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The phenomenon of "knocking" is associated with the peculiar process of combustion in an internal-combustion engine. The technical term "detonation" used in connection with this particular type of combustion has not so far been justified by direct experiments establishing the actual occurrence of the detonation or explosion wave. It is only natural that the greater number of investigators prefer to employ terms that do not possess any clearly defined physical sense, such as "knocking," "pinking," "cognement," "Klopfen." Moreover, the great majority of investigators declare themselves positively opposed to the identification of the knocking phenomenon with the detonation wave holding the formation of the latter in the engine to be impossible. Thus Whatmough (reference 1) writes

"The detonation blast" and detonation wave are quite different forms of inflammatory motion. The detonation blast denotes bodily projection of the highly compressed explosion gas from a hot pocket as compared with 'the detonation wave,' which is propellant high speed inflammation at a velocity limited by that of the receding combustible."

Brown and Watkins (reference 2), A. Egerton (reference 3), and P. Laffitte (reference 4) advance numerous arguments (different effect of the temperature elevation, facilitating the occurrence of "shock" in the engine and suppressing the occurrence of the explosion wave in the tube; absence of the effect of tetraethyl lead in the detonation phenomenon in the tube; the necessity for the occurrence of the detonation wave in a sufficiently long tube; finally the possibility of obtaining a true explosion wave in air-hydrocarbon mixtures) which force them to the position that "knock in engines does not appear to be necessarily attributable to an explosion wave" (reference 4, p. 418). Finally, the conception of "knock" as a phe-

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*"Le 'Cognement' dans un Moteur a Essence et l'Onde Explosive." Tech. Physics of the U.S.S.R., vol. 3, no. 9, 1936, pp. 803-823.

nomenon analogous to detonation wave is considered incompatible with the chemical theories of "knock" as, for example, the peroxide theory of Callender (reference 5) and of Moureau and Dufraisse (reference 6). "Knock" is associated with either auto-inflammation of a part of the charge due to the decomposition of accumulated peroxides or it is held with Dufraisse (reference 7) that

"The peroxides play somehow the part of a detonator, the flame is propagated with vibratory motion with an abrupt increase in the gas pressure" (p. 134). A similar definition is given by Egerton (reference 3) and Laffitte (reference 4).

"Knock in an engine is not necessarily associated with detonation, but rather with a type of vibratory combustion propatated with velocities of the order of tens of meters per second" (p. 401). These definitions of knock as a vibratory propagation of the flame are based on the well-known tests of Maxwell and Wheeler (reference 8) and are largely accepted by the investigators of combustion. (See also Morgan (reference 9) and Nielsen (reference 10).)

A definite solution of the problem of the physicochemical nature of knock as a certain form of combustion was made possible, however, only as a result of the direct recording of the flame propagation in the engine cylinder at normal operation and with knocking. This is the method followed by the investigators we shall now cite.

Withrow and Boyd (reference 11) in 1931, and Duchene (reference 12) in 1932 published the results of a photographic investigation, the first in the engine and the second in a bomb with a single-cycle adiabatic compression. The photographic records for the knocking regime obtained by these two investigators are essentially similar. Knocking is localized in the remaining portion of the charge the most distant from the spark plug and is recorded in the form of a trace perpendicular to the axis of motion of the recording paper. Withrow and Boyd consider this result as a support of the theory of the simultaneous autoignition of the last part of the charge. As additional confirmation, Withrow and Rassweiler give spectroscopic observations on the process of the oxidizing reaction occurring in the mixture before its autoignition. Duchene, however, on the basis evidently of indirect considerations sees in the similar photographic records a proof of the occurrence in the engine of an actual explosion wave.

However, as Prettre (reference 13, p. 51) justly remarks, "These authors have not been able to measure the velocity of this wave and photographs published would appear to indicate a velocity greater than those given by gaseous mixtures having a high explosive power."

It is noteworthy that Jouguet (reference 14) bases his doubts as to the formation in the engine of an explosion wave on reasons diametrically opposite. He considers that "the speed observed by M. Duchene of the order of 1,000 meters per second is actually too small for a true explosion wave" (p. 153). Prettre himself considers that, "Many objections may be made against the assumption of the instantaneous formation of a wave in the mixtures of air and hydrocarbon vapors. On the other hand, numerous arguments support the view of a simple simultaneous auto-inflammation as cause of the knock."

An attempt to solve this same problem of the definition of the mode of combustion corresponding to knock is also made by Schnauffer, making use of the method of ionization for recording the flame propagation (reference 15). For combustion accompanied by knock, Schnauffer obtains oscillograms testifying according to him to simultaneous auto-inflammation of a portion of the charge:

"Whereas, with no-knock combustion, inflammation occurrs with a sharply defined flame front so that we may speak of a steady propagation of the flame front, in the case of combustion with knock as the records show, the ignition of the last portion of the mixture occurs simultaneously at many points."

In his more recent tests conducted by a perfected method (reference 16), Schnauffer arrives at the same conclusion. Nevertheless, both in the test of Withrow-Boyd and Duchene, the data furnished by the recording method employed by Schnauffer were apparently insufficient for the solution of the problem under consideration. In fact, given a length of detonation zone in the combustion chamber of 5 centimeters and a normal speed of the explosion wave of the order of 2×10^5 centimeters per second, it is necessary to grant the possibility of recording intervals of time of the order of 10^{-5} second, a process which is manifestly beyond the limits of the oscillograph method.

Thus in none of the works cited above has it been suc-

successfully obtained a sufficiently clear physical definition of the combustion in the knocking engine, a definition based on reliable direct measurements. In particular, the question remains open of the relation between the phenomenon of knocking in the engine and the explosion wave. The solution of this problem is the object of our tests.

1. METHOD AND RESULTS OF THE TESTS

For the problem we have proposed ourselves and particularly for the resolution in the time of the phenomenon of high-speed combustion during knock, the method of photographic recording of the flame propagation free from inertia is particularly suitable. The method of Mallard and Le Chatelier (reference 17) which consists of photographing the flame propagation on a film moving perpendicularly to the axis of its propagation has been applied for the first time in an engine by Withrow and Boyd. While following fundamentally the method of the American investigators, we have introduced an essential modification, increasing considerably the speed of the film and thereby assuring the possibility of the direct measurement of the maximum speeds of the flame.

The tests were conducted on an engine specially constructed for this purpose having an aviation-type cylinder 127×140 millimeters (1.77 liters) displacement with inclined valves (fig. 1). The cylinder head has a slit 6 millimeters wide and 150 millimeters long closed by a conical-shape cock with a pyrex glass window. The latter is composed of two window pieces 75×17×19 millimeters with a partition between them corresponding to the white band on the photograph. In order to avoid the black deposit on the windows, the cock before the experiment was in the position A (fig. 2) and only at the instant of recording (at the instant of the opening of the electromagnetic switch regulated by the motion of the valves) was it put in position B. For recording, we made use of an apparatus with rotating drum having a maximum velocity up to 7,000 revolutions per minute, corresponding to a linear speed of 60 meters per second. The apparatus was provided with an objective of f = 1:2.

The cooling of the engine was by forced circulation of water or ethylene glycol. The engine was braked with a dynamometer. The compression ratio was constant and equal to 6.3. Ignition was by means of a coil at one of the ends of the chamber, the opposite opening being closed by a flat valve. The ignition angle was indicated by a neon lamp. Taking into consideration the fact that the knocking regime leading to self-heating of the combustion chamber cannot be stable, we have chosen the following order in the conduct of our tests. For a certain carburetor adjustment, a certain engine speed, position of the choke (normally entirely opened), jacket temperature, and ignition angle, there was first established a regime for which the engine operates without knock. Then immediately before opening the switch, the ignition angle was increased to a certain predetermined value with the aid of a special lever displaced on the interrupter disk. In this manner was recorded one of the first detonation cycles.

Shock and Explosion Wave

The discontinuous change in the character of the flame propagation associated with the occurrence of knock is clearly brought out by the comparison of the two photographs showing the regimes with normal combustion and with knock, respectively (fig. 3). In the case of normal combustion, the flame is propagated over the entire extent of the combustion chamber with a relatively small velocity of the order of 10-20 meters per second. Halfway over the flame travel, we observe an appreciable decrease in its velocity. If the combustion is accompanied by knock, the flame propagation maintains the same character with the exception of the last portion of the charge, where the trace of the flame is recorded by a line perpendicular to the axis of motion of the film with a striated structure in the zone of post-luminescence (fig. 4). These records as well as those of Withrow-Boyd and Duchene show that knock is associated with an abrupt change in the velocity of flame propagation localized in the portion of the charge which is burned last without changing the flame propagation in the preceding part of the chamber. This, however, does not solve the problem of the mode of combustion in the detonation zone. Is the combustion produced simultaneously in the entire mass of the detonating charge (accompanied by the disappearance of the flame front, according to Schnauffer) or is the flame front propagated with the very high velocity of an explosion wave? The answer to this question can be obtained only by recording the combustion with a sufficient displacement velocity of the recording paper.

The results of the gradual acceleration of the velocity of the recording paper from 3 to 30 meters per second are shown in figure 4. The records A, B, and C are here similar to those obtained by Withrow-Boyd and Duchene. The record D, however, recorded with a velocity of the paper of 30 meters per second, and particularly the photographs of figure 5 corresponding to velocities of 50 and 60 meters per second give a more accurate idea of the character of the combustion in the detonation zone. On figure 5-A and C the detonation zone takes up about 5 centimeters of the length of the chamber; on figure 9-B the detonation is produced in the immediate neighborhood of the chamber wall.

The records of figure 5 show that during knock there is produced not a simultaneous auto-inflammation of the last portion of the charge but a flame-front propagation with a finite velocity determined by the inclination of the flame trace. The exact measurement of this velocity is difficult because the detonating zone occupies a relatively unimportant part of the chamber. The measurements for constant carburetor adjustment, however, have given approximately identical values of the velocity and of the same order (about 2,000 meters per second) as the velocities of the detonation wave measured in the tube. As in the case of detonation in the tube, during the occurrence of an explosion wave in the engine there is formed a reflected detonation wave propagated in the burned gas. Its velocity (R), as follows theoretically, is always considerably below the velocity of the detonation wave (D).

D m/s	1980	2020	2200
R "	1500	1580	1760

The above results permit us to state that knock in the engine is associated with the instantaneous occurrence of a detonation wave with all the characteristics peculiar to it.

Shock Waves

The detonation or explosion wave represents according to the classical expression of Jouguet (reference 8, p. 323) "the coexistence of the mechanical and chemical phenomenon of the shock wave and of combustion." When the chamber wall is reached, the explosion wave is reflected, is propagated in the burned gas, and partially dissociated under the form of a shock wave. Our photograph records show the periodic reflection of the shock wave by the opposite wall of the chamber and partially by the partition of the window. The propagation of the unreflected shock wave occurs with gradual attenuation. This corresponds to the progressive decrease of the compression p_2/p_1 in the wave and consequently to the reduction in its velocity. Under the conditions in the engine, the phenomenon of the wave attenuation, somewhat reinforced by expansion, is extended about 70°-80° beyond the dead center. The velocities of the shock wave can be measured with greater accuracy than those of the detonation wave and give the following values for the waves after the first and sixteenth reflection:

D_1	m/s	1460	1520
D_{16}	m/s	930	980

The reduction of the shock wave velocity on the photographs obtained with a lower speed, as on figure 4 A-C, is brought out by the decrease in the frequency of the striae. It is from the frequency of these striae that Duchene has evaluated the mean velocity of the shock waves of the order of 1,000 m/s and Withrow and Rassweiler (reference 19) a value of the order of 800-900 meters per second. Vibrations of the same frequency have been obtained on indicator diagrams observed by Withrow-Rassweiler and Serruys (reference 20). Our tests show clearly that this mean velocity is considerably below the velocity of the first reflected wave whereas the velocity of the latter is less than the velocity of the flame-front propagation in the region of detonation. As follows from our tests, the definition of the detonation in the engine as "an advanced form of vibratory type of explosion" (Egerton) is in conformity with reality only in that subsequent to the occurrence of the detonation wave in the last part of the charge there is repeated and periodic reflection of the shock waves by the chamber walls.

Computation of the Velocity and Pressure of the Detonation Wave

The thermodynamic theory of the detonation and shock waves permits us to compute the velocity of the explosion wave as well as the pressure and temperature at the flame front from the initial condition of the gas and the equation of the chemical reaction. A computation of this kind has been performed for an air-fuel mixture by making the following assumptions:

The shock wave is produced during the final stage of combustion near the point of maximum pressure. We are therefore permitted to take for the initial condition of the gas at the instant of occurrence of the explosion wave the value of the maximum pressure obtained for normal combustion, and the temperature corresponding to this pressure according to the law of adiabatic compression $P^{\frac{1-k}{k}} T$ = constant. By assuming for the maximum pressure of normal combustion 25 atm and $k = 1.25$, we obtain for the temperature of the last portion of the charge $T_1 = 615°$ absolute (initial temperature $T_0 = 323°$ abs). Assuming the fuel to be equivalent to hexane, we obtain the equation of the reaction:

$$C_6H_{14} + 9.5O_2 + 35.7N_2 = 6CO_2 + 7H_2O + 35.7N_2 + 1007 \text{ cal}$$

The computation made from these data gave for the temperature of the shock-wave front $T_2 = 3390°$ abs. The velocity of the shock wave is correspondingly equal to 1850 meters per second, a value which approaches the experimental value if we take account of the possible errors in the assumptions and of the measurement of the wave velocity. The corresponding increase of the pressure at the shock wave front is $P_2/P_1 = 10.4$. This means that the occurrence of the explosion wave in the engine is accompanied by an abrupt pressure rise exceeding ten times the maximum pressure of normal combustion. Using the value of the pressure $P_1 = 25$ atm before the rise of the explosion wave, we obtain for the maximum pressure of the detonation wave $P_2 = 260$ atm.

All the indicators employed do not permit even approximately the evaluation of the actual pressures during knock. The indicator in this case measures the impulse of the force which under certain assumptions may be compared with the results obtained by computation.

Serruys (reference 21) has computed the duration of the detonation impulse by measuring the magnitude of the lag which takes place during the detonation near the point of maximum pressure on the diagram recorded by the Farnsborough indicator. He obtained a value of the order 10^{-4}

second. The order of this magnitude may also be evaluated by another method: namely, as the time interval between two consecutive impulses of the detonation wave and of the first wave reflected on the membrane of the indicator. For our engine cylinder with a diameter of 150 millimeters and given the velocity of the first reflected wave equal to 1,500 meters per second, this time interval is

$$\frac{0.15\times2}{1500} = 2\times10^{-4} \text{ sec}$$

a value which approaches very closely the result obtained by Serruys. Duchene and Verdier (reference 22) have constructed a special mechanical model that reproduces the intensity and the frequency of the impulses imparted to the Midgley indicator diaphragm during detonation. They have measured the "force of the knock" corresponding in their test to the impulse of a weight of 10 kilograms at a velocity of 3.6 meters per second on a piston of 100 millimeters diameter. For a unit of surface, this corresponds to an impulse of

$$\frac{10\times4\times3.6}{100\times3.14\times9.6} = 48\times10^{-3}$$

If we estimate the value of this impulse from the increase in the pressure at the explosion wave front, computed by us (235 atm) and from the interval between two consecutive knocks (2×10^{-4} sec), we obtain: $235\times2\times10^{-4} = 47\times10^{-3}$. Thus the impulse computed from the shock wave agrees with the result of direct measurement. This, however, does not prove the accuracy of the computation or of the direct measurement of the impulse. Nevertheless, this agreement may be considered as a new indirect proof of the occurrence in the engine of an actual explosion wave obeying the laws established by the thermodynamic theory of the detonation phenomenon as developed by Jouguet.

In one of his articles, Ricardo (reference 23, p. 258) has written: "The actual phenomenon of detonation coupled with the vexing question of whether or not it is a true detonation in the academic sense of the word, are problems for the chemist and physicist to decide. To the engineer and designer, the incidence and not the definition of detonation is the factor which determines the compression ratio he may employ, and therefore limits the power, output, and efficiency he can obtain."

Actually, however, the problem of the mode of combustion during the detonation, whether it occurs instantly as assumed by the theory of auto-inflammation, or with a considerable but finite velocity of the explosion wave, is not at all academic. The direct proof of the rise of an explosion wave in the engine permits us, with the aid of the thermodynamic theory of detonation, to compute, though approximately, the duration as well as the value of the detonation impulse and to evaluate the maximum pressure during the detonation, values that are very important from the practical point of view and that lend themselves only with difficulty to direct measurement.

Instant of Occurrence of Detonation Wave

The interval of time from the dead-center position to the instant when the detonation wave is produced depends on different factors. It decreases with increase in spark advance, with change in the carburetor adjustment, attaining its minimum value with a mixture that is close to the correct one, and varies finally with modifications of the fuel characteristics. By adding ethyl fluid or toluol to the fuel the instant of occurrence of the detonation wave recedes considerably from the dead center. There is also an increase in the distance from the spark plug to the point where the detonation is produced.

We have, in addition, conducted a series of tests in which we varied within wide limits (40° to 145°) the temperature of the cooling liquid: namely, ethylene glycol. On the basis of the photograph records obtained at a constant compression ratio (6.3), 800 revolutions per minute, spark advance 18°, we have measured the time interval (in degrees of angle of rotation of the flywheel) from the instant of dead center to the instant of occurrence of the explosion wave. From the variations of this value, it is possible to judge the effect of the change in temperature on the course of the chemical reactions which precede the detonation and prepare for it. For the pure fuel, we used three different carburetor settings corresponding to the following values of the excess air coefficient, 1.12, 0.9, and 0.75. The corresponding data for these three values are shown in figure 6. We may note that these results are confirmed by the tests conducted by Auer (reference 24, table 5 and fig. 7) if we take account of the fact that during these tests the mixture gradually leaned with increase in air temperature from 23° to 74°. In the case of lean mixtures the increase in the temperature leads, moreover, to a considerable increase (almost double) in the mean velocity of the flame propagation during normal combustion so that the combustion ends sufficiently near dead center. This shows that with high temperatures it is possible to obtain regular operation of the engine without backfiring in the carburetor with mixtures having excess air values beyond 1.2 such as is impossible with low temperatures. If the engine is operating with a mixture corresponding to maximum power, the mean velocity of propagation of normal combustion practically does not vary with increase in the cylinder-jacket temperature (fig. 7).

The results of these tests agree with and at the same time explain the observations made by Puisais and Moynot (reference 25) on the effect of the temperature regulation during intake on the power and efficiency of the engine. "This effect is very slight for a correct mixture within the normal limits of temperature variation. It increases with change in mixture richness. With lean regulation, an increase in the temperature decreases the fuel consumption and increases the power."

In the literature on the subject, we find certain references to the increase of the action of the tetraethyl lead as a result of the elevation of the cooling liquid temperature (reference 26). Our tests, however, do not confirm these observations. For a maximum-power mixture, the temperature elevation has practically no effect in changing the time interval up to the occurrence of detonation even when the fuel used has an ethyl content of 3 cubic centimeters per liter (fig. 8).

Detonation and Autoignition

Simultaneously with the occurrence of the explosion wave in the last part of the charge it is also possible for the phenomenon of autoignition to occur as a result of the local heating of the combustion chambers walls, a heating in great part due to the preceding detonation. This completely excludes any possibility of a stable detonation regime in the engine. With increase in the wall temperature, there is a decrease in the ignition lag and the autoignition point approaches the dead-center position. Figure 9 shows clearly this gradual approach of the point of autoignition. The flame front which is formed near the "hot point" is propagated toward the extremity of the chamber as well as in the direction of the flame front advancing from the spark plug. If the instant of autoignition is sufficiently close to the dead center, the normal combustion has sufficient time to consume the entire charge before the occurrence of the detonation wave (fig. 9d). The autoignition at the end of the chamber is represented by the insertion of a second spark plug not included in the electric circuit. The role of the hot point is assumed in this case by the electrode of the second spark plug near which the autoignition occurs. The record in figure 10 was obtained for an engine with great knock intensity, the photograph having been obtained at precisely the instant of disappearance of the knock when the engine had begun to operate in a normal manner. As appears from figure 10, this is explained by the fact that the two flame fronts - of the spark plug and of the "hot point" - have met sufficiently near the dead center before the detonation wave could be formed. The progressive increase in the hot-point temperature leads to autoignition during the compression and consequently to the stopping of the engine as has been shown by the tests of Dumanois (reference 27) and Serruys (reference 28). Our tests prove that the autoignition arising largely as a consequence of the detonation is a phenomenon essentially distinct from the latter both by its physical character, character of the flame propagation, and by its action on the engine operation.

Discussion of the Results

The method employed by us of high-speed recording of the flame propagation in the engine has provided a definite solution of the problem of the physical character of knock. Contrary to the opinion prevailing at present, knock in the engine is associated not with flame propagation of a vibratory type and not with simultaneous autoignition of the last part of the charge but with the sudden formation of an explosion or detonation wave propagated with a speed of the order of 2,000 meters per second. We have, however, very good reasons for supposing that the mechanism of occurrence of the explosion wave in the engine differs in a pronounced fashion from that of its formation in the oxygen mixtures in a tube.

2. FORMATION OF SHOCK WAVE

There exist three types of flame propagation in closed tubes, represented in figure 11. The first type (fig. 11-A), with decreasing speed, corresponds to the normal combustion (without knock) in the engine. The second is the vibratory type (fig. 11-B). The vibrations or the recoils of the flame front are caused by the action of compression waves of finite amplitude produced as a result of the considerable velocity of the combustion and reflected by the closed ends of the tube (references 29 and 30).

Given a sufficient length of tube, the compression waves which arise continuously accumulate, forming the front of the shock wave. The same factor (temperature elevation of the gas) which leads to the progressive acceleration of the velocity in the series of compression waves leads also to the continuous acceleration of the velocity of reaction and flame propagation in the predetonation zone (fig. 11-C). Thus, in oxygen mixtures, the shock wave is formed as a result of the auto-acceleration of the combustion in the predetonation zone. If the mixture is suitable for detonation, that is, if it is capable of igniting after compression by a shock wave with very short lag, then the formation of the shock wave results immediately in the rise of an explosion wave. It is also evident that in this case the mean velocity of the flame in the predetonation zone should be equal to the velocity of the initial compression wave, that is, of the order of magnitude of the velocity of sound (reference 31).

In the engine, however, the character of the flame propagation preceding the formation of the detonation wave is in no way distinguished from the normal combustion and is similar to figure 11-A. Here the mean velocity both for normal and for knocking regimes rarely exceeds 20 meters per second. Not only do we not observe any acceleration or recoil of the flame in the engine which are characteristic of oxygen mixtures but the rise of the explosion wave is ordinarily preceded by an abrupt slowing-down of the flame propagation so that the velocity approaches zero. (See fig. 4.) All this justifies the assertion that the shock wave which produces the detonation wave is not formed in the zone of normal combustion preceding the detonation of the engine. From this viewpoint, particular interest is attached to the observations of Schnauffer (SAEJ, 16, p. 22):

"Measurement of the speed of flame-front propagation during knocking in an engine carried out with this apparatus (microchronometer) gave speeds of 265 to 300 meters. In spite of very heavy detonation, no greater speed was observed. Hitherto published values of 2,000 meters and more per second for flame-propagation speed during detonation, which for the most part were ascertained in tubes, do not seem to represent the true state of affairs. The speed lies well below the speed of sound."

The inner contradiction of this observation is evident. In fact, if the observed speed refers to the normal zone of combustion, it never exceeds, as also the mean speed for the entire explosion chamber, 20-30 meters per second. This appears both from the tests of Withrow-Boyd and from our measurements as well as from the measurements conducted by Schnauffer himself (reference 15). At the same time, this velocity cannot be attributed to the zone of detonation where, according to Schnauffer, "the flame-front disappears and the combustion takes place simultaneously through the entire mass of the charge." To what then should this velocity be referred? It is a mystery which the author leaves unsolved for us.

Suitability of the Mixture for Detonation

The tests of Nielsen, Egerton, and others have shown that in the air-hydrocarbon mixtures (for example, pentane) similar to the fuels the detonation wave is not produced even in the case of very high initial pressures (up to 10 atm). Up to the present, the spontaneous occurrence of a detonation wave has only been observed in the case of hydrogen mixtures (reference 32) and of acetylene with air (reference 33).

Thus, we may consider as established:

1. The fact of the occurrence of the detonation wave in the engine during knocking;
2. The fact that the shock wave in the engine is not produced as a result of normal combustion preceding the detonation.

It is curious that the explanation of this contradiction should be furnished by the chemical theory of knocking generally opposed to the theory of the explosion wave. It has been best formulated by Egerton (reference 34) as the theory of preactivation. The conditions permitting the occurrence of detonation in the engine are determined by the reaction of oxidation which is developed as a chain reaction as a result of the heating of the mixture by the compression and the hot surface of the chamber and especially by the exhaust valve. The centers at which the reaction chains originate are probably provided by the products of the initial oxidation of the hydrocarbons: namely, the peroxides. The most activated part of the charge is naturally that which is consumed last and consequently remains the longest exposed to a high temperature; hence, it is there that the detonation wave arises.

The mechanism of the chemical activation of the mixture corresponds probably to reactions taking place during the induction period preceding the occurrence of the chemiluminescence (cold flame). As a proof, there may be pointed out, for example, the considerable increase in the aldehydes in the last part of the charge immediately before the occurrence of the detonation wave. This is shown by the method of sample analysis of Egerton and by the absorption spectra obtained by Withrow and Rassweiler (reference 35). The fuel-air mixture at the instant of completion of the induction period differs radically from the initial mixture by its tendency toward ignition with a very short lag and hence by its suitability for permitting the propagation of the shock wave. At the same time, the ignition of the activated mixture by the normal combustion front is produced with a sufficiently short lag to permit a local and rather rapid pressure rise which is characteristic of a shock wave. From this moment on, the combustion of the fuel-air mixture develops in a manner quite identical with the detonating combustion of oxygen mixtures. The role of ignition is here assumed by the normal combustion front in whose immediate neighborhood arises the front of the shock and detonation waves. This proximity of the point of occurrence of the explosion wave to the source of inflammation also takes place in oxygen mixtures with a high detonating value (such as acetylene) provided there is given a high initial pressure and a strong ignition.

It should be noted finally that preheating apparently permits the rise of a detonation wave in the fuel-air mixtures as well as in the bomb, according to the tests of Wellard and Mondain-Monval (reference 36). From this point of view it is easy to understand the reasons for the negative result of Egerton and others whose tests were conducted with high initial pressures but with low temperatures.

Detonation and Speed of Combustion

It is generally assumed that detonation in the engine arises as a result of too-rapid combustion. According to the rule of Ricardo (reference 37): "Detonation depends primarily upon the rate of burning of that portion of the charge first ignited, and it remains to discuss what actually controls its rate." In a more recent article (reference 38), Ricardo, developing the same line of thought, associates the occurrence of detonation in the engine with the velocity of the flame in the normal combustion zone: "It seems quite clear, that detonation is initiated only at the extreme end of the flame travel, due to the compression of usually some quite small portion of the unburned charge by the approaching flame; whether or not detonation will take place with any given fuel depends upon whether this unburned gas can get rid of its heat to the surrounding walls at a sufficient rate. This in turn depends upon:

1. The speed of the oncoming flame, which tends to increase very rapidly as it travels outwards from the point of ignition and therefore, in effect, upon the length of flame travel;

2. The temperature of the surfaces surrounding the residium of unburned charge;

3. The degree of turbulence etc."

We may note first of all the inner contradiction of the conception of Ricardo. According to him, the detonation may be eliminated by increasing the heat transmission of the last portion of the charge by a greater combustion time and turbulence. Nevertheless, and Ricardo admits it, the turbulence by facilitating the heat transmission at the same time accelerates the flame propagation. On the other hand, there remains without explanation the antidetonating effect of the reduction of the cylinder diameter and the flame travel, which Ricardo himself puts at the basis of his theory of the design of anti-detonating combustion chambers. Apparently, the reduction of the length of the chamber decreases the combustion time and is consequently equivalent to an acceleration of the latter.

Moreover, as shown by our photographic records, before the occurrence of detonation there is observed not an acceleration of the flame velocity but a sudden slowing down. The latter is explained by the variation, as the flame front is propagated, of the ratio of the fresh to consumed gas volumes. In the engine this effect is further increased by the expansion especially 10°-12° after dead center.

As is shown by our tests for combustibles with a high detonating value, the detonation is relatively retarded and is produced at 30°-40° after dead center with a spark advance of 18°. Auer (reference 24) in this tests, points to a still more retarded detonation up to 70° beyond dead center. It is evident that under these conditions detonation is produced during a strong reduction of the pressure and not as a result of a sudden rise in the latter and of the compression of the last portion of the charge as is usually assumed. Even in the case of a relatively advanced detonation (as a result of a large spark advance), we see in the indicator diagrams a horizontal line before the abrupt pressure increase during the detonation. This points to an interruption of the pressure rise before the detonation. All this leads to a revision of the widespread ideas of detonation as a result of an excessive speed of combustion. It is, on the contrary, more probable that the detonation is produced as an indirect result of the slowing down of the combustion in the engine. From this point of view, the presence or absence of detonation in the engine depends entirely on the chemical activation of the mixture which did or did not have time enough to be completed before the normal combustion is able to reach the end of the chamber. Consequently, as deciding factors, there are to be considered on the one hand the speed of propagation of normal combustion and on the other the initial temperature and the speed of oxidation. The lower this temperature the earlier in the compression will the growth of active centers take place (peroxides) and the nearer the dead center during expansion will the mixture become suitable for detonation.

It is interesting to note that the maximum velocities of flame propagation in the tube for hydrocarbon-air mixtures according to the measurements of Payman (reference 39) are almost identical:

	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
V cm/s	65	81	80	83	83

It is known that the initial temperature of oxidation for these hydrocarbons decreases with increase in molecular weight. It is only natural that the above series shows an increasing order of detonation value.

The new conceptions of the part played by the velocity of the flame propagation in the engine determine naturally new methods for the suppression of the phenomenon. The anti-detonating effect may be obtained not only by the slowing down of the chemical activation of raising of the initial oxidation temperature, to which action, for example, tetraethyl lead contributes, but also by acceleration of the flame propagation. It is to the latter action that may be attributed the anti-detonating effect obtained by turbulence, reduction of the flame travel, double ignition, decreasing considerably according to the tests of Marvin (reference 40) the combustion time, and finally, the addition of hydrogen to the mixture in the cylinder as shown by the tests of Egerton and of the Bureau of Standards of the United States (reference 41), the addition of hydrogen producing a notable acceleration of the flame propagation. The possibility of eliminating detonation in the engine as a result of accelerating the normal combustion is also well shown by our tests with the autoignition of the hot point (figs. 9 and 10).

The regulation of the time factor during combustion in the engine may also be utilized for the suppression of the detonation phenomenon. It should not be overlooked, however, that the acceleration of the normal combustion in the engine leads also to an increase in the maximum temperature of the last portion of the charge, which fact does not permit influencing the speed of oxidation of the latter. This limits the effect of the new methods for the elmination of the detonation phenomenon in the engine.

3. SUMMARY

1. By the high-speed-photography method, it has been possible to demonstrate the occurrence of a detonation or explosion wave with a velocity of the order of 2,000 meters per second in a gasoline engine during knock. Simultaneously, there was recorded the reflected detonation wave and the propagation of waves during knock periodically reflected from the chamber walls. Our photographs permit a very exact evaluation of the gradual variation of their velocities.

2. The effect of the cooling-fluid temperature on the occurrence of detonation was studied. The effect of a temperature increase was found to vary with the richness of the mixture. For lean mixtures, it was found that the flame propagation was accelerated as a result of the rise in temperature with the consequence of an even more stable operation of the engine utilizing those mixtures.

3. The occurrence of autoignition in the engine was investigated and its relation with the phenomenon of detonation established.

4. On the basis of experimental data general hypotheses were formulated, serving to explain the special mechanism of the occurrence of the detonation wave in the engine. According to the new point of view, the formation of the shock wave and of the explosion wave in the engine depends on the modification of the properties of the mixture as a result of the chemical activation preceding the ignition.

5. Certain considerations are adduced which show that the detonation, contrary to the prevalent opinion, is produced in the engine not as a result of accelerated combustion of the mixture but rather as a result of retarded combustion.

Translation by S. Reiss,
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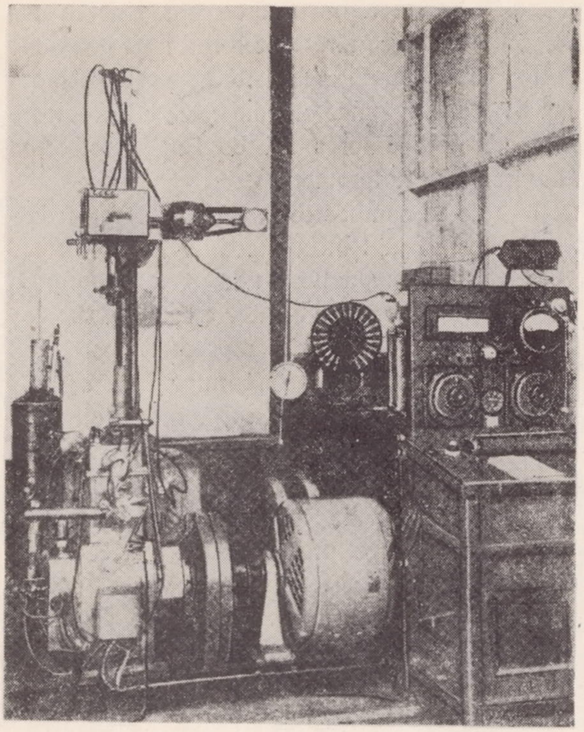


Figure 1.- General view of the engine.

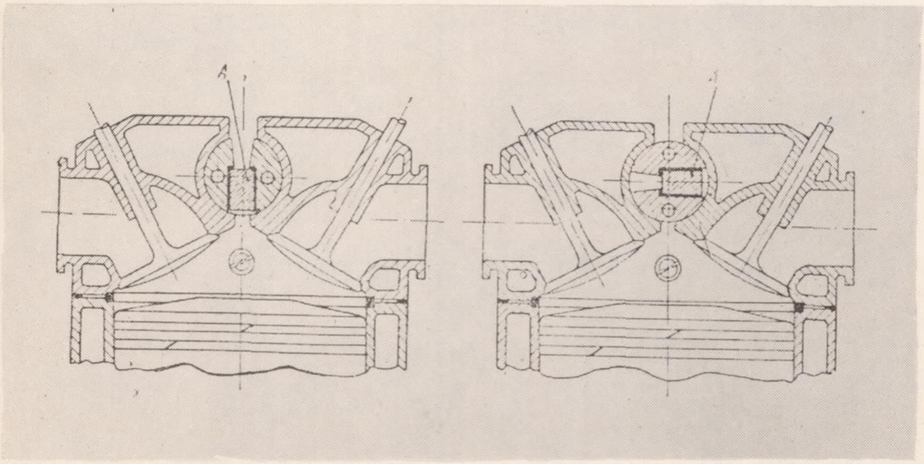


Figure 2.- Two positions of the cock in the cylinder head.

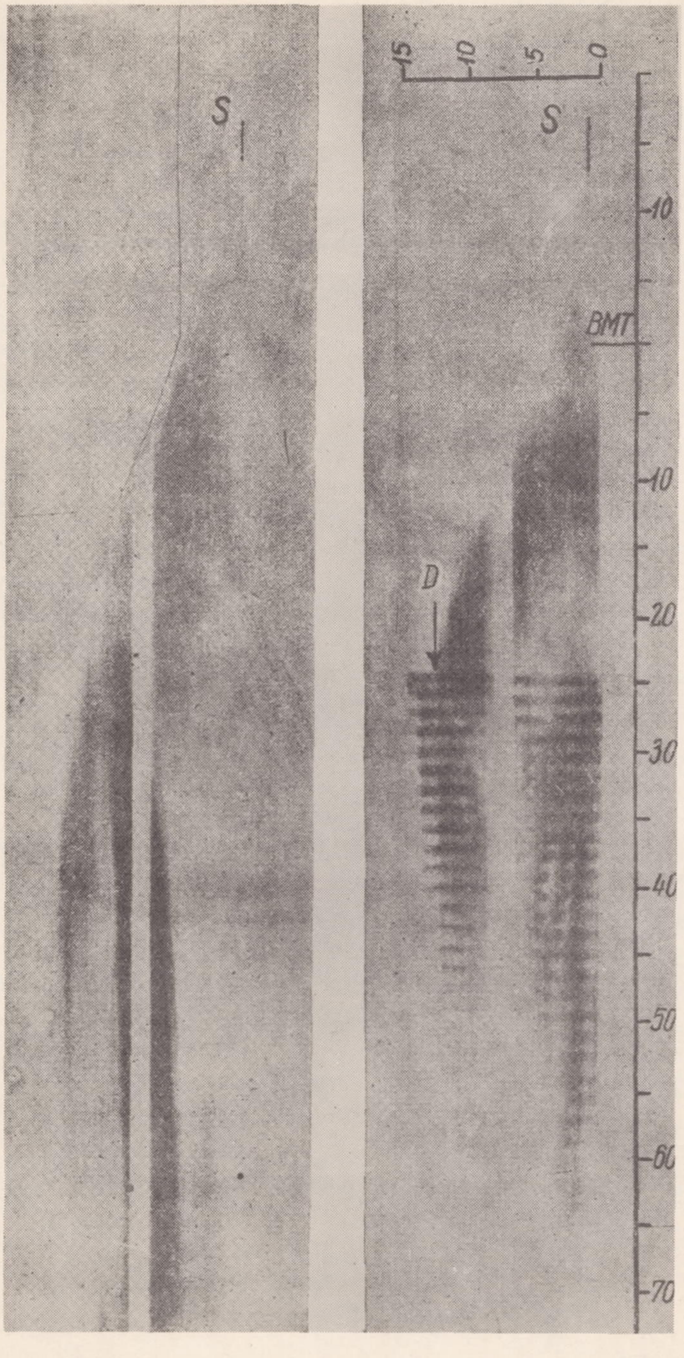


Figure 3.- Photo-records of normal combustion (A) and with detonation (B) in the engine. C- spark. D- point at which detonation is initiated.

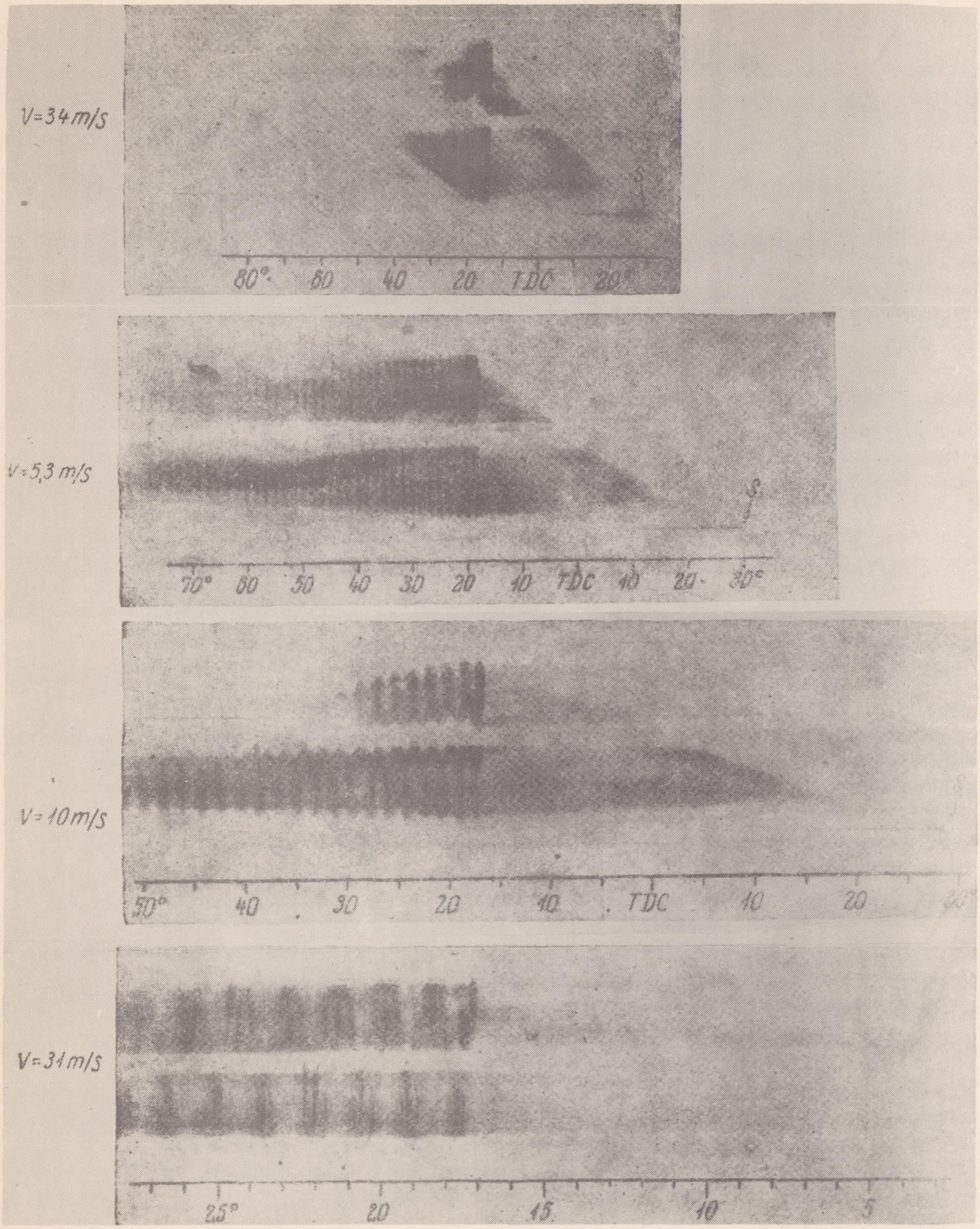


Figure 4.- Photo-records of combustion with detonation in the engine obtained with an accelerated velocity of the recording paper (from 3 to 30 m/sec.).

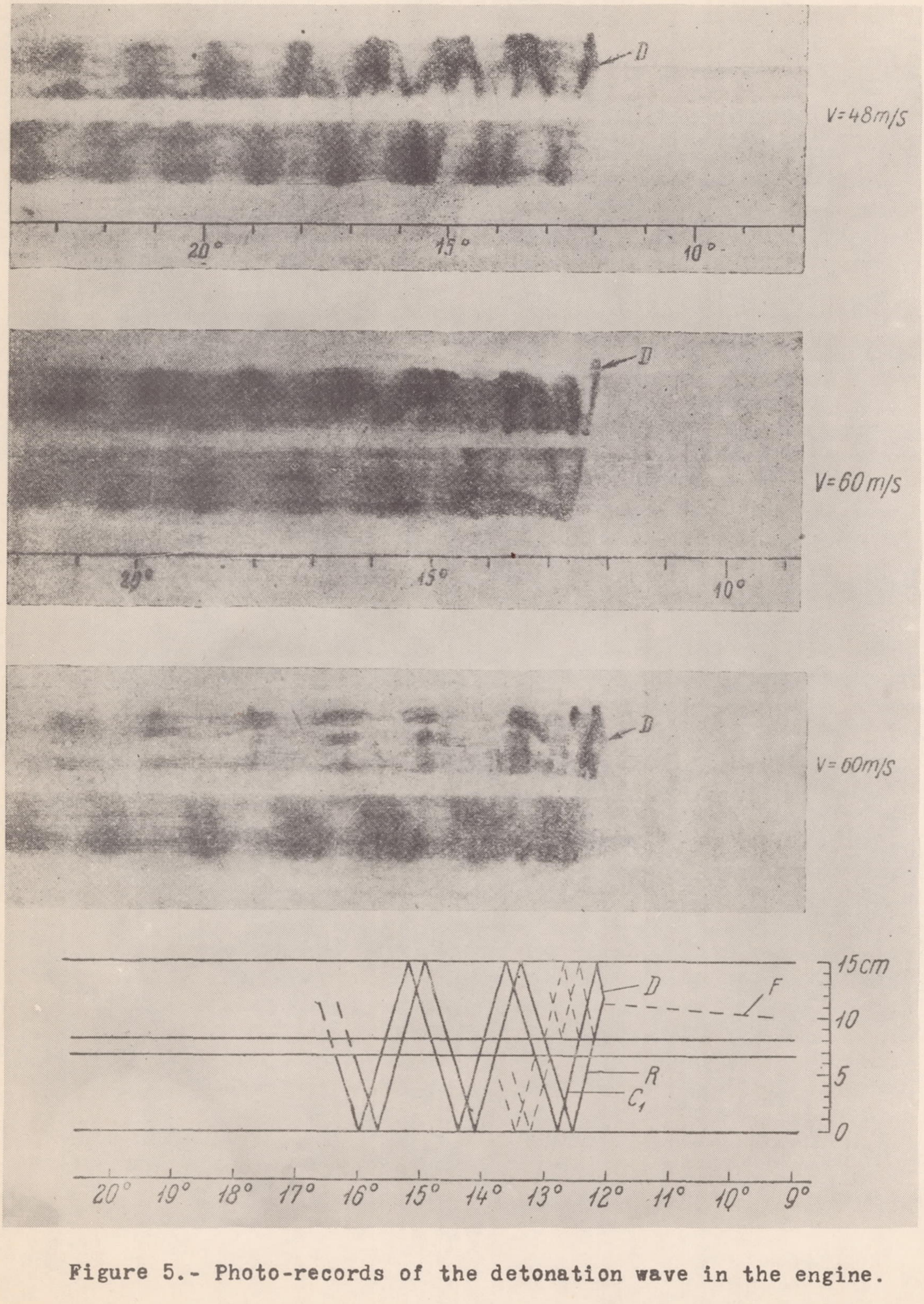


Figure 5.- Photo-records of the detonation wave in the engine.

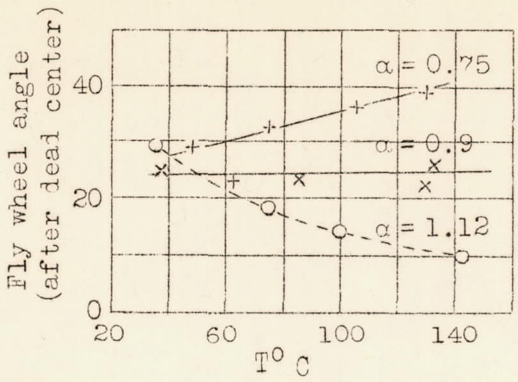


Figure 6.- Displacement of the instant of occurrence of detonation with temperature.

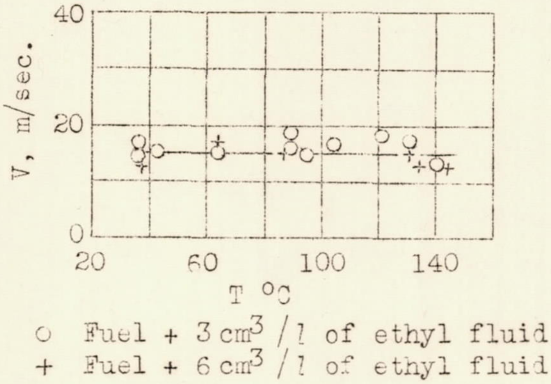


Figure 7.- Variation of the mean velocity of the flame with jacket temperature.

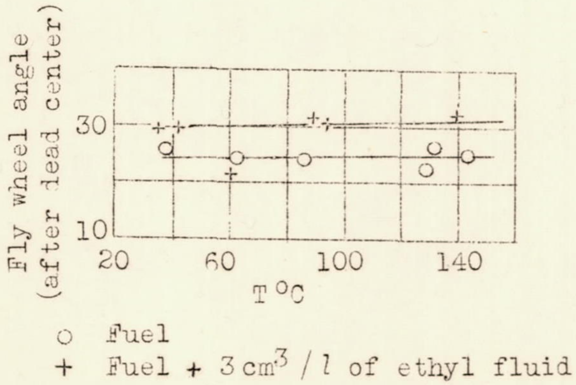


Figure 8.- Effect of the temperature on the time interval before the occurrence of detonation.

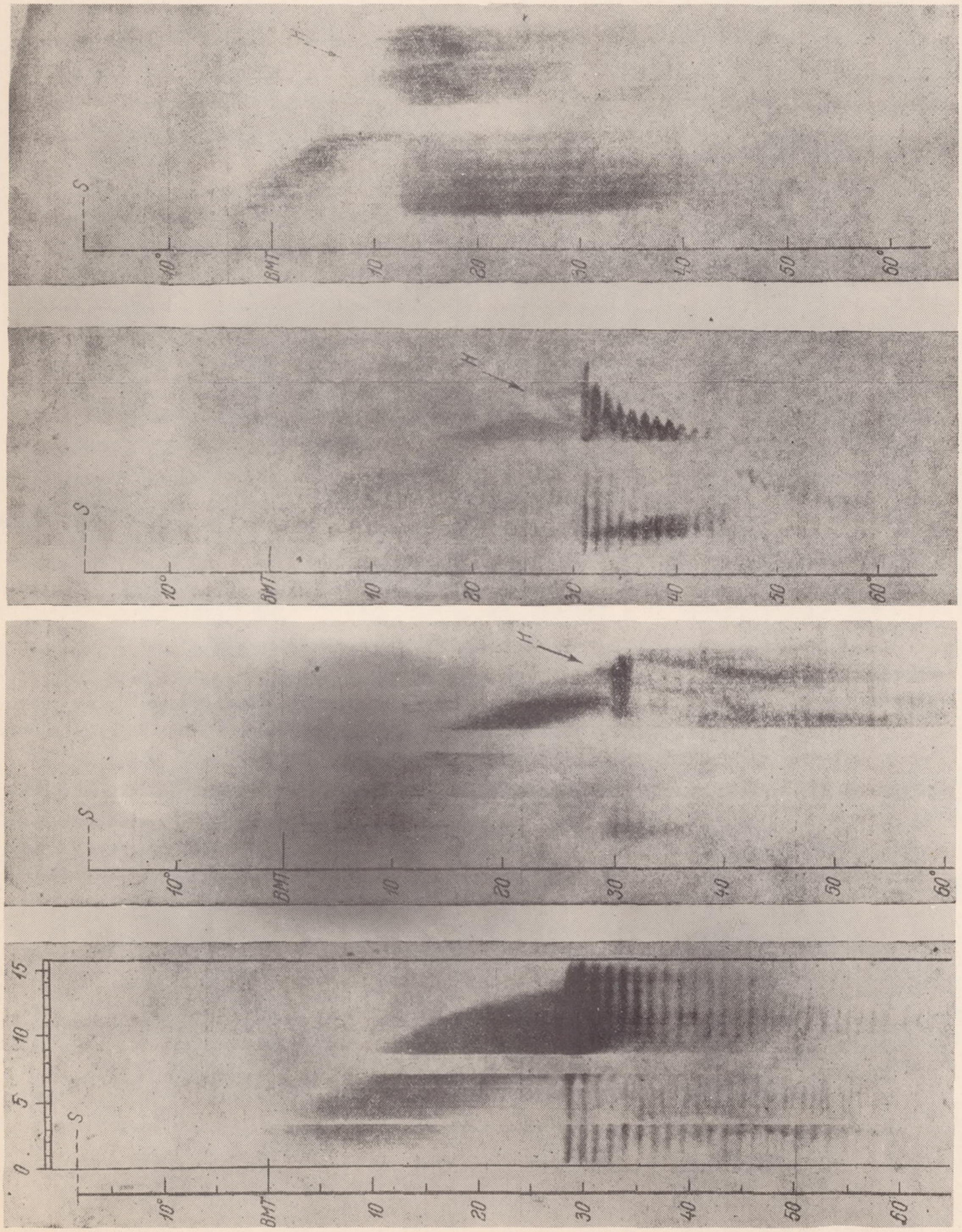


Figure 9. Detonation (D) and auto-ignition (H) in the engine.

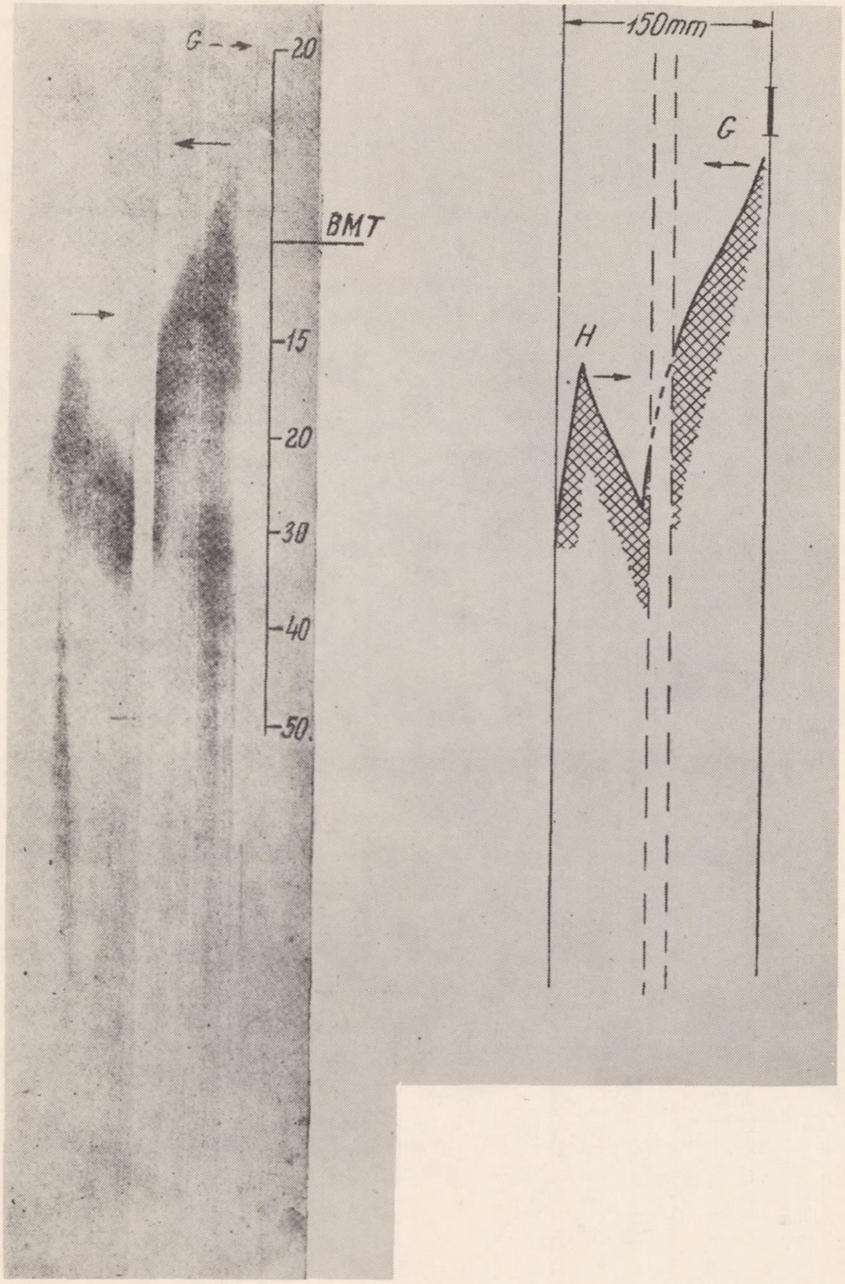
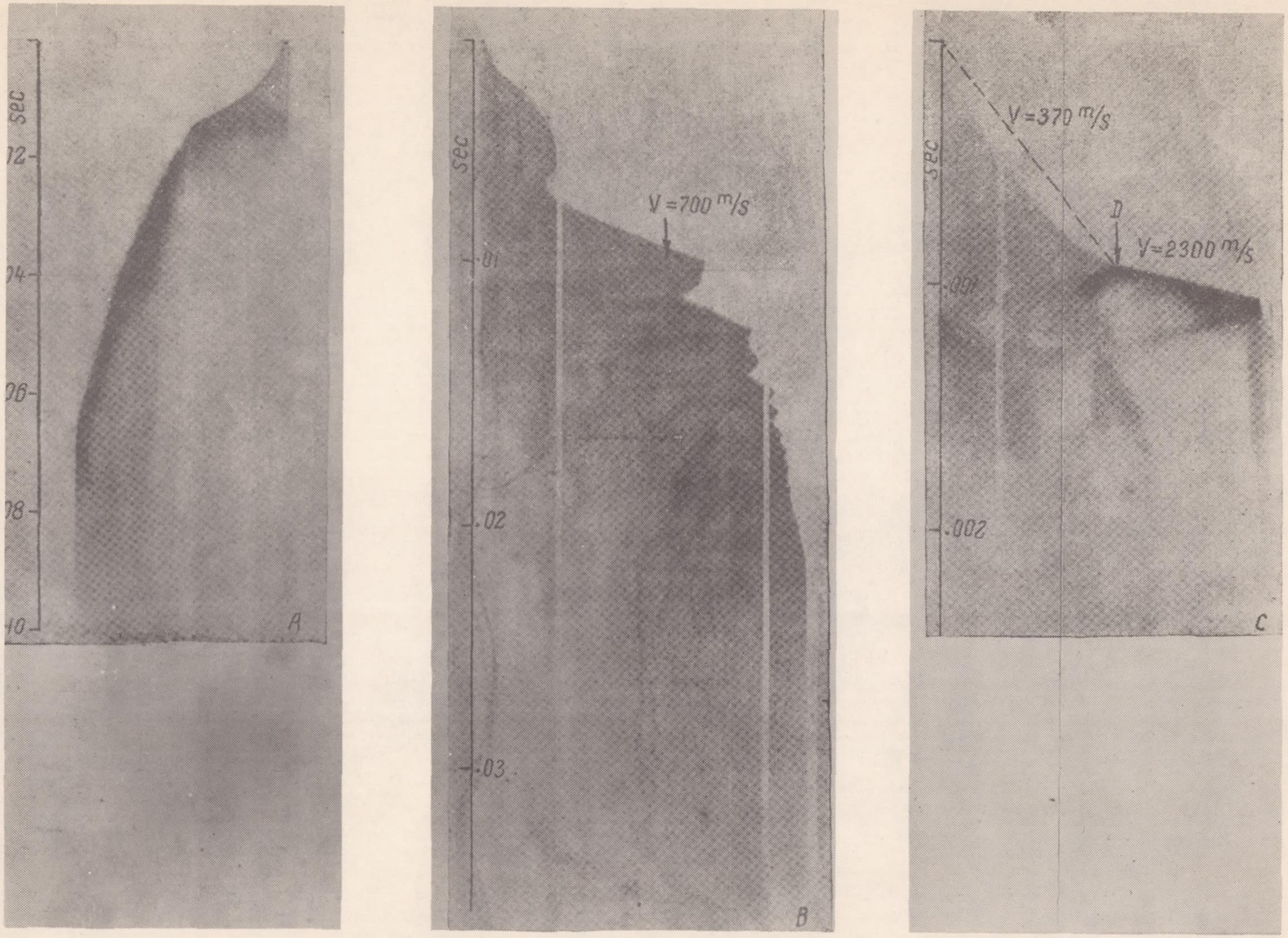


Figure 10.- Disappearance of the detonation as a result of the auto-ignition of the "hot point" (H).



A, Carbon monoxide-air mixture. B, Carbon monoxide-oxygen mixture. C, Ethane-air mixture.
Figure 11.- Three types of flame propagation in closed tubes. (Tests of Rivin and Voronkov)