REPORT No. 727

A STUDY BY HIGH-SPEED PHOTOGRAPHY OF COMBUSTION AND KNOCK IN A SPARK-IGNITION ENGINE

By Cearcy D. Miller

SUMMARY

The study of combustion in a spark-ignition engine given in Report No. 704 has been continued. The investigation was made with the NACA high-speed motion-picture camera and the NACA optical engine indicator. The camera operates at the rate of 40,000 photographs a second and makes possible the study of phenomena occurring in time intervals as short as 0.000025 second.

Photographs are presented of combustion without knock and with both light and heavy knocks, the end zone of combustion being within the field of view. Time-pressure records covering the same conditions as the photographs are presented and their relations to the photographs are studied. Photographs with ignition at various advance angles are compared with a view to observing any possible relationship between pressure and flame depth.

A tentative explanation of knock is suggested, which is designed to agree with the indications of the high-speed photographs and the time-pressure records.

INTRODUCTION

The results presented in this report represent a continuation of the study of combustion with the NACA high-speed motion-picture camera, the first results of which were published in 1941 (reference 1). A copy of reference 1 should be available to make possible a complete understanding of the present report. The photographs presented in reference 1 and some of those presented in this report are the same as those in the NACA technical film on normal combustion, preignition, and knock, which has been exhibited on many occasions.

The NACA high-speed motion-picture camera, which takes pictures at the rate of 40,000 per second, was developed in response to a demonstrated need for higher picture-taking speed in the study of combustion. The photographs published in reference 1 were primarily concerned with combustion in general. The photographs presented in this report relate primarily to knock. The indications of the photographs, in general, confirm conclusions drawn by Rothrock and Spencer in 1938 (reference 2) on the basis of less precise data.

Many theories have been advanced concerning the manner in which fuel knock takes place and much experimental work has been done in attempts to determine what happens during knock. It is now generally recognized that knock is associated with the last part of the charge to burn and apparently involves a sudden and very violent completion of the burning in the engine cylinder after a part of the burning has taken place at a normal rate. The chief differences in the various theories concern the manner in which the final portion of the charge is ignited, the rapidity with which the final burning takes place, and whether the knock can occur in a portion of the charge that is already apparently ignited and burning.

Probably the most commonly accepted conception of fuel knock is that it consists of autoignition of the end gas because of high pressure and temperature. Such autoignition has been shown in photographs taken by Withrow and Rassweiler (reference 3). Withrow and Rassweiler took their photographs at rates of 2250 to 5000 frames per second. Photographs presented in reference 1, however, indicate that knock takes place in such an extremely short time (5×10^{-5} sec or less) that it would be missed by a camera taking pictures at 2250 to 5000 frames per second. It therefore appears likely that, although Withrow and Rassweiler photographed autoignition, they did not photograph knock, which may or may not be preceded by autoignition, because knock occurs too quickly to be recorded by their method.

Weinhart (reference 4) determined flame travel by the method of ionized gaps and an oscillograph and concluded that autoignition, which he called pressure ignition, occurred in the end zone.

The theory that knock is caused by a detonation wave such as can be set up during combustion in long tubes has received considerable attention from various investigators. Sokolik and Voinov (reference 5) obtained evidence that they believed to be a confirmation of this theory. They took streak photographs on a rapidly moving film, using an engine with a narrow window extending across the top of the pent-roof cylinder head. Their photographs, taken at their highest available film speed, showed the flame traversing part of the chamber at a normal rate and then completing the burning at an extremely high rate. The streak photograph showed a slight slope in the trace of the final burning. They believed that the existence of this slope proved that the flame front itself accelerated very rapidly to complete the burning and that this quick completion of the burning is the cause of knock. The

conclusions that are presented herein, on the basis of the results given in this report and in reference 1, do not appear to be inconsistent with the streak pictures of reference 5, although such conclusions are not the same as those drawn by Sokolik and Voinov.

One theory has involved the assumption that a compression wave originates either behind the flame front or at the flame front and crosses the chamber ahead of the flame, causing ignition at the opposite side of the combustion chamber, such ignition being the direct cause of knock. The remarkable photographs (both schlieren photographs and direct photographs of the flame) taken by Payman and Titman (reference 6) show these occurrences in tubes. Boerlage (reference 7) shows photographs of combustion in an engine with autoignition occurring at the end of the combustion chamber farthest from the spark plug in a manner similar to that shown by Payman and Titman's photographs.

It was suggested in references 8 and 9 that knock is caused by the formation of explosive peroxides in nuclear drops during preflame combustion.

In previous work at this laboratory, Rothrock and Spencer (reference 2) have taken photographs at high rates of speed, using both schlieren photography and direct photography of the flame. The maximum rate attained in those tests was 2500 frames per second. The photographs indicated that, although autoignition ahead of the flame front may occur in conjunction with knock, it does not always do so and is not necessary for the occurrence of knock. The photographs in reference 2 also indicated that, when autoignition did occur in conjunction with knock, the knock itself and the high-frequency pressure waves accompanying knock did not appear until an appreciable time after the autoignition.

All the investigations of combustion in an engine prior to that of reference 1, however, have suffered one disadvantage in common: the rate of taking photographs has been too slow and the actual occurrence of knock has been too rapid to be accurately observed.

APPARATUS

The combustion apparatus and the optical set-up for schlieren photography are described in detail in reference 1. Figure 1 shows the NACA combustion apparatus diagrammatically. At the time of taking all the photographs of combustion with four spark plugs presented in this report, the injection valve was placed in opening H of the cylinder head. (See fig. 1.) At the time of taking all the photographs presented in reference 1 and those of this report in which the combustion was with one spark plug, or with one spark plug and a hot spot, the injection valve was in opening J. For the photographs of combustion with four spark plugs, spark plugs were used in each of the openings J, F, G, and E, whereas for the photographs of combustion with only one spark plug, this plug was in position E, as in reference 1. When a hot spot was used, it was in opening F, as in reference 1. No other changes were made in either the combustion apparatus or the optical set-up between the time of taking photographs presented in reference 1 and the taking of those given in the present report.

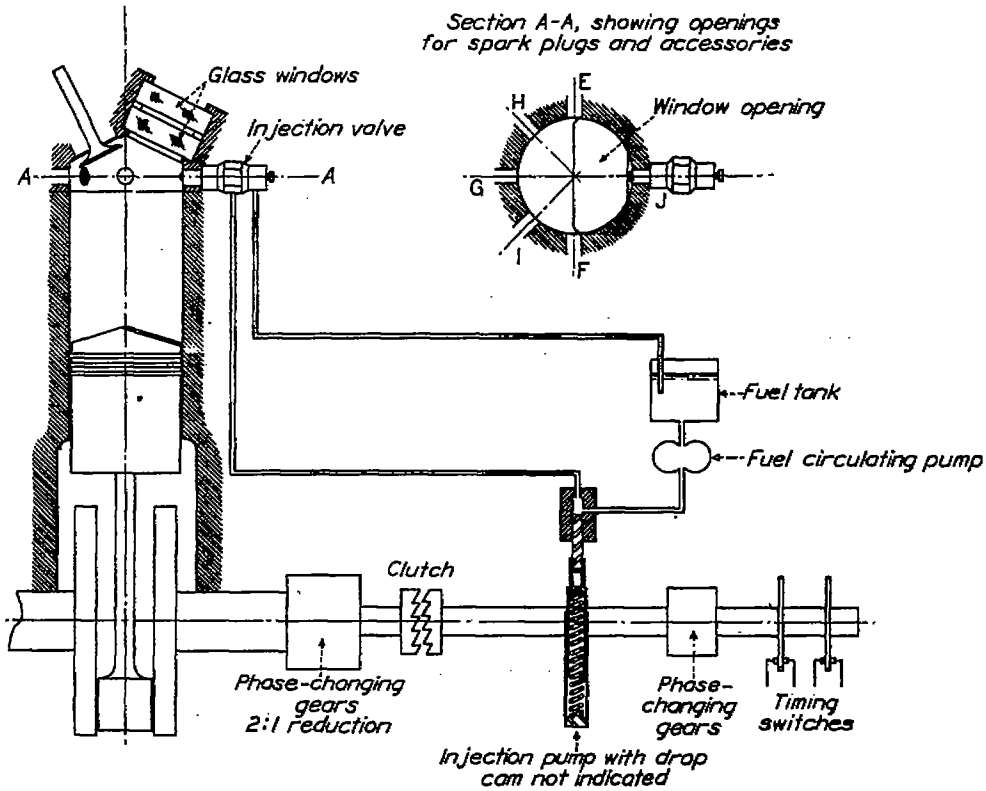


FIGURE 1.—Diagrammatic sketch of NACA combustion apparatus.

As in reference 1, the combustion apparatus was operated under its own power for only one cycle in each run, an entire series of photographs being taken of the combustion in the single cycle. The engine operating conditions were again kept constant as follows: Engine-coolant temperature, 250° F; compression ratio, 7.0; engine speed, 500 rpm; fuel-air ratio, approximately 0.08. With all photographs of combustion with four spark plugs, spark advance of spark plugs in E, J, and F positions was kept constant at 20° and spark advance of spark plug in G position was kept constant at 27°. Spark advance was made greater at G position in order to allow the flame front proceeding from this plug to arrive within the field of view at about the same time as the flame fronts from the other three plugs. With the photographs of combustion with one spark plug, spark advance was varied as shown in the figures.

The fuels used for the tests of the present report were C. F. R. reference fuel S–1 (a commercial grade of isooctane), C. F. R. reference fuels M–1 and M–2 (octane rating about 18), a blend of 80 percent S–1 with 20 percent M–2, and a blend of 50 percent M–2 with 50 percent 95-octane gasoline.

An optical indicator of the type described in reference 10 was used to obtain time-pressure records within the combustion chamber under conditions similar to those existing when photographs were taken. The optical indicator was mounted in a steel blank, which replaced the glass windows in the cylinder head. Because of this method of mounting, photographs and time-pressure records of the same combustion cycle could not be obtained with the apparatus available at the time of making the tests.

RESULTS AND DISCUSSION

NORMAL COMBUSTION

Some disagreement has existed as to whether combustion in a spark-ignition engine cylinder is completed in the flame front or is continued for a considerable distance back of the flame front. Although the photographs of reference 1 indicated the existence of a combustion zone of considerable depth in the direction of flame travel, attention was called in that paper to the possibility of explaining the apparent depth of the combustion zone on the basis of a curved flame of very small depth. The authors of reference 11 secured results from photographs and pressure records of combustion in a constant-volume bomb which lead them to believe that combustion continues for a considerable distance behind the flame front and that this distance decreases with increasing pressure.

Comparisons may be made between figures 2 to 5 of this report and figure 3 of reference 1 with the effect of pressure on depth of combustion zone in mind. These comparisons should, however, be used with caution, as will be explained later.

Figure 2 is a series of photographs showing nonknocking combustion with four spark plugs. This figure is comparable with figure 3 of reference 1, which was taken under similar conditions but with only one spark plug. The pictures are read from left to right through row A, then from left to right through row B, and so on. Thus, the order in which the pictures were taken is: A–1, A–2, A–3, . . . A–19, A–20, B–1, B–2, . . . J–19, J–20. In frame A–1 of figure 2 the flame that originated at the spark plug in opening F (fig.1) has just come into view. The dark area in the upper right portion of this frame, which is visible throughout rows A, B, and C, was caused by uneven illumination of the schlieren field and has no other significance. The uneven illumination was caused by imperfection in the optical set-up, possibly by warping of the mirror on the piston top. The flame coming from the spark plug in opening G (fig.1) first comes into view at about frame B–4 and the flames from spark plugs in E and J positions at about frame C–1.

In figure 3 of reference 1, during the early stages of flame travel, the mottled zone due to temperature gradients persisted for a very considerable distance back of the flame front, but the mottled zone became quite narrow in the direction of flame travel after the flame front had reached a position about halfway across the field of view. In that figure about half the contents of the entire combustion chamber, on a volume basis, had been reached by the flame front when the narrowing of the mottled zone occurred. In figure 2 of the present report, however, about half the contents of the combustion chamber have already been ignited when the flame from spark plug in G position (fig. 1) first comes into view. Yet the great depth of this flame, in the direction of flame travel, persists until well into row F, where more than half the contents of even that portion of the combustion chamber within the field of view has been ignited. This long persistence of the wide combustion zone is typical of flames that pass over the peak of the pent-roof piston.

If the depth of the combustion zone actually does decrease with increasing pressure, it should be expected to decrease during the later stages of flame travel because of the compression of the last part of the charge to burn by the parts that are ignited earlier. The abnormally long persistence of the wide mottled area with flames that have passed over the piston peak, however, cannot be explained on the basis of pressure. The gases on the far side of the combustion chamber are shielded from radiations originating on the opposite side of the piston peak during the early stages of flame travel. The absence of these radiations might have some effect on the rate of flame propagation or the rate of reaction that would

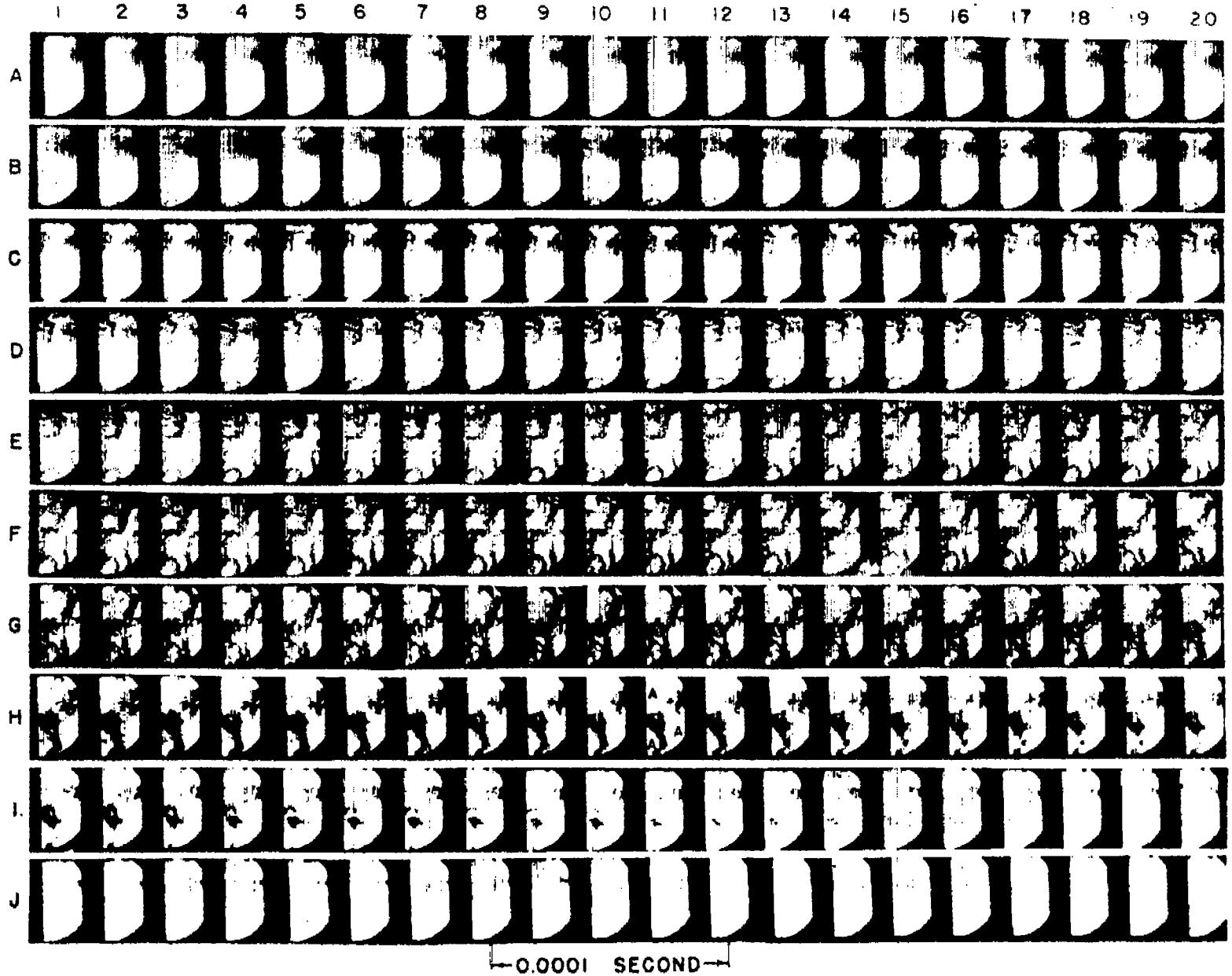


FIGURE 2.—High-speed motion pictures of a nonknocking explosion in a spark-ignition engine. Fuel, S-1; four spark plugs; spark advance, left-hand plug, 27°, other three plugs, 20°; A, regions already traversed by flame.

cause the abnormally long persistence of the wide mottled area. On the other hand, this persistence of the wide mottled area after passage of the flame over the piston peak can very reasonably be explained by the fact that the flame front could not be expected to be parallel to the line of sight immediately after passing around the corner at the piston peak.

Figures 3 and 4 of this report, figure 3 of reference 1, and figure 5 of this report constitute a series of substantially comparable records with spark advance of 0°, 10°, 20°, and 30°, respectively. For figures 3 and 4 of this report, the fuel was a blend of 80 percent S–1 with 20 percent M–2; for figure 3 of reference 1 and figure 5 of this report, the fuel was S–1. In figure 4 of this report, moreover, there was very late after-ignition from a hot spot in F position (fig. 1), a condition that did not exist in the other three figures. The flame from the hot spot is first clearly visible at about frame I–7, at the lower edge of the frame. It is believed, however, that none of the differences other than spark advance are important as concerns the depth of the mottled zone in the direction of flame travel.

In figures 3 and 5 of this report, with spark advance of 0° and 30°, respectively, the mottled zone never becomes so narrow as it does in figure 4 of this report and in figure 3 of reference 1, with spark advance of 10° and 20°, respectively. In figure 3 of this report, moreover, the entire combustion took place after top center, while in figure 5 the combustion was completed about 10° before top center. In figure 4 of this report the extreme narrowing of the combustion zone occurred substantially earlier in the flame travel than in figure 3 of reference 1, and this narrowing of the combustion zone did not persist to the end of the flame travel as it did in figure 3 of reference 1. The later broadening of the combustion zone in figure 4 is typical of the records taken under the conditions of figure 4 and has also been observed in a few cases with 20° spark advance. A consistent difference between the two conditions in this respect would be difficult to explain.

The comparisons of these figures indicate that the extreme narrowing of the mottled area occurs only with the piston within 10° or 15° of top center under the conditions of these tests. This fact is in agreement with the observation in reference 11 that the depth of the combustion zone decreases with increasing pressure. The increase in pressure, however, might cause increased uniformity of burning so that the flame front would exhibit less tonguing, and the narrowing of the mottled area with increased pressure might thus be explained on the curved-flame basis.

Some curvature of the flame front undoubtedly does exist and must certainly account for part of the width of the mottled area in the pictures. Such flame curvature, moreover, is variable and unpredictable. For this reason, no definite conclusions can be drawn from the comparisons of the figures. The indications are only suggestive.

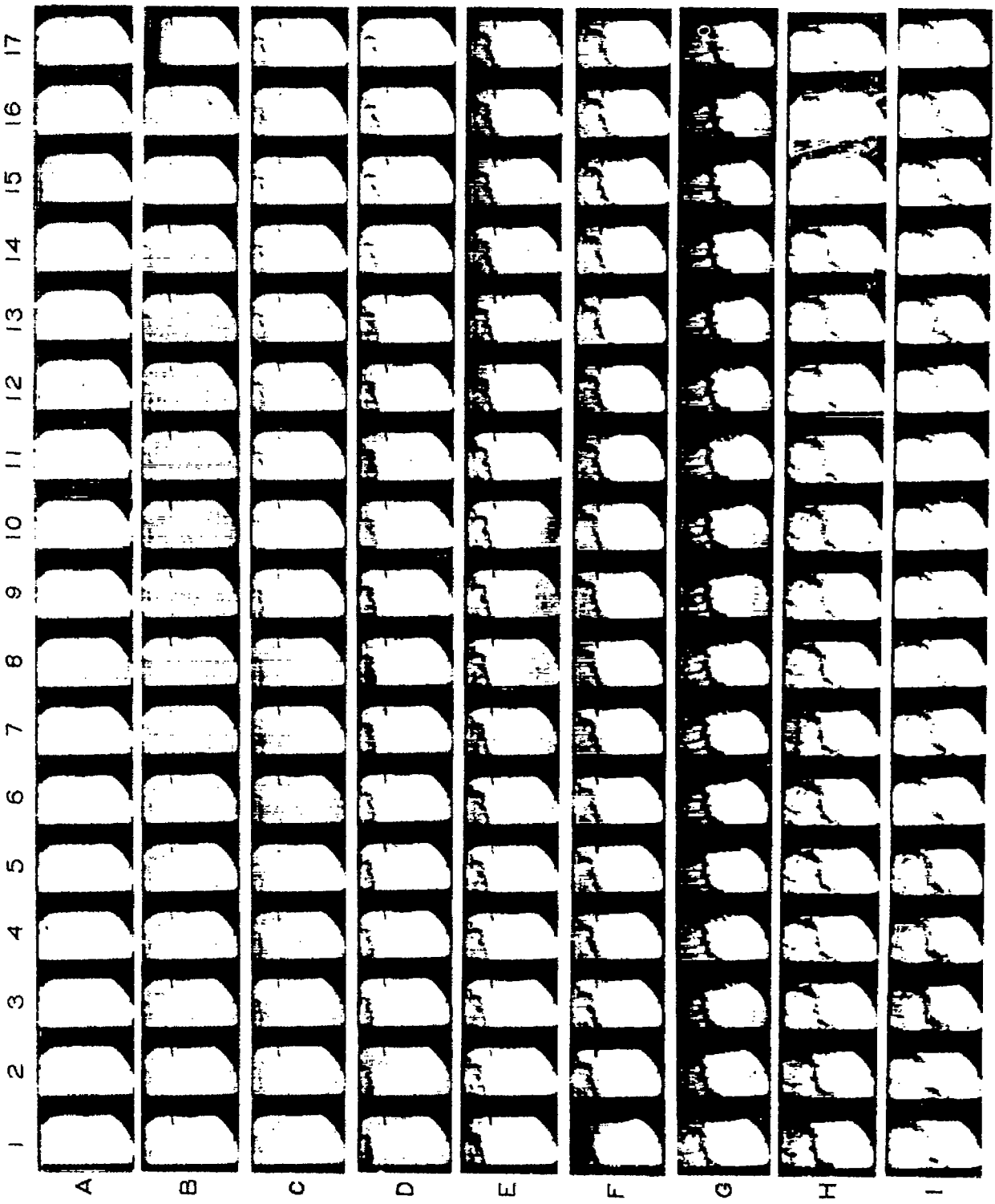
The authors of references 12 and 13 have presented analyses of motion-picture records correlated with time-pressure records in which they obtained fair agreement between mass inflamed as computed from the data of the motion pictures and mass burned as shown by the time-pressure records. Such agreement tends to support the assumption of a combustion zone of extremely small depth. There appears to be a possibility, however, that their pictures did not show the absolute flame front but an apparent flame front appreciably behind the true flame front. They treated the flame front, as it appeared in their pictures, as the position of the front at the end of exposure. This treatment would be strictly correct only if the time required for exposure were extremely short compared with the exposure time actually used.

There is a possibility that nearly all of the combustion is actually completed in the flame front but that certain portions of the reaction involving little energy release remain to be completed more leisurely.

KNOCKING COMBUSTION

At about frame H–11 in figure 2, all parts of the combustion chamber have been reached by the flame fronts. The light regions marked A in this frame are areas in which temperature gradients apparently no longer exist and combustion may be assumed to have been completed. These areas, however, are still extremely hot and would appear incandescent in any photograph that depended for its exposure on light originating in the combustion chamber. The mottled areas do not completely disappear from the pictures until about the end of row J, about 0.0012 second after the flame fronts have apparently reached all parts of the combustion chamber in frame H–11. This time interval is in great contrast with the corresponding period in a knocking combustion as shown in figures 6 and 7.

Figures 6 and 7 were taken under the same conditions as figure 2 but with fuels of progressively lower antiknock value. The fuel used for figure 6 was a blend of equal volumes of a 95-octane gasoline and C. F. R. reference fuel M–2. This blend was the same as used for figure 5 of reference 1, incorrectly reported in that reference as a blend of S–1 and M–2. Figure 6 of this report and figure 5 of reference 1 are comparable. The difference between them is in the number of spark plugs used and in the earlier ignition at one of the plugs in figure 6.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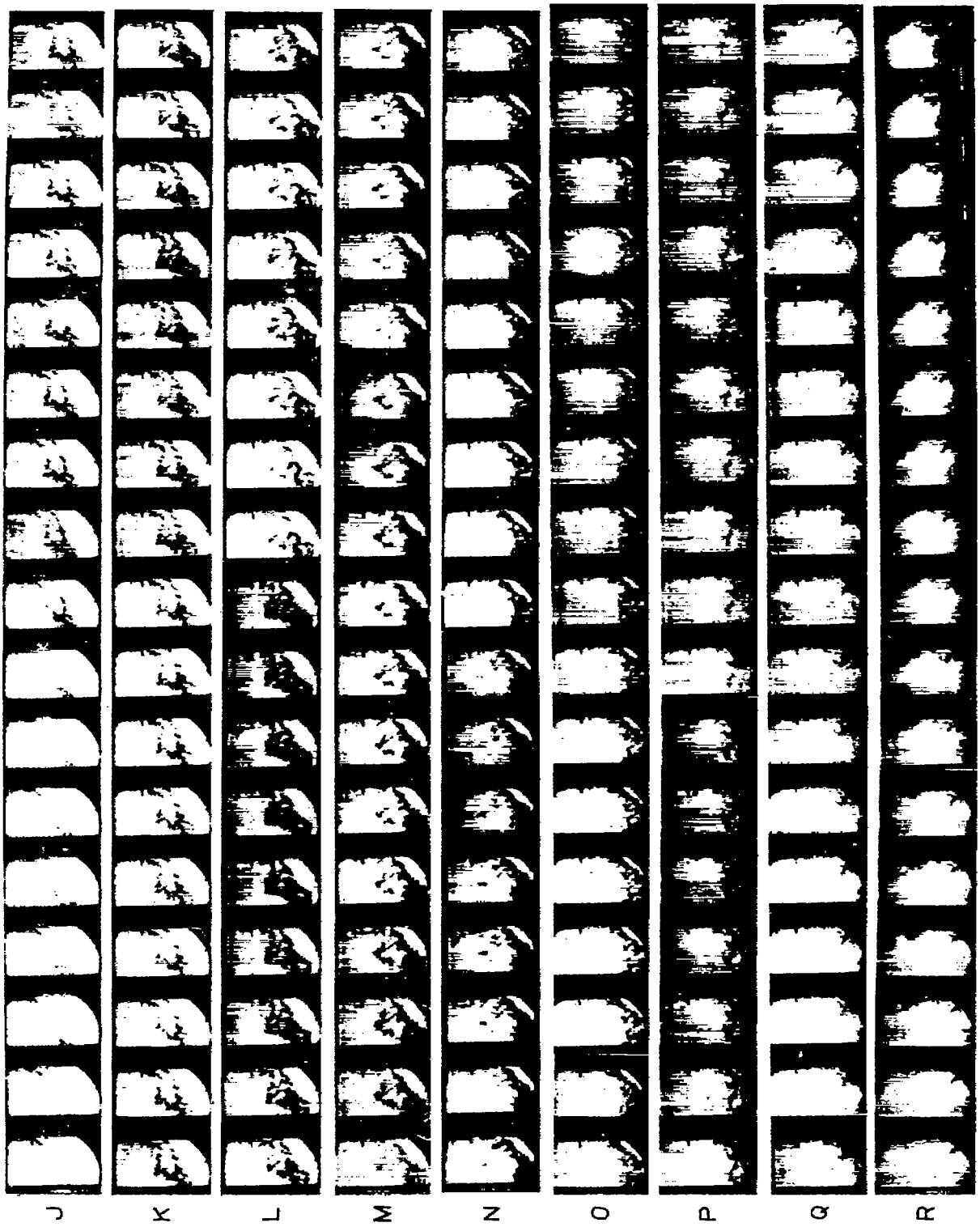
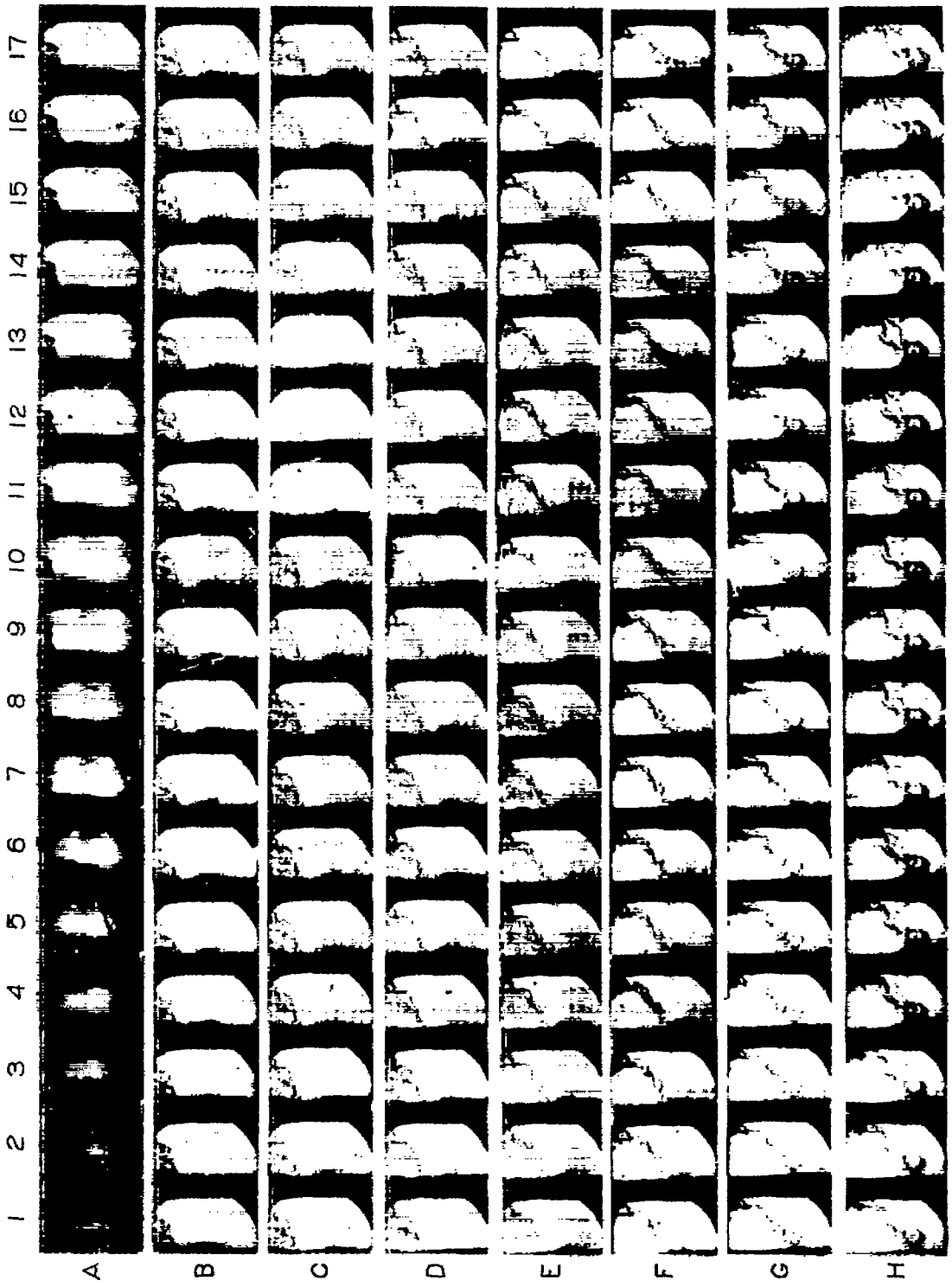


FIGURE 8.—High-speed motion pictures of a nonknocking explosion in a spark-ignition engine. Fuel, 50 percent M-1 with 20 percent M-2; one spark plug, spark advance, 0°.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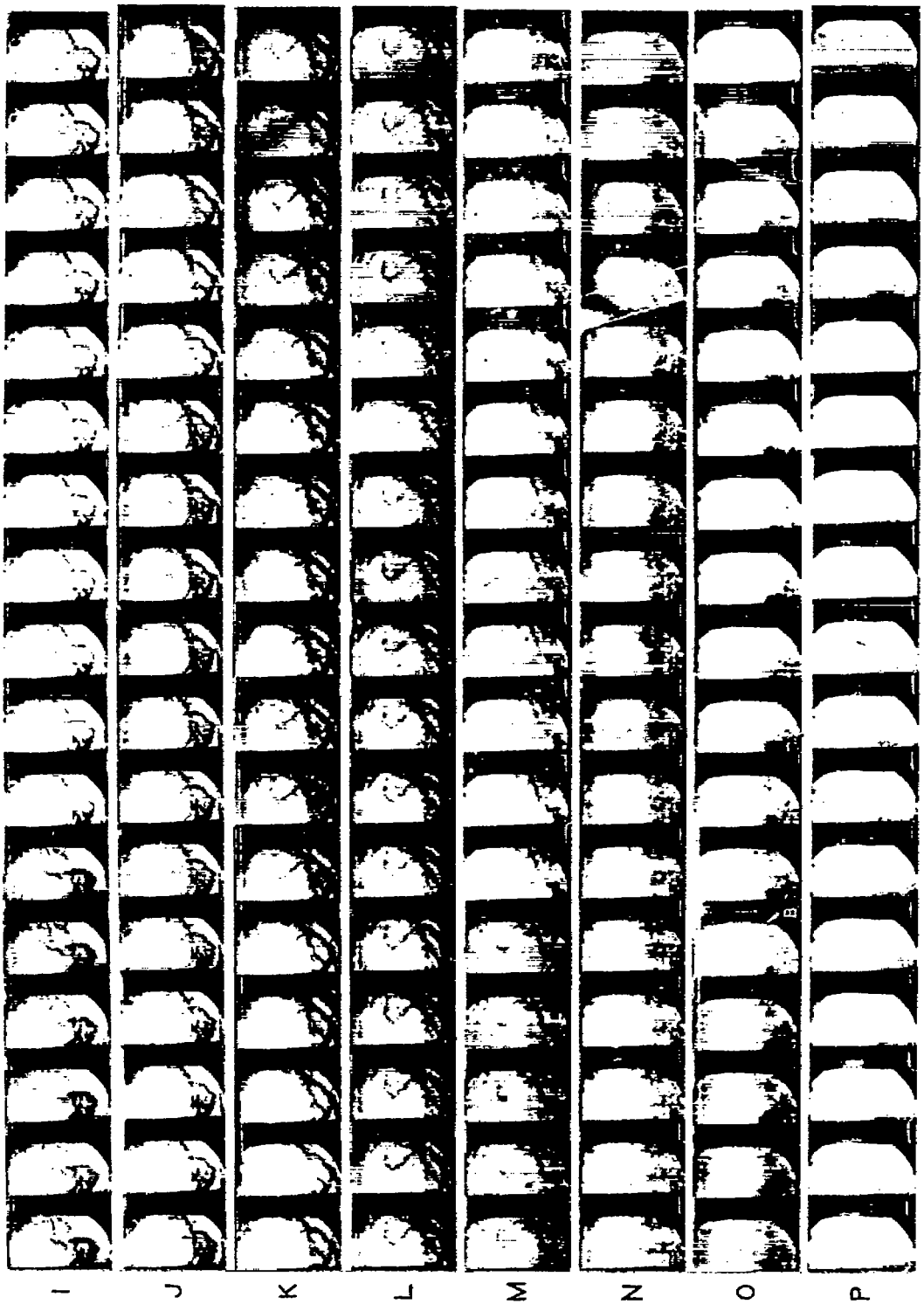

FIGURE 4.—High-speed motion pictures of an explosion in a spark-ignition engine with afterignition from hot spot and with very light knock. Fuel, 80 percent S-1 with 20 percent M-2; one spark plug; spark advance, 10°.

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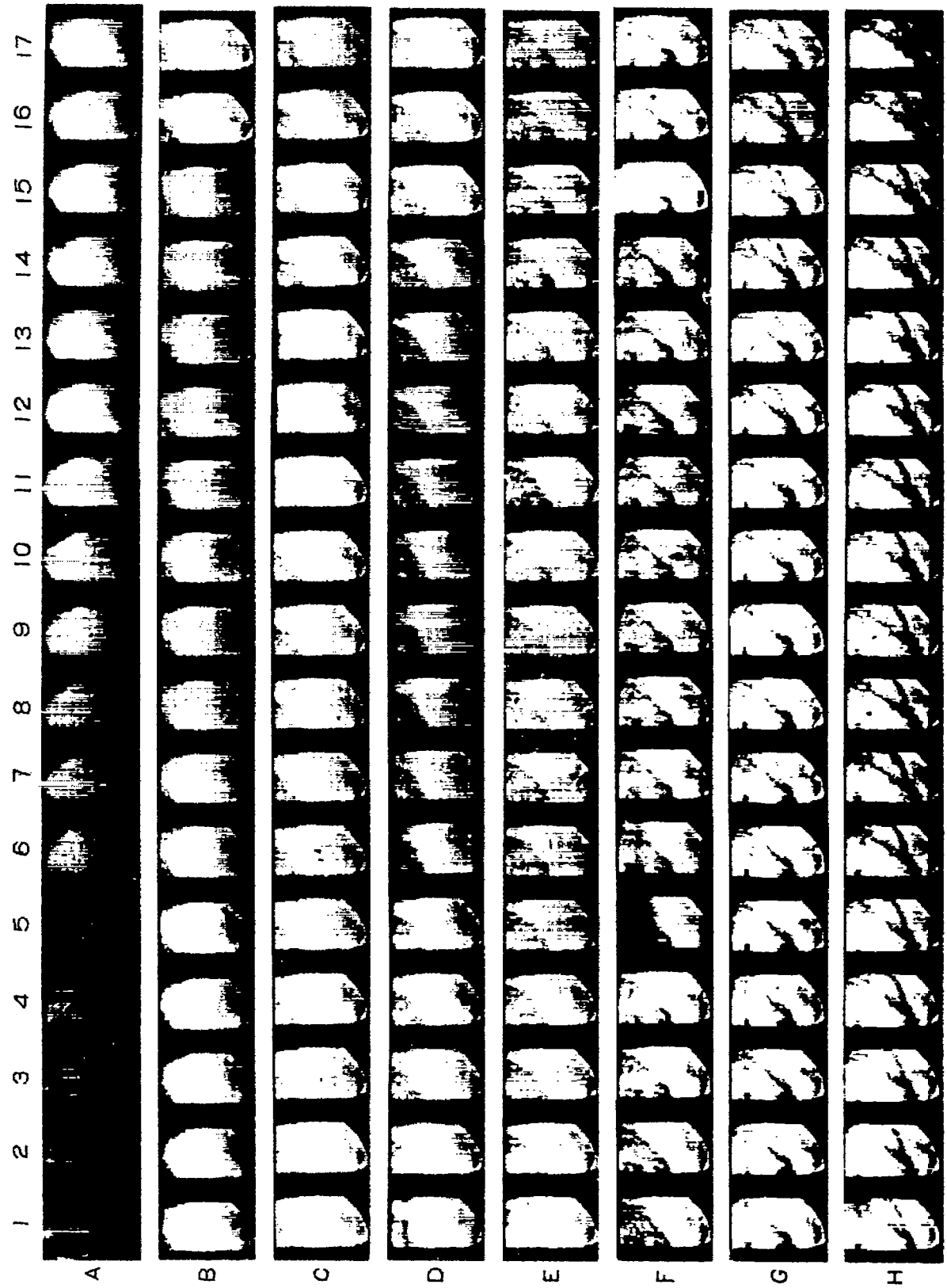
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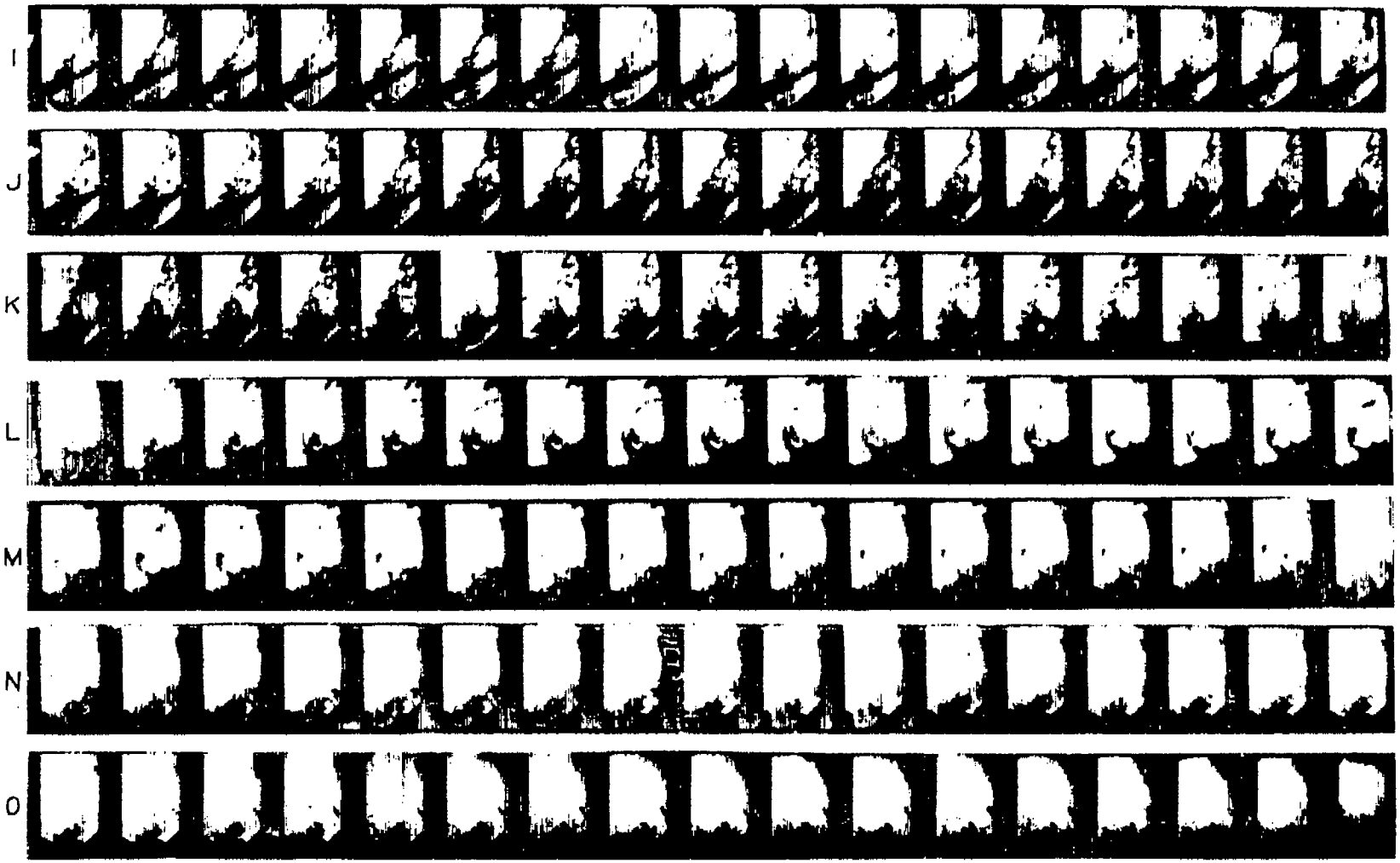


FIGURE 5.—High-speed motion pictures of a nonknocking explosion in a spark-ignition engine. Fuel, S–1; one spark plug; spark advance, 30°.

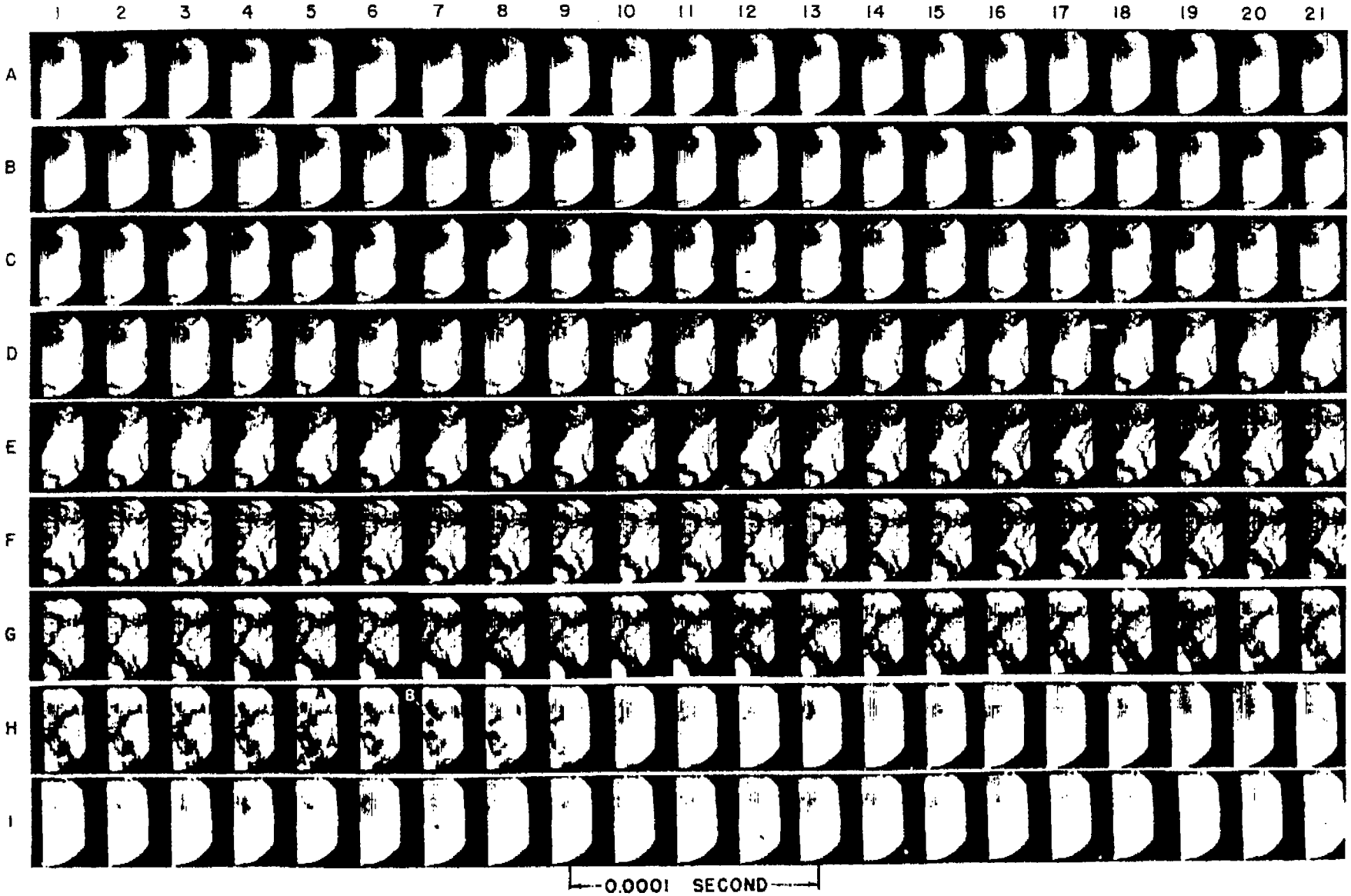


FIGURE 6.—High-speed motion pictures of a knocking explosion in a spark-ignition engine. Fuel, 50 percent 95-octane gasoline with 50 percent M-2; four spark plugs: spark advance, left-hand plug, 27°, other three plugs, 20°; A, regions already traversed by flame; B, blurring caused by knock.

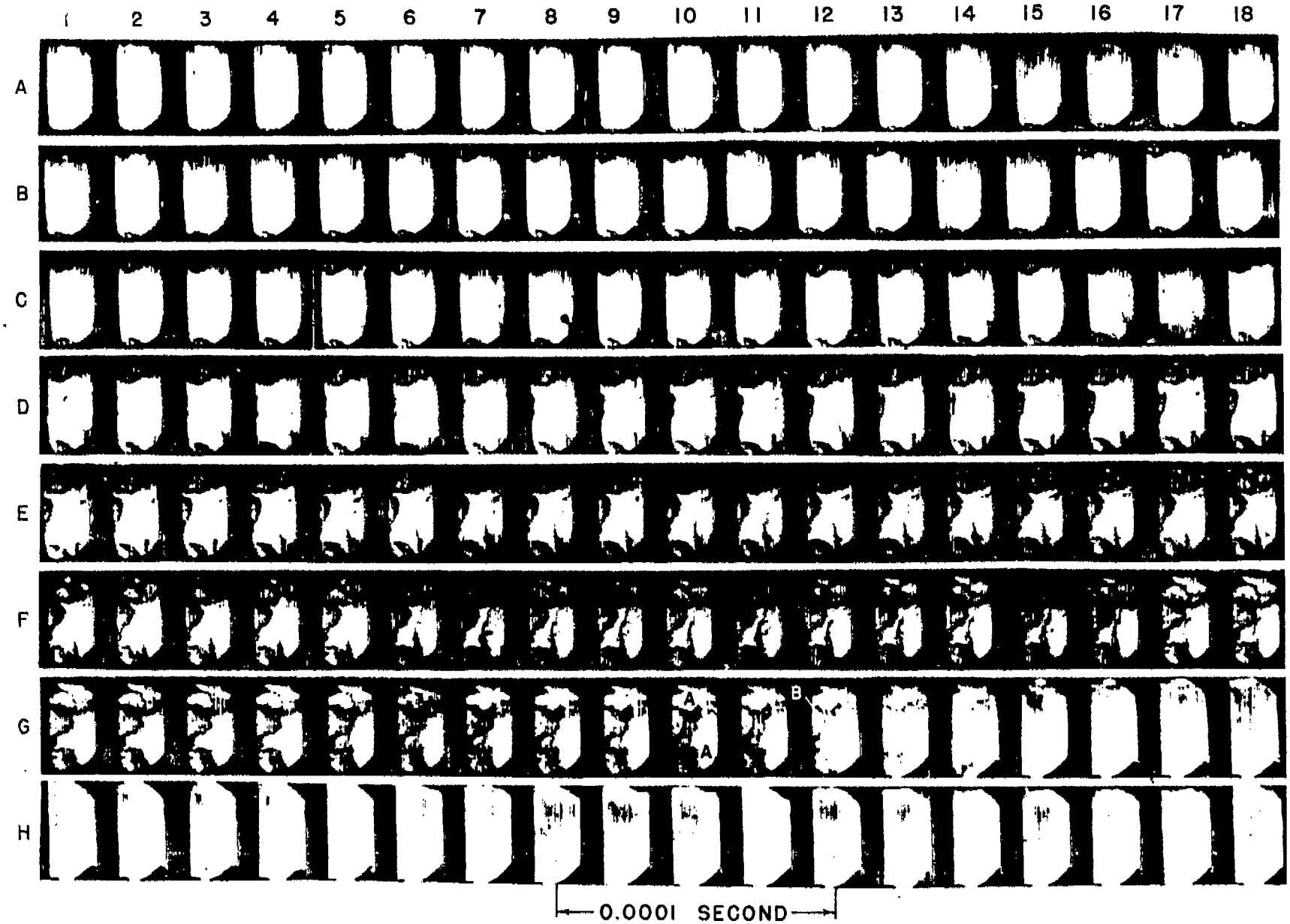


FIGURE 7.—High-speed motion pictures of a knocking explosion in a spark-ignition engine. Fuel, M-2; four spark plugs; spark advance, left-hand plug, 27°, other three plugs, 20°; A, region already traversed by flame; B, blurring caused by knock.

The areas marked A in figure 6, frame H–5, are regions in which temperature gradients have apparently ceased to exist and where combustion is probably complete. The knock is first visible in frame H–7 as a blur in the region designated by the letter B. By frame H–13 the knock has completely eliminated the mottled zone. This elimination of the mottled zone in 7/40000 (0.000175) second is in strong contrast with the very gradual fade-out of the mottled zone in the nonknocking explosion shown in figure 2. In figure 5 of reference 1, the mottled zone was eliminated by the knock in 1/40000 (0.000025) second, frames M–11 and M–12. It is obvious from the photographs that the knock in that case was much more violent than in figure 6 of this report. The difference, however, may possibly not be directly due to the use of one or of four spark plugs. Combustion began much earlier in the case of figure 6 and, in view of the very low engine speed, combustion may have proceeded much nearer to completion before severe conditions were reached a few degrees before top center, so that less energy was available for release during knock.

Figure 7 was taken under the same conditions as figure 6 except that a fuel, M–2, of still lower antiknock value, was used. In this figure knock is first visible in frame G–12 as a blurring in the region designated B. In this case the knock eliminates the mottled zone more quickly than in figure 6. At about frame G–13, moreover, a brilliant luminosity appears and this luminosity quickly develops throughout the visible portion of the chamber. This luminosity was not noticeable in figure 6. In frame G–13 and in some of the other frames, this luminosity is also visible below and to the right of the chamber. The appearance of the luminosity in this region and in the combustion chamber generally, with the heavier knocks, was explained in reference 1.

As with figure 5 of reference 1, when the photographs presented in figures 6 and 7 are projected as motion pictures, a violent bouncing of the gases is visible after occurrence of the knock. This bouncing of the gases is visible even when the knock is so light as not to cause the blurring that is visible in frame H–7 of figure 6 and frame G–12 of figure 7. In fact, the bouncing of the gases appears to be one of the most sensitive criterions of knock available.

An extremely light knock occurred in the combustion shown in figure 4. This knock resulted in a very slight blur in the region indicated by B in frame O–5. This blur can scarcely be detected in the reproduction shown in this report. When the original photographs of figure 4 are projected as motion pictures, however, the blur is seen to be unquestionably there. This knock occurred so late in the combustion process, and the ignition was so late, that the piston must have been far beyond top center. It would appear even possible that the conditions at the time of this knock were not so severe as they had been earlier in this same combustion process.

It is particularly important to note that the knock which appears at frame O–5 of figure 4 did not have the effect of eliminating the mottled zone as did the heavier knocks previously discussed. This fact does not seem to be consistent with the theory that the knock is simply a sudden completion of the burning. It is a considerable distortion of this theory to assume that in figure 4 at about frame O–5 the combustion suddenly partly completed itself, then slowed down again, and proceeded at the normal rate of nonknocking combustions. When the photographs of figure 4 are viewed as a motion picture, the impression is that a reaction occurs in the vicinity of frame O–5 which is very quickly completed and which leaves the gases bouncing but does not interfere with the normal combustion. This reaction, during the very short time of its existence, may have accelerated the normal process of combustion. Either it did not do so appreciably, however, or the normal combustion process dropped back to about the previous rate as soon as this reaction was over. With the heavier knocks, either the knock reaction so accelerates the normal combustion that it is very quickly completed or the knock is itself a very quick completion of the normal combustion.

If knock is assumed to be the same thing in one case as in another, the photographs suggest that knock is a sudden detonation of some substance which pervades the entire inflamed volume in greater or less concentration, that the concentration of this substance may determine the violence of the knock, and that the detonation of this substance accelerates the normal combustion process but does not bring it to a quick completion unless the concentration of the substance is sufficiently great. Such a substance would have to be stable under the conditions existing within the preknocking flame. Such substance might be a compound, compounds, or radicals.

The data presented herein are not sufficient to justify a definite conclusion that this hypothetical detonating substance is the true cause of knock. This explanation is simply suggested as one theory that appears to be consistent with the high-speed photographs.

Figures 6 and 7 show knocking combustions of very unequal severity. In figure 6, the last unignited portion of the fuel charge disappears in frame G–17, which is 11 frames previous to the first appearance of knock. On the other hand, in figure 7, which shows the more severe knock, the flame fronts never completely merge. Instead, beginning at about frame G–2, the unignited area becomes mottled spontaneously. In frame G–11 this spontaneous mottling of the unignited area has become so complete that this area cannot be distinguished from the area behind the flame fronts. Knock, however, did not occur until frame G–12. An entirely similar spontaneous darkening of the unignited zone, before knock occurred, is evident in figure 5 of reference 1. In that figure, in frame M–10, the darkening of this

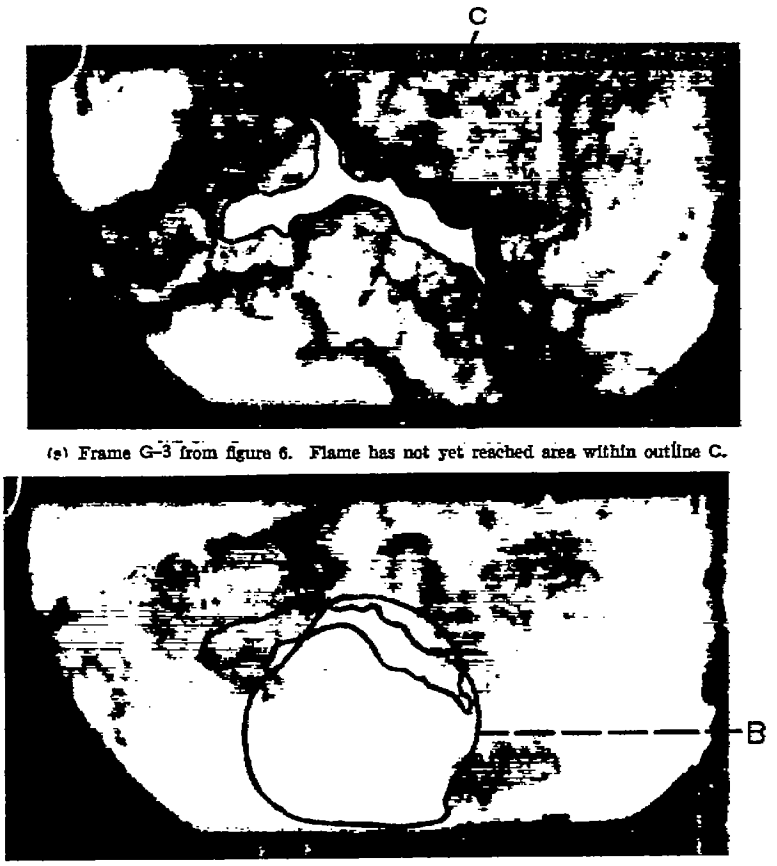
zone was remarkably dense; yet there was only the slightest evidence of the occurring of knock in the next frame, M–11.

It appears very likely that the mottling of the unignited zone is caused by autoignition, resulting from high temperature and pressure. Some reaction is unquestionably taking place in this region to cause the mottling. That this reaction results in a very rapid expansion of the gases in this zone is indicated by the fact that the flame fronts show practically no progress into this region after the spontaneous mottling begins. The rate of expansion in the unignited zone appears to be of the same order of magnitude as the rate of expansion of the gases behind the flame fronts. This fact would seem to indicate an ignited condition rather than a slow preflame combustion.

In figure 6 it may be argued that at the time knock occurred in frame H–7 there were pockets of unignited gas not visible because of tonguing of the flames and that the knock is due to autoignition of these pockets. On the other hand, in frame G–11 of figure 7 of this report and in frame M–10 of figure 5 of reference 1, it does not appear reasonable to suppose that there are any pockets that have not autoignited or that, if there were such pockets, their autoignition would be any different from the autoignition that was seen to take place previous to these frames. Knock, however, had not yet occurred in these frames.

These considerations do not appear to be consistent with the theory that knock is identical with autoignition of the end gas. The photographs do show, however, that C. F. R. reference fuels M–1 and M–2, which have a greater tendency to knock than isooctane, also have a greater tendency to autoignite. An attempt will be made later to determine whether there are fuels having a tendency to autoignite without the tendency to knock, with a view to finding more definitely whether the two phenomena are entirely unrelated.

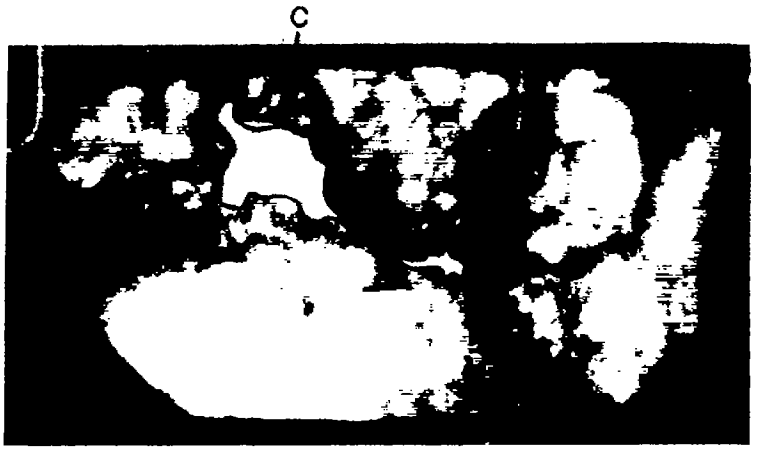
The pictures have even caused the question to be raised as to whether the knock ordinarily originates at the exact location of the end gas. In figure 8 are presented enlarged views of two frames, G–3 and H–7, from figure 6. Frame G–3 was exposed while a considerable part of the gas mixture had not yet been reached by the flame fronts. This part of the mixture is outlined with ink and designated C in the enlarged view of frame G–3 in figure 8 (a). An identical outline has been superposed on the enlarged view of frame H–7 in figure 8 (b). In this same frame the blurred region is outlined with ink and designated B. It will be noted that the center of the area B is considerably below the end-gas outline.



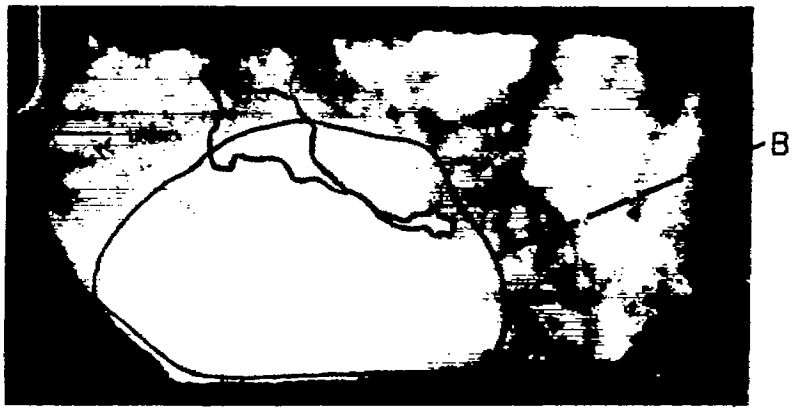
(a) Frame G–3 from figure 6. Flame has not yet reached area within outline C.

(b) Frame H–7 from figure 6. Knock has just occurred. Blurring within outline B is caused by knock.

FIGURE 8.—Two periods in the course of a knocking explosion in a spark-ignition engine.



(a) Frame G-1 from figure 7. Flame has not yet reached area within outline C.



(b) Frame G-12 from figure 7. Knock has just occurred. Blurring within outline B is caused by knock.

FIGURE 9.—Two periods in the course of an explosion with heavy knock in a spark-ignition engine.

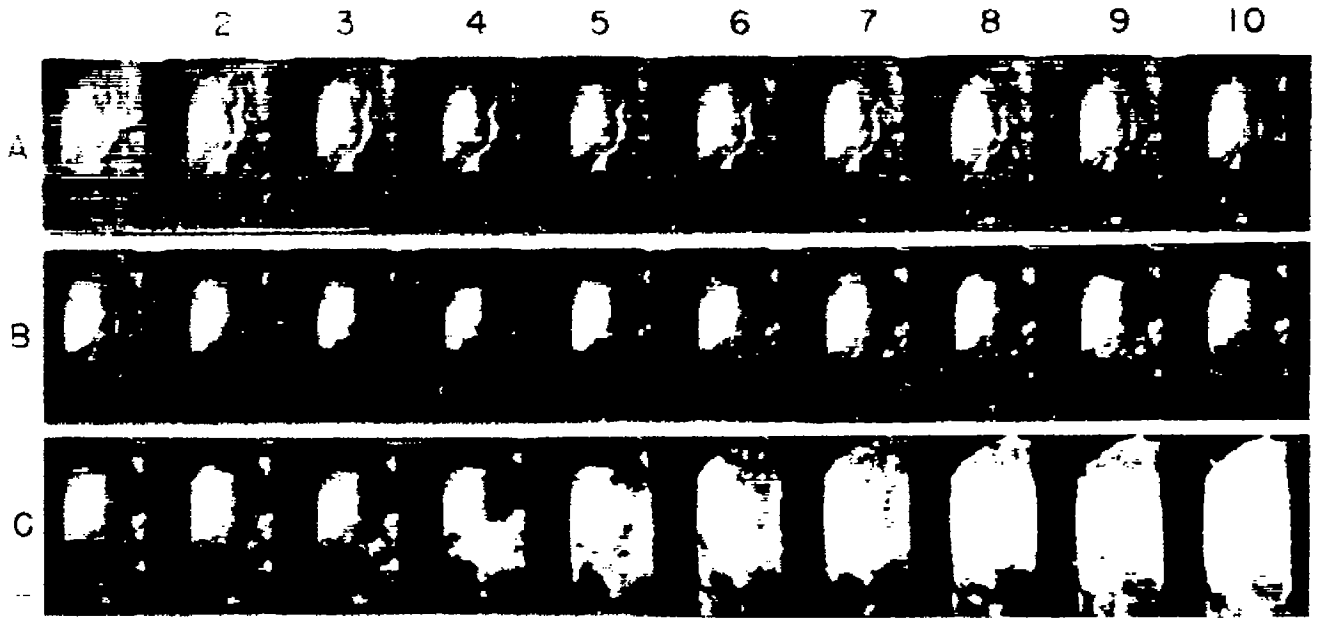


FIGURE 10.—High-speed motion pictures of portion of a knocking explosion in a spark-ignition engine. Fuel, M-1; four spark plugs; spark advance, right-hand plug, 27°, other three plugs, 20°.

Figure 9 presents a similar comparison of frames G–1 and G–12 from figure 7, with the same result. These results are typical results for this engine, operating with four spark plugs, with the camera running in its forward direction. The camera has a focal-plane-shutter effect that would tend to draw the blurred region below the end-gas zone in figures 8 and 9. The displacement appears to be greater, however, than would be explained by the focal-plane-shutter effect that does exist. The focal-plane-shutter effect is negligible for all phenomena seen in the pictures other than knock because of the slower occurrence of these phenomena.

camera in reverse, the blurring had the appearance of developing simultaneously throughout the chamber. The series presented in figure 10 was the only one in which there was any success in locating the apparent origin. This fact suggests that, in the particular engine used and with the engine conditions that existed in these tests, the knock tended to occur very near the bottom of the window. If the knock did occur at this position, the focal-plane-shutter effect with the camera running forward could not draw the knock below this position whereas, with the camera in reverse, the focal-plane-shutter effect could draw the knock upward or

(a) Frame A–3 from figure 10. Flame has not yet reached area within outline C.

(b) Frame C–4 from figure 10. Knock has just occurred. Blurring and luminosity within outline B are caused by knock.

FIGURE 11.—Two periods in the course of an explosion with heavy knock in a spark ignition engine. Camera in reverse.

Figure 10 presents a few frames of a series that was taken to check the effect of the focal-plane shutter on the apparent origin of the knock. This series was taken under exactly the same conditions as that of figure 7 except that C. F. R. reference fuel M–1 was used and the camera was operated in reverse, in order to reverse the focal-plane-shutter effect. The knock appears as a brightly illuminated and blurred region in frame C–4. Frames A–3 and C–4 of figure 10 are compared in figure 11. As would be expected, because of reversal of the focal-plane-shutter effect, the blurred area in this case is somewhat above the portion of the end gas that is in the same side-to-side position. This series is, however, not typical of other series taken with the camera running in reverse. In general, with the

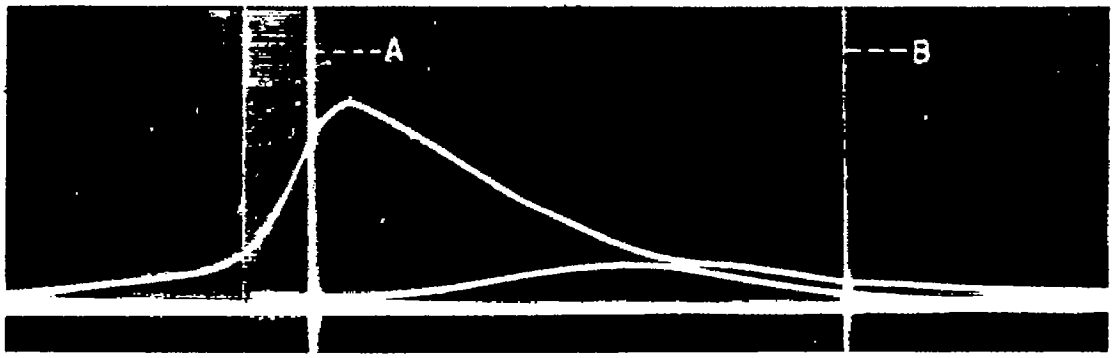
give it the appearance of occurring simultaneously throughout the chamber, depending on the propagation speed of the knock.

It must be admitted that the attempt to locate the origin of the knock with the NACA high-speed camera has produced inconclusive results up to the present time. Until a camera of higher speed or some other means has thrown more light on this point, however, there appears to be reason for some skepticism as to whether knock always occurs at the exact location of the end gas. Repeated observation of hundreds of shots as motion pictures has left the impression that knock may originate at any point within the mottled area in the pictures, whether this point be within the end gas or not.

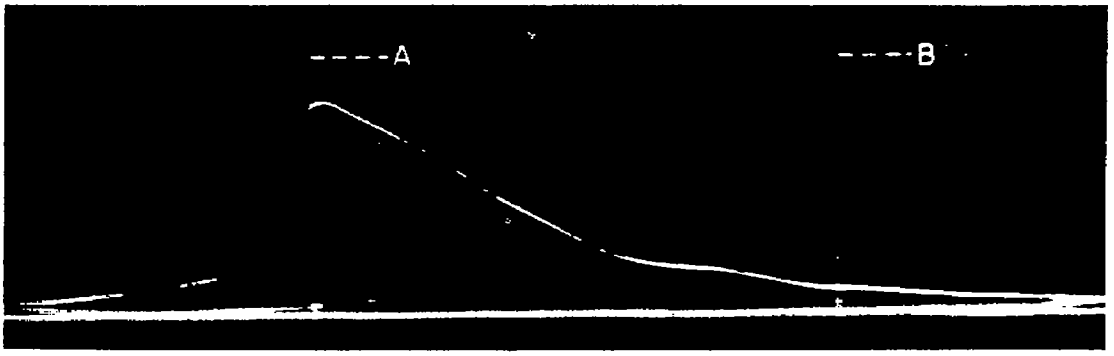
TIME-PRESSURE RECORDS

In figures 12 and 13 are presented time-pressure records taken with the optical indicator under conditions matching those of some of the photographs presented in this report and in reference 1. It should be emphasized that these records are not of the same combustion cycles represented by the photographs but of similar cycles. In any of the time-pressure records where vertical lines A and B appear, the line A is the record of a spark marking top center and the line B is the record of a spark marking the crank position 90° after top center.

The conditions of the record of figure 12 (a) correspond to those of figure 3 of reference 1; the record of figure 12 (b), to those of figure 7 of reference 1; and the record of figure 12 (c), to those of figure 2 of this report. As far as the time-pressure records or the photographs are concerned, the effect of a hot spot appears to be the same as that of a spark plug if the hot-spot temperature is such as to ignite the gases at the same time as the occurrence of the spark. Consequently, figure 12 may be regarded essentially as a comparison of results with one, two, and four spark plugs. With increase in the number of spark plugs, the pressure rise is seen to be progressively steeper, with the maximum pressure occurring progressively earlier relative to the crank angle.



(a) Fuel, S–1; one spark plug; spark advance, 20°.



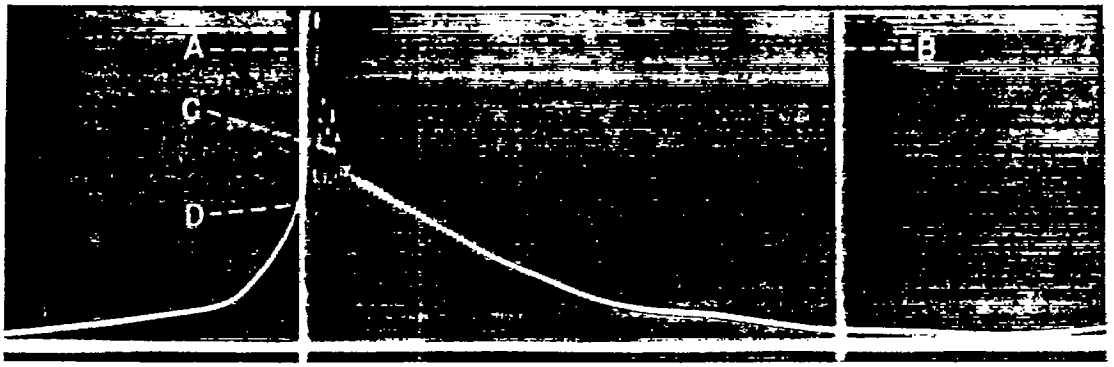
(b) Fuel, S–1; one spark plug with preignition from hot spot; spark advance, 20°.

(c) Fuel, S–1; four spark plugs; spark advance, 20° on three plugs, 27° on fourth plug.

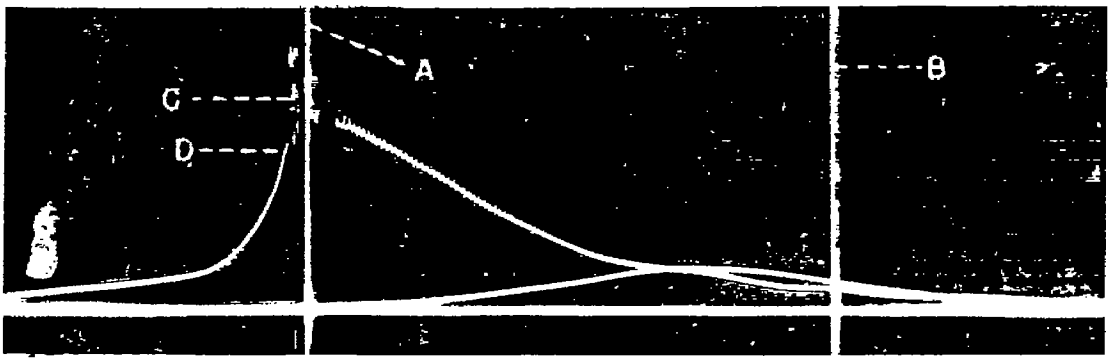
FIGURE 12.—Indicator cards for nonknocking explosion in a spark-ignition engine.

The time-pressure records of figure 13 are for knocking explosions. The correspondence of conditions is between figure 13 (a) and figure 5 of reference 1, between figure 13 (b) and figure 8 of reference 1, between figure 13 (c) and figure 6 of this report, and between figure 13 (d) and figure 7 of this report.

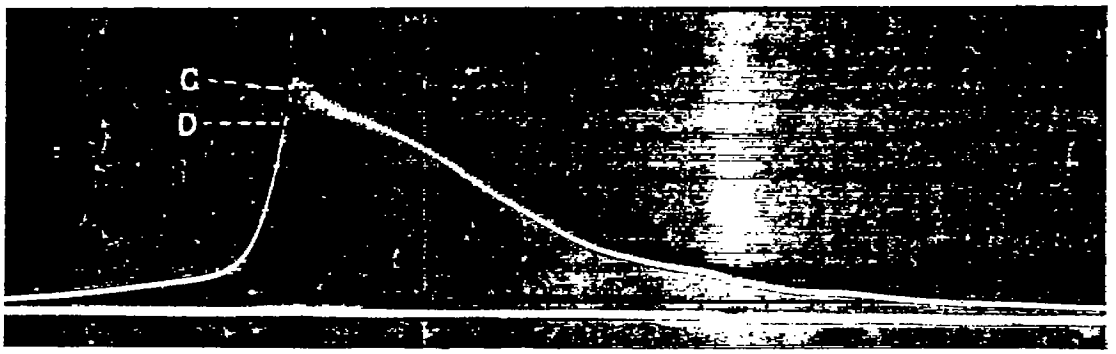
Comparison of the record of figure 13 (b) with the



(a) Fuel, 50 percent 95-octane gasoline with 50 percent M-2; one spark plug; spark advance, 20°.



(b) Fuel, 50 percent 95-octane gasoline with 50 percent M-2; one spark plug with preignition from hot spot; spark advance, 20°.



(c) Fuel, 50 percent 95-octane gasoline with 50 percent M-2; four spark plugs; spark advance, 20° on three plugs, 27° on fourth plug.

(d) Fuel, M-2; four spark plugs; spark advance, 20° on three plugs, 27° on fourth plug.

FIGURE 13.—Indicator cards for knocking explosion in a spark-ignition engine.

records of figures 13 (a) and 13 (c) shows that the hot spot again has the same effect as a spark plug in causing a steepening of the pressure rise and an advance of the position of maximum pressure. The comparison also shows that the hot spot has caused the knock to occur earlier in the record of figure 13 (b) than in that of figure 13 (a).

The violent pressure fluctuations, designated C in the four knocking time-pressure records, are characteristic of knocking explosions in a spark-ignition engine. Some of the fluctuations in these records have been touched up with white ink. The white ink has been placed, however, only on points where a trace is unmistakably present on the original film but too faint to reproduce in the prints. In agreement with the photographs, the time-pressure records show very violent and about equal amplitudes of vibration for the case of one spark plug with an equal mixture of 95-octane gasoline and M-2 and the case of four spark

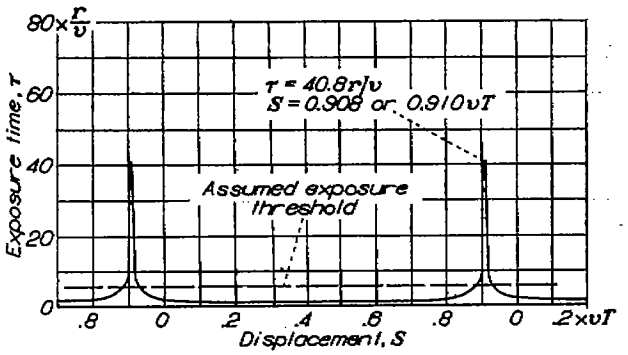


FIGURE 14.—Variation of displacement with exposure time for oscillatory motion superposed on constant-velocity motion. Maximum velocity of oscillatory motion equal to the constant velocity.

plugs with M-2. Also in agreement with the photographs, the records show a considerably smaller amplitude of pressure fluctuations for the case of four spark plugs with the equal mixture of 95-octane gasoline and M-2. They show an intermediate violence for the case of one spark plug and a hot spot, using the blended fuel.

The most interesting feature of these time-pressure records, as regards the theories of knock, is the appearance of pressure fluctuations of very small amplitude, or bright spots in the trace, a short time before the appearance of the violent fluctuations. These slight fluctuations are visible in each of the traces of figure 13 and in each case are designated D. They are, however, particularly clear as bright spots D in figure 13 (d). The two bright spots so clearly visible in this record have not been retouched. They could apparently only be caused by a small-amplitude vibration of the mirror of the optical indicator, the maximum downward velocity involved in such vibration being of the same order of magnitude as the motion of the mirror caused by the continuous pressure rise.

The darkening of a photographic emulsion is known to be very nearly a function of light intensity multiplied by time of exposure. If the upward motion of the light beam in the optical indicator is assumed to be the superposition of a constant velocity v, due to a continuous pressure rise, upon a sinusoidal vertical oscillation having a maximum velocity $v_{max}=v$, then the actual velocity V of the beam at any instant t, measured from the last time t_0 that the sinusoidal oscillation was at its lowest point, is expressed by the equation

$$V=v\left(1+\sin\frac{2\pi t}{T}\right) \tag{1}$$

where T is the period of the sinusoidal oscillation. The time of exposure τ of any point on the photographic emulsion swept over by the center of the beam will be expressed by the equation

$$\tau=\frac{2r}{v\left(1+\sin\frac{2\pi t}{T}\right)} \tag{2}$$

where r is the radius of the spot of light formed by the beam on the emulsion. Equation (2) will be quite accurate with extremely small values of r except where $V=0$, when it becomes indeterminate. Inasmuch as the intensity of the beam is constant, the darkening of any point in the trace will be practically a function of τ alone, on the assumption that the velocity V is very great relative to the movement of the film.

The displacement S of the beam from the position that it occupied at time t_0 is expressed by the equation

$$S=vt+\frac{vT}{2\pi}\operatorname{vers}\frac{2\pi t}{T} \tag{3}$$

If equations (2) and (3) are solved for various values of t and the resulting values of τ are plotted against the values of S, the curve shown in figure 14 is obtained. The important characteristic to observe in this curve is that it peaks very sharply in the regions where the sinusoidal oscillation has its maximum velocity downward. If the fact is kept in mind that the trace of figure 13 (*d*) is a positive print, the curve of figure 14 demonstrates graphically how the two bright spots designated D in figure 13 (d) may be interpreted as being the result of a very high rate of pressure rise at the indicator diaphragm combined with a sinusoidal fluctuation of pressure. A sinusoidal fluctuation of pressure could be caused by a system of compression waves traveling back and forth across the combustion chamber and being reflected at each collision with the chamber walls. A reflected wave could cause the bright spots in the traces without involving a sinusoidal variation of pressure at the diaphragm of the optical indicator. Variation according to any one of a number of laws would tend to have the same effect as long as the oscillation involved a maximum downward velocity of the light beam of the same order of magnitude as the constant upward velocity caused by the continuous

pressure rise. Indeed, the effect would be greatest with a shock wave in which the pressure rise is extremely rapid and the pressure drop is nearly linear with time.

The natural frequency of the indicator diaphragm, about 9000 cycles per second, undoubtedly has some influence on the appearance of the bright spots in the traces. The diaphragm, however, would never start vibrating with its natural frequency to cause the bright spots unless it received a shock in the form of either a sudden increase or a sudden decrease in the rate of pressure rise, which is the equivalent of a pressure fluctuation superposed on a continuous pressure rise. If the diaphragm were set vibrating at its natural frequency by a single shock, moreover, the first cycle of vibration would be of the greatest amplitude and each succeeding cycle would be of successively smaller amplitude. The bright spots in the trace would be equally spaced, if the slope of the trace were constant.

The three bright spots in the trace of figure 13 (c) violate both the requirement of decreasing amplitude and that of equal spacing. The first (lowest) of these three spots is faintest, indicating the least amplitude of vibration. The third (highest) of the three spots is brightest, indicating the greatest amplitude of vibration. A fainter spot might be due to a vibration of greater amplitude than that of a brighter spot, if the maximum beam velocity due to the vibration in the case of the fainter spot were greater than the constant upward velocity of the beam due to continuous pressure rise. The slope of the trace in figure 13 (c), however, appears to be not too steep to permit detection of any downward motion of the beam, and each of the three spots has the appearance of having involved no downward motion.

The slope appears to be constant through the three spots of figure 13 (c); yet the second and third spots are farther apart than the first and second. The distance between the first and second spots corresponds to the natural frequency of 9000 cycles per second, so that these two spots might have been caused by a single shock except that, in that case, the first spot should have been the brighter. The distance between the first and the third spots corresponds to the fundamental frequency of the vibrations following the knock in this trace, which is presumably the natural frequency of vibration of the gases in the combustion chamber. On the basis of this reasoning, the indicator diaphragm appears to have received at least two and probably three separate shocks just before the first violent pressure fluctuation.

In the case of figure 13 (a), three bright spots are visible. They are difficult to analyze because two of them are superposed on the timing line. The second one, however, appears to be brighter than the first. This fact indicates the probability of at least two shocks in this case. In figure 13 (b), only one visible shock can be seen.

At first glance, the two bright spots in figure 13 (d) seem to indicate that the vibration of the indicator diaphragm was of constant amplitude for at least two cycles just before knock occurred, because the two bright spots look very nearly alike. Possibly, at the time of exposure of the lower of these spots, the maximum downward velocity due to oscillation of the beam was a little less than the constant upward velocity due to continuous pressure rise and, at the time of exposure of the upper spot, the maximum downward velocity due to oscillation was a little greater than the constant upward velocity. Thus, the beam may have gone rapidly upward to the bottom of the lower spot, slowly upward to the top of the lower spot, rapidly upward to the top of the upper spot, slowly downward to the bottom of the upper spot, and finally violently upward into the real knocking vibrations. The appearance of the spots, however, suggests that the reverse is more likely true and that the second of the spots in this case may have been due to free vibration of the indicator diaphragm. The diaphragm very likely received only one visible shock in this case before the violent fluctuations began.

Time-pressure records have been taken with a piezoelectric pickup having a natural frequency many times greater than the frequency of the shocks indicated by the traces of figure 13. These records indicate shocks of the same type with time spacing of the same order as with the optical indicator.

The indicator traces suggest the idea that one or more small-amplitude pressure waves may be traveling back and forth through the combustion chamber just before the occurrence of knock. It appears consistent with all the traces of figure 13 to assume that these pressure waves, at first too small to be observed in the traces, travel back and forth across the chamber, increasing continuously in amplitude, at an increasing rate, until finally the increase in amplitude becomes extremely rapid, resulting in knock. A single such wave could cause shocks at the indicator diaphragm with nonuniform time spacing, if it did not travel in the same direction or if it did not follow the same course at each trip across the chamber. No evidence is yet available as to what might start such small-amplitude pressure waves. It would appear that, when knocking conditions are approached, these waves must either accelerate the combustion within their high-pressure regions in such manner as to build up the amplitudes of the waves or they must cause some reaction other than the normal combustion in such manner as to build up the amplitudes of the waves.

Photographs of violent knocks viewed as motion pictures have indicated a temporary retardation of flame travel shortly before the occurrence of knock, as indicated by the blurring of the pictures. This temporary retardation of flame travel may possibly be visual evidence of the existence of a wave of small

amplitude before knock. The retardation may instead be simply evidence of expansion of the end gas at too low a rate to register as a pressure wave on the indicator diaphragm caused by some preflame reaction in the end gas.

Evidence has been obtained indicating that the blurring in the high-speed photographs occurs simultaneously with the first violent fluctuation of the indicator. It therefore appears that the blurring cannot be associated with any of the small preliminary shocks.

Reflected pressure waves in the combustion chamber would move at too high a speed to be stopped by a camera having an exposure time of the order of 1/40000 second. A standing sinusoidal wave, however, of wave length equal to twice the diameter of the chamber might be expected to cause a periodic displacement of the configurations in the photographs from frame to frame as well as a periodic variation in the intensity of reaction as indicated by the density and sharpness of the mottling of the photographs.

When the original negative of row F and of the first 11 frames of row G of figure 7 is examined frame by frame on the projection screen, the periodic displacement of the configurations and the periodic variation of the reactions are distinctly visible. These phenomena are, however, extremely difficult to see in the reproductions as they appear in the figure. In cases of lighter knocks they are not so distinctly visible even on the projection screen. The phenomena might conceivably be visible even in pictures of nonknocking combustion, as the only evidence of incipient knock. They have not, however, been observed with any certainty with nonknocking combustion.

In cases such as that of figure 7, the periodic displacements are visible through considerably more than two or three cycles before the occurrence of knock, as indicated by the blurring of the pictures. This fact suggests the gradual build-up of a standing wave, the last two or three cycles before knock being the only ones of sufficient amplitude to register on the time-pressure trace.

The suggestion of the progressive build-up of a pressure wave might appear to be at variance with the previous suggestion that the knock may be the detonation of a substance which does not react in the normal combustion, a suggestion that is admittedly weakly supported. The wave, however, might possibly provide just the trigger action necessary to detonate such a substance under severe conditions of pressure and temperature.

Rothrock and Spencer (reference 2) have shown that an artificially produced pressure wave will not cause knock, even though such a wave is sufficiently intense to be registered on the time-pressure record, unless the conditions of temperature and pressure within the combustion chamber have already become so severe that knock might be expected to occur spontaneously. When the conditions were such that spontaneous knock might be expected to occur, however, they found that knock usually did occur simultaneously with the artificially produced pressure wave.

Another possible explanation of the shocks on the indicator diaphragm before knock is that certain minute portions of the charge reach knocking conditions a short time before the rest of the charge. Each of these minute portions of the charge may detonate as it reaches knocking conditions and may thus produce a mild shock wave without setting off the entire charge. This explanation differs from the one previously suggested in the fact that it supposes the waves before knock to be caused by the knocking reaction but not, in turn, to exert any influence on the knocking reaction. The observed displacements in the configurations, however, do not have such an appearance as to support this explanation; instead, they strongly suggest the reflected-wave theory.

CONCLUSIONS

1. Through the use of the NACA high-speed motion-picture camera and the NACA optical engine indicator new knowledge has been obtained concerning the phenomenon of fuel knock. The results strongly indicate the inadequacy of the commonly accepted autoignition theory of knock.

2. The photographs indicate that knock usually involves a sudden completion of combustion, although there is some indication that very light knocks may not always involve a sudden completion of combustion but that combustion may complete itself in the normal manner after knock has occurred. Time-pressure records, taken simultaneously with and having a determinable time relationship with the high-speed pictures, should be useful in clearing up this point.

3. There is indication of the gradual build-up of reflected pressure waves just before occurrence of knock. The simultaneous time-pressure records and high-speed pictures should shed further light on this point.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *December 9, 1941.*

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