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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 512

SOME FACTORS AFFECTING COMBUSTION IN AN INTERNAL-COMBUSTION ENGINE

By A. M. ROTHROCK and MILDRED COHN

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

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

2. GENERAL SYMBOLS

W, Weight $= mg$

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

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

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

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

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

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

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

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

V, True air speed

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

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

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

D_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 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

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

α, Angle of attack

ϵ, Angle of downwash

α_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 Mildred Cohn

SUMMARY

An investigation of the combustion of gasoline, safety, and diesel fuels was made in the N. A. C. A. combustion apparatus under conditions of temperature that permitted ignition by spark with direct fuel injection, in spite of the compression ratio of 12.7 employed. The influence of such variables as injection advance angle, jacket temperature, engine speed, and spark position was studied. The most pronounced effect was that an increase in the injection advance angle (beyond a certain minimum value) caused a decrease in the extent and rate of combustion. In almost all cases, combustion improved with increased temperature. For an increase in engine speed, the rate of pressure rise increased and the time interval in seconds between injection and the spark necessary to effect ignition was considerably shortened. Although all three fuels reacted in the same manner to these variable conditions, the reactions differed decidedly in extent. The results show that at low air temperatures the rates of combustion vary with the volatility of the fuel, but that at high temperatures this relationship does not exist and the rates depend to a greater extent on the chemical nature of the fuel.

INTRODUCTION

The investigation of the mechanism of combustion in an internal-combustion engine of either the spark-ignition or compression-ignition type is complicated by many factors. When burning a fuel such as diesel oil it is not known to what extent the reaction is a homogeneous one; that is, to what extent the reaction proceeds purely in the gaseous and vapor phase. A liquid-gas reaction may take place at the interface. There exists also the possibility of reaction at the surface of the cylinder and combustion-chamber walls. For the lower gaseous hydrocarbons it is known that at temperatures near the explosion temperature the homogeneous reaction predominates. The complex structure of the components in a fuel mixture allows a great number of possible reactions to take place in the engine. For the oxidation of pure methane, the simplest of the hydrocarbons, 8 compounds have been identified as products; whereas for ethane, the next member of the series, no less than 13 compounds have been identified. The difficulty of finding a suitable mechanism for the oxidation process and of following the course of the reaction is appreciated when the extreme rapidity of the reaction is considered in addition to the existence of the multiplicity of hydrocarbons in diesel fuel and gasoline, each molecule containing many carbon atoms.

In a heterogeneous system, such as exists in the combustion of a fuel introduced in the liquid form, the total rate of the reaction is determined by the slowest process. For the reaction in a spark-ignition engine, the slowest process is, in general, the rate of flame propagation—that is, the rate of heat transfer—to the unburnt gases ahead of the flame front. In a compression-ignition engine with its higher temperatures and pressures, the slowest process is the formation of a combustible mixture, for the mixture auto-ignites independently of any rate of flame propagation. The problem of producing this combustible mixture is dependent upon several factors: Injection-system characteristics, pressure and temperature of the air in the combustion chamber, rate of heat transfer from the hot air to the cold liquid, rate of fuel vaporization, rate of vapor diffusion, the time interval between the introduction of the fuel and the start of the explosive reaction, and the air-fuel ratio.

For comparative results some of these factors, such as the temperature and pressure of the air during the mixture formation period and the time interval elapsing between the introduction of the fuel and the beginning of the burning, may be investigated with both spark and compression ignition. The use of the N. A. C. A. combustion apparatus permits a range of these variables that would be destructive to an engine. By the employment of an igniting spark to initiate the explosive reaction, the time variable and the temperature and pressure conditions at the moment of ignition may be controlled and the variation in the rate of flame travel be decreased, although not entirely eliminated. The characteristics of the apparatus that make this mode of ignition possible at high compression ratios with fuels varying in volatility from gasoline to diesel fuel will later be discussed in detail. The pressure-time relationship throughout the entire cycle and the flame propagation in certain parts of the combustion chamber may be recorded by this apparatus.

APPARATUS AND METHODS

The N. A. C. A. combustion apparatus (figs. 1 and 2) consists of a single-cylinder test engine driven by an electric motor, and equipped with a high-speed camera and an optical indicator. The engine and the high-speed camera are described in detail in references 1, 2, and 3. The compression ratio of the engine during the present tests was 12.7. The fuel-injection mechanism used with the engine is so designed that only one injection of fuel takes place. A diagrammatic sketch of the optical indicator, which has been described in reference 4, is given in figure 3.

The engine temperatures were varied by changing the temperature of the glycerin circulated through the passages in the cylinder and cylinder head. The values of engine temperature given in the data are the temperatures of the glycerin as it left the engine. All temperatures listed are within $\pm 10°$ F.

The indicating spark described in reference 4 is used as the igniting spark in the spark-ignition tests. This spark is produced by the discharge of a 6-microfarad condenser at 220 volts through an automobile ignition coil. Three spark plugs were used. One had long electrodes so that the igniting spark occurred near the center of the combustion chamber. The second had short electrodes so that the igniting spark occurred at one edge of the combustion chamber. The third plug was so constructed that the spark gap was one-sixteenth inch from the piston crown with the piston at top center. The spark plugs were screwed into the opening in the side of the cylinder head that is marked in figure 1 "alternate position for injection valve."

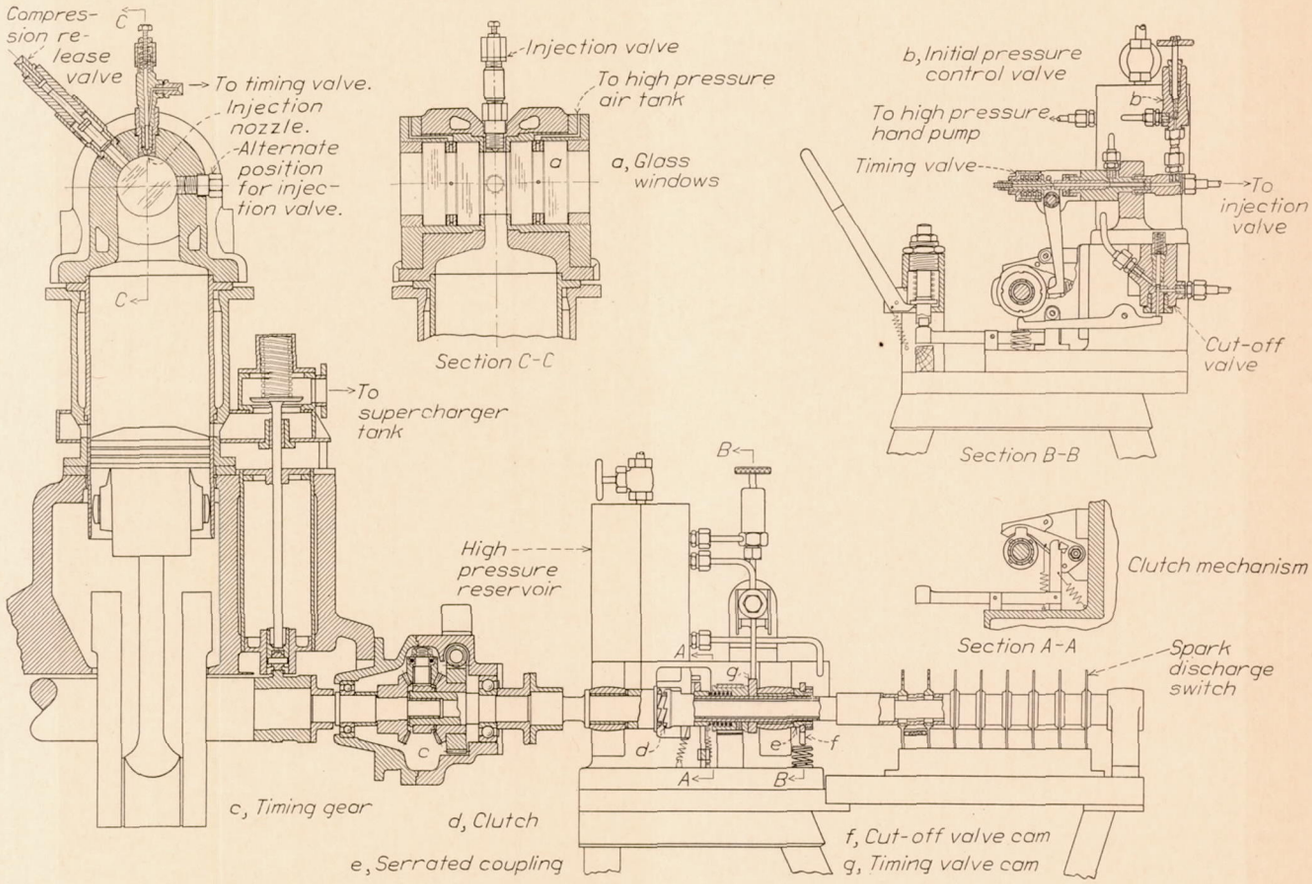

FIGURE 1.—Diagrammatic sketch of the N. A. C. A. combustion apparatus.

Figure 1 shows the engine with two glass windows on each side of the combustion chamber. During the present tests the windows were removed from the side opposite the camera and the optical indicator installed. (See fig. 2.) Such an arrangement made it possible to obtain simultaneously an indicator card showing the pressures in the cylinder and a photograph of the flame in the chamber. A metal plate with a $\frac{3}{16}$-inch horizontal slot was placed in front of the window so that a record of flame travel across the combustion chamber could be taken. The slot was in line with the spark gap when it was either in the center or at the edge of the chamber.

For a test, the engine was started and, when the required speed had been obtained, the room was darkened and the camera shutter opened. At a given signal, one operator pumped the fuel-injection-system reservoir up to the desired injection pressure. This operation closed the hydraulically operated compression-release valve so that full compression pressure existed in the combustion chamber every time the piston reached the top of its stroke. The other operator closed a switch lighting the instrument lamp inside the optical indicator and pulled the lever, causing one injection of fuel into the engine.

The fuel-injection nozzle used in all these tests had five round orifices which spread the fuel into a fan shape; a cross-sectional view of the nozzle and photographs of the fuel sprays from this nozzle are given in reference 3. The injection pressure was 4,700 pounds per square inch, and the injection valve was set to open at a pressure of 4,100 pounds per square inch. The injection period was approximately 0.0025 second. For the majority of tests the spark advance angle was set at 20° before top center.

Tests were made for the following conditions: Injection advance angle over the entire combustion range; jacket temperature from 100° F. to 300° F. at 50° intervals; and engine speeds of 570 and 1,550 r. p. m.

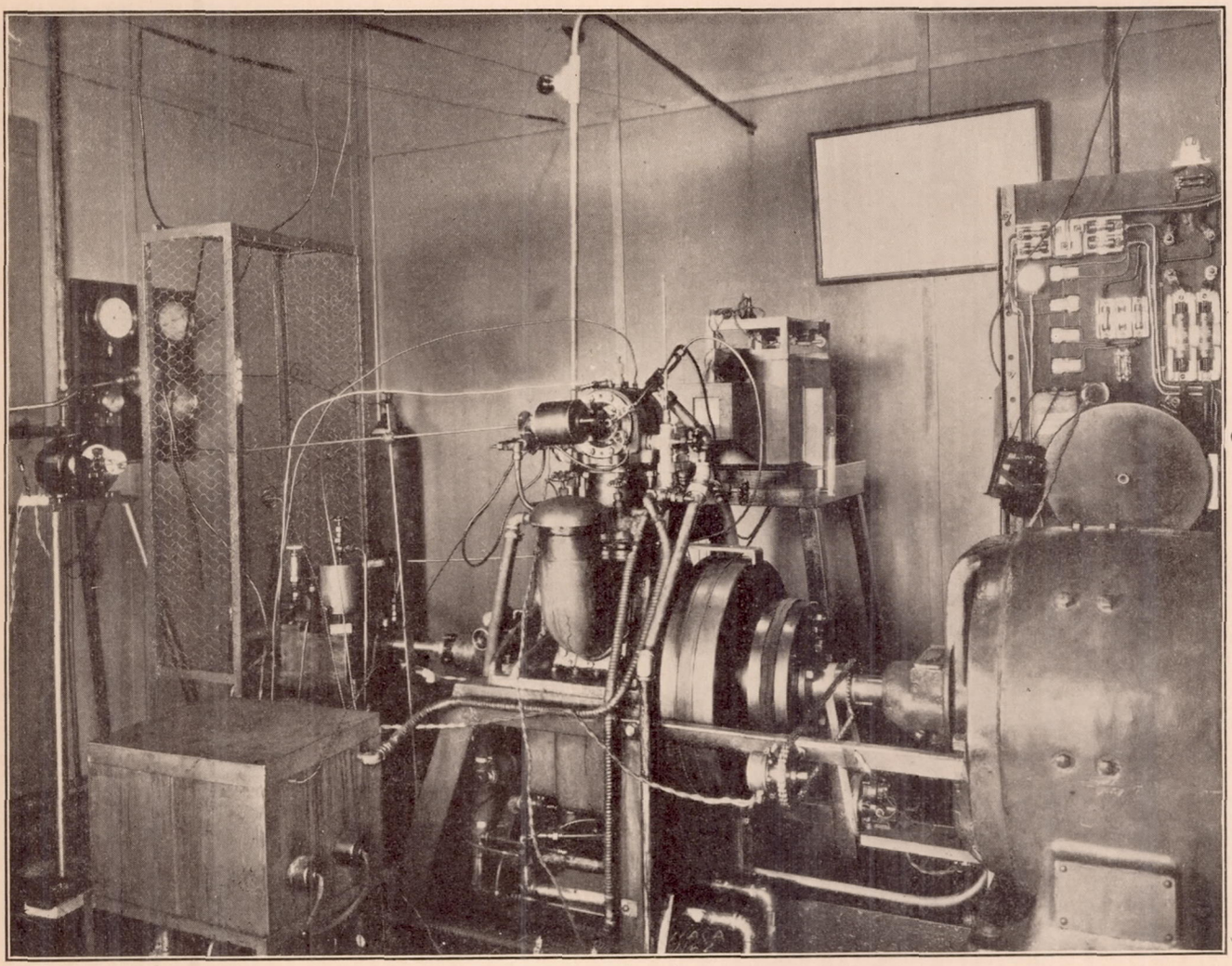

FIGURE 2.—Photograph of the N. A. C. A. combustion apparatus.

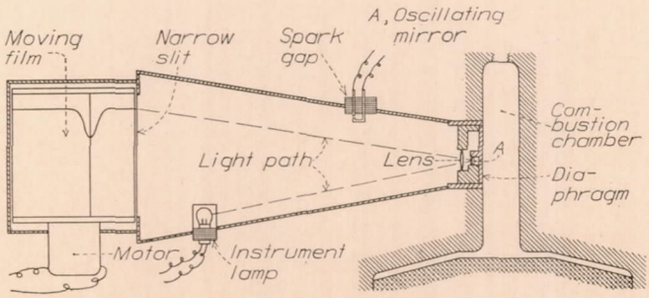

FIGURE 3.—Diagrammatic sketch of the optical indicator.

ANALYSIS OF VARIABLES

INJECTION ADVANCE ANGLE

The significance of varying the injection advance angle, in addition to the obvious effect of varying the time interval between injection and ignition, may be seen in figure 4 which shows the ratio of the absolute values of the air pressure, density, and temperature at the different points in the cycle to the initial values of pressure, density, and temperature. Injecting the fuel at different injection advance angles subjected it to different initial conditions and a different range of pressure, volume, and temperature.

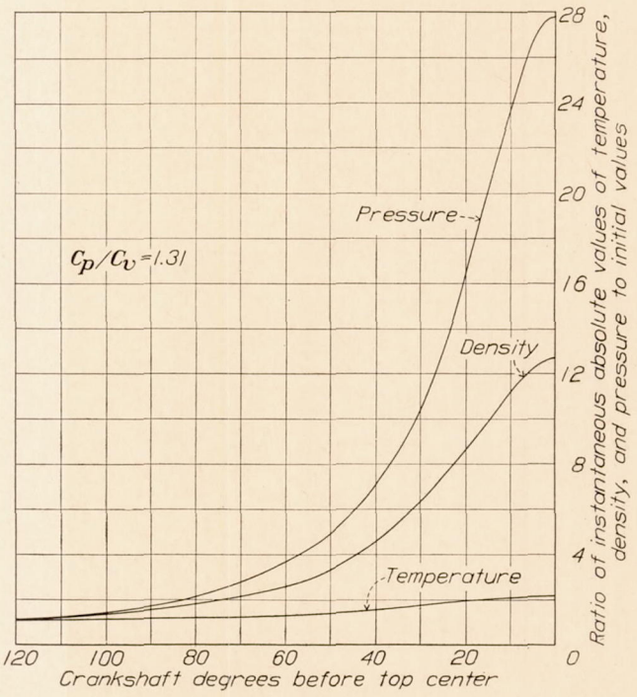

FIGURE 4.—Effect of crankshaft position on ratios of instantaneous absolute values of air temperature, density, and pressure to initial absolute values.

JACKET AND AIR TEMPERATURE

Because of the special characteristics of the apparatus as used in these tests, the temperature of the air charge was lowered considerably by compressing and decompressing the charge approximately 15 to 25 times (depending on the speed) before the introduction of the fuel. This lowering of the temperature of the air charge made it possible to ignite the mixture with a spark before auto-ignition took place.

The exact temperature at the start of compression was not known. Estimates made on the basis of the vaporization tests (reference 2) indicate that the air temperature at bottom center was considerably below 0° F. More recent tests in which a scavenging mechanism has been employed (reference 4) have shown that, without scavenging, it is necessary to maintain the jacket of the cylinder and combustion chamber at a temperature in excess of 300° F. in order to obtain results similar to those obtained with scavenging at a jacket temperature of 50° F.

There has been no direct determination of the air temperature within the combustion chamber at the start of compression and it is only known that this temperature is much lower than the measured jacket temperature and increases with the latter, although probably not to the same extent. The temperature variation causes another change in conditions, that is, an inverse variation of air density, so that the air-fuel ratio decreases as the initial engine temperature increases.

A system such as the one under consideration is affected by temperature in several ways. The distribution of the spray itself is influenced by increased temperature. Lowering of the viscosity, which tends to make smaller drops and more rapid spray disintegration, is a direct result of increased temperature (reference 5). The increased surface as the drops grow smaller facilitates heat transfer, dispersion, and surface reactions if such exist.

Increased heat transfer and vaporization are a natural consequence of increased temperature, particularly the vaporization of the higher boiling components that ignite most easily. It is an established fact that, in a given series of hydrocarbons, the ignition temperatures decrease as the molecular weight increases. This decrease is due to the fact that, with the greater complexity of the molecule, less energy of activation is required to break a bond with subsequent reaction. Where the time interval is short and vaporization not complete, raising the temperature not only furnishes a greater quantity of vaporized fuel but also a more reactive fuel containing a greater proportion of higher boiling components.

The rate of chemical reaction is more rapid at high temperatures. Even in those explosive reactions for which temperature has apparently little effect, at least the delay period or ignition lag is shortened, the reaction will start sooner and, being autoaccelerative thereafter, the net result will be greater in the given time.

The rate of thermal decomposition is greater at higher temperatures. The products of such decomposition are more difficult to ignite (reference 6) than the original substance. This effect is the only inhibitory action due to high temperatures and, as will be seen from the test results, the other factors outweigh it. The rate of thermal decomposition has a temperature coefficient equivalent to 1.3 for 10° C. for diesel fuel and 1.5 for gasoline according to Boerlage and Van Dyck (reference 7). From Frey's work (reference 8) the average rate increase for saturated hydrocarbons is threefold per 25° C. at 550° C. and fivefold at 400° C. As the temperature continued to be increased, the composition above a certain temperature would no

longer change due to the vaporization process. Though the increased rate of oxidation still overbalanced the increased rate of thermal decomposition (reference 9), one would expect the net effect of temperature increase at high temperatures to be lower.

The magnitude of the pressure rise varies inversely with the initial temperature $\left(\Delta P=\frac{P}{T}\Delta T\right)$, a relationship that may be easily derived from the gas equation if certain assumptions are made (reference 10). The rate of pressure rise therefore varies inversely with the initial temperature but directly with the rate of temperature rise or rate of heat input. The rate of heat input increases with increased temperature for it depends on the rate of chemical reaction, which increases with temperature. Obviously there must be some initial temperature that will result in an optimum rate of pressure rise since two factors are operative, one decreasing the rate of pressure rise with increased initial temperature, the other increasing the rate of reaction, thus increasing the rate of pressure rise with increasing temperature. A qualitative treatment of the effect of temperature on explosive reactions will be found in reference 10.

OTHER VARIABLES

With variation of engine speed, only the time element varied, the duration of a crankshaft degree at 570 r. p. m. being 2.7 times that at 1,550 r. p. m. There is little change in initial conditions for the same injection advance angle at different speeds.

Further experiments introduced other variables such as the spark-advance angle, which changed the conditions at the time of ignition, and the position of the spark, which gave some indication of the effect of mixture distribution in the combustion chamber. The method for comparing combustion in the different tests consisted of an examination of the flame photographs in conjunction with an analysis of the pressure-time curves (indicator cards). In the analysis of the latter, the kinetic rather than the thermodynamic considerations were stressed, that is, by finding the rate of pressure rise, the extent of the reaction as indicated by maximum cylinder pressures and by emphasizing the time element.

FUELS

The tests were run with three different fuels: Diesel fuel, hydrogenated safety fuel, and gasoline. The properties of a fuel from which behavior can be predicted are the distillation curve, which is known quite accurately (fig. 5), and the chemical nature, of which there is a rather limited knowledge. The boiling ranges of gasoline and diesel fuel were very wide; gasoline starting at about 160° F. and ending at about 420° F. and the diesel fuel starting at about 370° F. and ending above 690° F., the first 10 percent varying from 370° to 530° F. The hydrogenated safety fuel did not vary so much, 75 percent of it distilling between 330° and 375° F., and the entire range extending from 290° to 395° F. Considered with reference to their volatility, the fuels fall in the order: gasoline, safety fuel, diesel fuel. As to their chemical nature, it is known that diesel fuel and gasoline are both of a very complex nature, the former having the greater complexity as it consists of components more likely to decompose and yet more easily ignited. The hydrogenated safety fuel has a lower hydrogen-carbon ratio and, by the process of its production, must necessarily be more homogeneous, less complex molecularly, and more stable thermally than the other two fuels.

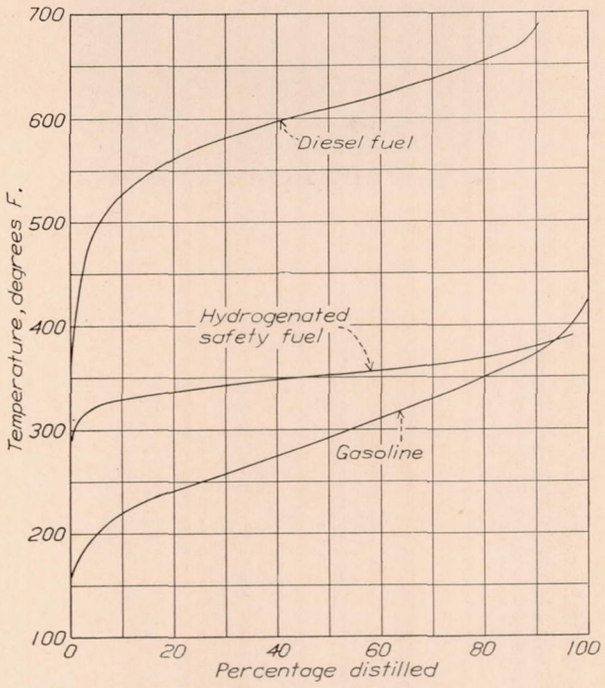

FIGURE 5.—Distillation curves of fuels tested.

TEST RESULTS

DIESEL FUEL

The effect of the injection advance angles on the combustion of the diesel fuel at an engine speed of 1,550 r. p. m. and at three different engine temperatures is shown in figures 6 and 7. The flame pictures shown at the top of the charts have the same abscissa as the indicator cards. At the left of figure 6 are shown contact prints of the original indicator cards. In some of the flame photographs the igniting spark is recorded at the right-hand edge. At an engine temperature of 200° F., combustion took place with an injection lead of 10° over the igniting spark. With a lead of 20° the combustion improved but became successively poorer as the injection was further advanced. Although in each case the photographic record showed that the flame propagated throughout, or nearly throughout, the visible portion of the

chamber, the combustion was far from complete, as evidenced by the low explosion and expansion pressures.

With an engine temperature of 300° F. (fig. 7), the effect of the injection advance angle between 47° and 67° before top center became negligible. This effect is also indicated at an engine speed of 570 r. p. m. (See figs. 8 and 9.) At this speed

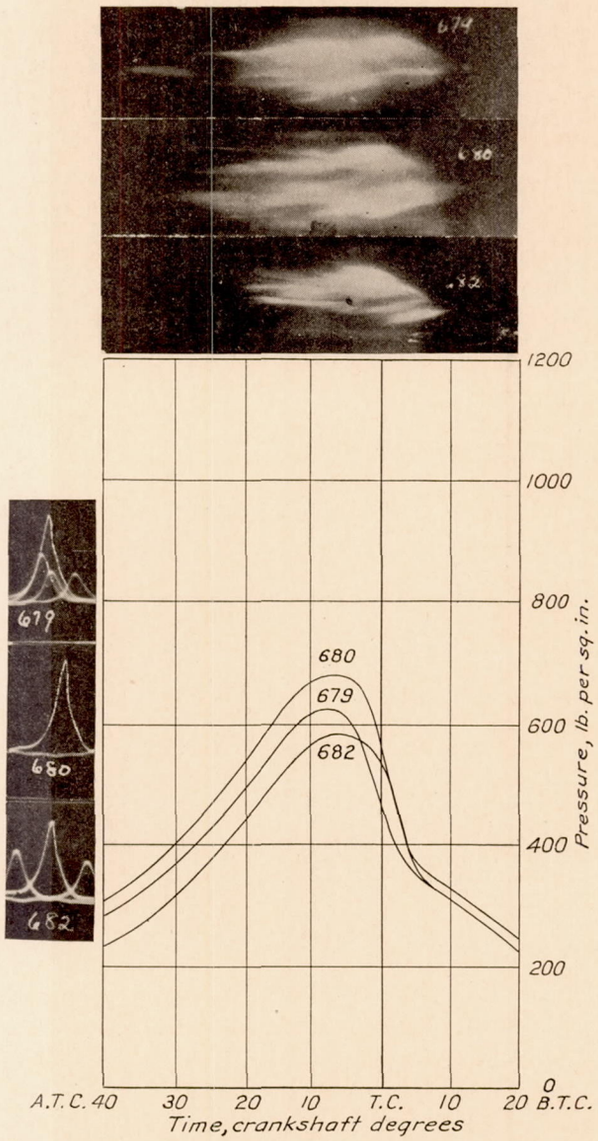

FIGURE 6.—Effect of injection advance angle on combustion of diesel fuel at engine temperature of 200° F.

Engine speed	1,550 r. p. m.
Fuel quantity	0.00027 lb.
Spark advance angle	20°.
Injection advance angle	679–30°, 680–40°, 682–50°.

combustion took place at an engine temperature of 150° F. (fig. 8), but the range of injection advance angles was extremely limited. With an injection advance angle of 55° the flame was recorded only in the center of the chamber close to the spark gap, but persisted for 40° or 50°. At an engine temperature of 250° (fig. 9), the effect of injection advance angle decreased considerably but the change in the intensity of the combustion could be noticed audibly. The test corresponding to record 570 was marked by knock; whereas the others in figure 9 were not. The extreme shortness of the flame is particularly noticeable. Record 570 also shows bright flashes of flame across the window. These bright flashes were characteristic of the explosion records accompanied by explosion shock, regardless of whether combustion was caused by spark or by auto-ignition.

The effect of engine temperature on combustion is demonstrated in figures 10 and 11. At an injection

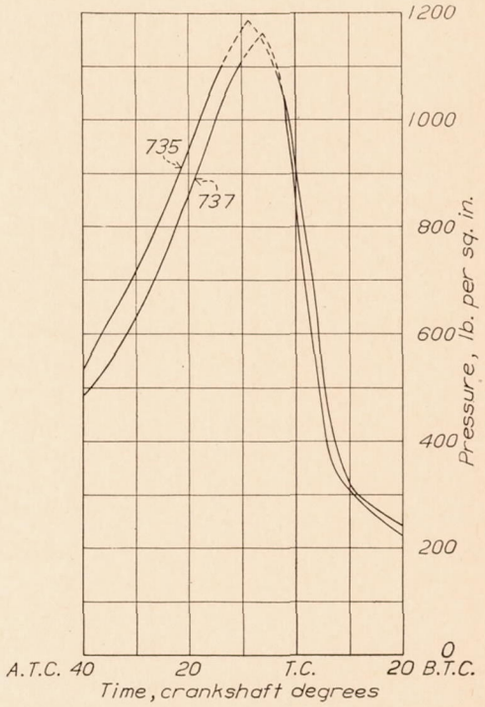

FIGURE 7.—Effect of injection advance angle on combustion of diesel fuel at an engine temperature of 300° F.

Engine speed	1,550 r. p. m.
Fuel quantity	0.00027 lb.
Spark advance angle	20°.
Injection advance angle	735–47°, 737–67°.

advance angle of 50° (fig. 11) the variation is considerable, but at an injection advance angle of 40° (fig. 10) it is much less. It was also found that an increase in jacket temperature from 150° F. to 200° F. effected more change than an increase from 250° F. to 300° F. At the higher temperature the period of inflammation of the gases was considerably shorter and was accompanied in some cases by considerable shock. In fact, with all the injection advance angles used at a temperature of 250° F. and an engine speed of 570 r. p. m., knock would at times occur, although it was most prevalent with an injection advance

angle of 40°, which was approximately the optimum angle at all engine temperatures for this speed.

The results show that the rate of combustion was controlled within fairly wide limits by the engine-jacket temperature and the fuel-injection advance angle. At an engine speed of 570 r. p. m. the optimum injection advance angle was 40° and at 1,550 r. p. m. the optimum value was 50° to 60°. These facts indicate that the rate of preparation of the fuel for combustion is not solely a function of time in crank degrees but of time in seconds as well.

The effect of ignition by the spark on the course of the combustion is shown in figure 12. Without the spark, the fuel auto-ignited with a high rate of pressure rise, accompanied by knock. With the spark, the fuel burned at a more moderate speed.

Table I records the number of explosions and misses obtained under each test condition investigated with diesel fuel. When the records showed that the combustion was strong, check runs were generally not made. When the combustion was weak or when the firing apparently was not regular, several runs were made for each set of test conditions. The range of ignitibility with respect to the injection advance angle, the engine temperature, and the engine speed can easily be seen. As the injection advance angle was increased for any one temperature, the percentages of explosions did not show much variation until the limit was approached and the explosions either became too weak to record or did not occur at all, in which case no indicator cards were taken and the data are not listed in the tables. As the engine temperature was increased the range of ignitibility increased until at the highest temperature all the injections resulted in explosions beyond a certain minimum injection advance angle.

HYDROGENATED SAFETY FUEL

The tests with the hydrogenated fuel, although manifesting the same major variations as the other fuels, exhibited these variations with greater regularity. In no cases did the hydrogenated fuel burn at a rate that resulted in combustion shock. Auto-ignition was very rare and, when it did occur, started late on the expansion stroke. With this fuel, a high engine temperature was required to operate consistently witb full-load fuel quantity.

The effect of injection advance angle on combustion at three different engine temperatures is illustrated in figures 13, 14, and 15. Figure 14 is one of the best examples of this effect. Not only do the rates of pressure rise vary in the definite order of 30°>40°>50° but also, as the injection advance angle is increased, the beginning of combustion is delayed, and the maximum cylinder pressure developed is lowered and reached at a later point in the cycle. The indicator cards show that, with this fuel quantity at about 60 percent of full load, combustion at the first two temperatures was optimum for an injection advance angle of 30°. At the highest temperature, 300° F. (fig. 15), combustion was optimum with an injection advance

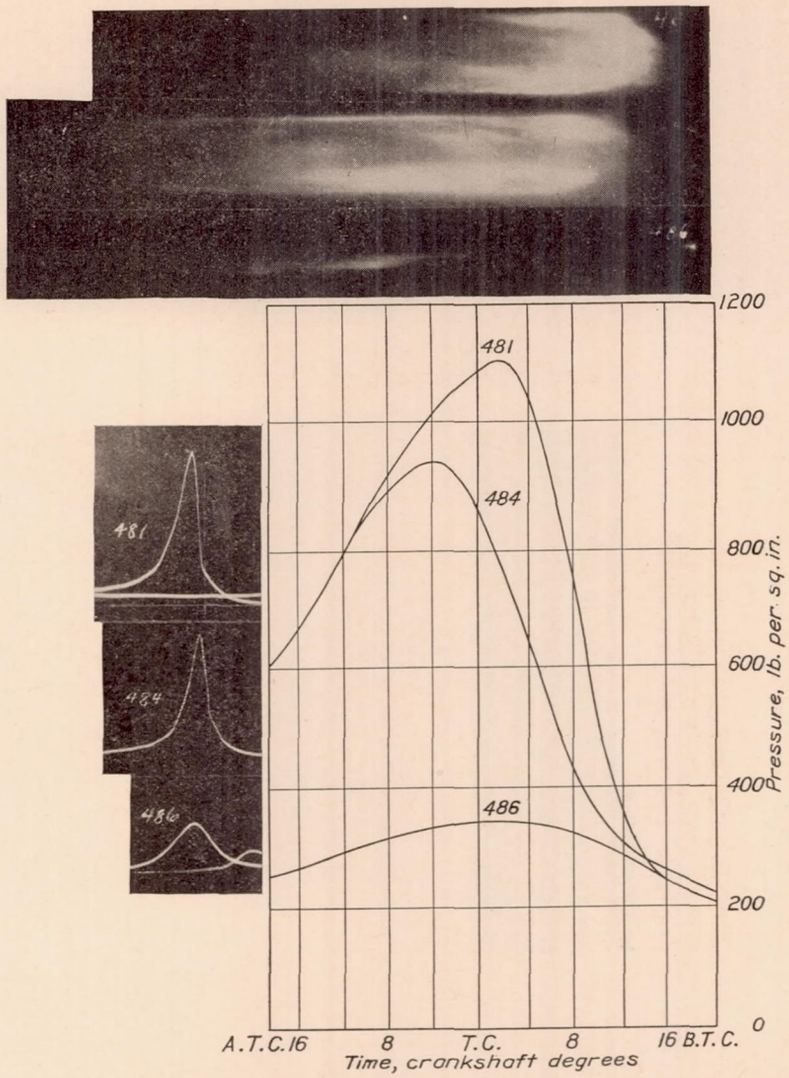

FIGURE 8.—Effect of injection advance angle on the combustion of diesel fuel at engine temperature of 150° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00024 lb.
Spark advance angle	20°.
Injection advance angle	481–35°, 484–45°, 486–55°.

angle between 30° and 40°, and persisted over a greater range of injection advance angles. The rates of pressure rise did not appear to be excessive nor did the combustions sound harsh.

In general, it was found that the pressure rise and the rate of pressure rise varied less with changes in injection advance angle and temperature in the combustion of safety fuel than with diesel fuel. Little change was caused by an increase of temperature from 250° F. to 300° F., consistent with the tendency already noted of a decreased effect of temperature at higher temperatures.

Table II summarizes the results of the effect of temperature and injection advance angle on ignitibility with the spark gap in the center and at the edge of the combustion chamber. (See fig. 16.)

At the highest temperature (300° F.) the range of ignition with the spark at the edge compares favorably with that for the spark at the center of the combustion chamber. Flame records 1057 and 1060 (fig. 16) show vibrations that had a frequency of approximately 10,000 per second. Although these vibrations started while the explosion pressure was still increasing, they continued for some time after maximum pressure was

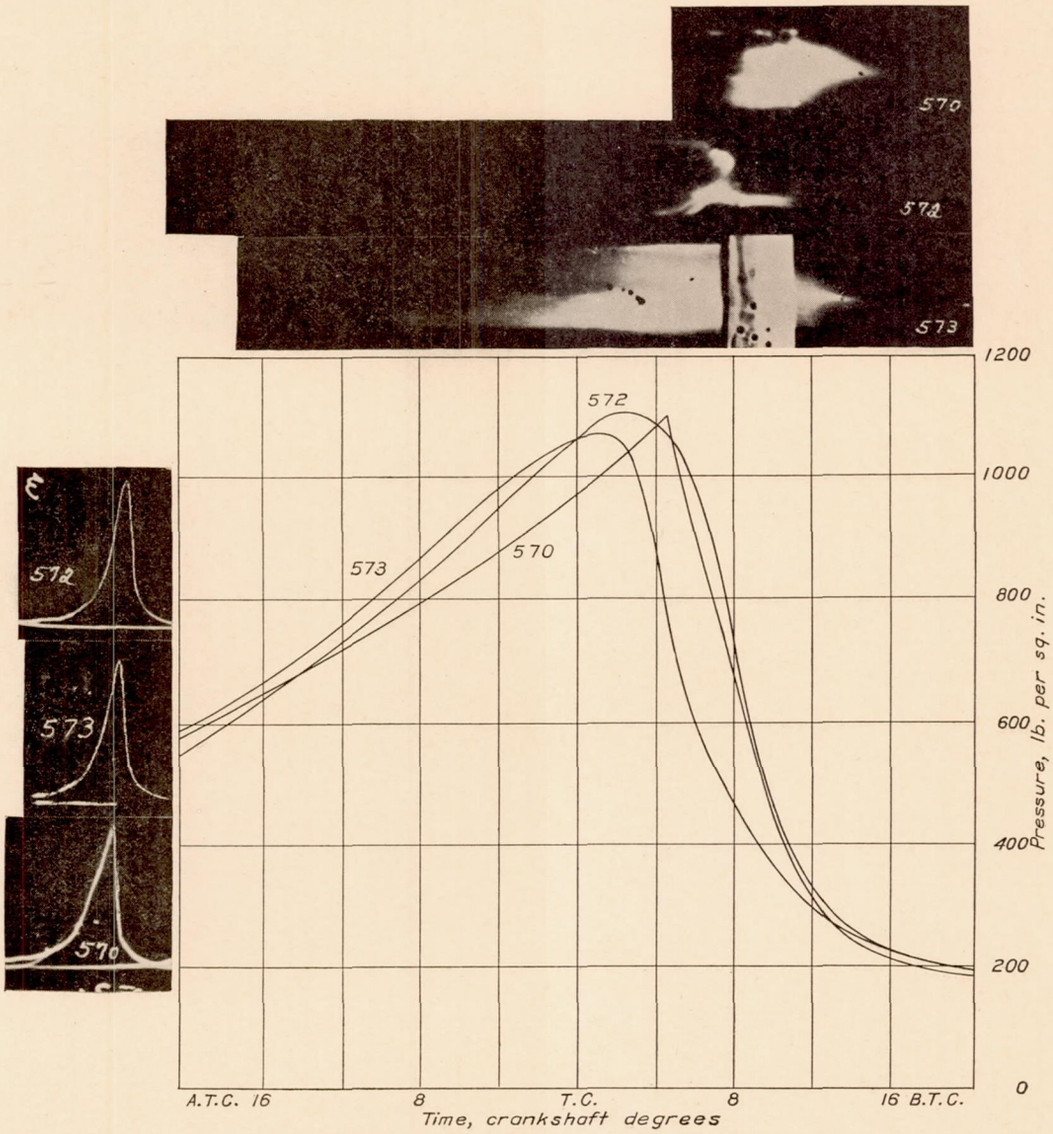

FIGURE 9.—Effect of injection advance angle on combustion of diesel fuel at engine temperature of 250° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00024 lb.
Spark advance angle	20°.
Injection advance angle	570–40°, 572–50°, 573–60°.

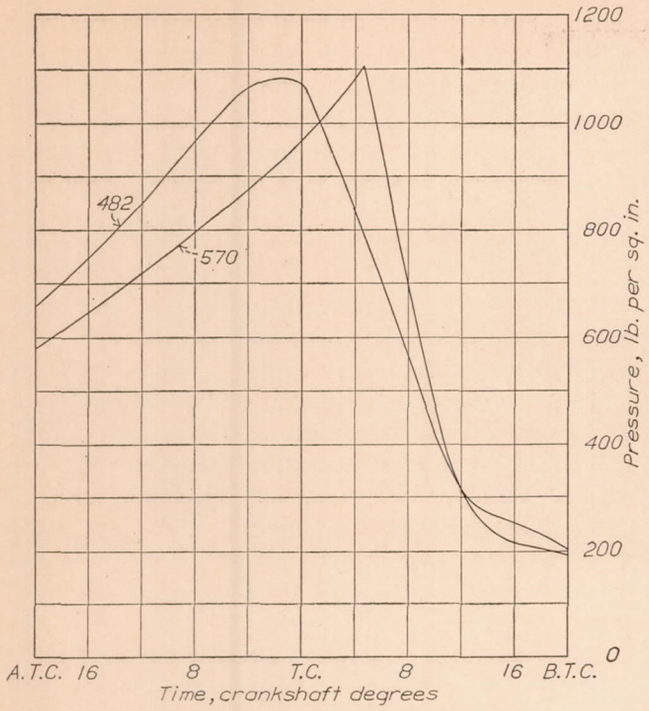

FIGURE 10.—Effect of engine temperature on combustion of diesel fuel with an injection advance angle of 40°.

Engine speed ..... 570 r. p. m.
Fuel quantity ..... 0.00024 lb.
Spark advance angle ..... 20°.
Engine temperature ..... 570–250° F., 482–150° F.

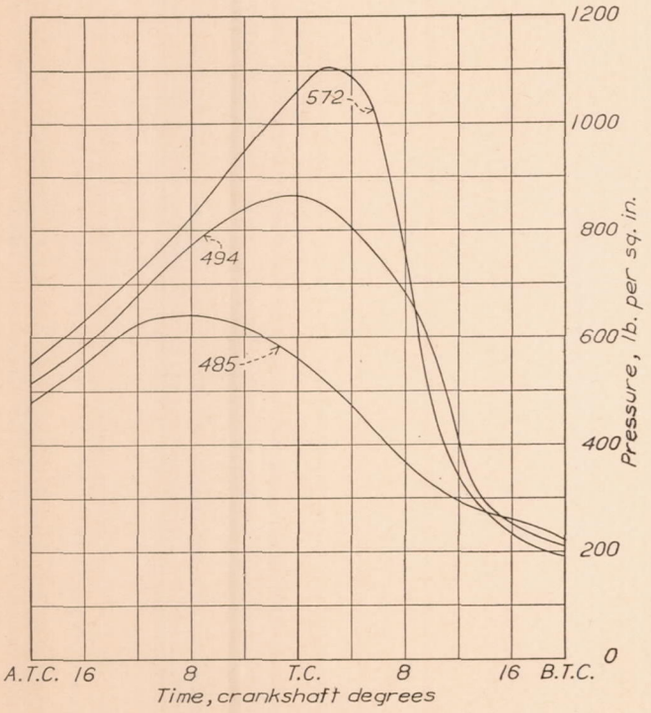

FIGURE 11.—Effect of engine temperature on combustion of diesel fuel at an injection advance angle of 50°.

Engine speed ..... 570 r. p. m.
Fuel quantity ..... 0.00024 lb.
Spark advance angle ..... 20°.
Engine temperature ..... 572–250° F., 494–200° F., 485–150° F.

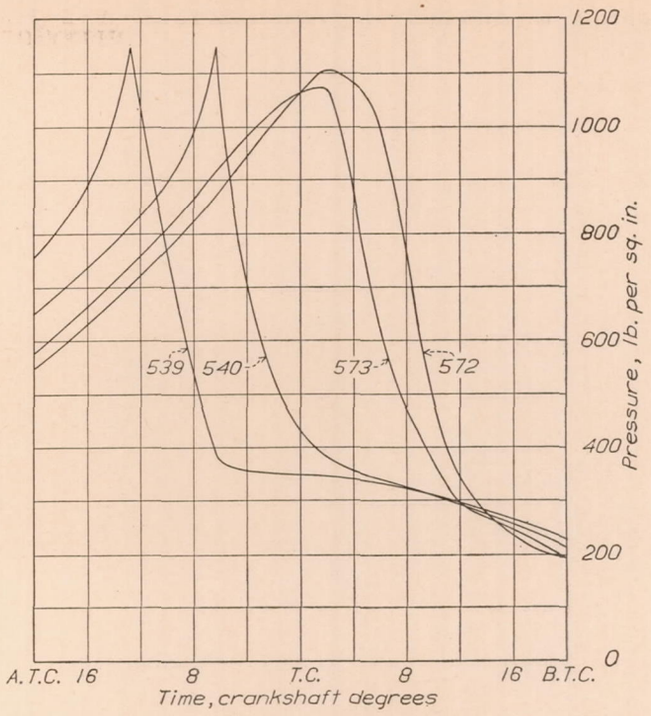

FIGURE 12.—Effect of ignition spark on combustion of diesel fuel at an engine temperature of 250° F.

Engine speed ..... 570 r. p. m.
Fuel quantity ..... 0.00024 lb.
Injection advance angle ..... 572 and 539–50°, 573 and 540–60°.
Spark advance angle ..... 572 and 573–20°, 539 and 540, no spark.

TABLE I.—EFFECT OF ENGINE TEMPERATURE AND INJECTION ADVANCE ANGLE ON IGNITIBILITY OF DIESEL FUEL

[Spark-plug gap at center of combustion chamber]

Engine temperature, °F.	Ignition	Injection advance angle, degrees B. T. C.											
		30	40	50	60	70	80	90	100	110	120	130	140
FUEL QUANTITY PER INJECTION, 0.00024 LB. ENGINE SPEED, 1,550 R. P. M.													
100	Explosions	0	1	1	2	2	----	----	----	----	----	----	----
	Misses	4	8	3	3	7	----	----	----	----	----	----	----
150	Explosions	0	1	1	1	1	----	----	----	----	----	----	----
	Misses	5	7	4	3	4	----	----	----	----	----	----	----
200	Explosions	2	1	2	1	1	1	1	2	----	----	----	----
	Misses	1	0	1	0	0	0	0	2	----	----	----	----
250	Explosions	2	1	2	3	3	2	1	----	0	----	1	----
	Misses	0	0	6	1	0	0	0	----	1	----	0	----
300	Explosions	0	1	2	0	1	1	1	----	1	----	1	----
	Misses	1	0	0	1	0	0	0	----	0	----	0	----
FUEL QUANTITY PER INJECTION, 0.00020 LB. ENGINE SPEED, 570 R. P. M.													
100	Explosions	----	2	2	4	0	0	0	0	----	0	----	0
	Misses	----	2	3	0	5	4	4	5	----	4	----	4
150	Explosions	3	2	2	2	----	----	----	----	----	----	----	----
	Misses	1	0	0	0	----	----	----	----	----	----	----	----
200	Explosions	2	1	1	1	1	1	1	----	----	----	1	----
	Misses	2	0	0	0	0	0	0	----	----	----	0	----
250	Explosions	0	1	1	1	1	1	1	1	1	1	----	----
	Misses	1	0	0	0	0	0	0	0	0	0	----	----

TABLE II.—EFFECT OF TEMPERATURE AND INJECTION ADVANCE ANGLE ON IGNITIBILITY OF HYDROGENATED SAFETY FUEL

[Engine speed, 570 r. p. m. Fuel quantity per injection, 0.00020 lb.]

Engine temperature, ° F.	Ignition	Injection advance angle, degrees B. T. C.									
		30	40	50	60	70	80	90	100	110	120
SPARK-PLUG GAP AT CENTER OF COMBUSTION CHAMBER											
100	Explosions	1	1	[1] 3	[1] 2	[1] 3	[1] 3	[1] 3	----	----	------
	Misses	0	0	0	0	0	0	0	----	----	------
150	Explosions	2	1	1	[1] 3	[1] 3	[1] 3	[1] 3	----	----	------
	Misses	1	0	0	0	0	0	0	----	----	------
200	Explosions	1	1	1	1	[1] 3	[1] 3	----	----	----	------
	Misses	0	0	0	0	0	0	----	----	----	------
250	Explosions	1	1	1	[1] 2	[1] 3	[1] 3	0	----	----	------
	Misses	2	0	0	0	0	0	3	----	----	------
300	Explosions	1	1	1	3	4	[2] 4	2	1	[3] 3	[1] 1
	Misses	0	0	0	0	4	7	5	6	5	9
SPARK-PLUG GAP AT EDGE OF COMBUSTION CHAMBER											
150	Explosions	0	0	2	0	----	----	----	----	----	------
	Misses	2	2	1	2	----	----	----	----	----	------
200	Explosions	0	0	0	0	----	----	----	----	----	------
	Misses	2	2	2	2	----	----	----	----	----	------
250	Explosions	----	2	0	1	0	----	----	----	----	------
	Misses	----	4	3	2	1	----	----	----	----	------
300	Explosions	2	1	5	1	1	1	1	4	5	5
	Misses	8	0	1	0	0	0	0	3	1	1

[1] All explosions weak. [2] 3 weak explosions. [3] 2 weak explosions.

reached. Since the frequency of these waves was very close to that of the indicator diaphragm, the results of the vibrations were shown on the indicator record as a broadening of the expansion line. It can be concluded from these records that the occurrence of these waves is not necessarily accompanied by knock. (See also references 11 and 12.)

GASOLINE

The results of the tests with gasoline at an engine speed of 1,550 r. p. m. are presented in table III. The table shows that for every engine temperature there was quite a range of injection advance angles at which some of the injections of fuel would ignite. Cards showing the greatest combustion efficiency were obtained with the 70° and 80° injection advance angles, decreasing as the injection advance angle increased beyond this optimum range.

The results of the test made at 570 r. p. m. are listed in table IV.

In general, for a constant injection advance angle combustion improved with rising temperature, but it was only for the earlier injection advance angles that the effect was considerable. At 1,550 r. p. m. a differ-

TABLE III—EFFECT OF ENGINE TEMPERATURE AND INJECTION ADVANCE ANGLE ON IGNITIBILITY OF GASOLINE

[Engine speed 1,550 r. p. m. Fuel quantity per injection, 0.00022 lb. Spark-plug gap at center of combustion chamber]

Engine temperature, °F.	Ignition	Injection advance angle, degrees B. T. C.															
		30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
100	Explosions	1	1	1	3	3	4	------	------	------	------	------	------	------	------	------	------
	Misses	8	7	6	6	1	0	------	------	------	------	------	------	------	------	------	------
150	Explosions	0	1	1	5	5	4	4	2	2	2	0	0	0	0	------	0
	Misses	4	4	5	0	0	1	1	3	3	3	5	5	5	4	------	5
200	Explosions	0	0	0	3	4	4	3	3	0	1	0	0	------	------	------	0
	Misses	4	4	4	2	0	0	2	2	5	9	5	5	------	------	------	4
250	Explosions	------	0	0	4	4	4	3	1	1	1	1	0	1	1	1	0
	Misses	------	4	4	6	0	0	1	4	4	4	3	4	3	3	3	3
300	Explosions	0	0	0	2	4	4	3	3	2	0	------	1	------	0	------	0
	Misses	4	4	4	2	0	0	0	1	2	4	------	3	------	4	------	4
350	Explosions	------	2	3	3	4	4	2	3	2	0	------	0	------	1	------	2
	Misses	------	2	1	1	0	0	1	1	2	4	------	4	------	1	------	2

TABLE IV.—EFFECT OF ENGINE TEMPERATURE AND INJECTION ADVANCE ANGLE ON IGNITIBILITY OF GASOLINE

[Engine speed 570 r. p. m. Fuel quantity per injection, 0.00037 lb. Spark-plug gap at center of combustion chamber]

Engine temperature, °F.	Ignition	Injection advance angle, degrees B. T. C.															
		30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
100	Explosions	0	1	2	1	0	0	0	1	1	0	0	0	0	0	------	0
	Misses	4	4	3	4	6	5	5	6	4	6	6	6	6	7	------	5
150	Explosions	1	4	4	3	1	0	0	0	0	0	1	------	------	------	------	------
	Misses	1	0	1	2	4	5	5	5	5	5	6	------	------	------	------	------
200	Explosions	0	3	3	3	2	1	0	------	------	------	------	0	------	------	------	------
	Misses	4	1	1	2	3	3	4	------	------	------	------	4	------	------	------	------
250	Explosions	0	3	2	3	2	1	0	0	0	1	0	------	------	0	------	0
	Misses	4	2	2	1	3	4	5	4	4	3	4	------	------	5	------	5
300	Explosions	2	4	3	3	3	1	0	1	1	1	0	0	2	0	1	0
	Misses	2	1	1	1	1	3	4	3	3	3	4	4	2	4	3	4

TABLE V.—EFFECT OF ENGINE TEMPERATURE AND INJECTION ADVANCE ANGLE ON THE IGNITIBILITY OF GASOLINE

[Engine speed 570 r. p. m. Fuel quantity per injection, 0.00037 lb. Spark-plug gap one-sixteenth inch above the top center position of the piston crown]

Engine temperature ° F.	Ingition	Injection advance angle, degrees B. T. C.						
		30	40	50	60	70	80	90
150	Spark explosions	6	5	2	0	0	0	0
	Compression explosions	0	0	2	2	0	0	0
	Misses	9	3	7	8	4	4	4
200	Spark explosions	0	6	1	0	0	0	0
	Compression explosions	0	0	0	2	1	0	0
	Misses	3	0	5	3	5	6	4
250	Spark explosions	1	5	0	1	1	0	0
	Compression explosions	0	0	1	1	0	4	5
	Misses	4	1	5	3	5	1	0
300	Spark explosions	2	5	3	0	0	0	0
	Compression explosions	1	0	1	2	4	5	4
	Misses	2	0	1	3	1	0	1

ence of 10° in the injection advance angle usually had a slightly greater effect than a 50° F. change in jacket temperature.

It was thought that the failure to fire with very early injection might be due to the fuel penetrating to the bottom of the combustion chamber before the occurrence of the igniting spark, which would leave little fuel in the top of the chamber near the spark plug. A spark plug was so constructed, therefore, that the gap was about one-sixteenth inch from the piston crown position at top center. Tests were made with 0.00037 pound of fuel per cycle at engine temperatures from 150° to 300° F. and with injection advance angles from 30° to 170° before top center. The results are given in table V.

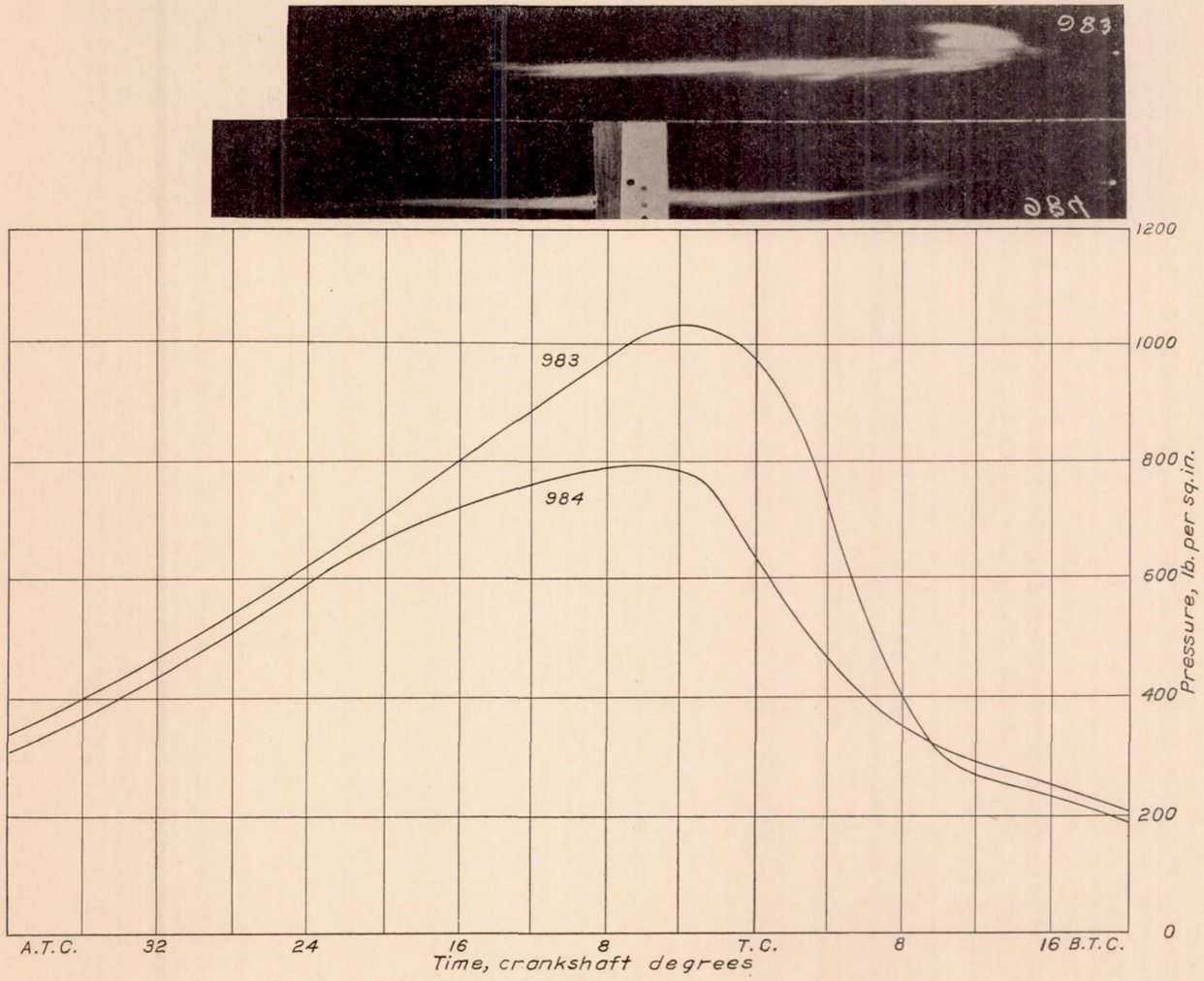

FIGURE 13.—Effect of injection advance angle on combustion of safety fuel at engine temperature of 100° F.

Engine speed ..... 570 r. p. m.
Fuel quantity ..... 0.00020 lb.
Spark advance angle ..... 20°.
Injection advance angle ..... 983-30°, 984-40°.

An examination of the indicator cards showed that the burning was efficient but, in some cases, slightly slower than with the spark in the center of the chamber. In a comparison of tables IV and V, it is seen that the spark ignitions at the optimum injection advance angle of 40° were more regular than those with the spark at the center of the chamber. The results indicate that, although the distribution of the fuel is a factor in controlling whether or not the spark ignites the mixture, it is not the only factor. Until further work has been done, therefore, the possibility that chemical changes in the fuel is a determining factor, must not be forgotten.

In previous tables, all auto-ignitions (compression ignitions) have been listed as misses but in table V the auto-ignitions have been listed separately. The method of distinguishing the ignitions is shown in figure 17. For flame records 409 and 412 no flame was recorded between the igniting spark and the first appearance of the flame and the flame does not show any definite progression across the chamber. The burning in each case was accompanied by severe combustion shock. In flame records 410 and 411 a definite progression of the flame took place and the pressure in the combustion chamber started to increase shortly after the spark had ignited the mixture. In tables I and II

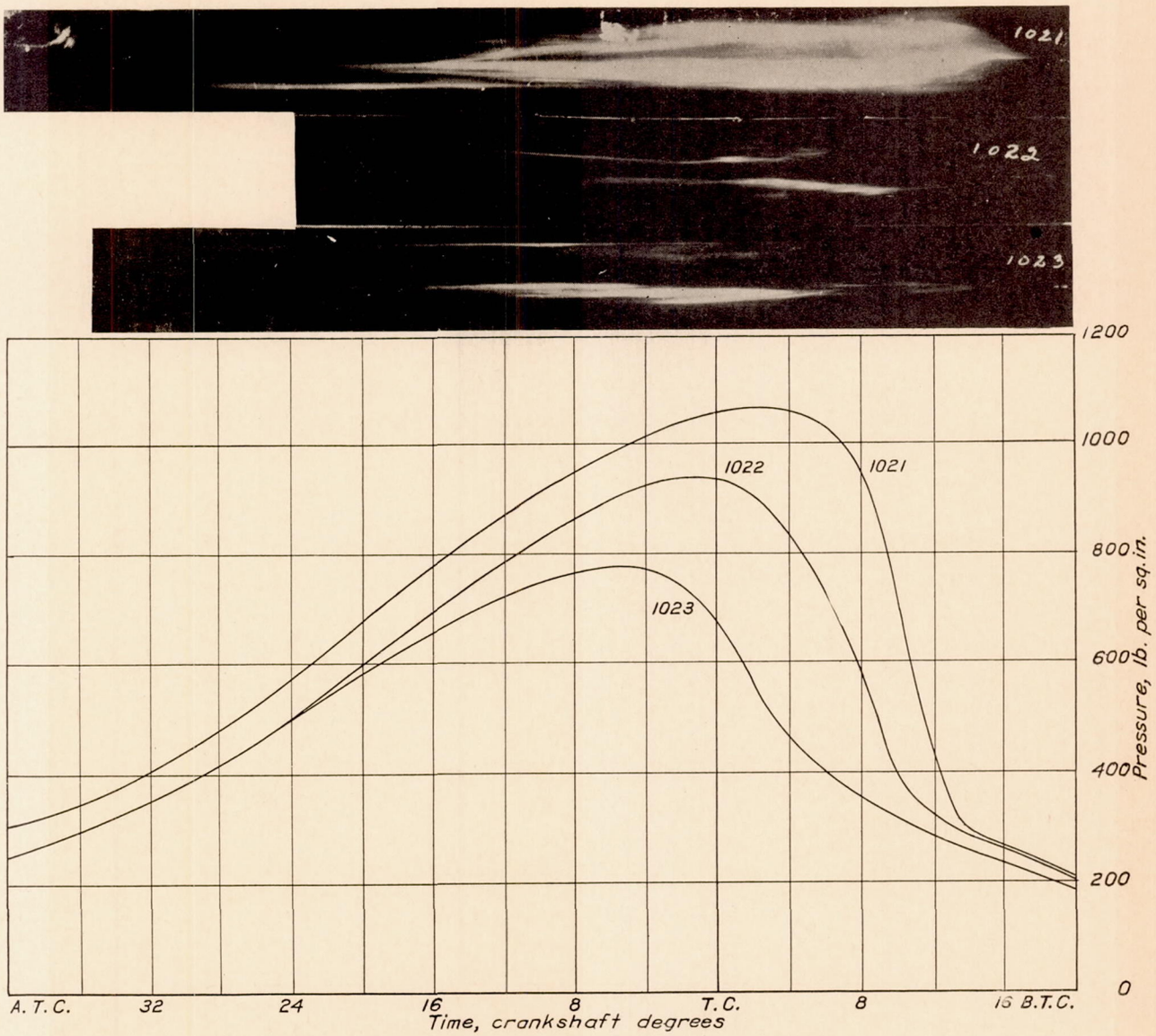

FIGURE 14.—Effect of injection advance angle on combustion of safety fuel at engine temperature of 200° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00020 lb.
Spark advance angle	20°.
Injection advance angle	1021–30°, 1022–40°, 1023–50°.

flame records similar to 409 and 412 have been classified as compression ignitions and listed as misses. All flame records such as 410 and 411 have been classified as spark ignitions and listed in these tables as explosions. Very little doubt can exist as to the accuracy of so classifying the latter type of flame record. In regard to the compression ignitions, the classification is not so certain. Recent tests conducted by Duchêne (reference 13) have disclosed a similar condition. In his photographic records, however, a definite persistence of flame around the igniting spark existed during an "ignition lag" similar to those recorded in the present work. After this local burning, the remainder of the mixture in the chamber suddenly burst into flame, giving an appearance similar to those in flame records 409 and 412.

In all tests where knock occurred, as evidenced by an audible shock, the indicator card showed a continually increasing rate of pressure rise until maximum pressure was reached, followed by a sudden arrest of effective burning and a comparatively rapid decrease of the pressure caused by cooling and leakage losses. (See fig. 10, record 570.) In the records for which there was no shock, the rate of pressure rise at first increased and then decreased, resulting in a well-rounded card at the maximum pressure. In 2 or 3 of

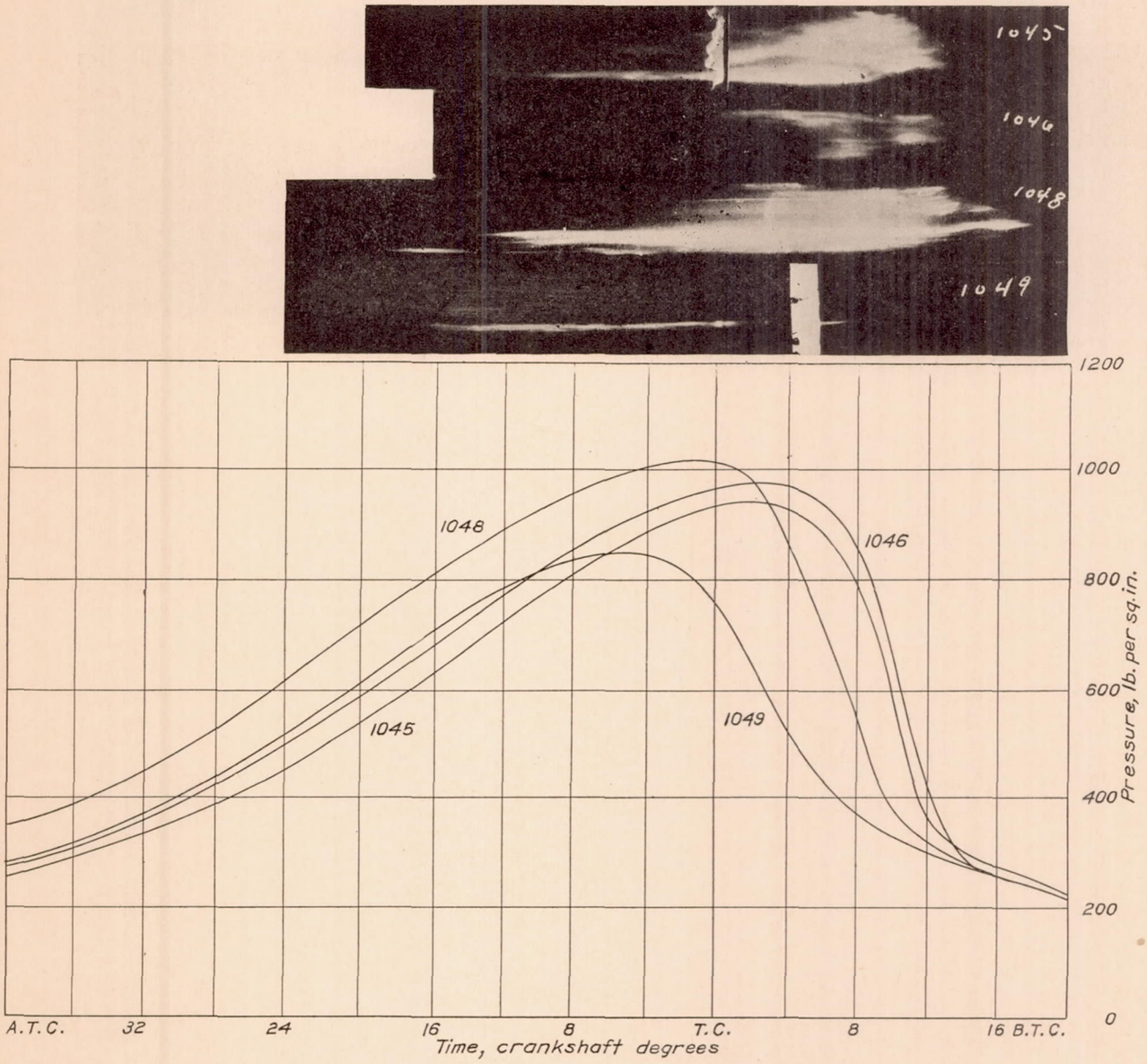

FIGURE 15.—Effect of injection advance angle on combustion of safety fuel at engine temperature of 300° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00020 lb.
Spark advance angle	20°.
Injection advance angle	1045–20°, 1046–30°, 1048–40°, 1049–50°.

the records for gasoline with very early injection, the characteristic knock card for conventional spark ignition was obtained, the rate of pressure rise first increasing, then decreasing, and just before maximum pressure was reached, suddenly increasing again. The maximum rate of pressure rise in the knocking records was not very much greater than that with some of the nonknocking records, so that the shock of the combustion cannot be attributed solely to the maximum rate of pressure rise.

DISCUSSION

In all this work it has been found that the rate of pressure rise increases with an increase in jacket temperature, indicating that the increased rate of the oxidation reaction overbalances all opposing tendencies. The fact that the net effect of an increase of 50° F. at the higher temperatures is much lower than for a similar change at the lower temperatures proves, however, that a condition is approached where the

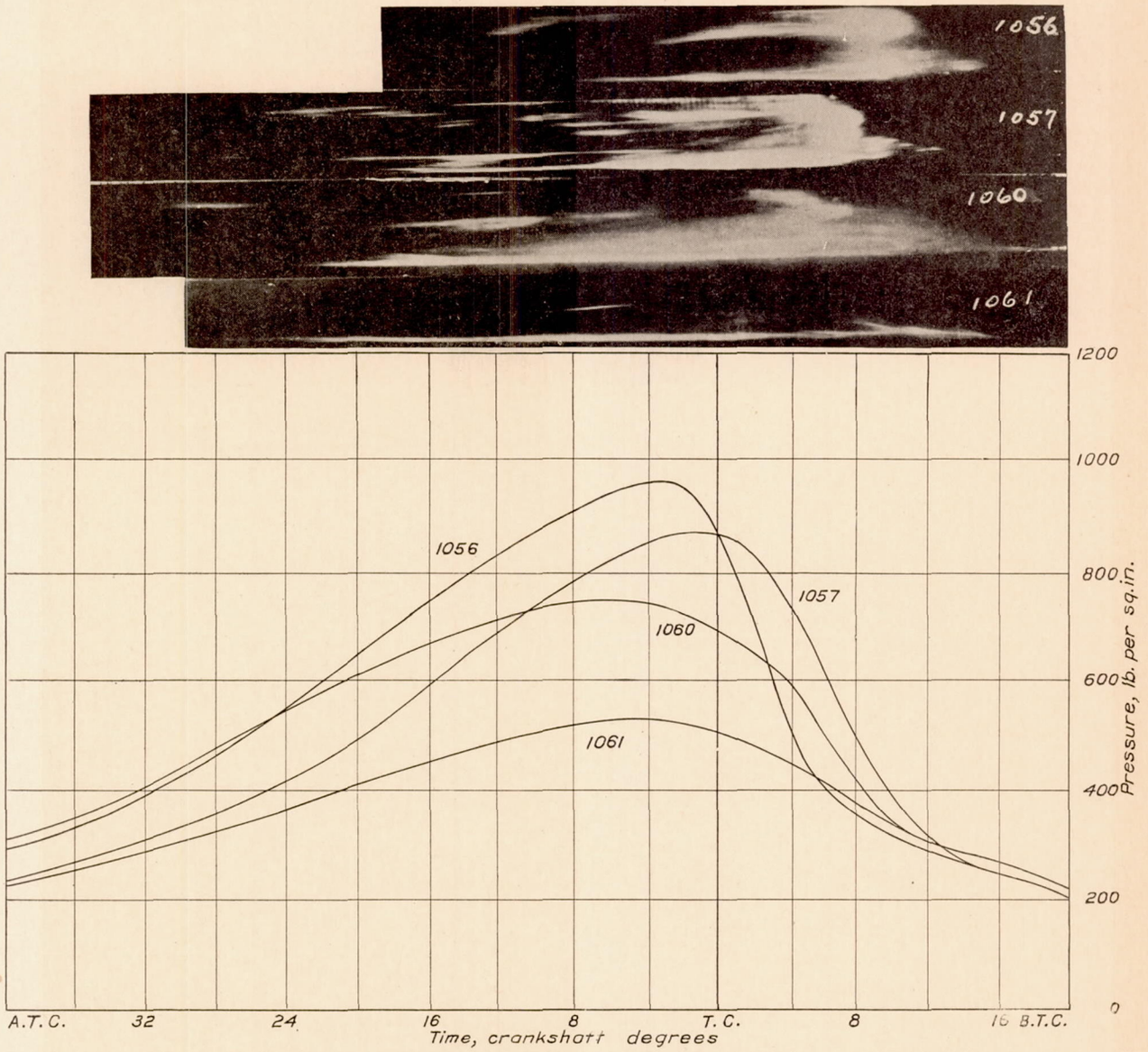

FIGURE 16.—Effect of injection advance angle on combustion of safety fuel with ignition spark in side of chamber and at engine temperature of 300° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00020 lb.
Spark advance angle	20°.
Injection advance angle	1056–40°, 1057–50°, 1060–60°, 1061–70°.

increased rate of heat input no longer compensates for the inverse variation of rate of pressure rise with initial temperature and the increased rate of thermal decomposition.

The consistent variation of combustion with injection advance angle is the most persistent of all the variations. With very short time intervals between injection and ignition, the failure to ignite or the small extent of combustion is due to the lean mixture caused by insufficient vaporization and diffusion. In more general terms, the time interval is insufficient for the heat transfer necessary for the activation of the fuel, regardless of what this process may consist. There may be several causes for the fact that maximum combustion appears at, or soon after, the beginning of the range of ignitibility, after which the combustion decreases with increasing injection advance angle and often stops altogether at a definite injection advance angle.

The difference in density for 10° differences in crank angle as well as the effect on spray distribution resulting therefrom is insufficient to cause the large difference in combustion, but it may be a contributing cause. Another reason for regarding this cause as insufficient lies in the fact that the greatest variation with injection advance angle is in the region where the air density changes least. Furthermore, experiments indicate that injection of the fuel at an advance angle of 80° and ignition at 60° before top center give results as satisfactory as those with injection at 40° and spark at 20°. The results indicate that the effect of initial conditions is not the determining factor.

Another possible explanation lies in the chemical composition of the vapor which must of necessity vary with the time and also with the pressure and temperature of the air during the time interval between the injection of the fuel and its ignition. Although this explanation would fit the data obtained, there has been no direct experimental substantiation such as might be afforded by the use of a gas-sampling valve.

Safety fuel has a comparatively constant boiling range and would therefore never be affected much by the changing temperature factor but only by the lengthened time with increasing injection advance angle. This fuel is consistent in not showing any marked effect with increased initial temperature.

Yet another possible cause exists for the limits of ignition at definite injection advance angles: The temperature and pressure required for ignition are a function of ignition lag. As Dixon has found (reference 14), these necessary conditions for ignition are dependent upon time lag alone and not upon any chemical change in the system previous to ignition. To draw an analogy is quite impossible because of the vast difference between the homogeneous systems Dixon investigated and the heterogeneous systems of the present investigation. No data are available on the magnitude and direction of this variation for the conditions and fuels employed in the present investigation.

Some of the variations in the behavior of the fuels can be explained on the basis of their properties. The effect on combustion of varying the injection advance angle is greatest for diesel fuel, less for safety fuel, and

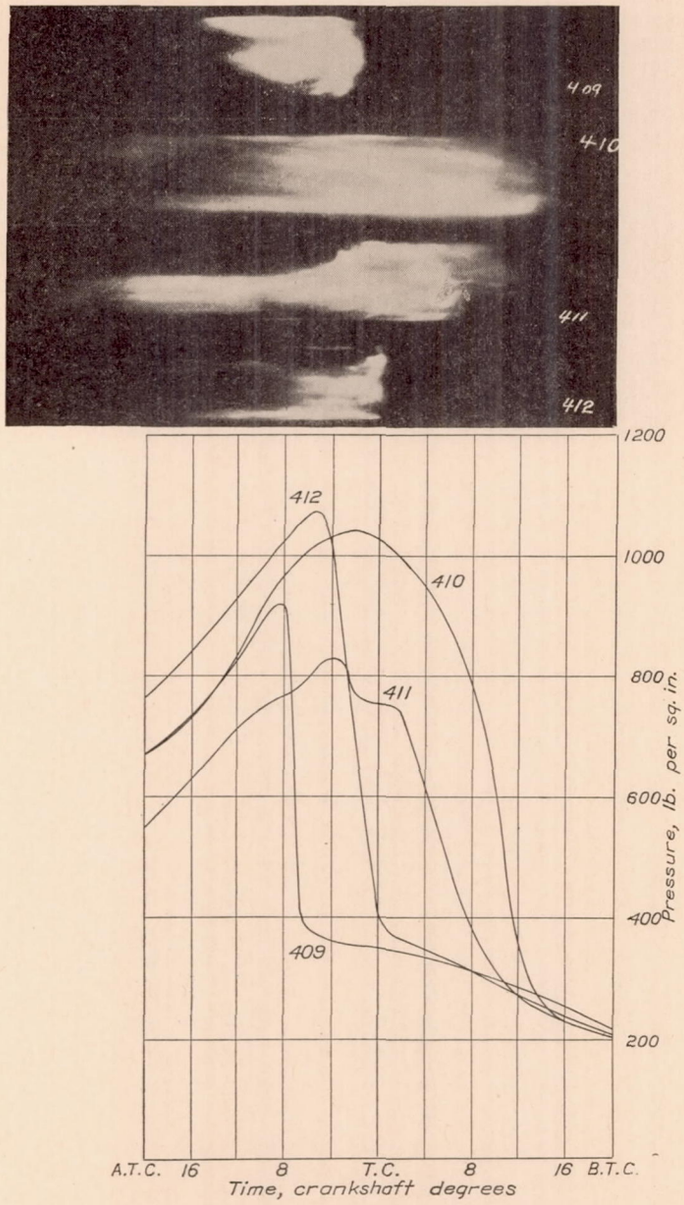

FIGURE 17.—Effect of injection advance angle on combustion of gasoline at engine temperature of 250° F.

Engine speed	570 r. p. m.
Fuel quantity	0.00024 lb.
Spark advance angle	20°.
Injection advance angle	409–23°, 410–43°, 411–63°, 412–83°.

least for gasoline, an order exactly opposite to the order of volatility. The small variation for gasoline is probably due to the fact that its decomposition products have ignition properties more similar to the original vapors. As Tausz and Schulte found (refer-

ence 15), the decomposition products of all fuels show little variation with respect to ignition temperature although the original fuels vary inversely at their boiling points if they are of the same chemical type. It follows that a fuel with a high boiling point will vary more with the products of its decomposition in regard to its ignition qualities than one with a low boiling point. Thus diesel fuel should display a greater variation with increased decomposition (that is, with increased injection advance angle) than gasoline since both are predominantly aliphatic and the former has a much higher boiling range (fig. 4). The diesel fuel should have a greater variation than gasoline or safety fuel not only because its boiling range is highest but because it is the least stable thermally. The rate constant of decomposition at 575° C. has been found by Frey (reference 8) to increase from 0.0002 second^{-1} for ethane to 0.08 second^{-1} for gas oil.

The maximum cylinder pressures developed and the rates of pressure rise usually vary in the same order but not to the same extent. Thus, the rate of pressure rise is higher for gasoline at low temperatures but almost the same as for the other two fuels at the higher temperatures. At 1,550 r. p. m. a rather complex relationship exists. At temperatures through 200° F., the rates of pressure rise are in the order of gasoline, diesel fuel, and safety fuel, although safety fuel has the highest maximum cylinder pressures. It is assumed that the temperature of 200° F. is too low to vaporize and burn the diesel fuel completely, and above 200° F. it is found that gasoline and diesel fuel have approximately the same rates of pressure rise with the diesel fuel developing the higher pressures. Safety fuel reacts more slowly and not to the same extent. As has been stated previously, the difference in rates of pressure rise between safety fuel and the other fuels is greater than the difference in the pressures.

Table VI presents a summary of the ranges of combustibility for the 3 fuels at the 2 engine speeds and at different temperatures. Only those injection advance angles are included for which over 50 percent of the injections resulted in spark ignition. It is obvious from the table that temperature has practically no effect on the range of combustibility of gasoline, a small effect on that of safety fuel, and a very great effect on that of diesel fuel. Although a high temperature is apparently required to cause the diesel fuel to react, once this high temperature is reached, the fuel will ignite over a much wider range. The results indicate that vaporization does not become effective in controlling the combustion except at temperatures much below those in the combustion chamber of a compression-ignition engine at the time of fuel injection.

If the combustibility ranges for the different fuels at an engine speed of 1,550 r. p. m. and a temperature of 200° F. are compared, it is evident that diesel fuel requires a minimum interval of 10° crank angle between injection and ignition, hydrogenated safety fuel 30°, and gasoline 40°. This order is the reverse of what would be expected if ignition varied with volatility. The only plausible explanation of this phenomenon is that diesel fuel requires the least energy of activation of the three fuels; that is, if the temperature is sufficiently high, the unstable highly active components, even if only a small amount is vaporized, require relatively little energy to start the reaction. Safety fuel, on the other hand, needs more time although it is vaporized to a greater extent and requires much more energy of activation, as further evidenced by the fact that this fuel would rarely auto-ignite (and later in the stroke in any case) when it did not ignite from the spark. For gasoline, the longest time interval is necessary and, as previously mentioned, the time interval is the same as that at the low speed. Nevertheless, at low temperatures, although diesel fuel will ignite sooner, it is the gasoline that gives the greater maximum cylinder pressures, showing definitely that the diesel fuel is not vaporized to as great an extent as the gasoline. At the higher speed (1,550 r. p. m.) the safety and diesel fuels would not fire regularly until a jacket temperature of 200° F. was used, furnishing further evidence of the necessity of vaporizing a sufficient quantity of fuel to insure ignition. From these results, the somewhat paradoxical conclusion is arrived at that if a temperature is assumed at which all the fuels will ignite, gasoline, the most volatile, will be the most difficult to ignite; that is, it will require the most time to form a combustible mixture.

TABLE VI.—RANGE OF INJECTION ADVANCE ANGLES RESULTING IN SPARK IGNITION

[Values given in crank degrees]

Engine temperature, °F.	Engine speed, r. p. m.	Gasoline [1]	Safety fuel	Diesel fuel
100	570	---------	30–40	35– 50
	1,550	60– 80	---------	---------
150	570	30– 60	30–50	30– 60
	1,550	60– 90	50–60	---------
200	570	30– 60	30–60	30–130
	1,550	60–100	50–90	30– 90
250	570	30– 60	30–60	30–120
	1,550	60– 90	50–90	30–130
300	570	30– 70	30–70	---------
	1,550	60–100	---------	(2)

[1] Data for gasoline at 570 r. p. m. are not directly comparable with the other data because of the increased fuel quantity used; i. e., 0.00037 pound instead of the 0.00020 pound used in other tests.
[2] Compression and spark ignition over entire range.

It has often been stated that the volatility of a fuel is no criterion of its suitability for use in an engine. The results of the present tests go one step further. They show that for the same fuel within certain limits the extent of vaporization is not the determining factor, once a certain minimum temperature is reached, since combustion decreased with the increased time

allowed for vaporization. This fact, however, does not lead to the conclusion that the fuel is not vaporized, or only negligibly vaporized, and that vaporization is not essential for ignition. On the contrary, there is reason to believe from previous experimental work (reference 2) that vaporization occurs very rapidly, a conclusion not inconsistent with the results found in the present tests.

If complete vaporization is assumed, as in the case of gasoline, the decreasing combustion with increasing injection advance angle can be explained by increased thermal decomposition of the vapor with increased time. If it is assumed that partial vaporization occurs, which is more likely for the diesel and safety fuels, not only does the increased thermal decomposition play a part but the variation in vapor composition and the lowered fuel atomization as well. With reference to thermal decomposition, no attempt is made to specify any exact mechanism of reaction but rather some type of reaction that produces molecules of a decidedly less active nature than those originally present.

CONCLUSIONS

Because of the special test conditions the present results are not directly applicable to conventional internal-combustion engines. The results, however, do lead to two important conclusions:

1. The characteristics of the combustion of a liquid fuel are determined primarily by its history from the time of injection up to the instant of ignition. Apart from the mode of injection, the factors controlling the course of the combustion therefore, are: (1) the time interval between injection into the combustion chamber and the ignition, (2) the temperature and pressure of the air and fuel mixture during this interval. If the mixture of the fuel and air is heterogeneous, the shorter the time interval (above a certain minimum) the better the combustion. As the temperature of the air is increased this effect of time is decreased.

2. Volatility of the fuel affects the rate of combustion only at temperatures considerably below those experienced in the conventional compression-ignition engine. At the higher temperatures it is the chemical characteristics of the fuel that exert the most influence. The less stable the fuel chemically, the more it is influenced by changes in the engine-operating conditions.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *September 11, 1934.*

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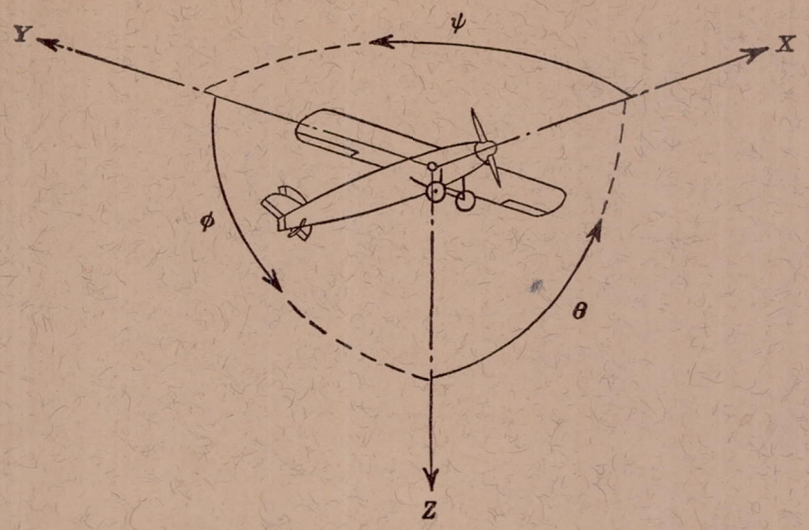

Positive directions of axes and angles (forces and moments) are shown by arrows

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

Absolute coefficients of moment

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

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

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

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

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

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

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

η, Efficiency

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

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

5. NUMERICAL RELATIONS

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

1 metric horsepower = 1.0132 hp.

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

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

1 lb. = 0.4536 kg

1 kg = 2.2046 lb.

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

1 m = 3.2808 ft.