File as NACA-TR-1287

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1287

SPARK IGNITION OF FLOWING GASES

By CLYDE C. SWETT, Jr.

1956

21

REPORT 1287

SPARK IGNITION OF FLOWING GASES

By CLYDE C. SWETT, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

National Advisory Committee for Aeronautics

Headquarters, 1512 H Street NW., Washington 25, D. C.

Created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight (U. S. Code, title 50, sec. 151). Its membership was increased from 12 to 15 by act approved March 2, 1929, and to 17 by act approved May 25, 1948. The members are appointed by the President, and serve as such without compensation.

REPORT 1287

SPARK IGNITION OF FLOWING GASES

By Clyde C. Swett, Jr.

SUMMARY

Research conducted at the NACA Lewis laboratory on ignition of flowing gases by means of long-duration discharges is summarized and analyzed. Data showing the effect of a flowing combustible mixture on the physical and electrical characteristics of spark discharges and data showing the effects of variables on the spark energy required for ignition of the combustible mixture are presented. A theory of ignition that has been developed to predict the effect of many of the gas-stream and spark variables is described and applied to a limited amount of experimental data.

The trends observed for ignition in flowing gases were similar to those observed in quiescent gases with the exception that increasing velocity and turbulence increased the ignition energy requirements. Lengthening of the discharge path by the flowing stream results in less energy being available to the important part of the discharge length. Flow also causes multiple discharges which should be avoided since they represent an energy loss. Less energy is required for ignition with an "arc" discharge than with a "glow" discharge. Effects of most of the variables on ignition energy requirements were predicted by theoretical equations; the effects of fuel-air ratio, however, required an empirical correction to the equations.

INTRODUCTION

Spark discharges are ordinarily used as the ignition source in aircraft engines. While such discharges are normally reliable sources of ignition, difficulty in starting jet engines has been encountered under these conditions:

(1) Ground starting in cold climates
(2) Altitude starting of auxiliary engines
(3) Altitude restarting of engines after flame blowout

Basic information on spark ignition of flowing gases might indicate the reasons for these ignition problems and might lead to the development of lighter weight, more efficient, and more reliable ignition systems.

For these reasons, the NACA Lewis laboratory has studied spark ignition in flowing gases; the object has been to promote understanding of the ignition process. The results of this work are reported in references 1 to 6. The present report summarizes and analyzes these results and points out their significance in relation to practical ignition problems.

The fundamental aspects of ignition of flowing combustible gases are considered in three sections of the report. First, the effect of gas velocity on the spark discharge is considered. The voltage necessary to form a spark, the physical shape of the spark discharge, and the electrical characteristics of the discharge under flow conditions are discussed. Second, the energy required to ignite flowing gases is considered. The parameters that affect the energy required for ignition are presented. The trends observed are compared with those observed with quiescent gases. Third, a theory which relates the factors affecting ignition is described. Correlations of experimental data based on the theory are presented. The concluding section points out the significance of the research in relation to practical ignition problems.

The following characteristics and parameters were investigated experimentally:

(1) Spark characteristics:
- Breakdown voltage
- Spark-discharge length
- Multiple discharges
- Current
- Voltage
- Voltage distribution
- Spark duration
- Energy
- Energy distribution

(2) Ignition energy parameters:
- Velocity
- Pressure
- Fuel-air ratio
- Temperature
- Turbulence
- Spark duration
- Electrode spacing
- Electrode diameter
- Electrode configuration
- Type of discharge
- Electrode material

(3) Ignition theory parameters:
- Velocity
- Pressure
- Fuel-air ratio
- Temperature
- Turbulence
- Spark duration
- Electrode spacing

Most of the research was conducted at pressures of 2 to 5 inches of mercury absolute. Limitations of energy-measurement equipment precluded operation at higher pressures where the energy requirements would be reduced. The research was conducted with two types of apparatus: (1) simple flow equipment that had no provisions for controlling turbulence and (2) equipment that had complete control of turbulence level. Only one combustible gas, a propane-air mixture, was used. This gas was ignited by a single long-duration spark discharge obtained from a resistance-capacitance ignition system.

SYMBOLS

a	constant
c_1, c_2, c_3, c_4, c_5	constants
c_p	specific heat at constant pressure
d_q	quenching distance of quiescent mixtures
E_{act}	energy of activation
E_c	energy in cathode region
E_{l_s}	energy in line source of ignition
E'_{l_s}	theoretical energy in line source of ignition required to heat ignition zone to flame temperature
E_p	energy in positive column
E_s	total energy of spark discharge
$f(\sqrt{\overline{u^2}})$, $f'(\sqrt{\overline{u^2}})$	functions of intensity of turbulence
i	current in discharge
J	conversion factor, heat to electrical energy
L_x	longitudinal scale of turbulence
m	mesh size of turbulence promoter
n	constant
P_{av}	average power in total spark discharge
P_{l_s}	average power in line source of ignition
p	static pressure
Q	heat of combustion of fuel
R	gas constant
r	radius of heated zone caused by energy in line source of ignition
s	electrode spacing
T_{am}	ambient temperature
T_F	flame temperature
$\mathcal{T}_{re}$	thickness of reaction zone across which the temperature change is $T_F - T_{am}$
t	time
t_s	spark duration
U	stream velocity
$\sqrt{\overline{u^2}}$	intensity of turbulence
v_c	cathode voltage drop
v_t	total voltage of discharge
X_f	mole fraction of fuel
X_O	mole fraction of oxygen
x	distance from turbulence promoter to spark electrodes
κ	thermal conductivity
ρ	density
Φ	work function of electrode

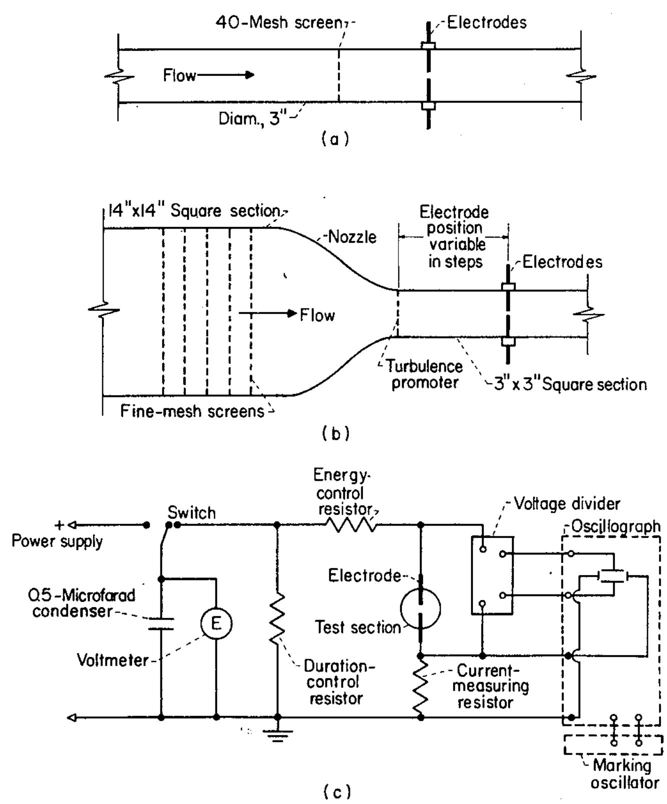
APPARATUS AND PROCEDURE

FLOW APPARATUS

The important features of the flow apparatus used are shown in figures 1(a) and (b). The complete systems are described in detail in references 2 to 6. Basically, the apparatus produced controlled-flow conditions of premixed propane and air in a test section in which the spark electrodes were located. Provisions were made for observing the spark and the flame. The criterion for ignition was appearance of flame downstream from the electrodes. In the simple flow apparatus (fig. 1(a)), the pressure, temperature, and velocity of flow were controlled. No attempt was made to vary the turbulence. The controlled-turbulence flow apparatus (fig. 1(b)) had a series of fine mesh screens to reduce the turbulence in a large section, a nozzle to accelerate the flow into the test section, a plate for installing different turbulence promoters upstream of the electrodes, and movable electrodes for varying the distance between the electrodes and the turbulence promoter.

IGNITION SYSTEM AND ENERGY MEASUREMENT

The ignition and energy-measuring systems used are described in detail in reference 3; they are shown schematically in figure 1(c). The condenser is charged and then discharged through a combination of resistors to cause a spark discharge.



(a) Simple flow apparatus.
(b) Controlled-turbulence flow apparatus.
(c) Ignition and energy-measuring equipment.
FIGURE 1.—Important features of flow apparatus and electrical equipment used for investigating spark ignition of flowing gases.

The energy and duration depend upon the relative values of condenser capacity, the voltage, and the resistances.

The voltage of the discharge was reduced by means of a balanced resistance-capitance voltage divider (ref. 3) and applied to the vertical plates of the oscillograph. A current-measuring resistance placed in series with the spark gap produced a voltage that was applied to the horizontal plates. These two voltages in conjunction with timing marks supplied by an oscillator gave an oscillogram from which energy and duration of the discharge could be determined.

The procedure used with this apparatus was as follows: the desired flow conditions were set, and a spark discharge was passed between the electrodes. Tests were run with varying amounts of energy until the minimum amount of energy that would cause ignition was determined. Then one or more oscillograms were obtained depending upon reproducibility at the particular condition. A more detailed description of the procedure used to obtain and analyze the ignition data is presented in references 1 to 6.

TURBULENCE MEASUREMENT

Descriptions of the hot-wire anemometer apparatus and methods used to measure the turbulence are included in reference 7. Single-wire probes measured the velocity fluctuations in the longitudinal direction, and ×-wire probes measured the velocity fluctuations in the lateral direction. A difference circuit was used in the lateral measurements to obtain the difference in velocity fluctuations from the two wires of the ×-wire probes. The spectrum of the turbulence was analyzed by means of a wave analyzer. An average-square computer totaled the kinetic energy in the velocity fluctuations to give the intensity of turbulence.

Measurements of the turbulence were made as follows: With the spark electrodes removed, the probe was inserted into the test section and located so that the hot wire would be at the center of the duct. After flow conditions were established using air in place of the combustible mixture, the intensity of turbulence was determined and a spectrum analysis made to determine the scale of the turbulence.

CHARACTERISTICS OF SPARK DISCHARGES IN FLOWING GASES

The characteristics of spark discharges in flowing gases were determined using air or a propane-air mixture. The ignition and energy-measuring system (fig. 1(c)) was used except for the breakdown voltage test, for which a simple power supply was used.

BREAKDOWN VOLTAGE

The breakdown voltage, or the lowest voltage that will cause a spark to be established between two electrodes, is one of the primary considerations in selecting an ignition system. The breakdown voltage of a spark gap in quiescent gas increases with electrode spacing and gas density and, to some extent, is dependent on the electrode configuration (ref. 8). The effect of gas velocity on voltage must also be known, since in aircraft jet engines a flowing fuel-air mixture must be ignited.

Figure 2 shows the effect of velocity and pressure on the direct-current breakdown voltage of 1/16- and 3/16-inch-diameter electrodes in air. These electrodes result in experimental data obtained under nonuniform (distorted) electrostatic field conditions. These data lie below Paschen's curve obtained for uniform or undistorted fields (ref. 8). For the larger electrode there is no effect of velocity on breakdown voltage. For the smaller electrode there may be a slight effect of velocity; however, for practical purposes the effect is negligible. Hence, it may be concluded that flowing gases do not have an adverse effect on the breakdown voltage of a spark gap.

SPARK-DISCHARGE LENGTH

The spark discharge established in a flowing gas ionizes a small channel of the gas. This ionized channel is subject to the motion of the stream. Therefore, the discharge should move with a velocity identical to the stream velocity.

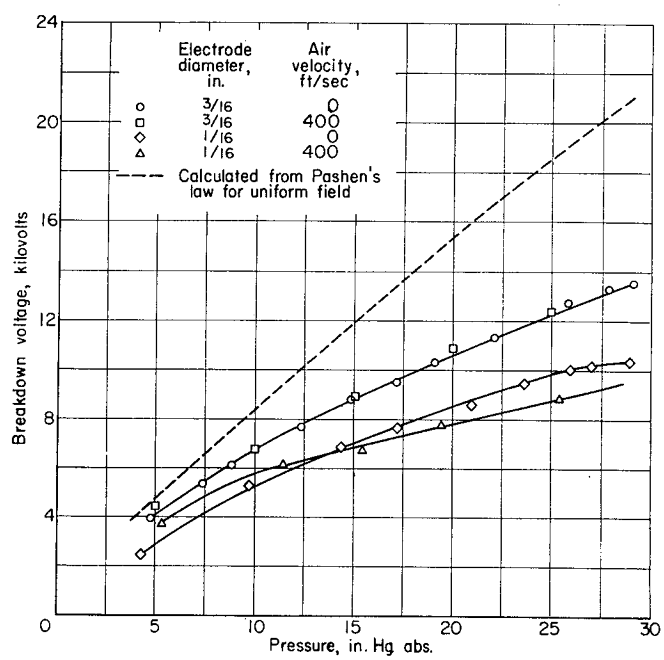


FIGURE 2.—Effect of pressure on direct-current breakdown voltage of spark gap in air. Temperature, 80° F; electrode spacing, 0.250 inch. (Data from ref. 1.)

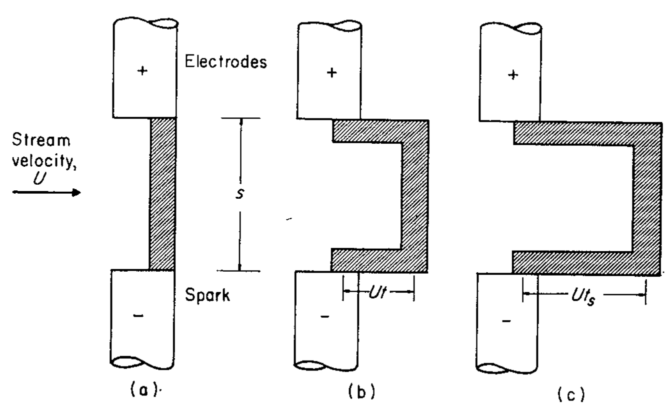


FIGURE 3.—Model of spark discharge in flowing gas showing lengthening of discharge path with time. (t, time; t_s, spark duration.)

The length of the discharge then varies with time and the shape approximates that shown in figure 3. At the instant the discharge is first established ($t=0$) in the flowing stream of velocity U, the discharge passes in a straight line between the electrodes. However, at some later times t and t_s (the instant the discharge ceases), the ionized path moves downstream and the discharge has the forms shown in figure 3. The paths shown in figure 3 are idealized; actually, considerable rounding of the discharge where the horizontal and vertical portions intersect would be expected. In theoretical analyses presented herein such rounding is neglected.

The distance traveled by the discharge at any time t is Ut, and the maximum distance traveled by the discharge is Ut_s. Some visual measurements have been made of the effect of U on the maximum distance traveled (fig. 4). The distances agree within 12 percent with the values calculated by multiplying U and t_s. The reasons for this large discrepancy may be that the technique for measuring durations was not fully developed at the time this particular set of data was obtained and that visual measurements were not very accurate.

The total spark length is made up of the horizontal and vertical lengths of the discharge and is equal to $s+2Ut$ for any time less than the discharge duration and $s+2Ut_s$ for the discharge duration. The value $s+2Ut_s$ is the maximum length that the discharge attains; rounding at the corners (fig. 3) shortens the length.

MULTIPLE DISCHARGES

The length and, hence, the resistance of the spark discharge are directly proportional to the stream velocity and time, so that for constant current the discharge voltage must increase with Ut_s. If this voltage increase is large enough to reach the breakdown voltage of the spark gap, a second spark is established directly between the electrodes, and the new discharge in turn also moves downstream. The first discharge ceases at the formation of the second discharge. The number of sparks that can be formed in this manner depends upon Ut_s and also on the voltage output characteristics of the spark source. These multiple dicharges should be distinguished from the repetitive discharges deliberately produced by commercial ignition systems. Such discharges may occur many times per second.

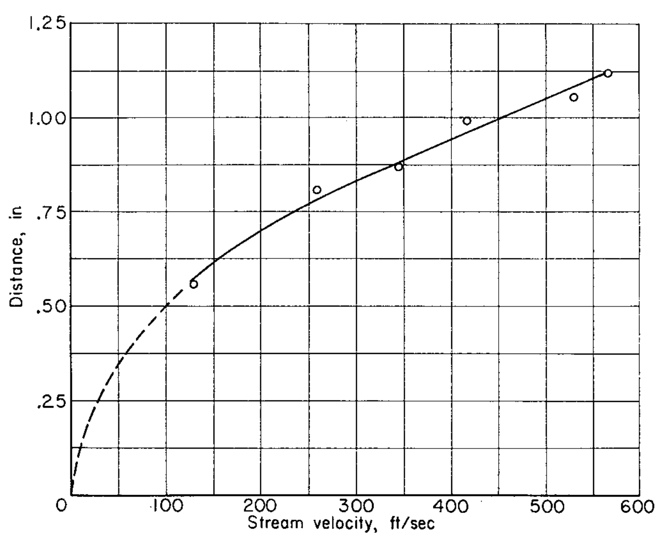


FIGURE 4.—Effect of airstream velocity on observed downstream displacement. Pressure, 11.36 inches of mercury absolute; temperature, 80° F; electrode spacing, 0.250 inch; electrode diameter, 3/16 inch. (Data from ref. 1.)

Table I shows the number of additional sparks formed after the initial spark for various conditions of air velocity, electrode spacing, electrode diameter, and pressure for one spark source. The number of sparks increases with increasing velocity, decreasing spacing, and decreasing pressure. For the data presented in table I, electrode diameter was unimportant. Increasing the duration of the discharge or the output voltage should also increase the number of sparks formed.

TABLE I.—NUMBER OF SPARKS AFTER INITIAL SPARK FOR VARIOUS CONDITIONS OF AIR VELOCITY, ELECTRODE SPACING, ELECTRODE DIAMETER, AND PRESSURE

[Data from ref. 1.]

Electrode spacing, 0.250 in.						Electrode spacing, 0.125 in.					
Air velocity, ft/sec	Pressure, in. Hg abs.					Air velocity, ft/sec	Pressure, in. Hg abs.				
	5.26	11.36	15.36	19.36	25.36		5.26	11.36	15.36	19.36	25.36
Electrode diameter, 1/16 in.											
0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	200	2	1	0	0	0
300	1	0	0	0	0	300	3	2	1	1	0
400	2	1	0	0	0	400	5	3	2	1	1
450	----	----	----	-------	0	450	----	----	----	----	1
480	----	----	----	-------	0	485	----	----	----	----	1
500	2	1	0	0	-----	500	7	5	3	2	----
550	3	1	1	0	-----	550	8	5	4	2	----
Electrode diameter, 3/16 in.											
0	0	0	0	[a]0, 0	-----	0	0	0	0	0	0
200	0	0	0	0	0	200	2	2	1	1	1, 0
250	----	----	----	0	-----	300	4	2	2	1	1
300	[a]1, 1	0	0	[a]0, 0	0	400	7	4	3	[a]3, 2	1
400	1	1	0	0	[a]0,0, 0	450	----	----	----	----	1
485	----	----	----	-------	[a]0,0, 0	480	----	----	----	----	3
500	[a]3, 3	1	0	[a]0,1, 0, 0	-----	500	9	4	3	3	----
560	3	1	----	-------	-----	550	----	[a]6, 6	4	----	----
565	----	----	[a]1, 0	[a]0,0, 0, 0	-----	555	----	----	5	----	----
570	----	----	----	0	-----	565	----	----	----	3	----
-------	----	----	----	-------	-----	575	9	----	----	----	----

[a] More than one observation made at this condition.

Multiple sparks are probably not desirable for ignition since the discharge energy is then distributed over too many separate channels or volumes. More energy is contained in the first of the multiple discharges than in the others, and that energy should be responsible for ignition.

CURRENT

The current of a spark discharge is determined largely by the impedance of the ignition source and to some extent by factors of the spark gap, especially in the case of long-duration discharges generated by a high-impedance source.

It can be shown that the current in the spark discharge using the ignition source shown in figure 1(c) should decrease exponentially during the life of the discharge if the gap resistance is constant. Actually, the resistance does vary somewhat so that the current does not decrease quite exponentially during the latter stages of the discharge, even under quiescent conditions. Also, as noted previously, the lengthening of the discharge under flow conditions increases the resistance so rapidly that there is a marked decrease in the

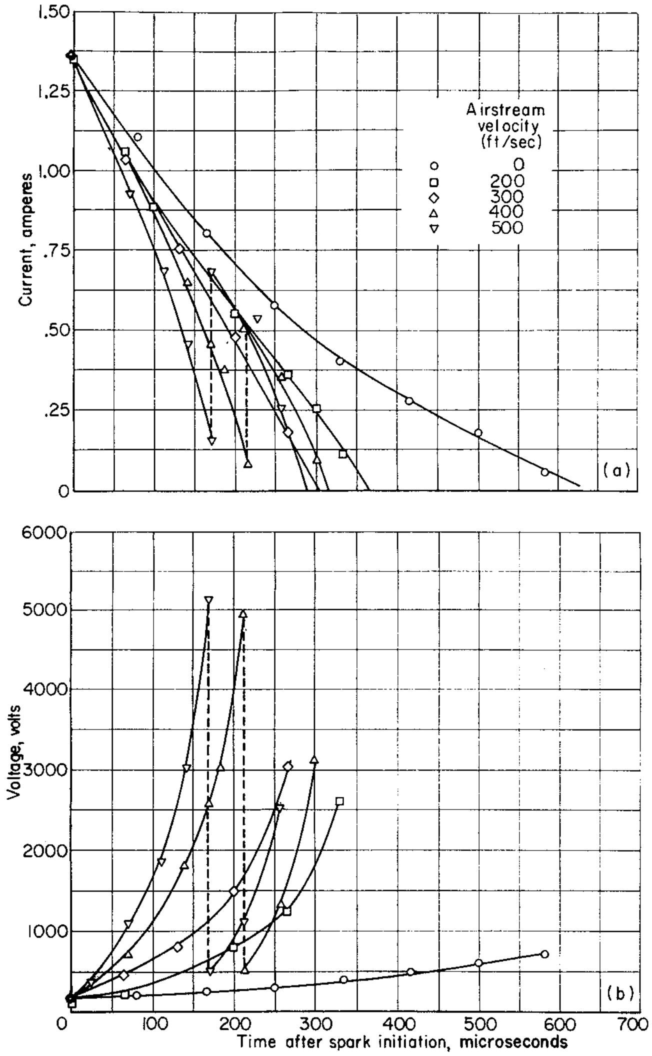


FIGURE 5.—Variation of voltage and current of spark discharge with time for various airstream velocities. Pressure, 11.36 inches of mercury absolute; temperature, 80° F; electrode spacing, 0.250 inch; electrode diameter, 3/16 inch. (Data from ref. 1.)

current. These effects are shown in figure 5(a), which compares the current and time characteristics of five discharges at various air velocities. At zero velocity the current decays almost exponentially. With flow the current decreases at a greater rate, the higher velocities causing greater decreases. Secondary spark discharges are formed at 400 and 500 feet per second as indicated by breaks in the curves (fig. 5(b)). The average rate of current decrease for the highest velocity is about twice that for no flow.

VOLTAGE

The total voltage of a discharge varies to a much greater extent with velocity than does the current. Total voltage also depends upon current, type of discharge, gas density, electrode spacing, and gas; it does not vary uniformly along the length of the discharge. Because this nonlinearity may have some bearing on the ignition process in combustible mixtures, this section discusses the component parts of the total voltage in addition to considering factors affecting the total voltage.

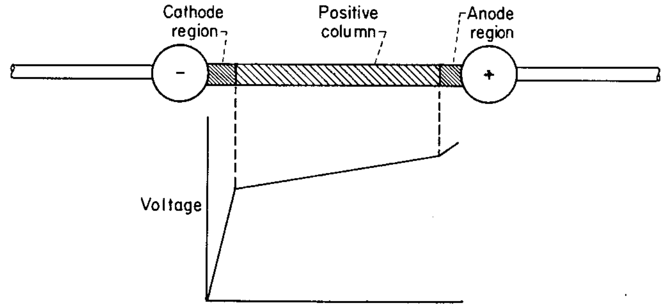


FIGURE 6.—Variation of voltage along constant-current discharge.

Component parts of the total voltage.—The total voltage of a discharge is the sum of the voltage drops in a number of specific regions along the length of the discharge. Consider the voltage along the discharge at any instant of time (fig. 6). At the negative or cathode end of the discharge there is a voltage change defined as the cathode drop. This drop can represent a considerable portion of the total voltage, and it occurs within an extremely short distance from the cathode. Next to the cathode-drop region is a region known as the positive column that occupies most of the discharge length. The voltage increases linearly with distance in this region. Between the end of the positive column and the anode there is another voltage change defined as the anode drop. This drop also occurs close to the electrode and has a magnitude approximately equal to the ionization potential of the gas (10 to 15 volts). Actually, both the anode and cathode regions contain one or more regions, but such division is unimportant for the present discussion. Reference 8 discusses all the regions in detail.

The cathode voltage drop determines the type of discharge that exists. Figure 7 shows how the cathode drop varies qualitatively with current and shows the general regions of the various types of discharges. The current of the spark discharge is continuously varying with time and therefore defines some portion of this curve. As the current is in-

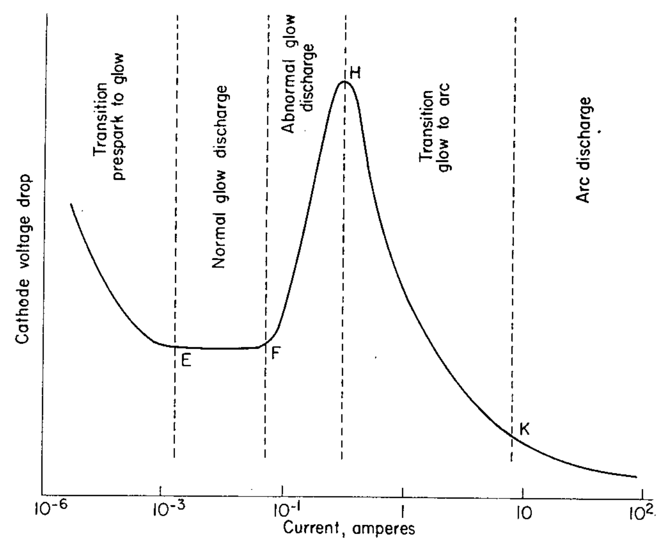


FIGURE 7.—Effect of discharge current on cathode voltage drop. (Data from ref. 16.)

creased from point E the voltage remains constant to point F. The region between E and F is defined as the normal glow discharge region. From F to H the voltage increases; this region is defined as the abnormal glow discharge region. From H to K the voltage decreases through a transition region with an arc discharge originating at point K. The cathode drop in the arc discharge can decrease to the order of magnitude of the ionization potential (10 to 15 volts). Frequently, the curve may be discontinuous between H and K, or the peak at H may not be observed; that is, the discharge may change from an arc to a normal glow without passing through the abnormal glow region.

Most of the ignition data reported herein were obtained with glow discharges. Therefore, the discussion is primarily concerned with the glow discharge, although many of the trends observed also apply to the arc discharge.

Methods are given in references 3 and 6 for determining cathode voltage drops experimentally at no flow and with flow, respectively. These methods assume the anode drop to be negligibly small. Figure 8 shows the cathode voltage drop determined for five electrode materials. The cathode drop is independent of current for the brass and cadmium electrodes. This effect is typical for the glow discharge (fig. 7). The cathode drop for the other metals is not independent of current, possibly because of the tendency of the discharge to be an abnormal glow discharge. The effect may also be partially due to experimental errors in the determination of the voltage.

The cathode-drop data shown in figure 8 correlate to a certain degree with the work function of the electrode material. The work function is a measure of the work required

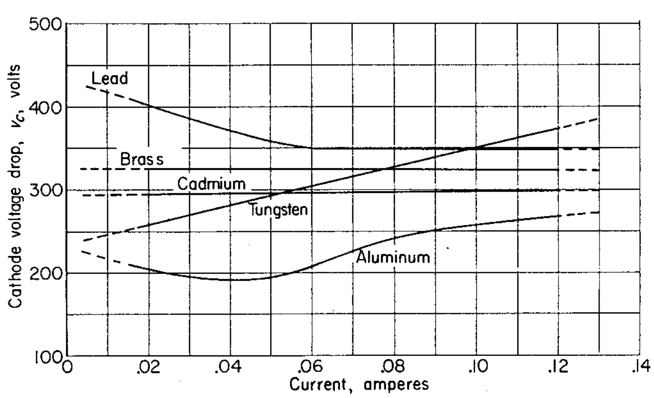


FIGURE 8.—Effect of current on cathode voltage drop for five electrode materials. Pressure, 3.0 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835; gas stream velocity, 5.0 feet per second; duration of discharge, approximately 600 microseconds. (Data from ref. 3.)

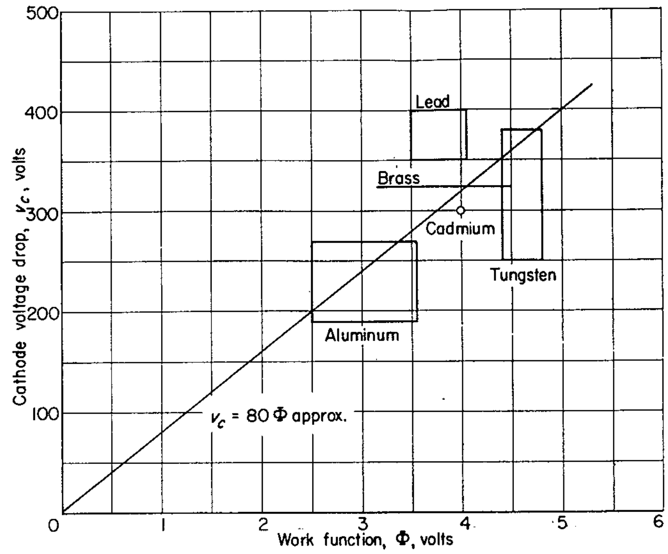


FIGURE 9.—Effect of work function on cathode voltage drop. Range of voltage drops from figure 8; range of work functions from reference 9.

to extract from the electrode the electrons that are necessary for maintaining the discharge. The correlation is shown in figure 9. The limits of the data cover the range of work functions found in the literature (ref. 9) and the range of cathode drops shown in figure 8.

The positive-column voltage is obtained by subtracting the cathode drop from the total voltage drop. The individual voltage drops, together with instantaneous-current data, determine the energies dissipated in the cathode region and in the positive column.

Total voltage.—The variation in voltage of a discharge with time is shown in figure 5(b). At zero velocity there is a gradual increase in voltage with time as the current decreases (fig. 5(a)). This effect is the result of the negative characteristic, that is, increasing voltage with decreasing current, typical of an arc discharge (fig. 7). With flow the rate of voltage increase is much greater because of lengthening of the discharge path. When the voltage reaches the breakdown voltage of the gap, approximately 5000 volts for the 400-foot-per-second curve, a new spark forms directly between the electrodes. The voltage then immediately falls to a low value and begins to increase again as the second discharge moves downstream.

With a glow discharge at high flow, the same trend found for the arc discharge is observed; however, at low or no flow the trend is opposite. That is, the voltage decreases as the current decreases during the life of the discharge. In this respect the glow discharge behaves somewhat like a resistance.

At the present time, the total voltage of a discharge cannot be predicted by any theoretical considerations. Empirically, the factors which determine the total voltage v_t have been shown to be related by the following equation:

$$v_t = v_c + 360s + 3460si \tag{1}$$

where v_c is the cathode drop, and the units are volts, amperes, and inches. A plot of this empirical equation is presented in figure 10. The total voltage varies linearly with spacing s when the current i is constant. In like manner, the total voltage varies linearly with current when the spacing is constant.

SPARK-DISCHARGE ENERGY

The most important characteristic of a discharge insofar as ignition is concerned is the energy dissipated in the discharge. The effect of several operating and design variables on the total energy and the division of total energy into its component parts are considered in this section.

Effect of variables on total energy.—The effect of velocity and pressure on total energy are shown in figure 11 for constant voltage, resistance, and capacitance of the ignition source. Energy increases with velocity and pressure. The energy increase occurs even with constant settings of the ignition source because of the manner in which the energy divides between the resistance of the discharge and the resistance in the ignition source. The discharge resistance is greatest at the higher velocity and, therefore, absorbs a greater portion of the energy. While the energy released in

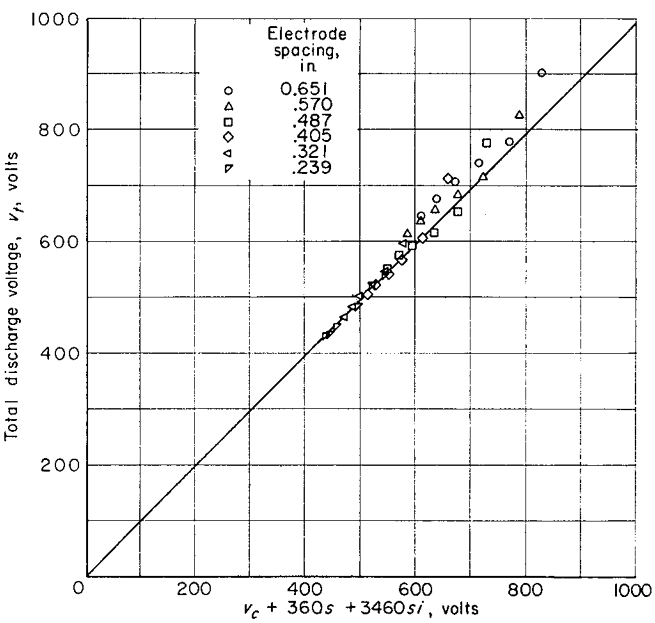


FIGURE 10.—Empirical correlation of total discharge voltage with cathode drop, electrode spacing, and spark current. Type of discharge, glow; electrode spacing s, inches; current i, amperes; cathode drop v_c, volts (325 for brass). (Data from ref. 3.)

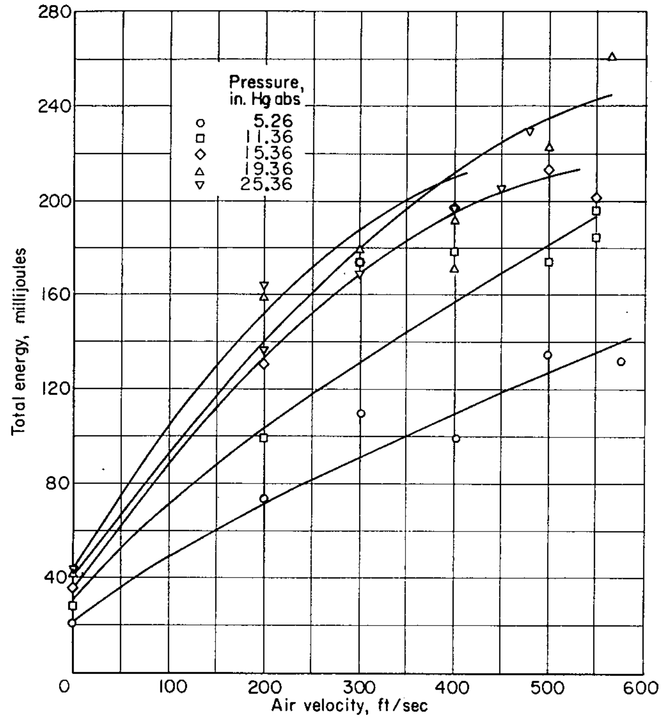


FIGURE 11.—Effect of air velocity and pressure on total discharge energy for constant settings of ignition system. Temperature, 80° F; electrode spacing, 0.125 inch; electrode diameter, 3/16 inch. (Data from ref. 1.)

the discharge increases with flow velocity, it is also distributed over a lengthening path. As is shown earlier, the path length of the discharge increases from s at no flow to $2Ut_s+s$ with flow.

The effect of temperature on total energy has been shown to be negligible over the range −67° to 80° F (ref. 1). An increase in electrode spacing with constant settings of the ignition system increases the energy because the discharge resistance increases without affecting the current markedly. The effect of electrode diameter is negligible.

Separation of total energy into its component parts.—The total energy of a spark discharge can be separated into its component parts when the voltage drop of each specific region along the discharge length is known. The voltage drop, determined as a function of time, is used with instantaneous-current values to determine energy. Since only two regions, cathode and positive-column, are considered, only the cathode energy need be determined. The positive-column energy is then the difference between the cathode energy and the total energy. The cathode energy represents a substantial part of the total energy. For example, reference 3 shows that one-third to one-half of the total energy is dissipated in the cathode region for a typical ignition condition.

SPARK DURATION

The duration of a spark discharge is primarily dependent on the relative values of resistance and capacitance in the ignition source, although factors of the gas stream do have

398301—57——2

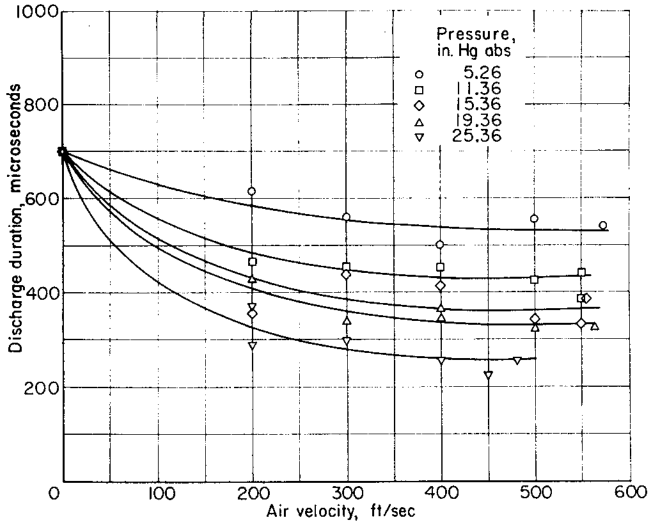


FIGURE 12.—Effect of air velocity and pressure on duration of discharge for constant settings of ignition system. Temperature, 80° F; electrode spacing, 0.125 inch; electrode diameter, 3/16 inch. (Data from ref. 1.)

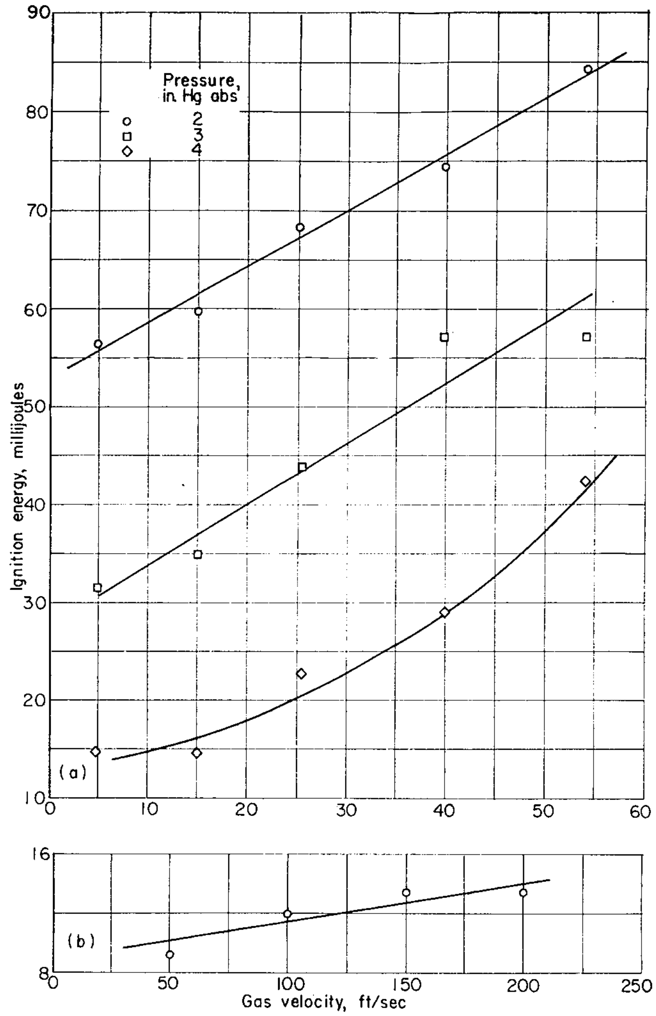
some effect. Figure 12 shows that the duration of the spark discharge is decreased by increasing the velocity and the pressure. Both of these factors increase the electrical resistance of the discharge and result in a larger voltage requirement. The maximum voltage of the spark source is reached in a shorter time (fig. 5(b)), and the discharge then ceases. Increasing the electrode spacing also causes the same result because it increases the length of the discharge.

EFFECT OF PARAMETERS ON IGNITION ENERGY REQUIREMENTS OF FLOWING GASES

The most important spark characteristic determining the ease of ignition is energy. If ignition is considered as a thermal mechanism, energy determines the amount of heat added, and hence the temperature rise of a volume of the combustible mixture. This section discusses the effects on ignition energy requirements of a number of variables that may be encountered in jet-engine operation. Some of the data to be presented were obtained at electrode spacings less than the quenching distance and so do not represent the minimum energy that would have been required with an optimum spacing. These data are indicated on the figures as having been obtained within the quenching distance.

VELOCITY

The effect of velocity on ignition energy is shown in figure 13. The required energy increases approximately linearly with velocity for both sets of data. The slopes of the curves are not directly comparable because of differences in pressure and electrode spacing. For example, figure 13(a) shows that an increase in mixture velocity from 5.0 to 54.2 feet per second required approximately a 300-percent increase in energy, whereas figure 13(b) shows that the energy increase is only about 50 percent for a velocity increase from 50 to 200 feet per second.



(a) Gas velocity and pressure. Data obtained in simple flow apparatus; electrode spacing, 0.25 inch (less than quenching distance); spark duration, approximately 600 to 800 microseconds. (Data from ref. 2.)

(b) Gas velocity. Data obtained in controlled-turbulence apparatus; electrode spacing, 0.37 inch; electrode diameter, 0.0225 inch; spark duration, approximately 500 microseconds. (Data from ref. 5.)

FIGURE 13.—Effect of gas velocity and pressure on energy required for ignition. Temperature, 80° F; fuel-air ratio, 0.0835.

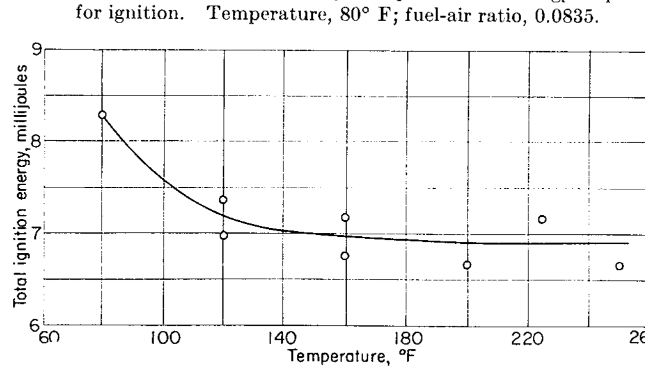


FIGURE 14.—Effect of initial temperature on total ignition energy. Pressure, 5.0 inches of mercury absolute; fuel-air ratio, 0.0835; gas velocity, 50 feet per second; electrode spacing, 0.37 inch; spark duration, 440 microseconds. (Data from ref. 6.)

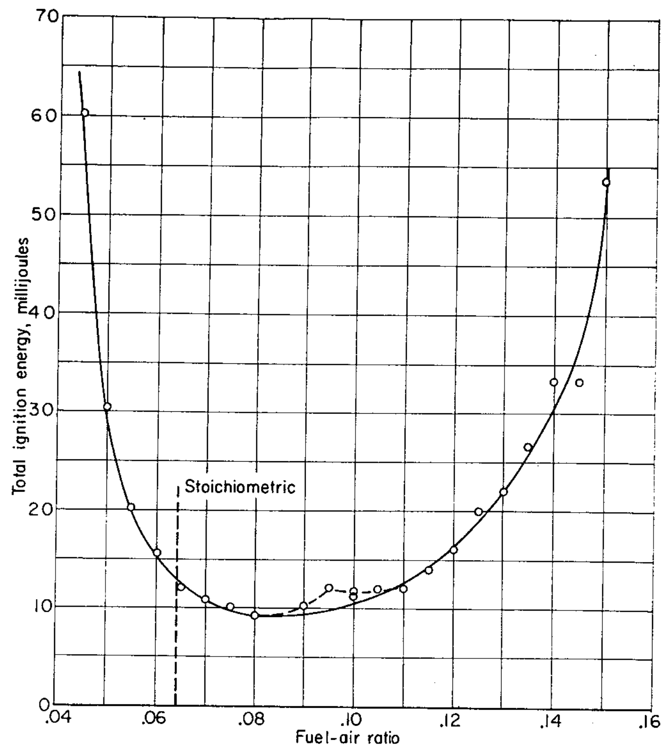


FIGURE 15.—Effect of fuel-air ratio on total ignition energy. Pressure, 5.0 inches of mercury absolute; temperature, 80° F; gas velocity, 50 feet per second; electrode spacing, 0.723 inch; spark duration, approximately 440 microseconds. (Data from ref. 6.)

PRESSURE AND TEMPERATURE

The effect of pressure on ignition energy is shown in figure 13(a). Energy decreases with increasing pressure in the same manner as found for ignition under quiescent conditions (ref. 10). The relation for ignition under flow conditions is $E \propto \frac{1}{p^n}$. The exponent n varies from about 1 to 2 for these data.

The effect of temperature (fig. 14) is also consistent with the trend found for quiescent gases (ref. 11) in that ignition energy decreases with increasing temperature.

FUEL-AIR RATIO

The effect of fuel-air ratio on ignition energy of flowing gases (fig. 15) is consistent with the trend observed for quiescent gases except that energy requirements are greater with a flowing mixture. The same fuel-air-ratio limits and minimum-energy point are observed. Close examination of the data points on the rich side of the minimum shows that the data might be better represented by the dashed line. Such double lobes have been observed in flammability-limit investigations with quiescent mixtures (ref. 12). The existence of a double lobe in figure 15 is questionable, however, and no great significance is attached to it.

TURBULENCE

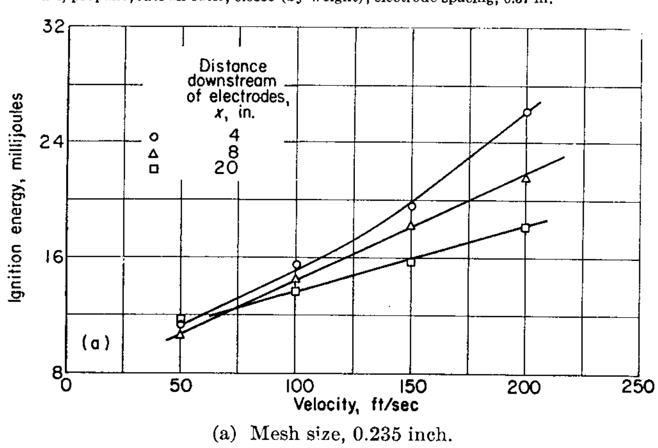
If a turbulence promoter such as a wire screen is placed upstream of the spark electrodes, the ignition energy requirement varies with the mesh size and the distance between promoter and electrodes. The trends are illustrated in figure 16, and the data are listed in table II. The ignition energy increases with increasing mesh size and with decreasing promoter-to-electrode distance.

TABLE II.—TURBULENCE AND IGNITION ENERGY DATA

[Pressure, 5.0 in. Hg abs; temperature, 80° F; data from ref. 5.]

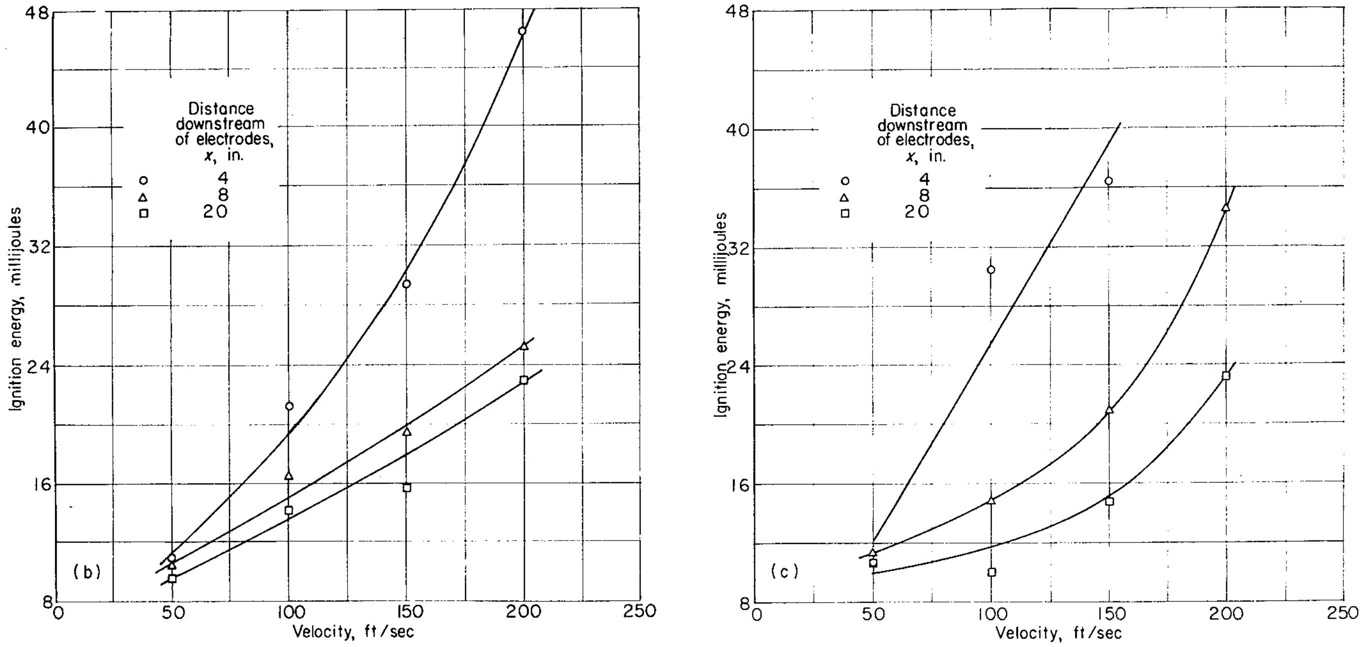
Mesh size of turbulence, promoter, in.	Velocity, U, ft/sec	Distance downstream, x, in.	Intensity of turbulence, $\sqrt{\overline{u^2}}$ ft/sec (a)	Scale of turbulence, L_x, in. (b)	Spark duration, t_s, microsec	Ignition energy, E_s, millijoules (c)
0.235	50	4	2.16	0.13	395	11.3
		8	1.19	.20	381	10.6
		20	.638	.35	415	11.6
	100	4	2.49	0.20	346	15.6
		8	1.88	.20	346	14.6
		20	.991	.30	325	13.7
	150	4	4.17	0.14	277	19.7
		8	2.35	.19	277	18.4
		20	1.26	.20	311	15.7
	200	4	5.76	0.15	277	26.4
		8	2.89	.20	277	21.7
		20	1.79	.30	249	18.27
0.525	50	4	3.44	0.17	464	11.0
		12	1.28	.26	450	10.6
		20	.868	.30	415	9.55
	100	4	7.34	0.20	415	21.2
		8	3.72	.23	381	16.5
		20	1.66	.30	388	14.1
	150	4	9.6	0.20	346	29.5
		8	5.25	.20	346	19.5
		20	2.62	.27	332	15.8
	200	4	11.8	0.19	318	46.4
		8	6.18	.20	346	25.2
		20	2.51	.30	318	23.0
0.625	50	4	4.0	--------	415	10.7
		8	2.03	--------	415	11.4
		20	1.03	--------	415	10.8
	100	4	7.04	--------	346	30.6
		8	3.61	--------	346	14.9
		20	1.76	--------	277	9.93
	150	4	9.08	--------	311	36.5
		8	5.68	--------	277	20.9
		20	2.55	--------	242	14.7
	200	4	11.8	--------	346	--------
		8	6.92	--------	277	34.6
		20	3.35	--------	208	23.2
No promoter	50	--------	--------	--------	346	9.28
	100	--------	--------	--------	311	12.0
	150	--------	--------	--------	242	13.5
	200	--------	--------	--------	208	13.5

[a] Obtained using air.
[b] Obtained using air. Data uncorrected for length of hot wire.
[c] Fuel, propane; fuel-air ratio, 0.0835 (by weight); electrode spacing, 0.37 in.



(a) Mesh size, 0.235 inch.

FIGURE 16.—Effect of velocity on ignition energy for various sizes and locations of turbulence promoters. Pressure, 5.0 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835; electrode spacing, 0.37 inch; electrode diameter, 0.0225 inch; spark duration, approximately 500 microseconds. (Data from ref. 5.)



(b) Mesh size, 0.525 inch. (c) Mesh size, 0.625 inch.

FIGURE 16.—Concluded. Effect of velocity on ignition energy for various sizes and locations of turbulence promoters. Pressure, 5.0 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835; electrode spacing, 0.37 inch; electrode diameter, 0.0225 inch; spark duration, approximately 500 microseconds. (Data from ref. 5.)

Attempts have been made to analyze the effects of turbulence promoters on ignition energy in terms of the characteristics of the turbulence produced. Figure 17 shows the effect of velocity, distance, and mesh size on the experimentally measured values of intensity of turbulence. As the ratio of distance to mesh size x/m is decreased, the intensity of turbulence increases. Comparison of the data of figures 16 and 17 indicates that the minimum ignition energy required increases with an increase in turbulence.

Another turbulence factor that must be considered is the scale of turbulence, which can be important in eddy diffusion. Table II shows values of scales and intensities of turbulence and ignition energies for various mesh sizes, promoter-electrode distances, and velocities. The scale of turbulence has no apparent effect on energy if data at constant velocity and at approximately constant intensity are compared, as in table III. Hence, for conditions covered by this work, scale of turbulence may be neglected.

SPARK DURATION

The effect of spark duration on the energy required for ignition at velocities of 5.0 and 54.2 feet per second and pressures of 3 and 4 inches of mercury absolute is shown in figure 18. As the spark duration was reduced from about 25,000 microseconds to about 100 microseconds, which was the limit of the measuring apparatus, the required energy decreased. The relation between energy and duration is not linear and is of the form $H \propto t_s^n$ where $n<1$. The decrease in energy with the shorter durations may be explained in terms of the spark-discharge length. Decreasing the dura-

TABLE III.—EFFECT OF SCALE OF TURBULENCE ON LINE-SOURCE AND TOTAL IGNITION ENERGIES

[Pressure, 5.0 in. Hg abs; temperature, 80° F; data from ref. 5.]

Mesh size of turbulence promoter, in.	Distance downstream, x, in.	Velocity, U, ft/sec	Intensity of turbulence, $\sqrt{\overline{u^2}}$ ft/sec	Scale of turbulence, L_x, in.	Line-source energy, E_L, millijoules	Total ignition energy, E_t, millijoules (a)
0.235	8	50	1.19	0.17	6.9	10.6
.525	12		1.23	.26	6.6	10.6
0.235	4	200	5.76	0.15	11.2	26.4
.525	8		6.13	.20	9.6	25.2

a Fuel-air ratio, 0.0835; electrode spacing, 0.37 in.

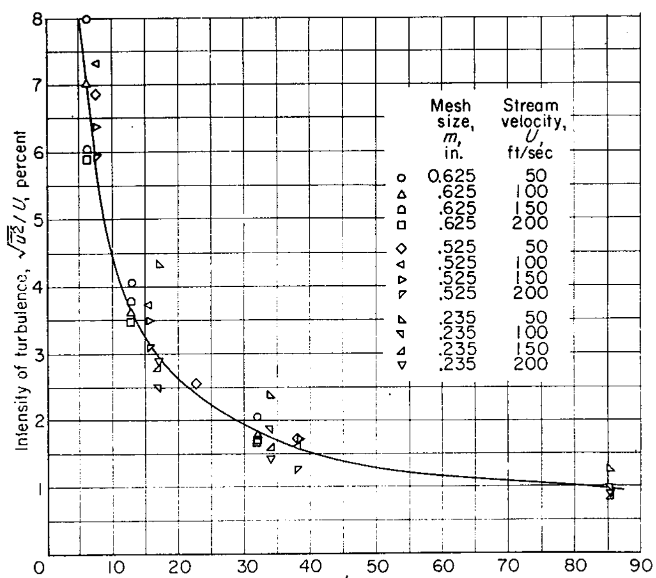


FIGURE 17.—Effect of x/m on $\sqrt{\overline{u^2}}/U$ for various values of mesh size and velocity. (Data from ref. 5.)

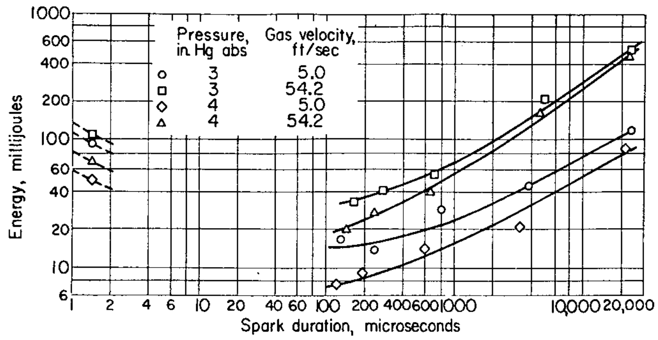


FIGURE 18.—Effect of spark duration on energy required for ignition. Temperature, 80° F; fuel-air ratio, 0.0835; electrode spacing, 0.25 inch (less than quenching distance). (Data from ref. 2.)

tion reduces the length of the discharge and thereby distributes the energy over a smaller volume. This distribution should result in a more effective ignition source.

An attempt was made to define minimum ignition requirements for very short duration discharges. A capacitance spark, that is, one obtained by discharging a condenser directly into the gap, was used. The energy values obtained in this manner, for a spark duration of 1.5 microseconds, are shown in figure 18. The fact that these energies are higher than those for longer duration sparks is contrary to the trends observed for spark durations between 100 and 25,000 microseconds. The discrepancy is explained in reference 3 as possibly being due to differences in the way the energy is distributed along the discharge length. It is not due to the fact that the data were obtained with electrode spacing less than quenching distance, since reference 3 shows the same trend with spacing equal to quenching distance.

ELECTRODE SPACING

As shown in figure 19, the effect of electrode spacing on ignition of flowing gases is similar to that observed for quiescent gases (ref. 10). As the electrode spacing was increased from about 0.25 inch, the energy required decreased for a variety of electrodes. With the smaller electrodes the spacing for minimum energy was not sharply defined. The increase in energy at spacings less than 0.65 inch is attributed to quenching of the initial flame zone by the electrodes. At the optimum spacing (0.65 in.), or arbitrarily assumed quenching distance, the quenching effect is a minimum. This quenching distance is the same as found for quiescent mixtures for the particular pressure and fuel-air-ratio conditions (ref. 10). The energy requirement increased at spacings greater than 0.65 inch for the same reason that the energy requirement increased with increased flow velocity, that is, the lengthening of the discharge path.

ELECTRODE DIAMETER AND CONFIGURATION

The effects of electrode diameter and configuration are also shown in figure 19. The data show that at the quenching distance (0.65 in.) the size or shape of the electrodes has no significant effect. However, at shorter spacings the larger electrodes require more energy for ignition because of their larger surface area for flame quenching. This same trend has been observed for capacitance sparks in quiescent mixtures (ref. 10). The fact that the sharp-needle electrodes

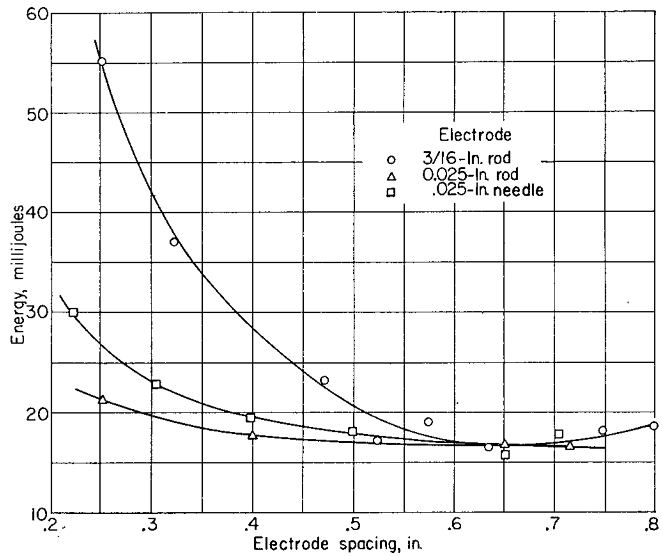


FIGURE 19.—Effect of electrode diameter, configuration, and spacing on ignition energy. Pressure, 3 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835; velocity, 5.0 feet per second. (Data from ref. 3.)

required slightly higher energy in spite of smaller surface area may possibly be due to differences in the manner in which the energy is distributed along the length of the discharge for sharp points and rods.

TYPE OF DISCHARGE

The type of discharge used affects the energy required. Figure 20 shows data obtained with stainless steel electrodes that resulted in a glow discharge and data obtained with cadmium electrodes that resulted in a discharge designated as an arc-glow discharge. This discharge started as an arc discharge but changed into a glow discharge. For most of its life it was an arc discharge, however. The glow discharge required a higher ignition energy than did the arc discharge. This effect was not due to differences in electrode material, for after many trials a glow discharge was obtained with the cadmium electrodes. The energy value so obtained was comparable to that obtained with the stainless steel electrodes.

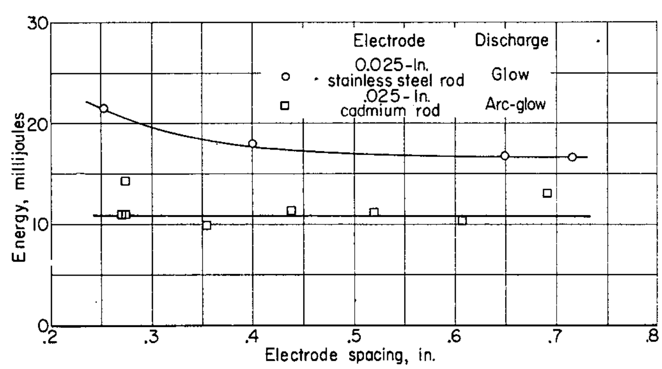


FIGURE 20.—Effect of electrode material and spacing on ignition energy. Pressure, 3 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835; velocity, 5.0 feet per second. (Data from ref. 3.)

The fact that the arc discharge has lower cathode and total energy may indicate that the positive-column energies of both arc and glow discharges were equal and that the ignition occurred in the positive column. There are no experimental measurements of cathode energies for the arc-glow discharge; the experimental method used for the glow discharge failed when such measurements were attempted because the transition between arc and glow upset cross-plotting techniques. Therefore, positive-column energies of the two discharges cannot be compared at the present time.

ELECTRODE MATERIAL

Investigations such as those reported in reference 13 indicate that electrode material has an effect on ignition in quiescent mixtures. The data show that decreasing density of the electrode material generally decreased the amount of energy required to ignite a flammable mixture. However, the type of discharge, that is, arc or glow, was not determined, and the observed effect may have been due to the type of discharge and not to the electrode material.

The effect of electrode material on ignition of flowing gases is reported in reference 3, which shows that at least for the glow discharge the ignition energy is negligibly affected by electrode material. Data reported in reference 3 may be summarized as follows:

Metal	Ignition energy, millijoules [a]
Lead	17.1±0.5
Brass	17.8±0.5
Cadmium	18.6±0.5
Aluminum	19.4±0.7
Tungsten	19.6±0.9

[a] Obtained with ⅜-inch-diam. spheres spaced 0.65 inch apart; pressure, 3.0 in. Hg abs; temperature, 80° F; velocity, 5.0 ft/sec; fuel-air ratio, 0.0335; spark duration, 600 μsec.

DEVELOPMENT AND TESTS OF A THEORY OF IGNITION OF FLOWING GASES

It is shown previously that a large number of variables affect not only the physical and electrical characteristics of a spark discharge but also the ease of ignition of a flowing combustible gas. Theoretical equations that show how these variables may be related for both nonturbulent and turbulent flow are discussed in this section. Experimental data that are available are then applied to these relations.

CONCEPT OF LINE SOURCE OF ENERGY

Most investigations of ignition of combustible gases consider total energy of the discharge as the experimental variable. It is noted earlier, however, that the total energy is not distributed uniformly along the length of the discharge and that the distribution may be important to ignition. Ignition may conceivably proceed from only a portion of the discharge length, and the energy contained in this length must then be the basis for theoretical analysis. The model used to develop a theory for the ignition of flowing gases is shown in figure 21. After a spark discharge moves downstream and is extinguished at time t_s, there exists a heated zone larger in diameter than the discharge itself but in a path coincident with that of the discharge. The vertical portion of the discharge (fig. 21) moves at stream velocity so that the same volume of gas is continuously heated, whereas the legs of the discharge lengthen with time so that fresh gas is continuously being heated at the electrode ends of the discharge. Hence, it may be considered that the zone surrounding the vertical portion of the discharge is at a much higher temperature than the legs and, therefore, constitutes a more probable zone of ignition. This vertical zone, or line source of ignition, is used in the development of the theory of ignition of flowing gases.

The line source of energy consists of a portion of the positive column of the discharge. The energy dissipated in the cathode region is assumed to be unimportant to the ignition process. This is a reasonable assumption, since, according to reference 8, in a glow discharge almost all of the cathode energy is lost to the cathode.

The energy in the line source of ignition can be calculated if two assumptions are made. The first assumption is that the total amount of energy in the discharge at any time varies linearly with time. Actually, for the ignition data presented herein the energy goes into the discharge somewhat more rapidly during the first part of the discharge; however, the assumption of uniform energy release is believed sufficiently accurate for practical use. The second assumption is that the power per unit length of discharge at any time is constant. The power can be based on either the total power if the cathode energy is assumed uniformly distributed throughout the gap or on the power in the positive column. Actually, in order to agree with the concept of the line source of energy, the power should be based on the positive column only; but for practical reasons involved in measurement of cathode energies, total power is used in most of the analysis. Correction of the data to include positive-column energies only is discussed later.

The average power P_{av} of the total energy E_s is E_s/t_s, where t_s is the spark duration. This average power is divided into two portions: the line source and the legs of the discharge. The relative amounts dissipated in each region depend upon the respective lengths of the legs and, hence, on time and gas velocity. The amount of power available for the line source at any instant is

$$P_{l_s}=\frac{s}{2Ut+s}P_{av}$$

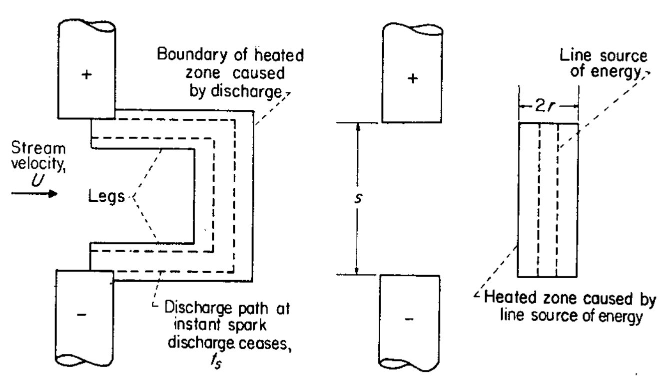


FIGURE 21.—Model used to develop concept of line source of energy.

The energy of the line source E_{l_s} is the integral of this instantaneous power with respect to time taken over the discharge duration or

$$E_{l_s}=\int_0^{t_s} P_{l_s}\,\mathrm{d}t$$
$$=\int_0^{t_s}\frac{s}{2Ut+s}\,\frac{E_s}{t_s}\,\mathrm{d}t \qquad (2)$$
$$=\frac{E_s s}{2Ut_s}\ln\frac{2Ut_s+s}{s}$$

Equation (2) assumes the cathode and anode energies to be uniformly distributed over the whole length of the discharge. If the cathode energy is assumed to be lost to the electrode, E_s in equation (2) may be replaced by E_p where $E_p=E_s-E_c$:

$$E_{l_s}=\frac{E_p s}{2Ut_s}\ln\frac{2Ut_s+s}{s} \qquad (3)$$

Equation (2) is used herein because E_c, and hence E_p, are difficult to measure accurately.

DEVELOPMENT OF THEORETICAL EQUATIONS

The process of establishing steady burning of a homogeneous fuel-air mixture from a long-duration discharge is visualized as follows: The line source of ignition is assumed to supply the heat necessary to raise the temperature of the heated zone to flame temperature. The initial flame then propagates if the heated zone is of proper volume to fulfill the condition that the rate of heat generation in the volume be equal to or greater than the rate of heat loss from the volume. An additional requirement is that the electrode spacing be equal to the quenching distance in order to preclude quenching effects. No heat losses from the heated zone either to the electrodes or to the gas during the spark duration are considered; also, no heat is considered to be supplied from any chemical reaction during this period.

The relation between ignition energy and operating variables can be determined by comparing the line-source energy with the theoretical amount of energy necessary to raise the temperature of the volume under consideration to flame temperature. The radius r of the heated volume (fig. 21) is the unknown dimension of the volume. Since both the rate of heat generation and the rate of heat loss are functions of the radius, equating these rates results in a value for the critical radius. The rate of heat generation in this heated zone is dependent upon the size of the volume and upon a reaction-rate term, whereas the rate of heat loss not only depends upon the size of the zone but also upon the method of heat transfer, that is, thermal conduction or eddy diffusion. According to the concept of a line source of energy, the zone is moving at stream velocity and, therefore, may be considered as a zone in a quiescent mixture if no turbulence is present. Heat is, therefore, lost from the zone by thermal conduction (neglecting radiation). If turbulence is present, heat can be lost by both thermal conduction and eddy diffusion. The equations have been developed for two cases: (1) heat transfer by thermal conduction when intensity of turbulence is low and (2) heat transfer by eddy diffusion when intensity of turbulence is high. In the latter case it was assumed that thermal conduction is negligible compared to eddy diffusion.

Nonturbulent flow.—The equations for the rate of heat generation and the rate of heat loss are those of reference 11 converted from the spherical to the cylindrical case:

$$\text{Rate of heat generated}=\pi r^2 d_q Q X_f X_O \rho^2 a e^{-\frac{E_{act}}{RT_F}} \qquad (4)$$

$$\text{Rate of heat loss}=\frac{2\pi r d_q \kappa (T_F-T_{am})}{\mathcal{J}_{re}}$$
$$=\frac{2\pi r d_q \kappa (T_F-T_{am})}{c_1 r} \qquad (5)$$

The term $c_1 r$ has been substituted for $\mathcal{J}_{re}$ as done in reference 11. This substitution is an approximation; proof for its use is as follows: Equating equations (4) and (5) and solving for r give

$$r=\sqrt{\frac{2\kappa(T_F-T_{am})}{c_1 Q X_f X_O \rho^2 a e^{-\frac{E_{act}}{RT_F}}}} \qquad (6)$$

Equation (6) gives the critical size of the zone and indicates that r is inversely proportional to the square root of reaction rate. In a flame front the thickness of the reaction zone $\mathcal{J}_{re}$ is approximately inversely proportional to the square root of the reaction rate; hence, r must be proportional to $\mathcal{J}_{re}$. The amount of energy necessary to increase the temperature of the zone from T_{am} to T_F is

$$E'_{l_s}=J\pi r^2 d_q \rho c_p (T_F-T_{am})$$
$$=\frac{2\pi J \kappa d_q c_p (T_F-T_{am})^2}{c_1 Q X_f X_O \rho a e^{-\frac{E_{act}}{RT_F}}} \qquad (7)$$

The theoretical energy should be equal to the line-source energy,

$$E'_{l_s}=E_{l_s}$$

$$\frac{2\pi J \kappa d_q c_p (T_F-T_{am})^2}{c_1 Q X_f X_O \rho a e^{-\frac{E_{act}}{RT_F}}}=\frac{E_s d_q}{2Ut_s}\ln\left(\frac{2Ut_s+d_q}{d_q}\right)$$

or

$$\frac{4\pi J U t_s \kappa c_p (T_F-T_{am})^2}{c_1 E_s Q X_f X_O \rho a e^{-\frac{E_{act}}{RT_F}}}=\ln\left(\frac{2Ut_s+d_q}{d_q}\right) \qquad (8)$$

Turbulent flow.—For turbulent flow the rate of heat loss depends on the rate at which mass is transferred by eddy diffusion through the cylindrical surface of area $2\pi r d_q$.

The two factors that control the diffusion process are the intensity and the scale of turbulence. When the scale of turbulence is large compared to the flame-front thickness as it is for this problem, the effect of scale on the diffusion process is negligible compared to the effect of intensity of turbulence; hence, the effect of scale is not included in the analysis that follows.

The rate of heat loss is a function of the product of surface area, density, specific heat, temperature difference, and a term representing the velocity with which heat moves through the surface. The velocity term can be represented by some function of the intensity of turbulence, or $f'(\sqrt{\overline{u^2}})$. The function involves the first power of $\sqrt{\overline{u^2}}$ in order to be correct dimensionally. Thus,

$$\text{Rate of heat loss} = 2\pi r d_q \rho c_p (T_F - T_{am}) f'(\sqrt{\overline{u^2}}) \tag{9}$$

For ignition conditions equation (9) equals equation (4). Solving for r gives

$$r = \frac{2c_p(T_F - T_{am})}{QX_fX_O\rho a e^{-\frac{E_{act}}{RT_F}}} f'(\sqrt{\overline{u^2}})$$

The theoretical energy required to increase the temperature of the heated zone to flame temperature under turbulent-flow conditions is

$$E'_{l_s} = J\pi r^2 d_q c_p \rho (T_F - T_{am})$$

$$= \frac{4\pi J d_q c_p^3 (T_F - T_{am})^3}{Q^2 X_f^2 X_O^2 \rho a^2 e^{-\frac{2E_{act}}{RT_F}}} f(\sqrt{\overline{u^2}})$$

where $f(\sqrt{\overline{u^2}})$ is a new function of the intensity of turbulence.

The relation between the theoretical and the line-source energies is therefore

$$\frac{4\pi J d_q c_p^3 (T_F - T_{am})^3}{Q^2 X_f^2 X_O^2 \rho a^2 e^{-\frac{2E_{act}}{RT_F}}} f(\sqrt{\overline{u^2}}) = \frac{E_s d_q}{2Ut_s} \ln\left(\frac{2Ut_s + d_q}{d_q}\right) \tag{10}$$

or

$$\frac{E_s Q^2 X_f^2 X_O^2 \rho a^2 e^{-\frac{2E_{act}}{RT_F}}}{8\pi U t_s J c_p^3 (T_F - T_{am})^3} \ln\left(\frac{2Ut_s + d_q}{d_q}\right) = f(\sqrt{\overline{u^2}}) \tag{11}$$

APPLICATION OF THEORETICAL EQUATIONS TO EXPERIMENTAL DATA

Only limited data are available to verify the theoretical equations. Although a considerable amount of data has been obtained, much of it cannot be used in the equations because of differences in type of discharge or because electrode spacings were less than the quenching distance. The data used with the equations following are those obtained with glow discharges and with spacing equal to the quenching distance.

Nonturbulent flow.—Data to be applied to the nonturbulent-flow equation were obtained with one fuel and one fuel-air ratio; hence, equation (8) may be reduced to

$$\frac{c_2 U t_s \kappa c_p T_F (T_F - T_{am})^2}{p E_s e^{-\frac{E_{act}}{RT_F}}} = \ln \frac{2Ut_s + d_q}{d_q} \tag{12}$$

where $\rho \propto \frac{p}{T_F}$. A plot of this relation is shown in figure 22 along with a table of the operating conditions and references for each point. The correlation is satisfactory for the limited data available.

Equation (8) indicates that there is an effect of fuel-air ratio. The data of figure 15 were applied to this equation which, for the operating conditions of the figure and for $\rho \propto 1/T_F$, reduces to

$$\ln \frac{E_s X_f X_O \ln \frac{2Ut_s + d_q}{d_q}}{T_F (T_F - T_{am})^2} = c_3 + c_4 \left(\frac{1}{T_F}\right) \tag{13}$$

A plot of the data using equation (13) is shown in figure 23. A single straight line, which would be predicted by the theory, was not obtained. There is a factor of about 2 between the values for the rich and lean ends of the curve. Possible reasons for this discrepancy are discussed later.

	Pressure, in. Hg abs	Velocity, ft/sec	Temperature, °F	Spark duration, microseconds	Electrode spacing, in.	Reference
○	3	5	80	600	0.65	3
□	5	50	225	440	.37	6
◇	5	50	250	440	.37	6
△	5	50	80	346	.37	5
▽	5	100	80	311	.37	5
◁	5	150	80	242	.37	5
▷	5	150	80	208	.37	5

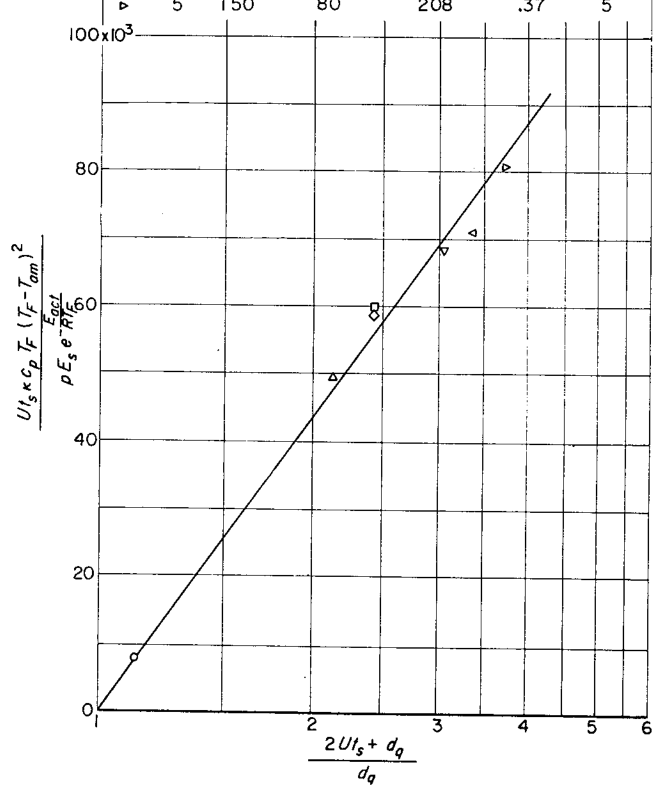


FIGURE 22.—Correlation of nonturbulent-flow data at fuel-air ratio of 0.0835.

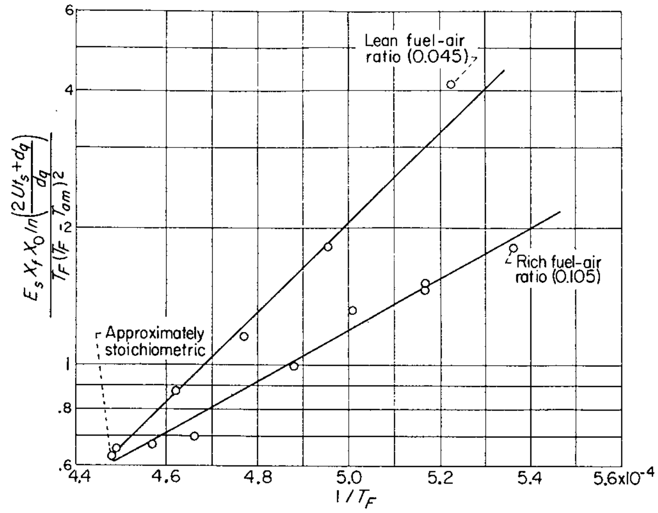


FIGURE 23.—Curve obtained by applying ignition-energy and fuel-air-ratio data to equation (13). (Data (fuel-air ratio 0.045 to 0.105) from fig. 15.)

Turbulent flow.—The data used to verify the turbulent flow equation (11) are those presented in figure 16. For the conditions used to obtain these data, equation (11) may be reduced to

$$\frac{E_s}{Ut_s}\ln\frac{2Ut_s+d_q}{d_q}=c_5 f\left(\sqrt{\overline{u^2}}\right) \tag{14}$$

Data calculated according to this relation are plotted in figure 24, which shows that a reasonably good correlation exists among the variables: energy required for ignition, stream velocity, and intensity of turbulence. The data correlated with an average deviation of 11 percent and a maximum deviation of 35 percent.

In developing the theory, the effect of scale of turbulence was considered unimportant. Experimental verification of this fact is indicated in table III, which shows a comparison of both line-source and total ignition energies at approximately constant intensities of turbulence but varying scales of turbulence. With the experimental errors involved and small variation in scale investigated, it must be concluded that the effect of scale, if any, is small.

DISCUSSION OF THEORY

The theory that is described in the preceding section and its experimental verification mark the first attempt to treat ignition of flowing gases and, as such, are greatly simplified. The many approximations and assumptions that are made may be summarized as follows:

(1) The analysis is based on a second-order reaction for the rate of heat generation.

(2) Diffusion processes are neglected.

(3) Radiation from the ignition zone is neglected.

(4) An approximation is made of thickness of the reaction zone.

(5) The average power of the discharge is assumed to be constant.

(6) The discharge is assumed to take the shape of a square-cornered U; rounding effects at the corners are neglected.

(7) Cathode energy is assumed evenly distributed along the length of the discharge.

(8) There are no heat losses from the heated zone left by the spark during the duration of the discharge.

(9) There is no heat resulting from chemical reaction in the heated zone during the duration of the discharge.

Many of these assumptions could be removed from the theory, but the theoretical treatment would be unduly complicated.

The data used to verify the theory are limited in scope. This is the result of using data from one type of discharge (glow). Glow discharges are mostly obtained at low pressures, and arc discharges are obtained at higher pressures. Energy measurements cannot be made at higher pressures, because the small amount of energy required for ignition at high pressures becomes comparable to the energy stored in the capacitance of the voltage divider. This latter energy is not measured by the oscillographic technique used.

The effects on ignition energy of all operating variables except fuel-air ratio were correlated by the theoretical relations. Other investigators have also encountered inconsistencies in variable-fuel-air-ratio data. For example, in reference 10, which describes an ignition theory of quiescent gases that is separate and distinct from the one described herein, data obtained over a range of fuel-air ratios did not correlate with theoretical relations. The trends observed with the two theories may be compared by calculating the ratios of theoretical to experimental energy for the two sets of data. The term

$$\frac{4\pi J U t_s \kappa c_p (T_F-T_{am})^2}{c E_s Q X_f X_O \rho a e^{-\frac{E_{act}}{RT_F}} \ln\frac{2Ut_s+d_q}{d_q}}$$

derived from equation (8) represents the ratio of theoretical to experimental energy for the data contained in this report. The values of κ and c_p in this equation were assumed constant, and a value of 26 kilocalories per mole was used for E_{act}. The energy ratios for the two sets of data were multiplied by constants in order to adjust the energy ratios to a

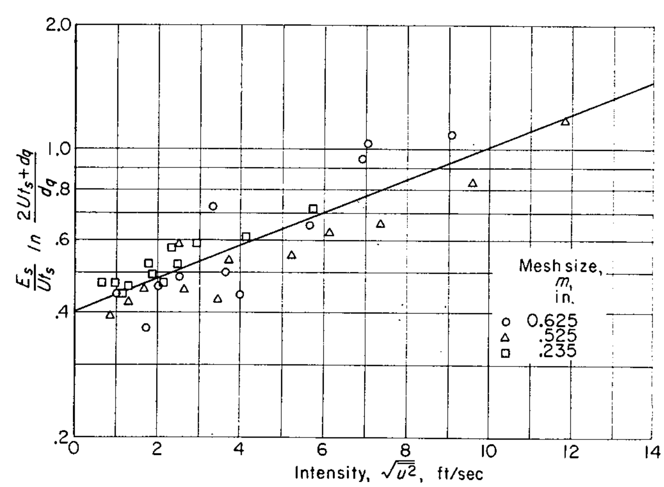


FIGURE 24.—Correlation of ignition data with intensity of turbulence. Pressure, 5.0 inches of mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835. (Data from ref. 5.)

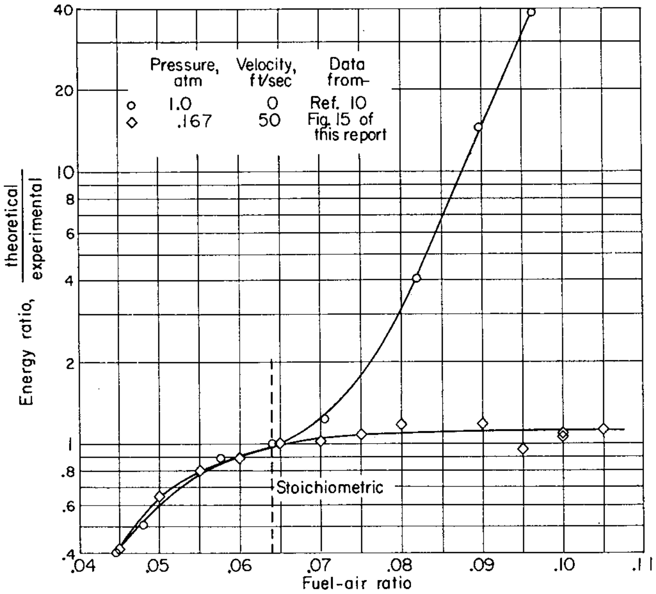


FIGURE 25.—Comparison of theoretical-to-experimental energy ratios with those of reference 10. Both sets of data adjusted to 1.0 at approximately stoichiometric fuel-air ratio.

value of 1.0 at an approximately stoichiometric fuel-air ratio. The adjusted data are plotted against fuel-air ratio in figure 25. Both theories give predicted results that deviate from experimental results in the same direction. While neither theory can be used to predict trends exactly, the theory described herein more accurately predicts trends at richer than stoichiometric fuel-air ratios.

In reference 6 variable-fuel-air-ratio data were correlated empirically by multiplying the term in the left side of equation (13) by the factor $1-\frac{0.02}{X_f}$, where X_f is the mole fraction of the fuel. This correlation is shown in figure 26. A value of activation energy was calculated from the slope of the curve to be 24.8 kilocalories per mole, which agrees with literature values.

While the correction term $1-\frac{0.02}{X_f}$ was determined empirically, it may have theoretical significance. For example, the term may correct the total energy E_s to a value $E_s\left(1-\frac{0.02}{X_f}\right)$ or $E_s-\frac{0.02E_s}{X_f}$. This may indicate the possibility of energy loss occurring before ignition; the loss would be dependent on the total energy and on fuel concentration. The loss may occur by heat conduction and be dependent on temperature and time. Considering the heated zone left by the spark, the temperature of the zone should be roughly dependent on E_s. The term $1/X_f$ can represent time if ignition time lag is assumed to be inversely proportional to X_f, as is reported in reference 14. The concept of an energy loss, however, is questionable for two reasons. The theory considers the heated zone left by the spark as being at or near flame temperature so that the time lag should be insignificant. Also, since time lag is affected by pressure (ref. 15), a pressure term that might or might not destroy previous correlations should be included in the equations.

The term $1-\frac{0.02}{X_f}$ might also be a correction term to the total energy for variations in energy distribution along the spark path. As noted earlier, for practical reasons the total energy of the discharge instead of the positive-column energy was used in the theoretical calculations, although results have indicated this latter energy to be the important factor. Therefore, if the positive-column energy were used in the theory, the energy would be E_s-E_c or $E_s\left(1-\frac{E_c}{E_s}\right)$. If the ratio of cathode to total energy E_c/E_s were sufficiently dependent on X_f, the discrepancy between theory and experiment could be explained. Figure 27 shows that E_c/E_s does actually decrease with increasing X_f for both low and high velocities; however, the decrease is only about 20 percent. While this correction for cathode energy would improve the fuel-air-ratio correlation somewhat, a much larger factor is needed.

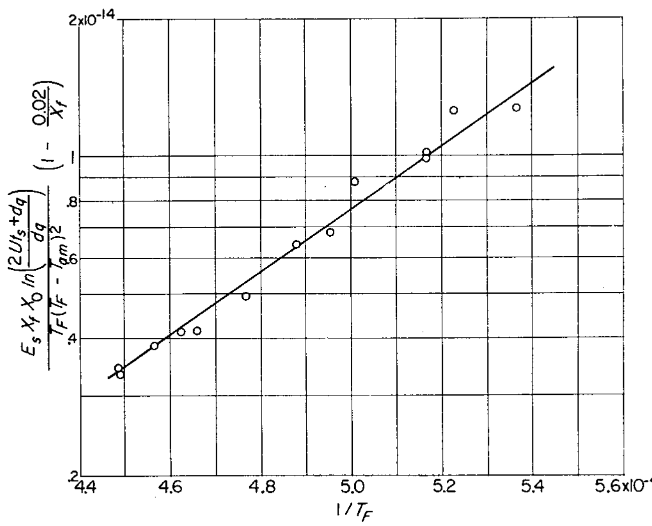


FIGURE 26.—Empirical correlation of ignition energy data (fig. 15) obtained over fuel-air-ratio range of 0.045 to 0.105.

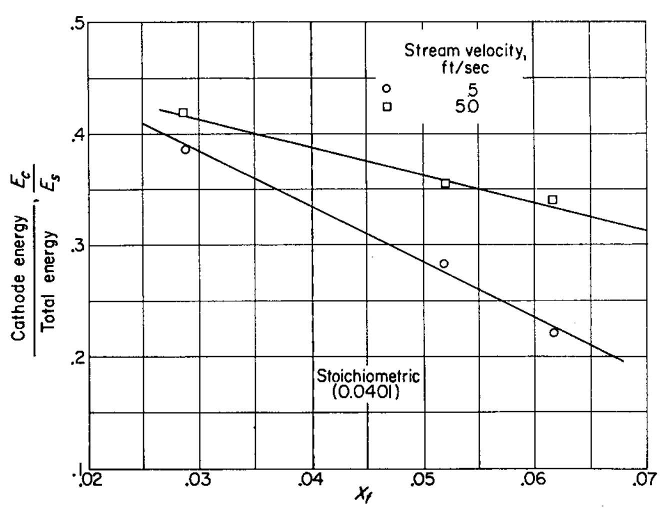


FIGURE 27.—Effect of fuel concentration on ratio of cathode energy to total ignition energy. (Data from ref. 6.)

There are probably other factors that may be responsible for the observed discrepancy. Preferential diffusion of the deficient reactant in the combustible mixture could be a contributing factor, as discussed in reference 10. Or possibly some cool flame mechanism that results in different activation energy in lean and rich mixtures may be present. Both of these items are qualitatively in the right direction to account for this difference between lean and rich data. Actually, a combination of the above factors may be responsible for the discrepancy. Further research on all the factors discussed is indicated.

SIGNIFICANCE OF RESULTS IN RELATION TO PRACTICAL IGNITION PROBLEMS

Most research on spark ignition reported in the literature has been conducted with quiescent gases; the work contained herein comprises the bulk of information that is available on ignition of flowing gases. The purpose of this section of the report is to point out the significance of this latter information with relation to practical ignition problems.

The experimental data on ignition of flowing gases show that the energy required for ignition is low even under severe velocity, pressure, and turbulence conditions. The amount of energy is measured in millijoules, whereas in aircraft operation an amount of 3 joules or more is not uncommon. It is obvious that there is room for improvement in ignition. Any means whereby lower ignition energies would be obtained would lead to the development of simpler, lighter weight, more efficient, and possibly, more reliable ignition systems.

One cause of the high ignition energy requirement in engines must be the mixture composition, which is quite different from the homogeneous composition used herein. The fuel-air ratio near the line source of ignition in an engine depends upon the degree of atomization of the fuel, on fuel-spray and air-flow patterns, and on the rate of vaporization of the fuel. This localized fuel-air ratio varies with operating conditions, and at any one operating condition, varies with time because of the fluctuating flow patterns that are inherently present in combustors. With these nonsteady heterogeneous mixture conditions, the ignition energy requirements may be many times greater than energy values reported herein. Temperature may also be important in ignition of the heterogeneous mixture, for some energy is needed to vaporize the liquid drops, the colder drops requiring more energy than warmer drops. Decreasing fuel volatility should also increase the energy requirements. All these factors can have adverse effects on ignition and, therefore, pose problems in the design of ignition systems.

Ignition in an engine should occur preferably in a sheltered region, that is, a region where low turbulence and low velocity exist. Such a region is difficult to find in the practical jet-engine combustor. The high mass-flow rates together with the air-entry-hole arrangements required to achieve high combustion efficiencies and uniform outlet temperature profiles make it difficult to provide such regions. Although turbulence is not desirable for easy ignition, it appears to be necessary for propagation of the initial flame throughout the combustor. Therefore, ignition systems must be designed for the necessary turbulent condition. However, turbulence by itself, as shown herein, does not result in excessive energies if the mixture conditions are suitable.

Low velocities and short spark durations are desirable because they result in short spark-discharge length. Spark-discharge length is responsible for many of the trends observed. It determines current, voltage, energy and energy distribution, occurrence of multiple discharges, and ignition characteristics. The current and the voltage have little practical significance, but the other factors are important.

Increased discharge length due to either velocity or time increases the resistance of the discharge and thereby changes the division of energy among the legs of the discharge, the line source of ignition, and the impedance of the ignition source. The larger the discharge resistance, the smaller the loss in the impedance of the ignition source; hence, the efficiency of the ignition system is actually increased by increased discharge length. For a low-impedance source this increase in efficiency may be insignificant, however.

Although the efficiency of the system is improved, the amount of energy that goes into the line source of ignition is actually decreased as velocity is increased. Larger portions of the energy are then wasted in the legs of the discharges. Thus, as the length is increased with flow velocity and time, it becomes necessary to increase the total amount of energy if ignition is to be obtained.

Lengthening of the discharge path is also responsible for the occurrence of multiple discharges. Multiple discharges should normally be avoided because only one of the discharges may be expected to cause ignition. The energy in the other discharges is wasted. In the case of homogeneous mixtures, the first of the multiple discharges should cause ignition because it contains more energy than subsequent discharges. In the case of heterogeneous mixtures found in engines, however, one of the subsequent discharges might occur in a better fuel-air mixture and so cause ignition even though it has an energy somewhat smaller than the energy of the first discharge. Ease of ignition depends upon the actual variation of fuel-air ratio with time. Without knowledge of this variation, it is impossible to conclude that multiple discharges are desirable. It is also impossible to determine what the energy content and sparking rate should be for the repetitive discharges produced by commercial ignition systems. A reduction in the fuel-air-ratio fluctuations would lead to lower energies and lower sparking rates.

It is noted previously that the smaller the discharge length, that is, the lower the velocity and the shorter the spark duration, the smaller is the amount of energy required for ignition. However, the ignition energy at extremely short durations is higher than that found at somewhat longer durations. This, however, has only been observed under low-velocity conditions. With high velocities the short-duration discharge would be expected to require less energy than the long-duration discharge because of the reduced discharge length.

This research has indicated another significant fact which may not be generally known; namely, the breakdown voltage is not affected by the flowing stream. It is just as easy to establish a spark discharge in a flowing stream as in a quiescent one. No voltage limitation is, therefore, imposed on an ignition system when it is used to ignite a flowing gas.

Finally, the significance of the theoretical research is in predicting how ignition energy requirements will be affected by a number of parameters. Exact values of energy may not be given by the theory, but at least the order of magnitude of energy change can be predicted. The results confirm the concept of a line source of ignition.

This research may be summarized to give the following ideal environmental conditions for ignition by electrical discharges:

(1) Low gas-stream velocity
(2) High pressure
(3) Location of discharge in best mixture composition
(4) High gas-stream temperature
(5) Low turbulence in gas stream
(6) Optimum spark duration as dictated by gas-velocity condition
(7) Electrode spacing maintained at quenching distance
(8) Small electrodes, if electrode spacing is less than quenching distance
(9) Arc discharge in preference to glow discharge

These conditions are desirable from ignition considerations only. For over-all engine operation, all of the conditions may not be practical.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, *June 20, 1956*

REFERENCES

1. Swett, Clyde C., Jr.: Investigation of Spark Gaps Subjected to Altitude and Air-Velocity Conditions. NACA RM E8I17, 1948.
2. Swett, Clyde C., Jr.: Spark Ignition of Flowing Gases. I—Energies to Ignite Propane-Air Mixtures in Pressure Range of 2 to 4 Inches Mercury Absolute. NACA RM E9E17, 1949.
3. Swett, Clyde C., Jr.: Spark Ignition of Flowing Gases. II—Effect of Electrode Parameters on Energy Required to Ignite a Propane-Air Mixture. NACA RM E51J12, 1951.
4. Swett, Clyde C., Jr., and Donlon, Richard H.: Spark Ignition of Flowing Gases. III—Effect of Turbulence Promoter on Energy Required to Ignite a Propane-Air Mixture. NACA RM E52J28, 1953.
5. Swett, Clyde C., Jr.: Spark Ignition of Flowing Gases. IV—Theory of Ignition in Nonturbulent and Turbulent Flow Using Long-Duration Discharges. NACA RM E54F29a, 1954.
6. Swett, Clyde C., Jr.: Spark Ignition of Flowing Gases. V—Application of Fuel-Air-Ratio and Initial-Temperature Data to Ignition Theory. NACA RM E55I16, 1955.
7. Mickelsen, William R., and Laurence, James C.: Measurement and Analysis of Turbulent Flow Containing Periodic Flow Fluctuations. NACA RM E53F19, 1953.
8. Cobine, James Dillon: Gaseous Conductors. McGraw-Hill Book Co., Inc., 1941.
9. Becker, J. A.: Thermionic Electron Emission and Absorption. Pt. I. Thermionic Emission. Rev. Mod. Phys., vol. 7, no. 2, Apr. 1935, pp. 95–128.
10. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Academic Press, Inc., 1951.
11. Fenn, John B.: Lean Inflammability Limit and Minimum Spark Ignition Energy. Ind. and Eng. Chem., vol. 43, no. 12, Dec. 1951, pp. 2865–2868.
12. DiPiazza, James T., Gerstein, Melvin, and Weast, Robert C.: Flammability Limits of Hydrocarbon-Air Mixtures. Reduced Pressures. Ind. and Eng. Chem., vol. 43, no. 12, Dec. 1951, pp. 2721–2725.
13. Thornton, W. M.: The Reaction between Gas and Pole in the Electrical Ignition of Gaseous Mixtures. Proc. Roy. Soc. (London), ser. A, vol. XCII, no. A634, Oct. 1, 1915, pp. 9–22.
14. Jackson, Joseph L., and Brokaw, Richard S.: Variation of Spontaneous Ignition Delays with Temperature and Composition for Propane-Oxygen-Nitrogen Mixtures at Atmospheric Pressure. NACA RM E54B19, 1954.
15. Brokaw, Richard S., and Jackson, Joseph L.: Effect of Temperature, Pressure, and Composition on Ignition Delays for Propane Flames. Fifth Symposium (International) on Combustion, The Reinhold Pub. Corp., 1955, pp. 563–569.
16. Druyvesteyn, M. J., and Penning, F. M.: The Mechanism of Electrical Discharges in Gases of Low Pressure. Rev. Mod. Phys., vol. 12, no. 2, Apr. 1940, pp. 87–174.

U. S. GOVERNMENT PRINTING OFFICE: 1957