NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 359

AN INVESTIGATION OF THE EFFECTIVENESS OF IGNITION SPARKS

By MELVILLE F. PETERS, WAYNE L. SUMMERVILLE
and MERLIN DAVIS

1930

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

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

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

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

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

ρ, Density (mass per unit volume).

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

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

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

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from C. G. to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

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

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

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

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

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

i_t, Angle of stabilizer setting with reference to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/s, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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NAVY BUILDING, WASHINGTON, D. C.

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SUMMARY

The effectiveness of ignition sparks was determined by measuring the volume (or mass) of hydrogen and of oxygen which combines at low pressures. The sparks were generated by a magneto and an ignition spark coil. It was found that with constant energy the amount of reaction increases as the capacitance component of the spark increases. The use of a series spark gap may decrease or increase the amount of reaction, the effect depending upon the amount and the distribution of capacitance in the circuit. So far as the work has progressed, it has been found that sparks reported by other investigators as being most efficient for igniting lean mixtures cause the largest amount of reaction. Differences between the amount of reaction with a magneto spark and an ignition spark coil were noted. The method appears to offer a means of determining the most efficient spark generator for internal-combustion engines as well as determining a relation between the character of spark, energy, and effectiveness in igniting inflammable mixtures.

INTRODUCTION

For several years the National Advisory Committee for Aeronautics has been interested in automotive ignition, and during the years 1917 to 1923 sponsored such a study at the Bureau of Standards. This work dealt mainly with the characteristics of spark generators and the probable effects resulting from the use of such auxiliary apparatus as condensers, series spark gaps, etc. In 1928 the National Advisory Committee for Aeronautics and the Bureau of Aeronautics of the Navy decided to renew the study of ignition, and this report deals with one phase of the renewed investigation.

In renewing the work, it was considered desirable to investigate the effectiveness of the spark as such in producing reaction between fuel and oxygen. It is not possible to determine this by using explosive mixtures such as are burned in an engine under operating conditions, but it is possible to select conditions in which the reaction produced by the spark itself will not cause further reaction. Such conditions may be obtained by working with explosive mixtures at low pressures of the order of 3 cm of mercury or lower, or with very lean mixtures at higher pressures.

Morgan, Wheeler, and Thornton (Reference 1) have found that the ability of a spark to ignite a lean mixture is dependent not so much upon the total energy in the spark as upon its character. Determinations of the amounts of gas which are caused to react by sparks of various characteristics but of approximately equal energy content may serve to point the way to a more detailed explanation of the numerous obscure phenomena observed in automotive ignition.

SELECTING THE EXPERIMENTAL CONDITIONS

The experiments herein reported were made with explosive mixtures at low pressures. Choice of this method for the first work was determined by the fact that the technique is much simpler than that required in working with lean mixtures at higher pressures.

In choosing the conditions of the experiments, it was desirable that these be as closely related to those occurring in automotive ignition as was practicable, even though the pressures in the two cases are so widely different. The known facts about sparking potentials suggest the conditions to be fulfilled. It will be useful to review briefly the salient facts relating to sparking potentials (Reference 2) to show how they may be applied in the case under consideration.

It is well known that if a gradually increasing potential is applied to two fixed electrodes in a gas, a spark will pass across the gap when the potential difference reaches a certain value. This is known as the sparking potential. It is also known that for a given distance between the electrodes there is a gas pressure for which the potential is a minimum. As a result of numerous experiments, the generalization known as Paschen's law was announced. It was first stated in the form that for any one gas the sparking potential depends only upon the product of gas pressure and distance between electrodes. Later experiments at various temperatures showed that the sparking potential was determined primarily by the product of distance and gas density sometimes loosely called the mass of gas between the electrodes.

Carr (Reference 3) has studied the change in sparking potential over a pressure range that will give values for the product $d.s$ above and below the minimum sparking potential for a number of gases (d is the density of the gas and s the distance between electrodes). The results for hydrogen and for oxygen are shown in Figure 1. For pressures above the minimum sparking potential these results agree with those obtained with short spark gaps at high pressures.

In determining the sparking potential it is sometimes necessary to maintain the potential as long as 15 minutes before the discharge takes place. Baille (Reference 2) has found that if one spark is passed every five seconds the voltage at which the discharge takes place remains constant (Reference 4). If the rate is increased to two sparks per second, the crest voltage is reduced 7 per cent, whereas a continuous passage of sparks reduces the crest voltage 10 per cent. The sparking potential is also affected by many other conditions, among which is the electrostatic charge upon the walls of the container. Without considering further the various conditions such as shape, temperature or material of the electrodes, etc., which may affect the sparking potential, Paschen's law suggests that, in the apparatus to be used in the proposed experiments, the dimensions be chosen so that the product of gas density and distance between electrodes be made as nearly equal to the product of gas density in the engine cylinder under operating conditions times distance between spark plug electrodes as is consistent with limitations imposed upon the design by other considerations. In the tube, as in the engine, it is not the sparking potential as previously defined but the potential which will produce a spark immediately, known as the peak voltage, which is of importance.

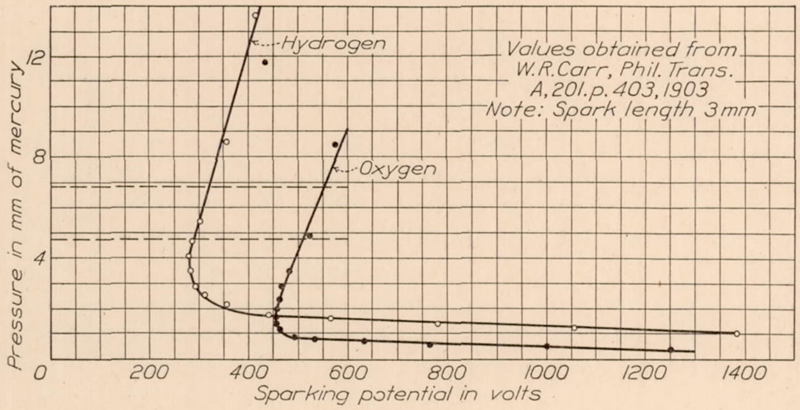

FIGURE 1

In a low-pressure discharge tube the condition suggested by Paschen's law can be met by making the distance between electrodes sufficiently great. For reasons to be discussed presently, the tube was immersed in liquid air and contained a mixture of two volumes of hydrogen and one of oxygen, at a pressure of 2 mm of mercury or less. In an engine having a 5 : 1 compression ratio and a 1 mm spark gap the product of density and distance is roughly proportional to $5\times760\times0.1=380$. To obtain an equivalent product in a tube under the conditions described above, the distance s between the electrodes would be given by the relation

$$s=\frac{380}{2\times\frac{373}{86}}=44\text{ cm},$$

where the factor $\frac{373}{86}$ has to be introduced in the denominator to take care of the difference in density of the gases at the temperature of liquid air, −187° C. or 86° absolute, and the temperature of the gases in the engine, assuming that the temperature of the gases at the beginning of the compression stroke are 100° C. or 373° absolute.

While it would be desirable to study the number of molecules which unite per spark using gasoline and air, the use of hydrogen and oxygen greatly simplifies the work. Gasoline being a mixture of many kinds of hydrocarbon molecules would be unsatisfactory to use as a standard, because once the original supply was exhausted it would be impossible to obtain a like gasoline. This is not the only disadvantage. A spark discharge passing through the gasoline-air mixture would probably leave many molecules in various stages of oxidation, so that a complete chemical analysis would be required to determine the effects of the different spark discharges. Hydrogen, however, is easy to obtain in the pure state. The single product of combustion is water vapor and this may be removed by using phosphorus pentoxide, calcium chloride, etc., or by freezing it out with liquid air. Moreover, hydrogen mixed with other gases is used in many engines to-day, so that hydrogen is included in the field of fuels in use. The use of oxygen eliminates the formation of oxides of nitrogen which are formed in the discharge tube in the presence of nitrogen and oxygen. Since the main object of this work is to obtain a method for comparing ignition systems, the use of hydrogen and oxygen is not objectionable.

Considerable work has been done on the combination of hydrogen and oxygen. S. C. Lind (Reference 5) has studied the combination by α-ray impact. Dickinson (Reference 6) has found that combination takes place in the presence of excited mercury vapor. R. D. Rusk (Reference 7), using a Geissler discharge tube, determined the rate at which hydrogen and oxygen combined at low pressures when currents of 2 to 10 milliamperes passed through the tube. Besides this he found that if a discharge is passed through a mixture consisting of two volumes of hydrogen to one of oxygen at pressures greater than 3 cm, an explosion follows. At 3 cm pressure the gas burned quietly and at pressures below this "combination occurred only by collision." In the work to be described, the density of the gas mixture was considerably below the maximum which Rusk's experiments showed to be permissible. This was considered a useful precaution as the instantaneous currents to be used were many times larger than those in Rusk's experiments. A. K. Brewer and J. Westhaver (Reference 8) have studied the synthesis of ammonia in the glow discharge. They used a discharge tube immersed in liquid air to freeze out the ammonia as formed and found that the rate of synthesis was independent of the pressure and dependent only upon the current. The currents used were 4 to 70 milliamperes.

In 1927 Prof. R. W. Wood suggested to one of the authors the advantages of using a discharge tube immersed in liquid air for studying the afterglow of mixtures of nitrogen and oxygen. He pointed out that a definite volume of the gases could be used and the change in pressure noted, or the gases could be drawn through the tube and a sufficient amount of the end products frozen out and analyzed. Due to lack of time the work was not completed, but it seems worth while to point out the nature of the results, since some of the observations have been used as a guide in the work described in this report. With the static or constant volume method definite changes in pressure were observed. Since a small volume was used, there was not sufficient material collected to analyze. When the gases were drawn through the tube for some time, a considerable quantity of ozone was obtained, and also a yellowish substance which was probably an oxide of nitrogen. Due to the presence of ozone, a violent explosion took place after removing the liquid air, so that an analysis of the yellow substance was not made. It may be well to mention that this seems to support Strutt's contention that oxides of nitrogen are formed in the discharge tube under conditions suitable for the well-known afterglow obtained with mixtures of nitrogen and oxygen.

The method used in studying the combination of hydrogen and oxygen in the discharge tube was the static method. It is similar to that used by Brewer and Westhaver in the study of the synthesis of ammonia. Undoubtedly some ozone was formed in the discharge tube. In the presence of molecular and atomic hydrogen it does not seem likely that the percentage condensed on the wall would be great enough to affect the results over the pressure range used in making the computation. If it did, the most effective spark should cause the formation of the greatest amount of ozone as well as water, so that the method could be used for the comparison of the effectiveness of sparks. As a special experiment, it would be interesting to study the formation of ozone in the presence of other gases at liquid air temperatures.

DESCRIPTION OF APPARATUS

The discharge tube used in this work was made from a flask having a volume of 175 cm^3, this being about the largest size that could be immersed in liquid air with the containers available. Since atomic hydrogen is formed during the discharge and may combine on the walls of the tube, it was considered advantageous to make the distance between the walls of the flask and the electrodes as large as practicable. The electrodes were therefore mounted near the center of the flask and about 12 mm apart. There was therefore no glass near the path between the electrodes. With this arrangement it is possible to electroplate the electrodes, as suggested by Dr. W. W. Nicholas, without materially changing any dimensions of importance, and thus to investigate the effect of electrode material upon the mass of gases which combine. With this design the value of *d.s* was proportional to 7 as compared with the value of 380 previously calculated as corresponding to engine conditions. However, the apparatus was intended primarily to study the applicability of the method, and it was therefore not necessary to adhere so closely to the representative conditions. It was also desired to study at some future time the effect of the electrode material upon ignition.

Figure 2 is a photograph showing the arrangement of the apparatus used in this work. A is the gas generator, B is a liquid-air trap for drying the gases entering the discharge tube C, D a trap, E a mercury seal, and G a gauge for measuring pressures. Figure 3 is a drawing of the gas generator. The outer chamber has two platinum electrodes and these were used as cathode and anode so that it was possible to draw two volumes of hydrogen and one of oxygen into the system. To provide for varying the mixture ratio of hydrogen and oxygen a third platinum electrode was placed in an inner chamber, so that the two electrodes in the outer chamber could be used as cathode or anode. In this work, however, but one mixture ratio was used, i. e., two volumes of hydrogen to one volume of oxygen. The electrolyte was sodium hydroxide.

The discharge tube C, shown in Figure 4, was made from a pyrex flask. The lead wires were brought into the tube with the usual tungsten pyrex glass seals and connected by platinum wires to two platinum electrodes 1 cm. square. The platinum used in this tube was especially purified metal prepared at the Bureau of Standards and is equal in purity to the pure metal used for the Bureau of Standards' thermocouples. It probably contained not more than 0.001 per cent of combined heavy metals. Capillary glass tubing was used to connect the discharge tube to the generator and gauge. The dotted line shows the height of the liquid air surrounding the tube when in use. To avoid water condensing around the electrode leads it was necessary to put glass tubes outside of the lead wires with the lower ends immersed in liquid air and the upper ends filled with cotton. As the liquid air evaporated inside these glass tubes it passed out through the upper end, thus preventing water vapor of the atmosphere from reaching the electrodes. The trap D was surrounded by liquid air whenever the liquid air level in the discharge tube was allowed to fall appreciably below the level indicated by the dotted line. This was done to prevent vapors from diffusing back into the discharge tube. During the operation of the tube the vapors were frozen out in that portion of the capillary tube shown between the dotted line and the discharge tube.

At the beginning of a run trap D was immersed in water at room temperature, and during the run the difference between the temperature of the room and water bath was never greater than 2° C. This trap was used to assist in the establishment of temperature equilibrium throughout the system. During the discharge cold gases were forced out of the tube into the remainder of the system, and after the discharge the gases flowed back into the tube. The trap thus assisted in heating up the cold gases before they passed into that portion of the system which was heated or cooled by the gases in the room. The warm air entered the discharge tube through the capillary tube which was immersed in liquid air, and this with the low pressures used rapidly brought the gases to the temperature of the liquid air. During a run the temperature of the gases in the trap was probably lowered slightly, as was the temperature of the gases in the gauge and tubing, but the water bath certainly helped to reduce this lowering and to assist in the establishment of a uniform temperature. The temperature of the room in which the apparatus was located was controlled so that it did not change by more than 2° or 3° C. during the day. The temperatures of the liquid air, of the water bath surrounding trap D, and of the room were taken with the other

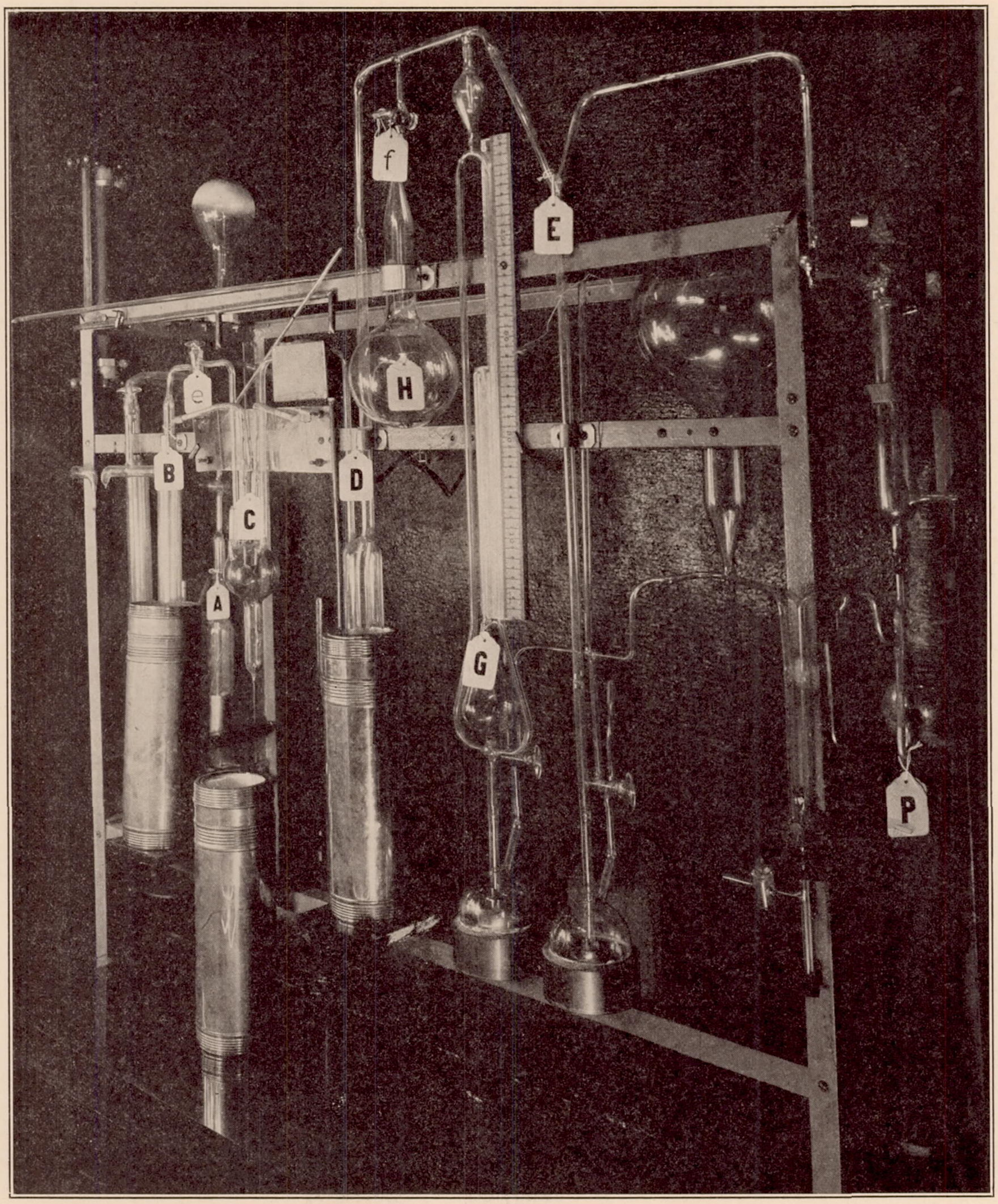

FIGURE 2

readings and the observed temperatures were used in computing the results.

In making pressure measurements with a McLeod gauge the rise of mercury in the tube connecting the gauge to the system changed the volume of the gases in the apparatus. In the apparatus first used there was sufficient gas forced into the discharge tube, which was immersed in liquid air, to upset the temperature equilibrium of the system while making the pressure measurements. By making D sufficiently large and connecting the gauge to the system with two pieces of 3 mm capillary tubing, the changes in volume when making a reading was about 0.1 per cent, so that readings could be made without altering the temperature equilibrium of the system.

As mentioned before, when a discharge takes place in the tube the pressure of the gas increases, and some of it is forced into the remainder of the system. After the discharge has passed, warm gas flows back into the tube, so that it requires time for the system to regain a condition of equilibrium. Besides this, a certain time must elapse between sparks, otherwise the sparking voltage will be lowered. In this work the range covered required the passing of several thousand sparks, so that the time involved in assuring equilibrium between sparks would be great. Although with smaller time intervals equilibrium may not be established between sparks, it was thought, if the same conditions were established for each spark after the first, that for comparisons a shorter interval would be satisfactory. It is true that following a heavy discharge the system may not return to the same initial condition as that following a weak discharge, but this would be expected to increase slightly the difference to be noticed between the mass affected in the two cases. For this work a time interval of 1.7 seconds between sparks was selected, and it fitted in nicely with the motor and gear ratio available.

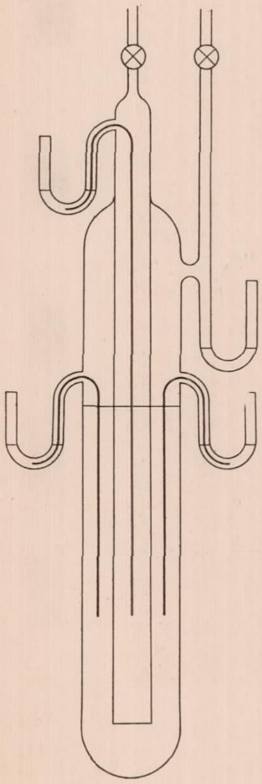

FIGURE 3

Figure 5 shows a photograph of the apparatus used for producing discharges in the tube. The disk D which is rotated by means of a gear train from one end of a motor makes contact by means of commutator segments with two brushes (*e*, *e′*) which complete the circuit between the discharge tube and magneto. (A 12-cylinder aviation type magneto was used.) Attached to the disk is a counter, so that the number of sparks passing into the tube may be noted. The magneto is connected to the other end of the motor shaft and its speed is regulated to correspond to an engine speed of 375 r. p. m. by the gear ratio between the motor and magneto. With this arrangement the rate at which sparks are passed into the tube may be kept constant while the speed of the magneto may be changed by means of the motor magneto gear ratio. The disk and magneto were thus synchronized, so that the spark from the magneto always passed through the discharge tube in the same direction. In the photograph, A is the magneto and B the motor. At E is shown a spark gap through which the unused sparks are discharged. F is a graduated spark gap permanently connected in series in the circuit. When not in use the gap is closed. In this way the introduction of the spark gap did not disturb the other constants of the electrical circuit. The gap electrodes were made of steel one-eighth inch in diameter with flat faces.

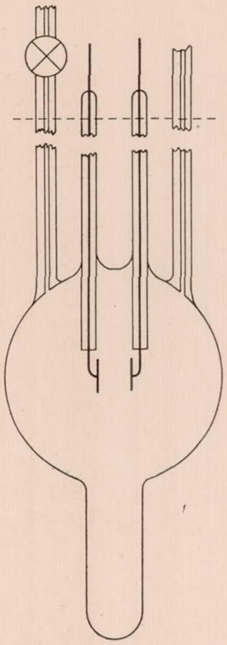

FIGURE 4

Both mica and oil condensers were used. The capacitance of the oil condenser could be varied from 0.001 μf to 0.004 μf where μf signifies microfarad. The complete mica condenser consisted of eight separate units so arranged that they could be used independently or connected in parallel. The capacitance and power factor of the units were determined by the electrical division of the Bureau of Standards. The power factors of these condensers were practically zero.

The resistance consisted of a column of dilute sulphuric acid in which were immersed two platinum wires. The container was quartz.

EXPERIMENTAL PROCEDURE

The following was found to be a satisfactory routine for the work. The entire system is pumped down to less than 10^{-5} mm of mercury, and while pumping is continued the discharge tube is baked at a temperature of 500° C. for 60 minutes by means of an electric furnace. During the first 40 minutes the volatile material in the tube is driven off and removed by the pump, then liquid air is placed around the trap D to prevent the return of any vapors, as pumping and baking continue. After a slow cooling the tube is ready for use.

At this point in the procedure the trap B and the tube C are immersed in liquid air and the trap D immersed in a water bath at 50° C. By partly opening stopcock e a mixture of two volumes of hydrogen and one volume of oxygen is drawn through the system for 15 minutes, after which a water bath at room temperature is placed around trap D and the gas mixture drawn through the system for 30 minutes. By manipulation of cock *e* and seal E the pressure is then adjusted to an approximate desired initial value, after which readings of the pressure are taken at 5-minute intervals for a period ranging from 15 to 30 minutes; i. e., until successive readings check and show a condition of pressure equilibrium. During these and all subsequent readings the liquid air at C is maintained at the level shown by the dotted line in Figure 4.

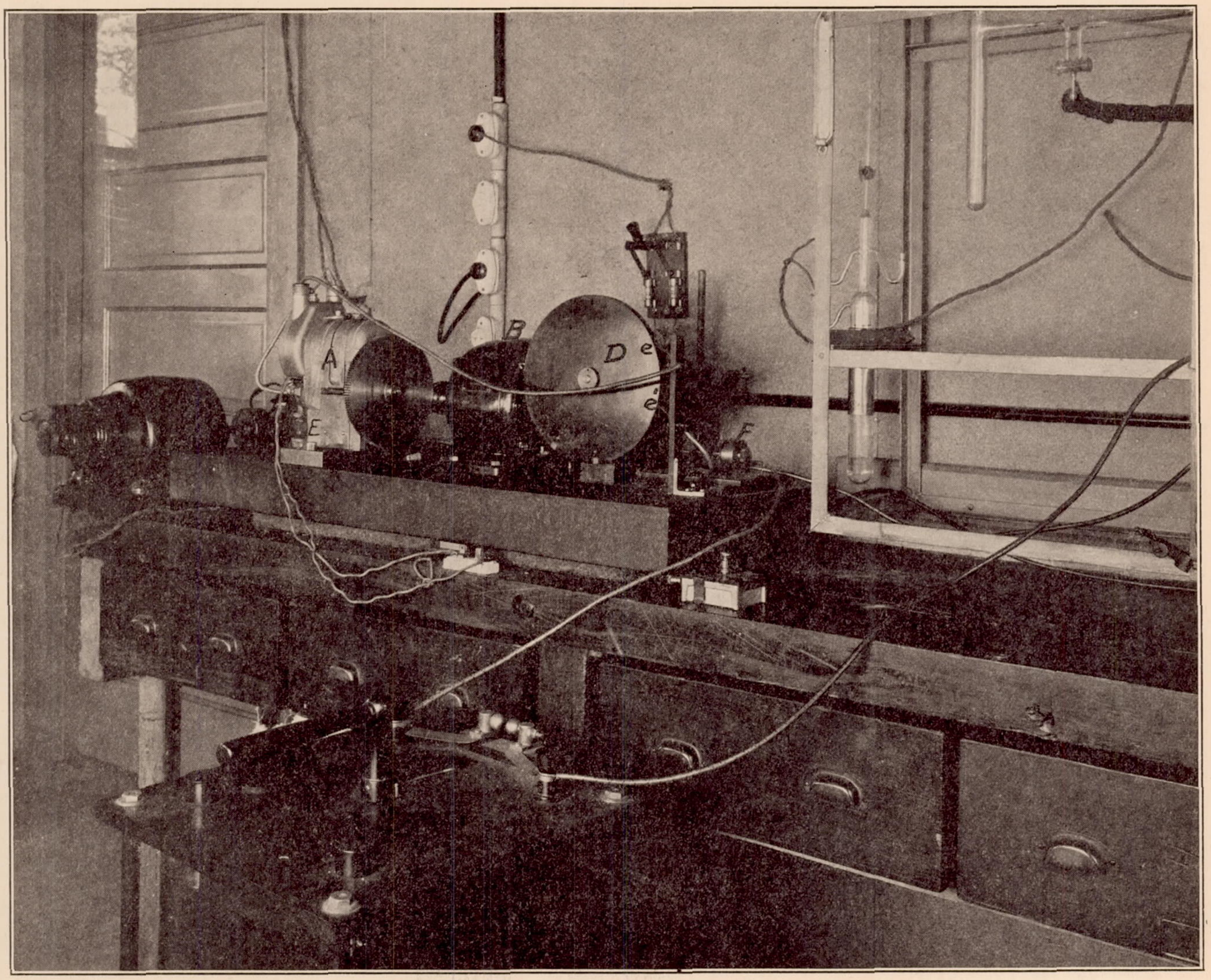

Figure 5

The magneto is then started; the switch connecting it to the tube is closed as a stop watch is started; and the flashes of the spark discharge counted until the counter reading is verified. The flashes are watched during the run to detect any failure of the discharge. After a predetermined number of discharges the switch is opened and the watch is stopped. The magneto is then stopped and a series of pressure readings taken at 5-minute intervals as before. When a set of such runs has been completed and the apparatus is no longer in use, the water bath D is replaced by one of liquid air to prevent contamination of the tube by vapors from the pump. For later series of runs the procedure is duplicated except that the tube is not baked out for each series.

Before the mass of gas which reacts due to the spark discharge could be computed it was necessary to know the relation between quantity of gas consumed and a given change in pressure. While this might have been deduced from the volume, pressure and temperature of the system it seemed more satisfactory to determine this by a special experiment. The method chosen was to immerse the tube in liquid air and the trap in water at room temperature, allow the system to come to the state of equilibrium, and then cause the gas to expand into a flask of known volume and containing a predetermined pressure, such that the change in pressure in the system corresponded to the changes observed in the experiment.

This determination was repeated over the pressure range used in this work. The flask H (fig. 2), into which the expansion takes place, is the standard. Its volume is known to better than 0.1 per cent. The gases used were two volumes of hydrogen to one of oxygen.

The apparent volume of the system was computed from the formula

$$V_o=\frac{(P_2-P_1)V_1}{(P_o-P_2)}$$

where

P_o = pressure in the system before expanding the gas into H.
P_1 = pressure in the standard flask H before the gas from the system entered.
P_2 = pressure in system and H after gas expanded from the system into H.
V_o = apparent volume of the system.
V_1 = 811.0 cm^3 = volume of H.

From this formula it is seen that a small percentage error in reading P_o, P_1, or P_2 may produce a large percentage error in their difference. When the determinations were first made the values obtained differed as much as 8 per cent. Later it was possible to make a series of volume determinations which differed by less than 1 per cent. To do this it was necessary to stop the mercury just below the cut-off of the McLeod gauge, allow time for equilibrium to be restored, and raise the mercury slowly. If the mercury is brought up rapidly, gas may be forced into the bulb of the gauge which will change the pressure reading.

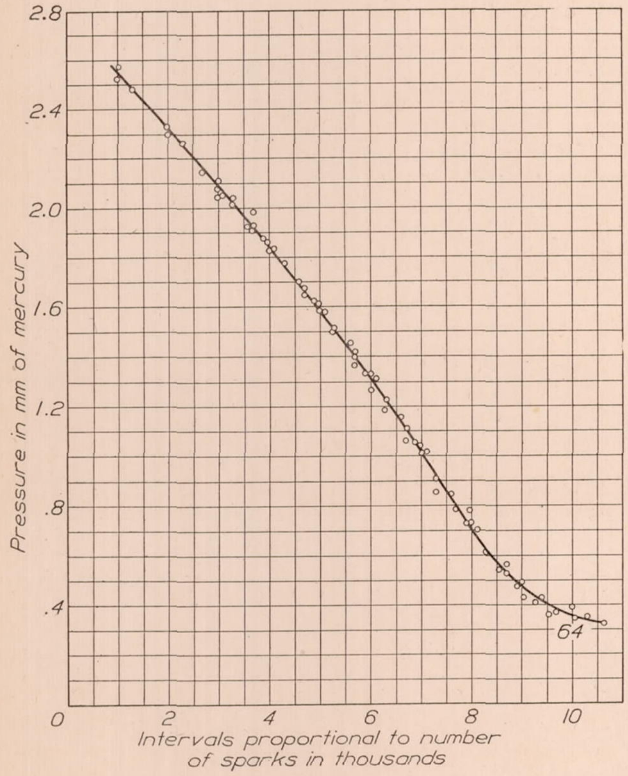

FIGURE 6

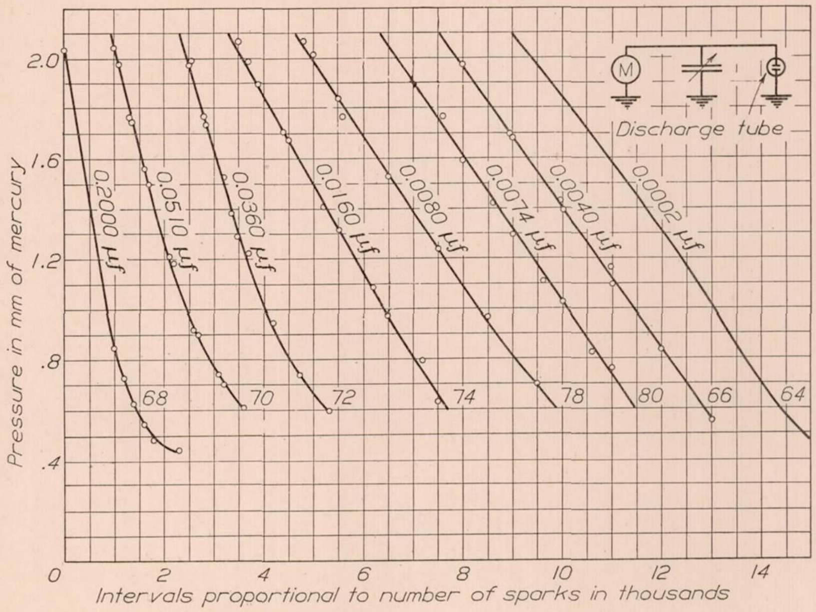

FIGURE 7

RESULTS.

The curves plotted with pressure as ordinates and the number of sparks as abscissas are shown in plots 6 to 11. The second column of Table II identifies the curve shown on the plot while the third column gives the electrical arrangement.

The results obtained with the magneto connected to the discharge tube without additional capacitance, series gap or resistance are shown in Figure 6. The capacitance of the lead wires and disk D (fig. 5) from the magneto to and including the tube was 0.0002 μf. This curve is based on the results of 13 runs made at different times. In starting the work two runs were made with this arrangement. Single runs were then made with the capacitance shown in Figure 7, followed by another run with the original arrangement. This served as a means of determining the constancy of the system. If no changes were found, the runs on capacitance were repeated. By adopting this procedure, the second set of runs on capacitance was not made until some days later. The other curves were obtained in a similar manner, and the continual checking of the magneto and tube accounts for the 13 runs. In plotting the results the initial pressure on the curve was not taken at zero sparks, but was plotted so as to fall on the curve at the equivalent pressure. The initial pressure then determined the position of the origin. This was possible because it was changes in pressure over a specified pressure range which were of interest, so that it was not necessary to obtain the same initial pressure for each run.

Figure 7 shows the results obtained as the capacitance is changed from 0.2 μf to 0.0002 μf. Curve 68 is a single run and it is questionable whether it should be compared with the other curves. In making the run, it was necessary to count the sparks because only approximately half of the possible sparks passed through the tube. The recorder indicated 2,170 sparks for the first thousand passing through the tube by count. The other points were obtained by counting, and it was noted that the ratio between the number of recorded and counted sparks was approximately constant. Since the current passing through the tube and charging the condenser was always in the same direction, it is quite possible that it required two impulses from the magneto to raise the condenser to the sparking potential. This was found to be the case later, because, if a condenser was placed across the spark gap and the magneto rotated so that it sparked half the time, the condenser was found to be sufficiently charged to cause a heavy discharge to take place each time after the gap length was decreased.

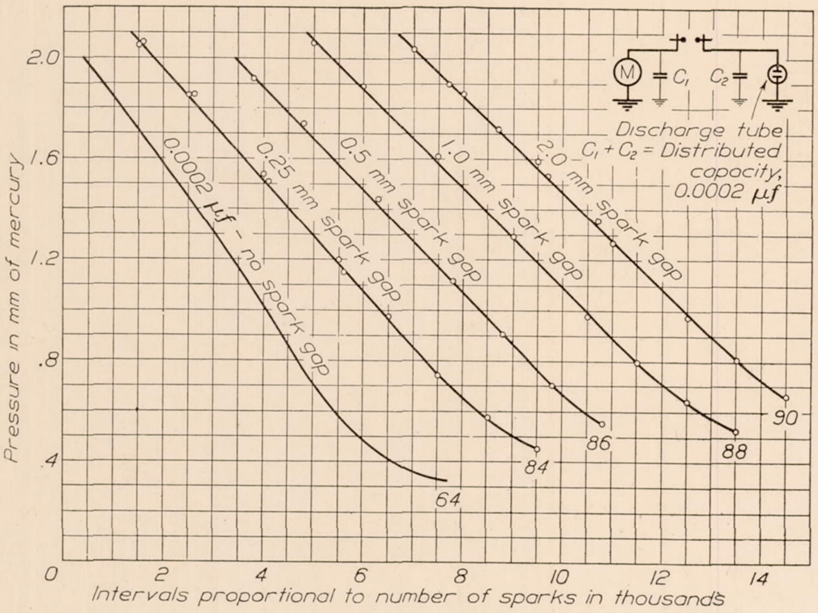

FIGURE 8

Figure 8 shows the curves obtained with a series gap. They show that the change in pressure per spark is less with a series gap than without it. The curves also show that a greater decrease is noted with the initial opening of the gap, in this case 0.25 mm, than with a subsequent increase in opening to 2.00 mm.

Figure 9 shows the curves with a resistance in parallel with the tube with and without a spark gap in series with the leads from the magneto.

Figure 10 shows the curves with a 1 mm series gap with capacitance across the tube, and again with it across the magneto. Condensers with a capacitance of 0.004 μf and 0.002 μf were used. In the case of the larger capacitance the curve is much steeper with the capacitance across the magneto side.

Figure 11 shows runs made with a 9-cylinder magneto, a Liberty ignition coil, and the same coil with a series gap. These were connected to an engine which was turned over at the rate of 40 r. p. m. by means of a dynamometer. The determinations were made with the discharge tube shown in Figure 4, connected to a system whose volume was not determined. Since the mass of gas combining in any case is proportional to the slope of the curve, comparisons may be made between these three curves. They can not be compared with the curves shown by Figures 6–10 because these data were obtained on another system.

The volume of the system used in obtaining the results given in Table II was determined and found to be 1,093 cm^3 at 23° C. The method used in the determination of this volume has been discussed and the results obtained are given in Table I.

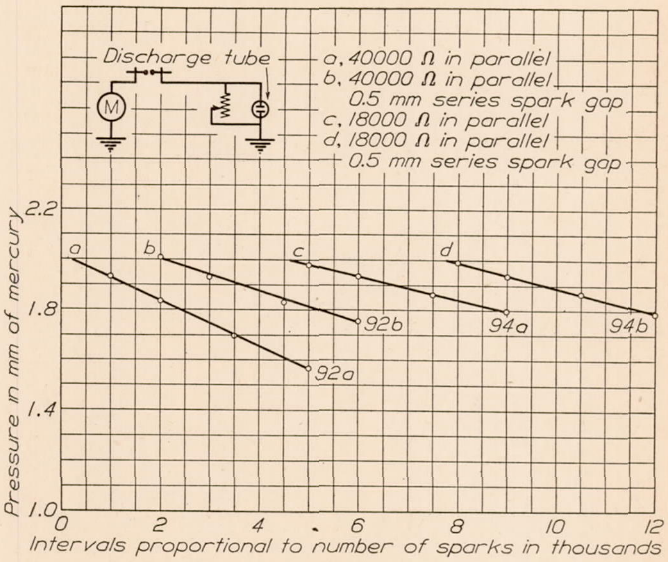

FIGURE 9

TABLE I

Initial pressure in system	Final pressure in system	Apparent volume of system at 23° C.
2.087	1.837	1,088
1.760	1.504	1,098
1.576	1.265	1,088
1.213	1.044	1,097
1.064	0.840	1,094
		[1] 1,093

[1] Average.

Figures 6 to 10 show that while the plotted values do not lie on a straight line they may be taken as straight over a limited range. Referring to Figure 1 and remembering that the density of the gas at −187° C. is roughly 3.4 times as great as it is at 23° C., the equivalent pressure range, except for the values given with shunted resistances, is shown by the dotted lines on the plot. Thus the density of the gas at 2 mm pressure and −187° C. is the same as $3.4 \times 2 = 6.8$ mm pressure at 23° C. This corresponds to a pressure range on the curves of 2 mm to 1.4 mm of mercury. The curves with parallel resistances were extrapolated to cover this range. The volume of gas ignited per spark may now be computed from the expression,

$$V_1 = \frac{(P_1 - P_2)}{760} \times 1{,}093 \text{ cm}^3 \text{ at } 23° \text{ C. and } 760$$

mm pressure, and at 0° C. and 760 mm pressure the volume becomes

$$V_0 = \frac{273}{296} V_1 \text{ cm}^3$$ so that the volume of gas ignited is

$$V_0 = \frac{1{,}093 \times 0.6 \times 273 \times 1{,}000}{760 \times 296} = 796 \text{ mm}^3 \text{ and}$$

$$\frac{796}{\text{Number of sparks}} = \text{volume in mm}^3 \text{ ignited per spark.}$$

Table II also gives the volume of gas ignited at 0° C. and 76 mm pressure. This is approximately the pressure a tube would have with a 1 mm spark gap and a gas temperature of 0° C. so that it would have the same mass of gas between electrodes of unit area as in the discharge tube. Figure 12 shows the increase in volume of gas ignited as the capacitance is increased. The value given at 0.2 μf is questionable, because, as mentioned before, only one-half of the possible number of sparks passed through the tube. If this value were eliminated, a straight line could be drawn which would roughly represent the relation between capacitance and volume of gas ignited. In this case it would be proportional to the energy in the capacitance component of the spark which has been shown to be $1/2\ CV^2$, where V, the sparking potential of the tube, is constant. C is the capacitance of the circuit in parallel with the discharge tube.

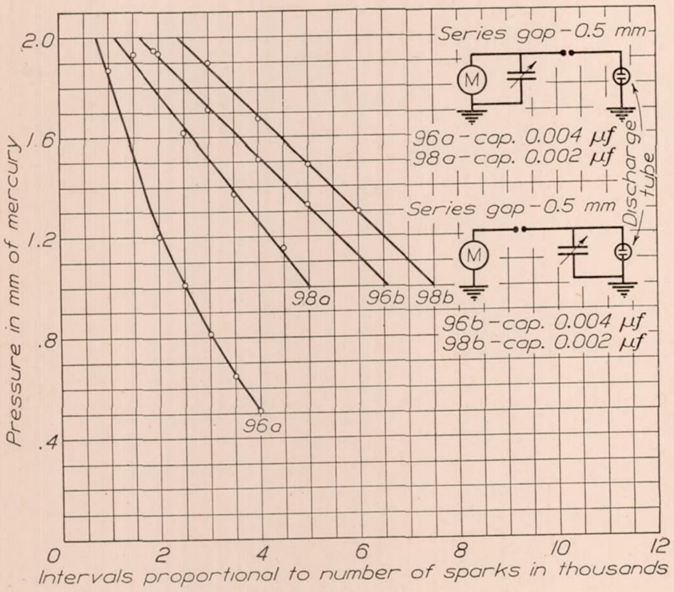

FIGURE 10

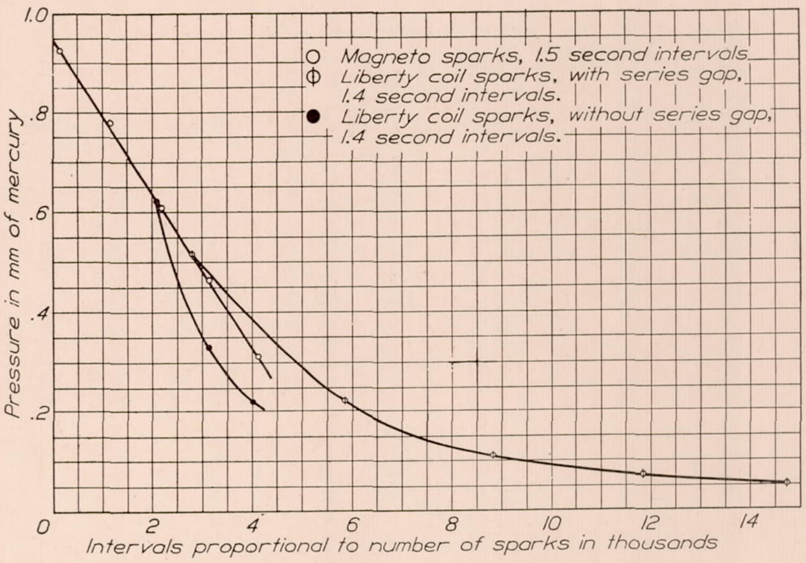

FIGURE 11

TABLE II

Plot No.	Curve	Electrical constants	Number sparks required to cause the pressure to drop from 2.0 mm. to 1.4 mm	Volume ignited 760 mm pressure	Volume ignited at 0° C. 76 mm pressure
6, 7, 8	64	0.0002 μf in parallel	2, 320	0. 34	3. 4
7	66	0.004 μf in parallel	2, 140	0. 37	3. 7
7	80	0.0074 μf in parallel	2, 050	0. 39	3. 9
7	78	0.008 μf in parallel	1, 970	0. 40	4. 0
7	74	0.016 μf in parallel	1, 690	0. 47	4. 7
7	72	0.036 μf in parallel	870	0. 91	9. 1
7	70	0.051 μf in parallel	750	1. 06	10. 6
7	68	0.2 μf in parallel	490	1. 63	16. 3
8	84	0.25 mm series gap	2, 740	0. 29	2. 9
8	86	0.5 mm series gap	2, 930	0. 27	2. 7
8	88	1. 0 mm series gap	3, 070	0. 26	2. 6
8	90	2.0 mm series gap	3, 160	0. 25	2. 5
9	92a	40,000 ohm resistance, no gap	6, 600	0. 12	1. 2
9	92b	40,000 ohm resistance, 0.5 mm series gap	9, 300	0. 09	0. 9
9	94a	18,000 ohm resistance, no gap	12, 700	0. 06	0. 6
9	94b	18,000 ohm resistance, 0.5 mm series gap	11, 700	0. 07	0. 7
10	96a	0.004 μf magneto side of 0.5 mm series gap	960	0. 83	8. 3
10	96b	0.004 μf tube side of 0.5 mm series gap	2, 960	0. 27	2. 7
10	98a	0.002 μf magneto side of 0.5 mm series gap	2, 330	0. 34	3. 4
10	98b	0.002 μf tube side of 0.5 mm series gap	3, 070	0. 26	2. 6

Figure 13 shows the volume of gas ignited as the series spark gap opening is increased. A greater decrease in the mass of gas ignited takes place with the first 0.25 mm opened than with an additional opening of 1.75 mm.

Figure 14 shows the change in the volume with resistances of 40,000 ohms, and 18,000 ohms in parallel with the discharge tube, with and without an auxiliary spark gap in series with the parallel combination.

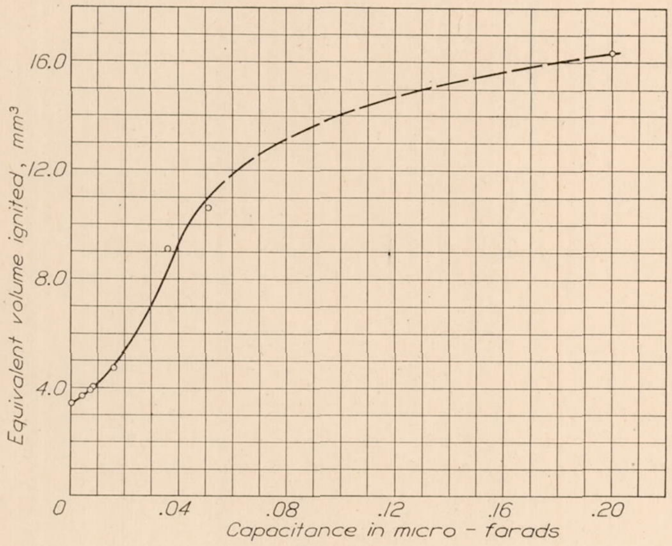

FIGURE 12

Figure 15 shows by line (A) the change in volume of gas ignited with a series gap as the capacitance on the magneto side is increased, and by (B) the change in volume when the capacitance is increased on the discharge tube side. The value at 0.0002 μf is the capacitance of the magneto, discharge tube, and lead wires. Curve C shows the change in volume with capacitance without a series gap. This shows that in some cases where the capacitance is high on the magneto side a series spark gap may help ignition, while if the capacitance is high on the tube or spark plug side it may not.

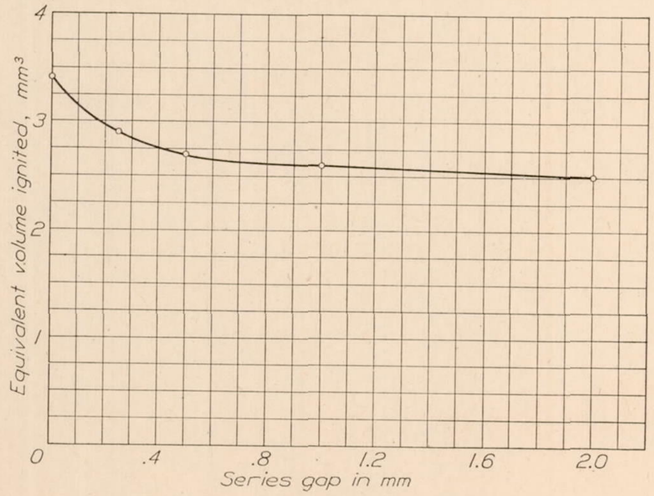

FIGURE 13

CONCLUSIONS

With the discharge tube used in this work and the circuits shown on Figures 7–10, the results may be stated as follows:

With constant total energy in the spark, the volume or mass of gases which combine increases with an increase in capacitance.

The volume of gases which combine is decreased with an auxiliary series spark gap if the capacitance of the circuit is small.

The volume of gases which combine with an auxiliary series spark gap is increased if the capacitance across the magneto is increased, and little change is noted if the capacitance across the tube is increased.

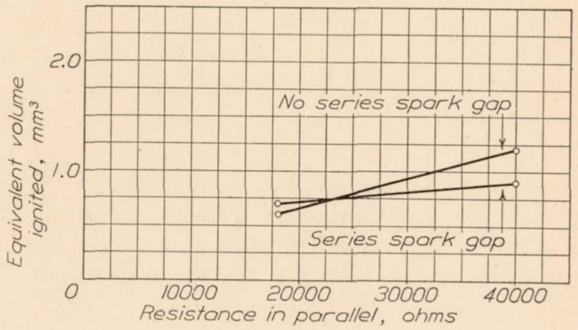

FIGURE 14

The volume of gases which combine is decreased if a resistance is shunted across the tube.

If a series spark gap is used, the volume of gases which combine is greater than without the gap if the resistance is low enough.

Figure 11 indicates that the method may be used to select the most effective spark generator. (It is well to pointout that this comparison was made at speeds below those found in practice, 80 r. p. m.)

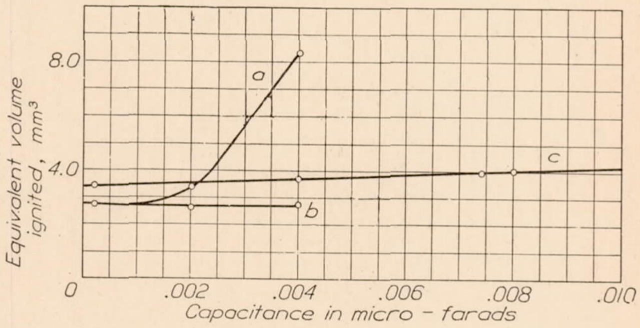

FIGURE 15

DISCUSSION OF RESULTS

Silsbee and Fonseca (Reference 9), using a Bosch D–6 magneto, found no appreciable change in the total energy of the spark when capacitances of 0.0017 μf and 0.0034 μf were placed across a spark gap in a calorimeter. Morgan (Reference 1) has found that if a spark from a magneto is passed through an explosive mixture, this spark being so feeble that an explosion does not take place, and then the capacitance across the gap is increased by means of a variable condenser, an explosion may follow. Morgan suggests the idea that the ability of a spark to ignite a mixture depends on the character of the spark, since the total energy of the spark which ignited the mixture was no greater, and probably less than that of a spark which failed to ignite it. What appears to be an explanation of Morgan's results follows at once from the curve shown by Figure 12. Here the volume of gases which receive sufficient energy from the spark to combine increases with an increase in capacitance. At the present stage of the work this seems a reasonable explanation.

Assuming the resistance of the circuit and discharge tube to be negligible in comparison with the reactance it is possible from available data to estimate roughly the maximum instantaneous current, total energy, energy in the capacitance component, and the energy in the inductive component of the discharge for all the electrical arrangements. Referring to Figure 12 the maximum instantaneous current is 10 amperes with the capacitance of the leads and magneto 0.0002 μf, and 330 amperes with 0.2 μf. With the smaller capacitance about 0.1 per cent of the energy is in the capacitance component or "head" and the remainder in the inductive component or the "tail." With the larger capacitance about 80 per cent of the energy is in the head.

The expression (Reference 10) "condensive portion of the spark" is used to denote that part of the spark which occurs immediately upon the breakdown of the gap. It is oscillatory in nature and highly damped and is due to the discharge of the energy which, prior to the breakdown of the gap, had been stored in the capacitance of the secondary circuit. This portion is commonly called the spark proper or head. The maximum current in this portion may be hundreds of amperes which exists for a few microseconds. What is called the inductive portion, the arc, or sometimes the tail of the spark, is that portion of the discharge which occurs after the oscillations of the condenser portion have ceased. It represents the discharge of the energy, which prior to the breakdown of the gap had been stored in the magnetic field of the coil (and electrostatically in the primary condenser). It is characterized by a current flow of a few milliamperes which gradually decreases to zero in a few milliseconds.

In a general way, it seems that the mass of gas ignited is closely related with the maximum current, but until measurements are made with a cathode ray oscillograph more can not be said. However, the trend of the results as shown in Figure 12 is in general accord with the idea that "hot sparks" are more effective, and changes which increased what in one sense or another might be considered the "intensity" of the spark were found to increase the mass of gas which reacted.

A second possible explanation for the increase in volume with an increase in maximum current is that the electrodes may become sufficiently heated to cause burning to take place.

These results can not be taken to answer completely the question as to what is the best spark for ignition, because many other factors must be taken into consideration. Since the tube used in this work had a much lower sparking potential than found in automotive engines, the numerical values are not directly applicable to the automotive engine. However, the general order in which the results vary with changes in the dimensions of the electrical circuit seems to be borne out by engine experience. If a tube is selected with a larger *d.s* the numerical values obtained should perhaps come closer to agreeing with experience. The curve on Figure 12 suggests the interesting inference that the volume of gases ignited increases with the cross section of the spark (as it appears to the eye at high pressures) increases. With the usual spark plug gap of 1 mm, the pressure required to give an equivalent *d.s* of the tube would be 76 mm of mercury at 0° C. If capacitance is added, the cross section of the spark appears to increase and so does the volume of the gas ignited.

Bureau of Standards,
Washington, D. C., *April 1930.*

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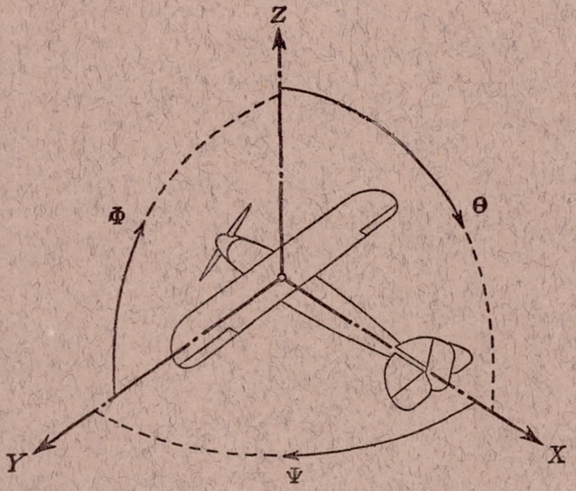

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L=\frac{L}{qbS} \qquad C_M=\frac{M}{qcS} \qquad C_N=\frac{N}{qfS}$$

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

4. PROPELLER SYMBOLS

D,	Diameter.
p_e,	Effective pitch.
p_g,	Mean geometric pitch.
p_s,	Standard pitch.
p_v,	Zero thrust.
p_a,	Zero torque.
p/D,	Pitch ratio.
V',	Inflow velocity.
V_s,	Slip stream velocity.
T,	Thrust.
Q,	Torque.
P,	Power.
	(If "coefficients" are introduced all units used must be consistent.)
η,	Efficiency $=T\,V/P$.
n,	Revolutions per sec., r. p. s.
N,	Revolutions per minute, r. p. m.
Φ,	Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.