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REPORT No. 622

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A PHOTOGRAPHIC STUDY OF COMBUSTION AND KNOCK IN A SPARK-IGNITION ENGINE

By A. M. ROTHROCK and R. C. SPENCER

1938

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By A. M. ROTHROCK and R. C. SPENCER

Langley Memorial Aeronautical Laboratory

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REPORT No. 622

A PHOTOGRAPHIC STUDY OF COMBUSTION AND KNOCK IN A SPARK-IGNITION ENGINE

By A. M. Rothrock and R. C. Spencer

SUMMARY

A photographic study of the combustion in a spark-ignition engine has been made, using both schlieren and flame photographs taken at high rates of speed. Although shock waves are present after knock occurs, there was no evidence of any type of sonic or supersonic compression waves existing in the combustion gases prior to the occurrence of knock. Artificially induced shock waves in the engine did not in themselves cause knock. The photographs also indicate that, although auto-ignition ahead of the flame front may occur in conjunction with knock, it is not necessary for the occurrence of knock. There is also evidence that the reaction is not completed in the flame front but continues for some time after the flame front has passed through the charge.

INTRODUCTION

Speculation and controversy concerning the nature and causes of combustion knock have existed from the very earliest recognition of knock as a problem associated with the spark-ignition engine. Various investigators have gradually added to the general fund of knowledge and, at the present time, it is generally accepted that combustion knock is associated with the last part of the charge to burn (references 1 and 2).

Early in 1936, the N. A. C. A. started a program of research on combustion in a spark-ignition engine, using the altered N. A. C. A. combustion apparatus. The preliminary results obtained from these tests are given in reference 3. A later investigation, reported herein, was carried out during the summer and fall of 1936. In the later study the physical phenomena accompanying knocking combustion were investigated by schlieren photography, high-speed motion pictures, and indicator cards.

APPARATUS AND METHOD

In the present tests, the N. A. C. A. combustion apparatus was used in conjunction with a high-speed motion-picture camera, an optical-type pressure indicator, and the N. A. C. A. spark-photography apparatus. The combustion apparatus (references 3 and 4) is a 5- by 7-inch single-cylinder test engine with a glass window in the cylinder head, so that the combustion may be studied photographically. The engine is motored at the test speed by an electric motor and is then fired once by injecting and igniting a single charge of fuel. The engine temperature is maintained constant by circulating hot glycerin through the engine. A diagrammatic sketch of the combustion apparatus is shown in figure 1. The cylinder head is of the pent-roof type, similar in shape to the one used by Schey and Young in the tests reported in reference 5. In the present design the space normally occupied by two valves on one side of the head is taken by the opening for the glass window. As the engine fires only once, the two remaining valves operate simultaneously and act both for exhaust and intake. The valves are timed to open 55° before bottom center on the power stroke and to close 35° after bottom center on the following compression stroke. Six spark-plug locations are provided in the cylinder head, affording alternate positions for the injection valve, the spark plugs, and the auxiliary fittings.

The ignition system employs a condenser discharge through an induction coil with the discharge occurring on "make" instead of "break" as in the conventional system. Maximum variation in timing with this system is about $\pm 1°$ of crankshaft rotation.

The observation window, roughly 2½ by 5 inches (fig. 1), consists of two heavy glass plates with an air space between them. Compressed air is admitted to the space between the plates.

The injection system, a cross section of which is included in figure 1, is spring-operated. The spring is held compressed by a rocker arm, holding the lapped plunger retracted and leaving a port uncovered in the side of the sleeve. Fuel is circulated under pressure by a primary pump through the sleeve and thence to the injection valve, which is arranged to permit continuous circulation of the fuel (reference 4). For the injection of the fuel, the rocker arm is released by a drop cam. The fuel is delivered to the injection valve at a pressure of about 2,500 pounds per square inch.

The fuel quantity is regulated by changing the length of the plunger travel. During most of the tests, a seven-orifice injection nozzle (fig. 2) was used. This nozzle is similar to the one used by Schey and Young in the work reported in reference 5. The injection valve was mounted opposite the intake valves so that the fuel was injected counter to the intake air flow. Injection was timed to start 20° after top center on the intake stroke and the injection period was about 120°.

The engine-jacket temperature was maintained at 250° F. throughout the tests. The compression ratio was 7.0. The injection started at 20° A. T. C. on the intake stroke and, for the full-load fuel quantity, lasted for about 0.015 second. For the tests at an engine speed of 500 r. p. m., the spark advance was 30° B. T. C. and, at 1,500 r. p. m., it was 20° B. T. C. The earlier spark was used at the lower speed to increase the tendency to knock.

Four fuels having different octane ratings were used in the tests: A commercial iso-octane with an octane number of 100, containing approximately 90 percent 2, 2, 4 trimethyl pentane; aviation gasoline to Army Specification Y–3557–6, having an octane number of 87; ordinary automobile gasoline having an octane number of about 65; and a special fuel having an octane number of 18. In addition, blends of the 18-octane fuel with the 65-octane gasoline were used, having estimated octane ratings of approximately 30, 40, and 50, a straight-line relationship for the mixtures having been assumed.

The pressure indicator has been described in reference 6. A steel blank, which fits into the window opening, is used for mounting the indicator directly in the combustion-chamber wall.

Three different types of photograph were taken: (1) High-speed 16 mm motion pictures; (2) streak schlieren photographs using a continuous light source and moving film, recording the combustion travel along a narrow slit across the chamber; and (3) spark schlieren motion pictures. The last method uses the same film-drum camera as the second, but the light for the schlieren photographs is furnished by a series of spark discharges and the entire window is photographed.

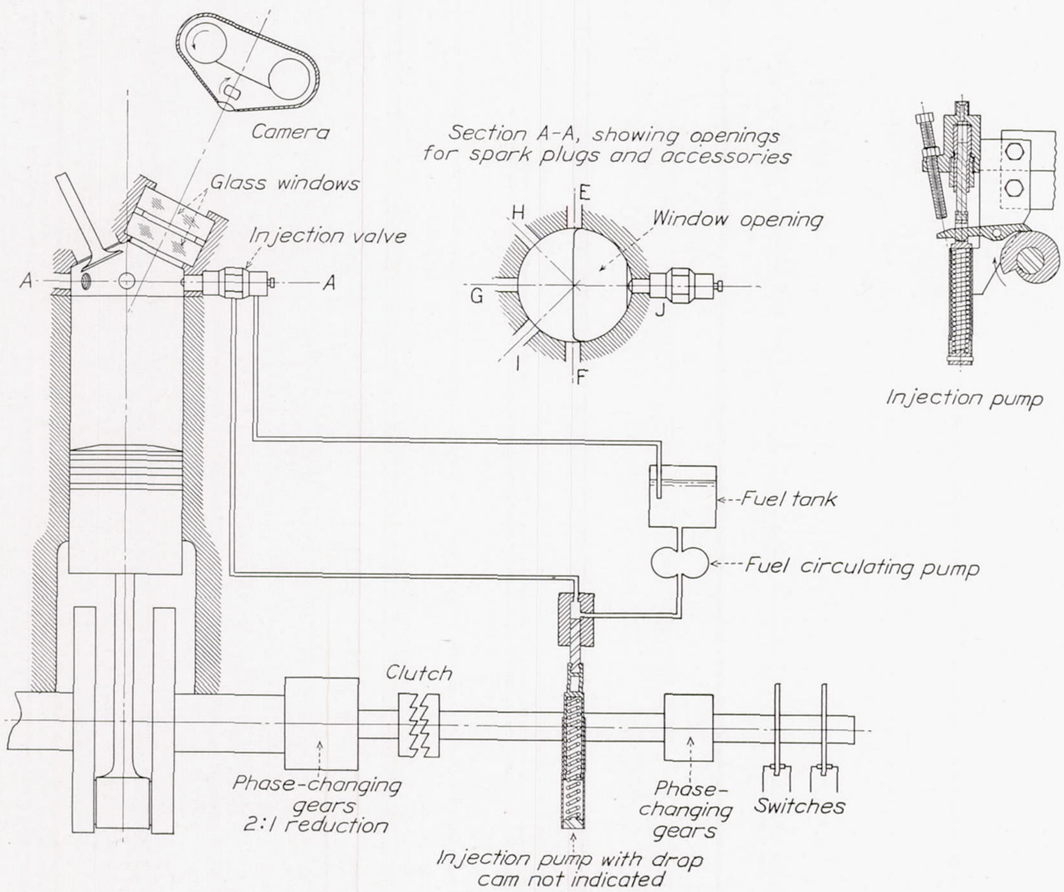

FIGURE 1.—Diagrammatic sketch of combustion apparatus.

The high-speed motion-picture camera (reference 7) was mounted above the combustion apparatus with the camera lens on the center line of the window and parallel to the plane of the window. The N. A. C. A. spark-photography apparatus has been described in reference 8. For these tests, the apparatus was used in conjunction with the schlieren optical arrangement (reference 9), by which slight differences in index of refraction of a gaseous medium may be made visible or photographed. The differences may be caused by air flow, by waves traveling through the medium, or by temperature differences.

During most of the tests in which the schlieren method was used, the film-drum camera of the spark-photography apparatus was used in conjunction with a high-intensity arc light. The optical arrangement is shown diagrammatically in figure 3. In this set-up, light from the arc is brought to a focus on the round hole in the metal plate by the first lens. This round hole, placed at the principal focus of the second lens, serves as the source of light. Light passing through the second lens is rendered parallel and is directed into the combustion chamber by the mirror and reflected back slightly offset from its original path by the mirror on the piston. The settings of the mirrors are such that the light is brought back through the second lens and to a focus slightly to one side of the original source. Thus it is possible to insert a small mirror in the optical path just before the light comes to a focus and to reflect the entire beam at a right angle. The round stop to obtain the schlieren effect is placed in the plane of the image, allowing only an annular ring of light to pass. The film drum of the camera is placed at the image of the combustion chamber formed by the second lens. A stop with a 1/8-inch slit is placed in front of the film drum, so that the image of only a 1/8-inch strip across the combustion chamber is photographed. An electromagnetic shutter is synchronized with the engine, so as to expose the film for only the part of the cycle that is of interest.

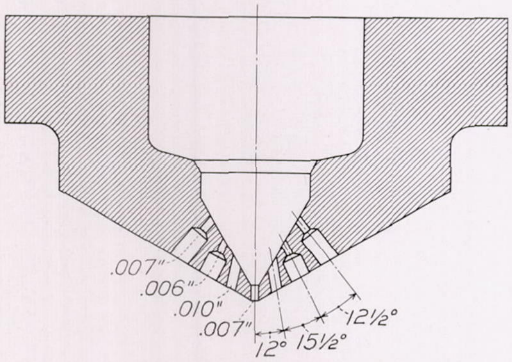

FIGURE 2.—The seven-orifice nozzle.

When sparks are used as the light source for the schlieren pictures, the round-hole light source is replaced by a horizontal spark gap enclosed in a glass tube to confine the spark to a straight path, and the stop to obtain the schlieren effect consists of a slit in a plate. The condensers and distributor of the spark-photography apparatus give 13 sparks at a rate of about 1,000 per second.

With the schlieren set-up, most of the light from the combustion flame is eliminated in the optical train and does not register on the film. The combustion front is accompanied by a marked temperature increase and is therefore recorded on the film. Sound waves or compression waves, which are accompanied by local changes in density, also are shown by the schlieren method. A ½-inch space on the side of the chamber nearest the usual position of the spark plug was not covered by the mirror on the piston.

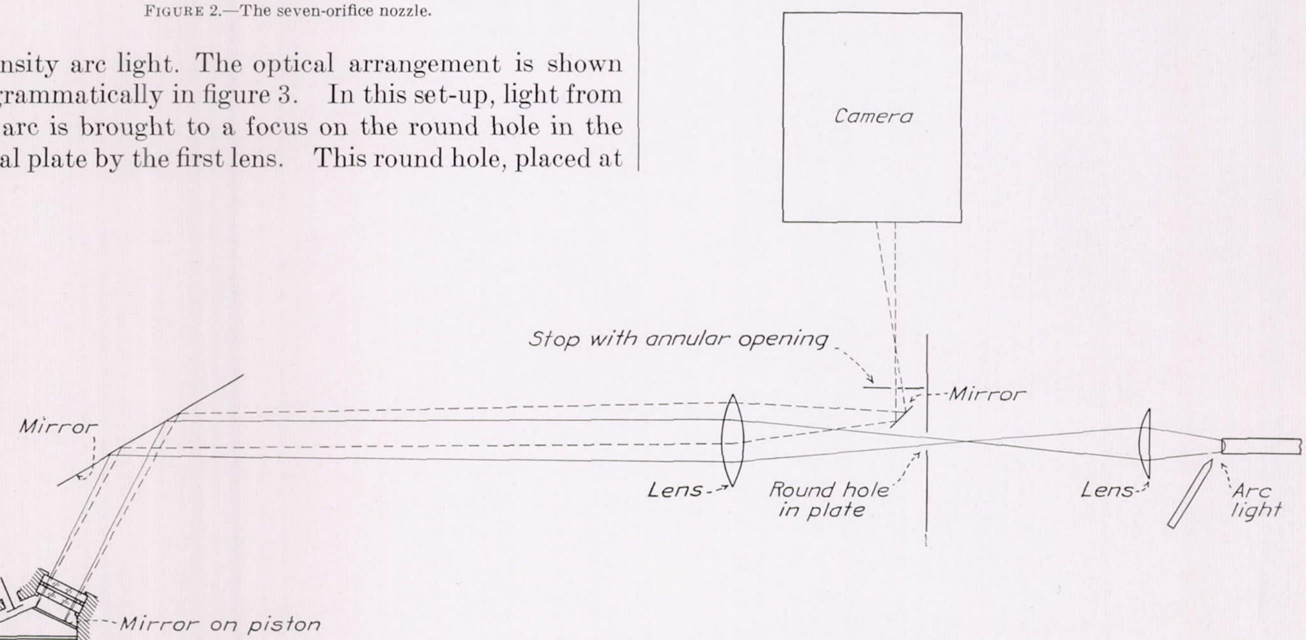
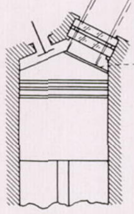

FIGURE 3.—Diagrammatic sketch of schlieren set-up.

RESULTS

The high-speed motion pictures reproduced in figure 4 show the effect of air-fuel ratio on nonknocking flame propagation with spark plugs at E and F (fig. 1). These tests were made at an engine speed of 1,500 r. p. m. The irregular flame fronts are characteristic of all the flame photographs that have been taken. The rate of flame propagation was somewhat slower for the lean mixtures, and two distinctly different types of afterburning were present in the rich and lean mixtures.

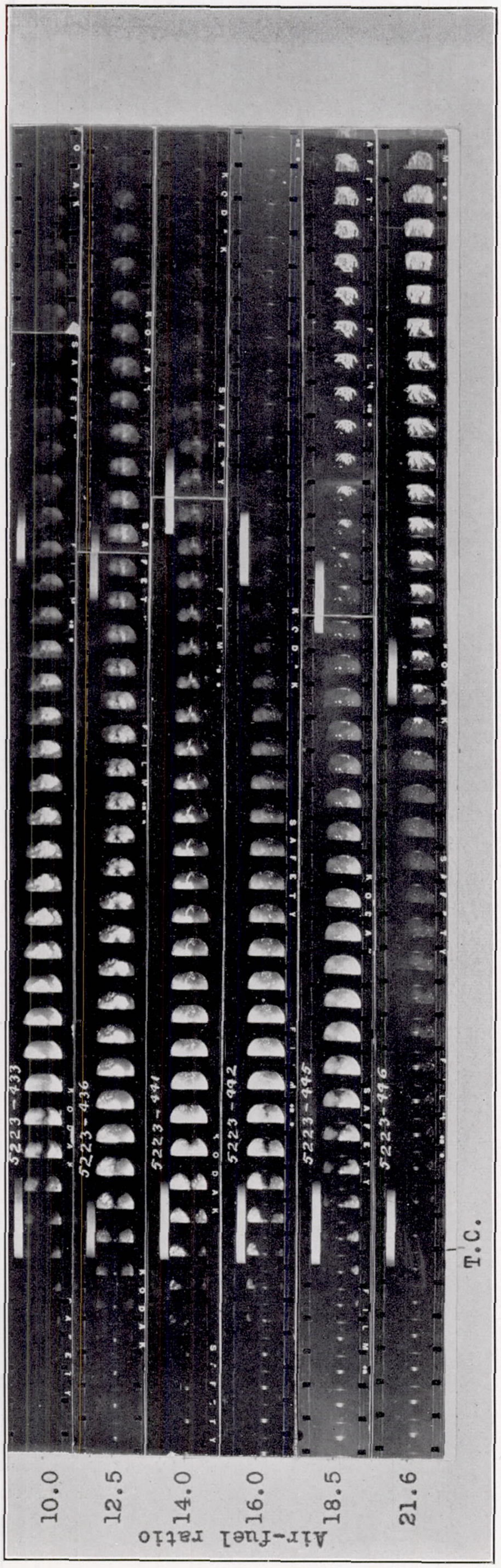

FIGURE 4.—Effect of air-fuel ratio on flame propagation. White marks on upper edge of each film correspond to T. C. and 90° A. T. C. Engine speed, 1,500 r. p. m.; two spark plugs; 87-octane fuel.

Details of the photographs are shown to better advantage in the enlargements in figures 5 and 6. In figure 5, at air-fuel ratios of 10 and 12.5, after the flame apparently passed through part of the chamber, an area of very bright illumination appeared behind the flame front as in the frames marked C, and in the succeeding frames this area spread rapidly across the window. In the last frames of the enlargements this bright area is the most prominent feature of the photograph. These areas, which appear suddenly and spread rapidly, do not behave like other regions of brightness, such as the region in the lower part of the window at an air-fuel ratio of 10 and the other bright spots that appear in many of the pictures. Withrow and Rassweiler observed a somewhat similar effect in their tests (reference 2) and attributed it to burning lubricating oil. This explanation appeared reasonable in their case because the brightness appeared as soon as the flame reached the edge of the cylinder. The piston and cylinder of the N. A. C. A. combustion apparatus, however, are lubricated by graphite and the apparatus has no oil in the crankcase. Hence, some other explanation must be sought. The effect appeared only at the richer mixtures and is probably associated with incomplete combustion. For the ratios of 18.5 and 21.6 the flame completely crossed the chamber; then, after the charge had apparently been burned, "afterburning" began and continued until long after the exhaust valves opened. To the eye the exhaust appeared a brilliant violet color.

Enlargements of the burning at the air-fuel ratio of 18.5 are shown in figure 6, and it can be seen that the flame had traversed the chamber by 30° after top center. The afterburning, as shown in the figure, always originates near the spray nozzle and is probably caused by the sudden addition of a small amount of fuel to the hot combustion gases, which still contain oxygen. Records of the pressure in the injection system indicated that a secondary injection of fuel might occur more than one crankshaft revolution after the start of the main spray. One other possible source of fuel is the well between the nozzle seat and the spray orifices. Approximately 0.003 gram of fuel is trapped in this well. It is not known whether such a small quantity of fuel vaporizing into the combustion gases could cause the intense illumination shown in the figures. Further tests are being conducted on the effects of air-fuel ratio.

In most of the photographs, small local areas of brighter illumination appear throughout the flame. These areas are not believed to be caused by uneven distribution of the fuel inasmuch as 100-octane fuel, differing little in volatility from the other fuels, burned with very uniform illumination.

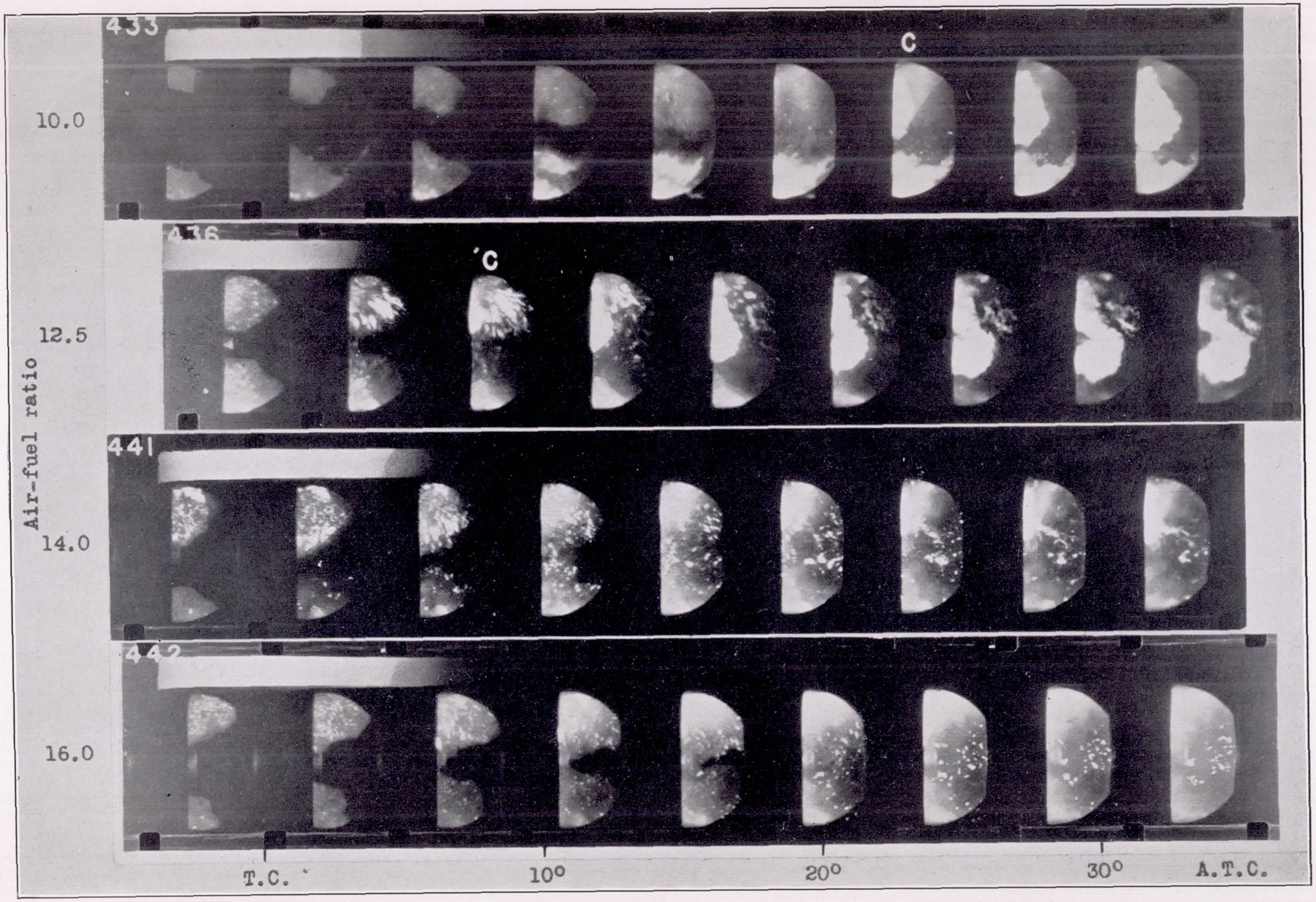

FIGURE 5.—Effect of air-fuel ratio on flame propagation. Enlargements of high-speed motion pictures of figure 4 for air-fuel ratios of 10, 12.5, 14, and 16. Engine speed, 1,500 r. p. m.; two spark plugs; 87-octane fuel.

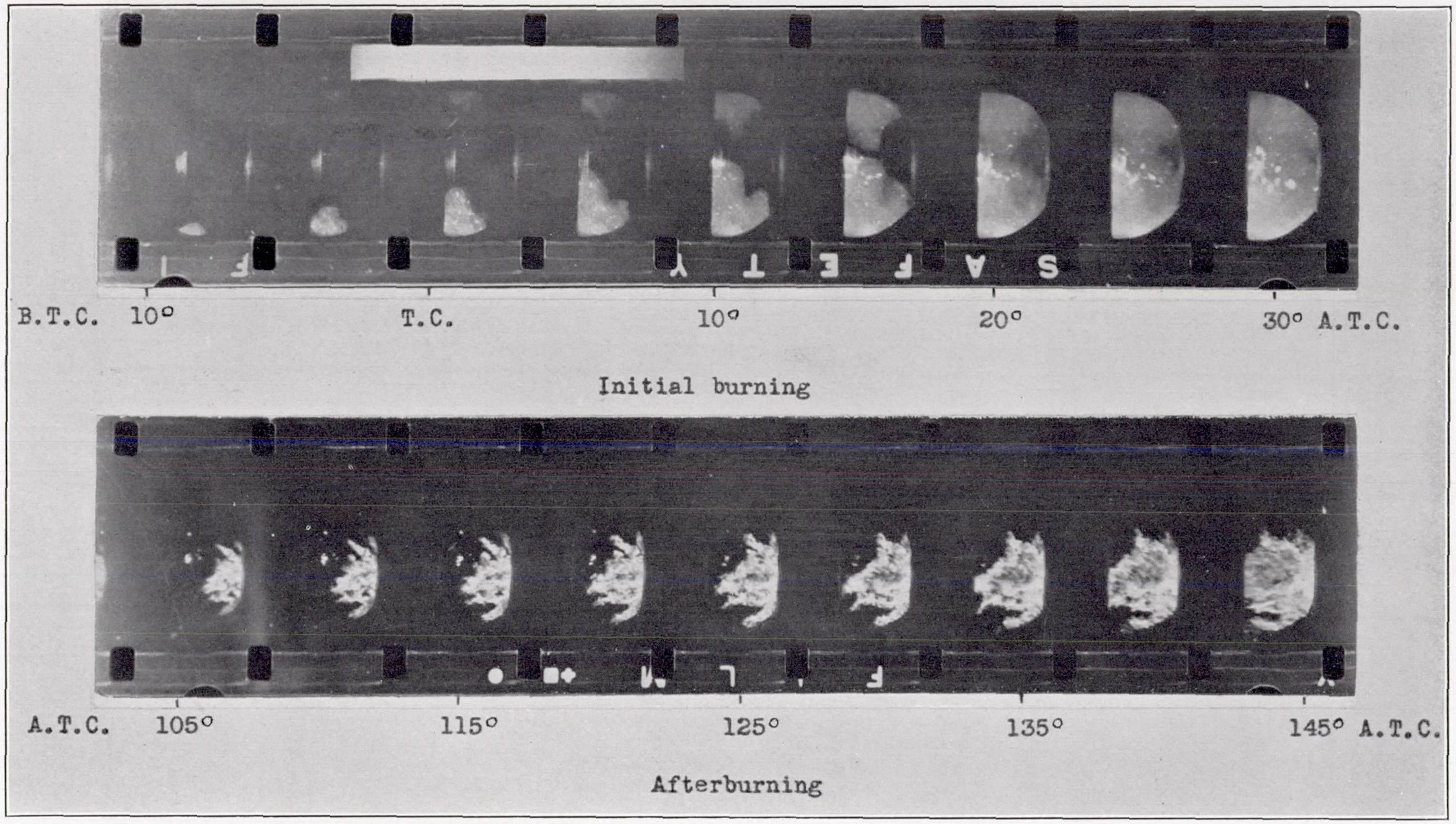

FIGURE 6.—Afterburning of lean mixture, after flame has traversed charge. Air-fuel ratio, 18.5; exhaust valves open 125° A. T. C.; engine speed, 1,500 r. p. m.; two spark plugs; 87-octane fuel.

The high-speed motion pictures in figure 7 show the flames for fuels of different octane ratings with one spark plug at E. The outlines of the flames, for the first several frames, have been marked by a series of white dots for purposes of reproduction. Details of the photographs are more easily seen in the enlargements of figures 8 and 9. The photographs show an even illumination and a uniform rate of flame propagation for the nonknocking burning with the 100-octane fuel. For the knocking explosions, there was a sudden and definite increase in the intensity of illumination at the time in the cycle that knock occurred. This sudden increase in brightness at the time of occurrence of knock is characteristic of all the knocking explosions and increases in intensity with increasing violence of knock. It is not to be confused with the bright light given off by the 100-octane fuel, which has a very high actinic value, the inflamed area being very bright and uniform throughout the entire explosion. The first appearance of the bright illumination is indicated by the frame marked A. It will later be shown that the time of appearance of the bright light coincides exactly with the appearance of pressure waves, hence may be used to indicate the first appearance of knock.

The records for octane ratings of 18 and 30 show a sudden inflammation of the end gas just prior to the appearance of the bright illumination. The photographs for the 40- and 50- octane fuels also indicate that a sudden inflammation of the end gas took place but, in this case, the sudden increase in flame travel and the sudden increase in illumination are shown in the same frame. The record for 65-octane fuel shows that the flame proceeded at a uniform rate across the chamber; then, after the chamber was filled with flame, the characteristic bright light associated with knock appeared. As nearly as can be determined, the violent vibrations that appear on indicator cards of knocking explosions correspond in point of time to the appearance of this bright light. The vibrations shown on the indicator cards for the 65-octane fuel were more violent than those for explosions of some of the fuels of lower octane ratings.

Figure 10 is a composite of indicator cards and streak schlieren photographs, taken with fuels of different octane ratings. The spark plug (at E, fig. 1) was located at the bottom of the strip as it is shown in the figure. For 100-octane fuel, the rate of combustion-front travel was somewhat slower than the rate for the other fuels. This result may or may not be significant. There is no indication of any vibration in the gas. The maximum pressure shown by the indicator card for the 100-octane fuel is about 800 pounds per square inch.

Each of the other three records shows knocking explosions with the characteristic gas vibrations, the frequency of which corresponds approximately to the frequency recorded on the indicator cards. The slit through which the photographs were taken did not

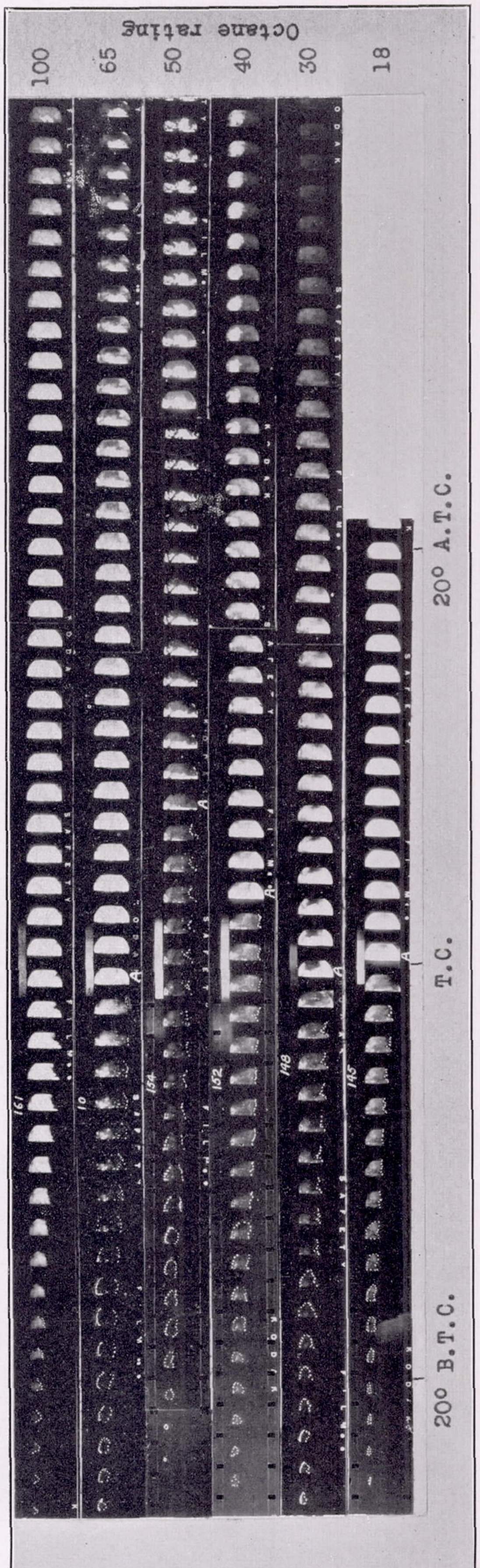

FIGURE 7.—High-speed motion pictures showing effect of fuels of different octane ratings on combustion knock. Air-fuel ratio, 14; A, first evidence of knock; engine speed, 500 r. p. m.; one spark plug.

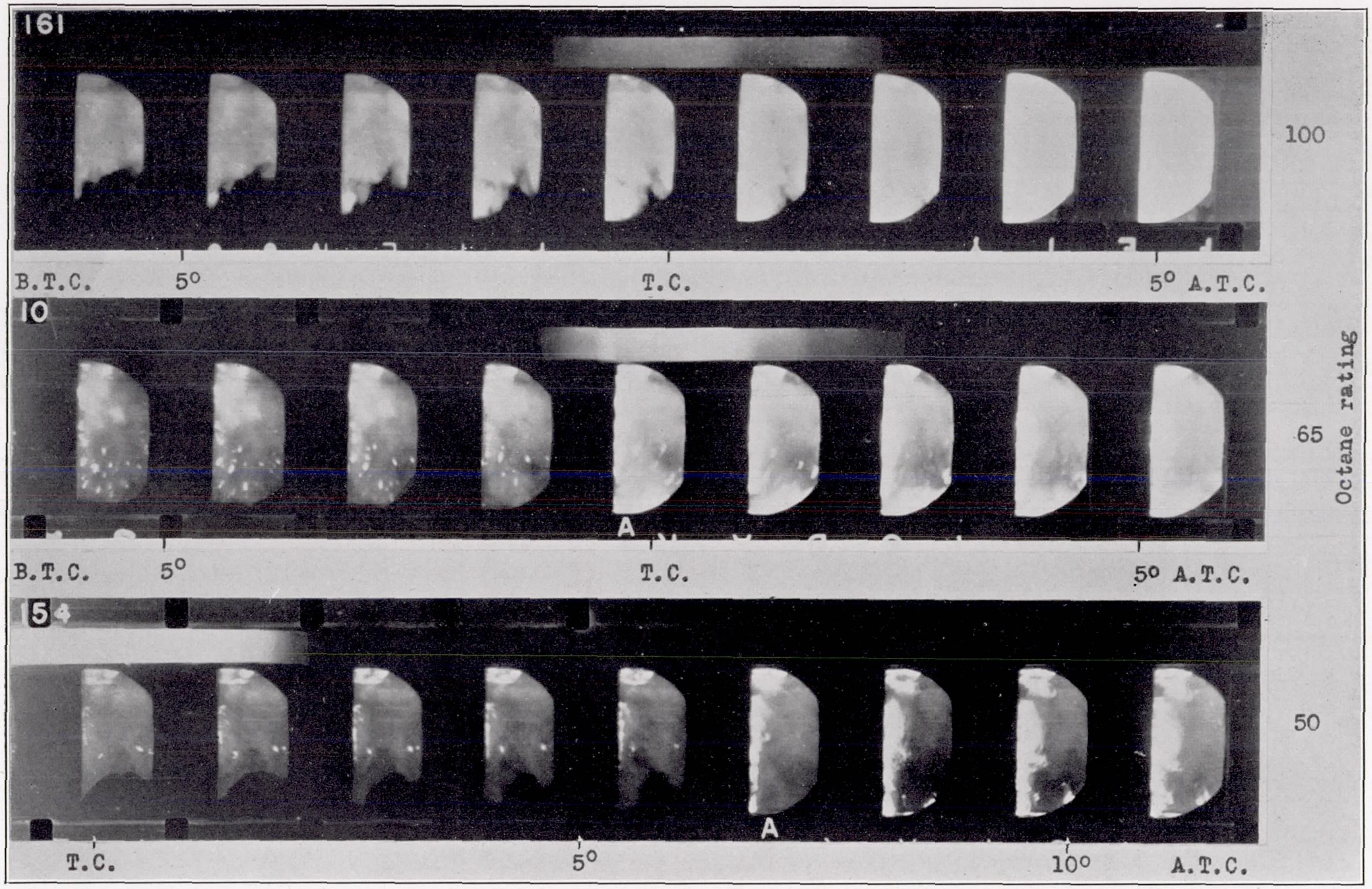

FIGURE 8.—Enlargements of high-speed motion pictures showing effect of different octane ratings on combustion knock. Air-fuel ratio, 14; A, first evidence of knock; engine speed, 500 r. p. m.; one spark plug. Octane ratings, 100, 65, and 50.

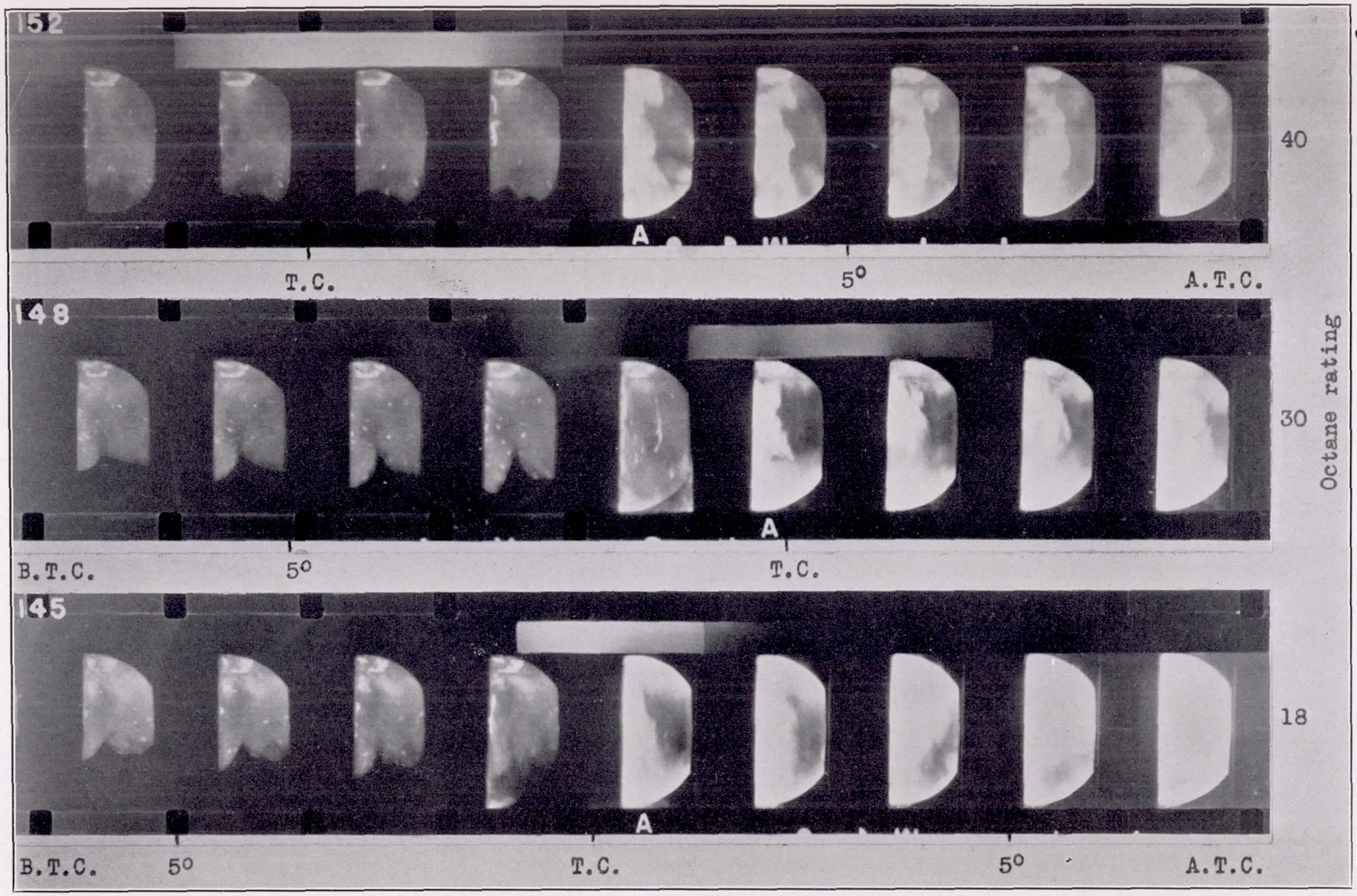

FIGURE 9.—Enlargements of high-speed motion pictures showing effect of different octane ratings on combustion knock. Air-fuel ratio, 14; A, first evidence of knock; engine speed, 500 r. p. m.; one spark plug. Octane ratings, 40, 30, and 18.

necessarily include the knocking zone. With the two fuels of lowest octane number, there is a marked reverse movement in the combustion front before the appearance of the gas vibrations. The indicator cards for these two fuels show a sudden slight rise in pressure just prior to the violent vibrations in the pressure record. Evidently there is a sudden release of energy during this latter part of the burning, and it appears probable that the slight rise in pressure prior to knock bands is the same as the frequency of the waves in the schlieren record, visible in the right-hand portion of the record; they begin simultaneously with the pressure waves and are believed to be caused by successive reillumination of the charge as the pressure waves passed through it. Therefore either a sudden appearance of a brighter light, as at A in figure 7, or the appearance of pressure waves may be used to indicate the start and occurrence of knocking.

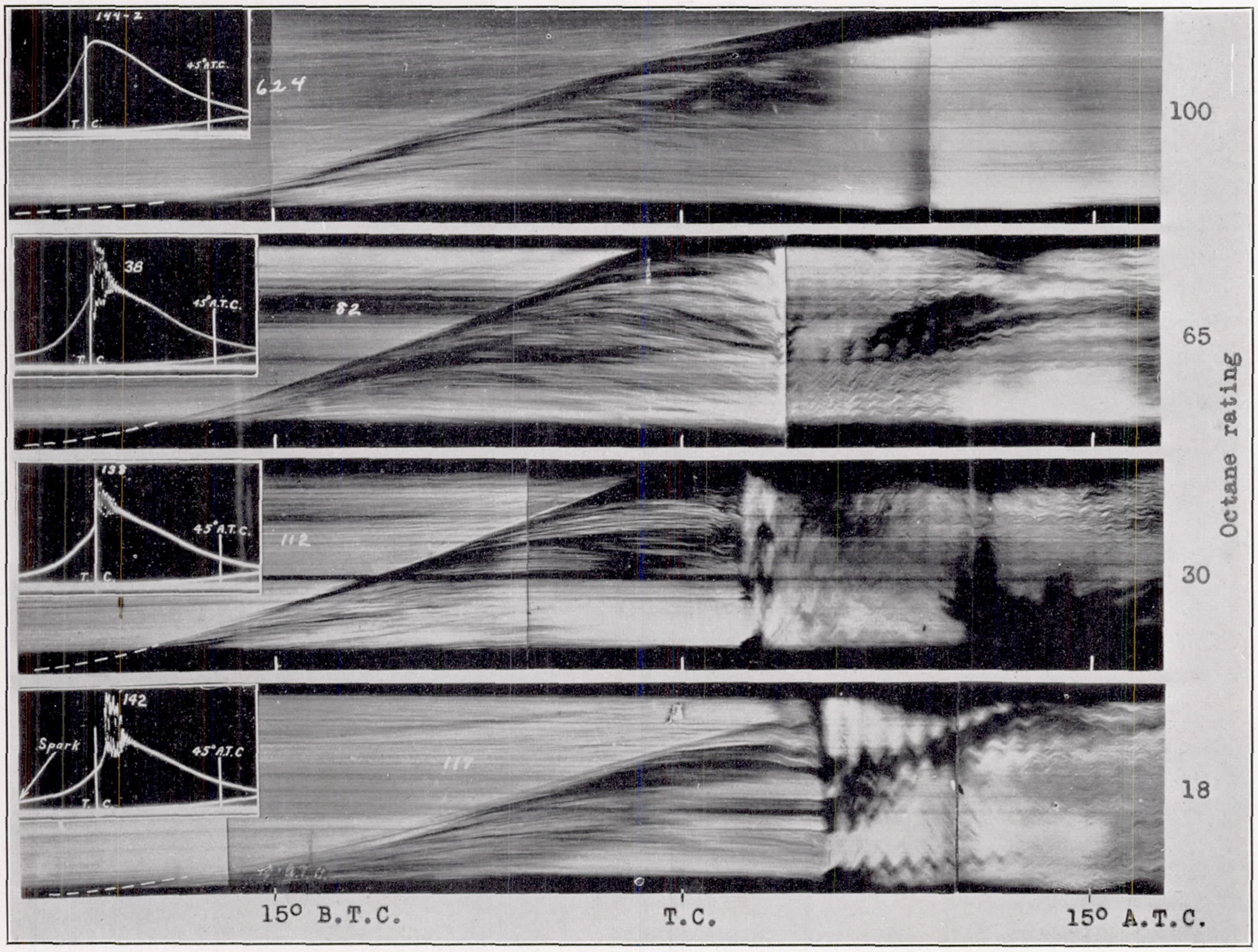

FIGURE 10.—Indicator cards and schlieren photographs showing effect of different octane ratings on combustion knock. Air-fuel ratio, 14; engine speed, 500 r. p. m.; one spark plug.

and the reverse movement in the combustion gases are caused by the auto-ignition of the end gas. It is important to note that only the records for explosions in which auto-ignition is indicated show this slight rise.

For the record presented in figure 11, adjustments were made to the optical system to permit more of the intensely brilliant light from the knocking combustion to record on the film. In this case, some of the light from the combustion prior to knock also recorded in the ½-inch space nearest the spark plug, where the mirror did not cover the piston. The series of vertical bright bands across the record are evidently successive images of the ⅛-inch slit. The "frequency" of these

Motion pictures of the flame and spark schlieren motion pictures taken simultaneously but from slightly different angles are reproduced in figure 12 for a single spark plug at position G. When the refractive index of the charge is uniform throughout, the spark schlieren field appears uniformly illuminated except for spots, lines, and shaded areas caused, respectively, by dirty spots, strain lines, and irregularities in the mirror or window surfaces. When combustion appears in the field, it is visible because of the temperature change and, with the type of schlieren arrangement used, the combustion front appears darker than the field. The region back of the combustion front also appears dark

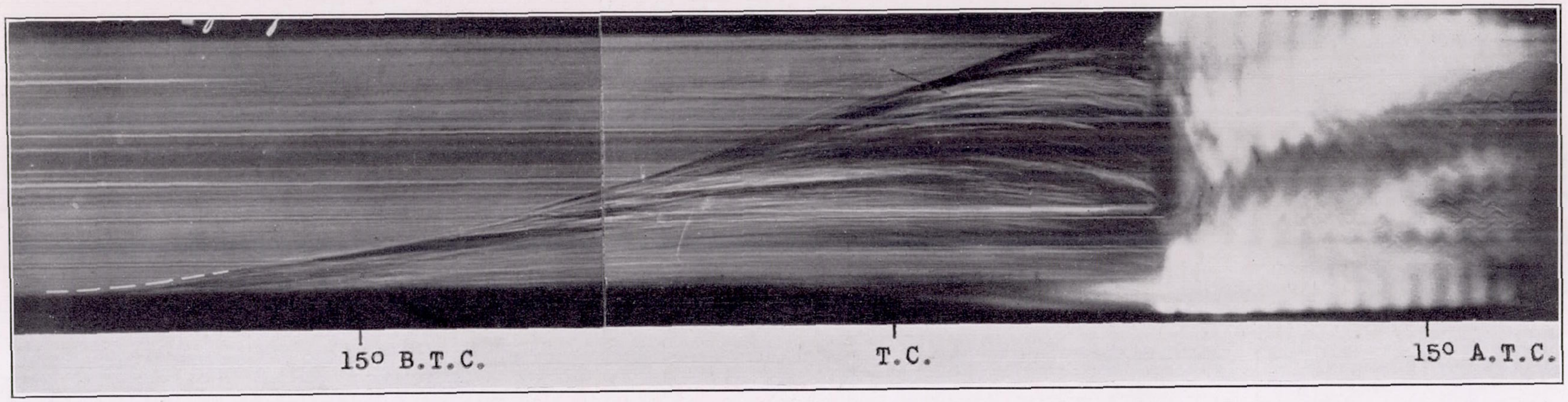

FIGURE 11.—Schlieren photograph of knocking combustion, with light from knock recording on film. Air-fuel ratio, 14; engine speed, 500 r. p. m.; one spark plug; 50-octane fuel.

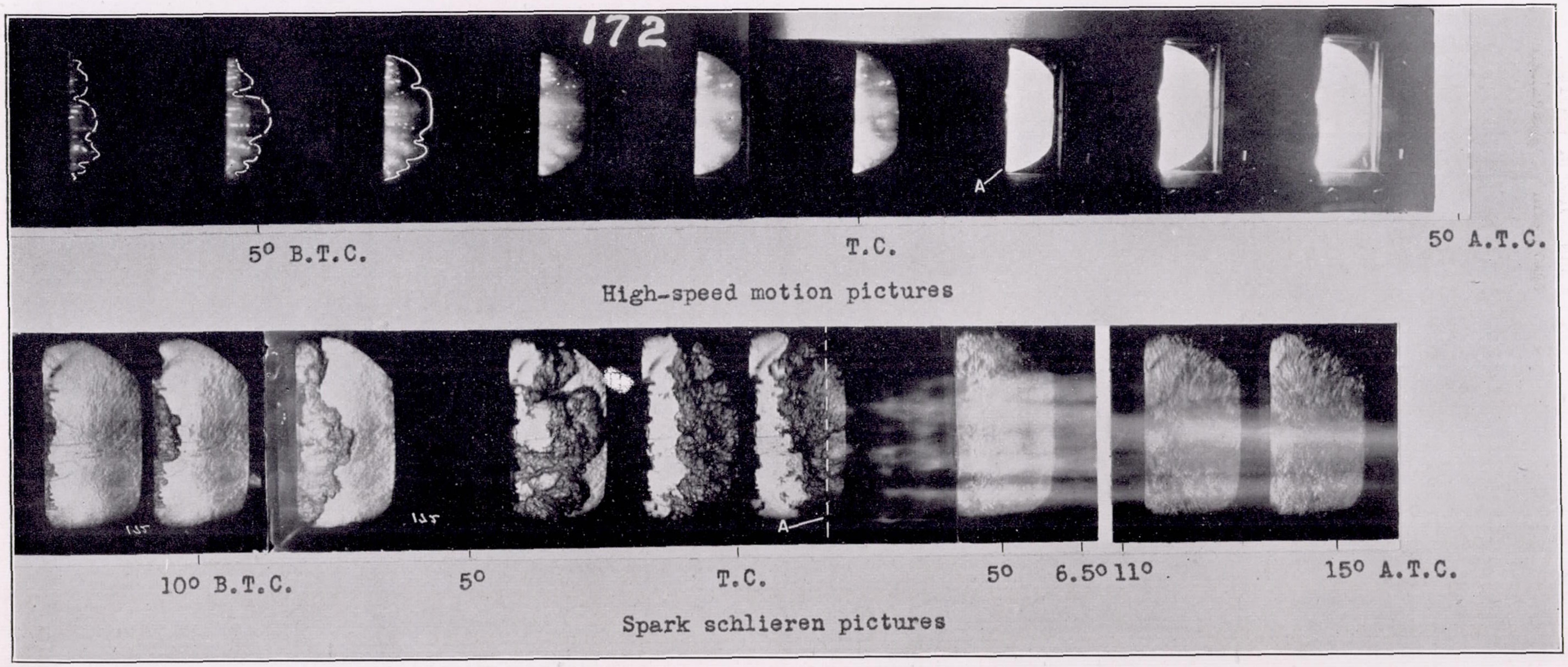

FIGURE 12.—High-speed motion pictures and spark schlieren photographs taken simultaneously, showing flame propagation and knock. Air-fuel ratio, 14; A, first evidence of knock; engine speed, 500 r. p. m.; one spark plug at back of chamber; 65-octane fuel.

for a distance of from 1 to 2 inches, then a sharp line of demarcation appears between this dark region and the area that has been burned. This dark region will hereinafter be referred to as the "reaction zone." One of the most striking features of the spark schlieren pictures is the sharp distinction between the reaction zone and the burned gases behind it, which appear fully as uniform in refractive index as the unburned charge ahead of the flame.

In the photographs of figure 12, since the spark plug was located at the back of the chamber, the combustion was halfway across the chamber before it was visible. The first frame on the left of the schlieren series shows the field as it appeared before the flame reached the window. The irregular dark region along the left-hand edge of the window, which might at first be taken for the combustion front just appearing in the field, was caused by the fuel spray that struck the upper edge of the mirror and evaporated, leaving a slight deposit of dust and carbon particles. The combustion front appears first in the second frame. The third frame shows the front still farther across the window and, in the fourth frame, the combustion front had almost crossed the window, with some areas of unburned charge still remaining. In this frame, the clear spaces back of the reaction zone (on the left in the figure) first appeared. The reaction zone in this case appeared to cover somewhat more than half of the 2½-inch width of the window. In the next frame (fifth from the left), the combustion front had crossed the window and the rear edge of the reaction zone had become more even, leaving a clear space between the edge of the window and the rear of the reaction zone. The reaction zone advanced very little between the fifth and sixth frames and, immediately after the sixth frame, knock occurred. The time of occurrence of knock was determined by the fogging of the film by the sudden bright light accompanying knock. Line A indicates the beginning of the fogged streaks. The point where the streaks start, of course, is the point at which the light from the knocking combustion at the left-hand edge of the window first struck the film.

After the reaction zone has passed through the chamber, the spark schlieren pictures again show a relatively clear field. There are no longer any large regions of different refractive index but the entire field has a rippled or corrugated appearance. These ripples may indicate air flow, local areas of smoke or soot, or some system of heterogeneous waves in the combustion gases. Referring to the high-speed motion pictures of figure 12, note that the frame just to the left of top center corresponds most nearly in time to the fifth schlieren picture. The direct flame photograph makes no distinction between the reaction zone and the burned region. Furthermore, the most intense light, as shown by the flame photograph, came from the region back of the reaction zone where the schlieren photograph shows no marked temperature gradients.

It should be noted particularly, when the spark schlieren pictures are compared with the flame pictures, that the outlines of the combustion front as shown by the schlieren pictures appear to correspond very closely to the outlines of the visible flame in the flame pictures. The third frame from the left of the flame photographs and the fourth frame of the schlieren photographs correspond fairly closely in point of time.

In the first three frames of the motion picture, the flame front has been outlined in white for purposes of reproduction. By the fourth frame, the flame had covered most of the chamber and, in the next two frames, it covered the chamber and the intensity of illumination increased. Knock then occurred, and the brilliant illumination was first evident in the frame marked A, just after top center.

Investigations of combustion in bombs have indicated that shock waves, originating at or behind the flame front, may traverse the charge at a velocity greatly in excess of the flame velocity and gain such intensity as to cause auto-ignition of the charge at the opposite end of the chamber (reference 10). Although the streak schlieren photographs of knocking combustion (figs. 10 and 11) showed no evidence of such waves, a further investigation was undertaken to determine the effect of artificially induced waves on the knocking tendency.

Figure 13 is a composite of indicator cards and streak schlieren photographs and shows the effects of artificially induced shock waves on the combustion. The waves were induced by discharging a 2-microfarad condenser charged to 30,000 volts through a 0.004-inch diameter copper wire stretched inside the engine at E. When the condenser was discharged, the wire exploded with considerable violence. At these conditions, knock was intermittent when no shock waves were induced. Figure 13 (a) shows the wire exploding behind the combustion front that was started by a spark plug at E, when the combustion was about halfway across the chamber, as indicated by the point B. The shock waves traversing the chamber caused pronounced ripples in the trace of the combustion front as it was alternately accelerated and decelerated. There is no indication that knock occurred. Figure 13 (b) is a similar photograph, with the wire exploding slightly earlier. Knock occurred in this case, but there is no indication that it was influenced by the shock waves from the exploding wire. When the combustion was started from the spark plug at E, the wire could not be exploded at any later time than shown because the wire melted from the combustion heat.

Figures 13 (c) and 13 (d) show the effect when the combustion started from the opposite side of the chamber (spark plug at F); the wire exploded when the combustion was about halfway across the chamber. The charge knocked both times. Figure 13 (e) shows the wire exploding at a later stage of the burning; in this case there was no knock.

Records (not shown) taken with the wire exploding after the combustion crossed the chamber always showed knock occurring at the same time the wire exploded. Apparently if the charge was about ready to knock of its own accord, the shock from the exploding wire acted as a "trigger" to set off the knock.

The indicator cards (fig. 13) were taken at conditions similar to those represented by the schlieren records and show the gas vibrations caused by the exploding wire. Records 566 and 561 show no knock, whereas each of the other cards shows that knock occurred at or near the end of the combustion period.

The amplitude of the shock waves shown in figure 13 is comparable with the amplitude of the waves set up by moderate knock. There is no indication, however, that waves of this intensity will in themselves cause knock.

Figures 14 and 15 are schlieren photographs showing combustion, with and without knock, started from two spark plugs on opposite sides of the chamber (E and F). In both photographs of figure 14 the two combustion fronts apparently meet and continue through each other, covering about half of the remaining distance across the chamber before merging with the general pattern of the burning. The combustion space is about 1 inch deep at this time, so there is little possibility that the two fronts passed each other at different levels in the chamber. In the knocking explosion, the two flame fronts had met before knock occurred.

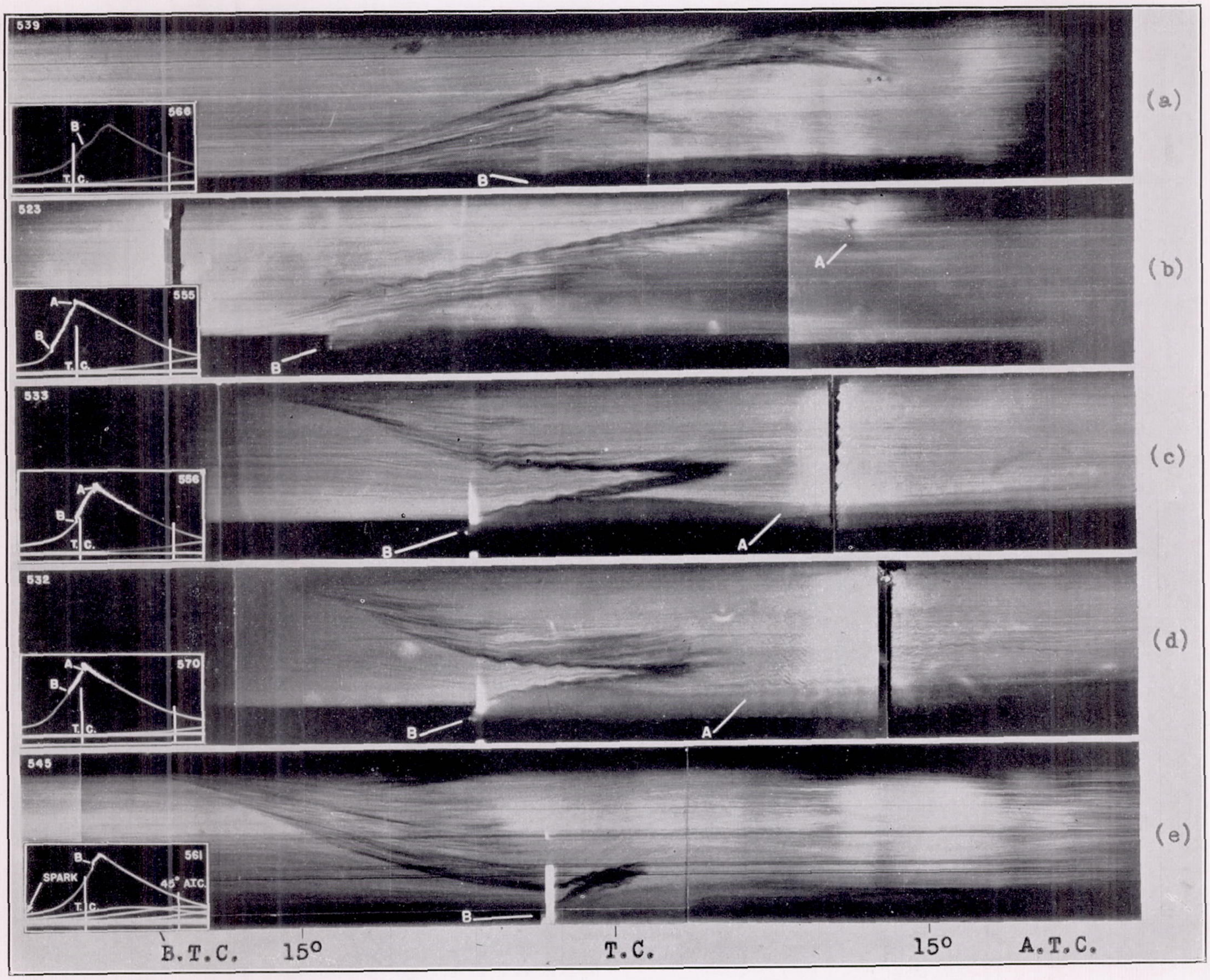

FIGURE 13.—Indicator cards and schlieren photographs showing effect of exploding wires on combustion knock. Air-fuel ratio, 14; A, first evidence of knock; B, wire explodes; engine speed, 500 r. p. m.; one spark plug; 87-octane fuel.

Figure 15 also shows that the two combustion fronts in the knocking explosion met each other before knock occurred, so that no region of noninflamed charge remained in the visible field to auto-ignite. A region of noninflamed charge may have existed in the half of the combustion chamber not covered by the window. The photographs of the nonknocking explosion show the reaction zones meeting at the fifth frame from the left. A small, roughly triangular region still remained on

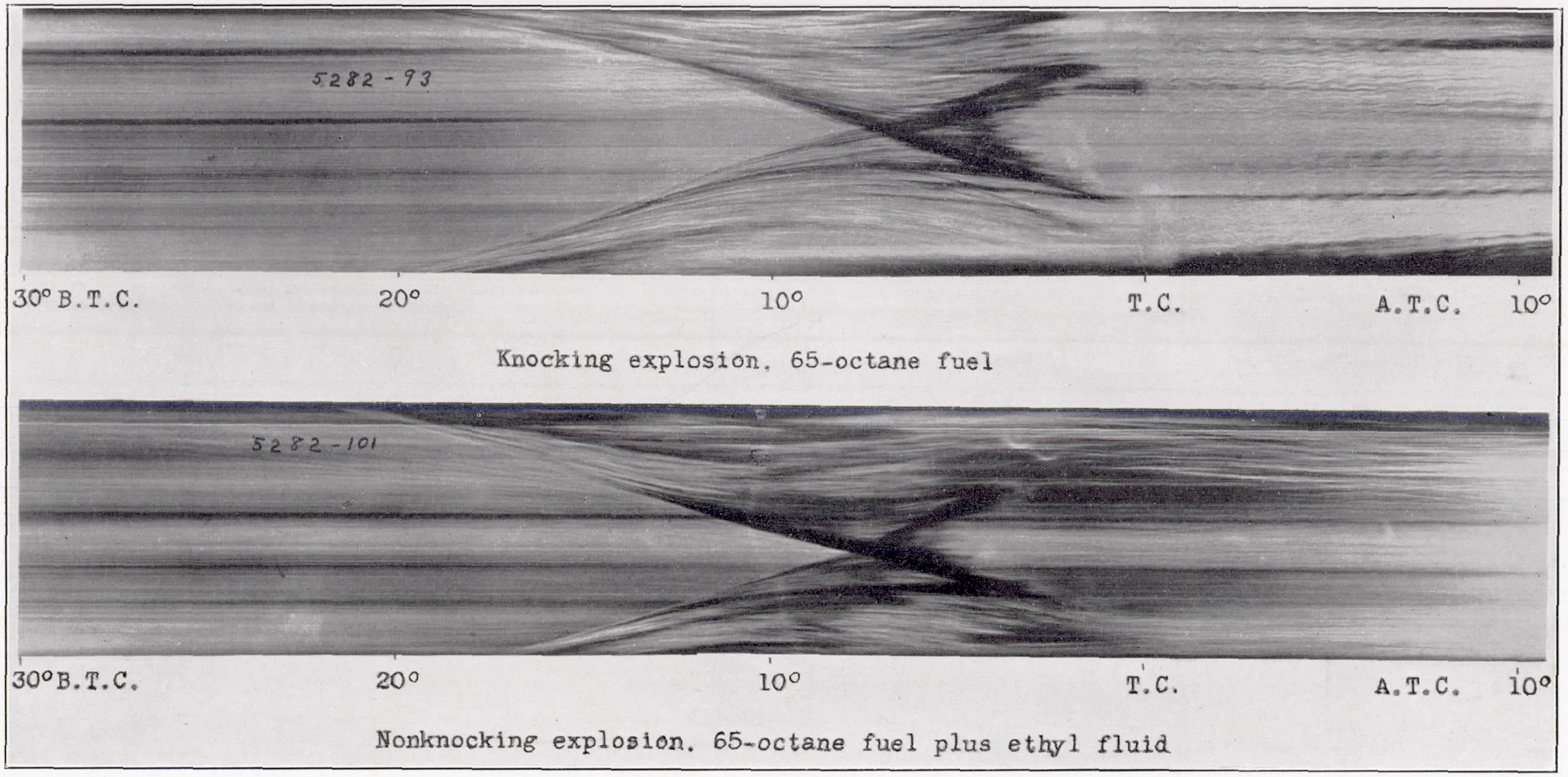

FIGURE 14.—Schlieren photographs showing two flame fronts passing through each other. Air-fuel ratio, 14; engine speed, 500 r. p. m.; two spark plugs.

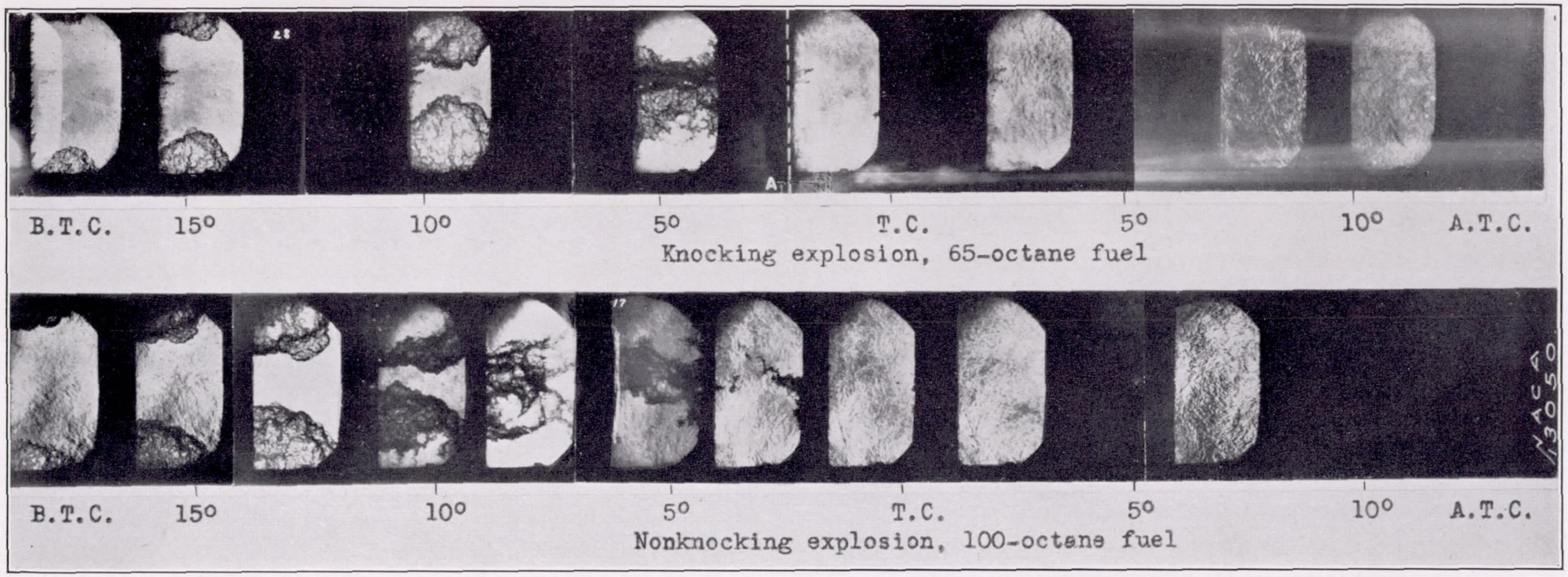

FIGURE 15.—Spark schlieren photographs of knocking and nonknocking explosions. Air-fuel ratio, 14; A, first evidence of knock; engine speed, 500 r. p. m.; two spark plugs.

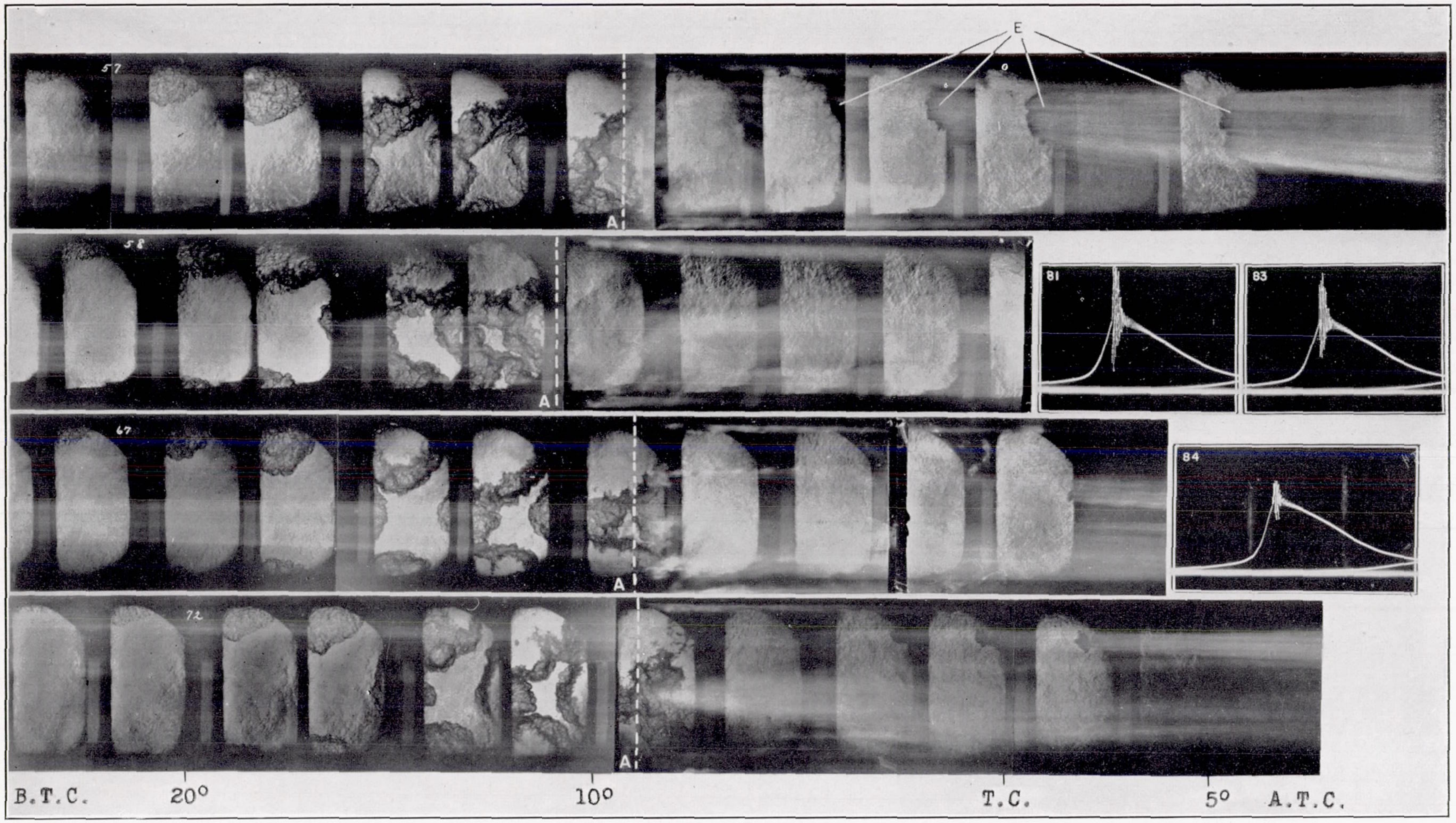

FIGURE 16.—Schlieren photographs and indicator cards of knocking explosions with last part of charge to burn localized beneath window. Air-fuel ratio, 14; A, first evidence of knock; E, indications of smoke; octane rating, between 50 and 60; engine speed, 500 r. p. m.; four spark plugs; spark advance, left-hand plug 30°, other three plugs 27°.

the right-hand side of the frame, as yet not reached by the reaction. The sixth frame shows the reaction zone still persisting, though somewhat narrower than in the previous frame. Apparently the entire chamber had been reached by the reaction. In the seventh frame, most of the reaction zone had disappeared but a small spot, corresponding roughly in shape and location to the noninflamed spot in the fifth frame, still persisted. The appearance of the succeeding frames is very similar to that of the corresponding frames for the knocking explosion, showing only the rippled or corrugated appearance characteristic of the combustion gases when the reaction is apparently completed.

In order to insure that the last part of the charge to burn was in the field of view, photographs (fig. 16) were taken showing the combustion when four spark plugs were so arranged that the last point reached by combustion was directly beneath the window. The four spark plugs were located at E, F, G, and J, and the injection valve was located at H. The spark plug at G was timed to fire 3° ahead of the other three plugs, so that the combustion front from the back of the chamber reached the window with the other three combustion fronts. In each of the four strips of photographs, the combustion fronts approached each other from the four sides of the window, localizing a small portion of the charge directly beneath the window. The bottom strip in figure 16 (record 72) shows that the four combustion fronts had merged before knock occurred, and other photographs that have been taken with this arrangement indicate the same merging preceding knock. Generally, the last frame before knock occurred showed a small region not yet reached by the combustion, as shown in the other three strips in figure 16. There is no reason to believe, however, that this small region had not been reached by the combustion before knock occurred because in each case sufficient time for the combustion fronts to merge had apparently elapsed between the time the last frame before knock was taken and the time of occurrence of knock. The white dashed lines, marked A on the figure, correspond to the position of the left-hand edge of the image of the window when knock occurred. Inasmuch as the film was wrapped on a rapidly rotating drum and the light from the knock continued for as long a period as one revolution of the drum, the fogged streaks usually continued around the film and show on the left-hand part of the pictures.

In no case, in the more than 50 photographs taken at these same conditions, was there any indication of any auto-ignition ahead of the combustion fronts, or of any sudden increase or decrease in the speed of combustion propagation.

The indicator cards shown in figure 16 are representative cards taken at the same conditions as the photographs. It is seen that the intensity of knock varied greatly from cycle to cycle. The extreme violence of the vibrations in record 81 is probably caused by the location of the indicator diaphragm immediately above the last portion of the charge to burn. It was noted during the work that fine cracks appeared in the surfaces of the glass mirror and the window in the general region of the last part of the charge to burn. These cracks were probably caused by the intense heat of the knocking combustion.

Another feature of interest appears in the upper strip of figure 16. In the eighth frame from the left, a small dark area appears in the image, where no light was transmitted. This area (marked E) grows rapidly larger in the succeeding frames. Simultaneously, with the appearance of the opaque area, a very bright fogged streak begins in exactly the same region and grows larger in unison with the opaque area. Evidently this area, although opaque to the light from the sparks for the schlieren pictures, is at the same time emitting light of extreme intensity. It is believed that the opaqueness of the area is caused by smoke. The appearance of black smoke in connection with knock is often observed. This black smoke is frequently encountered with the combustion apparatus, which is kept free from carbon and is run without oil. Evidence of the same effect appears to a lesser extent in the other pictures of figure 16, and to a greater or a lesser degree in a great many of the photographs of knocking explosions. Record 117 (fig. 10) shows the same effect in a streak schlieren picture.

Schlieren photographs of four explosions are shown in figure 17, in which the spark plug was located at position H so that the flame traveled diagonally across the window. With this arrangement, the half of the chamber not covered by the window was crossed by the combustion before combustion was completed under the window, and the last portion of the charge to burn was located in a part of the chamber most of which was in the field of view of the camera. The outline of the cylinder is shown in white around the frame photographed just prior to knock. In each case, the combustion is shown to be either across the chamber or almost across, before knock occurred.

DISCUSSION

Any study of combustion in internal-combustion engines is necessarily handicapped by the fact that the individual investigator works with relatively few types of engines; whereas the results must be correlated with a great variety of engines and operating conditions. This handicap is particularly true in a photographic study of combustion, where the combustion-chamber shape and engine operating conditions are necessarily limited.

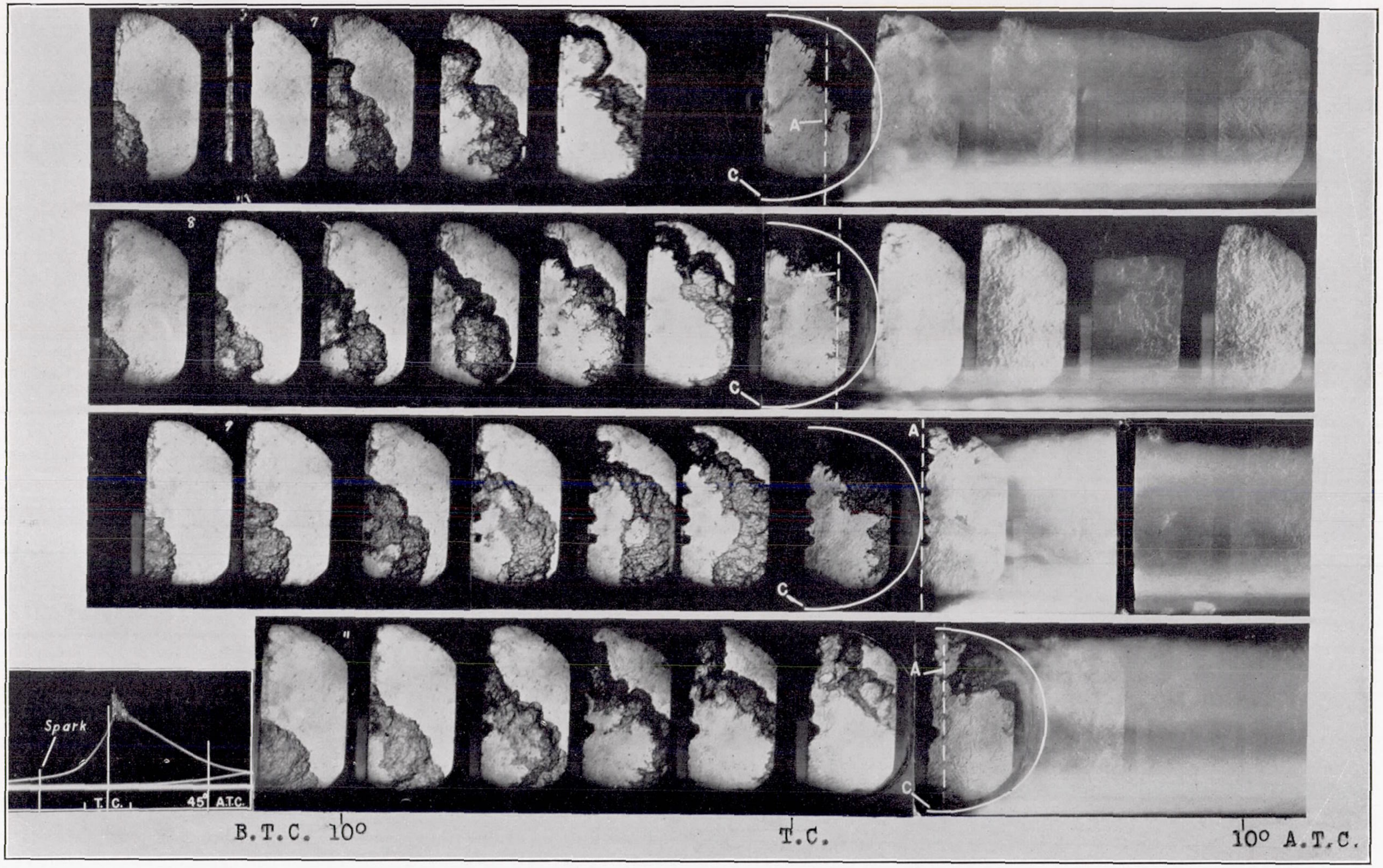

FIGURE 17.—Schlieren photographs and indicator card of knocking explosions with one spark plug at H (fig. 1). Air-fuel ratio, 14; A, first evidence of knock; C, outline of cylinder; engine speed, 500 *r. p. m.*; spark advance, 30°; 75-octane fuel.

The combustion apparatus in its present form is very similar to some types of engine, with the exception that, inasmuch as the combustion apparatus fires only once, there can be no exhaust gases present in the charge. The cylinder walls are also cooler than would be the case in an engine running continuously. The preliminary tests reported in reference 3 have shown that the apparatus behaves in a manner similar to that of a conventional engine, and it is believed that data obtained with this engine are as generally applicable as are the results obtained on any one engine.

Shock waves.—Payman and Titman (reference 10) have published a series of flame and schlieren photographs of explosions and detonations in a tubular bomb. These photographs show very clearly the formation of a shock wave preceding the combustion front and causing auto-ignition at the end of the bomb. It has been believed that possibly a similar wave may occur in engines under knocking conditions. The data presented in this report show no evidence of any such high-velocity wave and show, in addition, that if such waves are artificially induced in the engine cylinder they do not cause knocking. The flame photographs shown by Boerlage (reference 11), however, are very similar to the flame photographs shown by Payman and Titman, which show auto-ignition at the end of the combustion chamber. The schlieren photographs of Payman and Titman show the auto-ignition to be caused by a shock wave. Although the auto-ignition of the charge at the end of the combustion chamber away from the spark plug in Boerlage's tests may be caused by the hot wall of the chamber, the possibility of a detonation wave must not be overlooked.

The brilliant light given off by knocking explosions is evidently caused by the shock waves that follow knocking, further compressing the hot gases in the combustion chamber. The record in figure 11 shows this phenomenon to best advantage. The recompressed gases may be so highly heated by the shock waves that dissociation occurs, giving free carbon in the exhaust and resulting in smoke, as indicated in figure 16. The light areas shown in figures 10 and 13 at about 15° A. T. C. are due to the change in the direction of the light beam caused by the piston slap and are not to be confused with the sharply defined phenomenon shown in figure 11 or the light streaks shown in figures 12, 15, 16, and 17.

Relation of auto-ignition to knock.—Some of the photographs shown herein indicate that auto-ignition of the last part of the charge to burn occurred during some of the more severe knocking explosions. (See figs. 9 and 10.) This result is in accordance with the findings of Withrow and Rassweiler reported in reference 2. In a number of other instances, however, the combustion front appeared to be across the chamber before the occurrence of knock, as is shown in figures 8 and 10 (record 82) to 17. The explosions shown in figures 16 and 17 knocked with extreme violence, yet the reaction fronts had crossed the chamber before knock occurred. Results similar to these have been obtained in a bomb by Maxwell and Wheeler (reference 12). Their photographs of explosions of hydrocarbon vapors and air show, in a number of instances, the flame traversing the chamber before knock occurred. They also obtained ignition of the unburned charge ahead of the advancing flame, although the explosions in those cases were no louder than usual and the pressure records showed no unusual features. Some investigators have suggested the probability that more than one kind of knock can occur. Stansfield and Thole (reference 13) mention three types as being possible; namely, "true pinking"; auto-ignition of the unburned portion of the charge when compressed adiabatically by the advancing frame front; and preignition. They define preignition as auto-ignition of unburned mixture either before the spark passes or, more usually, before more than a small part of the charge has burned. Boerlage and his coworkers (references 14 and 15) mention "pink" and "knock" as being distinct phenomena.

It is probable that the distinction should be limited to that between "knocking" (detonation) and "postignition." Postignition is a secondary combustion front originated by a hot surface ahead of the primary combustion front, whereas knocking is a gaseous reaction taking place with sufficient violence to set up sonic or supersonic waves in the combustion gases. Postignition may result in rough running from excessive flame velocities as found by Souders and Brown (reference 16), which may in turn develop into knocking. A distinction becomes particularly important in the matter of rating fuels. The fact that Withrow and Rassweiler's results (see reference 2) show a time interval of about 0.0013 second for the knocking explosion to fill the unburned portion of the chamber indicates that the phenomena they recorded may have been postignition from the combustion chamber wall rather than knocking. The same fact may be true in regard to the results presented by Boerlage in reference 11.

Duration of the reaction.—The afterburning (as distinct from postignition) shown in figure 5 for rich mixtures indicates that a reaction causing a reillumination of parts of the charge may occur after the flame front has passed through the charge. The two streak schlieren photographs of figure 14 and all the spark schlieren photographs indicate that some reaction which changes the density of the charge or, more precisely, the refractive index, continues for some time after the combustion front has passed through the charge. This interpretation of the schlieren photographs presupposes that no extreme curvature or tilting of the combustion front occurs. If the combustion advanced across the chamber as a narrow tongue, with a region of unburned charge between the inflamed region and the window, then the upper surface would appear as a dark area in the schlieren field. Undoubtedly, some curvature of the combustion front does exist but the extreme distortion necessary to produce the large dark areas shown seems improbable, particularly when it is considered that no such curvature can be seen about the edges of the flame as seen from above. Rassweiler and Withrow (reference 17) mention the possibility of error caused by observation of a curved flame front. They say, however, that observations in an engine used for studying absorption spectra indicated that throughout most of the flame propagation the curvature of the flames in the vertical plane is not very marked.

Some disagreement exists in the literature concerning the probability of burning in the mixture after the flame front has passed. In the combustion of gaseous mixtures, Lewis and von Elbe (reference 18) hold that no cogent arguments have been advanced in favor of afterburning and that the evidence available supports the theory that the reaction is completed very quickly. Among others, Ellis and Morgan (reference 19) and Souders and Brown (reference 16) have conducted tests that they believe indicated the presence of afterburning. The illumination in the region back of the reaction zone before maximum pressure is reached can, of course, be caused by the adiabatic compression of these gases (reference 18).

The researches of Maxwell and Wheeler on the combustion of hydrocarbon vapors (reference 12) led them to conclude that combustion is not completed in the flame front, in either knocking or nonknocking explosions, but that in a knocking explosion the reaction is not continuous, being completed very suddenly following a certain delay period after the flame front has passed through.

In the combustion of gasoline-air mixtures, Withrow, Rassweiler, and coworkers have conducted tests which indicated that the reaction was completed in a very narrow zone. Tests with the sampling valve (reference 20) indicated that the free oxygen at a point in the combustion chamber disappeared almost as soon as the flame arrived. Experiments with the spectrograph (references 21 and 22) showed that the spectrum of the flame fronts was characteristic of burning hydrocarbons and that the spectrum of the afterglow was characteristic of carbon dioxide. In the sampling-valve experiments, however, it appears possible that the reaction may have completed itself after entering the sampling valve. The analysis presented in reference 17 is based on the assumption that the reaction is completed in the flame front. The final curves of "percent mass burned" agree remarkably well with the curves of "percent pressure rise"; hence, it may be that the portion of the charge left unburned after the flame front passes is small.

In general, the photographs presented herein indicate that reaction continues for an appreciable time after the combustion front passes through. If the photographs are accepted as showing that the combustion was across the chamber before knock occurred, then again it must be believed that the reaction is not completed in the combustion front and that knocking combustion probably consists of a sudden and very violent completion of a reaction already started.

CONCLUSIONS

1. No evidence was found that shock waves or any type of violent compression waves are associated with knock until after the actual occurrence of knock. Artificially induced shock waves in the engine did not in themselves cause knock.

2. Although auto-ignition ahead of the flame front may occur in conjunction with severe knock, probably it is not necessary nor does it always occur with knock.

3. The photographs indicate that the reaction is not completed in the combustion or flame front but continues for some time after these fronts have passed through the charge.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *December 6, 1937.*

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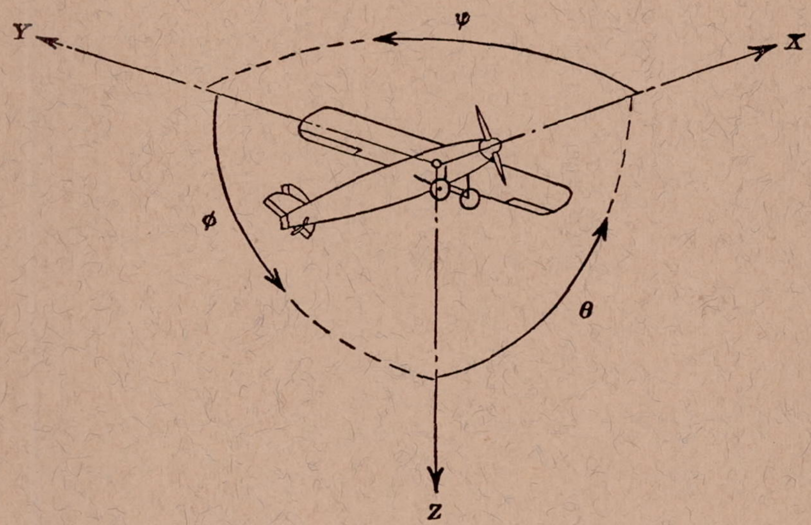

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$

C_s, Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$

η, Efficiency

n, Revolutions per second, r.p.s.

Φ, Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp.=76.04 kg-m/s=550 ft-lb./sec.

1 metric horsepower=1.0132 hp.

1 m.p.h.=0.4470 m.p.s.

1 m.p.s.=2.2369 m.p.h.

1 lb.=0.4536 kg.

1 kg=2.2046 lb.

1 mi.=1,609.35 m=5,280 ft.

1 m=3.2808 ft.