INVESTIGATION OF THE ENERGY CONTENT OF HIGH VOLTAGE IGNITION SOURCES

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A poster and paper presented at the 1993 Halon Alternatives Technical Working Conference' described differences in inerting concentrations of Halon 1301 required to inert methane, as reported by various researchers, and offered an explanation for these differences. The paper hypothesized that the actual (effective) energy contained in the NMERI DC capacitive discharge ignition source used in the explosion sphere testing was less than the 70 joules stored in the capacitors and was also less than the energy used by other researchers. At that time, no measurement of the energy was made. As part of a recently-completed program [2*] determining the effects of test parameters on flammable refiigerant test methods, the energies of the NMERI DC ignition source and a higher voltage capacitance system, each of which contained the same stored energy, were measured and compared.

Initially, a literature review and analysis were made to investigate the impacts of various electrical parameters on the formation of the spark and the ignition of a flammable gas. As a result of this review, an electrode simulator was constructed and bench testing of various electrode shapes was undertaken. A new ignition source utilizing high voltage capacitors but having identical stored energy as the standard NMERI DC source was fabricated. The effective energy present in the arc between the electrodes in the simulator was measured for each of the two sources.

LITERATURE SEARCH AND ANALYSIS

The ignition source provides energy to the layer of flammable gas immediately surrounding the source. If the amount of energy is sufficiently high, the next gas layer is ignited and so on. This ignition results in an explosion if enough energy is provided. Rises in the temperature and pressure of the gas result fiom the ignition. Eventually, the explosion reaches the edge of the enclosure or dissipates naturally. The magnitude of the explosion can be measured by pressure transducers as an increase in pressure. If an additive, called an inertant, is mixed with the flammable gas, the energy transfer between layers may be reduced, and the magnitude of the explosion is lowered. In general, the more inertant, the more the suppression until no measurable explosion occurs. If the explosion measured is less than a certain level, inertion is said to have occurred. The process begins, however, with the addition of sufficient energy into the flammable gas to ignite the first layer of gas.

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Mixtures are flammable only within specified fuel-to-air ratios, which may be affected by many parameters. Likewise, the amount of inertant required to reduce the explosion overpressure varies with the fuel-to-air ratio. The ignition source may be among the most critical parameters in determining repeatable flammability limits or inertion concentrations. In a paper on the determination of flammability properties of pure refiigerants and mixtures,[3] Richard and Shankland found differences of 2.4% in the lower flammability limit (LFL) for difluoromethane (HFC-32 or R32)—(13.8% vs. 11.4% at 95° C, a 17% variability)—when ignited with copper wire as compared to a match, and much greater differences have been found for more "marginally flammable" refrigerants. Sources that have been used to ignite flammable mixtures include matches, pyrotechnic igniters (including electric matches), electric sparks, mechanical sparks, glowing wires, and hot surfaces. Alternating current (AC) sparks, as well as the more traditional direct current (DC) sparks, have been used. Of the above sources, the two most likely to be repeatable are the match and the electric spark (AC or DC), and most inertion and flammability testing have been accomplished using those two ignition sources. The criterion for flammability is whether a flame would be self-sustaining once the effects of the ignition source has dissipated. However, it must first be ascertained that the ignition is sufficiently energetic to ensure ignition and flame propagation in the absence of any inertant.

The electric spark is a very fast-acting ignition source, on the order of 10^{-8} to 10^{-7} seconds discharge time, and, therefore, the energy is highly concentrated. Sparks have been studied for years, primarily because of their importance in the internal combustion engine. Variables in electric sparks include:

(1) AC vs. DC. Previous NMERI testing involving inertion of propane and methane by Halon 1301 has indicated that 120 volts AC (VAC) boosted through a transformer can ignite mixtures that cannot be ignited by a DC spark of a stored energy (in the capacitors) of up to 100 J. However, neither the energy nor the duration of the AC spark was measured or controlled.

(2) Electrodes. The shape, diameter, separation distance, and materials may be critical. Most references indicate that above the quenching distance $d_{||}$—the minimum gap between electrodes that will successfully quench (prevent) ignition—the shape of the ends of the electrodes is not important.[4] However, Lewis and von Elbe also state that for large spark energies, $d_{||}$ actually increases, due to the increased heat transfer produced by the turbulence of the larger spark.'

(3) Energy. Most electric sparks are produced by a the discharge or a capacitor; many also have an inductive component. The energy level in a capacitive spark is commonly defined as the stored electrical energy in the capacitors, $\frac{1}{2}FV^2$, where F is the capacitance (in farads) and V is the voltage (in volts) to which the capacitors are charged (actually, the voltage before and after discharge must be considered). If there are no losses between the capacitor and the electrodes, all energy is transferred into the spark. However, even in this case, some of that energy will be required to initiate the spark and will not be available to ignite the flammable mixture. The energy deposited at a sufficient temperature to initiate a freely propagating flame is called ε_{eff} and may be up to two orders of magnitude less than the stored energy, depending upon the voltage to which

the capacitors were charged and the chamber volume size.[6] The energy loss due to the high-voltage transformer used in previous NMERI testing has been estimated at 15%, however it is believed that the actual loss is much higher.

(4) Circuit parameters. It is known that inductance in the ignition circuit results in a different type of spark than that without inductance' and that ignition energy is dependent not only on the resistance and capacitance of the circuit, but also on the product of the two, the discharge time constant.[8] These parameters were not investigated in this study.

The electrode geometry is an important consideration when testing materials. Before the arc occurs, the resistance of the air must be broken down and the shape of the ends affects the breakdown of the air gap. Three major geometries are considered, all of which use a round stainless steel rod with only the ends differing in shape.

(1) Flat type. The first type of electrode has a flat end (Figure 1) which is a standard geometry. This type of electrode will produce less predictable results that the other two types of electrodes because of the flat surface and the relative sharp edges at the ends of the rods. There will be electrical field enhancement at the edges but none on the face (except due to the non-smooth surface).

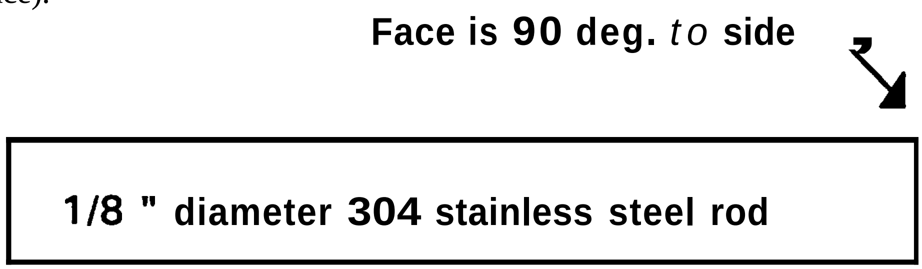

Figure 1. Flat Type Electrode.

(2) Hemispherical type. The second type of electrode is the hemispherically shaped rod (Figure 2). The ends of this type of electrode should be made so that the radius of the end of the electrode is the same as the radius of the body of the electrode. This type of rod eliminates field enhancement so that breakdown of the gap occurs more uniformly.

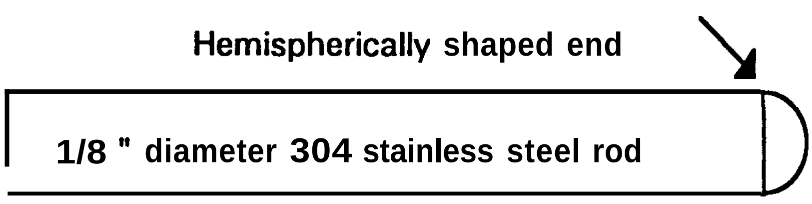

Figure 2. Hemispherical Type Electrode.

(3). Conical type. The third type of electrode is the conical electrode (Figure 3). This rod is specifically designed to provide field enhancement at the tips forcing a breakdown to occur more often at the tips. The conical electrodes in these tests had their ends machined at 45 degrees.

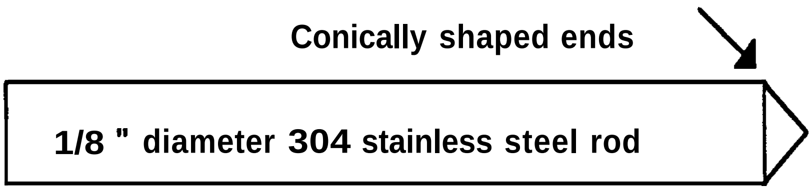

Figure 3. Conical Type Electrode.

EQUIPMENT

Bench Test Setup.

The first apparatus was developed to conduct bench tests on the electrical ignition systems and measure the energy in the spark gaps. A Plexiglas stand to hold the electrodes was constructed. One end of the stand was movable and attached to a micrometer which allowed the electrodes to be moved a precise distance apart. This apparatus was used to evaluate the shape of the ends of the electrodes, to determine the minimum voltage required to initiate an arc, and to measure the energy in the spark gap for both the low and the high voltage sources. Figure 4 illustrates this apparatus as it was used to measure the energy in the spark gap.

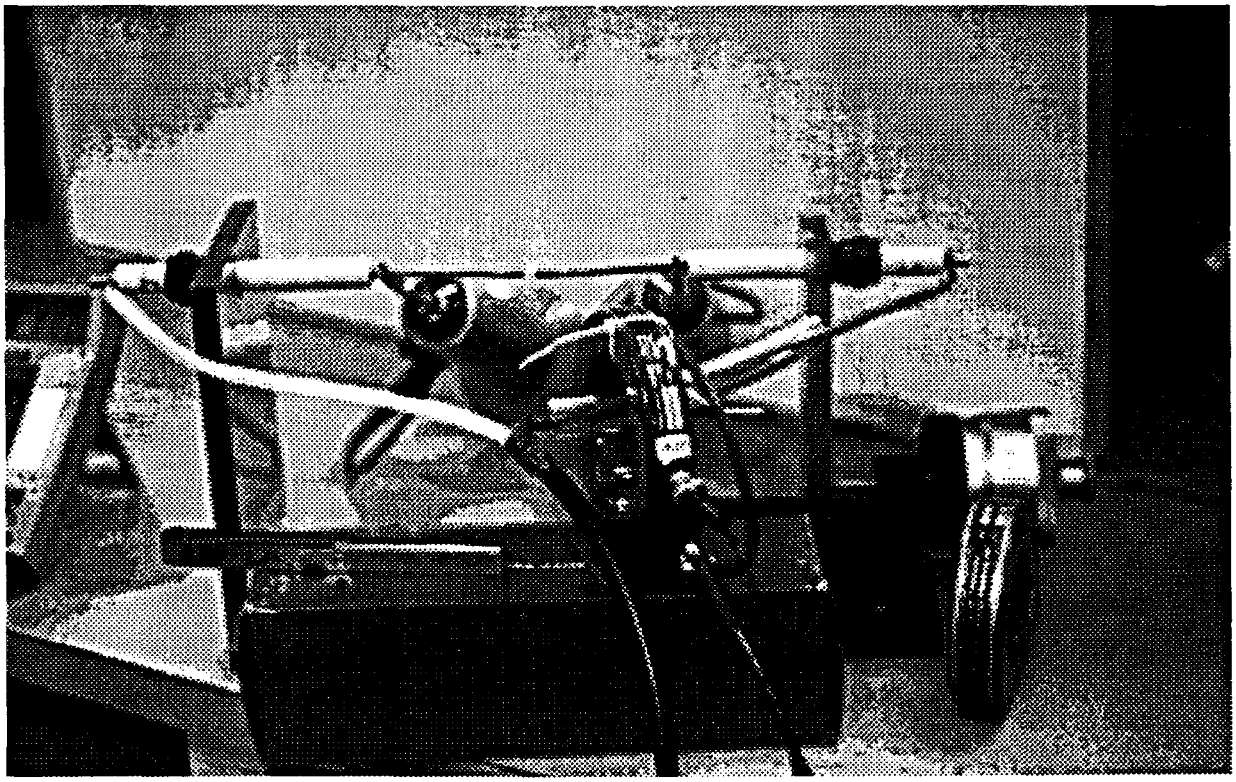

Figure 4. NMERI Electrode Simulator.

Ignition Sources.

Electrical ignition sources can be well defined in terms of the ignition circuit components and, therefore, can produce electric arcs of repeatable energy. Since the electrical components are typically "off the shelf," different researchers can test using similar test equipment. While there are many different categories of DC discharge circuits, only two different types are considered here. Both are capacitive discharge circuits driving a pair of electrodes with a specified electrode spacing. The difference between them is the voltage at which the capacitors are charged. Low voltage is typically considered as having a capacitor charging bank voltage (V_{bank}) of under 500V, while high voltage is considered as having a V_{bank} of over 500 V. However, the energy stored in the capacitors is governed by the value of the capacitance and the charging voltage, and both circuits can contain the same stored energy.

Both the low and high voltage sources have advantages and disadvantages. Figure 5 illustrates a typical circuit schematic diagram of either type. The electrical ignition used in this testing consisted of two entirely different configurations, one each in the low voltage and high voltage region.

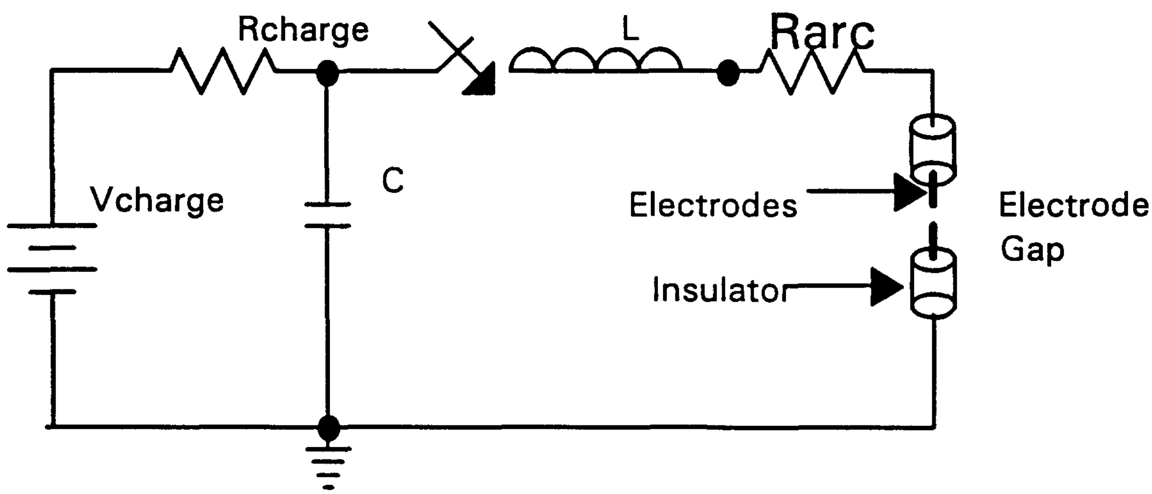

Figure 5. Typical Discharge Circuit.

(1) Low Voltage Ignition Source. The low voltage source is typically inexpensive. The physical layout of the circuit design can be minimized while achieving high energy storage. The safety of the operator is also maximized due to the low operating voltage. The disadvantage of this circuit is the requirement of a step up transformer to increase the electrode gap voltage sufficiently to cause the gap to break down. A typical oil burner or illumination transformer presents problems due to saturation of the metal core material causing a lower output voltage, and energy loss in the transformer core material. Using non-metallic materials for the core will minimize this effect.

The low voltage configuration was a capacitive discharge using a NMERI-designed Mutual Inductance Particle Velocity (MIPV) box (Figure 6). This box contained three

2000-mF capacitors connected in parallel (approximately 7000 mF measured), a 1.3 mH series inductance, and a relay control interface. The output switch is an ECG5548 silicon controlled rectifier (SCR). It had an interface to the computer that allowed the computer to charge the capacitors to the correct voltage and discharge the capacitors when required.

The bank is charged to the appropriate voltage (up to 200 V) to achieve the desired stored energy and discharged through a Franceformer® ignition transformer (model LA4V) to the electrodes. The conical electrodes were used due to their more reliable ignition performance. The advantage of this system is a low voltage pulse is sent to the transformer, and only a short run of automobile ignition wire with the high voltage pulse is present. Because of the low voltage up to the transformer, even though the capacitors stored up to 100 joules of energy, no special safety precautions were required.

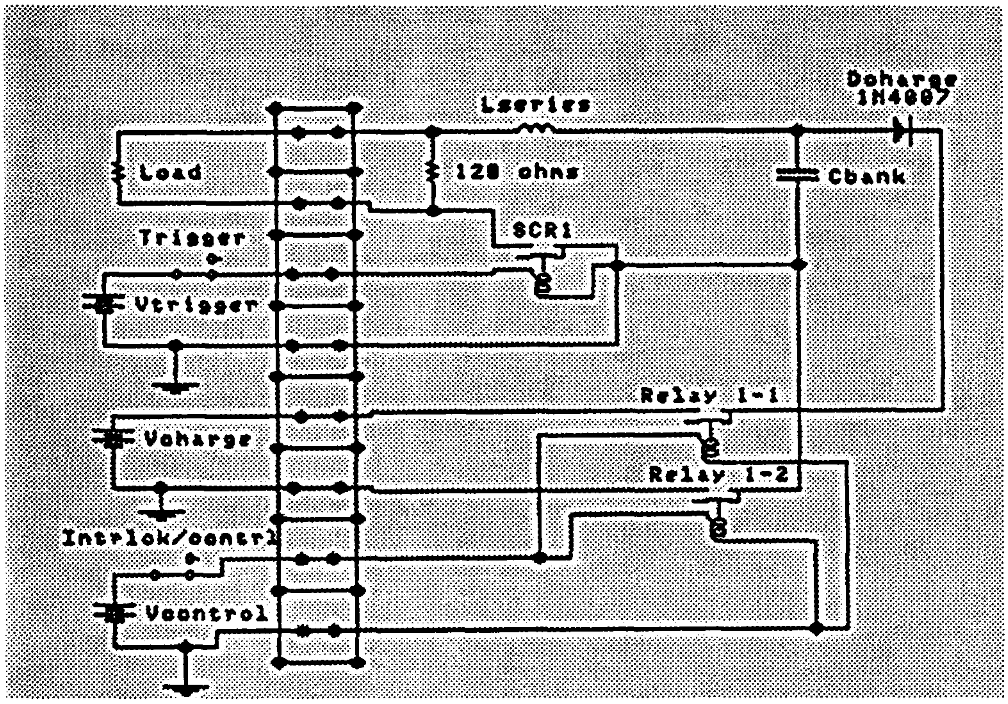

Figure 6. Mutual Inductance Particle Velocity (MIPV) Box Schematic.

(2) High Voltage Ignition Source. The high voltage source is typically more expensive due to the materials involved in the circuit design. Additionally, because of the greater energy stored in the capacitors, the components are physically larger and physical layout must be a priority. The higher voltages require greater care when operating, both for human and equipment safety. High voltage should only be handled by specially trained personnel. There are, however, several advantages to this type of circuit, the first being that higher charging voltages give higher stored energy with smaller capacitors based on

$$E = \frac{1}{2} F V^2 \qquad (1)$$

This smaller capacitance can be combined with smaller inductances to provide short discharge times. **This** results in higher peak discharge currents so that the peak power is greater while the stored energy is the same as the low voltage source using

$$P = E/t \tag{2}$$

where P = power (in watts), E = energy (in joules), and t = the time that energy is flowing (in seconds). The main electrical disadvantage to this circuit is that if long discharge times are desired, physically large and costly inductors are necessary.

The high voltage ignition system developed for this testing consisted of two separate configurations. The first consisted of a standard 1 mF capacitor bank and a series inductance and a series inductance of approximately *6* mH. The second configuration, which was used in the refiigerant testing, added a **2.5** W series wirewound resistance to elongate the discharge pulse. No step-up transformer was necessary due to the capacitor ratings, and, therefore, there are no transformer losses. Experimental diagnostics were sufficient to determine gap voltage, discharge current, gap power, and gap energy.

While the ignition was simple in terms of the number of components, it required large and expensive parts. The four capacitors were approximately **0.245** µF and were charged by a Glassman constant voltage/current power supply with a peak voltage of 20 kV and peak current of 15 mA. Two high-voltage relays were used, one for discharging the capacitors across the load and one for an emergency "dump" in case the capacitors could not be discharged through the load.

Safety was of paramount concern with this configuration. The system was enclosed in a **3-ft (1 m)** plywood cube, with all high-voltage components mounted on Plexiglas and separated for safety. All wiring was high-voltage wires. After all tests, the capacitors were grounded using a grounding rod, and were grounded between tests to prevent buildup of charge.

MEASUREMENT TECHNIQUES

The measurement of the energy in the spark gap involved the use of two Tektronix P6015A high voltage probes, one on the end of each electrode. These probes measured the high frequency voltage data that, when integrated with the current data, provided the actual energy in the spark gap. Three different current probes, a Pearson, a Stanganese, and a Rogowski, were used at different stages in the program to provide the current data. The data were recorded on a four-channel Tektronix recording oscilloscope, which was contained within a screen box to reduce noise to an acceptable level.

Data were stored in a format compatible with manipulation by standard spreadsheet software (Table 1). The spreadsheet stores the voltages on either side of the gap (V1 and V2), the voltage potential between them (Gap Voltage), the voltage seen at the current probe (Pearson V), the current from the Pearson probe, and calculates the total input energy, in joules, up to that time increment. The current and voltage for each side of the electrode were multiplied to give the input energy.

It is important to note that this methodology uses the only procedure to precisely determine the energy in the spark. The energy and power in the gap are measured only after the voltage in the gap collapses to 100 volts (the voltage between the electrodes has broken down and the arc occurs). Eventually, the voltage between the electrodes is reduced to a level such that the gap will not conduct, and the arc ceases to exist.

TABLE 1. TYPICAL DATA SPREADSHEET.

Time (ms)	V1 ($Vx10^{-3}$)	V2 ($Vx10^{-3}$)	Gap Voltage (V)	Pearson V ($Vx10^{-3}$)	Current (A)	Input Energy (J)
1.00E+01	3.48E-01	-3.68E-01	7.16E+02	2.84E-03	2.48E-02	1.53E-01
1.01E+01	3.48E-01	-3.76E-01	7.24E+02	2.72E-03	2.36E-02	1.54E-01
1.01E+01	3.40E-01	-3.76E-01	7.16E+02	2.92E-03	2.56E-02	1.55E-01
1.02E+01	3.40E-01	-3.76E-01	7.16E+02	2.68E-03	2.32E-02	1.56E-01
1.02E+01	3.40E-01	-3.76E-01	7.16E+02	2.32E-03	1.96E-02	1.57E-01
1.03E+01	3.48E-01	-3.76E-01	7.24E+02	2.60E-03	2.24E-02	1.57E-01
1.03E+01	3.40E-01	-3.76E-01	7.16E+02	2.72E-03	2.36E-02	1.58E-01
1.04E+01	3.40E-01	-3.76E-01	7.16E+02	2.56E-03	2.20E-02	1.59E-01
1.04E+01	3.40E-01	-3.84E-01	7.24E+02	2.72E-03	2.36E-02	1.60E-01
1.05E+01	3.32E-01	-3.84E-01	7.16E+02	2.64E-03	2.28E-02	1.61E-01
1.05E+01	3.48E-01	-3.76E-01	7.24E+02	2.56E-03	2.20E-02	1.61E-01
1.06E+01	3.40E-01	-3.76E-01	7.16E+02	2.60E-03	2.24E-02	1.62E-01
1.06E+01	3.40E-01	-3.76E-01	7.16E+02	2.52E-03	2.16E-02	1.63E-01
1.07E+01	3.48E-01	-3.76E-01	7.24E+02	2.44E-03	2.08E-02	1.64E-01
1.07E+01	3.40E-01	-3.76E-01	7.16E+02	2.76E-03	2.40E-02	1.65E-01

The data in the spreadsheet is then converted to the waveform by using the utility **CNVRTWFM** Ver 1.8, which is a DOS utility for converting the waveforms stored in the oscilloscope to other waveform formats. Formats generated include CURVE? response compatible binary, and ASCII and generic spreadsheet Mathcad and .WFM files. Figure 7 contains plots of the current and voltage measured for a typical test, and Figure 8 is a plot of the energy in the spark.

RESULTS

Electrode and Spark Gap Evaluation

A series was conducted using the bench simulator and the low voltage ignition source to determine the relationship of electrode shape and spark gap separation on the ability of the arc to bridge the spark gap. Several other factors, such as the length of the wires between the transformer and the source, were also investigated.

Table **2** lists the minimum capacitor charging voltage for each electrode shape and separation for which the spark was generated. At close separations, the voltage required did not vary significantly and the pointed electrodes require greater voltage to generate a spark. For the

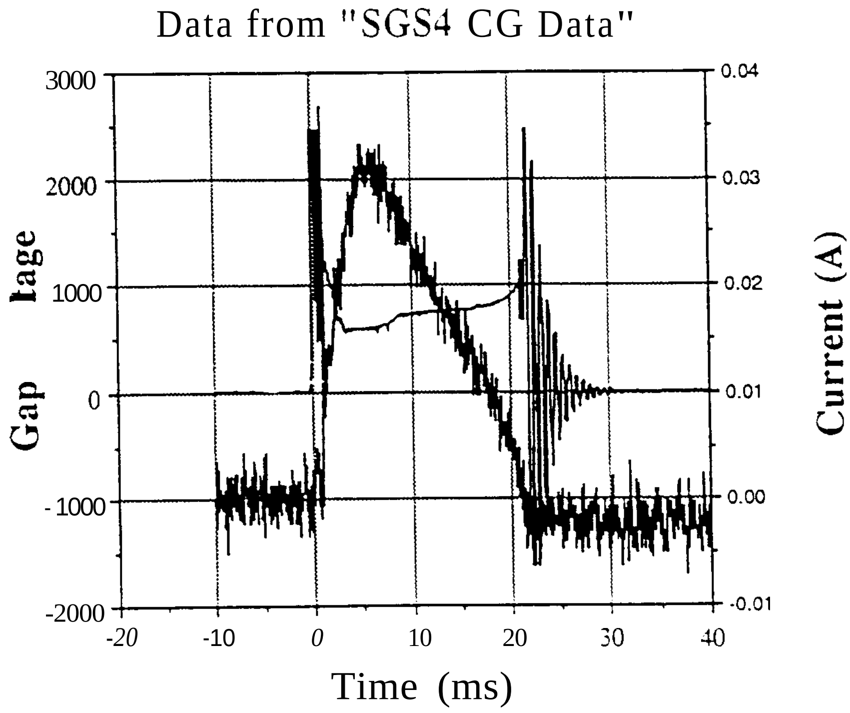

Figure 7. Typical Plot of Current and Voltage.

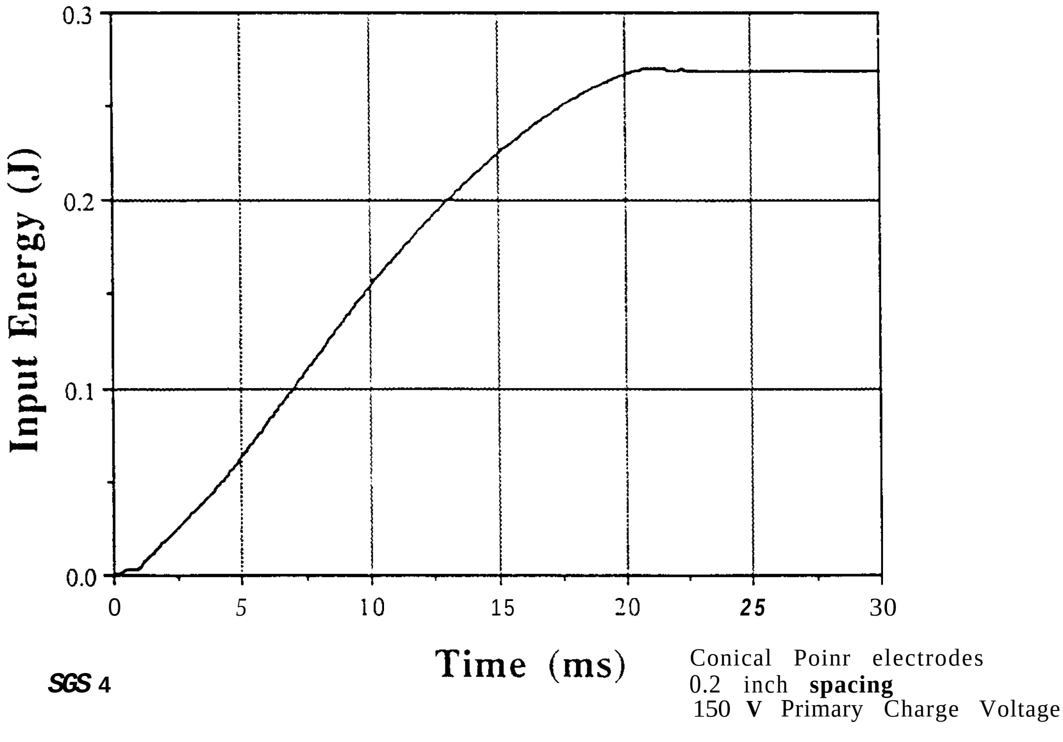

Figure 8. Typical Plot of Integrated Values.

other spacings, including the 0.240-inch (6-mm) spacing used in previous NMERI testing, the pointed electrodes require less voltage than the other shapes

TABLE 2. REQUIRED VOLTAGES TO GENERATE ARC (VOLTS).

Electrode Shape	Electrode Separation (in/mm)			
	0.025/0.64	0.240/6.0	0.500/12.7	0.700/17.8
Round	26	103	135	153
Square	23	73	111	151
Pointed	27.5	70	97	145

It was also very apparent that the electrodes required cleaning between tests as after 2 to 3 tests, the arc failed to strike at voltages where it had struck the previous test. When the electrodes were lightly sanded with fine sandpaper, the arc struck again for several tests until the procedure had to be repeated. Therefore, when the low-voltage DC ignition source is used, especially at low voltages, the electrodes should be sanded between each test.

One other variable investigated during this series was the length of the wire between the output of the MIPV box and the transformer. The previous NMERI setup involved a long run (over 40 ft (13 m)) of power line. A comparison of this long wire run with a shorter (3 ft [1 m]) wire indicated that the longer run requiring 80-82 volts to strike the arc, while the shorter run required only 73-76 volts. This indicates that the connections between all components should be minimized for optimum results.

Energy Measurement

NMERI testing in the explosion sphere prior to this time used the low voltage ignition method. Because of the difficulty in measuring high voltage, the energy content in this spark had never measured, and it became a priority of this program to measure the energy actually in the spark. The technique developed involved the measurement of current and voltage each side of the spark gap.

The energy present in the gap due to the standard NMERI low voltage source has been analyzed and plotted (Figure 9) using the methodology described earlier. In general, the spark contained a measured energy of between 0.15 and 0.26 J for charging voltages of 125,168, and 198 volts. These correspond to stored energies of 27.4, 98.7, and 137.2 J, based on the actual measurement of circuit components, resulting in an efficiency of between 0.2 and 0.5 percent. As postulated earlier, the major component of this loss is believed to be saturation of the iron core in the transformer, which passes energy effectively over long time periods (such as occur in AC) but which cannot pass a rapid pulse, as occur in DC sparks.

The measured energy in the high voltage source was considerably higher than in the low voltage source, ranging from 3 J at 7.5 kV to 10 J at 17.5 kV (Figure 10). It was apparent by the sound and light emitted that it was larger also. The stored energies corresponding to these values range from 28J to 1535. Although this energy is still a small percentage of the total stored energy

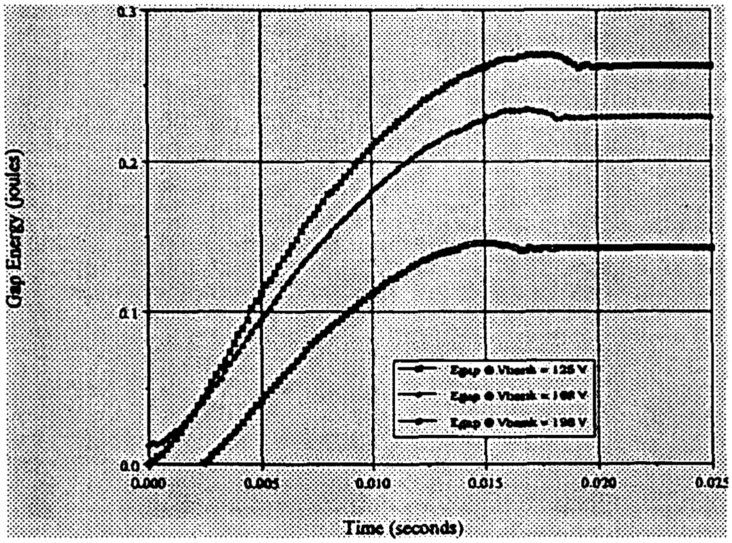

Figure 9. Gap Energy vs. Voltage, Standard **NMERI** DC Source

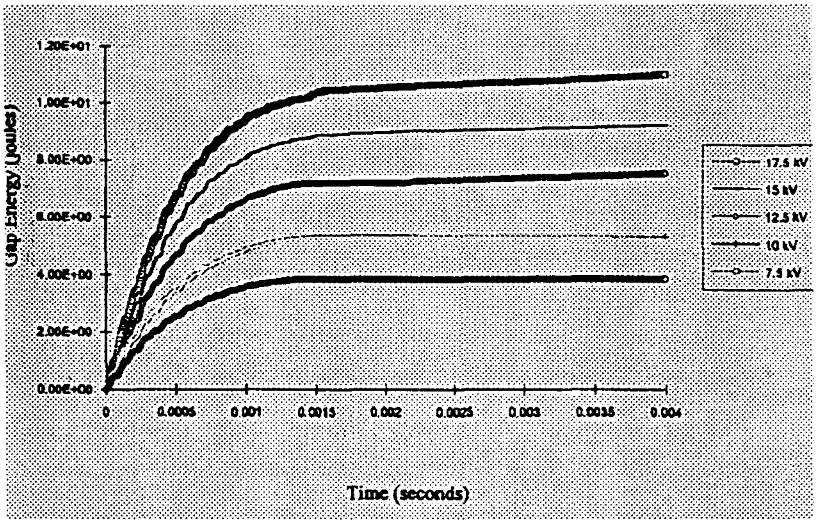

Figure 10. Gap energy vs. Voltage, High Voltage Source

(6.5 - 10%), it is nonetheless an order of magnitude higher than the low voltage source. These values, while only reflecting the tested sources, give **an** indication of the energy actually present in the spark gap for various types of ignition sources, and assist in evaluating the effect of energy on the ignition of flammable gases.

This high voltage source was then used in five flammability tests. The computer used to record data was turned off and all instrumentation (thermocouples and wires) disconnected for safety. Tests were successfully conducted using **7.5** kV, 10 kV, and **12.5** kV charging voltages. However, when using **15** kV, the spark occurred external to the test apparatus, damaging the transducer used to measure overpressure. Testing using this source was immediately discontinued at this point. Should this type of ignition be used for testing in the future, additional research is required to make the entire system safe for this type of voltage.

CONCLUSION

The hypothesis presented in the earlier paper, namely that the energy contained in the standard NMERI DC spark was far lower than the 70 joules stored energy, has been proven. It has also been shown that an alternate DC ignition system using a higher capacitor charging voltage can produce a spark with an energy content of one order of magnitude higher than the current one even at comparable capacitor storage energies. However, the high voltage inherent in such a system creates safety hazards for both humans and equipment, and to use a system will require additional research.

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