



RESEARCH MEMORANDUM

MINIMUM IGNITION ENERGIES OF SIX PURE HYDROCARBON

FUELS OF THE C₂ AND C₆ SERIES

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SUMMARY

Minimum spark-ignition energies at reduced pressures are reported for ethane, ethylene, acetylene, n-hexane, cyclohexane, and benzene; and the mean energy-pressure dependence is established to be $E \propto 1/P^{1.76}$ for four of the fuels investigated. A relation between ignition energy E and maximum flame velocity U_{\max} is also presented. This relation includes all the experimental data plus data from other investigators and may be expressed approximately as $U_{\max} \propto 1/E^{0.8}$. Such interdependence of the minimum ignition energy and maximum fundamental flame velocity permits a reasonable estimation of either from the other with an accuracy sufficient to discern large differences in various pure fuels.

INTRODUCTION

The combustion process and burner-performance characteristics are ultimately the net function of physical and chemical properties of the fuel-oxidant mixture, and investigation of such fundamental fuel properties is now in progress at the NACA Lewis laboratory. As a part of the over-all program, the minimum energy required to ignite a fuel-air mixture was considered for investigation, not only because of its obvious implications in engine starting, but also because it may be directly related to the control of the entire combustion process. The minimum ignition energies for six hydrocarbon fuels are reported herein.

Previous investigations of ignition energy utilized various techniques, such as heat transfer from heated bodies, adiabatic compression, various types of spark, flame, or spontaneous ignition caused by mixing individually heated volumes of fuel and air. This investigation employed a controlled-duration capacitance spark as the igniting source for a quiescent combustible mixture contained in a small bomb.

Investigations of spark-ignition energies of various fuels have not been extensive. The ignition energies obtained by Calcote have been summarized in reference 1, but most of the energies reported are for stoichiometric mixtures only. Since the minimum ignition energy for many of the fuels investigated occurs in regions far richer than stoichiometric, comparison of fuel type on the basis of minimum values is impossible. Others (reference 2) report minimum values for a limited number of fuels but for a wide range of fuel-air ratios. Extension of these data is deemed desirable so that there may be a consistent basis for fuel-type comparisons.

The present work was undertaken to extend the scope of available data and to report minimum ignition-energy values and their pressure dependence for a systematic investigation of various pure fuels. This report presents the minimum ignition energy of six hydrocarbon fuels of the C_2 and C_6 series, namely, ethane, ethylene, and acetylene and n-hexane, cyclohexane, and benzene.

APPARATUS AND PROCEDURE

The apparatus for this investigation consisted of (1) an inlet and mixing system, (2) an ignition bomb, and (3) an energy-measuring circuit. The entire apparatus is shown schematically in figure 1. Everything except the energy-measuring circuit was maintained at 100° F with an air thermostat.

The inlet system consisted of a manifold and 35-liter reservoir provided with suitable gages and manometers for mixture preparation. A motor-driven bellows-sealed mixer was provided for fuel and air mixing. Gaseous or liquid fuels could be used and air was provided from a standard type-F compressed-air cylinder.

The ignition bomb is essentially that described by Guest (reference 3) and is shown in figure 2. The bomb is of stainless-steel construction and has a total volume of approximately 680 cubic centimeters. It is provided with two adjustable Lucite-insulated electrodes, two diametrically opposed Lucite windows for observation, a quartz window for ultraviolet irradiation of the electrode gap to facilitate breakdown, and an iron-constantan thermocouple for gas-temperature measurement.

The electrodes were number-74 high-speed drills soldered into a 1/8-inch brass rod and were sealed into a 1-inch-diameter Lucite insulator. A vacuum-tight sliding seal between the bomb and electrode assembly was maintained by a greased O-ring seal. Electrode spacing was measured with a micrometer mounted on the bomb base.

The ignition and measuring circuit is similar to that described in reference 4 with a few minor modifications and is shown diagrammatically in figure 3.

The ignition circuit employs a 30-kilovolt power supply to charge a capacitor bank of total capacitance of 0.6 microfarads, the capacitor voltage being measured by a 0- to 20-kilovolt multiple-range electrostatic voltmeter. The capacitor charged and discharged through a single-pole double-throw magnetically operated air switch, which isolated the power supply from the discharge circuit. Resistor R_2 was varied from 10,000 ohms to 0.25 megohm to vary the energy supplied to the gap, while R_3 was varied to 13,000 ohms to provide suitable oscilloscope deflection; R_1 was fixed at 500 ohms to provide a spark duration of approximately 1000 microseconds.

A capacitor-resistor voltage divider was employed to measure the gap voltage. This type of divider was selected for its favorable divider frequency range and was balanced with respect to ground potential. The divider was balanced to ± 0.7 percent over a frequency range of 60 cycles per second to 70 kilocycles per second and was checked to ± 1.5 percent by a discharge of known voltage through a fixed circuit. Instantaneous gap current and reduced gap voltage with superimposed timing marks were photographically recorded from the oscilloscope trace and interpreted by the method described by Swett (reference 4).

The over-all circuit and oscilloscope capacitance characteristics fixed a minimum energy level of approximately 0.001 joule. Spark reproducibility and energy-measurement accuracy decrease for spark energies below this limit.

All data were obtained on premixed fuel-air mixtures of known concentration, temperature, and pressure. The minimum ignition energy for such known conditions and a given gap width was approached from the low side by passing consecutive sparks and adjusting the capacitor voltage, R_2 , and R_3 . Ignition of the mixture was defined as the occurrence of propagation from the spark source into the surrounding gas to an extent sufficient to yield a 5-millimeter pressure pulse in the system. For all data reported, ignition was obtained by a single spark in a mixture not previously sparked. Ignition energies so determined for a given mixture and various gap widths defined the minimum energy for that mixture. Repeating the procedure for various mixture strengths defined the minimum ignition energy as a function of fuel-air ratio. Data from this investigation are presented on this basis.

The series of six fuels investigated, the source, and the purity are presented in table I.

RESULTS AND DISCUSSION

When the minimum ignition energies reported for the six fuels covered in this investigation are considered, certain experimental limits should be kept in mind: (1) All ignition energies reported are those for mixture temperatures of 100° F and a spark duration of approximately 1000 microseconds. Errors introduced by spark-duration deviations as great as 10 to 20 percent, however, are negligible, since the circuit characteristics are such that 90 percent of the total spark energy is released in the first 500 microseconds. (2) The equivalence ratio ϕ is defined as the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio, and the range covered for each fuel investigated was only of sufficient width to obtain the minimum energy value for each fuel. The pressure range investigated was also experimentally limited, the limits being 50 to 200 millimeters of mercury absolute. (3) The accuracy of all minimum energies reported is estimated to be ± 8 percent. This figure is the net result of circuit-component calibration accuracy plus an allowance for energy reproducibility from spark to spark. Check points for the data presented, however, exhibit an average reproducibility of ± 4.4 percent with a maximum deviation of ± 8 percent.

By the procedure outlined in a previous section, minimum spark-ignition energies for six hydrocarbon fuels of the C_2 and C_6 series were determined. These fuels included ethane, ethylene, and acetylene of the C_2 series and hexane, cyclohexane, and benzene of the C_6 series. The minimum ignition energy is presented as a function of the equivalence ratio. Each data point of the curves presented is the minimum value of a plot of energy against gap width for a mixture of the indicated equivalence ratio. Typical energy-gap curves are presented in figure 4. This minimum should also define the optimum gap width or quenching distance. However, the energy-gap curves obtained in this investigation were relatively flat and frequently bilobed, so that an accurate quenching distance could not be defined. The flatness of the curves resulted from the relatively low quenching action of the needle electrodes. The cause of the lobed structure is unknown and was not reproducible from run to run. The minimum energies, however, were reproducible and were independent of the type of energy-gap curve obtained. In general, however, most quenching-distance - energy data of this investigation fall within the range established by other investigators (reference 5, p. 415).

The minimum ignition energies of ethane were obtained at the five pressures of 200, 150, 100, 75, and 50 millimeters of mercury absolute and are presented in figure 5. The accuracy and reproducibility of the

50-millimeter data, however, are lower than those quoted previously because of moderate arc- to glow-discharge oscillations and the approach to the flammability limit for some points. However, frequent and suitable reruns did establish the 50-millimeter data to an estimated accuracy of ± 12 percent. These ignition-energy data of ethane thus established an energy-pressure dependence.

Ethylene and acetylene data shown in figure 6 were obtained only at a pressure of 100 millimeters of mercury absolute. This pressure was selected because of limitations imposed by circuit and spark characteristics and was the highest pressure that could maintain the ignition-energy level for both fuels above the 0.001-joule lower limit specified for the circuit. Furthermore, for these fuels, lower pressures generally induced such severe arc- to glow-discharge oscillations that the oscillograph traces were uninterpretable.

The minimum ignition energies of the C_6 fuel series including hexane, cyclohexane, and benzene (fig. 7) were determined only at the two pressures of 200 and 100 millimeters of mercury absolute. Such a two-point pressure check was believed to be sufficient to compare the energy-pressure dependence obtained with ethane.

Minimum spark-ignition energies are similarly reported by others in references 1, 2, and 5. These investigators utilized a capacitance spark as the ignition source, and spark energies were calculated from the circuit characteristics and the relation $E = \frac{1}{2} CV^2$. Minimum ignition energies for ethane at four pressures from 1.0 to 0.2 atmosphere and for hexane, cyclohexane, and benzene at 1 atmosphere are reported in reference 2. Ignition energies for stoichiometric air mixtures of ethane and ethylene at a pressure of 1 atmosphere, as well as of acetylene at five pressures ranging from 1.0 to 0.04 atmosphere, are reported in reference 1. Since the data of reference 1 are limited to an equivalence ratio of 1 for these fuels, a strict comparison on the basis of minimum values is impossible. However, since the minimum for these fuels occurs close to an equivalence ratio of 1 and the curves are relatively flat in this region, an approximate comparison may be made. Table II presents a complete summary and comparison of the results of this research with the results obtained by other investigators.

Limited data of other investigators have indicated that the minimum ignition energy - pressure dependence is of the form $E \propto 1/P^x$ (references 1 and 2). In order to establish the ignition energy - pressure dependence and to evaluate x in the relation $E \propto 1/P^x$,

ethane data and C_6 data from this research were plotted logarithmically as a pressure function in figure 8. The experimental energy-pressure relation is immediately apparent. Line slopes calculated individually for each fuel are indicated in table II, and the constancy of slope for all four fuels justifies a single line representation. This line has a slope of -1.76 , and the pressure dependence is thus $E \propto 1/P^{1.76}$. The results of linear extrapolations to 760 millimeters of the logarithmic plot for each fuel are also tabulated in table II and compared with other available data. Agreement at 1 atmosphere is quite good, though at reduced pressures, the deviation of ethane data of reference 2 is 20 to 30 percent which results from the greater slope (-1.84) of the data of reference 2.

In order to check further the energy-pressure dependence established in the preceding paragraph, ignition energies of ethylene and acetylene at 100 millimeters were extrapolated to 1 atmosphere by assuming the constant slope of -1.76 . Ethylene exhibits good agreement with previously reported values for atmospheric ignition. The extrapolation of acetylene data to 760 millimeters yields an ignition energy of 0.0000512 joule. This value is in poor agreement with that reported in reference 1, being high by a factor of 2.55. However, if the slope of -2.1 found in reference 1 is used for acetylene, the extrapolated value becomes 0.000025 joule compared with the measured ignition energy at 760 millimeters of 0.000020 joule (reference 1). A different slope for acetylene is reasonable, since many of its combustion properties differ greatly from those of other hydrocarbons.

The minimum ignition energies obtained in this investigation were plotted against the maximum flame velocity reported in references 6 to 10 for the same fuels. The maximum flame velocities U_{max} reported were obtained from either the tube method or the bunsen cone and for this purpose, no distinction between the two methods is made. Either method, however, gives U_{max} for atmospheric pressure; ignition energies used are therefore also the values extrapolated to 760 millimeters. Ignition-energy data from other sources are also used in order to include more fuels. It should be remembered, however, that since that data were collected from various investigators, experimental consistency is lacking; hence, the utility of the relation is limited to the prediction of approximate relations only.

The relation of the maximum flame velocity to the minimum ignition energy is presented in figure 9 and all data used are collected in table III. The data of other investigators are included only where "minimum" ignition-energy values can be obtained from available data.

2596

The fuel-air data of this investigation as well as those of other investigators then define an exponential relation of the form $U_{max} \propto 1/E^{0.8}$. This relation, however, is valid only at a pressure of 1 atmosphere. The data define a reasonably good straight line, the maximum deviation of 20 percent being considerably greater than the average of 5.7 percent. It should also be noted (table II) that agreement of the acetylene data obtained by extrapolation with the -1.76 slope shows only slight deviation from the correlation, though the ignition energy is 2.5 as great as published values.

SUMMARY OF RESULTS

An investigation to determine the minimum ignition energies of several pure hydrocarbon fuels was conducted at various pressures. The results of this investigation may be summarized in the following statements:

1. The mean dependence of minimum ignition energy and pressure for four hydrocarbon fuels was expressed by the approximate relation $E \propto 1/p^{1.76}$.

2. At a pressure of 1 atmosphere, an exponential relation between the maximum flame velocity and the minimum ignition energy of the order $U_{max} \propto 1/E^{0.8}$ appeared to exist, but an accurate evaluation of this relation must await more consistent data. Such interdependence of the minimum ignition energy and maximum fundamental flame velocity permits a reasonable estimation of either from the other with an accuracy sufficient to discern large differences in various pure fuels.

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TABLE I - SOURCE AND PURITY OF
FUELS INVESTIGATED

Fuel	Source	Estimated purity (percent)
Ethane	Ohio Chemical & Mfg. Co.	95
Ethylene	Ohio Chemical & Mfg. Co.	99.5
Acetylene	Burdett Mfg. Co.	99
<u>n</u> -Hexane	Phillips Petroleum Co.	99
Cyclohexane	Phillips Petroleum Co.	99
Benzene	NACA	99

TABLE II - IGNITION ENERGIES OF SIX HYDROCARBON FUELS AT
ATMOSPHERIC AND REDUCED PRESSURES



Fuel	Pressure (mm Hg)	Minimum ignition energy (joules)			Line slope x in $E \propto 1/P^x$
		NACA	Bureau of Mines ^a	Experiment, Inc. ^b	
Ethane	200	0.00245	0.0028	-----	-----
	150	.0040	.0048	-----	-----
	100	.0074	.010	-----	-1.724 (NACA)
	75	.0130	^c .017	-----	-1.840 (Bureau of Mines)
	50	.0270	^c .035	-----	-----
	760	^c .00024	.00025	0.000285	-----
Ethylene	100	0.00435	-----	-----	-----
	760	^c .000124	0.000112	0.000096	-----
Acetylene	100	0.00180	-----	0.00138	-----
	760	^c .0000512	-----	.000020	-2.1 (Experiment, Inc.)
n-Hexane	200	0.0025	-----	-----	-----
	100	.0083	-----	-----	-1.731 (NACA)
	760	^c .000248	0.000241	-----	-----
Cyclo- hexane	200	0.00245	-----	-----	-----
	100	.0085	-----	-----	-1.795 (NACA)
	760	^c .000223	0.000229	-----	-----
Benzene	200	0.00240	-----	-----	-----
	100	.0082	-----	-----	-1.773 (NACA)
	760	^c .000225	0.000217	-----	-----

^aReference 2.

^bReference 1. Equivalence ratio, 1.

^cExtrapolated values.

TABLE III - MAXIMUM FLAME VELOCITIES AND MINIMUM IGNITION ENERGIES
OF 13 HYDROCARBON FUELS

[Pressure, 760 mm]



Fuel	Minimum ignition energy (joules)	Reference for minimum ignition energy	Maximum burning velocity (cm/sec)	Reference for maximum flame velocity
Hydrogen	0.00002	1	267	6
Acetylene	.000051	NACA	141	8
Propyne	.000115	(a)	69.9	7
Ethylene	.000124	NACA	68.3	7
Cyclopropane	.00024	1	47.5	9
Diethyl ether	.00019	2	40.1	(b)
Propane	.00025	2	39.0	7
Methane	.00029	2	33.8	7
n-Hexane	.000248	NACA	38.5	7
Cyclohexane	.000223	NACA	38.7	7
Benzene	.000225	NACA	40.7	7
Ethane	.00024	NACA	40.1	7
Isooctane	.00028	(c)	34.9	11

^aUnpublished data obtained at Experiment, Inc.

^bUnpublished data obtained at NACA Lewis laboratory.

^cData obtained at a commercial laboratory.

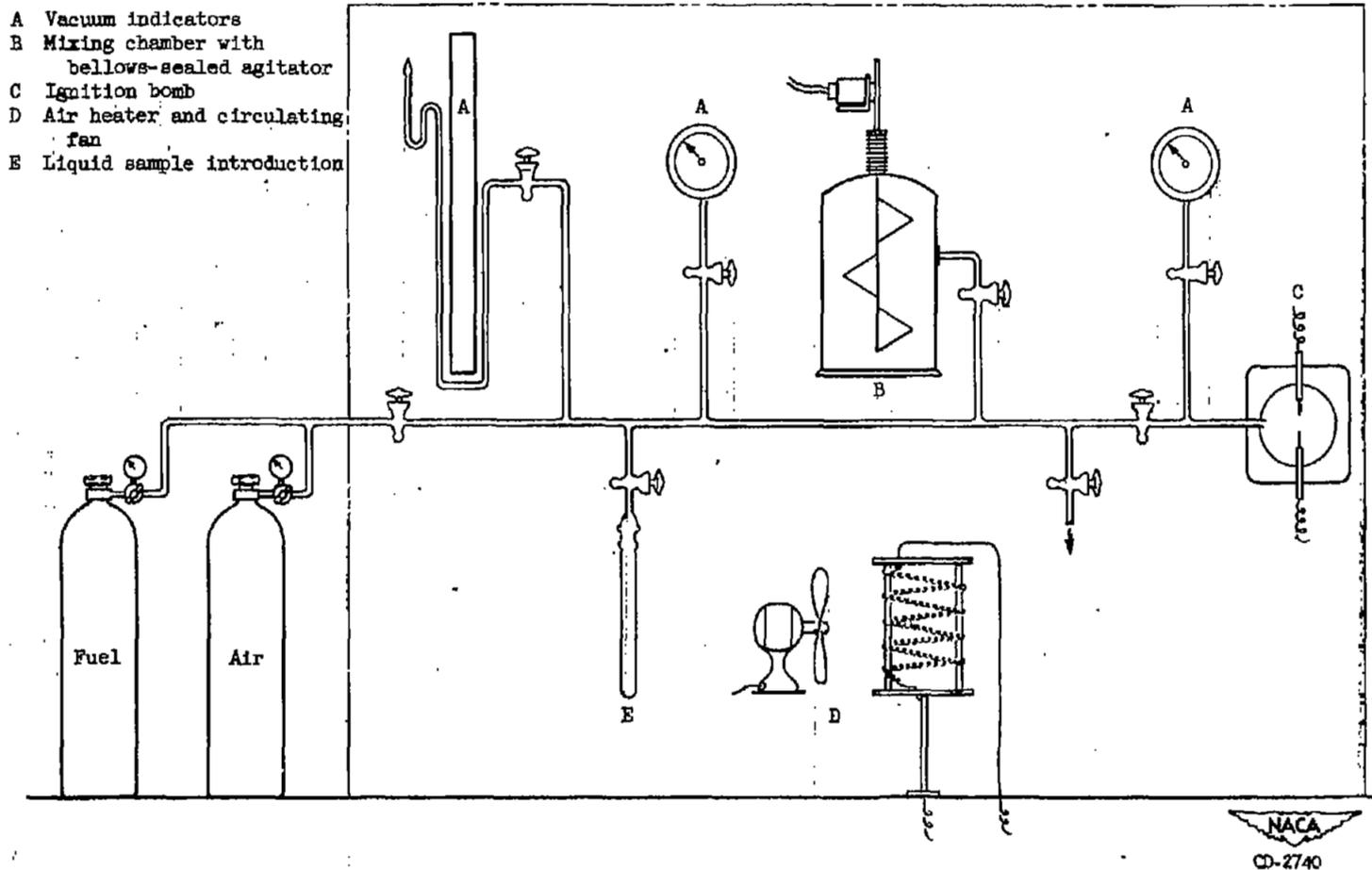


Figure 1. - Schematic diagram of inlet and mixing system for ignition apparatus.

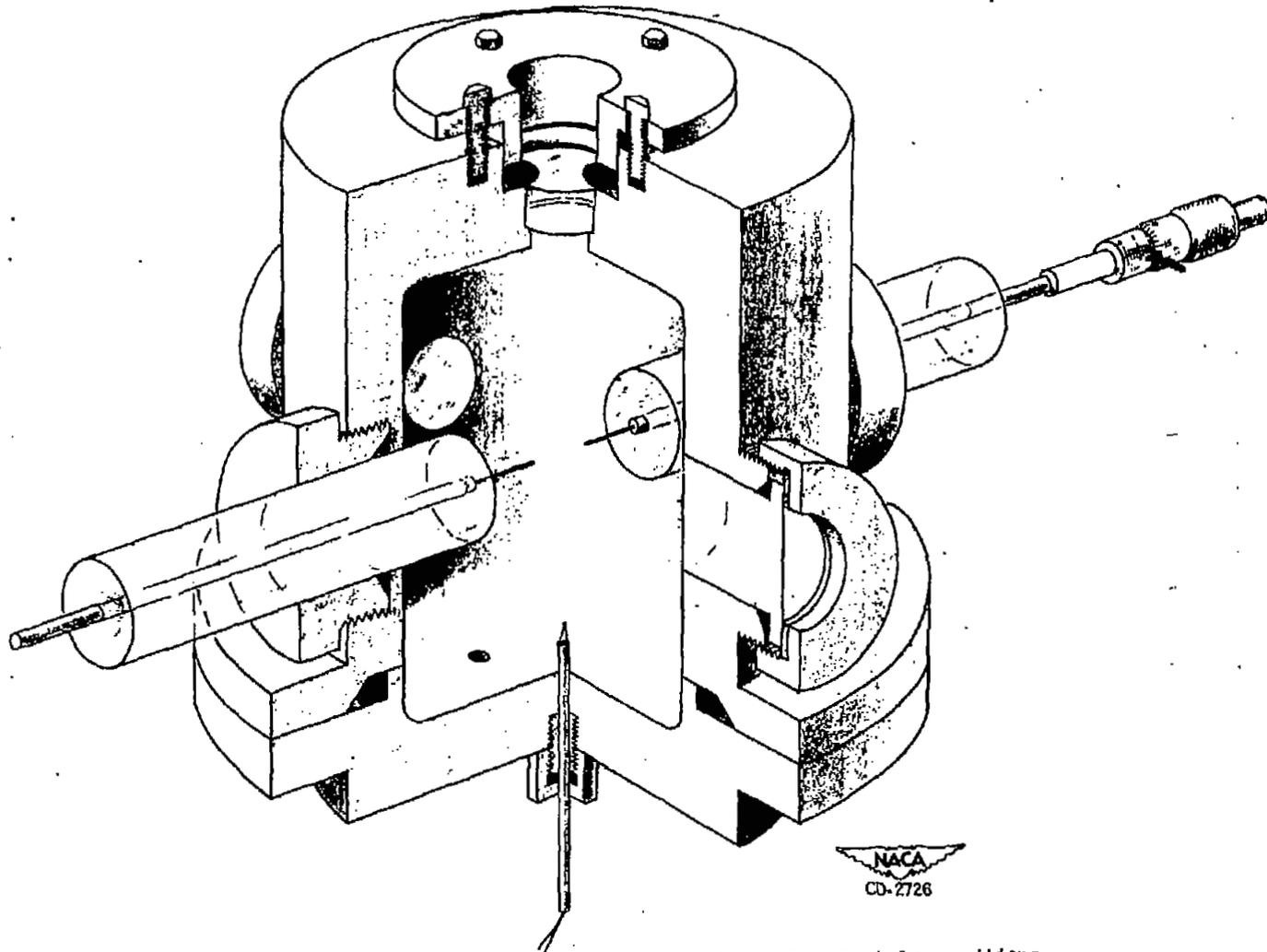


Figure 2. - View of ignition bomb, showing electrode and window positions.

A Single-pole double-throw air switch
 B Capacitor bank - six 4- μ f, 2500-v capacitors
 C Ignition bomb
 D Voltage divider (approximate reduction, 5:1)
 E Oscilloscope
 F z-axis input

G Audio oscillator
 R_1 Fixed resistance, 500 ohms
 R_2 Variable resistance, 10,000 ohms to 0.25 megohm
 R_3 Variable resistance, 1000 to 13,000 ohms
 V Electrostatic voltmeter

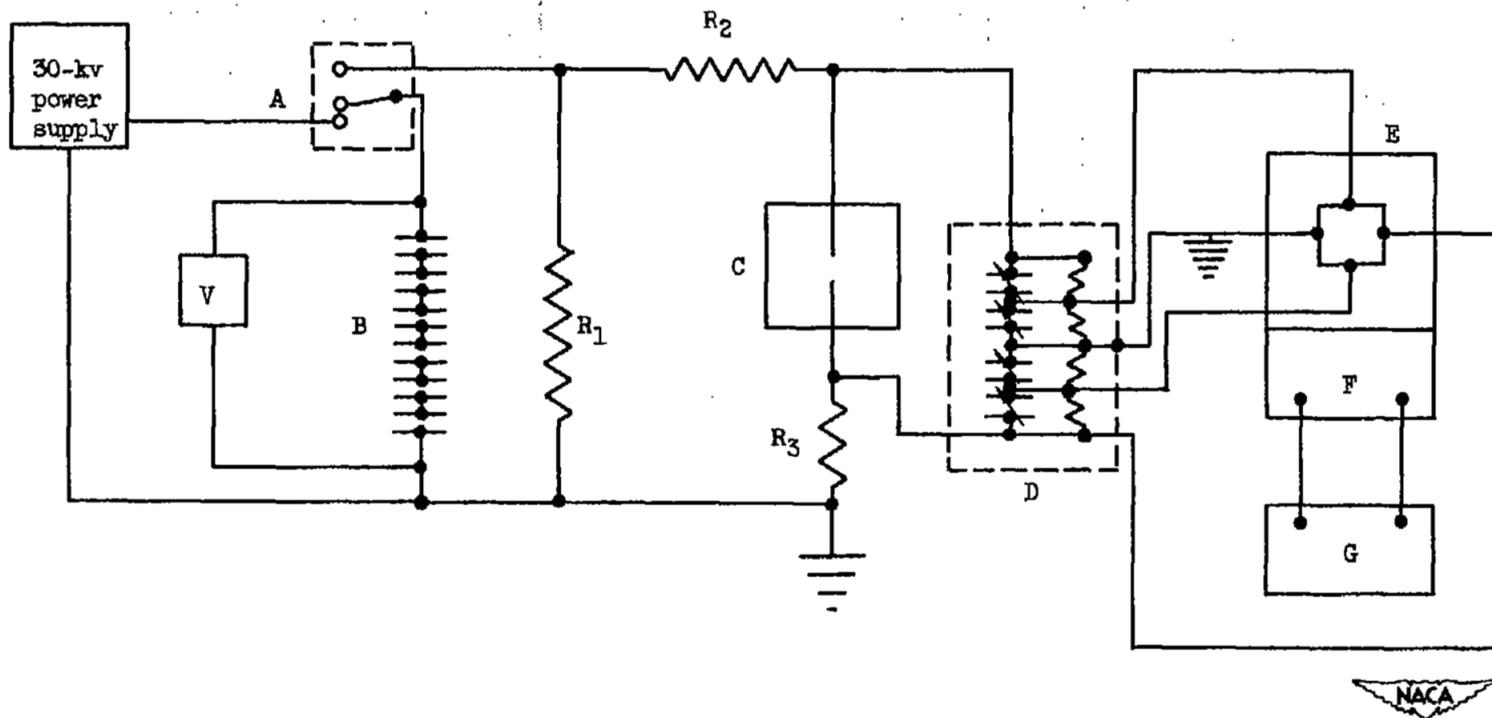


Figure 3. - Schematic diagram of ignition and energy-measuring circuit.

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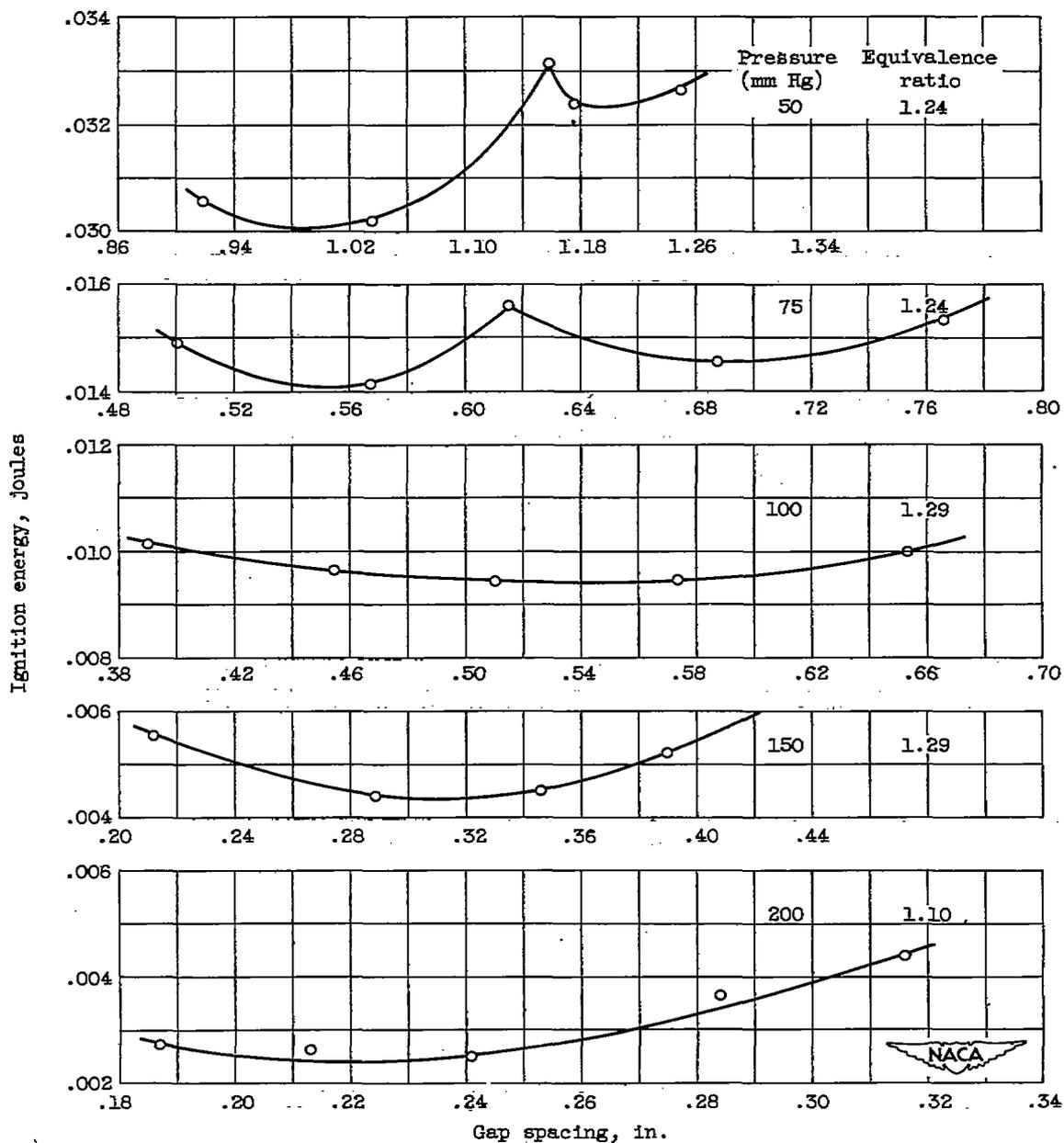


Figure 4. - Typical energy-gap curves obtained. Ethane-air data.

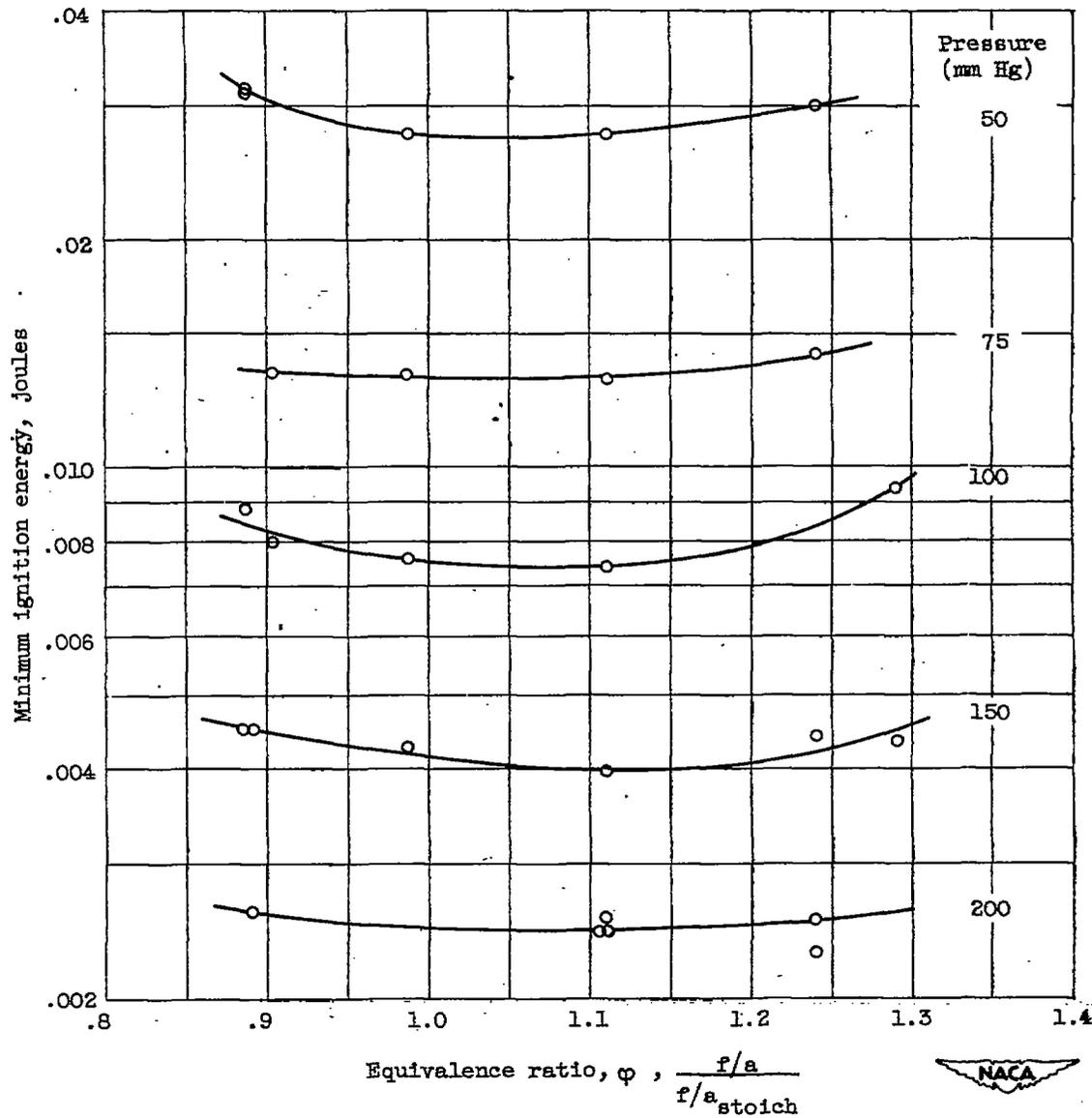


Figure 5. - Minimum ignition energy of ethane-air mixtures at reduced pressures.

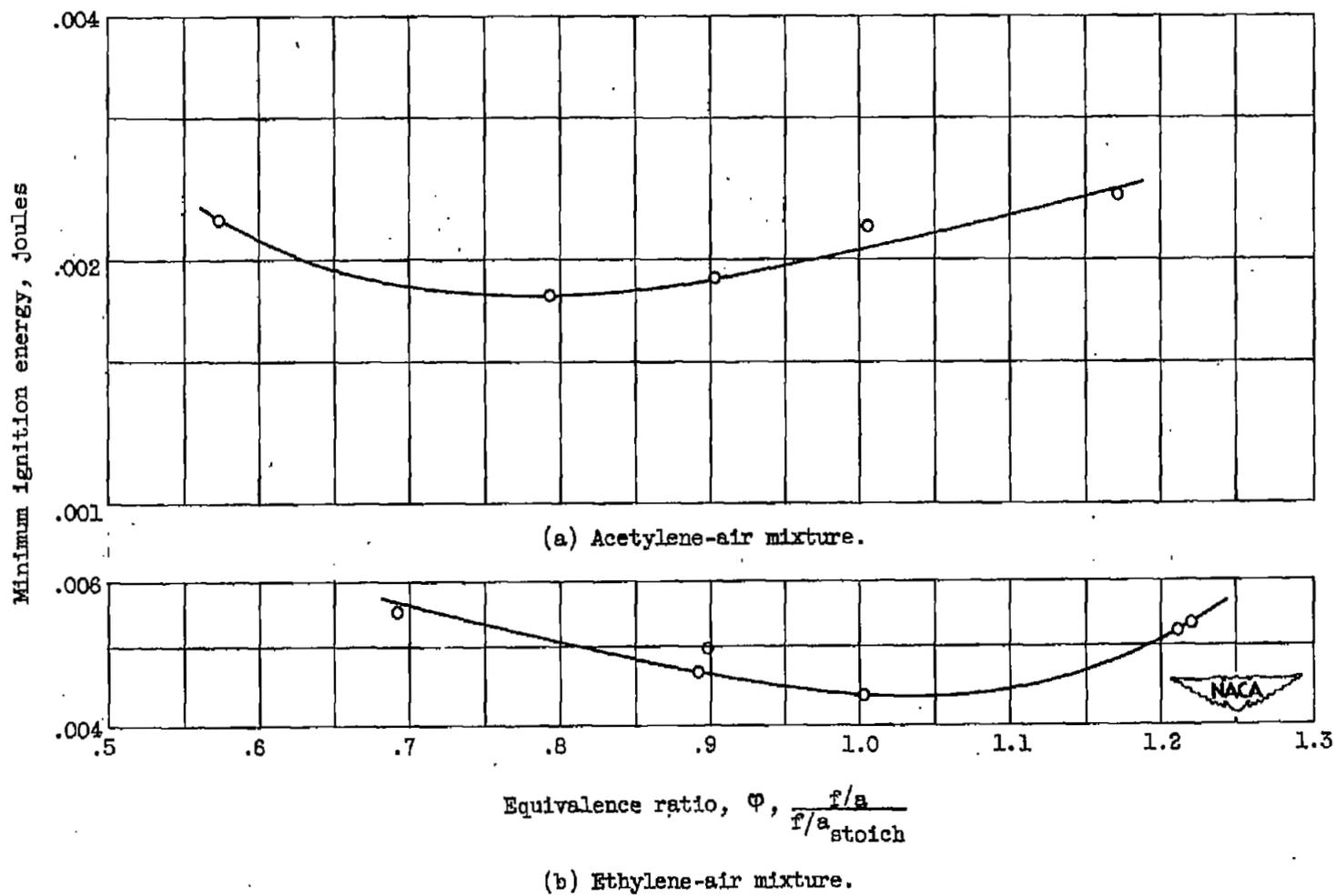
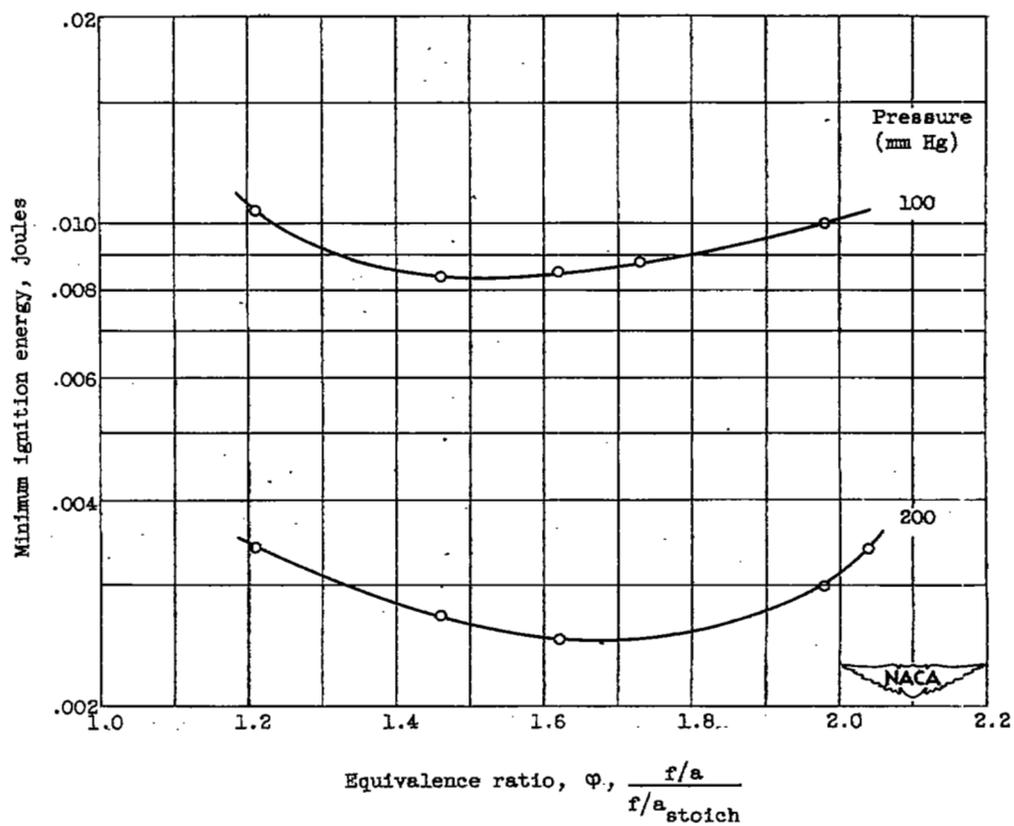
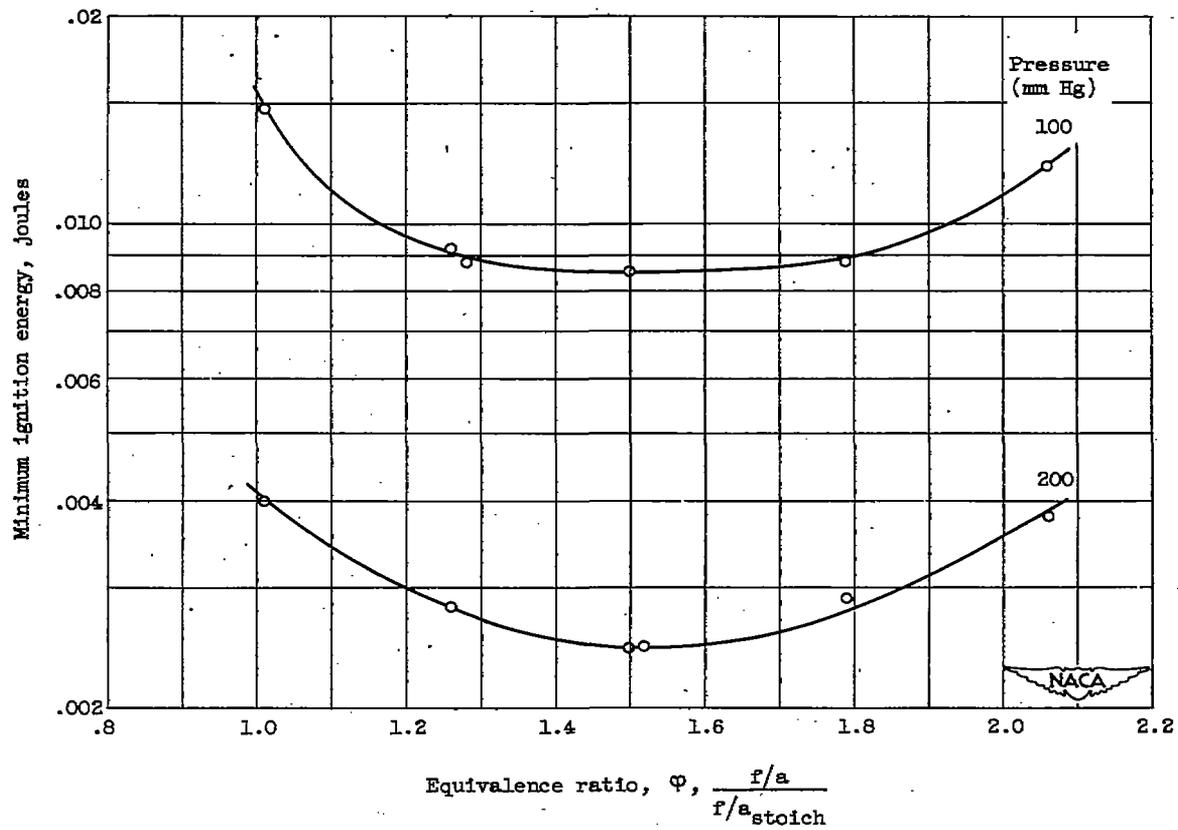


Figure 6. - Minimum ignition energies at pressure of 100 millimeters of mercury absolute.



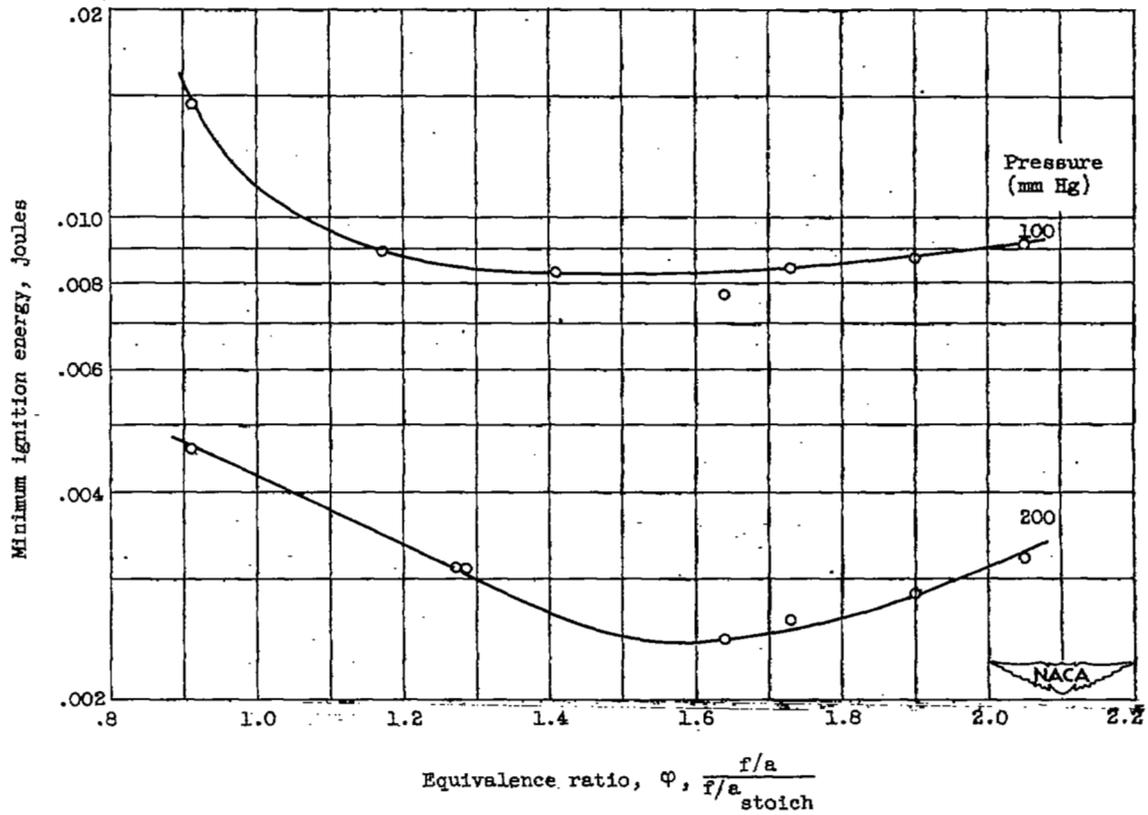
(a) n-Hexane - air mixtures.

Figure 7. - Minimum ignition energies at reduced pressures.



(b) Cyclohexane-air mixtures.

Figure 7. - Continued. Minimum ignition energies at reduced pressures.



(c) Benzene-air mixtures.

Figure 7. - Concluded. Minimum ignition energies at reduced pressures.

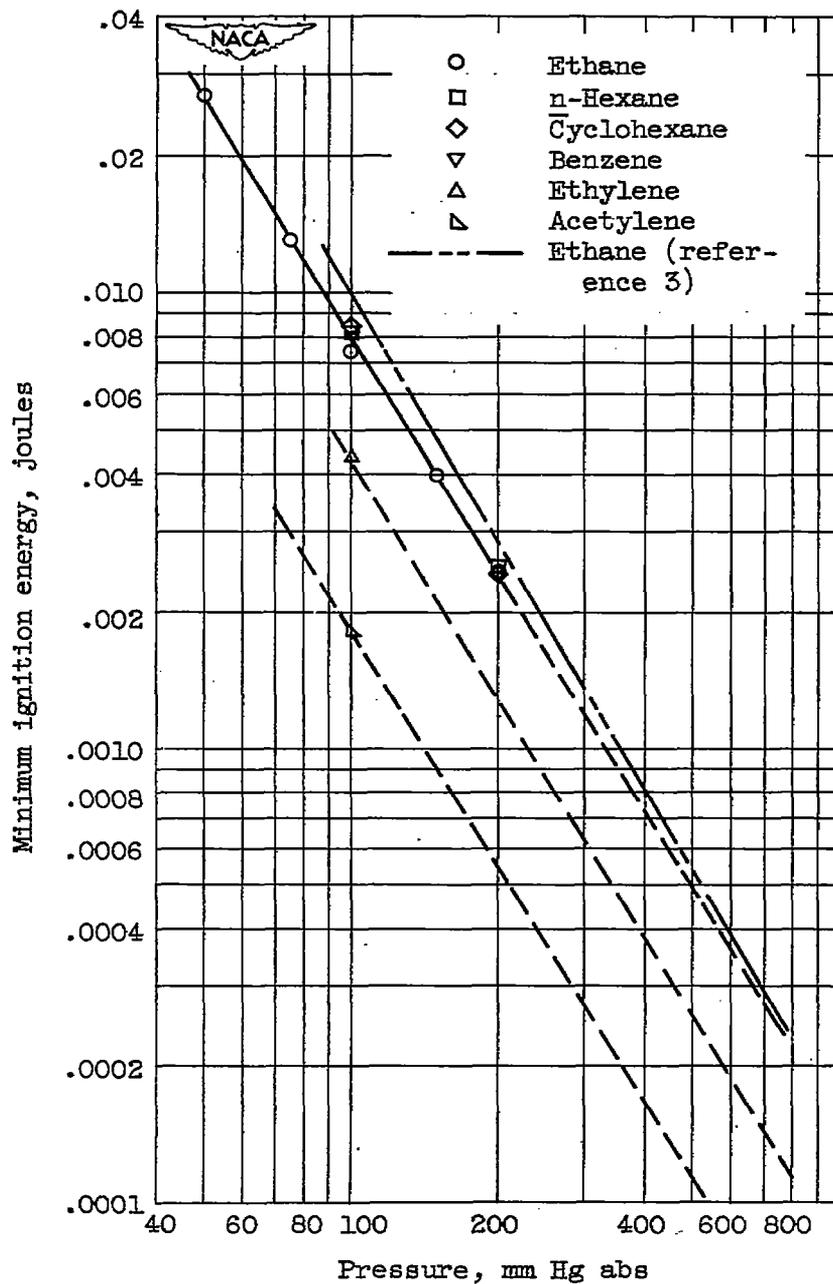


Figure 8. - Pressure function of minimum ignition energy of four pure hydrocarbons and constant slope extrapolation of ethylene and acetylene data.

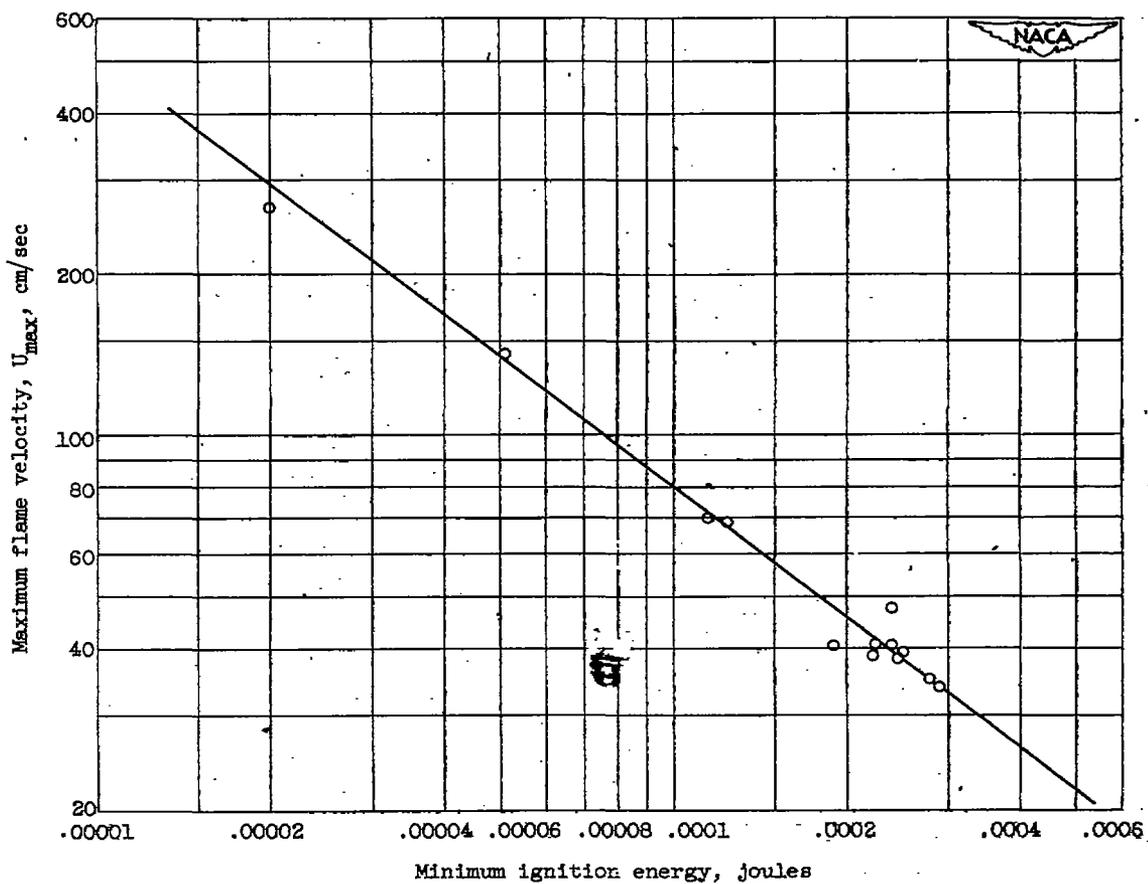


Figure 9. - Relation of maximum flame velocity and minimum ignition energy at pressure of 760 millimeters of mercury absolute.

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