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REPORT No. 435

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FUEL VAPORIZATION AND ITS EFFECT ON COMBUSTION IN A HIGH-SPEED COMPRESSION-IGNITION ENGINE

By A. M. ROTHROCK and C. D. WALDRON

1932

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h	k. p. h.	mi./hr.	m. p. h.
		m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

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

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

ρ, Density (mass per unit volume).

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

Specific weight of "standard" air, 1.2255 kg/m$^3 = 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

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

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) 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_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

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 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/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_o, 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 C. D. WALDRON
Langley Memorial Aeronautical Laboratory

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

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FUEL VAPORIZATION AND ITS EFFECT ON COMBUSTION IN A HIGH-SPEED COMPRESSION-IGNITION ENGINE

By A. M. Rothrock and C. D. Waldron

SUMMARY

The tests discussed in this report were conducted to determine whether or not there is appreciable vaporization of the fuel injected into a high-speed compression-ignition engine during the time available for injection and combustion. The effects of injection advance angle, fuel boiling temperatures, fuel quantity, engine speed, and engine temperature were investigated. The results show that an appreciable amount of the fuel is vaporized during injection even though the temperature and pressure conditions in the engine are not sufficient to cause ignition either during or after injection, and that when the conditions are such as to cause ignition the vaporization process affects the combustion. The results are compared with those of several other investigators in the same field. The tests were conducted with the N. A. C. A. combustion apparatus.

INTRODUCTION

Since Doctor Diesel's invention of the compression-ignition engine, extended researches have been conducted on fuel vaporization and the effects of this vaporization on the combustion. Originally it was believed that the fuel went through four distinct stages: Injection, vaporization, ignition, and combustion. This idea was held by Riepell, Alt, Neumann, as well as by Diesel himself. (References 1 and 2.) As research on the combustion process progressed Alt and Neumann came to the opinion that there was insufficient time between injection and ignition to allow for the vaporization of any appreciable quantity of fuel. This opinion was accorded general acceptance in Germany and the United States.

Preliminary results obtained by Rothrock with the N. A. C. A. combustion apparatus (reference 3) indicated, however, that not only was some of the fuel vaporizing under the conditions of engine operation, but also that this vaporization was considerable even at compression pressures and at air temperatures too low to result in auto-ignition of the injected fuel.

A series of tests was therefore conducted to determine definitely whether or not vaporization did occur and if so the effect of this vaporization on the process of combustion. The purpose of this report is to present the results of these tests on which a preliminary note has already been published. (Reference 4.) The work was done by the National Advisory Committee for Aeronautics at Langley Field, Va.

APPARATUS AND METHODS

The N. A. C. A. combustion apparatus has been described in detail in reference 3. A diagrammatic sketch of it is presented in Figure 1. The apparatus is so constructed that a single-cylinder test engine is driven at the desired speed by an electric motor. By engaging the clutch, the camshaft of the injection system makes a single revolution at one-half engine speed, and a single charge of fuel is injected into the combustion chamber of the engine. High-speed motion pictures are taken of the injection process by means of the apparatus shown in Figure 2. In the present investigation the arrangement and rate of discharge of the electric condensers were such that 13 exposures were taken at the rate of 1,000 per second. When combustion took place its illumination was also recorded on the film. The film used was ordinary commercial film.

The passages around the cylinder and in the cylinder head are connected to a tank containing glycerin which is circulated through these passages. By means of electric heating coils in this tank, the glycerin, as it leaves the engine jackets, can be maintained at temperatures as high as 400° F. It is possible to inject the fuel with or without combustion of the fuel spray by changing the temperature of the glycerin. Most of the present tests were made at temperatures below that required for combustion so that the complete process of vaporization and condensation could be studied.

Two additions have been made to the apparatus since it was described in reference 3. A circuit breaker in series with a switch operated by the injection system camshaft has been added. This circuit breaker is connected in series with a small spark gap placed in front of the photographic film. As a result, a line is recorded on the film as the piston passes through top center in the cycle during which injection takes

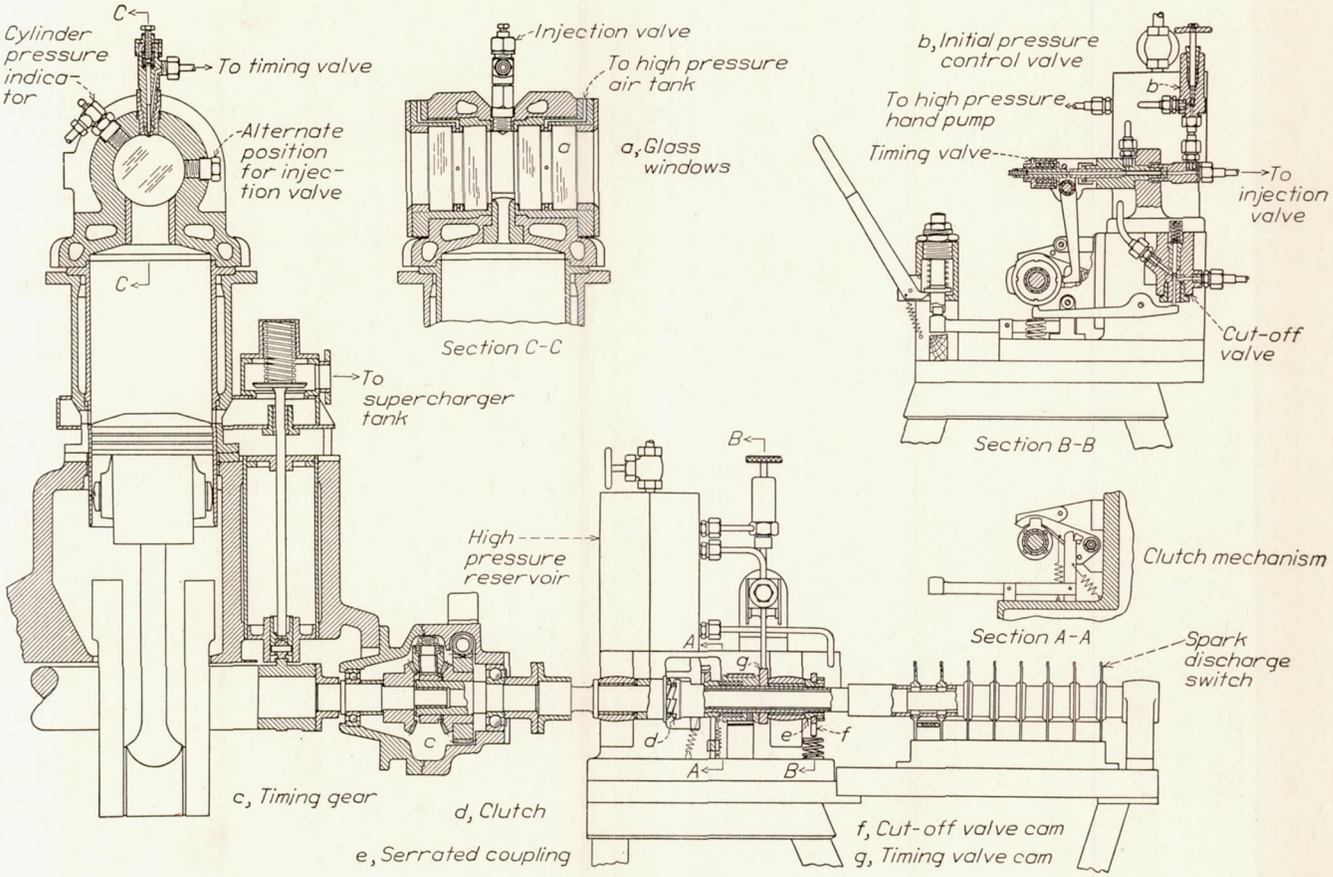

FIGURE 1.—Single-cylinder test engine and fuel-injection system

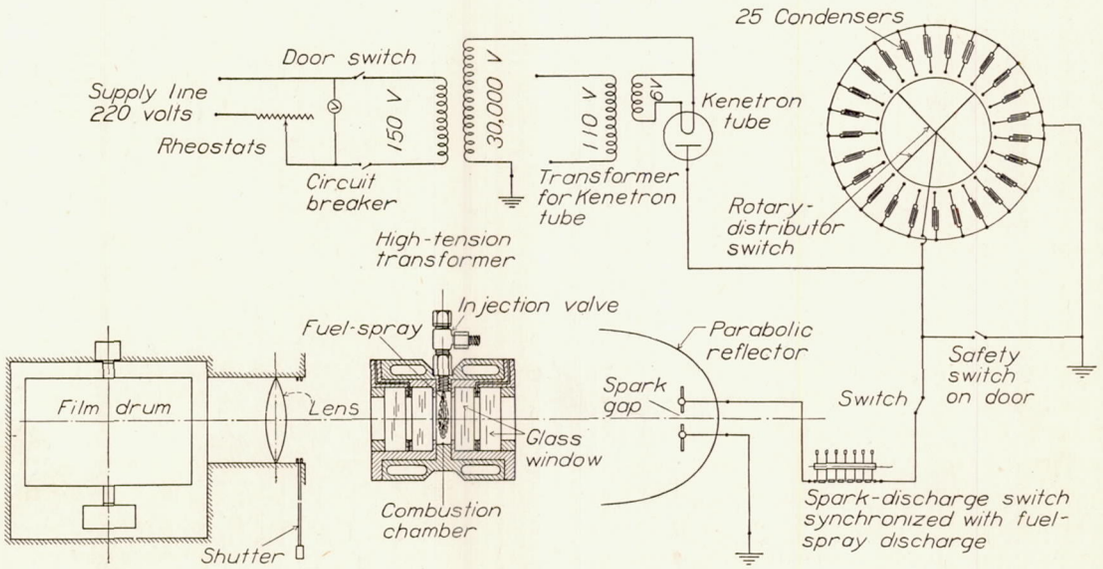

FIGURE 2.—Photographic apparatus

place. A compression release valve has been installed so that the compression is released on the cycles following that during which injection takes place. This latter change has been made to remove the necessity of determining whether or not combustion of the fuel occurs in the cycle during which the fuel is injected or during some succeeding cycle. (See reference 3.)

In the tests made with this valve the engine was brought up to speed with the valve open. The fuel pressure in the reservoir of the injection system was then brought to the desired value. This operation also closed the compression release valve. The time elapsing between the closing of the valve and the operation of the clutch which caused the injection of the fuel was 1 second or less. Consequently, the time interval during which the glass windows were subject to the high pressures and temperatures was greatly reduced. Also the heat losses as discussed in reference 3 caused by the repeated compression and expansion of a single charge of air were reduced.

With the present apparatus, it is not always possible to reproduce the test conditions because of both atmospheric and engine conditions. The chief deviation occurs in the gas leakage past the piston rings in the engine. The amount of the leakage is indicated by the maximum compression pressure, which was in every case recorded by the trapped-pressure method. (Reference 5.) In the following table are tabulated the maximum pressures recorded with all the data presented, together with a brief description of the causes of any considerable variation.

Figure No.	Window performance	Engine temperature °F.	Maximum cylinder pressure lb./sq. in.	Valve opening pressure lb./sq. in.	Injection pressure lb./sq. in.	Engine speed r. p. m.
5	Glass windows broken at irregular intervals.	100	450	4,000	4,000	1,500
6		100	455	4,000	4,000	1,500
7		100	460	4,000	4,000	1,500
8		100	460	4,000	4,000	1,500
9		100	460	4,000	4,000	1,500
10		100	460	4,000	4,000	1,500
11		100	440	4,500	4,000	1,000
12		100	400	4,500	4,000	500
13		150	470	4,000	4,000	1,500
Compression release valve installed. New piston rings installed and seated						
14	No windows broken.	200	570	4,200	4,100	1,500
15		250	570	4,200	4,100	1,500

During the taking of the test data the greatest difficulty encountered was caused by failures of the glass windows. Since these windows are expensive and since repeated failures score the cylinder liner, it was advisable to accept these differences in gas leakage rather than to attempt to repeat all tests under the same conditions. Fortunately, the differences do not affect the conclusions drawn from the data. The failure of the glass was eliminated after the compression release valve was installed.

OUTLINE OF TESTS

An examination of the photographs presented in reference 3 showed that when the Diesel fuel was injected into the combustion chamber the appearance of the spray after cut-off was quite different from that observed in the previous photographs taken at room temperature. When the injection occurred early in the cycle the chamber cleared rapidly following the cut-off of injection and remained clear for the remainder of the 70-crank-degree time interval included during the taking of the high-speed motion pictures. However, when the injection started closer to top center so that the photographs included more of the expansion stroke, the exposures showed that the chamber became fogged at approximately 35° after top center and that the time at which the fogging occurred was not very sensitive to these injection advance angles. In addition, the fogging occurred in some cases between two successive exposures, a time interval of approximately 0.0005 second. This fogging was attributed to condensation of the vaporized fuel at the point on the down stroke of the piston at which the partial pressure of the fuel vapors in the combustion chamber reached their saturated vapor pressure. In the present investigation, therefore, a series of tests was made which would show the occurrence of certain definite phenomena, provided that the fuel was vaporizing and then condensing.

The test conditions and the phenomena which must occur, provided that vaporization and condensation take place, are as follows:

Variable-injection advance angle.—Provided that the fogging of the chamber is caused by condensation of vaporized fuel, the time in the engine cycle at which condensation occurs should not show much variation over a wide range of injection advance angles. A small change might be observed because of the cracking of the vaporized fuel from the initial hydrocarbons to lighter hydrocarbons having a lower boiling point. In this case early injection advance angles should give a later condensation point because of the longer time interval during which the fuel is in contact with the hot air in the combustion chamber. Because it was believed that this variable would provide one of the most certain checks on the theory, the injection advance angle was varied in all tests from 50°, in some cases 80°, before top center to top center in 10° increments.

Different fuels.—The point of condensation should be dependent on the vapor pressures of the fuel used. Consequently, a series of tests was made using denatured ethyl alcohol, gasoline, hydrogenated safety fuel, kerosene, and Diesel fuel (fuel oil). The atmospheric distillation curves of samples of each fuel are shown in Figure 3. Vapor-pressure curves that give

the comparative boiling temperatures under pressure of fuels similar to four of the fuels are shown in Figure 4. These data are not from actual samples of the fuels tested, but are taken from reference 6. According to the condensation theory, the time interval between top

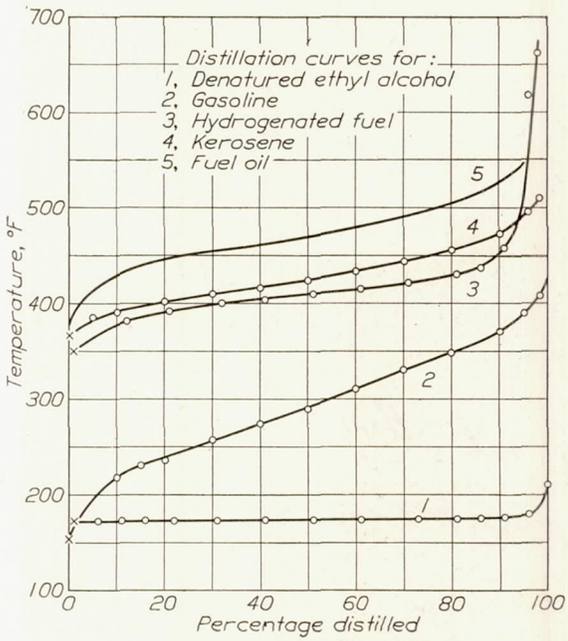

FIGURE 3.—Distillation curves of fuels tested

center and the point at which the fogging of the chamber occurred should decrease as the boiling temperature of the fuel increased, or as the vapor pressure of the fuel decreased.

Different fuel quantities.—Since the saturated vapor pressure of a fuel depends only on the temperature and since given weights of a fuel vapor will have a definite value of vapor pressure at the various volumes and corresponding temperatures that exist during the expansion stroke of the engine, the intersection of the saturated vapor-pressure curve of the fuel with the curves of the vapor pressure for the given weights of fuel under the temperature and volume conditions in the engine will give the temperature and consequently the crank position at which these weights of fuel should condense. If condensation occurs in the engine, the effect of varying the fuel quantity on the time in the engine cycle at which condensation takes place should show the same trend whether the data are obtained experimentally or theoretically. Computations show that this relationship requires that, as the fuel quantity is decreased, the time after top center at which the condensation takes place would increase at an increasing rate. The fuel quantities used in this series of tests varied from 0.00080 to 0.00004 pound per injection. In all tests the injection period was approximately 25 crank degrees.

Different engine speeds.—Since the point in crank degrees at which condensation should take place is of necessity a function of temperature and pressure, it should remain independent of engine speed, except for the increased cooling losses and gas-leakage losses, as the speed of the engine is decreased. Consequently, tests were made at engine speeds of 1,500, 1,000, and 500 revolutions per minute.

Different engine temperatures.—Increasing the engine temperature decreases the radiation and conduction on losses from the air during the compression and expansion stroke and consequently maintains higher air temperatures throughout the cycle. Therefore, increasing the engine temperature throughout the cycle should cause the condensation to take place at a later point on the expansion stroke. In order to test the effect of temperature, runs were made at outgoing glycerin temperatures of 100°, 150°, 200°, and 250° F.

TEST RESULTS AND DISCUSSION

VARIABLE-INJECTION ADVANCE ANGLE

All the spray photographs presented show the effect of the injection advance angle on the vaporization and condensation of the injected fuel. The discussion

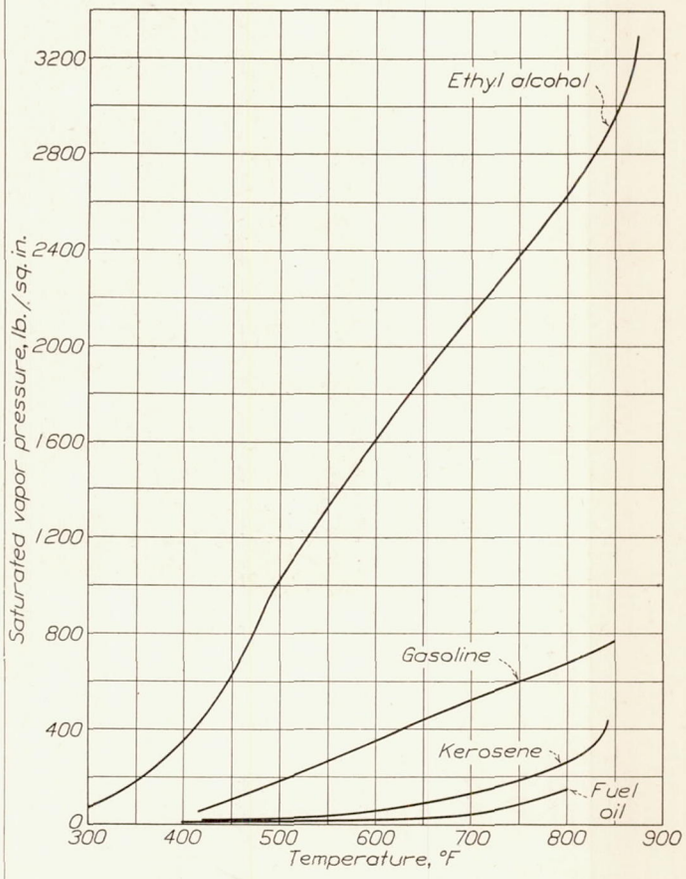

FIGURE 4.—Saturated vapor-pressure curves for fuels similar to those tested

in this and the following paragraph, however, will be limited to Figures 5 to 9, which contain the data for the different fuels. In each photograph a line has been drawn to indicate top center and a second line has

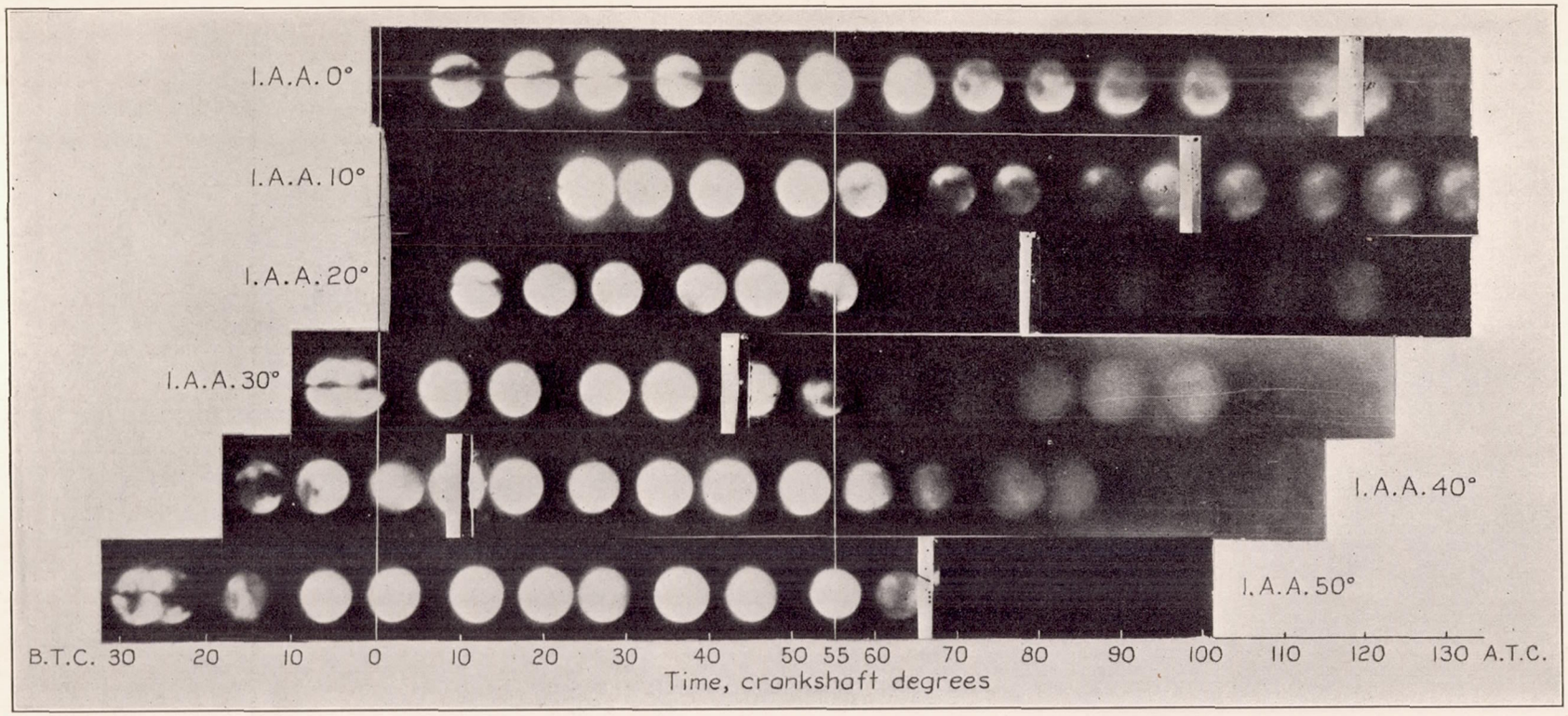

FIGURE 5.—Vaporization of ethyl alcohol. Engine r. p. m., 1,500. Engine temperature, 100° F. Fuel quantity, 0.00025 pound. Discharge-orifice diameter, 0.020 inch

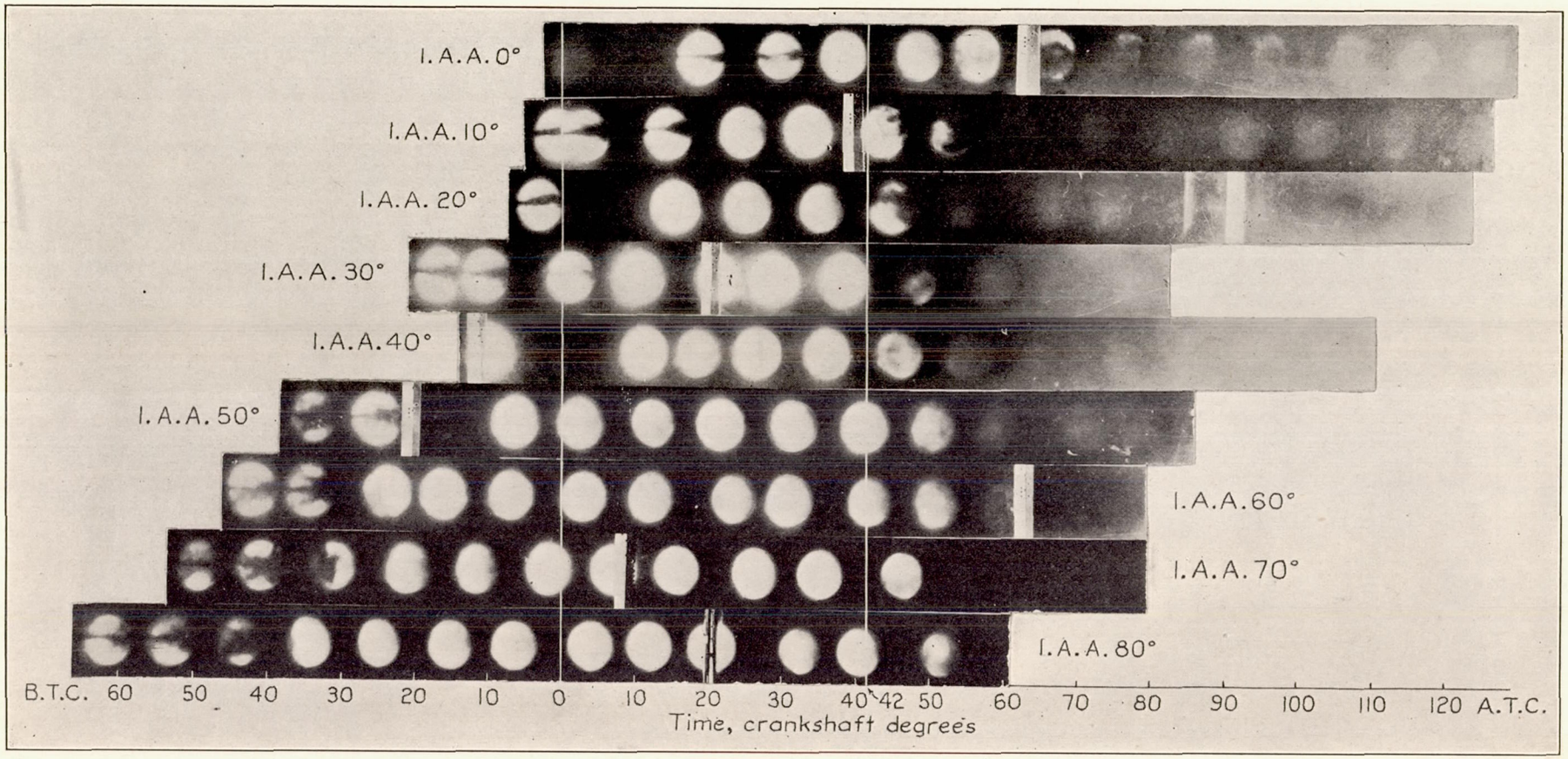

FIGURE 6.—Vaporization of gasoline. Engine r. p. m., 1,500. Engine temperature, 100° F. Fuel quantity, 0.00025 pound. Discharge-orifice diameter, 0.020 inch

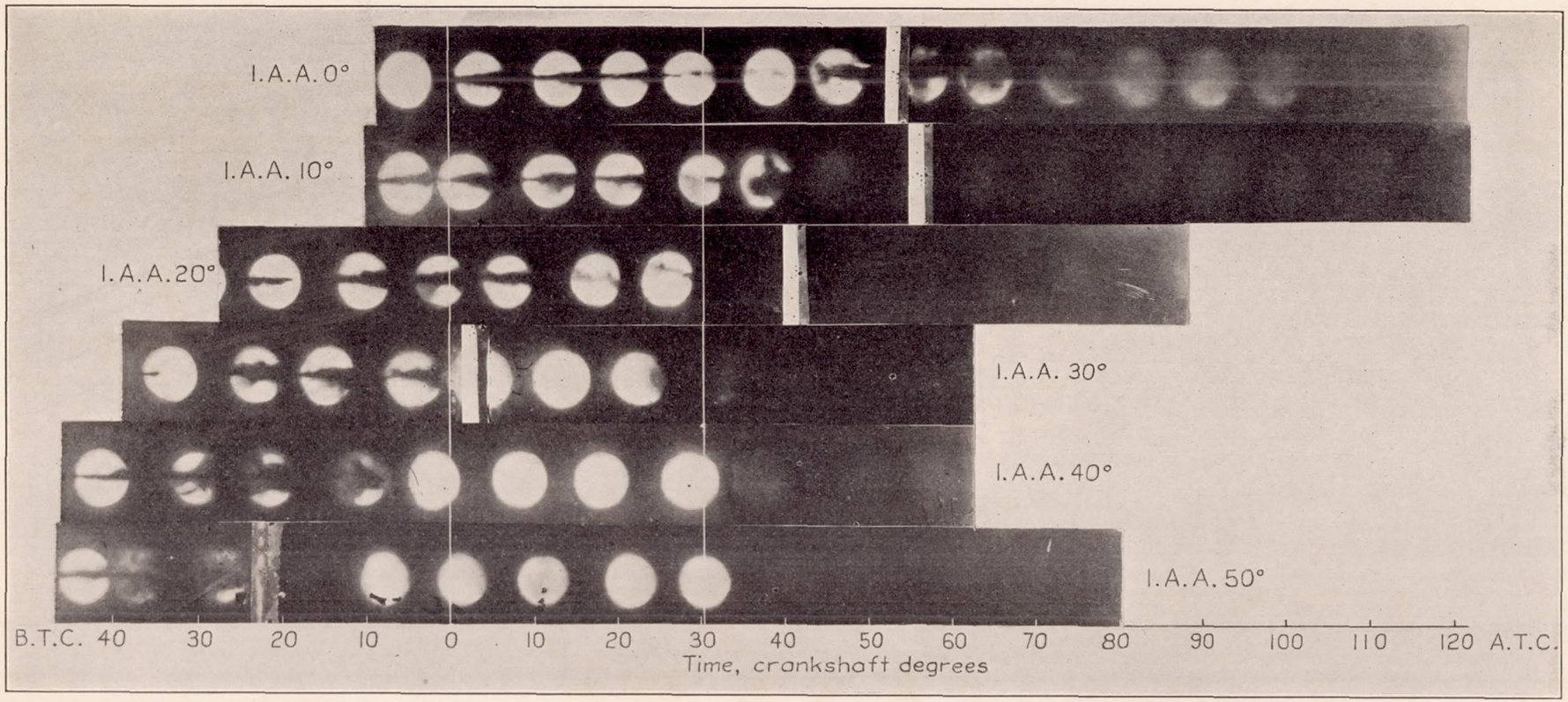

FIGURE 7.—Vaporization of hydrogenated fuel. Engine r. p. m., 1,500. Engine temperature, 100° F. Fuel quantity, 0.00025 pound. Discharge-orifice diameter, 0.020 inch

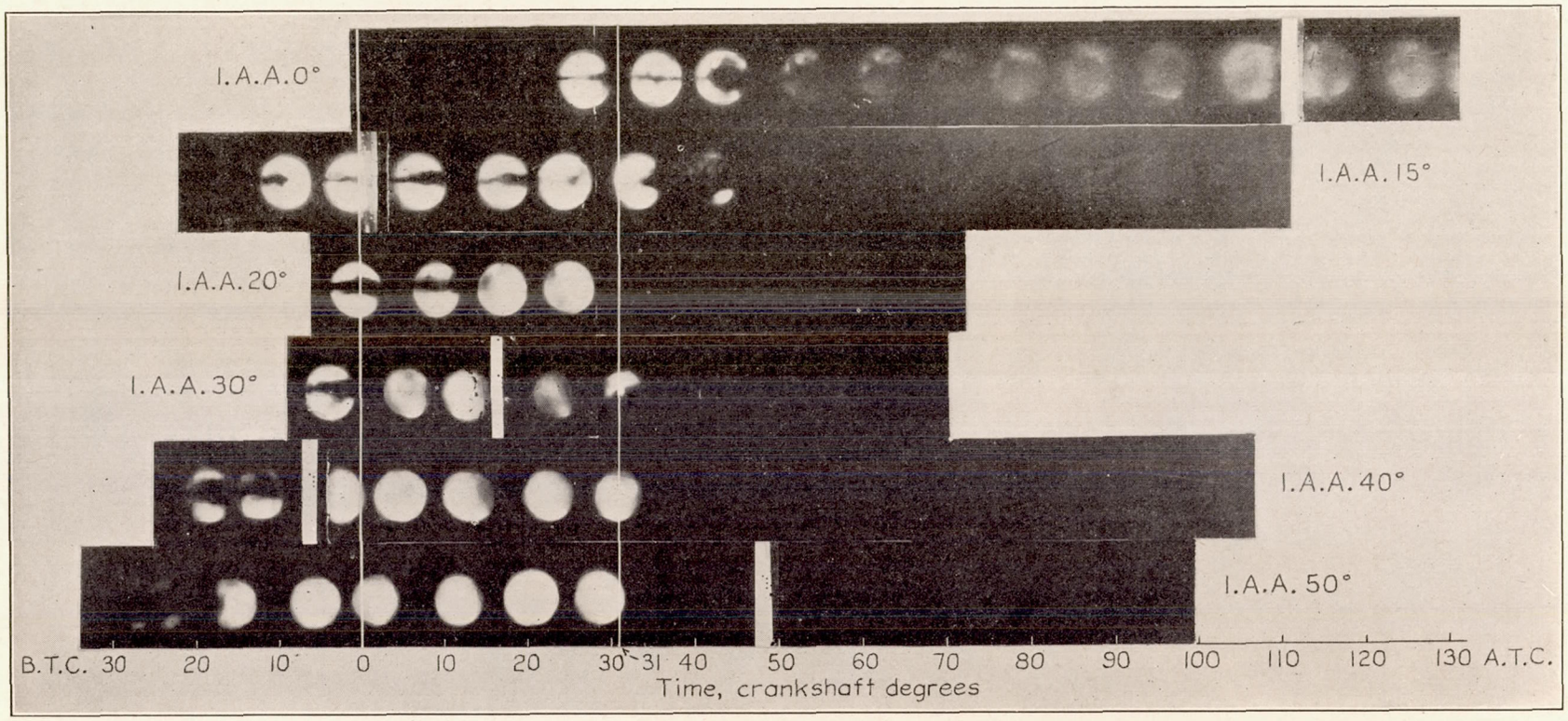

FIGURE 8.—Vaporization of kerosene. Engine r. p. m., 1,500. Engine temperature, 100° F. Fuel quantity, 0,00025 pound. Discharge-orifice diameter, 0.020 inch

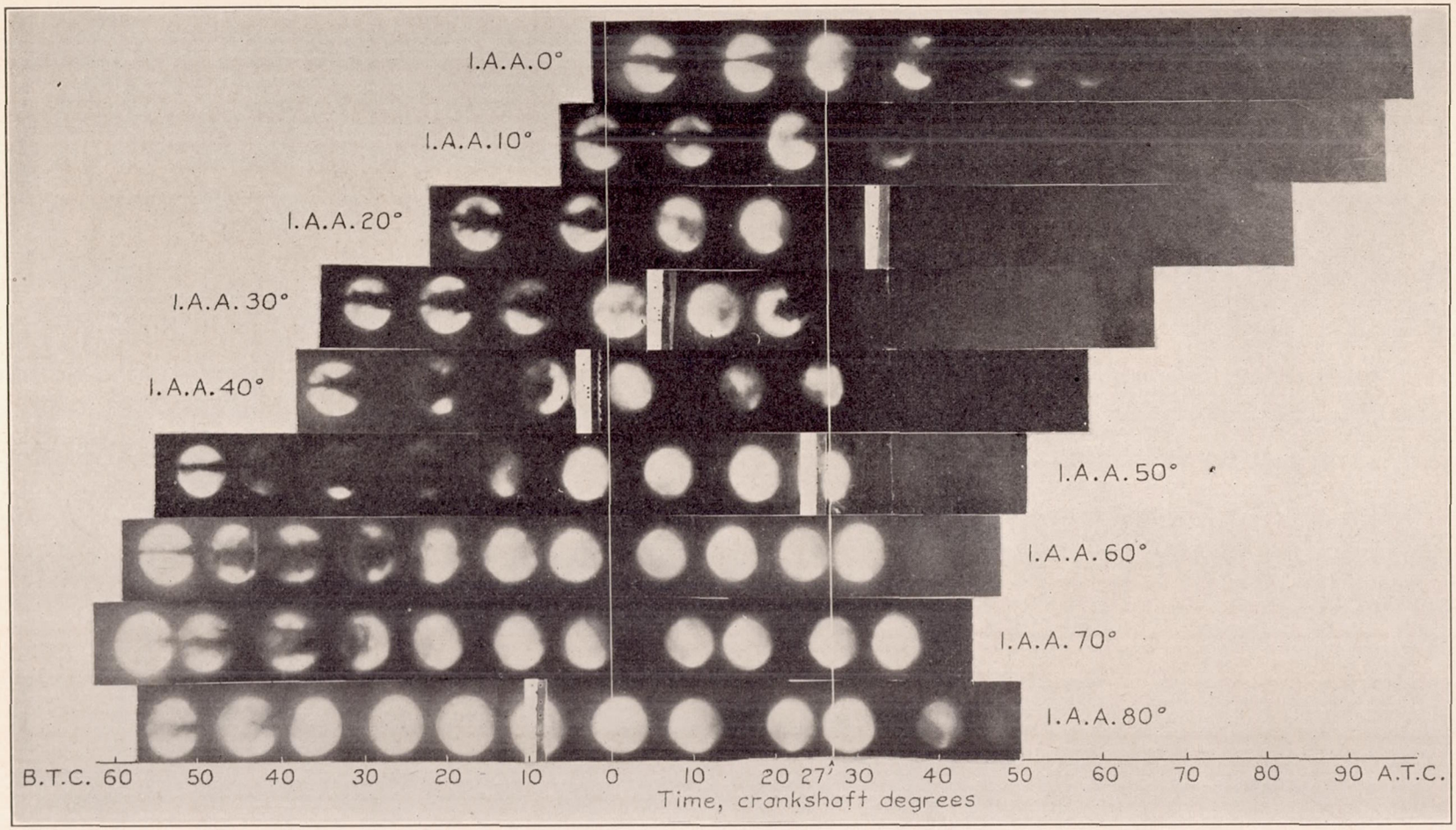

FIGURE 9.—Vaporization of fuel oil. Engine r. p. m., 1,500. Engine temperature, 100° F. Fuel quantity, 0.00024 pound. Discharge-orifice diameter, 0.020 inch

been drawn through the center of the last clear exposure at an injection advance angle of 40° or 50° before top center. In general, as the injection advance angle (I.A.A.) was decreased, the point of condensation in crank degrees after top center at first decreased and then increased, although the change was slight, approximately 10°, in comparison with the variation in advance angle. An examination of the vapor-pressure data presented by Joachim and Rothrock (reference 6) shows that the vapor-pressure curves of the fuels were not reversible. In each case as the temperature of the bomb in which the pressures were measured was lowered the vapor pressures were higher than those recorded when the bomb was heated. This nonreversibility indicates that chemical changes took place in the fuels so that the final products after cooling the bomb contained lighter hydrocarbons than those which were in the original fuel. The longer the fuel was subjected to the high temperatures and pressures in the combustion chamber, the greater was the time available for these chemical changes to take place. Consequently, it is to be expected that with the early injection advance angles the fuel in the chamber after condensation had a lower boiling temperature and higher saturated vapor pressure than that which was originally injected. As the injection advance angle was retarded less of the lighter hydrocarbons were formed and consequently the condensation took place at a slightly earlier point on the expansion stroke. When the injection started at 10° before or at top center the mixing of the fuel and fuel vapors was not as complete as with the earlier injection. This phenomenon is shown by the uneven manner in which the light from the spark discharges was blotted out. The condensation point again retarded with the late injection because the time was too short for vaporization to be completed and consequently the partial pressures of the fuel vapors were decreased.

Considering the figures as a whole, it can be said that the point at which condensation occurs does not vary with injection advance angle, excepting large angles that cause cracking of the fuel and small angles that do not give sufficient time for complete vaporization of the fuel. Consequently, it can be concluded that the first requirement of the vaporization theory is satisfied.

Effect of boiling temperature of the fuel.—Figures 5 to 9 show the results obtained with the different fuels. With denatured ethyl alcohol (fig. 5) the vaporization during the following injection was sufficient so that no fuel was seen from soon after injection cut-off until approximately 55° after top center. With an injection advance angle of 50° the fuel between 20° and 10° before top center was fairly well diffused throughout the chamber as is shown by the hazy image. For the eight successive exposures the chamber remained clear and then again became hazy when the condensation took place. (Compare third and twelfth exposures.) With injection at 40° before top center some of the fuel was still unvaporized at 6° before top center. Some condensation took place at 58° after top center and condensation became practically complete in the next exposure. With injection starting at 30° before top center, some of the spray core is visible in the first two exposures and condensation started a little before 55° after top center. The results for injections starting at 20° before top center are similar to those for 30°. With injection starting at 10° before top center the condensation was less rapid or else the fuel vapor had not diffused throughout the air; consequently the mixture was not homogeneous. The same is true for injection starting at top center. For this last case it is interesting to note how the fuel disappeared from around the core of the spray. (See the first, second, third, and fourth exposures.) In no case was the condensed fuel sufficient to block out all the light on the original negative from the spark discharges.

The photographs obtained with gasoline (fig. 6) are similar to those obtained with ethyl alcohol, except that the vaporization does not appear to have been as rapid and the condensation started earlier in the stroke, approximately 42° after top center. When condensation took place less of the light was transmitted through the combustion-chamber windows than was the case with the ethyl alcohol. The dispersion of the fuel spray before vaporization was greater with the earlier injection advance angles, which is to be expected, since the temperatures in the chamber during injection are lower and consequently the vaporization is not so rapid. With injection starting at top center the blocking out of the light was uneven throughout the chamber for some time after the condensation started.

With the hydrogenated safety fuel (fig. 7) the condensation took place at approximately 30° after top center. Again with the greater injection advance angles the distribution before vaporization was more marked than with the lesser angles. This difference was, of course, affected to some extent by the air flow in the chamber. (See reference 3.) With injection starting at top center a slight amount of unvaporized fuel was visible at 39° after top center. The next exposure shows, as would be expected, that the condensation took place around this nucleus. The same phenomenon is shown with injection starting at 10° before top center.

With kerosene (fig. 8) the condensation occurred at approximately the same point as with the hydrogenated fuel, 31° after top center. This is to be expected from a comparison of the distillation curves of the two fuels. Again the condensation around any visible nuclei (second and third exposures, I.A.A. 0°) is shown. When the condensation took place the light from the spark discharges was completely obstructed with the

exception of the photograph having injection starting at top center. In this case a slight increase in light intensity is shown as the piston approached bottom center, probably caused by the decrease in the density of the charge in the cylinder.

The condensation of the fuel oil (fig. 9) occurred at approximately 27° after top center. In no case was the vaporization complete when the injection advance angle was 30° or less. In all cases the condensation completely obstructed the light from the spark discharges, although with the injection advance angle of 0° the obstruction was not complete until 55° after top center.

Comparing all the photographs of this series, we see that the point of condensation occurred closer to top center as the boiling point or boiling range of the fuel increased, which fulfills the second requirement of the vaporization theory. The vaporization was more complete the earlier the injection advance angle with the higher boiling range fuels. With the fuels having the lower boiling range the vaporization was considerable for all injection advance angles tested. It can be concluded that in high-speed, compression-ignition engines the fuel during and after its injection vaporizes considerably and that if combustion is not started until after the end of injection the combustion takes place from the vapor phase and not from the liquid phase as has been generally believed. The results indicate that it is possible, and probable, that in every case the combustion is also started from the vapor phase and not from the liquid phase. Of course, with the conventional fuels which consist of a mixture of hydrocarbons it is not necessary for vaporization to be complete before ignition takes place, but only for a sufficient quantity of that fraction which has the lowest ignition temperature to be vaporized and heated to the auto-ignition temperature. The quantity which will be sufficient to start combustion with inflammation will depend on the rate of heat loss from and to the gases in the combustion chamber.

Effect of fuel quantity injected.—The results of the tests with different quantities of fuel oil are shown in Figures 9, 10, and 11. The fuel quantities were measured by injecting 10 charges of fuel into a container screwed onto the injection valve and weighing the container before and after injection. In the determination of the weight of fuel the injection took place into air at atmospheric pressure instead of into air at pressures of from 400 to 500 pounds per square inch. However, since the rate of fuel discharge through the injection valve nozzle varies as the square root of the pressure difference, the decrease when the discharge took place into the combustion chamber should have been small. The different fuel quantities were obtained by inserting in the injection value nozzles with different size discharge orifices. Consequently, a variation in the drop sizes of the injected fuel should be expected. As Lee (reference 7) has shown, this variation should not be sufficient to affect the general conclusion drawn from the tests.

With 0.00017 pound of fuel (fig. 10) the photographs were similar to those with 0.00024 pound, although the chamber was cleared of visible fuel earlier on the compression stroke with an injection advance angle of 50°. As before, vaporization was not complete with an injection advance angle of 30° or less. The photograph for an injection advance angle of 0° shows the condensation taking place around the unvaporized portion of fuel in the chamber. As in all the previous tests, the diffusion of the fuel before vaporization was greater the earlier the injection advance angle.

The results shown in Figure 11 for 0.00004 pound of fuel show a much later point of condensation, 45° after top center, than with the larger fuel quantities. This result is to be expected because of the decrease in the heat necessary to vaporize the fuel charge, and because of the decrease in the partial pressure of the fuel vapor. With injection advance angles of 20° or more before top center no fuel was visible for the first part of the expansion stroke before the condensation took place. With injection starting at 10° before and at top center, fuel was visible but not to such an extent as with the two larger fuel quantities. The photographs show that even when the spray penetrated and distributed through only a small part of the chamber before vaporizing the distribution was quite uniform when the fuel condensed. In no case was all the light on the negative obstructed after the condensation took place. This phenomenon gives us a clue as to the extent of the vaporization. We can conclude that 0.00004 pound of fuel on condensing will obstruct an appreciable amount of the light. With 0.00024 pound of fuel, approximately the amount required for complete combustion of the air, no fuel was visible with the early injection advance angles and very little was visible following injection cut-off with the later injection advance angles. Therefore, it is safe to say that a considerable amount of the fuel was vaporized in the time allowable for injection and combustion.

Another reason for thinking that the chamber being clear soon after cut-off is an indication of almost complete vaporization is that Lee (reference 7) and De Juhasz (reference 8) show that a very small amount of the fuel is in the outer envelope of a spray. However, this outer envelope is clearly photographed (reference 3) showing that when the chamber clears, there can be very little unvaporized fuel in the chamber.

Effect of engine speed on vaporization.—The effect of engine speed on the vaporization of the fuel sprays is shown in Figures 9, 12, and 13. At an engine speed of 1,000 revolutions per minute the photographs are similar to those obtained at a speed of 1,500 revolutions

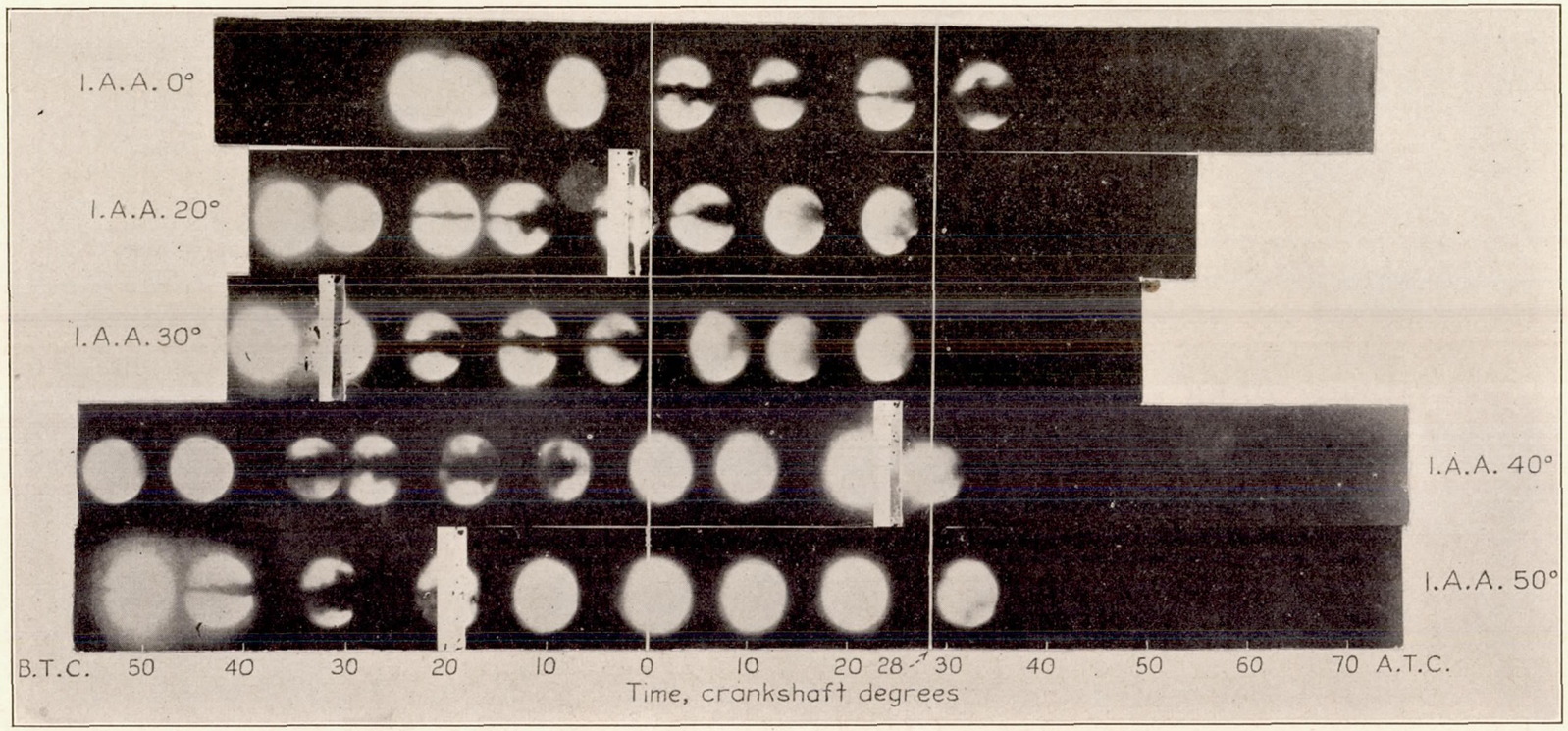

FIGURE 10.—Vaporization of fuel oil with 0.00017 pound fuel. Engine r. p. m., 1,500. Engine temperature, 100° F. Discharge-orifice diameter, 0.015 inch

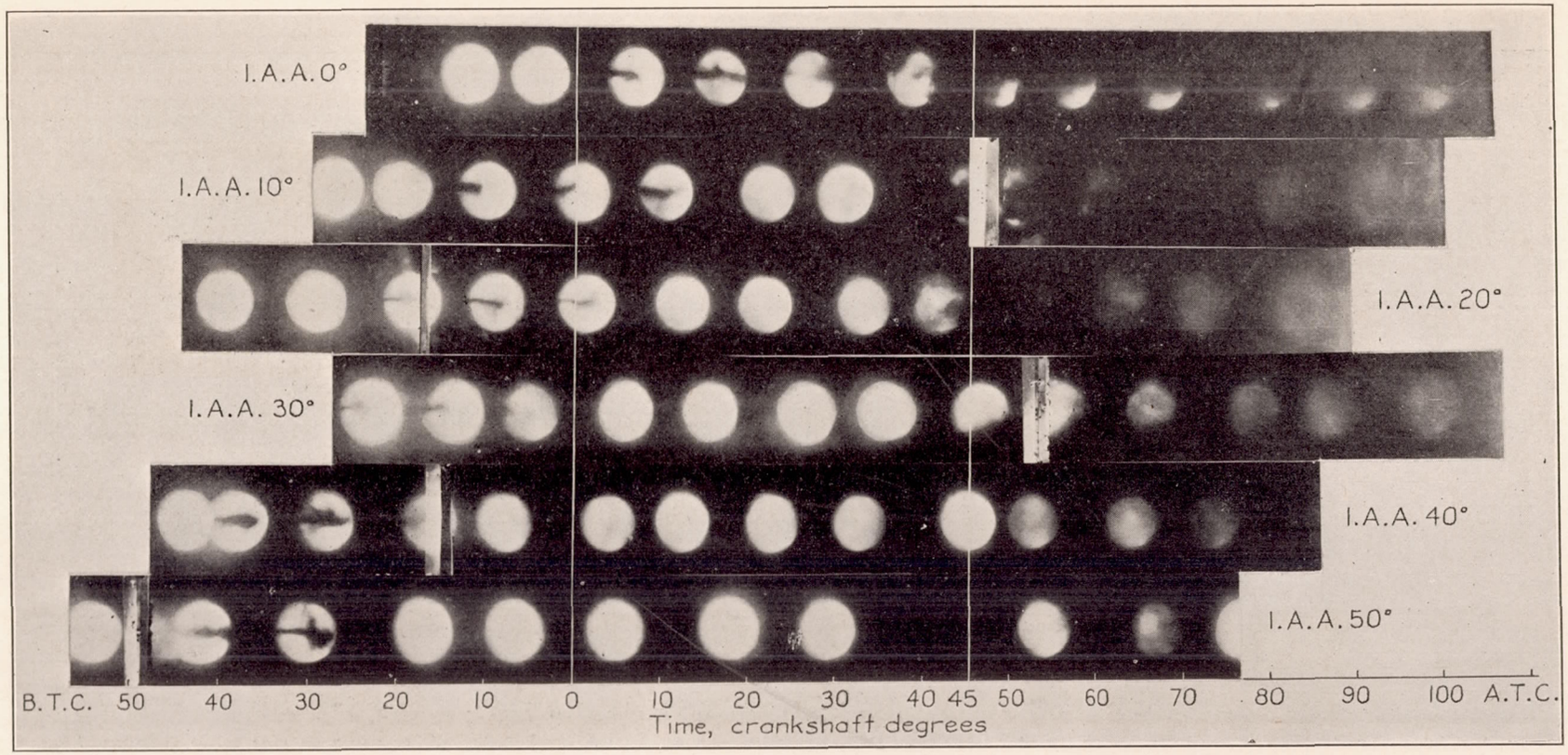

FIGURE 11.—Vaporization of fuel oil with 0.00004 pound fuel. Engine r. p. m., 1,500. Engine temperature, 100° F. Discharge-orifice diameter, 0.008 inch

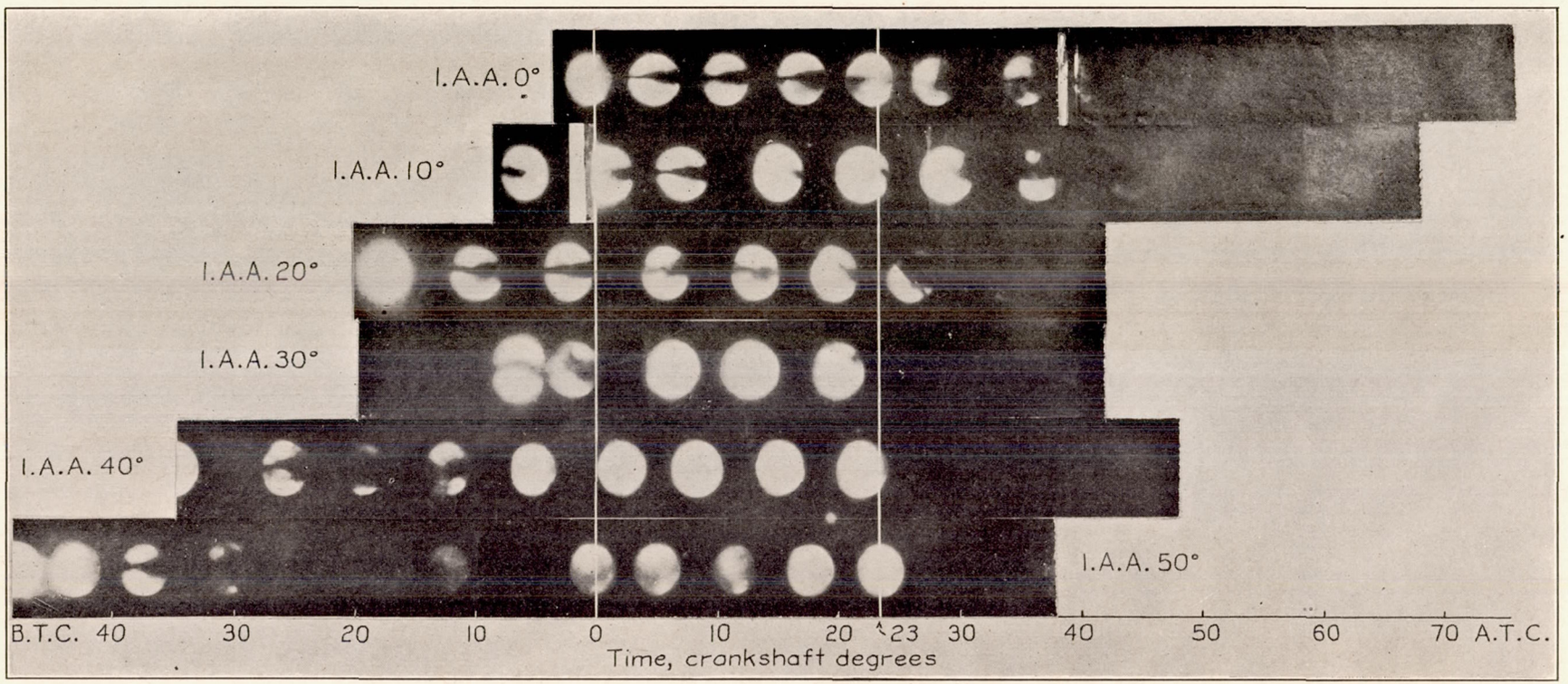

FIGURE 12.—Vaporization of fuel oil at 1,000 r. p. m. Engine temperature, 100° F. Fuel quantity, 0.00025 pound. Discharge-orifice diameter, 0.020 inch

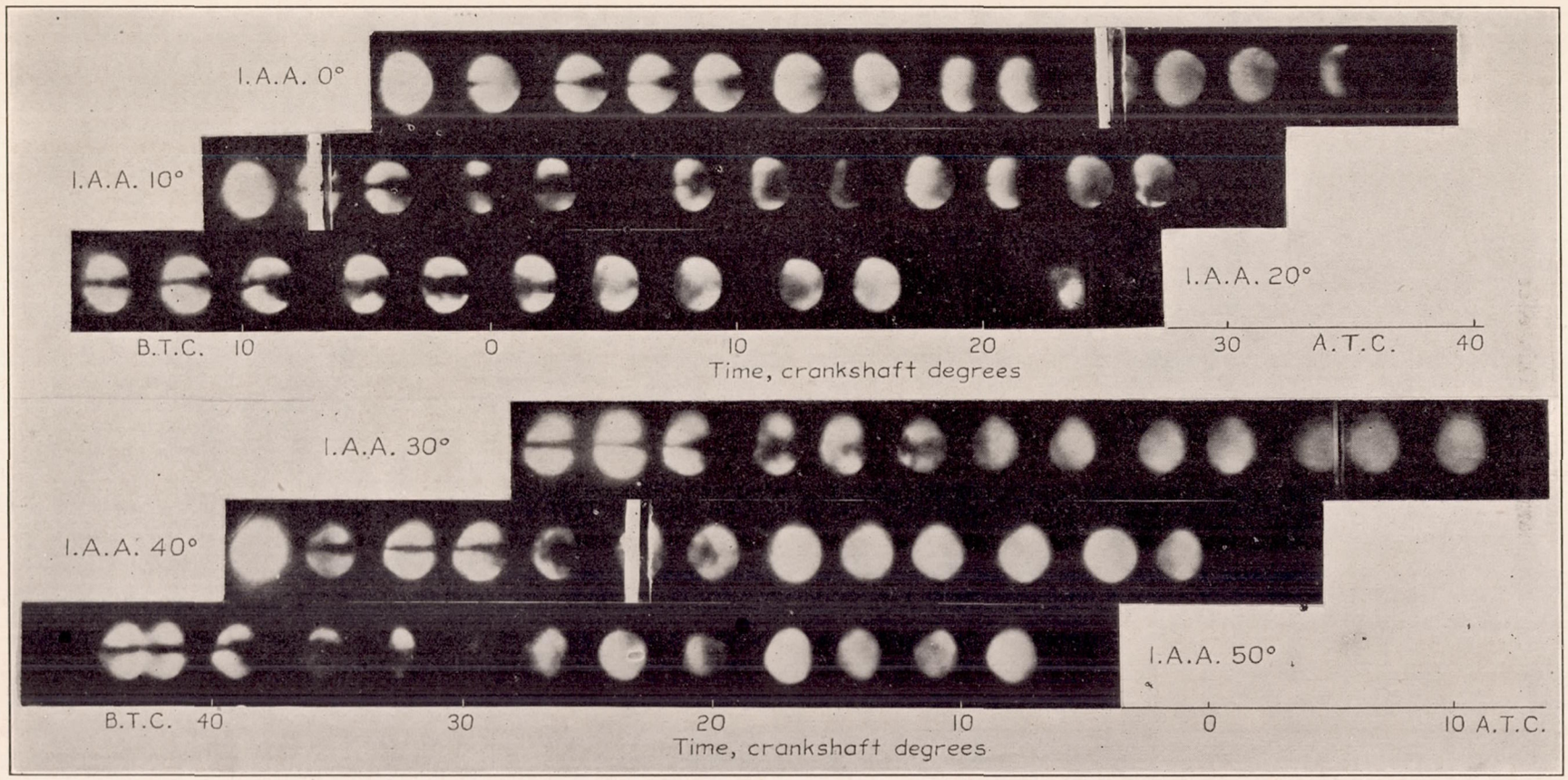

FIGURE 13.—Vaporization of fuel oil at 500 engine r. p. m. Engine temperature, 100° F. Fuel quantity, 0.00023 pound. Discharge-orifice diameter, 0.020 inch

per minute. With an injection advance angle of 50° the fuel first diffused through the chamber completely blocking out the light from the spark discharges and then vaporized and condensed at approximately 23° after top center. With an injection advance angle of 40° the initial diffusion before the vaporization was not so complete and the vaporization appeared to be more complete than with the earlier injection start. With an injection advance angle of 30° the vaporization was more complete than was the case at 1,500 revolutions per minute for the same injection advance. This is attributed to the longer time interval during which the fuel was subjected to the higher temperatures because of the lower engine speed. The slightly earlier condensation at the slower speed can be attributed to the lower temperatures in the combustion chamber caused by the greater heat and gas-leakage losses.

At an engine speed of 500 revolutions per minute the vaporization process with respect to time in seconds was slower than at the two higher speeds because of the slower rate of temperature change. The condensation point was later for an injection advance angle of 0°, starting about 32° after top center, although with an injection advance of 20° the condensation started between 20° and 30° after top center. The condensation occurred slightly earlier at the speed of 500 revolutions per minute than at the higher speeds because of the greater heat losses of the air in the combustion chamber. The magnitude of the loss is indicated in the maximum cylinder pressures at the three speeds which were 460, 440, and 400 pounds per square inch at 1,500, 1,000, and 500 revolutions per minute respectively. (These values of maximum cylinder pressures are averages. The values varied by ±10 pounds per square inch.)

A comparison of the three figures shows that since the distribution characteristics of the fuel sprays as well as the rate of vaporization of the spray vary with speed, the combustion characteristics must of necessity also vary. However, the variation is not of sufficient magnitude to cause any great difficulty, as is shown by the numerous successful examples of engines which run with a considerable speed range.

Effect of engine temperature.—The effect of engine temperature on vaporization is shown in Figures 9, 14, 15, and 16. Figure 9 shows condensation to have occurred at 27° after top center when the engine temperature was 100° F. Figures 14 and 15 show condensation to have occurred 37° and 67° after top center when the engine temperature was respectively 150° and 200° F. No condensation up to 130° after top center was shown on the films when the engine temperature was 250° F. The retarding of the condensation point at the higher engine temperatures satisfies the last requirement of the vaporization theory. Figures 14 and 15 show the blotting out of the light to have been less complete than the blotting out that occurred at 100° F. engine temperature. This effect was probably caused by the fuel being broken down more completely into the lighter gases at the higher temperatures, leaving less of the heavier gases to condense.

During the 100° F. test the blotting out occurred earliest with an injection advance angle of 20°. The photographs taken when the engine was at 150° and 200° F. do not show the condensation to have occurred later as the injection-advance angle was made larger.

Taking the different temperature tests as a whole, it can be said that higher temperatures affect the condensing of the vaporized fuel, probably causing more complete cracking of the fuel before condensation can occur. These higher temperature tests also show a more rapid rate of vaporization.

An examination of the different temperature tests shows that there was no ignition of the fuel until the engine temperature was 200° F. Figure 15 shows that ignition occurred when the injection advance angle was increased to 30° before top center and that the fuel ignited about 5° after top center. The fuel apparently burned with a red flame as the film was not much affected by the light of the combustion. When the injection advance angle was raised to 40° the fuel apparently burned with a much whiter flame and ignition seemed to occur throughout the chamber at the same time, although occurring no earlier than with the 30° advance angle. With an injection advance angle of 50° ignition occurred about 2° after top center, but the flame did not seem as bright as the previous combustion. Increasing the advance angle to 60° caused ignition to retard to 5° after top center again and combustion was brighter than with the 50° advance angle, but not as bright as with the 40° angle. When injection started 65° before top center ignition was retarded to about 15° after top center and combustion seemed to be brighter around the sides of the chamber than in the center. This series of tests was repeated and the same phenomenon was again recorded. The following explanation of this action is offered.

As the fuel is injected into the combustion chamber two types of chemical action tend to take place. As Neumann (reference 10) and Wollers and Ehmcke (reference 11) have shown, the heavier hydrocarbons tend to decompose into lighter, more stable hydrocarbons, and free hydrogen. This decomposition increases the auto-ignition temperature of the mixture. On the other hand, the heavier hydrocarbons also tend to form unstable peroxides with the oxygen present in the air. These unstable peroxides result in a low auto-ignition temperature. (An excellent discussion of the peroxide formation and its effect on combustion is given by Mardles in reference 12.) Both these changes are affected by temperature. If

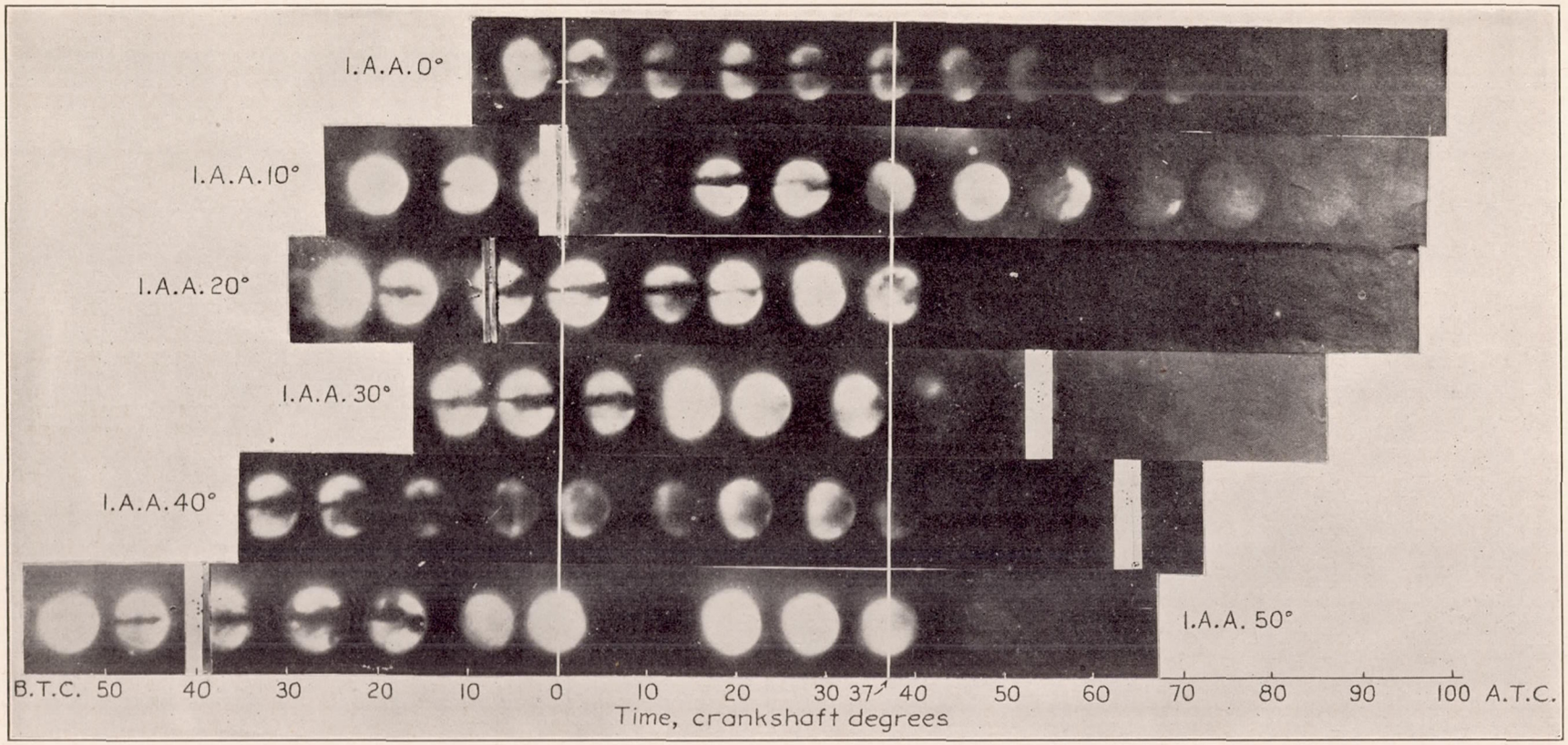

FIGURE 14.—Vaporization of fuel oil at 150° F. engine temperature. Engine r. p. m., 1,500. Fuel quantity, 0.00029 pound. Discharge-orifice diameter, 0.020 inch

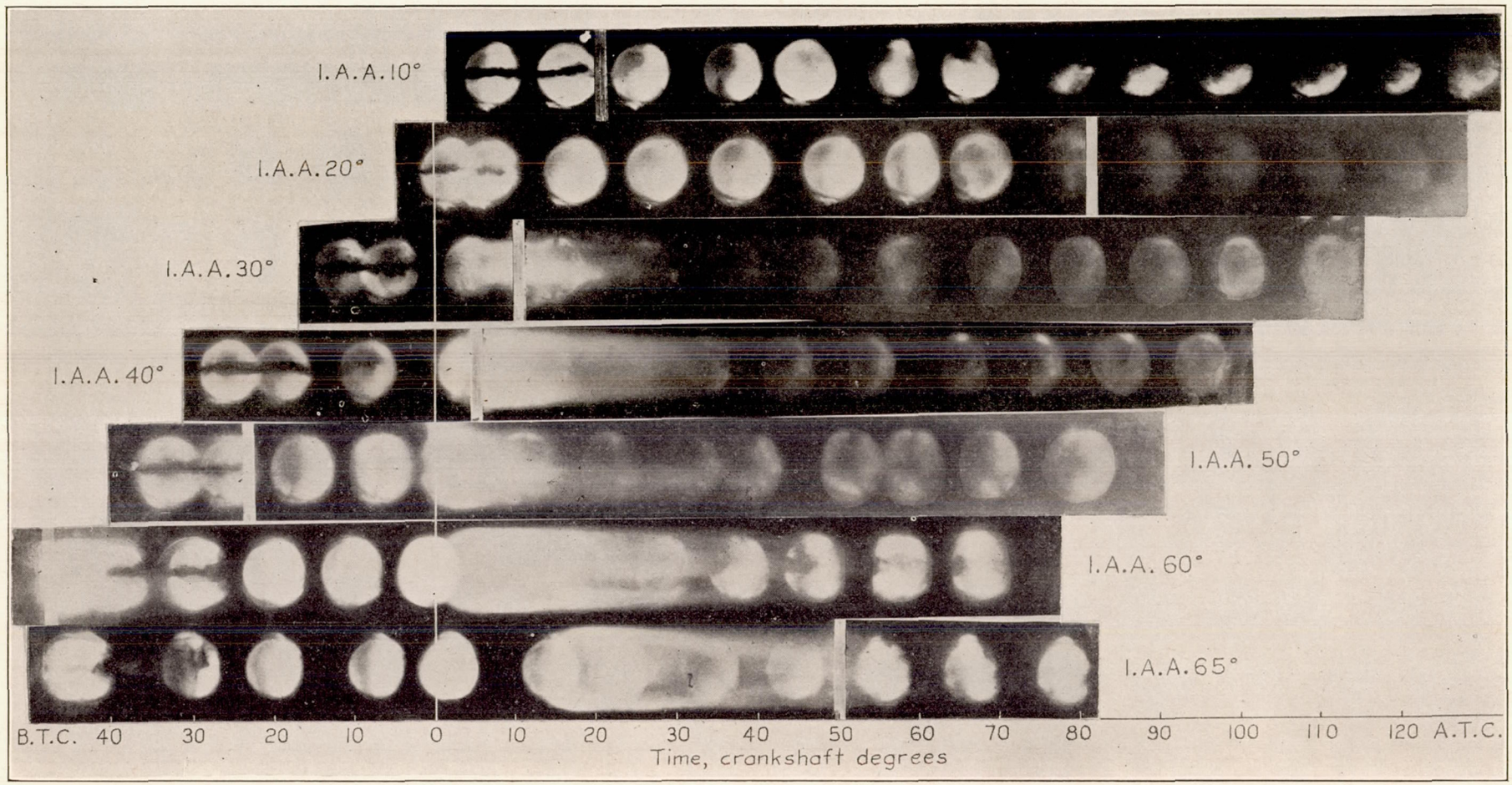

FIGURE 15.—Vaporization and combustion of fuel oil at 200° F. engine temperature. Engine r. p. m., 1,500. Fuel quantity, 0.00029 pound. Discharge-orifice diameter, 0.020 inch

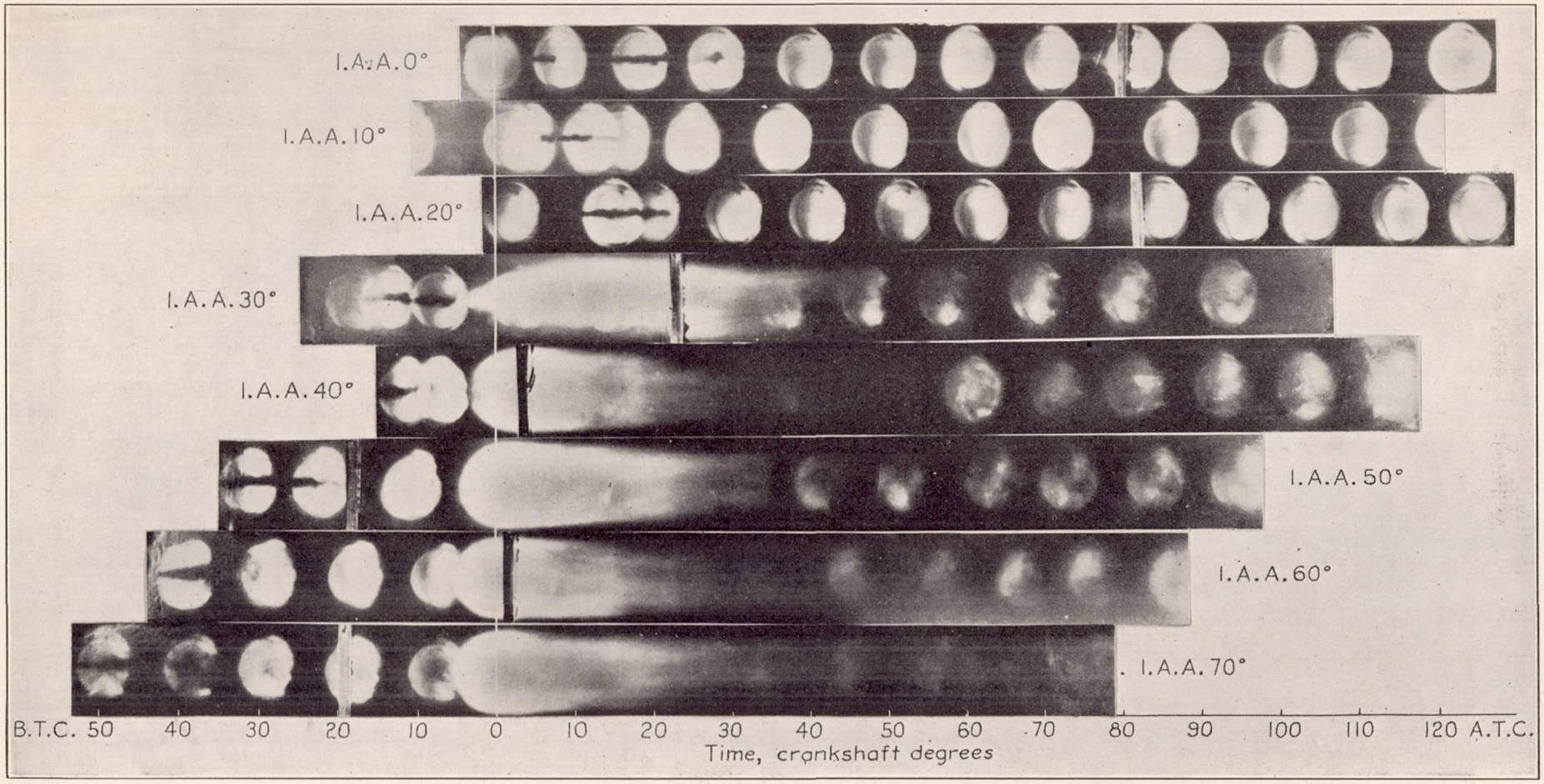

FIGURE 16.—Vaporization and combustion of fuel oil at 250° F. engine temperature. Engine r. p. m., 1,500. Fuel quantity, 0.00029 pound. Discharge-orifice diameter, 0.020 inch

the decomposition takes place at the lower temperature, then with the earlier injection the lighter hydrocarbons will be formed at the expense of the peroxides and consequently the auto-ignition temperature and the auto-ignition lag will be increased. The acceptance of this hypothesis depends, of course, on the results of further experimentation.

When the engine temperature was 250° F. ignition did not occur until the injection advance angle was increased to 30° before top center. However, when ignition took place it started at, or slightly before, top center around the edge of the spray and not at an indeterminate point or points throughout the chamber. Although the combustion seemed quite intense, there was a definite time interval that elapsed before the flame spread throughout the chamber. Further injection advance did not change the time of the start of ignition but did cause the burning to start simultaneously throughout the chamber. Subsequent tests in which indicator cards were taken simultaneously with the combustion photographs showed that this simultaneous start of combustion is accompanied by violent combustion shock ("detonation"). A comparison of this figure with the preceding one shows that the increased temperature tended to make the combustion more uniform and more intense, and also that the engine temperature was an important factor in controlling the rate of combustion.

COMPARISON OF PRESENT RESULTS WITH THOSE OF OTHER INVESTIGATORS

In 1918 Neumann published a series of articles (reference 10) on the results of tests conducted to determine the significance of the vapor pressures of various fuels in relation to the suitability of the fuels for use in compression-ignition engines. He based his analysis on the hydrogen preferential theory, according to which ignition starts from the combination of the oxygen with the free hydrogen liberated by the decomposition of the hydrocarbons in the fuels. His data, however, are of interest since recent work has shown that combustion starts through the formation by the vaporized hydrocarbons of hydroxyls or peroxides.

Before discussing Neumann's results it is well to distinguish between the terms "fuel vapor" and "fuel gas" as used by him and subsequently by Wollers and Ehmcke. By fuel vapor is meant the original hydrocarbons the fuel contained which have changed from the liquid to the vapor phase. By fuel gas is meant the decomposition products of the original hydrocarbons. These decomposition products consist essentially of the lighter hydrocarbons, methane predominating, after complete vaporization of the fuel.

Neumann's experiments consisted essentially of obtaining vapor-pressure curves for representative aliphatic and aromatic fuels suitable for compression-ignition engines. By applying heat at a constant rate to the fuels he was able also to obtain information on the time rate of vaporization. In addition he analyzed the resulting gases for free hydrogen, methane, ethane, and heavier hydrocarbons of the ethane series. The analyses showed him that when the fuels were heated sufficiently to be completely vaporized and then cooled the action was not reversible. This same phenomenon is shown in the results published by Joachim and Rothrock.

Neumann assumed that the greater the rate of decomposition of the fuel and the yield of free hydrogen the greater was the ease with which the fuel was ignited. More recent results have shown that the free hydrogen becomes a factor only when ignition is not started from the unstable hydrocarbons at a temperature below the auto-ignition temperature of the hydrogen. Neumann may be correct in stating that those fuels which yield free hydrogen at the higher temperature are more suitable for engine operation, not because of the free hydrogen present, however, but because of the greater instability of the molecules. The rates of fuel-gas formation which he also supposed to be an indication of the suitability of the fuels for engine use can, therefore, be used as a criterion to a certain extent.

Neumann concluded that the rate of formation of the decomposition products should not be too rapid but rather steady and consistent. This statement must, however, be modified according to the relationship between the auto-ignition temperature of the fuel and the boiling temperature. Where the auto-ignition temperature is considerably in excess of the mean boiling temperature it is advisable to have a slow rate of vaporization so that ignition will take place before the fuel is completely vaporized. Otherwise the burning will take place with sufficient rapidity to cause combustion shock. On the other hand, if the auto-ignition temperature is near the mean boiling temperature it is advisable to have the vaporization take place rapidly.

Unfortunately, these two conditions are difficult to obtain. The photographs of the fuel spray and of the combustion have shown that for a wide range of volatility the rate of vaporization is sufficiently fast in all cases to affect combustion, and that with the fuels consisting essentially of the lighter hydrocarbons the rate of vaporization is too fast to permit combustion to start before the vaporization is completed. The results obtained at an engine temperature of 200° F. show that Neumann was correct in concluding that the formation of the lighter hydrocarbons before the start of combustion is detrimental and that although combustion may take place under such conditions the heat of combustion is insufficient to cause the whole

charge to burn. It can be concluded that the difficulty encountered in burning the predominantly aromatic fuels in the compression-ignition engine is principally a function of the chemical structure of the fuel which results in a high auto-ignition temperature.

The next important research on the combustion phenomena following that of Neumann's was conducted by Wollers and Ehmcke. (Reference 11.) Their investigation was conducted to determine whether or not it was possible to force early ignition by the addition of small amounts of easily ignitible fuels. They found, as had Neumann, that the total hydrogen content of the fuel was not the primary factor in rating the fuels according to their suitability for use in compression-ignition engines. They also concluded that the boiling range of the fuel was not indicative of the fuel's suitability for use in compression-ignition engines. The present tests have shown, however, that the boiling range does have a marked influence on the combustion shock of the fuel. Wollers and Ehmcke's tests on the relation of the gasification process to the combustion phenomena are extremely interesting. They concluded that in the aliphatic series the C–H bonds were stronger than the C–C bond and that consequently the combustion was started through a breaking down of the hydrocarbons in the C–C bonds. With the aromatic compounds, however, the process was reversed. In this case the cyclic C–C bonds were stronger than the chain C–H bonds and the split took place in the latter. Their auto-ignition tests showed that the auto-ignition temperature of a fuel was dependent not on the physical properties of the liquid fuel but on its chemical structure. In further proof of this they showed, as Neumann had, that the final decomposition products of all the fuels they tested when completely vaporized were identical. In regard to the ignition temperature they concluded that in homologous series the ignition temperature decreased with increasing molecular weight. This conclusion had since been checked by other investigators for the normal compounds. Wollers and Ehmcke did not, however, discard the theory that vaporization precedes ignition, for they state, "After the fuel has been injected, a momentary vaporization takes place. Under the influence of the high temperature prevailing in the compression chamber the vapor molecules are loosened in the direction stipulated by the chemical constitution. The valences made reactive by this loosening absorb oxygen eagerly. Ignition and further burning takes place." Although the vaporization of the fuel does not affect the auto-ignition temperature, the present tests have shown that the vaporization does affect the course of the combustion.

After the publication of Wollers and Ehmcke's report the theory was advanced, based upon that report and other work, that not only did vaporization have no effect on the combustion but that combustion started from the liquid and not the vapor phase. It is difficult to understand why so many investigators took this stand inasmuch as the above-mentioned report compared only the ignitibility from the gaseous and from the vapor phase and presented no material in support of the nonvaporization theory. Nevertheless, Wollers and Ehmcke's results, together with the fact that fuels could not be compared according to their volatilities alone, led many of the leading workers in the field to discard the vaporization phase in discussing combustion. Little attention was paid to the fact that because of the wide variation in the chemical constituents of the fuels tested it is hardly plausible to believe that the volatility only of the fuel should determine its suitability in a compression-ignition engine. Nor was it realized that although the vaporization had no effect on the auto-ignition temperature it might have a decided effect on the course of the combustion.

Alt (reference 1) in discussing Wollers and Ehmcke's work states that "if vaporization were important for ignition, then the higher the ignition point above the boiling point, the better it [the fuel] would be [for compression-ignition engines]." Actually the opposite is true. The closer the ignition temperature of the fuel is to the boiling temperature the greater the probability of starting combustion before the fuel is completely vaporized and so preventing combustion from taking place at an excessive rate with the resulting rough running and knocking of the engine. Alt also brought forth the fact that with many of the fuels the ignition temperature is below the mean boiling temperature. This does not affect the theory that vaporization precedes combustion since, as Tausz and Schulte (reference 13) have shown, the ignition temperature of a fuel is that of the fraction which ignites at the lowest temperature. The boiling point of this fraction may or may not be below the mean boiling point, and ignition is started when the vapor of this fraction reaches the auto-ignition temperature regardless of whether or not the heavier fractions have been vaporized in the meantime. An examination of the data presented by Alt shows that with the three fuels for which both ignition temperatures and boiling temperatures are given, paraffin oil, light tar oil, and vertical furnace tar, the suitability of the fuels for compression-ignition engines is in the inverse order of the difference between the auto-ignition temperature and the mean boiling temperature, −9°, 224°, and 365° F., respectively.

Sass (reference 2) in his investigation placed considerable weight on the results obtained by Wollers and Ehmcke and felt that they presented convincing evidence against the possibility of the formation of fuel vapor in the combustion chamber of the compression-ignition engine. The additional data presented by Sass do not prove or disprove the vaporization theory, although he held that they did disprove it. Sass con-

siders the ignition temperature of acetylene as given by Wollers and Ehmcke as the criterion for showing that the ignition temperature of the fuel as measured by him in a hot-bulb engine was lower than the ignition temperature of the vaporized fuel. Not only were his ignition temperatures measured in air at high density which would of itself lower the auto-ignition temperature, as Tausz and Schulte have shown, but he also precludes the ignition of the unstable peroxides or hydroxyls formed during the early stages of vaporization. Sass agreed with Tausz's explanation of the ignition according to the peroxide formation theory but states that the peroxide formation need take place only in a relatively small portion of the molecules in the fuel drop. No proof, however, has been presented to show that peroxide formation takes place in the liquid phase although Mardles (reference 12) has shown that peroxide formation does take place in the vapor phase.

Neumann (reference 14) in a later report presented theoretical and experimental results on the heating of the fuel drops in the spray. He started from the relationship that the rate of heat input from the air to the drop is equal to the rate of heat absorbed by the drop to increase its temperature plus the rate of heat absorbed by the vaporization of the drop. The analysis is based on the assumption that the air/fuel ratio throughout the chamber was constant. It is further assumed that the temperature at the outside surface of the drop is equal to that of the rest of the air in the chamber and that the temperature of the inside surface is equal to the temperature of the fuel drop which has at any instant the same temperature throughout. Although such computations do give results which are of value from a qualitative standpoint, their value from a quantitative standpoint is questionable. Neumann found that the computed values for the rate of heat transfer to the drop were much lower than those experienced in the bomb which he used for his tests. He attributed the difference to chemical reactions of an exothermal nature which preceded the actual ignition of the fuel. The present results show that Neumann's computed results, which indicated that less than 1 per cent of the fuel vaporized during the time available in the engine, are far from correct and that actually the speed of vaporization is so great that a considerable part of the fuel can vaporize even though the temperature conditions are too low to cause ignition.

Tausz and Schulte (reference 13) realized the necessity of determining ignition temperatures under pressure, and temperature conditions similar to those employed in the engine and consequently built their apparatus accordingly. They state (reference 13) that "Ignition depends on the chemical composition of the fuel and the preceding chemical changes, which differ for different pressures and temperatures. Physical conditions, such as fineness of division and diffusion, have no immediate effect on the ignition temperature, but affect only the completeness and rapidity of the combustion." Although they did not believe that there was sufficient time for complete vaporization of the fuel to take place they do state that "rather in the most favorable cases only the outer layer of a drop evaporates and mingles with the air and ignites at the requisite temperature. The higher temperature, thus produced, then causes the ignition of all the rest of the fuel." This latter statement is in agreement with the ideas of Diesel. However, the present results show that the rate of vaporization of the fuel is much greater than was previously believed. In fact it is of sufficient rapidity to permit practically all the fuel in the combustion chamber to be vaporized before ignition occurs. Tausz and Schulte realized that the ignition temperatures of Wollers and Ehmcke were those of the decomposition products produced in the absence of oxygen and not of the original vapors of the fuels, but nevertheless they precluded the idea of extensive vaporization previous to ignition.

In testing fuels (chemical compounds) which did not decompose on boiling, Tausz and Schulte found that "the temperature of ignition was independent of whether the fuel is present in the form of a vapor or of a fog and whether in this latter case, the drops are large or small." It is in these tests that proof is given of the necessity of vaporization before ignition of the fuel. These investigators tested over 100 chemical compounds covering saturated aliphatic hydrocarbons, unsaturated aliphatic hydrocarbons, cyclic compounds and their derivatives, aromatic hydrocarbons, derivatives of aromatic hydrocarbons, terpenes and camphors, heterocyclic compounds, aldehydes, alcohols and their derivatives, aliphatic acids, aromatic acids, and various fats and mineral oils. With three exceptions, the auto-ignition temperatures of the chemical compounds in oxygen were always equal to or greater than the boiling temperature of the liquid. For one of these, nonylic acid, the difference was small, 6° F., which can be attributed to experimental error. Of the other two, stearic acid and undecylenic acid, stearic acid is known to decompose on heating. In addition Tausz and Schulte distilled two different crude oils and collected the distillates at given temperature increments. The ignition temperatures of the distillates were then determined. They found that "the ignition point of the crude product is approximately that of the fraction which ignites at the lowest temperature," and that this temperature was higher than the boiling temperature of the fraction, which presents further proof that even with the complex fuels vaporization precedes ignition.

CONCLUSIONS

There are two main conclusions to be drawn from the data presented. First, there is considerable vaporization of the injected fuel in a high-speed compression-ignition engine during the time available for injection and combustion. Second, this vaporization affects the course of combustion.

There are also several detailed conclusions:

1. The percentage of the fuel vaporized before ignition is a function of the boiling temperature or temperatures of the fuel, the injection advance angle, the engine temperature, and the engine speed.

2. If the ignition lag is too great the vaporization is accompanied by sufficient breakdown of the heavier hydrocarbons into lighter hydrocarbons to affect the time and course of the combustion.

3. Unless combustion is started before the fuel vapors have diffused throughout the chamber the combustion will start throughout the chamber almost simultaneously with consequent combustion shock.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *May 4, 1932.*

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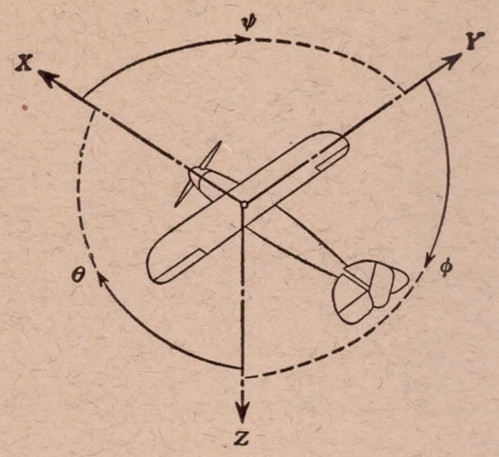

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$$C_l=\frac{L}{qbS} \qquad C_m=\frac{M}{qcS} \qquad C_n=\frac{N}{qbS}$$

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 $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.
1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.