constant:

| | |
|---|---|
| Compression ratio | 7.1 |
| Jacket and head temperature, °F | 250 |
| Fuel-injection timing, intake stroke, degrees A. T. C. | 20 |
| Spark timing, degrees B. T. C.: | |
| At G | 27 |
| At E, At J, At F | 20 |
| Fuel-air ratio | Approximately 0.08 |
| Inlet-air conditions | Atmospheric |
| Engine speed, rpm | 550 |

Spark timings of 27° and 20° B. T. C. were selected in order that knock would occur at top center where it could be best photographed and in order that the knocking zone would be well within the field of view.

Fuels and additives used during the present investigation included:

M-2 or M-3 fuel
M-2 or M-3 fuel with tetraethyl lead
S-1 or S-2 fuel with amyl nitrate

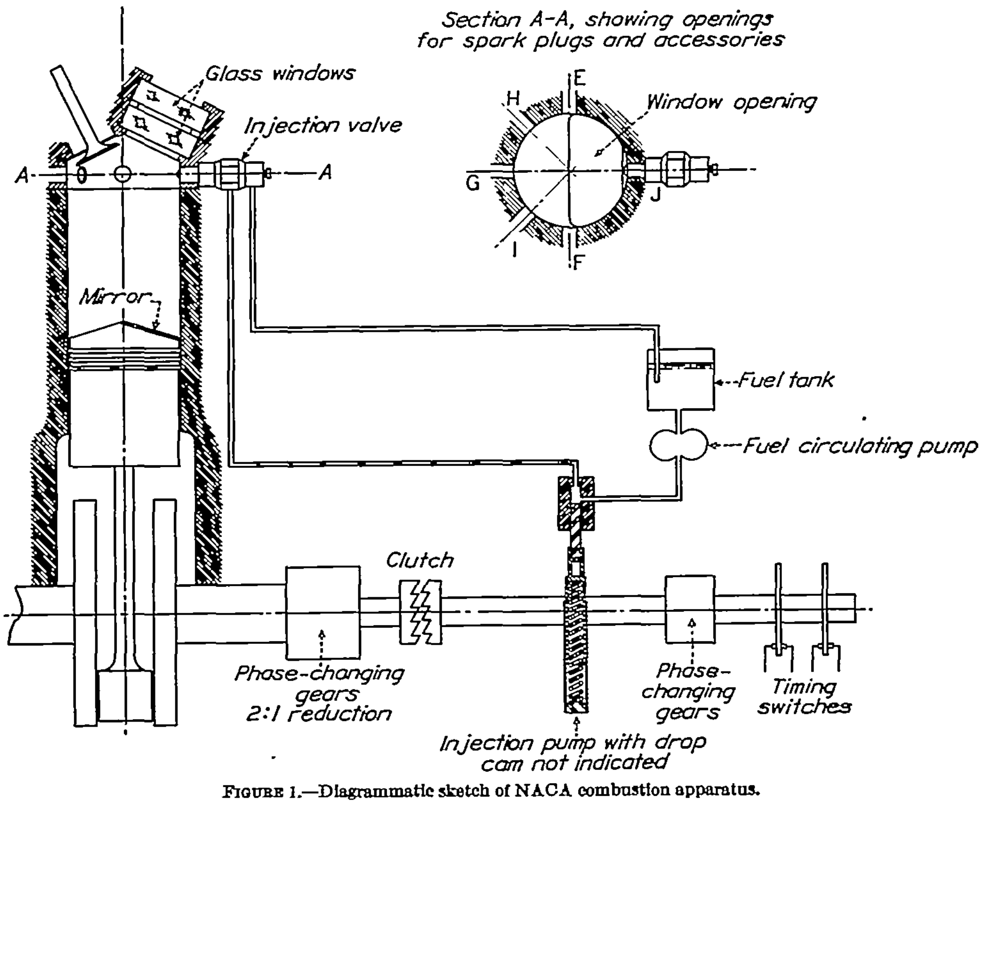



FIGURE 1.—Diagrammatic sketch of NACA combustion apparatus.

**Optical arrangements for taking high-speed pictures.**—The optical setup for taking schlieren photographs of combustion with the NACA high-speed camera is explained in detail in reference 1.

**Pressure-time records.**—Pressure-time records for the combustion cycles were taken with a piezoelectric quartz crystal pickup placed in opening I (see fig. 1) in the cylinder head. The pickup was coupled to the vertical input of a 9-inch cathode-ray oscillograph through a suitable amplifier and the oscillograph sweep circuit was synchronized with the engine crankshaft. The resulting pressure-time trace on the oscillograph screen was photographed with a 5- by 7-inch plate camera. In order to avoid the necessity of timing and synchronizing the camera shutter, the oscillograph was so arranged that the trace would be visible only during the single combustion cycle of the engine. The single visible oscillograph sweep was obtained by arranging a contactor on the engine to trip a brilliancy-control switch at the start of the firing cycle. With this arrangement, it was possible to open the shutter on the plate camera before beginning a run, fire the engine, and then close the shutter as soon as practicable.

## METHOD OF ANALYSIS

**Measurement of flame areas.**—Figure 2 is a series of photographs of combustion with heavy knock. The fuel used with this series was M-2 reference fuel with an extremely high concentration of tetraethyl lead, 200 ml TEL per gallon of fuel. The order of reading the photographs is through the top row from left to right, then through the second row from left to right, and so on. The picture-taking order is A-1, A-2, A-3, . . . A-20, A-21, B-1, B-2, . . . H-20, H-21.

Four spark plugs were used in the combustion cycle of figure 2. As in the figures of references 1, 2, and 3, the flames are visible as dark mottled regions. The flame from the spark plug in G position (see fig. 1) is just beginning to come into view in frame A-11 of figure 2. The flame from the spark plug in E position begins to be visible at about frame B-13. The flame from J position appears at about frame C-2. The flame from F position never becomes visible as an independent flame in figure 2. Knock first appears as a blurring of the part of the field indicated by the letter B in frame G-7.

The series of photographs shown in figure 2 was analyzed with the object of revealing preknock vibrations; the analysis was made by carefully measuring certain areas of each frame with a polar planimeter. In order to make these measurements, an image of each frame was projected onto a white sheet of paper from the original negative. This image was enlarged above the size appearing on the negative until the image was approximately one and one-half times the actual

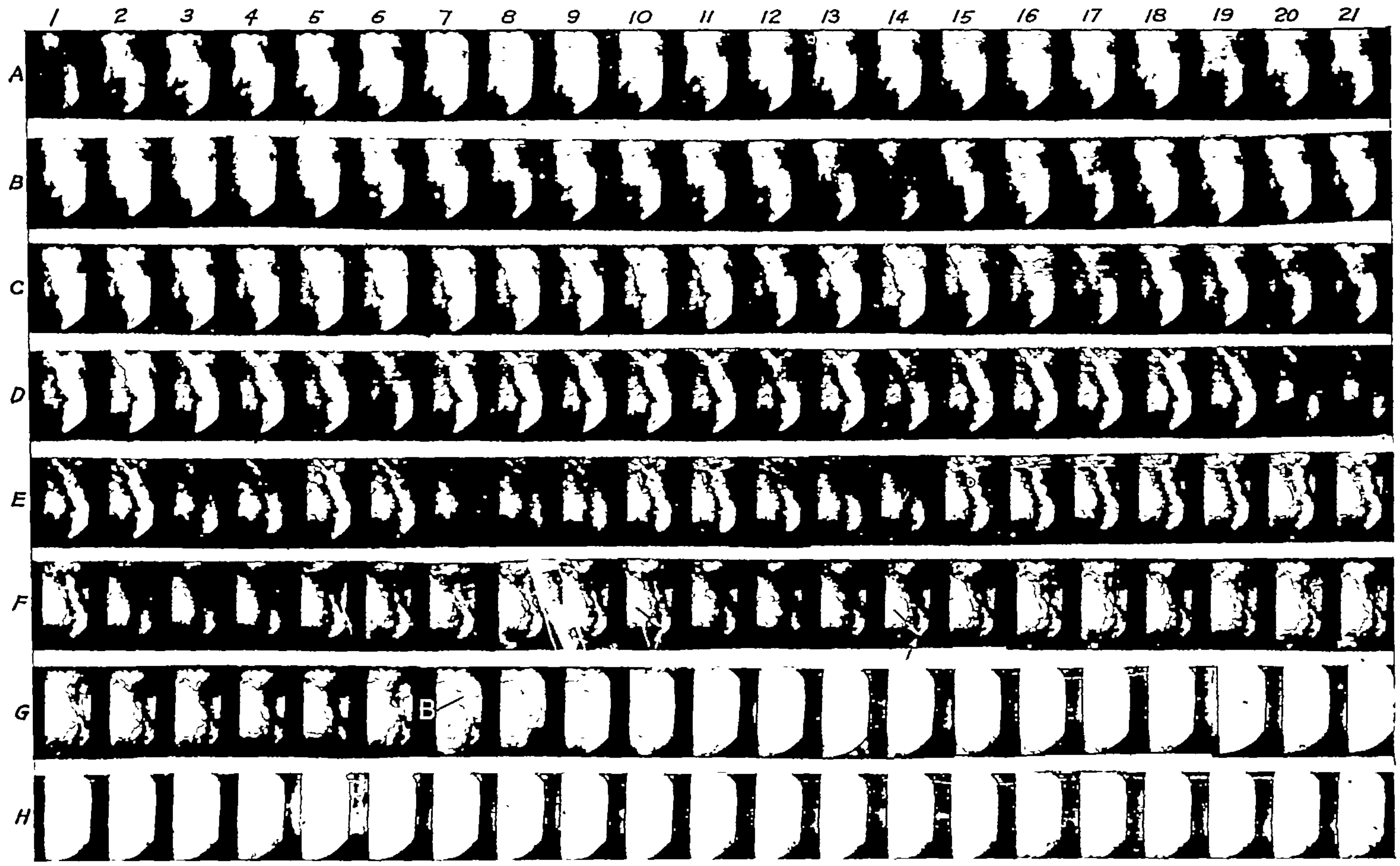
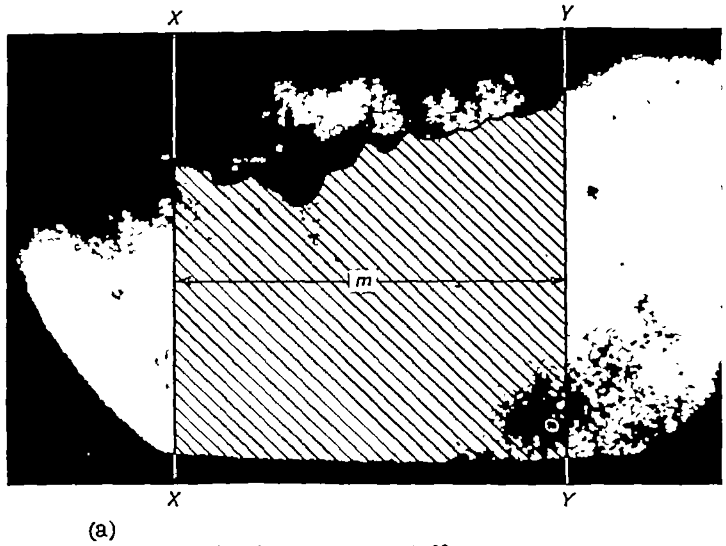


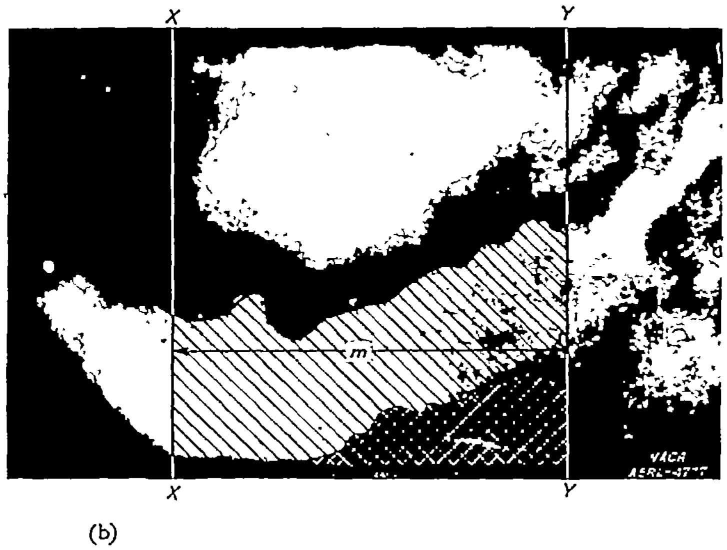

FIGURE 2.—High-speed motion pictures of vibratory combustion cycle in an engine cylinder. M-2 fuel plus 200 ml TEL per gallon. B, blurring caused by knock. (See fig. 4 (a).)

size of the corresponding portion of the combustion chamber in the engine. The outline of each individual frame was then traced on the paper as well as the outline of each flame front visible in the image.

Two of the enlarged images from figure 2 are reproduced in figure 3. Figure 3 (a) is the enlargement of frame B–20 from figure 2; figure 3 (b) is the enlargement of frame E–5.




(a) Enlargement of frame B-20, figure 2.




(b) Enlargement of frame E-5, figure 2.

FIGURE 3.—Diagram showing areas to be measured in computing mean flame-front velocities for combustion cycle shown in figure 2.

After the frame outlines and flame-front outlines were traced, two parallel lines were drawn across each frame, lines X–X and Y–Y in figures 3 (a) and 3 (b). For the different frames these lines were drawn as nearly as possible in the same positions relative to the frame outline. The positions of the lines were arbitrarily selected for each photographic series in such a manner that each line would pass through some part of the end zone in the few frames just preceding knock. For this purpose, "end zone" is defined as the area not yet passed through by flame fronts as seen in the photographs. Selection in this manner of the parallel lines X–X and Y–Y permitted an exact definition of areas to be measured with the planimeter from the first frame of the photographic series almost to the frame in which knock became visible.

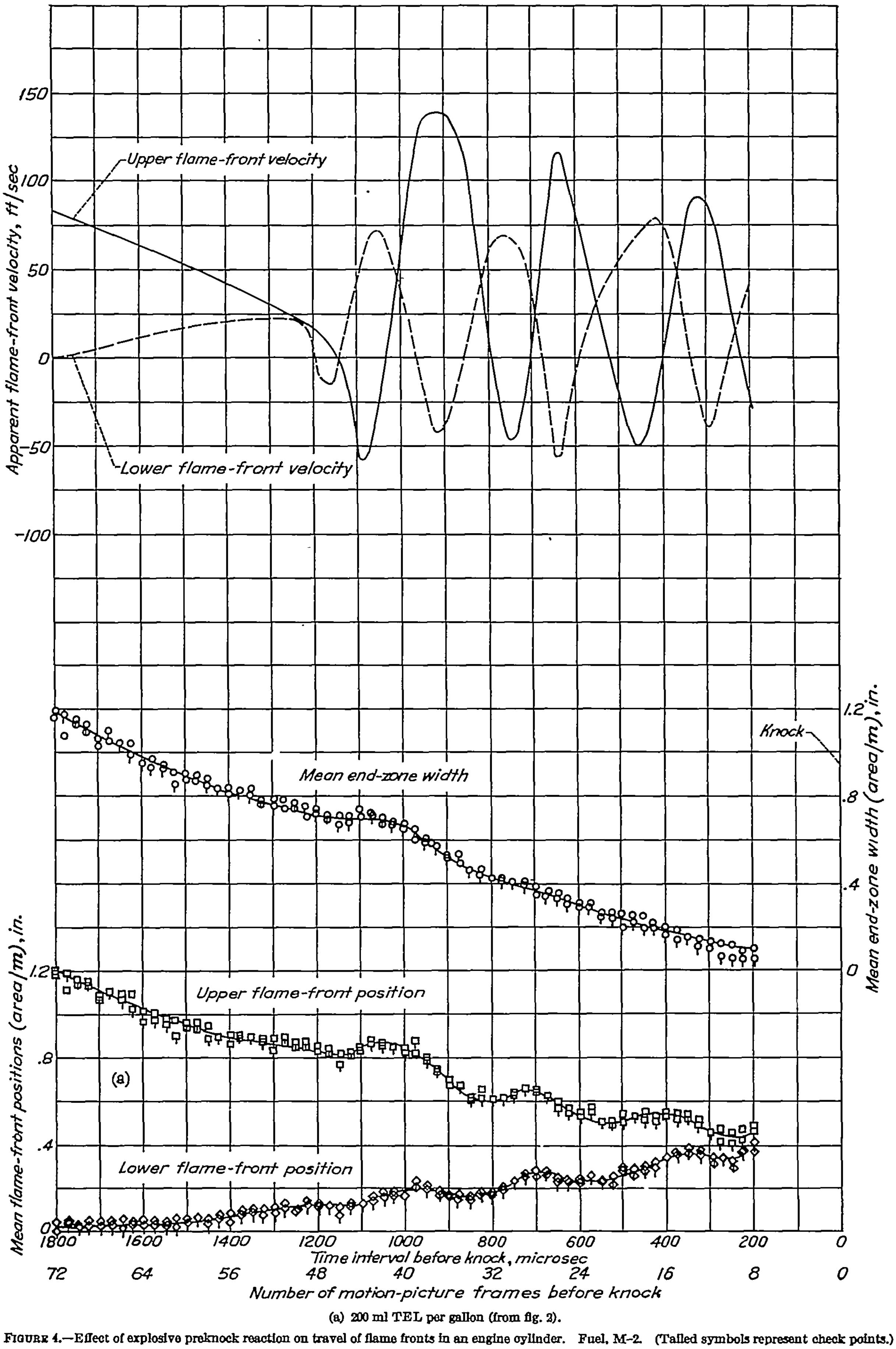
The shaded area in figure 3 (a) was measured. This area may be defined as all that portion of the area of the frame located under the upper flame front and between lines X–X and Y–Y. This area will be referred to throughout this report as the "area under upper flame." Upper flame, throughout the report, will be understood as the flame that originated at the spark plug in G position. (See fig. 1.)

In figure 3 (b) the area under upper flame was measured just as in figure 3 (a). In figure 3 (b), the light area shaded with black lines and the dark area sectioned with white lines were both included in the area under upper flame. In addition to the measurement of area under upper flame, an independent measurement was made of the dark area sectioned with white lines in figure 3 (b). This dark area sectioned with white lines in figure 3 (b) will be referred to throughout this report as the "lower flame area." The lower flame will be understood to mean the flame that originated at the spark plug in J position. (See fig. 1.)

Throughout the report, the term "end-zone area" will be used to designate all that portion of the frame area located between lines X–X and Y–Y of figures 3 (a) and 3 (b) and between the upper and lower flame fronts. Thus, in each case, the end-zone area will be the measured area under upper flame minus the measured lower flame area.

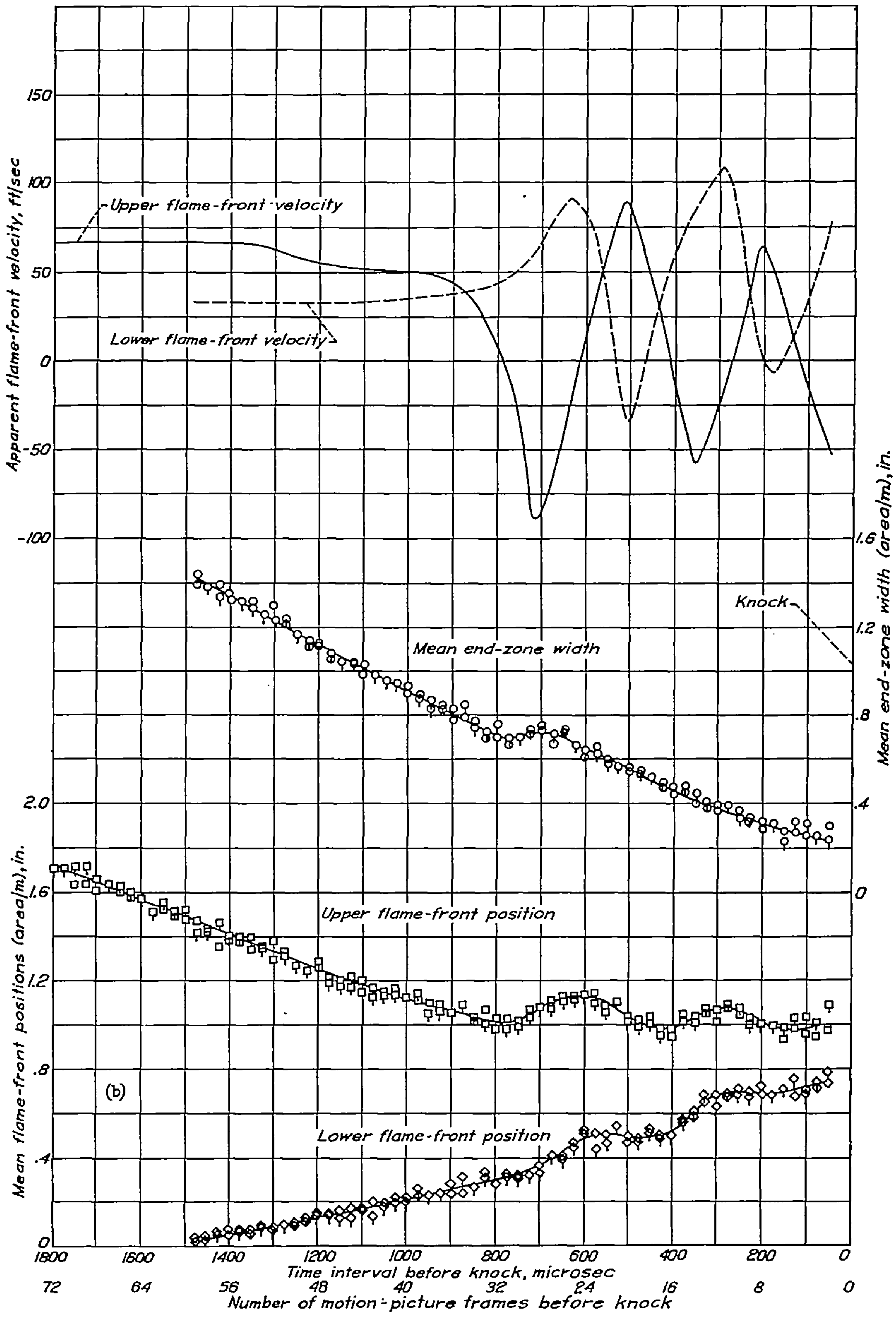
**Plotting of planimeter measurements and fairing of curves.**—Figure 4 (a) presents graphically the results of the measurements described for the photographic series of figure 2. The scale of abscissas in this figure is time before knock in microseconds. Thus, zero on the abscissa scale represents the time at which frame G–7 was exposed, or the time at which knock occurred; 200 on the abscissa scale represents a point in time 200 microseconds before the occurrence of knock, or the time at which frame F–20 was exposed; and so on. All plotted points on the curves of upper mean flame-front position (area under upper flame/$m$), lower mean flame-front position (lower flame area/$m$), and mean end-zone width (end-zone area/$m$) represent the results of planimeter measurements for the frames corresponding to the abscissas. In each case, the measured area or the difference between measured areas was divided by the horizontal dimension $m$ (see fig. 3) to give the mean position of the flame front with reference to the bottom of the frame or the mean width of the end zone, respectively. The mean flame-front position or the mean end-zone width was then multiplied by a suitable factor to convert it to actual combustion-chamber dimensions and the mean flame-front positions and mean end-zone width were plotted from frame to frame.

Faired curves were drawn representing the trends of the plotted values of upper mean flame-front position, lower mean flame-front position, and mean end-zone width. In the drawing of these curves only systematic or periodic trends



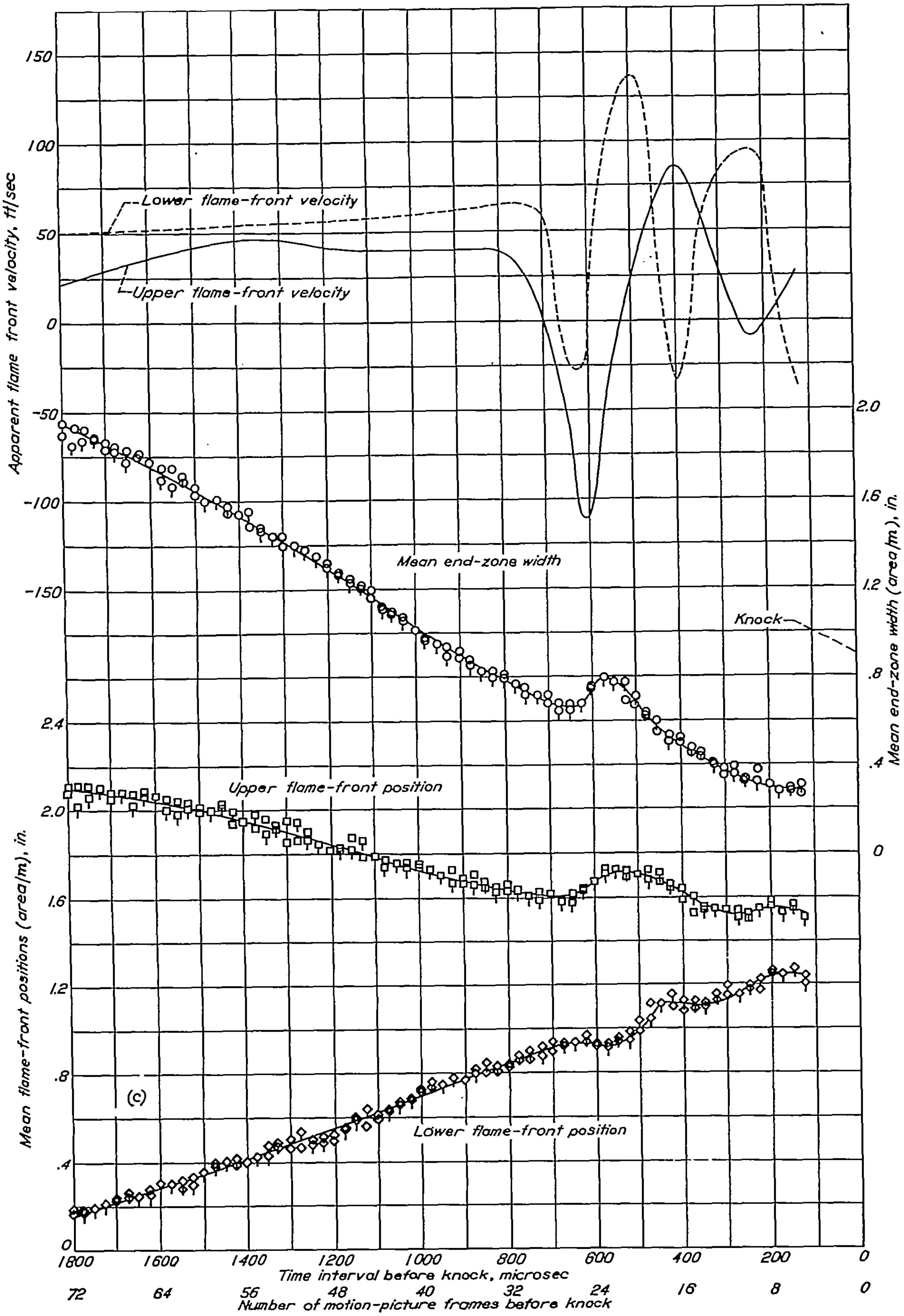

(a) 200 ml TEL per gallon (from fig. 2).

FIGURE 4.—Effect of explosive preknock reaction on travel of flame fronts in an engine cylinder. Fuel, M-2. (Tailed symbols represent check points.)



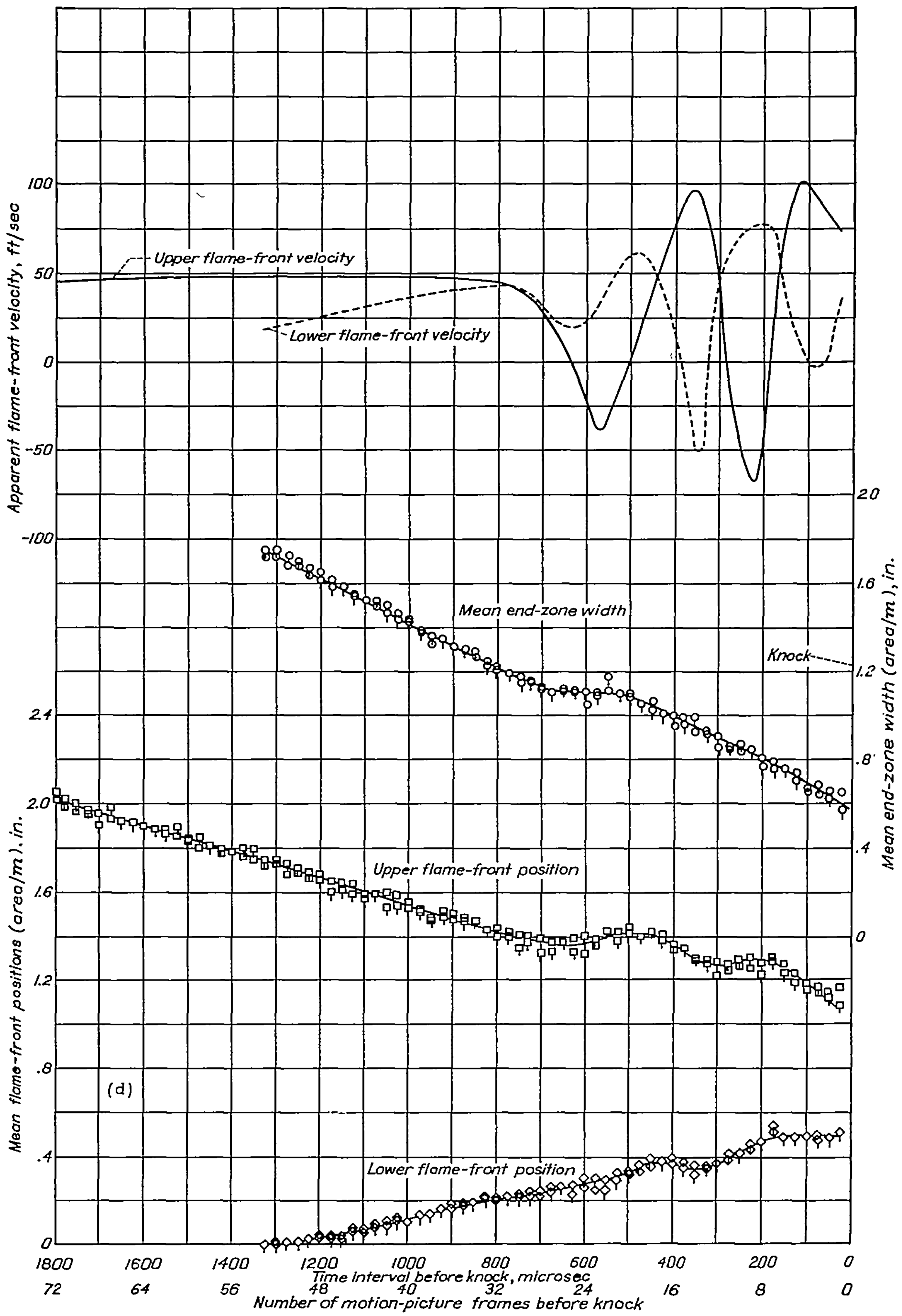

(b) 80 ml TEL per gallon.

FIGURE 4.—Continued. Effect of explosive preknock reaction on travel of flame fronts in an engine cylinder. Fuel, M-2. (Tailed symbols represent check points.)



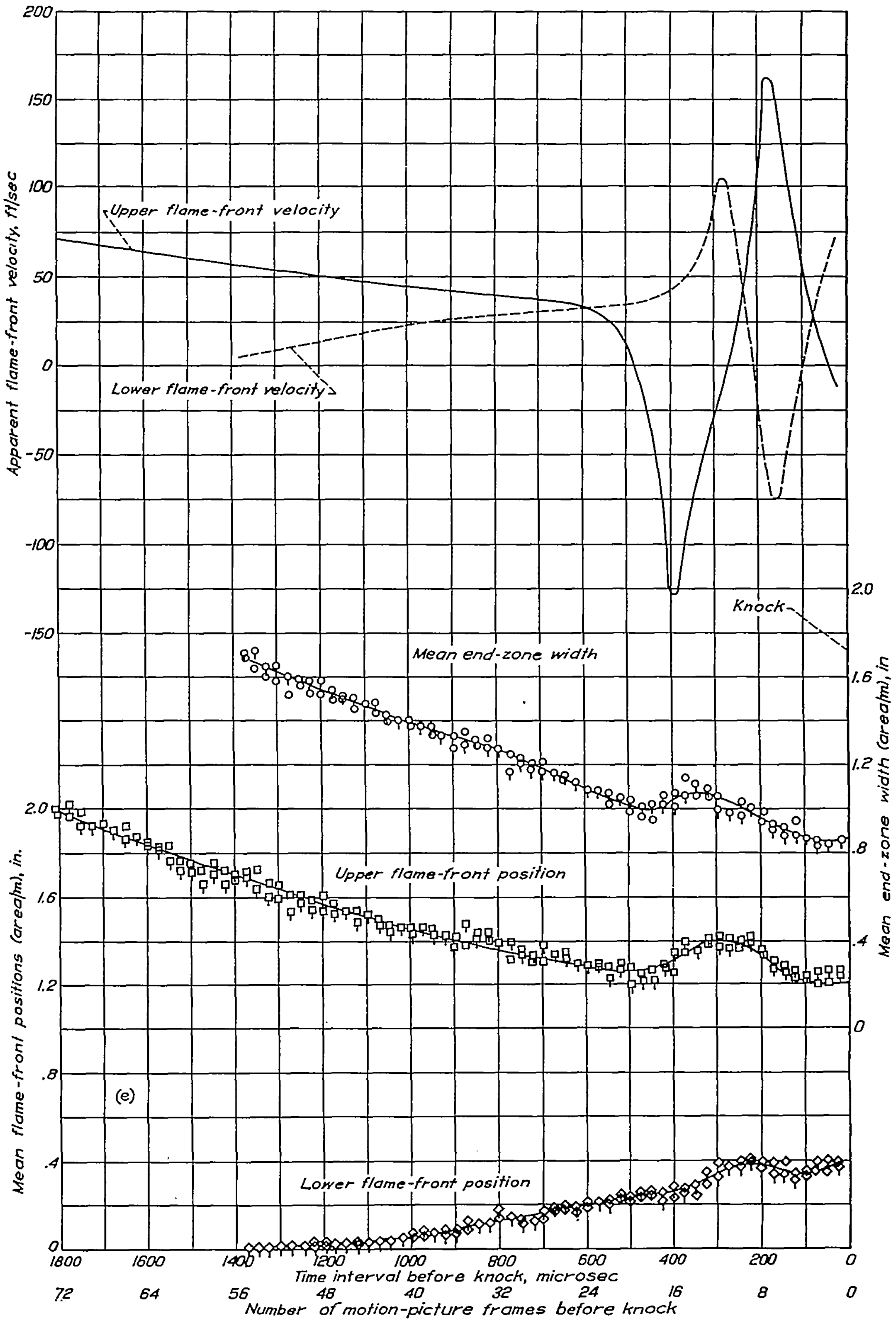

(c) 50 ml TEL per gallon.

FIGURE 4.—Continued. Effect of explosive preknock reaction on travel of flame fronts in an engine cylinder. Fuel, M-2. (Tailed symbols represent check points.)




(d) 40 ml TEL per gallon (from fig. 5).

FIGURE 4.—Continued. Effect of explosive preknock reaction on travel of flame fronts in an engine cylinder. Fuel, M-2. (Tailed symbols represent check points.)




(e) 10 ml TEL per gallon.

FIGURE 4.—Concluded. Effect of explosive preknock reaction on travel of flame fronts in an engine cylinder. Fuel, M-2. (Tailed symbols represent check points.

were observed. Unsystematic fluctuations of the plotted values that did not exceed the limit of reproducibility of the determinations were ignored. In order to better define apparent flame-front travel and show up random deviations, check measurements for all the runs in figure 4 were made. Each set of curves in the figure therefore presents the results of two independent tracings, measurements, and plots.

The upper and lower apparent flame-front velocities plotted in figure 4 (a) were computed from the relationship, velocity$=\frac{\Delta s}{\Delta t}$, where $\Delta s$ is the mean flame-front advance from frame to frame as shown by the faired curve of apparent mean flame-front position and $\Delta t$ is the time interval of 25 microseconds between frames. In each case, positive velocity was taken as being in the original direction of flame-front travel. The curve showing apparent upper flame-front velocity is therefore a mechanical approximation of the negative derivative of the curve of upper mean flame-front position. The ordinates of this curve were converted to units of feet per second. The curve showing apparent lower flame-front velocity is the positive derivative of the curve of lower mean flame-front position multiplied by the conversion factor. No plotted points are indicated for the apparent flame-front velocities because these curves were determined from the faired curves of upper and lower mean flame-front positions.

## RESULTS AND DISCUSSION

The preknock period.—The curves of figures 4 (b), 4 (c), 4 (d), and 4 (e) represent the results of planimeter measurements of four series of photographs taken under conditions similar to those of figure 2, but with different tetraethyl-lead concentrations. The test conditions were the same in each

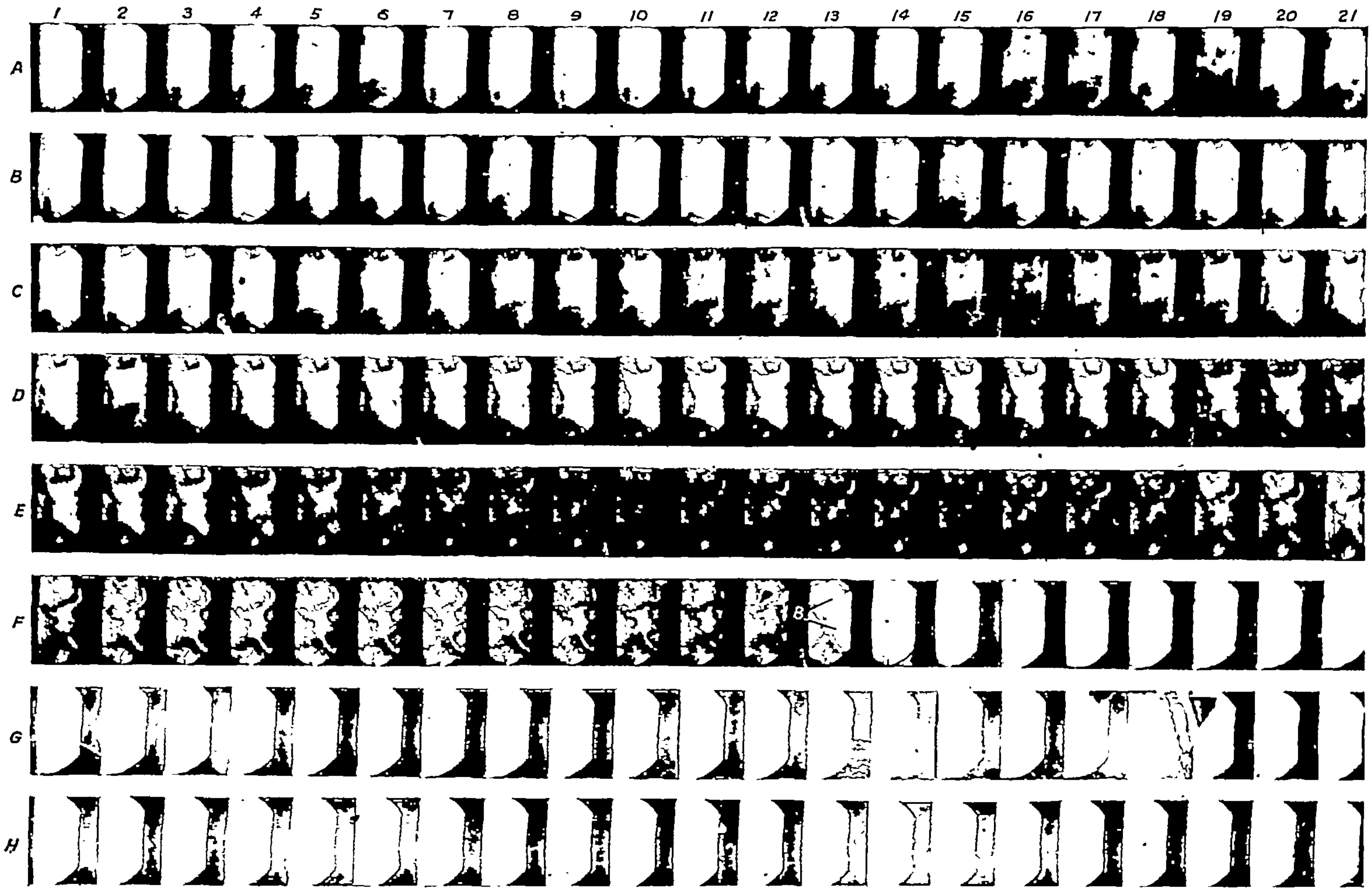



FIGURE 5.—High-speed motion pictures of vibratory combustion cycle in an engine cylinder. M-2 fuel plus 40 ml TEL per gallon. B, blurring caused by knock. (See fig. 4 (d).)

case except that the amount of tetraethyl lead was varied, as shown on the figures. The series of photographs from which figure 4 (d) was obtained is reproduced in figure 5. The three series of photographs from which figures 4 (b), 4 (c), and 4 (e) were obtained are not reproduced because they are not believed to be of sufficient interest to justify inclusion.

None of the curves in figures 4 (a) to 4 (e) extend all the way to the point of knock. The curves were discontinued at the frames where the upper and lower flames merged within the region between lines X–X and Y–Y (see figs. 3 (a) and 3 (b)) to such an extent that the areas to be measured became indeterminate.

It was shown in reference 3 that the characteristic knocking blur, such as is seen in frame G–7 of figure 2 and frame F–13 of figure 5, occurs simultaneously with the onset of heavy knocking vibrations. This blur is consequently regarded as representative of a specific reaction that is the direct cause of heavy spark-ignition fuel knock. Throughout this report, the reaction that causes the knocking blur will be referred to as "knock" because this reaction is believed to be the most usual cause of objectionable noise and cylinder vibrations.

It is immediately obvious from a glance at figures 4 (a) through 4 (e) that vibrations are set up in the gases in the combustion chamber before knock occurs. These vibrations before knock will be referred to hereinafter as "preknock vibrations."

**Origin of preknock vibrations.**—Examination of the flame-front-velocity curves in figure 4 reveals that the preknock vibrations generally begin with a retarding of both upper and lower flame fronts. Very soon after the vibrations begin, however, the fluctuation of the lower flame-front velocity becomes 180° out of phase with the fluctuation of the upper flame-front velocity, positive velocity being taken as the forward direction for each of the two flame fronts. The curve of end-zone width in each case has a hump that begins to develop very quickly after the initial retardation of the flame fronts, as should be expected from geometric considerations. There is, however, only one hump in each end-zone-width curve. In each case that part of the end-zone-width curve immediately after the hump appears to have about the same slope as the portion immediately preceding the hump.

Examination of either the flame-front-velocity curves or the flame-front-position curves gives no indication whatever that the preknock vibrations generally increase in amplitude after the first vibration. More often the amplitude diminishes with the later cycles.

The simplest explanation of the observed facts appears to be that the preknock vibrations are set up by an explosive exothermic reaction in the end zone that is completed within a period probably less than 300 microseconds. If this exothermic reaction continued at a constant rate after the hump in the end-zone-width curve, the reaction should cause a change in the slope of the curve from the value existing before the hump unless the reaction has the effect of increasing the flame velocity relative to the gas molecules by just the right amount to compensate for the continuing expansion of the gas in the end zone. If the reaction continued intermittently at each compression by the preknock vibrations, as suggested in reference 2, there should be a hump in the end-zone-width curve for each fluctuation of flame-front velocity and the fluctuations in flame-front velocity should steadily increase in amplitude.

The conclusion may therefore be made that, under the conditions of these tests, an exothermic reaction occurs in the end zone a few hundred microseconds before knock. This reaction causes an explosive expansion of the end zone and the explosive expansion of the end zone sets up vibrations in the gases that continue by their own momentum until knock occurs. Because the end zone, in the cases shown in figure 4, is not located at the combustion-chamber walls but well toward the center of the chamber, explosive expansion of the end zone should be expected to set up not only the fundamental mode of vibrations but harmonics as well. For the runs shown in figure 4, the harmonics apparently were so quickly damped out that they could not be observed. After the damping out of the harmonics, the end zone moved up and down with the flame fronts without measurable fluctuation in its area.

When the photographs are viewed on the projection screen as motion pictures, an explosive reaction is visible in the end zone at the time the preknock vibrations begin. This reaction has the appearance of a sudden slight darkening in the end zone, which is not entirely homogeneous. This darkening cannot usually be seen in the figures because it is less pronounced than the frame-to-frame variation in exposure intensity introduced by the camera. In order to see the reaction it is necessary that the eye be able to integrate the effect of a number of frames over a short period of time, as is the case when the photographs are projected at the rate of 16 frames per second.

In many cases when the photographs are projected as motion pictures, the end zone can be seen to darken every time the preknock vibration carries the combustion-chamber contents down toward the end zone and to become less dark

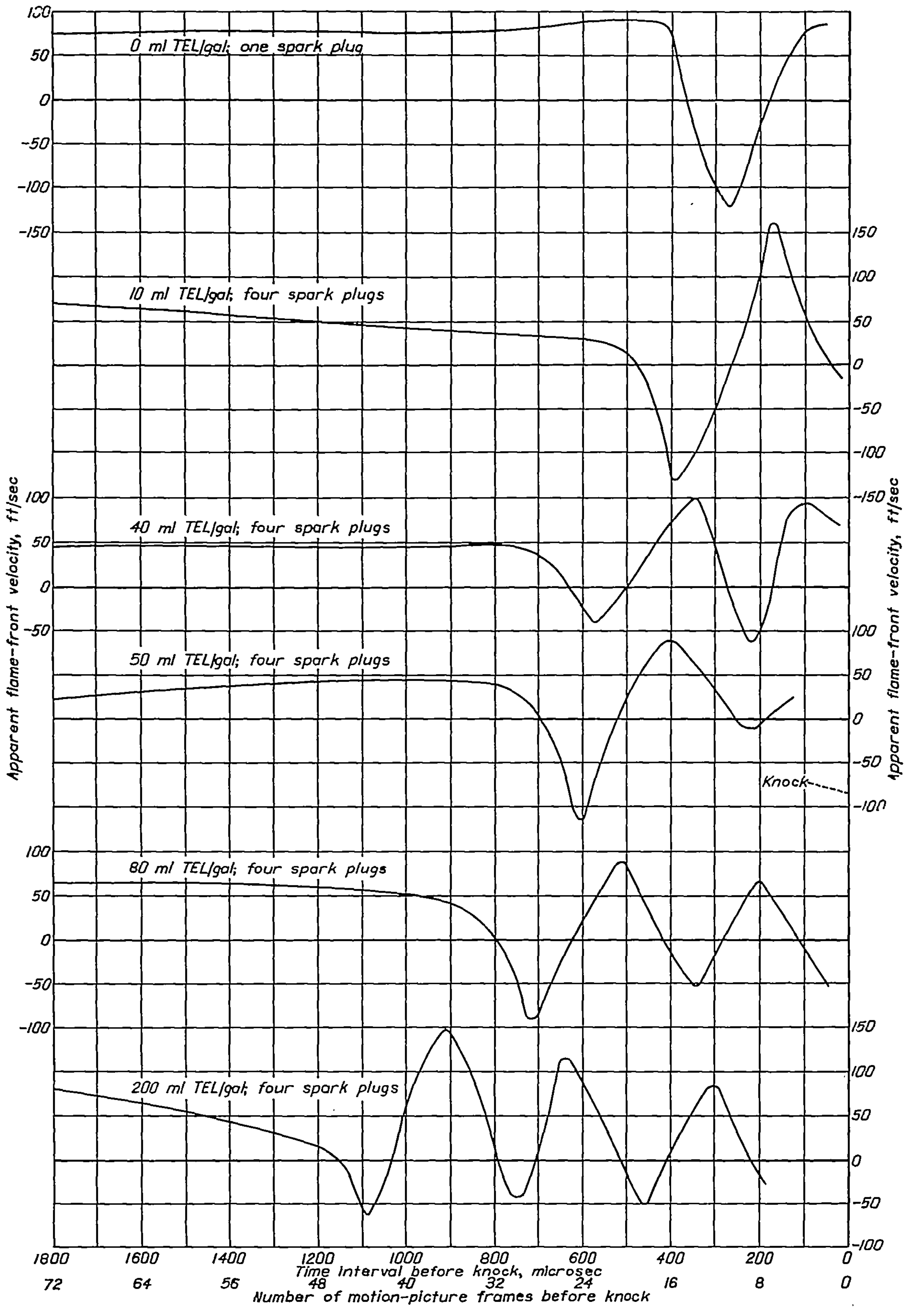



FIGURE 6.—Apparent upper-flame-front velocities in an engine cylinder as affected by preknock explosive reaction. Fuel, M-2.

every time the vibration carries the chamber contents up away from the end zone. If this observed effect represents either an exothermic or endothermic reaction in the end zone, the rate of such reaction is too low to have any definite effect on the end-zone-width curves in figure 4. The conclusion therefore appears to be justified that, if any such intermittent reaction exists, it is only incidental as far as the preknock vibrations are concerned. The intermittent reaction is caused by the preknock vibrations but does not play an appreciable part in sustaining these vibrations.

**Effect of tetraethyl lead on preknock vibrations.**—The curves of figure 4 clearly show that extremely high tetraethyl-lead concentration caused a marked increase both in the number of cycles of preknock vibration and in the length of the time interval during which the preknock vibrations existed.

Figure 6 has been prepared for more convenient observation of the effect of tetraethyl lead on preknock vibrations. This figure shows upper flame-front-velocity curves for six different combustion cycles. The test conditions were the same for all cycles except as to the tetraethyl-lead concentration and the number of spark plugs used. As the tetraethyl-lead concentration is increased from zero in the uppermost curve to 200 milliliters per gallon in the lowest curve, the time interval between the start of preknock vibrations and the occurrence of knock itself systematically increases. Two successive curves in this figure may show the same number of cycles of preknock vibrations but not the same time of start of preknock vibrations relative to time of knock.

In figure 6 the uppermost curve represents a combustion cycle in which only one spark plug was used in G position. (See fig. 1.) The other five curves represent cycles in which four plugs were used. These five curves are the ones shown in the upper portions of figures 4 (a) to 4 (e) in reverse order. The curve for a combustion cycle in which only one spark plug was used is included in figure 6 because no curve is available for the case of zero tetraethyl-lead concentration representing operation with four spark plugs. Changing from one spark plug to four did not appear to have any definite effect on the time of initiation of the preknock reaction, as is shown in figure 7.

The number of measured combustion cycles might be thought insufficient to justify definite conclusions concerning the effect of tetraethyl lead, but it should be borne in mind that the measurements have been made for the purpose of presenting in concrete form phenomena that have been clearly observed on the projection screen. Observation as motion pictures of 45 cycles of combustion with varying tetraethyl-lead concentrations bears out the conclusion that increasing lead concentration increases the time interval throughout which the preknock vibrations occur.

In order further to demonstrate the relationship between duration of preknock vibrations and the tetraethyl-lead concentration, points are plotted in figure 7 for all combustion cycles of which planimeter measurements have been made. The ordinate of each point is the time interval between the first passage of the upper-flame-front-velocity curve through zero and the occurrence of knock. In all cases the fuel was M–2 reference fuel. The plotted points indicate a straight-line relationship between the lead concentration and the time interval through which preknock vibrations occur. Points in the range of lead concentrations ordinarily used in practical engine operation might possibly change the slope of the curve of figure 7 in this range, if it were possible to obtain such points with sufficient accuracy. Nothing but a straight line appears justified, however, through the entire range from 0 to 200 milliliters per gallon on the sole basis of the points plotted in figure 7.

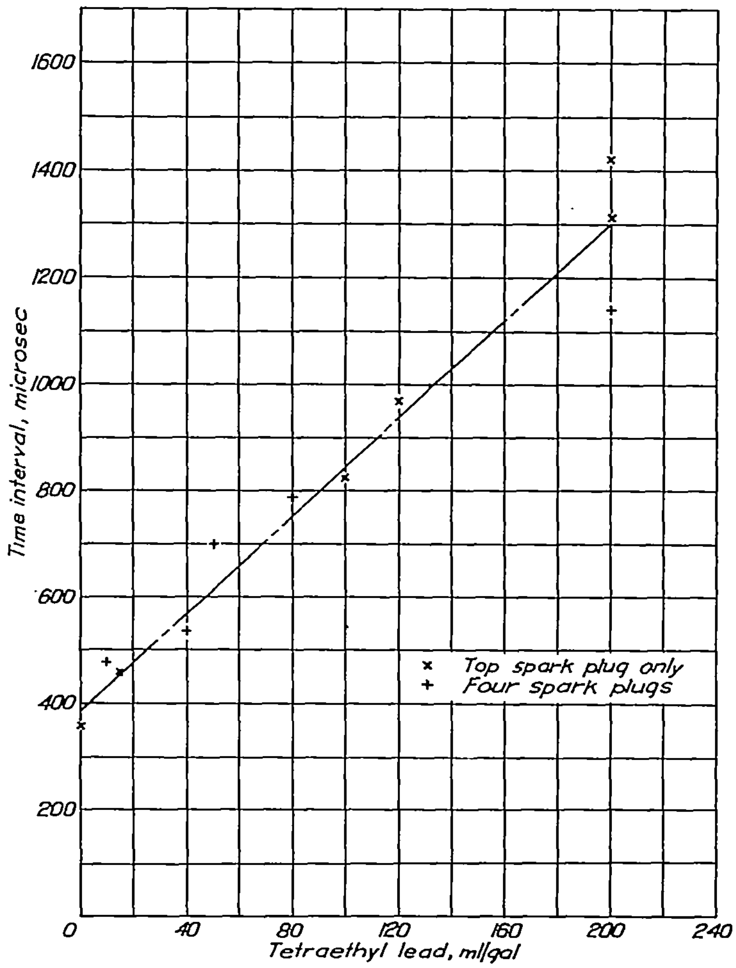
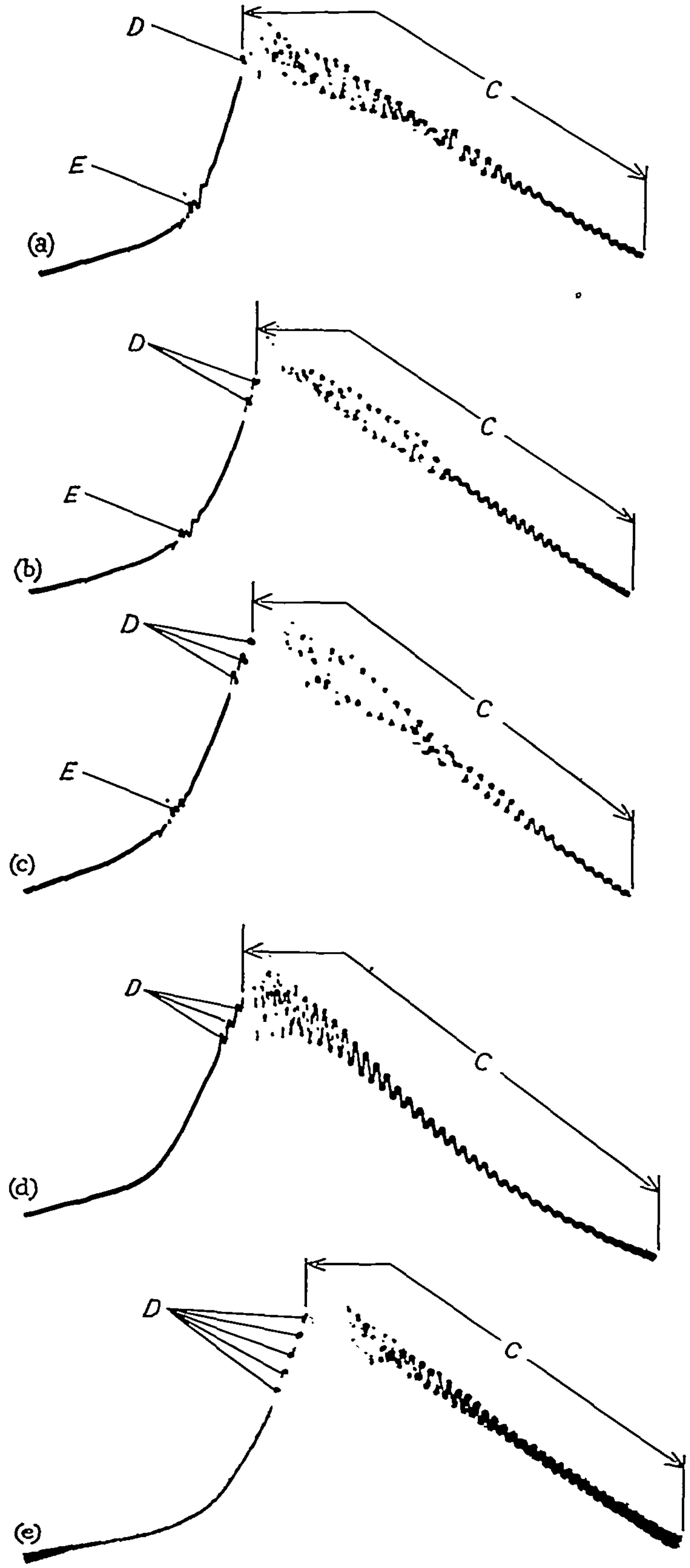



FIGURE 7.—Effect of tetraethyl-lead concentration in M–2 fuel on time interval between preknock explosive reaction and knock in an engine cylinder.

The effect of tetraethyl lead of increasing the time interval throughout which preknock vibrations exist is verified by pressure-time records. Pressure-time records taken with tetraethyl-lead concentrations of 0, 20, 40, 80, and 200 milliliters per gallon are reproduced in figure 8. Fuel in each case was M–3, three spark plugs were used in positions E, F, and G (see fig. 1), and the piezoelectric pickup was placed in opening I (see fig. 1). The spark plug in opening J was omitted in order to bring the combustion end zone against the chamber wall, previous tests having shown that knocking vibrations register more intensely on the piezoelectric pickup under this condition.




(a) 0 ml TEL per gallon. (b) 20 ml TEL per gallon.
(c) 40 ml TEL per gallon. (d) 80 ml TEL per gallon.
(e) 200 ml TEL per gallon.

FIGURE 8.—Effect of tetraethyl-lead concentration on preknock vibrations in combustion cycles using M-3 fuel. C, knocking vibrations; D, preknock vibrations; E, timing impulses.

In figure 8, the irregularities designated E on the traces are due to timing impulses and have no significance relative to the pressure in the combustion chamber. The preknock vibrations are designated D and the region of the knocking vibration is designated C. In general, the earliest knocking vibrations cannot be seen because they moved the electron beam of the oscilloscope up and down too rapidly for the trace to register on the photographic film. The trace simply disappears at the point where knock occurred and does not reappear until the knocking vibrations have lost most of their amplitude.

In the case of zero tetraethyl-lead concentration, the pressure-time record shows one cycle of preknock vibrations. This increases to two, three, three, and five cycles, respectively, with concentrations of 20, 40, 80, and 200 ml TEL per gallon.

The question naturally arises whether the effect of tetraethyl lead of increasing the time interval throughout which preknock vibrations exist is due to a hastening of the explosive preknock reaction or to a retarding of the true knock reaction. This question is closely connected with another question: whether the occurrence of knock causes power loss by preventing complete combustion. Examination of the original negatives from which the pressure-time records of figure 8 were reproduced reveals that knock occurred in each case very nearly at the time when the average pressure throughout the combustion chamber had reached its probable maximum. For the purpose of this discussion, the average combustion-chamber pressure at any instant is considered as being halfway between the peaks and the valleys of the knocking vibrations on the pressure-time record. The records of figure 8, moreover, are typical of all records obtained with M-3 reference fuel plus tetraethyl lead, 39 records in all. The fact that the peak pressure invariably occurs at the time of knock suggests that, if tetraethyl lead retards the occurrence of knock, it also increases the peak pressure. Such a conclusion must be correct unless the tetraethyl lead has a compensating effect of decreasing the rate of pressure rise. This conclusion would mean that the occurrence of knock causes a virtual termination of the release of chemical energy that would have occurred later in the cycle if the knock had not developed.

The electronic apparatus used in this investigation was not considered to have sufficient reproducibility to determine whether the peak pressure attained with high tetraethyl-lead concentration was consistently higher than that attained without tetraethyl lead. A subsequent investigation (reference 6) has definitely shown, however, that heavy knock does bring a virtual end to the release of chemical energy that would otherwise have developed later in the combustion cycle. This finding was to be expected in view of the fact that heavy knock always causes large quantities of free carbon to be formed. It appears reasonable, therefore, that tetraethyl lead in large concentrations postpones the occurrence of knock to a later time in the combustion process and that it may have no effect on the time of occurrence of the preknock reaction. No definite conclusion on this point, however, can be made at this time.

**Irregular preknock vibrations.**—In figures 9 and 10, flame-front-velocity curves and pressure-time records are presented which show irregularities in the preknock vibrations. The concentration of tetraethyl lead for both curves of figure 9

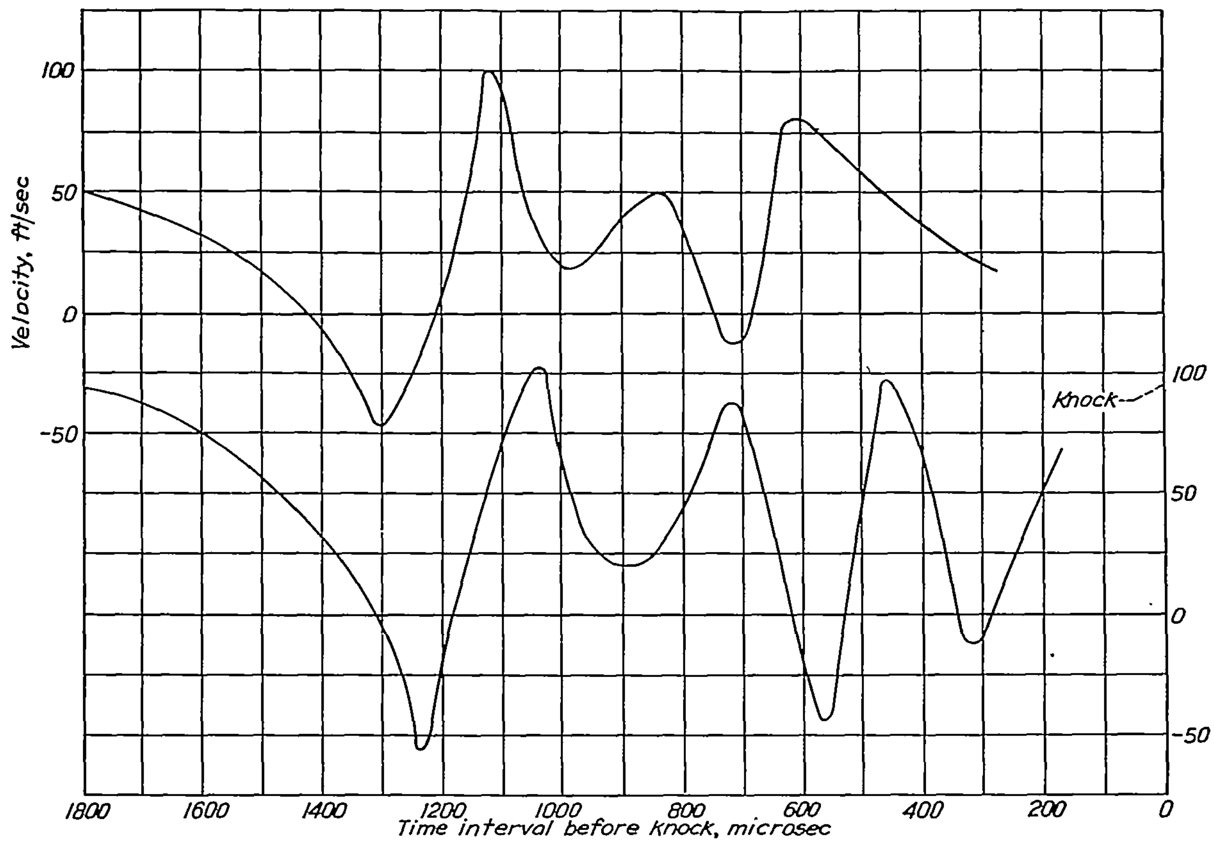
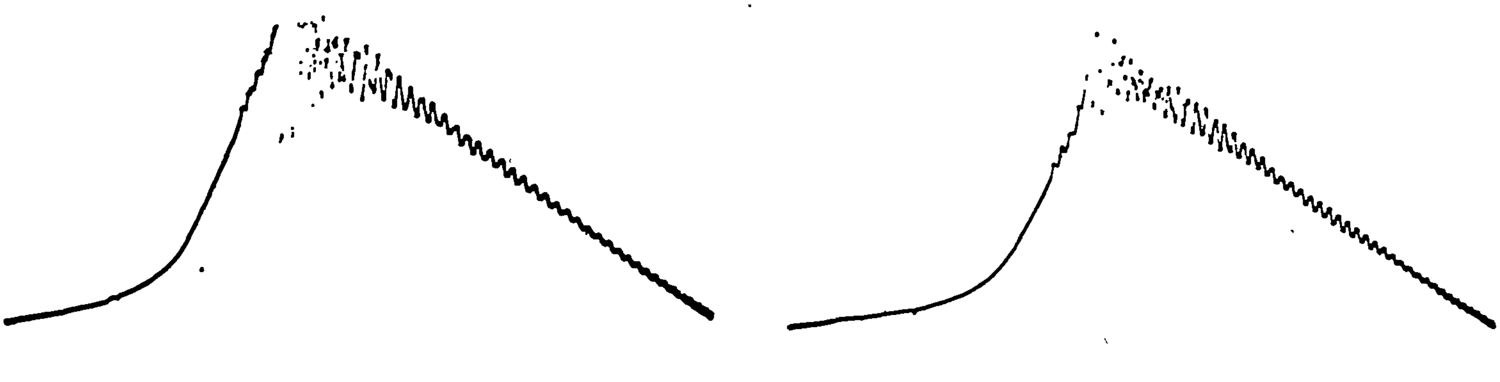



FIGURE 9.—Apparent upper-flame-front velocities in an engine cylinder showing measured irregularities in flame-front progression. M-2 fuel plus 200 ml TEL per gallon.

was 200 milliliters per gallon. In figure 10 the concentration was 200 milliliters per gallon for one record and 160 for the other. Engine operating conditions were the same as those of the preceding figures. Figures 9 and 10 show a lack of uniformity in the amplitude and period of the successive cycles of preknock vibration in contrast to the uniform vibrations seen in figure 4. The uniform vibrations are of the more usual type. The irregularities of the preknock vibrations of figures 9 and 10 can very well be explained by the existence of vibrations of a higher mode than the fundamental. Occurrence of the preknock reaction in different parts of the combustion chamber should be expected to cause a more or less preponderance of higher modes of vibration, depending on the exact location of the end zone.

**Relation of explosive preknock reaction to true knock reaction.**—Sufficient data are not yet available to conclude whether the explosive preknock reaction that sets up the preknock vibrations is a necessary prelude to the true knock



(a) (b)

(a) 200 ml TEL per gallon. (b) 160 ml TEL per gallon.

FIGURE 10.—Pressure-time records of combustion cycles showing irregular preknock vibrations. Fuel, M-3.

or whether this preliminary reaction is only an incidental phenomenon that occurs with some fuels. The existence of the phenomenon in some cases demonstrates the complexity of the knock problem.

In figure 4 of reference 2, the occurrence of very light knock in frame O–5 was observed without a quick dissolution of the mottled combustion zone. It was suggested that in this case the knock seemed to occur and then leave the normal burning to complete itself in the usual manner. The preknock reaction revealed in the present investigation may have occurred in frame O–5 of figure 4 of reference 2 in a minute end-zone pocket so late in the combustion process that the true knock never had an opportunity to develop. The completion of the combustion required about 300 microseconds (12 motion-picture frames) after frame O–5, which is a very reasonable time interval between the explosive preknock reaction and the true knock.

The explosive preknock reaction might very possibly be regarded as "incipient knock" in cases where the normal burning is completed before the true knock has an opportunity to occur.

**Preknock autoignition.**—In references 1, 2, and 3 the possibility that autoignition may occur in the end zone before knock is extensively discussed. The results presented in the preceding sections have definitely shown that an explosive exothermic reaction occurs in the end zone before knock and it would seem most plausible to assume that this reaction is autoignition. On the basis of these results, however, a definite conclusion cannot be made as to whether the burning is continuing in the end zone at the time knock occurs. The combustion may occur in more than one distinct stage, with comparative inactivity between stages. Dixon and coworkers (references 7 and 8) have shown that in the explosion of cyanogen and several hydrocarbons the carbon is first burned to CO, which later burns to $CO_2$ at a much slower rate.

Definite evidence has been found of at least two types of preknock autoignition that are apparently independent of the reaction that sets up the preknock vibrations. One of these two types of preknock autoignition may be seen in figure 11. The high-speed photographic series shown in figure 11 was obtained with the use of S–1 fuel admixed with approximately 5 percent of amyl nitrate. Two spark plugs fired in this case, in G and F positions (see fig. 1). Test conditions were otherwise the same as in figures 2 and 5. The general darkening of the pictures apparent in frames D–5 to D–16 of the figure is due to faulty processing and cannot be associated with any combustion phenomenon. At about frame F–13 in figure 11, very small dark spots begin to appear

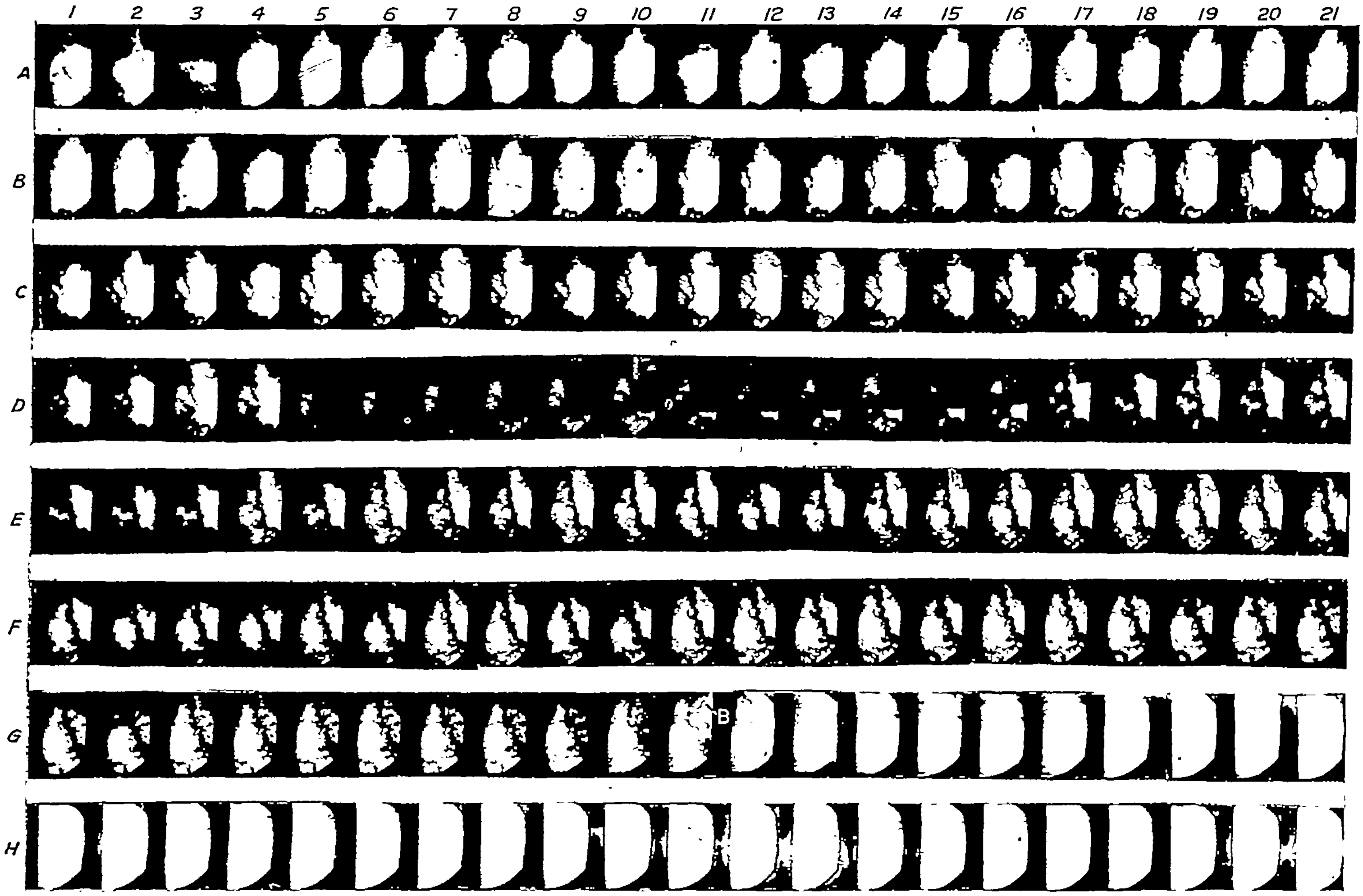



FIGURE 11.—High-speed motion pictures of combustion cycle in an engine cylinder showing autoignition before knock. S–1 fuel plus 200 ml amyl nitrate per gallon. B, blurring caused by knock. (See fig. 12.)

within the end zone and well distributed throughout the entire end-zone area. In the frames following F–13 these dark spots steadily grow until in frame G–10 they cover the entire area of the end zone. Knock first appears as a brightly luminous streak along the right-hand edge of frame G–11 and as a general blurring of the entire mottled region of the same frame.

The dark spots that develop and grow within the end zone in figure 11 have the same appearance as the mottling that has been interpreted as representing the combustion zone in flames emanating from spark plugs. The spots represent some type of reaction that originates at points and propagates itself outward through the unignited charge in all directions from these points. To contend that this reaction is not autoignition requires a concept that is probably entirely new in preflame reactions; namely, a preflame reaction that propagates itself from point to point in the same manner and at about the same speed as a normal flame.

Curves of apparent flame-front velocity and flame-front position plotted against time are shown in figure 12 for the photographs of figure 11. These curves show that measurable preknock vibrations did not occur and, therefore, that a measurable explosive preknock reaction such as caused the vibrations in the cases of M–2 fuel with and without tetraethyl lead had not occurred up until a time 50 microseconds before the occurrence of knock. About 1200 microseconds before knock, a retardation of the flame front occurred that did not cause vibrations. This retardation may have been due to an unusual effect of swirl of the combustion-chamber contents. The portion of the flame-front-position curve just before knock has no irregularity such as would indicate an exothermic effect of the end-zone autoignition. Any exothermic effect of the end-zone autoignition that actually did exist should, in fact, probably not be evident on the curve. In frame G–6 of figure 11, only five frames before knock, eight prominent autoignition spots are visible. The diameters

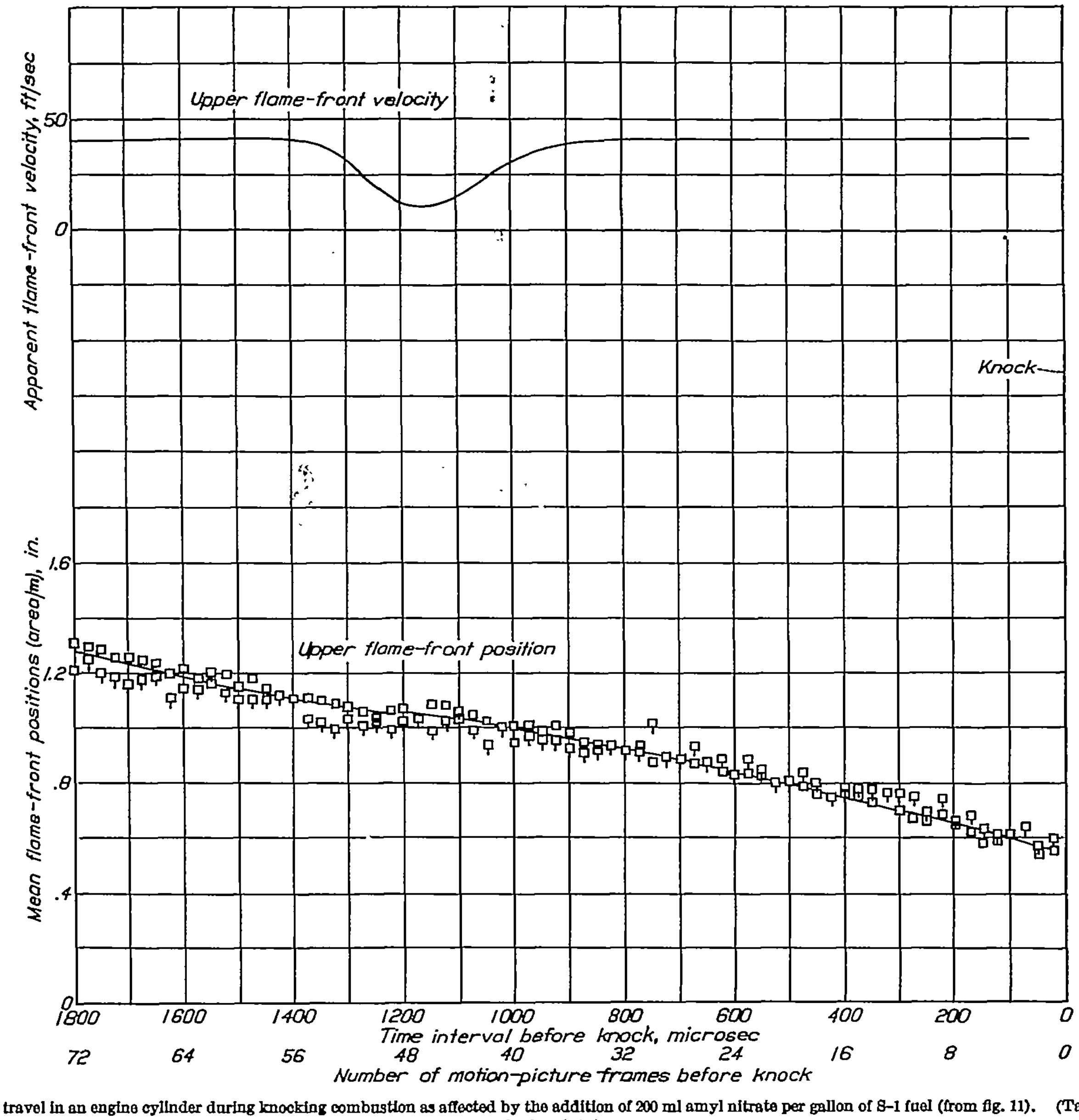



FIGURE 12.—Flame travel in an engine cylinder during knocking combustion as affected by the addition of 200 ml amyl nitrate per gallon of S–1 fuel (from fig. 11). (Tailed symbols represent check points.)

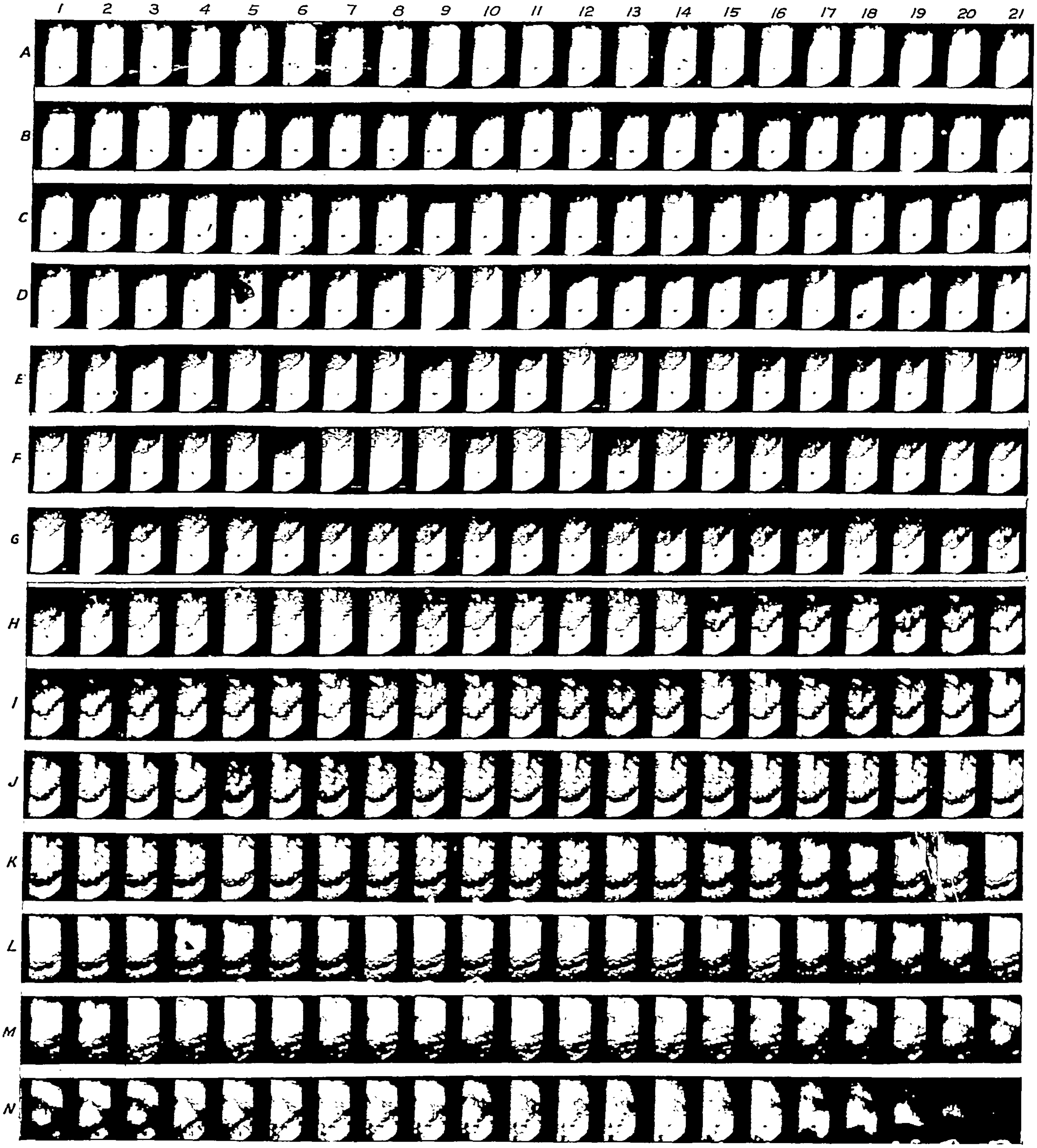



FIGURE 13.—High-speed motion pictures of combustion cycle in an engine cylinder showing autoignition before knock. S-2 fuel plus 400 ml amyl nitrate per gallon.

of these spots, converted to combustion-chamber scale, average about 0.2 inch. The actual area of the visible end zone in this frame is 1.15 square inches which, with the combustion-chamber depth of about 1 inch, indicates an end-zone volume of at least 1.15 cubic inches. If the autoignition spots are assumed to be spherical, their combined volume is 0.0335 cubic inch. In this frame, therefore, the apparent autoignited volume is only 2.9 percent or less of the total end-zone volume. In the frames following G–6, the demarcation between end-zone and spark-ignition flame becomes so confused that the planimeter measurements are undependable.

The pin-point autoignition that is so apparent in figure 11 can also be seen on close inspection in figure 2. If the two arrows directed at frame F–10 in figure 2 are extended until they intersect, the point of intersection will be on a fairly well-developed point of autoignition. The arrows at frame F–14 indicate a similar point of autoignition.

A somewhat different type of preknock autoignition, which involves the development of an autoignition flame front near the combustion-chamber wall, is shown in figure 13. The fuel in this case was S–2 reference fuel admixed with 10 percent amyl nitrate. Only one spark plug fired, in E position. (See fig. 1.) The time of injection of fuel for figure 13 was 90° A. T. C. on the intake stroke, 70° later than with all the other photographs of this report and of references 1, 2, and 3.

At about frame J–15 in figure 13 a slight mottling begins to develop in the end zone. In the neighborhood of frame K–1 this end-zone mottling begins to become concentrated near the combustion-chamber wall opposite the spark-ignition flame front. After frame K–12 the mottling progresses steadily away from the combustion-chamber wall toward the spark-ignition flame front at the same time that pin points of autoignition develop in the clear space just ahead of the spark-ignition flame. At frame M–20 the entire end zone has disappeared.

When the photographs of figure 13 are projected as motion pictures, the unmistakable visual interpretation is that a flame develops by autoignition at the combustion-chamber wall on the side of the end zone farthest from the spark-ignition flame front. The autoignition flame front and the spark-ignition flame front then propagate steadily toward each other; at the same time pin-point spots of autoignition develop in the end zone until the end zone has been entirely consumed.

From the visual aspect, knock of the type that has been extensively studied in this report and in references 1, 2, and 3 did not occur in figure 13. At about frame N–1, however, the fading out of the mottled zone began to occur so much more rapidly than is the case with normal combustion that the mottling completely disappeared before frame N–14. The dark spot that is seen in frames N–15 to N–19 is a spot on the combustion-chamber window. The shading just above the center of the same frames is an optical defect introduced by rocking of the piston mirror and has nothing to do with combustion. When the photographs of figure 13 are projected as motion pictures, a moderate knocking shock is clearly visible, beginning at about frame N–1. It is obvious from observation of the projected photographs that this knocking shock did not develop simultaneously with the autoignition which was clearly visible before frame N–1; instead it accompanied some change in the combustion process which began at about frame N–1 and which resulted in the quick dissolution of the mottled zone between frame N–1 and frame N–14.

The end-zone reaction shown in figure 13 might well be of the same type as shown in photographs of knocking combustion by Withrow and Rassweiler (reference 9), which are the chief experimental support of the simple autoignition theory of knock. The travel of the autoignition flame through the end zone in figure 13 requires about 1,250 microseconds (50 frames), which is comparable with the time occupied by autoignition in the photographs of reference 9.

## CONCLUSIONS

The test conditions for the experiments of the present report included only one value of compression ratio and one value of fuel-air ratio. Usual engine operating conditions were not reproduced, inasmuch as the fuel charge was injected into the cylinder on the intake stroke and residual combustion products were not present in the chamber. Because knock takes on many different aspects under different conditions, some of the following conclusions should be considered definite only for conditions approximating those of the test.

1. The existence of small-amplitude vibrations before knock, which was suggested in reference 2, has been fully proved with M–2 and M–3 reference fuels under the test conditions.
2. The preknock vibrations are caused by an explosive exothermic reaction in the end zone, which also causes some darkening in schlieren photographs of the end zone.
3. The preknock vibrations do not build up progressively into knock, as was suggested in reference 2.
4. Adding large quantities of tetraethyl lead to the fuel causes a linear increase in the time between the explosive preknock reaction and the true knock reaction, with a consequent increase in the number of cycles of preknock vibration.
5. With the addition of amyl nitrate to S–1 and S–2 reference fuels, autoignition occurs throughout large end-zone volumes an appreciable length of time before knock occurs, and even, in some cases, without the occurrence of severe knock.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *September 11, 1944.*

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