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Spencer, R. C. Fuels and Lubricants (12) R 710
Analysis and Testing (8)
Fuels, Liquid - Testing (42680);
Preignition (73542)

Preignition characteristics of several fuels under simulated engine conditions

National Advisory Committee for Aeronautics, Washington, D. C.

U.S. Eng. Restr. 1941 21 photos, diagr, graphs

The preignition characteristics of a number of fuels were studied under conditions similar to those encountered in an engine. The conditions were simulated by suddenly compressing a fuel-air mixture in contact with an electrically-heated hot spot in the cylinder head of a combustion apparatus. Schlieren photographs and indicator cards were taken of the burning, and the hot-spot temperatures necessary to cause ignition under various conditions were determined. The maximum permissible specific outputs with the various preignition fuels could hot be correlated with their ignition temperature.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 710

PREIGNITION CHARACTERISTICS OF SEVERAL FUELS UNDER SIMULATED ENGINE CONDITIONS

By R. C. SPENCER

CLASSIFIED DOCUMENT

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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	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

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

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

V True air speed

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

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

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

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

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

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

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

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

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

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

γ Flight-path angle

2626°

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By R. C. SPENCER
Langley Memorial Aeronautical Laboratory

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By R. C. Spencer

SUMMARY

The preignition characteristics of a number of fuels have been studied under conditions similar to those encountered in an engine. These conditions were simulated by suddenly compressing a fuel-air mixture in contact with an electrically heated hot spot in the cylinder head of the NACA combustion apparatus. Schlieren photographs and indicator cards were taken of the burning, and the hot-spot temperatures necessary to cause ignition under various conditions were determined.

It is pointed out that preignition and knock are separate and distinct phenomena although they frequently occur in conjunction. The flame originated by preignition has the same characteristics as the flame originated by a spark plug, the only difference being the time and the location of ignition. Preignition may result in knock by advancing the time of ignition.

The maximum permissible specific outputs with the various preigniting fuels could not be correlated with their ignition temperature; but it is believed that some combination of ignition temperatures, heat of combustion, and specific heats of the combustion products of the fuel may furnish a means of predicting the maximum permissible performance.

Depreciation of preigniting fuels with an increase in engine speed can be explained by the increase in the temperatures of thermally isolated portions of the combustion chamber, particularly the spark plugs, with an increased output of the engine. Although the ignition temperature increases with the engine speed, the increase is less than the increase of the temperature of such hot spots owing to an increased output.

It was found in the course of the work that, with this apparatus, cutting out one of two diametrically opposed spark plugs did not increase the tendency to knock but, on the contrary, reduced the knocking tendency; the effect was similar to that obtained by retarding the spark.

INTRODUCTION

Two distinct types of fuel failure have been recognized for many years: preignition and fuel knock or detonation. Either of these phenomena, occurring in a high-output aircraft engine, may cause engine failure.

According to Ricardo (reference 1), Hopkinson suspected the difference between preignition and knock as early as 1904. Hopkinson and Ricardo fitted a long steel bolt into an engine cylinder and then, using an indicator, watched the gradual transition from normal to premature ignition as the bolt heated up. They found that genuine preignition was accompanied by a dull thud and that the engine stalled after a short period of running because the burning occurred early on the compression stroke. There was no trace of the ringing noise characteristic of fuel knock.

Sparrow in 1925 gave a very complete discussion of the differences between knock and preignition. His opinions as published in reference 2 agree well with present-day knowledge of the subject.

Fuel knock consists in a sudden and extremely violent completion of the combustion in an engine cylinder after part of the burning has taken place at a normal rate. High local pressures and temperatures result and violent shock waves are set up in the combustion gases, causing a characteristic high-pitched ping or ringing noise in the engine. The high local temperatures and pressures may, by themselves, cause engine failure or the local overheating may lead to preignition and subsequent failure.

Preignition is exactly what the name implies—ignition of the charge before the instant at which the charge is intended to be ignited by the spark. On many occasions, preignition cannot be detected because it occurs only slightly before the spark passes, so that the advance in the time of peak pressure is not great enough to be appreciable. At times, the condition causing preignition (overheated spot in the combustion chamber, overheated exhaust valve or spark plug, etc.) may be rapidly aggravated, each successive explosion occurring earlier in the cycle, until the engine may fail because of overheating or it may stall or break because of the pressures occurring on the compression stroke. Instances have been reported in which preignition has set in and engine failure has resulted before the operator had time to stop the engine. Preignition has all the effects of an advanced ignition spark.

With paraffinic fuels such as are now used in this country, knock and preignition frequently occur in conjunction. When knock occurs, the accompanying high local temperatures and pressures and the more rapid radiation of heat cause overheating of parts of the combustion chamber, which may lead to preignition. The situation is thus intensified because the earlier ignition causes the engine to knock harder. If the situation is reversed, with preignition occurring first, the earlier ignition may cause knock in the same manner as advancing the spark and the knock will cause still earlier ignition; the final result will then be the same as before.

Rothrock and Biermann (reference 3) have shown that, in any particular engine, the density and the temperature of the last part of the charge to burn are the primary factors affecting the knocking tendency. The data of reference 3 also show that preignition must be treated separately from knock if the fuels are to be satisfactorily rated in the engine. In the case of knock, the maximum permissible performance increases with speed for a constant spark advance; whereas, with preignition, the indication is that the maximum permissible performance decreases with engine speed.

All engine fuels can preignite. Among the high-output fuels that are available at the present time, certain fuels have very great resistance to knock but, when the engine conditions are conducive to overheating, these fuels preignite. Such fuels may, for convenience, be called preigniting fuels. If fuels of the preigniting type are to be used in modern aircraft engines, the establishment of some relationship similar to that developed in reference 3 for knocking fuels would be desirable for rating the fuels in terms of maximum premissible performance in engines. In any case, their behavior must be studied in detail in order that engine conditions may be so controlled as to utilize them to their best advantage.

Typical examples of fuels of the preigniting type are di-isobutylene, benzene, toluene, and methanol. In reference 4, Heron and Gillig report engine tests in which the ratio of the maximum power outputs of these fuels to that of iso-octane is given. At low speeds and low engine-jacket temperatures, the permissible power output of these fuels was considerably higher than that of iso-octane. In each case when the engine speed or the engine-jacket temperature was increased, however, the ratio of the permissible power output of the test fuel to that of iso-octane was reduced and, in some cases, the positions of the test fuel and of iso-octane were reversed, with iso-octane becoming the better fuel. In each of the tests of di-isobutylene, benzene, toluene, and methanol reported in reference 4, the type of fuel failure was either preignition or afterfiring. Afterfiring is defined as firing after the ignition has been cut off.

Serruys (reference 5) has reported the results of a study of the variables affecting preignition. In order to extend the knowledge of this subject, the NACA has recently conducted a series of tests on the relative ignition temperatures of fuel-air mixtures of a number of fuels when compressed in contact with a heated surface in an engine. The ignition temperature was considered to be the temperature of the heated surface. The results of the investigation are given in this report.

COMBUSTION APPARATUS

Most of the tests described herein were carried out with the NACA combustion apparatus in conjunction with the NACA optical-type pressure indicator, the NACA spark-photography apparatus, and three different electrically heated hot spots.

The combustion apparatus has been described in reference 6. It consists essentially of a 5- by 7-inch single-cylinder test engine with a large glass window in the cylinder head to permit the combustion to be studied photographically. The engine is driven at the test speed by an electric motor and is then fired once by injecting and igniting a single charge of fuel. The fuel is injected during the intake stroke. The engine temperature is maintained by circulating heated glycerin through the coolant passages. A diagrammatic sketch of the apparatus is shown in figure 1. The cylinder head is of the pent-roof type normally having two exhaust and two intake valves. In the present design, the space ordinarily occupied by the two exhaust valves is used for the glass window. As the engine fires only once, the two intake valves, which operate simultaneously, serve for both intake and exhaust. The cycle is as follows: The valves are already open for intake, then open again for exhaust, and remain open for the next intake. The engine being run without oil, the results cannot be affected by oil in the mixture.

AUXILIARY EQUIPMENT AND FUELS

The pressure indicator is described in reference 7. It was mounted in a steel blank, which was installed in the window opening in place of the glass window.

The spark-photography apparatus (reference 8) consists of a battery of high-voltage condensers and a rotary distributor so arranged that the condensers are discharged consecutively, furnishing a series of spark discharges. For these tests, the apparatus was used in conjunction with a schlieren optical arrangement (reference 9) by which slight differences in index of refraction can be made visible or can be photographed. The spark arrangement used gave 13 sparks at a rate of about 1,000 per second.

A detailed description of the schlieren optical set-up and of the method of interpreting the photographs is given in reference 6.

The three hot spots were electrically heated but differed considerably in design. The first, designed to furnish a hot surface flush with the surface of the combustion chamber, consisted of a diaphragm across the end of a fitting screwed into a spark-plug hole. A connector attached to the center of the diaphragm served as the electrical lead-in, and the circuit was completed through the metal of the cylinder head. Accurate determinations of the hot-spot temperature were difficult with this arrangement because the thermocouple could not be placed at the hottest point of the diaphragm. Difficulty was also experienced with burning-out of the diaphragm. All the spark photographs and the indicator cards shown in this report were made with the hot diaphragm. After several tests had been made, a glow plug such as is

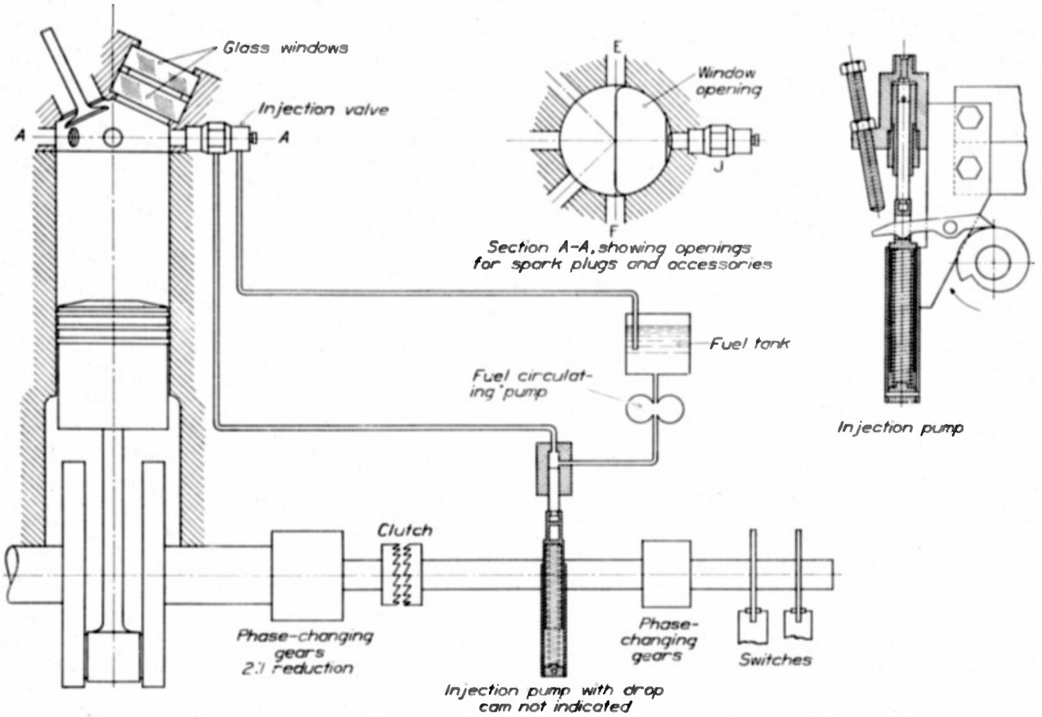


FIGURE 1.—Diagram of combustion apparatus.

sometimes used as a cold-starting aid for compression-ignition engines was installed. The thermocouple was welded near the midpoint of the heating coil of the glow plug.

In order to provide a more accurate check of the ignition temperatures of the fuels, a third hot spot was constructed, consisting of a length of nichrome wire about 1/16 inch in diameter and about 1½ inches long, supported from a fitting in the center of the opening for the optical indicator. The thermocouple was attached to the center of the wire. Temperatures were determined by a chromel-alumel thermocouple and a sensitive millivoltmeter.

It is known that the area of the hot spot affects the ignition temperature of a fuel-air mixture. Some attempt was therefore made in the construction of the third hot spot to use a wire size and length comparable with that used in the glow plug. The work of Paterson (reference 10) showed that the ease of ignition of coal gas-air mixtures increased with the size of the hot igniting source. Lewis and von Elbe (reference 11) point out that temperatures required for local ignition by a heated point or wire are often greatly in excess of those required for ignition by a heated surface.

When a spark plug was used, it was located at E (fig. 1). The hot spots fitting into the spark-plug opening were located at F; the single-wire hot spot was located in the center of the window opening.

Fuel injection was started at 20° A. T. C. on the intake stroke.

Ten different fuels were used in the investigation:

C. F. R. S-1 reference fuel (97 percent 2, 2, 4-trimethyl pentane by volume. A. S. T. M. octane number, 99.3; Army octane number, 99.7)
Di-isobutylene
Benzene
Toluene
Isopropyl alcohol
Methanol

Di-isopropyl ether blend (60 percent Stanavo aviation gasoline, 40 percent di-isopropyl ether by volume; plus 3.0 ml tetraethyl lead per gal)

Toluene blend (56 percent toluene, 21 percent low vapor pressure natural aviation gasoline, 23 percent isopentane by volume; plus 3.0 ml tetraethyl lead per gal. A. S. T. M. octane number, 96.76, average of 10 laboratories)

Two experimental 87-octane gasolines

In addition, blends of C. F. R. S–1 and M–1 reference fuels and blends of these fuels with tetraethyl lead were made up and tested. (M–1 fuel has an A. S. T. M. octane number of 19.)

The engine conditions were as follows:

Compression ratios	7.0 and 9.5
Engine-coolant temperatures, measured at outlet	150° F, 250° F, 310° F (one test), and 325° F
Engine speeds	500 and 1,000 rpm

Fuel-air ratios were varied from 0.04 to 0.13 for most of the fuels and from 0.06 to 0.20 for methanol. The air quantity was estimated on the assumption that, at the time the valves closed, the air temperature in the cylinder had reached a value midway between the inlet-air temperature and the engine-coolant temperature. The air pressure in the cylinder when the valves closed was atmospheric (reference 12). Fuel quantity was determined by catching single injections in a vial filled with cotton and weighing the vial on a chemical balance.

METHODS OF OBTAINING DATA

Three different types of data were taken: schlieren photographs, indicator cards, and ignition temperatures of the different fuels at various fuel-air ratios.

The general procedure in making a test was as follows: The engine was brought to speed by the electric motor, the current of the heating element was turned on, and the engine was kept motoring at constant speed. When the millivoltmeter showed that the temperature of the hot spot had reached equilibrium at the desired value, a trip lever was pulled, injecting the single charge of fuel into the engine. The hot-spot temperature was systematically varied until a temperature was reached at which the charge would just ignite.

Ten or more tests were made at each condition when the minimum ignition temperature was being determined, and from 3 to 10 records were taken at each condition when indicator cards or schlieren photographs were being taken.

During most of the work, the inlet valves of the engine were shrouded in such a manner that the intake air was directed in a circular path around the axis of the cylinder. Air movement of this type has been shown to be conducive to very regular operation of the engine, successive cycles reproducing each other very closely (reference 12).

CORRECTION OF DATA

The recorded ignition temperature depends greatly upon the attitude of the hot wire or coil with respect to the direction of the air movement in the cylinder and upon the location of the thermocouple on the heated portion. Unless the thermocouple was located at the hottest section of the wire, the recorded temperature was too low. Inasmuch as the moving air in the cylinder had a large cooling effect, any change in the way in which the hot wire or coil was turned was very likely to change the location of the hottest section. This effect is shown in figure 2. The recorded

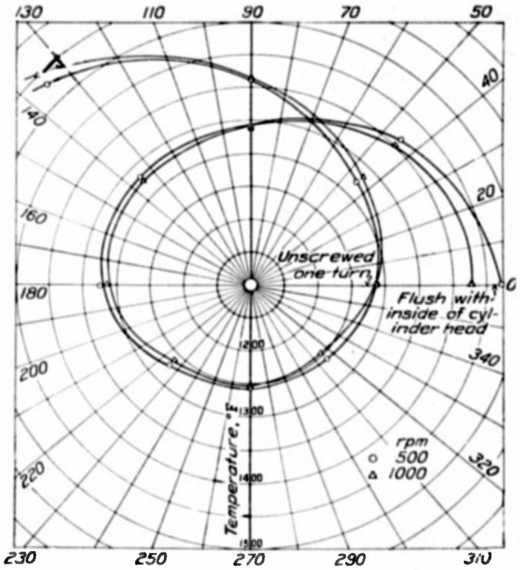


FIGURE 2.—Ignition points of benzene for different heated-coil positions. Compression ratio, 7.0; engine-coolant temperature, 250° F; thread pitch of fitting, 1.5 millimeters.

ignition temperatures for benzene are plotted on polar coordinates for a number of different angular settings of the glow-plug hot spot. The coil of the glow plug was first placed just flush with the inside of the cylinder head and then unscrewed in 45° intervals; readings were taken at each 45° interval. Inspection of figure 2 shows that great care must be taken to avoid being misled by some freak setting of the hot spot. For instance, the choice of suitable settings lead to the conclusions that: The ignition temperature decreased with increase of speed, it increased with increase of speed, and speed had no effect. After a great deal of experimentation, the hot spot was so installed as to be fully exposed to the air stream instead of being subject to eddy currents. Results obtained at this position are believed to be reliable.

Burning out of the hot wire or breakage of the thermocouple occasionally made a new installation necessary. Each new installation caused some change in the recorded ignition points of the fuels; the ignition point of the S-1 fuel was therefore always determined after a new installation. When a table was made for comparison of the ignition points of all the fuels, the values were so adjusted as to be comparable with the highest value recorded for the S-1 fuel. For example, the value actually determined for di-isobutylene at 500 rpm was 1,250° F. The value for the S-1 fuel with the same hot-spot installation was 1,355° F, a difference of 105° F. The highest recorded value for S-1 fuel was 1,555° F; the di-isobutylene was therefore assigned an adjusted ignition temperature of 1,450° F. No corrections were applied to the various curves of ignition temperature against fuel-air ratio. The data in any one figure are therefore comparable among themselves but are not necessarily comparable with the data in other figures.

TESTS WITH C. F. R. ENGINE

A few tests were conducted on a C. F. R. engine for the purpose of checking the trends found with the combustion apparatus. This engine differs from the standard fuel-testing unit in that it has a high-speed crankcase, a conventional automotive-type down-draft carburetor instead of the three-bowl fuel-testing carburetor, a conventional throttle control instead of a throttling orifice, and a special cylinder head having four 18-millimeter spark-plug openings instead of two. The locations of the spark-plug openings are shown in figure 3. The engine was coupled to a 30-horsepower direct-current dynamometer.

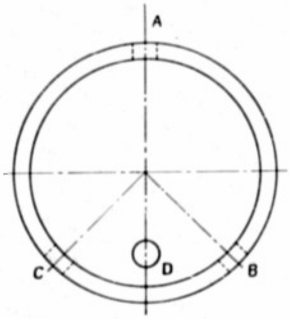


FIGURE 3.—Location of spark-plug holes in C. F. R. engine.

The glow plug (heated coil) was used as the hot spot for the C. F. R. engine tests. It was installed in the engine in position B, with the spark plug in position A (fig. 3). In this position, the heated coil was not diametrically opposite the spark plug.

The engine tests were made as follows: The engine was run under load until conditions became constant; the current to the hot spot was then turned on, and its temperature was gradually increased until the engine continued firing when the ignition switch was momentarily opened. Pressures in the engine were indicated by a piezo-electric indicator using a cathode-ray oscillograph. With this instrument, any pronounced advance in the time of ignition caused by the hot spot was easily detected by the change in the shape of the indicator card.

Engine test conditions were as follows:

Compression ratio	7.0
Engine-coolant temperature	212° F
Engine speeds	1,000 and 2,000 rpm
Spark advance	35°

Fuels used were C. F. R. S-1 reference fuel, toluene, benzene, isopropyl alcohol, and di-isopropyl ether.

RESULTS AND DISCUSSION

NATURE AND EFFECTS OF PREIGNITION

A fuel may tend to preignite and still have great resistance to knock. This fact is shown in figure 4, which presents indicator cards taken with the combustion apparatus for S-1 fuel, benzene, and methanol for engine conditions severe enough to cause the S-1 fuel to knock. Neither the benzene nor the methanol knocked; furthermore, it is known to be extremely difficult to force either benzene or methanol into actual recognizable fuel knock although thudding and rough running will occur. On the other hand, benzene and methanol are both known as preigniting fuels, but S-1 fuel is not.

Although preignition is recognized to be ignition by a hot spot in the engine before the intended time for ignition of the charge by the spark, the character of the flame and the manner in which the combustion takes place have been largely a matter of speculation. The photographs in figure 5 show that the flame started by a small hot spot is similar to the flame originated by the spark plug itself. The upper strip of photographs shows the burning when ignition was caused only by the spark plug. Burning started at the top of the photograph, being first visible as the dark region at the top of the fifth frame from the left. The flame traversed the chamber and burning was completed shortly after top center. The second strip of photographs shows the burning when ignition caused by the hot spot occurred after the ignition by the spark. The burning started by the spark plug appeared at the top as before and partly traversed the chamber. As the flame front approached the hot spot at the opposite side of the chamber, ignition took place from the hot spot, and the flame from the hot spot merged with the flame from the spark plug (ninth frame).

The lowest strip of photographs in figure 5 shows the burning when the hot spot was sufficiently heated to ignite the charge before the spark occurred. In this case, the flame started from the hot spot at the bottom of the photographs and had almost traversed the chamber before the flame from the spark plug became visible in the sixth frame from the left. The effect of preignition of this character would depend on the characteristics of the fuel being used. With toluene, as in this case, knock would not occur but the engine would lose power and failure might occur from overheating or the engine might stall. If a knocking fuel were used, the excessive ignition advance might cause fuel knock because of the higher peak pressure and temperature and the consequent overheating would further aggravate the preignition. Large numbers of photographs were taken of the preignition of various fuels, and all of them indicate that the flame originated by preignition has the same characteristics as the flame originated by a spark plug. The only difference is in the time and the location of the ignition.

The indicator cards of figure 6 show the effect of preignition and of a second spark plug in changing the point at which peak pressure occurs. In record 389 the engine was running near the limit for the fuel, with very light knock. Record 390 shows that, when two spark plugs were used on opposite sides of the chamber without changing the ignition timing, peak pressure occurred earlier in the cycle and nearer top center and the knock intensity was increased. For record 392, the hot spot was used in place of one spark plug. The temperature of the hot spot was so adjusted that ignition occurred at about the time the spark passed at the spark plug. The effect of the hot spot was therefore the same as that of the second spark plug in record 390; the peak pressure occurred nearer top center and was higher than with one plug, and knock occurred as before. Record 394 shows the pressure conditions when the hot spot was hot enough to cause very early ignition. Most of the charge burned early on the compression stroke. Such early ignition causes the engine to expend considerable energy in compressing the already burned gases and would result in a serious loss of power, engine stoppage, or failure.

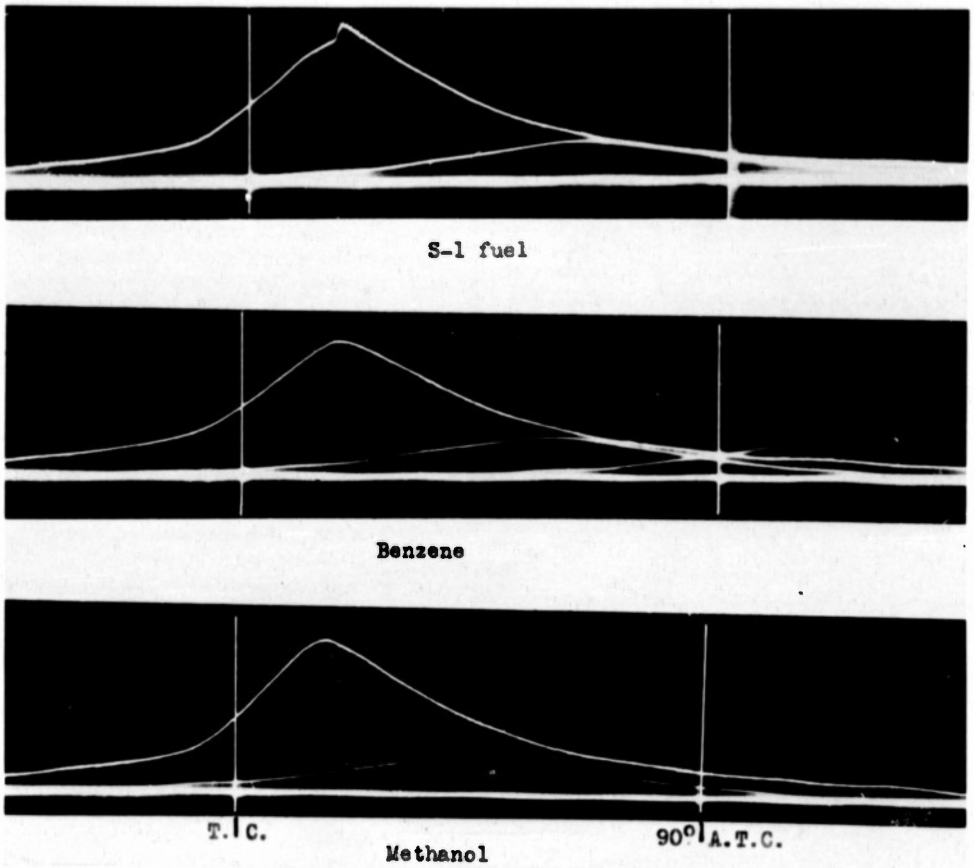


FIGURE 4.—Indicator cards for three fuels. Compression ratio, 7.0; engine-coolant temperature, 310° F; engine speed, 500 rpm; spark advance, 30°; one spark plug. Mixture ratio for complete combustion.

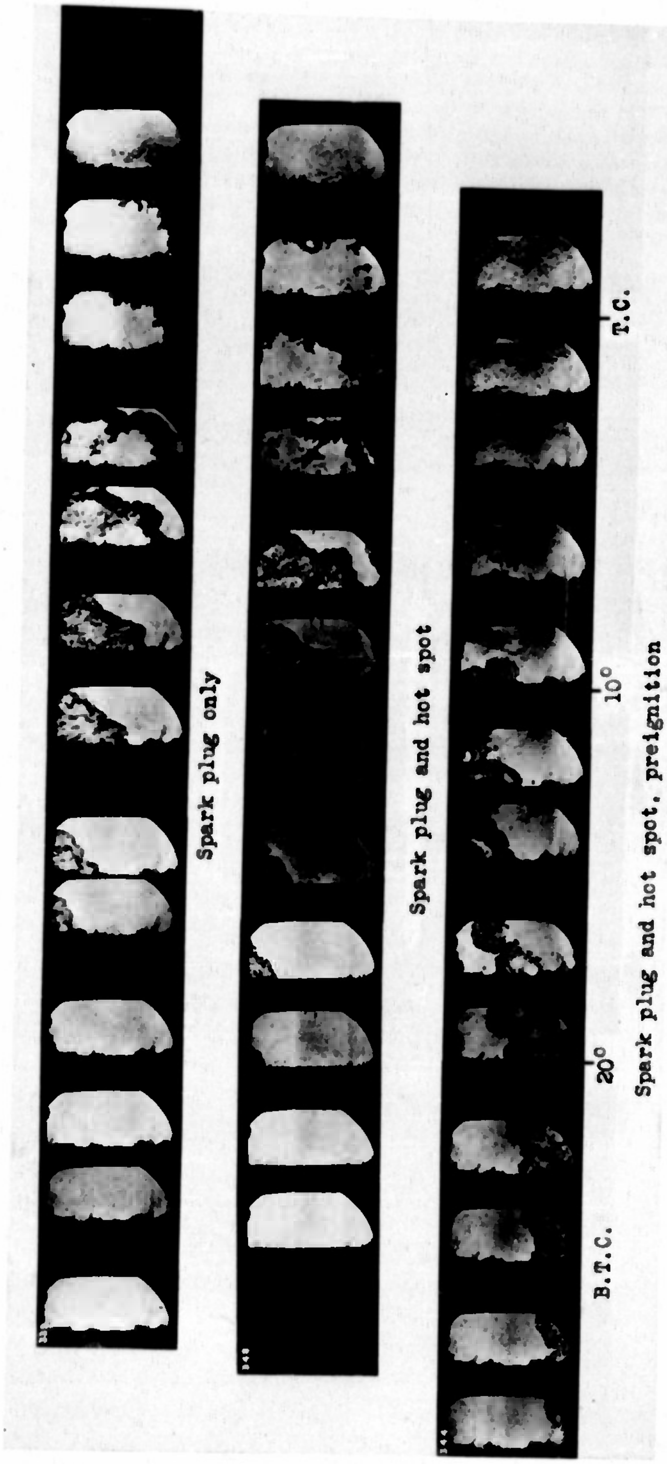


FIGURE 5.—Spark schlieren photographs of burning started by spark plug and by hot spot. Spark plug at top; compression ratio, 7.0; engine-coolant temperature, 250° F; engine speed, 500 rpm; fuel, toluene.

The data of figure 6 clearly show the way in which preignition can cause knock by advancing the point at which peak pressure occurs. Comparison of records 389 and 390 also indicates that the cutting out of one spark plug, when an engine is running on two plugs, may not increase the tendency to knock but, on the contrary, may decrease it. The reason in this case is obvious: The use of only one spark plug instead of two had the same effect as retarding the ignition timing. This result is at variance with the opinion of engine operators in general, and it is very desirable that precise engine data should be available to clarify the point. Unpublished data taken at this laboratory, on two different liquid-cooled cylinders, have not furnished conclusive information. It appears probable that the effect varies depending on engine conditions. It might be thought that, in an actual engine, the spark plug which is cut out overheats and causes preignition.

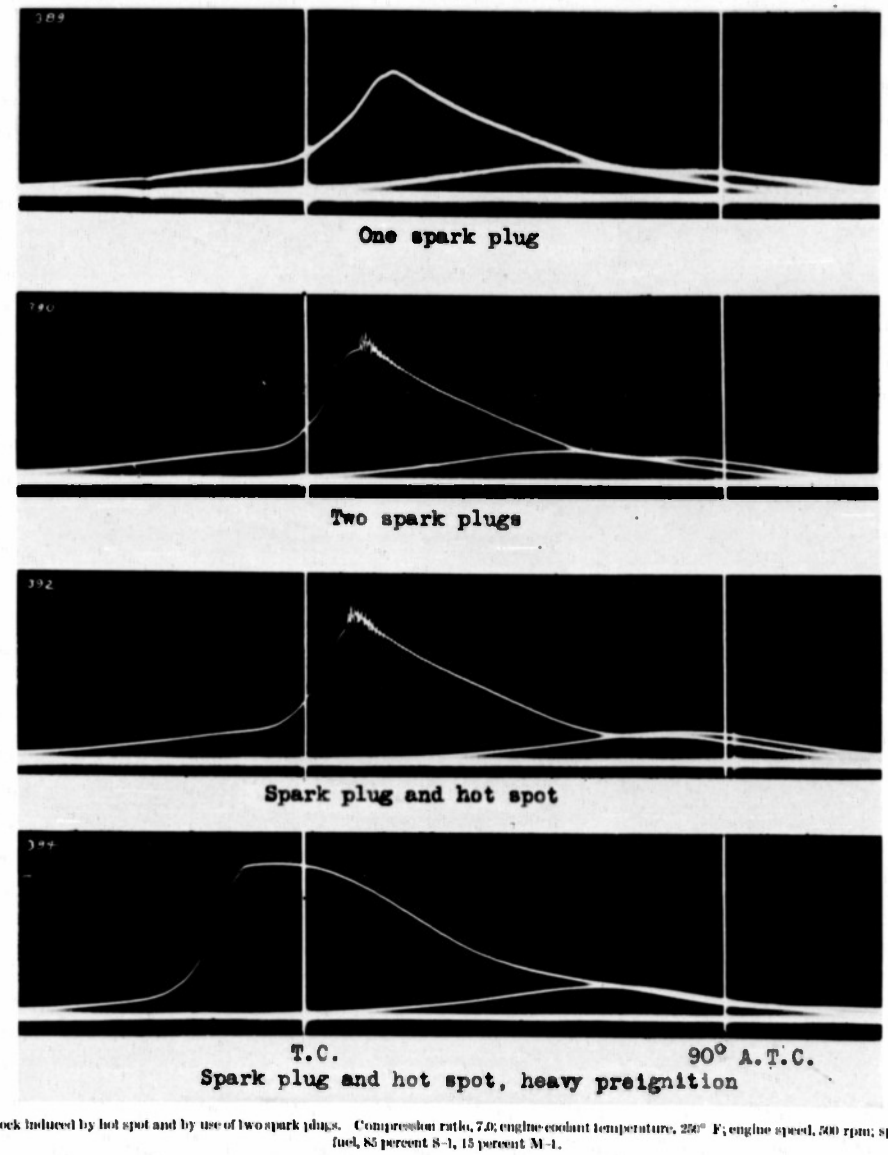


FIGURE 6.—Knock induced by hot spot and by use of two spark plugs. Compression ratio, 7.0; engine-coolant temperature, 250° F; engine speed, 500 rpm; spark advance, 10°; fuel, 85 percent S-1, 15 percent M-1.

Rothrock and Biermann have reported, however, that, when one spark plug was cut out on a single-cylinder test engine, its electrode temperature immediately decreased. (See reference 13.)

The indicator cards of figure 7, taken at an engine speed of 1,000 rpm, show the effects of advancing the spark, of using two spark plugs, and of moderate preignition. Record 426 shows the pressures for a spark advance of 25° when one spark plug was used. Knock did not occur. When the spark was advanced to 30°, as in record 416, knock occurred. When two spark plugs were used and the spark was set at 25°, the engine knocked as shown by record 423. The use of two spark plugs had the same effect as advancing the spark. With the hot spot just hot enough to ignite the mixture at about the same time that the spark occurred, thus acting as a second source of ignition and advancing the time at which peak pressure occurred, knock occurred again as shown by record 428.

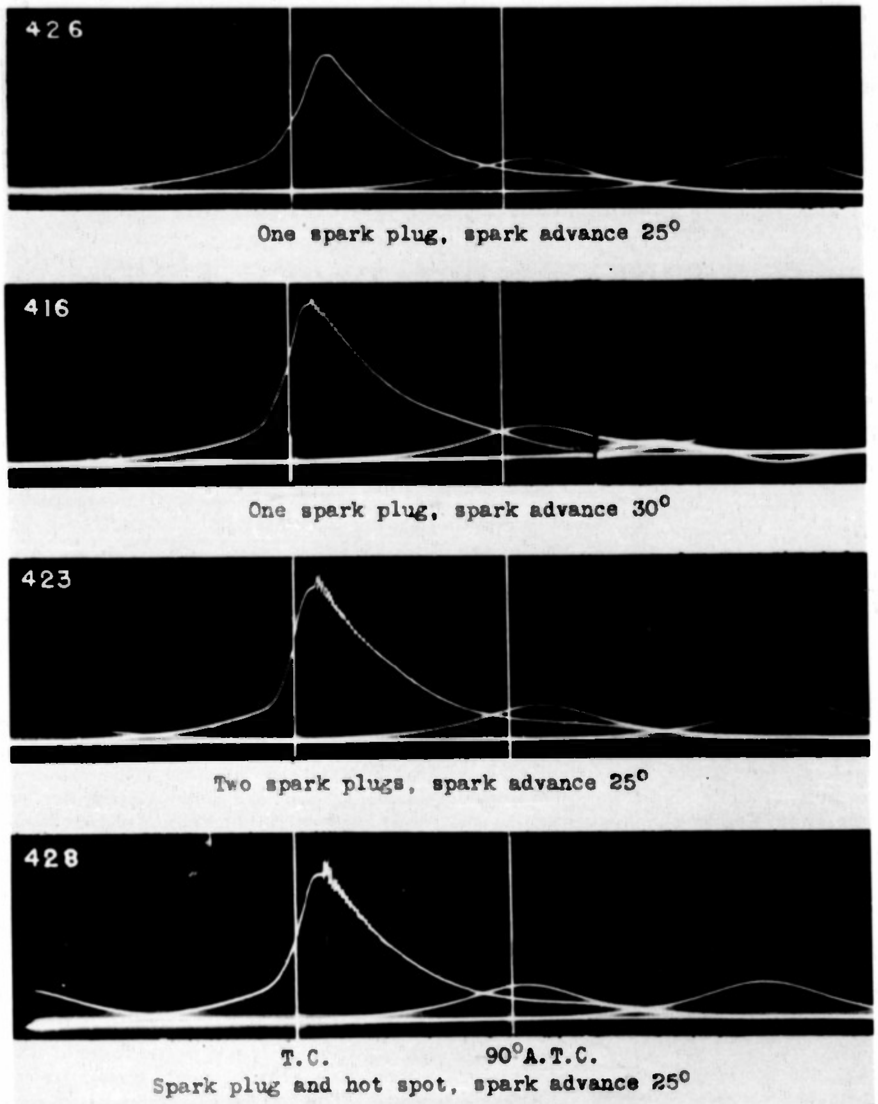
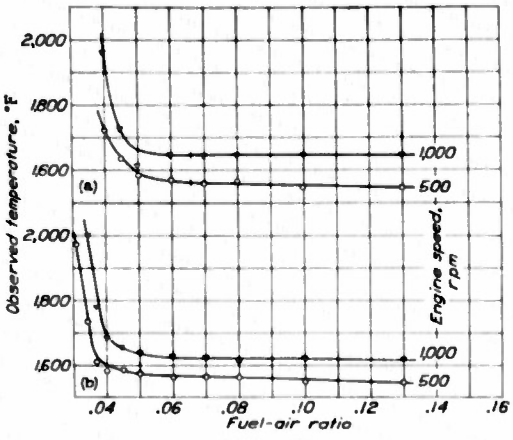


FIGURE 7.—Knock induced by hot spot, by use of two spark plugs, or by advancing the spark. Compression ratio, 7.6; engine-coolant temperature, 250° F; engine speed, 1,000 rpm; fuel, 85 percent S-1, 15 percent M-1.

FACTORS AFFECTING PREIGNITION

In reference 5, Serruys shows the effects of engine speed, intake-air pressure and temperature, fuel-air ratio, compression ratio, and turbulence of the charge on preignition. The duration of contact of the mixture with the hot spot, the fuel-air ratio, and the density and the temperature of the charge in the engine are the fundamental factors covered by these variables. The engine speed and the turbulence of the charge affect the duration of contact of the mixture with the hot spot. The intake-air pressure and temperature, the engine-coolant temperature, and the compression ratio affect the density and the temperature of the charge in the engine. In addition, the engine speed, the compression ratio, the fuel-air ratio, and the intake-air density affect the total power output of the engine and hence affect the temperature of the inner combustion-chamber wall. The temperature of the combustion-chamber wall will, in turn, affect the tendency toward preignition.



(a) S-1 fuel.
(b) Benzene.

FIGURE 8.—Effect of speed on ignition temperature. Compression ratio, 7.0; engine-coolant temperature, 250° F; ignition by hot wire.

Effect of engine speed.—The duration of contact of the mixture with the hot spot decreases as the speed is increased; the velocity of air flow is also increased so that, if any tendency for swirl exists, the mixture will be carried past the hot spot faster and the duration of contact will be further shortened as the speed is increased. The auto-ignition of fuels is generally recognized to be a function of both time and temperature. If the duration of contact is short, the temperature of the igniting surface must be higher than it would be if the contact were of longer duration. Quantitative measurements of this effect have been made by Paterson (reference 10), who ignited mixtures of coal gas and air by hot, rapidly moving pellets. On the basis of this knowledge, one would expect the ignition temperature to increase with the engine speed. That the ignition temperature increases with the engine speed was shown in reference 5. It is also shown by the present results plotted in figure 8.

Care should be used in applying the results for the effects of engine speed because, as the speed of a running engine increases and the total output accordingly increases, the temperatures of poorly cooled areas of the inner surface will increase on account of the greater heat flow and the consequent higher temperature gradient even though the coolant temperature is maintained constant. Although the hot-spot temperature necessary to cause ignition increases with engine speed, the increase is smaller than the increase of inner-wall temperature because of increased output. This effect may explain the fact that preigniting fuels depreciate with increase of engine speed.

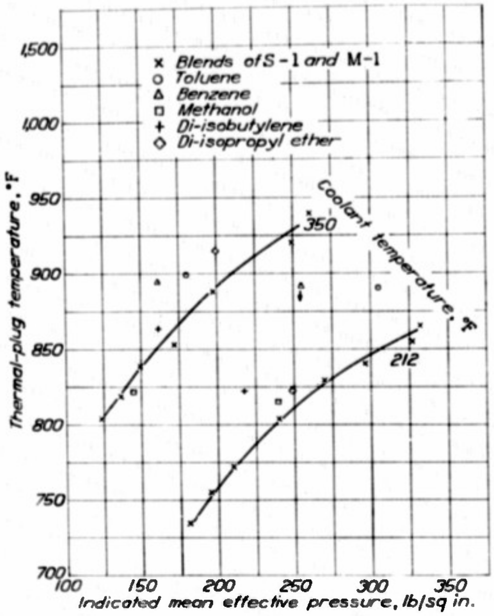
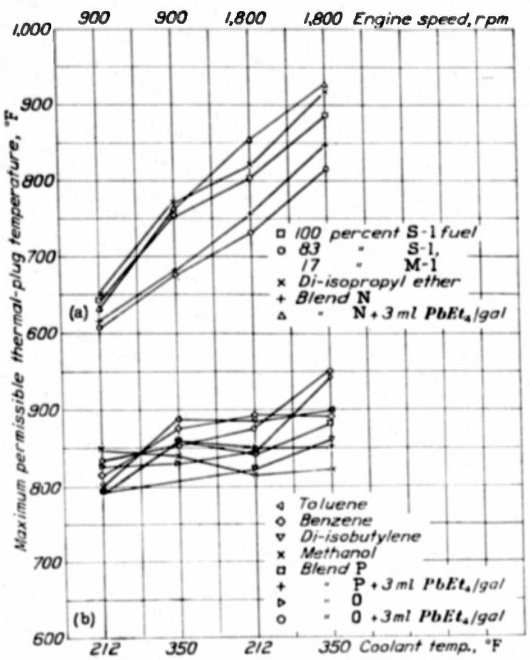


FIGURE 9.—Effect of indicated mean effective pressure on thermal-plug temperature. Engine speed, 1,800 rpm. Data from reference 4.

Figure 9, which is plotted from data given in reference 4, shows that the inner cylinder-head temperature does increase with increased power output. The data show the temperatures of a thermal plug in the cylinder head, recorded for the engine conditions at which the fuels failed. This thermal plug consisted of a metal disk mounted in a spark-plug hole. A thermocouple was mounted in the disk. The temperature of the thermal plug was not necessarily the temperature of the hottest surface inside the cylinder but was an indication of the trend of the temperatures of parts of the chamber that were not well cooled. The points for the blends of S-1 and M-1 fall along a smooth curve but those for the other fuels show considerable divergence from the curve. The scatter of these points shows that some fuels will cause considerably higher cylinder-wall temperatures than others do for the same indicated mean effective pressure. This fact will be discussed later.

Effect of engine temperature.—The difference in the way in which fuels of the preigniting type respond to changes in the temperature of the inner surface of the combustion chamber, as compared with fuels of the knocking type, is shown in figure 10, plotted from data in reference 4. In figure 10 (a) are plotted the thermal-



(a) Knocking fuels.
(b) Preigniting and afterfiring fuels.

FIGURE 10.—Effect of engine operating conditions on maximum permissible thermal-plug temperature. Data from reference 4.

plug temperatures at which the knocking fuels failed at engine speeds of 900 and 1,800 rpm and at coolant temperatures of 212° and 350° F. In figure 10 (b), the thermal-plug temperatures at which fuels of the preigniting type failed are plotted. Inspection of figure 10 (b) shows that the preigniting fuels failed at about the same thermal-plug temperature regardless of the engine condition. When the hottest part of the chamber reached the ignition point of the fuel, preignition set in. Thus, the power output of the engine was limited by the amount of heat flow that could be accommodated by the cylinder head and by the cooling system of the engine. The knocking fuels, being limited by the temperature and the density of the mixture, were less sensitive to the cylinder-wall temperature and, as shown by figure 10 (a), the thermal-plug temperatures increased as the engine conditions became more severe.

In figure 11 are shown the ignition temperatures of the toluene blend and S-1 fuel at different engine-coolant temperatures and for two engine speeds. The coolant temperature had but little effect on the surface temperature necessary for ignition. This effect is not to be confused with the effect of increased coolant temperature in an actual engine where, if the engine runs hotter, there will be an increase in the temperature of any

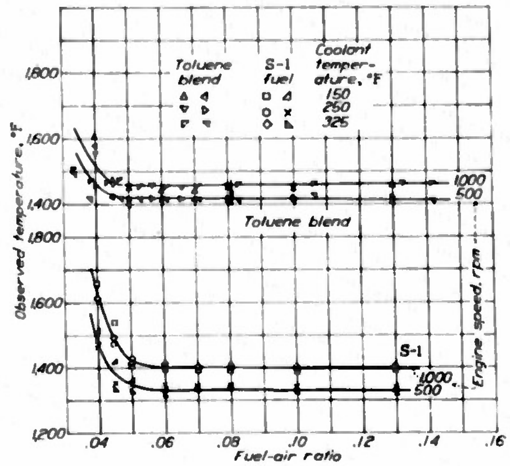
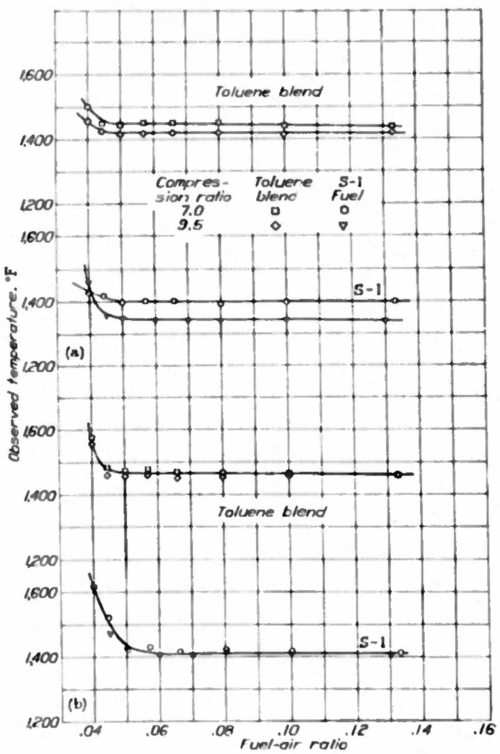


FIGURE 11.—Effect of engine-coolant temperature on ignition of toluene blend and S-1 fuel. Compression ratio, 9.5; ignition by heated coil.



(a) Engine speed, 500 rpm.
(b) Engine speed, 1,000 rpm.

FIGURE 12.—Effect of compression ratio on ignition of toluene blend and S-1 fuel. Engine-coolant temperature, 250° F; ignition by heated coil.

hot spots in the combustion chamber and a corresponding increase in the tendency toward preignition.

Effect of compression ratio.—The data in figure 12 show the effects of changing the compression ratio upon the hot-spot temperature required for ignition of the toluene blend and S-1 fuel. Figure 12 (a), for an engine speed of 500 rpm, shows a decrease of about 60° F for S-1 fuel and of 25° or 30° F for the toluene blend when the compression ratio was changed from 7.0 to 9.5. At an engine speed of 1,000 rpm, the effect

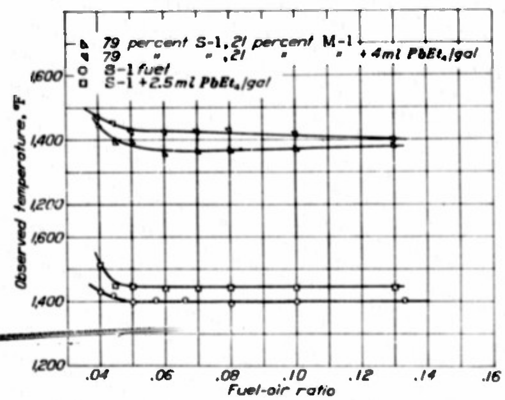


FIGURE 13.—Ignition of two fuels with and without addition of tetraethyl lead. Compression ratio, 7.0; engine-coolant temperature, 250° F; engine speed, 500 rpm; ignition by heated coil.

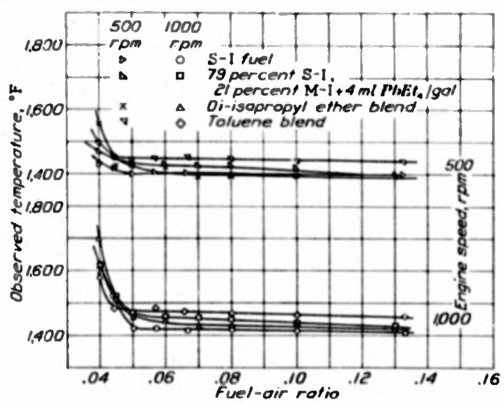


FIGURE 14.—Ignition of four 100-octane fuels. Compression ratio, 7.0; engine-coolant temperature, 250° F; ignition by heated coil.

was very slight, as shown by figure 12 (b). The reason for the difference in results with increase in speed is not known.

In reference 5, the data show a decrease of about 80° F when the compression ratio was changed from 4.5 to 6.5 at an engine speed of 1,250 rpm. In general, a decrease in ignition temperature is evident with an increase in compression ratio.

Effect of antiknock rating and of tetraethyl lead.—Some correlation apparently exists between the antiknock values of paraffinic fuels, both clear and leaded, and their ignition points, either as determined in the combustion apparatus or as determined in an apparatus like the Moore type. Typical values of ignition temperatures for various fuels are shown in reference 14; reference 5 also gives a comparison of the ignition points of fuels of different antiknock value. In general, the ignition temperatures of the paraffinic fuels increase with an increase of the antiknock value, although some variation occurs. It is necessary, of course, in a comparison of ignition temperatures, that they be determined by the same method and preferably with the same apparatus and by the same operator.

On the basis of the increase in ignition temperature of the paraffinic fuels with an increase of antiknock value, the addition of tetraethyl lead to a paraffinic fuel would be expected to increase the ignition temperature. This effect is seen in figure 13, which shows the effect of adding tetraethyl lead to S-1 fuel and to a mixture of S-1 and M-1 fuels.

When the tested fuels are not limited to the paraffins, there is as yet no correlation between the ignition points and the antiknock value. Even paraffinic fuels that have been brought to the same antiknock value by the addition of tetraethyl lead may differ in ignition temperatures. This effect is shown in figure 14,

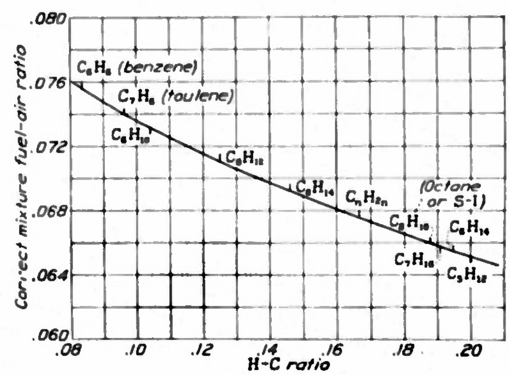


FIGURE 15.—Fuel-air ratios for complete combustion of several hydrocarbons.

where the ignition points of four 100-octane fuels are plotted. All four fuels show somewhat different ignition temperatures, although the S-1 fuel and the mixture of S-1 and M-1 fuels are both paraffinic in type. The addition of lead to the mixture raised its antiknock value to that of the S-1 fuel but raised its ignition temperature above the value for S-1 fuel.

Effect of fuel-air ratio.—The chemically correct fuel-air ratios for complete combustion of several typical hydrocarbons are shown in figure 15. Ignition temperature is plotted against fuel-air ratio in figure 8 and figures 11 to 14. All these figures show the same general trend, with very little effect of fuel-air ratio until a mixture ratio is reached somewhat leaner than the ratio for complete combustion. At these leaner mixtures, the ignition temperatures show a sharp upward trend. It might be expected that the ignition points would again be higher at the richer mixtures. In these tests, as the fuel-air ratio was increased, readings became increasingly erratic until ignitions could only occasionally be obtained. Increase of the hot-spot temperature did not, however, increase the consistency of ignitions. In the tests reported in reference 5, Serruys found that the minimum temperature for ignition occurred at a mixture strength somewhat on the rich side of the theoretical value and that the ignition temperatures increased fairly rapidly with

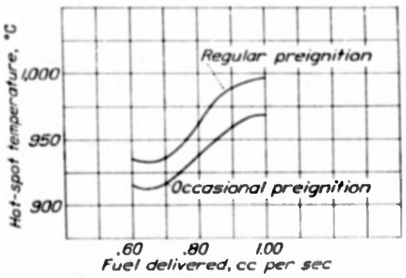


FIGURE 16.—Effect of mixture strength. Coolant-outlet temperature, 60° C; engine speed, 1,250 rpm. Data from reference 5.

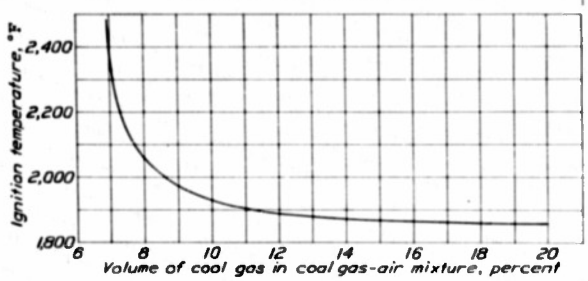


FIGURE 17.—Ignition of coal gas-air mixtures by hot moving pellet. Platinum pellet, 2 millimeters in diameter; velocity, 21 meters per second. Chemically correct mixture, 21 percent. Data from reference 10.

increasing richness of the mixture. The trend found in reference 5 is shown by figure 16.

Paterson's work in reference 10 was carried out almost exclusively with mixtures on the lean side of the chemically correct mixture (21 percent coal gas by volume). His data at richer mixtures were erratic but led him to believe that the ignition temperature was higher at the richer mixtures. A cross plot of his data from figure 4 of reference 10, showing ignition temperature against mixture percentage, is given as figure 17. The data do not extend beyond the 20-percent mixture, but the shape of the curve on the lean side conforms fairly well to the shape of the curves in the present report. The chief difference is in the point at which the curve begins to bend sharply upward. The curves in the present work turn upward shortly after reaching the lean side of the chemically correct mixture; whereas, the curve of figure 17 does not bend sharply until mixture ratios far on the lean side are reached. The curve for methanol, however, determined during the present work, extends considerably into the lean region before breaking upward, as shown by figure 18, which gives curves for toluene, benzene, S-1 fuel, and methanol. The chemically correct fuel-air ratio for complete combustion of methanol is about 0.155.

COMPARISON OF IGNITION TEMPERATURES OF DIFFERENT FUELS

The curves of ignition temperatures against fuel-air ratio for all the fuels tested show the same trends. The data for the complete list of fuels have therefore been selected at a fuel-air ratio slightly richer than the chemically correct ratio and are presented in tabular form. In table I the recorded ignition temperatures of the fuels have been adjusted so as to be comparable, as discussed in a previous section. Values not adjusted were already directly comparable.

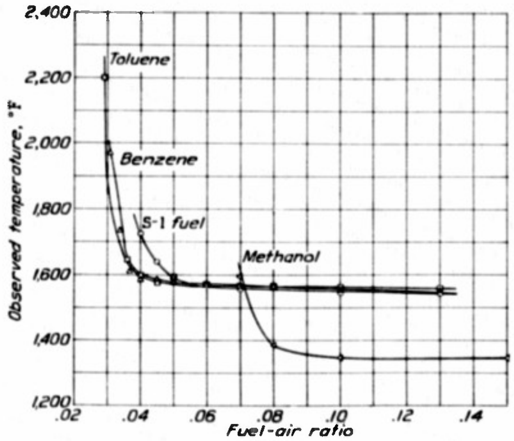


FIGURE 18.—Ignition of four fuels. Compression ratio, 7.0; engine-coolant temperature, 250° F; engine speed, 500 rpm; ignition by hot wire.

TABLE I—IGNITION TEMPERATURES OF FUELS

[Compression ratio, 7.0; engine-coolant temperature, 250° F; fuel-air ratio, 0.07 except as noted; ignition temperature in ° F]

Fuel	Engine speed, rpm	
	500	1,000
S-1+2.5 ml tetraethyl lead	[a] 1,600	[a] 1,700
Toluene blend	[a] 1,600	[a] 1,695
Isopropyl alcohol [b]	1,585	1,675
87-octane blend 1	[a] 1,575	[a] 1,650
87-octane blend 2	[a] 1,575	[a] 1,645
79-percent S-1, 21-percent M-1+4 ml tetraethyl lead	[a] 1,575	[a] 1,675
Toluene	1,560	1,615
Benzene	1,560	1,620
S-1 fuel	1,555	1,645
Di-isopropyl ether blend	[a] 1,550	[a] 1,660
79-percent S-1, 21-percent M-1	[a] 1,520	[a] 1,660
Di-isobutylene	[a] 1,450	[a] 1,555
50-percent S-1, 50-percent M-1	[a] 1,400	[a] 1,585
Methanol [c]	1,325	1,390

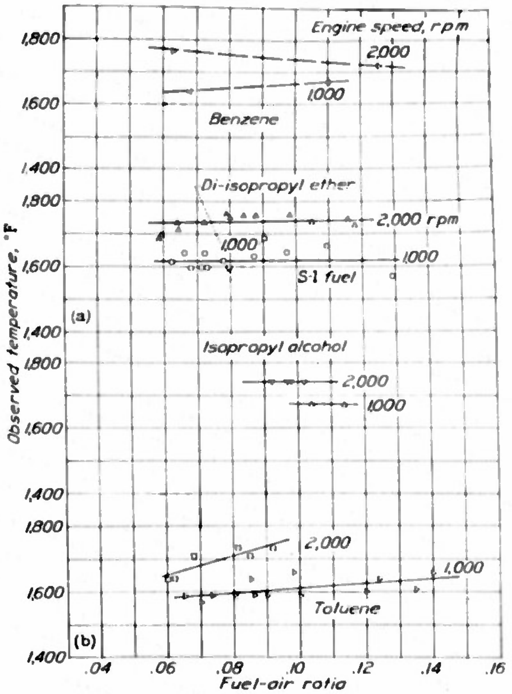
[a] Adjusted value. [b] Fuel-air ratio, 0.10. [c] Fuel-air ratio, 0.15.

The fuels are arranged in table I roughly in descending order of ignition temperatures. Differences of 25° F or less in the recorded temperatures are not considered particularly significant, but several facts are apparent from the data shown. The addition of tetraethyl lead to S-1 fuel and to a mixture of 79-percent S-1 and 21-percent M-1 fuels caused a definite increase in the ignition temperatures. (This effect is shown throughout the complete range of fuel-air ratios in fig. 13.) Under these conditions, the ignition temperatures of toluene and benzene were apparently about the same as that of S-1 fuel. The ignition temperature of the toluene blend was definitely higher than that of the pure toluene.

It is interesting to note that the ignition temperatures of methanol and di-isobutylene are decidedly lower than those of the benzene and the toluene.

TESTS WITH C. F. R. ENGINE

Figure 19 shows the results of the tests carried out on the C. F. R. engine using the glow-plug hot spot. The



(a) S-1 fuel, benzene, and di-isopropyl ether.
(b) Toluene and isopropyl alcohol.
FIGURE 19.—Ignition of various fuels in C. F. R. engine.

data do not extend as far either to the lean or to the rich side as do the corresponding data from the combustion apparatus because (1) the engine would not run at leaner or richer mixtures than those shown and (2) in some cases, there was insufficient fuel on hand to obtain more than one or two points on the curve. Figure 19 (a) shows the recorded temperatures for S-1 fuel, benzene, and di-isopropyl ether. The di-isopropyl ether available was sufficient for only one run; the indication is that the ignition temperature at an engine speed of 1,000 rpm is slightly higher than that of S-1 fuel at the same engine speed. Operation with this fuel was very smooth and steady.

The effect of engine speed for the C. F. R. engine was comparable with that obtained for the combustion apparatus, as is shown by the data for S-1 fuel and benzene. The temperatures recorded on the C. F. R. engine at 1,000 rpm are surprisingly near those recorded on the combustion apparatus at 1,000 rpm. Inasmuch as different types of hot spot were used and as the recorded temperatures depended greatly on the position of the hot spot, the character of the air flow past it, and other factors, the agreement of the temperatures with those in table I is probably fortuitous.

Figure 19 (b) shows the recorded temperatures for toluene and isopropyl alcohol. The speed effect is again prominent, and a downward trend at leaner mixtures at an engine speed of 2,000 rpm is also evident. The engine ran very irregularly at the leaner mixtures when ignition was started only by spark but, when ignition was started by the heated coil, the engine operated smoothly. This effect can undoubtedly be attributed to the large and intense source of ignition furnished by the heated coil.

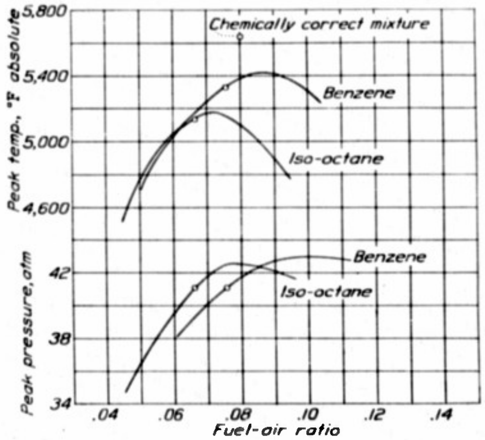


FIGURE 20.—Effect of fuel-air ratio on estimated peak temperatures and peak pressures. Compression ratio, 5; initial temperature, 112° F; initial pressure, 1.0 atmosphere. Data from reference 15.

The heated coil received a part of its heat from the combustion in the engine, and the rest of the heat was obtained by electrical heating. In the case of methanol, the heated coil reached the ignition temperature of the methanol very quickly after the engine started firing and without the addition of electrical heating. The engine could therefore not be run with methanol as fuel because the engine always stalled a few moments after it was started. As nearly as could be determined, preignition started when the hot-spot temperature was between 1,375° and 1,400° F.

BEHAVIOR OF BENZENE IN THE ENGINE

An interesting phenomenon was encountered during the preignition tests with benzene. At fuel-air ratios near the theoretical ratio for complete combustion, preignition after it had once started became entirely uncontrollable and stalled the engine very quickly, even though the heating current was turned off as soon as preignition started. This effect invariably occurred at fuel-air ratios near the theoretical but, at ratios somewhat higher or lower than the theoretical, the preignition could be readily controlled by varying the heating current. When preignition started at the ratios where it was uncontrollable, the temperature of the heated coil immediately began to rise very rapidly, even with the heating current turned off.

It appears unusual that the ignition temperatures of benzene and iso-octane (S–1 fuel) should be so nearly the same and yet that benzene should have such unfavorable preigniting tendencies. Figure 9 showed that benzene gives rise to higher thermal-plug temperatures than does iso-octane at the same indicated mean effective pressure; therefore, when benzene is used, the preigniting tendency is greater. In figure 20, the peak pressures and the peak temperatures resulting from the burning of benzene-air and iso-octane-air mixtures are shown plotted against fuel-air ratio, as calculated by Goodenough and Felbeck (reference 15). The combustion gases, when benzene is used, reach a higher temperature than with iso-octane because of the difference in the heat capacities of the products of combustion of the two fuels. When benzene is used in an engine, the engine will therefore run hotter than it would run with iso-octane. In the discussion included in reference 14, R. V. Kerley mentioned that the higher luminosity of the benzene flame may cause higher engine temperatures because of the greater radiation.

CORRELATION OF FUEL BEHAVIOR WITH IGNITION TEMPERATURE

On the basis of the results obtained and the foregoing discussion, any method of evaluating the performance possibilities of fuels with respect to their preigniting tendencies will probably have to take into account the heat capacity of the combustion products and the heat of combustion of the fuel, as well as the ignition temperature. A method of testing in an engine might be developed in which both the combustion-chamber-wall temperature at some specified output and the ignition temperature of the fuel would be determined for each fuel.

CONCLUSIONS

1. The flame originated by preignition has the same characteristics as the flame originated by a spark plug; the only difference is the time and the location of ignition.

2. The results indicated that preignition, in addition to its serious effects when it becomes considerably advanced, may cause knock by advancing the ignition timing.

3. The data indicate that in an engine having ignition by two spark plugs, cutting out one spark plug may not necessarily increase the tendency to knock but, on the contrary, may reduce the knocking tendency; the effect would be similar to that obtained by retarding the spark.

4. Depreciation of preigniting fuels with an increase in engine speed can be explained by the increase in the temperature of the poorly cooled portions of the combustion chamber, such as spark plugs, with an increased output of the engine. Although the ignition temperature increases with engine speed, the increase is probably less than the increase of the temperature of such hot spots.

5. The unfavorable preigniting tendency of benzene can probably be attributed to the fact that the benzene flame reaches a higher temperature than the gasoline flame, causing higher temperatures of the inner surface of the combustion chamber. Consequently, benzene might preignite at engine outputs that do not cause preignition of, for example, 100-octane gasoline.

6. Differences in the ignition temperatures of the various fuels tested (with the exception of methanol) were not strikingly great, and the maximum permissible specific outputs with the fuels could not be correlated with their ignition temperatures. It appears possible that some combination of ignition temperature, heat of combustion, and specific heats of the products of combustion may determine the maximum output of a preigniting fuel.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *September 16, 1940.*

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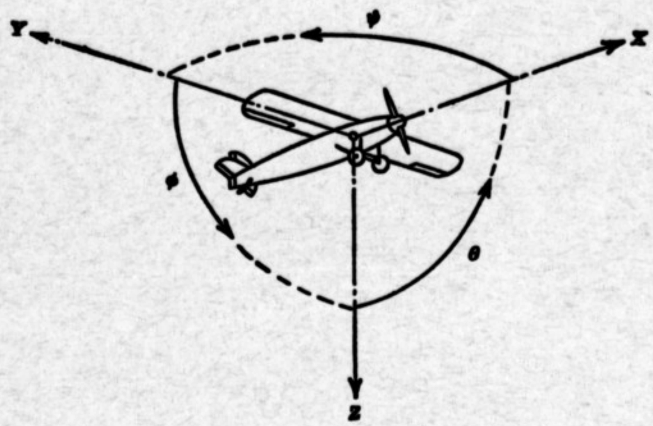
U. S. GOVERNMENT PRINTING OFFICE: 1941



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

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

Absolute coefficients of moment

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

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

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

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

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

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

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

η Efficiency

n Revolutions per second, rps

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

5. NUMERICAL RELATIONS

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

1 metric horsepower=0.9863 hp

1 mph=0.4470 mps

1 mps=2.2369 mph

1 lb=0.4536 kg

1 kg=2.2046 lb

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

1 m=3.2808 ft

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TSDIN FORM 60 A (10 MAR 47)

RESTRICTED

Spencer, R. C.

AUTHOR(S)

DIVISION: Fuels and Lubricants (12)
SECTION: Analysis and Testing (8)
CROSS REFERENCES: Fuels, Liquid - Testing (42680); Preignition (73542)

ATI- 20792
ORIG. AGENCY NUMBER
R 710
REVISION

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FORG'N. TITLE:

ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Washington, D. C.
TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Restr.	1941	21		photos, diagr, graphs

ABSTRACT

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NOTE: Requests for copies of this report must be addressed to: N.A.C.A., Washington, D. C.

WDH FORM 60 A (10 MAR 47)

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FORG'N. TITLE: *Re Autoignition*

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By George R. Jordan USCO

Signature and Grade

Date APR 1949