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MEMORANDUM REPORT M69-29-1

A SURVEY OF THE METHODS OF TESTING THE ELECTROSTATIC SENSITIVITY OF SOLIDS

by

William E. Perkins

December 1969

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MEMORANDUM REPORT M69-29-1

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by

William E. Perkins

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Pitman-Dunn Research Laboratories
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Philadelphia, Pa. 19137

December 1969

FOREWORD

The author wishes to acknowledge and thank Mr. D. G. Kirk, formerly of the Chemistry Research Laboratory of Frankford Arsenal, for his active participation in the conduction and preparation of this survey.

ABSTRACT

During the processing of ordnance items involving explosive or pyrotechnic materials, accidental explosions or fires are occasionally reported which are attributed to electrostatic discharges.

To augment studies being conducted at Frankford Arsenal, a survey of literature and visits to other governmental and non-governmental agencies were made to obtain information related to electrostatic considerations of solids which are explosive or inflammable. The findings include a description of potential problems and the measurement of their magnitude, along with a description of the various designs of equipment employed and methods used to conduct tests.

Although the approaches and methods differ as influenced by materials and applications considered, in general, solids that cannot be initiated by electrostatic discharges with energies less than 0.015 joule are considered safe to handle.

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INTRODUCTION

In the processing of explosives and inflammable materials, many accidental detonations and ignitions have occurred due to the accumulation and subsequent discharge of static electricity. It has been realized for many years that these discharges come from the human body and various types of equipment and machinery, but little is known of their characteristics.

An early and logical approach to solve the problem was the attempt to ground, electrically, all workers and objects which would be expected to accumulate an electrostatic charge. This approach reduced, but did not completely eliminate, the hazard.

A more recent approach involves the attempt to study the physical characteristics of sparks and to correlate methods of producing detonations or ignitions. As an outcome of these studies, laboratory devices have been developed which can produce sparks of characteristics quite similar to those experienced under actual working conditions. Several research programs are presently being conducted to determine the susceptibility of a wide range of materials to detonation or ignition by these laboratory-produced sparks under controlled conditions of type and magnitude. Consequently, the inclusion of electrostatic sensitivity testing has been inaugurated for explosives and inflammable materials.

The increasing use of powered zirconium, which is very easily ignited electrostatically, has given rise to a widespread concern over the spark sensitivity problem. As a result, studies have been initiated in many agencies but, unfortunately. the methods and devices being considered have been developed independently of one another, so very little correlation exists between the testing procedures and electrostatic spark characteristics.

Since this Arsenal is actively engaged in the use of explosives and flammable materials, this survey was initiated to study sources of information and existing programs concerned with electrostatic examinations so that, if possible, a universal test procedure with standard equipment could be established. This survey was limited in scope to the testing of nondispersed solid materials, such as small quantities of granular or compacted materials, and did not concern itself with liquids, gases, and dust dispersions in air which are considered to be different in nature and not applicable to the solution of the immediate problem.

The following is a discussion of the results of the survey and contains recommendations for the establishment of a standard electrostatic sensitivity testing program.

BACKGROUND OF SURVEY

This survey was conducted in two phases: first, the literature available on the subject was reviewed, and second, visits were made to observe electrostatic sensitivity tests being conducted, to obtain first-hand information pertinent to the various methods being used.

The literature reviewed consisted almost entirely of reports published by various governmental and industrial research organizations, for very little information could be found in periodicals and books. The majority of the reports perused contained descriptions of specific test installations of their particular applications, with the notable exception of five reports from the British Explosives Research and Development Establishment[1,2,3,4,5*] which attempt to explore the basic physical theories and their applications.

Most of the ideas related to the mechanical aspects of the test equipment were derived from first-hand observations and helpful suggestions of personnel consulted at various agencies. A list of places visited and names of persons contacted is contained in the Appendix to acknowledge others contributing to this survey.

DESCRIPTION OF ELECTROSTATIC HAZARDS

An electrostatic charge may be built up on a material or object under a variety of conditions. Usually, a rubbing process or some other method of intermittent contact between two bodies, both insulated from ground, produces an accumulation of a charge on each body, the two being opposite in polarity. The tendency of a body to retain this charge depends upon the medium in which it is located and the distance separating it from all adjacent conductors and from ground. The accumulation can be measured by a quantity known as capacitance. The area of contact over which the charge is dissipated must also be considered, and the mathematical relationship involved for the ideal situation of two parallel planes is:

$$C = \frac{22.45\ KA}{10^8 t}$$

*See REFERENCES.

where: C = capacitance (microfarads, μf)

K = dielectric constant of material between planes

A = area of plane (square inches)

t = thickness or distance between planes (centimeters)

The relationships among capacitance, charged voltage, magnitude of the charge, and the energy of the charge are as follows:

$$C = Q/V$$

$$E = 5\ CV^2 = 5\ QV$$

where: C = capacitance (microfarads)

Q = charge (microcoulombs)

V = voltage (volts)

E = energy (ergs)

When a charge is retained on a body for a measureable period of time, a discharge will occur when the body is brought adjacent to or in contact with a grounded conductor. If the voltage of the charge exceeds approximately 300 volts, the discharge will occur in the form of a spark as soon as the distance between the body and the grounded conductor becomes just less than the maximum distance which the charged voltage will arc. If an explosive or a flammable material lies in the path of such a discharge, a hazard is present.

The three common locations at which hazardous charges are found are:

(1) On the particles of the hazardous materials being handled during pouring operations;

(2) On machinery used in the processing of the material.

(3) On persons who come in contact with the material.

Some studies have been made to determine the maximum hazard obtainable under conditions of industrial handling and processing.

Of the three common locations of charge accumulations mentioned, the mutual charging of particles by pouring from or agitation upon conductive sheeting appears to produce the smallest charge, thereby causing a hazard only in the case of very sensitive materials. The charges produced by this action are very difficult to measure, and virtually no information of a quantitative nature is available.

Static charges developed on machinery are, on the other hand, quite easy to measure with electrostatic voltmeters or other devices which can measure electrostatic fields or leakage rates from charged bodies. Because of the variety of situations to which the term "machinery" is applicable, a statement of definite charge magnitudes would be useless. It can be said, however, that the maximum hazards obtainable from machinery are of an order of magnitude quite similar to those obtainable on the human body.

Many efforts have been made to measure, quantitatively, the electrical characteristics of the human body. This may be regarded as the most dangerous potential source of electrostatic initiation because high energy charges are developed and effective grounding is difficult to obtain. The most universally accepted maximum hazard limits are probably those set forth by the Bureau of Mines [6] where values of 300 pf capacitance and 10,000 volts are considered reasonable, yielding a discharge energy value of 0.015 joule. This source determined capacitance of 100 to 400 pf for individuals insulated from the floor by rubber-soled shoes or 3/4 inch thick glass, choosing 300 pf as a value obtainable under usually high, but not extreme, conditions. These values have been substantiated by tests that were conducted at the Allegany Ballistics Laboratory.[7]

Measurements at the Explosives Research and Development Establishment (ERDE) of the United Kingdom show a human capacitance ranging from 150 to 600 pf, with the 400 to 500 pf being the most common range.[3] The resistance of a point contact on the finger tips was measured and found to lie in a range between 100,000 and 300,000 ohms. A larger contact area under humid conditions reduced this value to 10,000 ohms.

Research on the charging of an individual has been conducted at the Franklin Institute,[8] but these studies were made for a specific sensitivity application, so more information is needed to thoroughly assess the hazard. An attempt was made to determine the resistance of the body and of the leakage paths from the body to ground. These tests indicate a wrist-to-wrist resistance of 5,000 ohms, on the average, with limits of 1,000 to 100,000 ohms obtainable, and a wrist-to-ground resistance of the order of 10,000,000 ohms average. These resistance values did vary and were significantly affected by relative humidity, with a three-fold increase during a drop from 82 to 66 percent RH.

Other studies determined the degree of isolation of the individual from ground or the leakage resistance of the shoe. It was found that a damp shoe has a resistance of the order of 10,000 ohms, while the magnitude for a dry shoe is about 100,000 to 400,000 ohms. Thus, again, the effect of moisture is a significant factor and is considered to be the most important influence on the capacitance of the human body.

Some attempts have been made to formulate a mathematical determination of human capacitance.[8] One such method assumes that the body is a sphere of area equal to the actual surface area of the body:

$$C = 1.1 R + 0.88 \frac{KA}{t}$$

where C = capacitance (pf)

R = 1/2 of individual height (cm)

K = dielectric constant of shoe sole (usually about 5)

A = area of shoe sole (square cm)

t = thickness of shoe sole (cm)

Another method assumes that the sole of the foot and the floor are parallel planes separated by the shoe sole as the dielectric, making applicable the equation previously mentioned, i.e.,

$$C = \frac{22.45 KA}{10^8 t}$$

An interesting capacitance effect was found to be produced in the following way. When an individual is charged, another person moving close to this individual will gain an induced charge. If the person having the induced charge moves away, the originally charged individual will experience a voltage rise and a decrease in capacitance, so the total energy of the charge is not affected.[8]

It is estimated that the human body could be charged to about 30,000 volts for a short period of time at a very low capacitance and a high leakage resistance. At high capacitance values and low resistance paths to ground, very little voltage can be accumulated because of rapid leakage. It is thought that the greatest hazard, in terms of total energy stored, is in the range of 5,000 to 10,000 volts and 100 to 400 pf, although data are insufficient to substantiate this "educated guess." The values of 150 pf at 10,000 volts or 75,000 ergs are reported for a person with light rubber shoe soles.[8] This value is relatively close to the 150,000 ergs reported by the Bureau of Mines.[6]

DESCRIPTION OF ELECTROSTATIC SENSITIVITY TESTING

The general method followed in all successful testing for electrostatic sensitivity has been to charge a known capacitance to a known voltage and to discharge this energy through the material to be tested while noting the results. Audio or visual records are made to establish whether detonation or ignition takes place. This information is presently being obtained with a wide variety of equipment, but many basic similarities are apparent. Most devices in current use are patterned to some degree after the apparatus built by the Bureau of Mines in 1942 and redesigned in 1948.[6] These devices have a common disadvantage in that most of them are laboratory-built items with "home-made" parts, and each has been subjected to redesigning so that results obtained are for limited applications.

Voltage Sources

The basic components of these devices include one or more capacitors and a d-c voltage source. Voltage sources in use are either constant or variable, with the variable types having a zero to 5,000; zero to 10,000; to zero to 20,000 range, while the constant voltage types are usually at the 5,000 or 10,000 volt levels. Any reliable type of d-c power source in the above-mentioned levels appears to be acceptable. Electrostatic voltmeters are usually included to measure the charged voltage immediately prior to discharge.

Capacitors

Nearly all devices can vary the capacitance, either with a group of small capacitors connected in parallel, so that any combination can be included in the circuit, or with a single variable vacuum capacitor, which allows very low values to be reached.

A widely used method is the employment of a circular switch which can be turned to the proper position such that any one capacitor may be included in the circuit (Figure 1A). This method makes the connection of capacitance combinations impossible unless the capacitors are present in groups. The sliding parts require considerable attention to keep contacts clean and smooth.

Another method of selection involves a group of capacitors in parallel, each connected to the circuit by a SPST* switch, so that any combination may be included in the circuit (Figure 1B). An improved variation involves a SPDT** switch in place of the other, so that any capacitor not connected in the testing circuit is connected

*Single pole, single throw switch
**Single pole, double throw switch

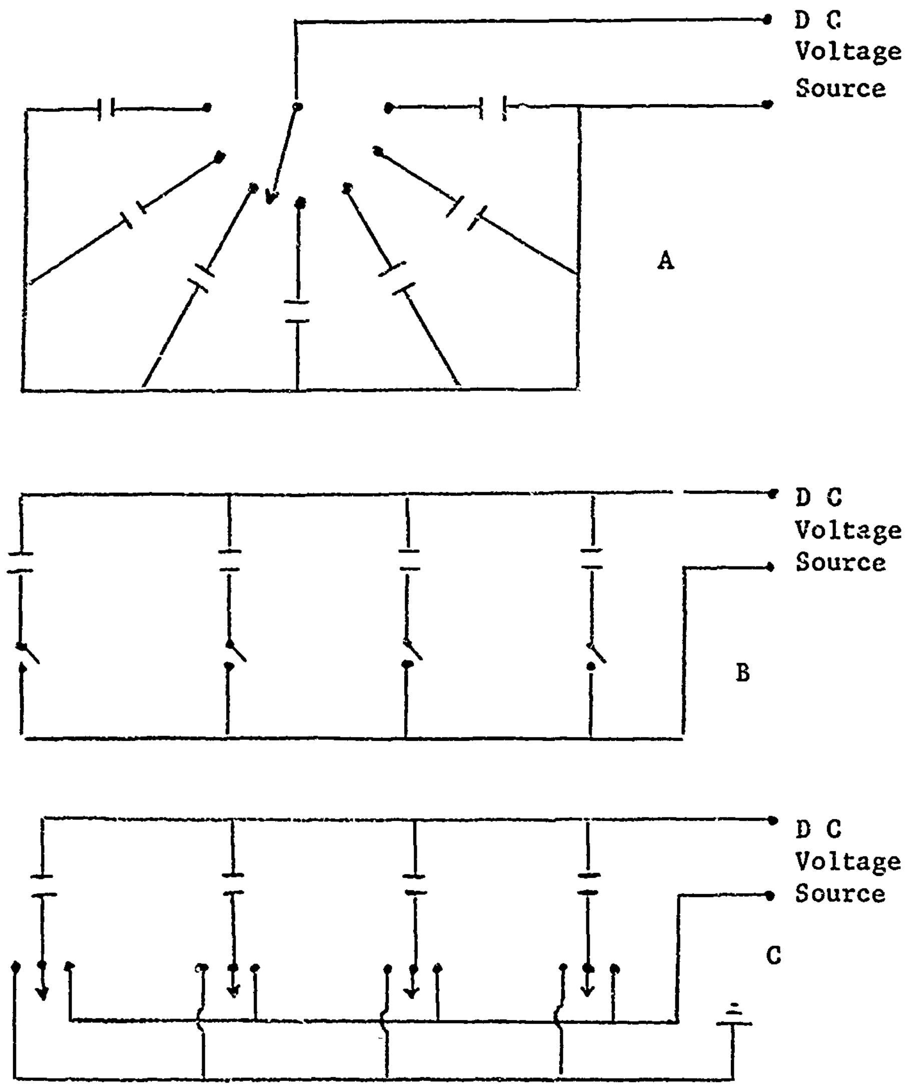


Figure 1. Capacitor Arrangements

to ground for safety purposes (Figure 1C). This type of arrangement appears to be precise, safe, easy to maintain, and relatively easy to design for cleanliness, low resistance, and low leakage.

The above system is sometimes further modified by eliminating switches and using double-pronged bridge plugs having nonconductive handles (plastic or wood) to connect the various capacitors. This method is sufficiently accurate, but presents a possible danger to the operator if the proper insulation or short-circuiting devices are not used.

In one device currently in use, the capacitors are merely placed in a Lucite or Plexiglas box, as required, and connected to the lead wires by means of a pair of clamps. This is believed to be time-consuming and potentially dangerous, but it does eliminate many problems encountered in the switching methods previously described.

The capacitors in existing equipment encompass a wide range of values. The lower limits vary from 25 pf to about 4,000 pf, and the upper range from about 0.1 μf to 4.0 μf.

Discharge Triggering

One of the most important features of an electrostatic tester, and the one which presents the most differences in construction, is triggering the discharge. Methods used could be placed in three major classifications:

(1) Those in which the electrodes are placed at the desired distance, and the energy is released by an electronic triggering device, such as a thyratron.

(2) Those in which the electrodes are a part of the charged portion of the circuit by a switching operation, and the energy is released when the electrodes are moved rapidly to a preset distance by either gravity or a spring.

(3) Those in which the electrodes are a part of the charged portion of the circuit by a switching operation, and the energy is released when one electrode is moved slowly toward the other until a spark is obtained. The movable electrode is then immediately retracted.

The most widely used approach is the one described in Method 2, but others have seen limited use. Method 1 has the advantage of eliminating the variable gap length since there is no electrode movement. In both Methods 2 and 3 the gap length is variable with voltage but, fortunately, each is usually conducted at constant voltage, thereby eliminating this gap length variable. Since the discharge of the energy will always take place through the maximum gap, the voltage rupture will take place at the same gap distance whether the closure is rapid (as in Method 2) or slow (as in Method 3). Method 3 does, however, have other disadvantages in that the immediate retraction of the electrode may prohibit a quantitative discharge of the total energy on the capacitor, and the slow closure of the gap may result in a charge leak-off.

Electrodes

The electrodes almost universally used consist of a metal point and a metal plane. In the case of the moving-electrode apparatus, the moving electrode is invariably the upper one, which is a point (usually a metal phonograph needle) and readily replaceable. The gap is most often adjusted by raising or lowering the metal plane electrode by means of a threaded arrangement. The sample is placed on the lower electrode, usually in a small hemispherical depression to avoid excessive scatterings.

There are several ways in which the rapid closure of the electrode can be accomplished. Some of these arrangements make provisions for the isolation of the discharge circuit from the charging circuit before or during the gap-closing operation. The simplest is, undoubtedly, the free-falling electrode. This technique has been employed by several laboratories, two of which did furnish notable examples.

The Atlas Chemical Industries, Inc., Tamaqua, Pennsylvania, use an electrode which is merely held in place by a rope during charging. After switching the capacitor from the charging circuit to the discharging circuit, the electrode is dropped to a preset level by releasing the rope.

The Naval Ordnance Laboratory (White Oak) uses a device acknowledged to be a copy of the moving electrode apparatus employed at the Explosives Research and Development Establishment and built by Dr. R. M. H. Wyatt of that British organization.[2] In this device, the carriage containing the point electrode rests upon a cam which can be rotated by twisting a rod extending through the outer case of the apparatus. When the cam is in one position, the electrode is raised, and a half turn of the cam produces a free fall to the lowered position. This device is arranged in such a manner that when the cam and electrode are held in the raised position, the capacitors are connected to the charging circuit, but when the cam is turned and the electrode drops to the lowered position, the connection to the charging circuit is opened and the capacitor is isolated during the discharging step (Figure 2).

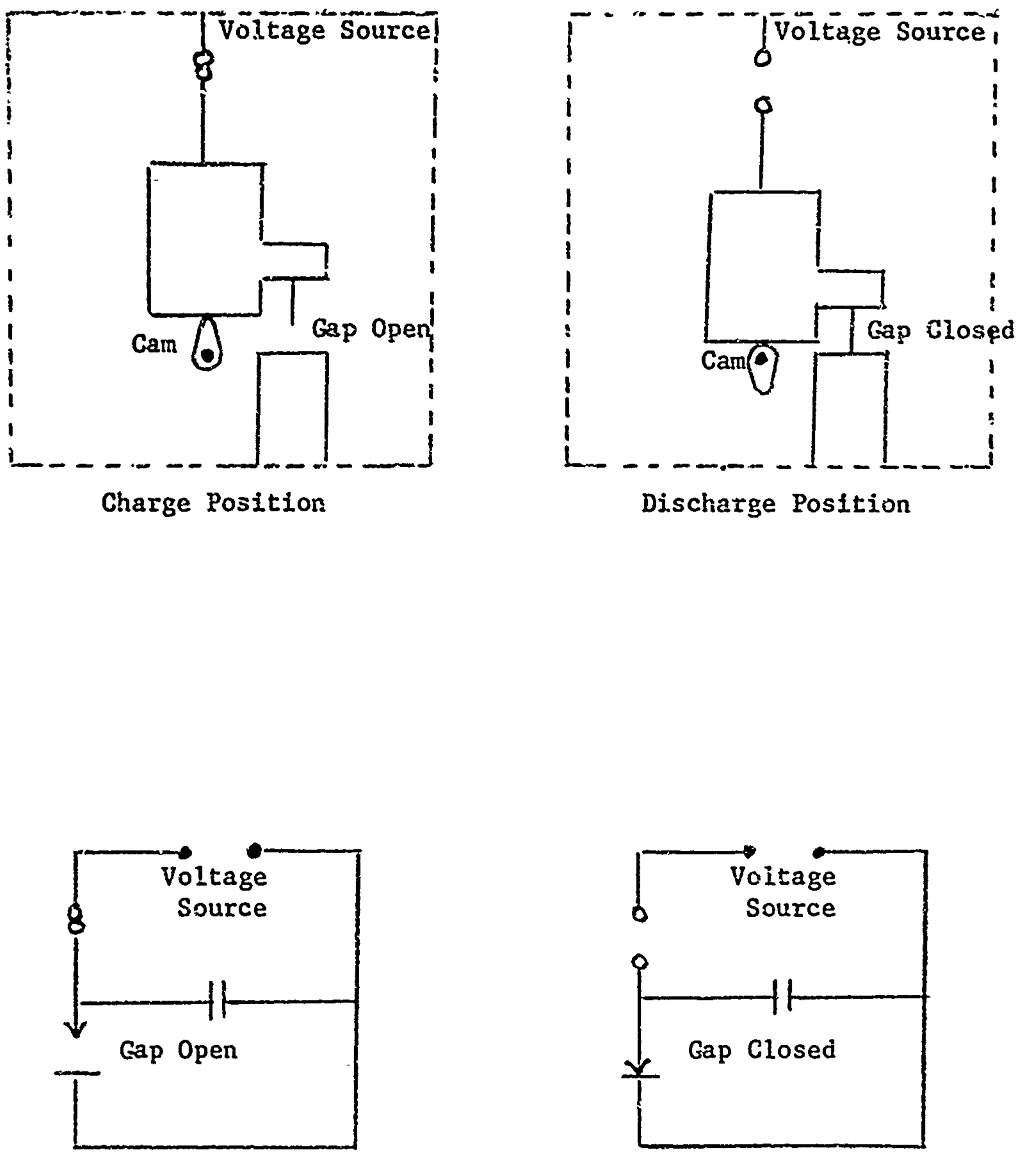


Figure 2. Diagram Showing Principle of Operation of Apparatus in Use at Naval Ordnance Laboratory or Explosives Research and Development Establishment

Another simple but effective closure arrangement in use is a push rod, or lever arrangement, in which pressure is applied against a return spring.

A different type of closure is one being used in an apparatus at Picatinny Arsenal. [9] In this installation the electrode is rapidly lowered by means of an electric motor which contains a timing mechanism such that the gap will remain closed for a preset time (on the order of tenths of a second), followed by a precision return to the starting point. The major disadvantage of this device is the chance of producing multiple discharges due to a relatively long period in the closed position.

The Bureau of Mines now has a spring-driven closure-and-return device to take the place of the one mentioned in their 1953 report. [6] This trigger (shown in Figure 3) contains a needle electrode "A" mounted on rod "B" which is free to slide through the housing "C." The two shorter rods, "D" and "E," are hinged by pins "H," "I," and "J," as shown. Spring "G" is attached between pin "I" and a fixed wall hook "K." When the handle "F" is pulled to the left, pin "I" moves, raising "B," and a latch "L" is engaged. When the device is located in this position, the spring is under maximum tension. When the latch "L" is extracted, the spring contracts, pulling pin "I" to position "M," thereby rapidly lowering the electrode holder "B" to its lowest attainable position and retracting it immediately. Handle "F" must be pulled to the left again to cock the device for subsequent tests, and the position of the plane electrode is adjusted if the desired minimum gap was not obtained.

No provision has been made for the isolation of the charging circuit, but the closure time is very short and a high resistor is placed between the power supply and the capacitor, making multiple discharging unlikely.

An arrangement similar to this, but minus the spring, is used by the makers of photoflash bulbs at Sylvania Electric Products, Inc., Montoursville, Pennsylvania. This apparatus relies on the manual ability of the operator to achieve rapid closure and return.

An apparatus employing the gap closure method devised by the Bureau of Mines, as just described, and the Explosives Research and Development Establishment (ERDE) method [3] has been designed and built by Mr. A. T. Wiebke of the Naval Ordnance Test Station, China Lake, California. In addition to the isolation of one side of the capacitor by the E.R.D.E. method, a solenoid switch has been included which is activated upon the isolation of one side to subsequently isolate the other side of the capacitor by a switching operation. Instead of using a gap at the point of closure, the needle is actually brought in contact with the plate. To avoid

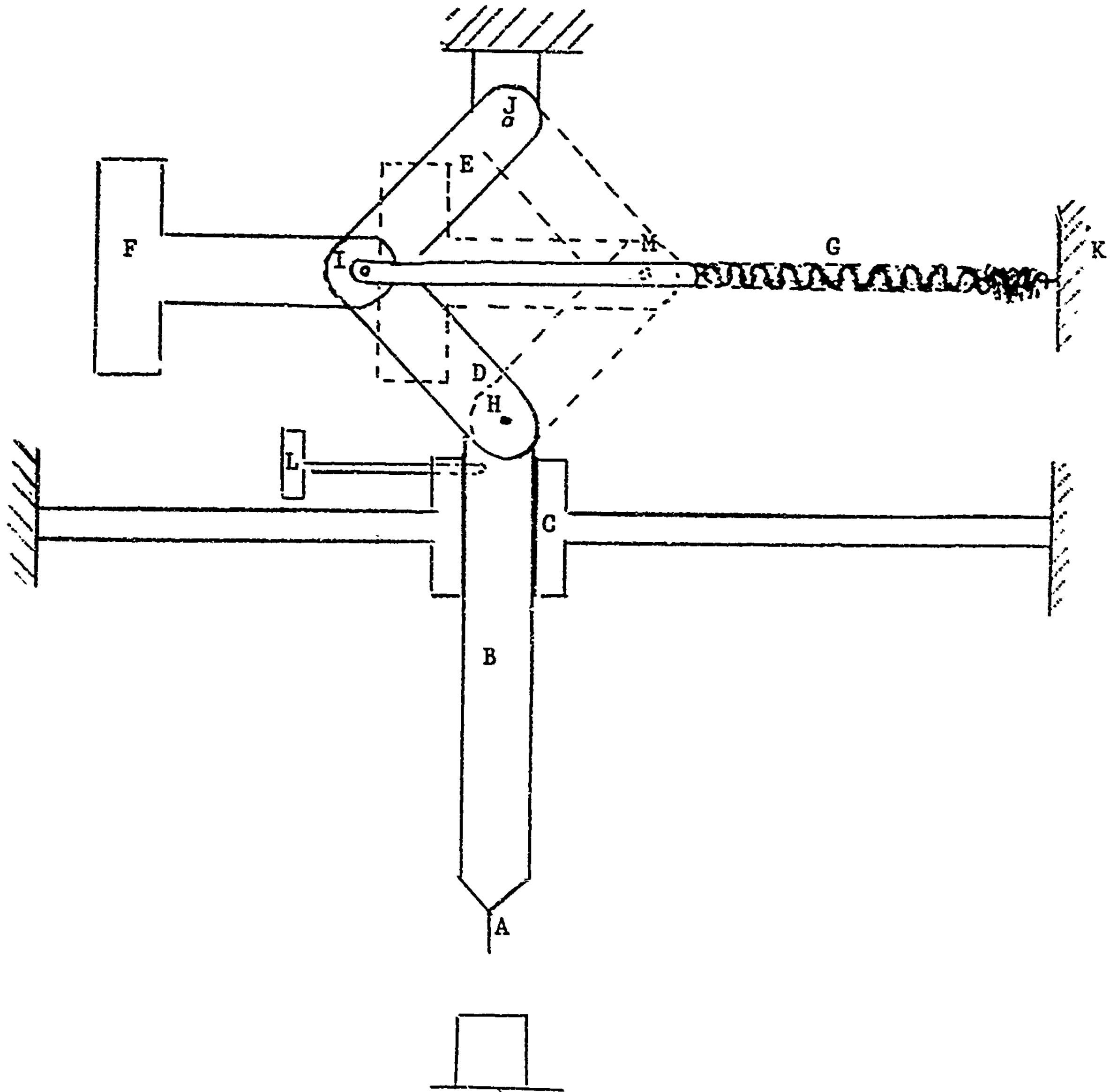


Figure 3. Diagram showing Operation of Bureau of Mines Gap Closure Apparatus

the possibility of impact ignition, the needle is suspended in place by a small spring, to produce a "shock-absorber" effect. In order to assure contact, the plate is raised so that the needle-contacting fixture effectively over-travels the closure point by 1/32 inch. The spring was mounted to prevent bouncing during the gap-closure operation. The schematic of the apparatus is shown in Figure 4.

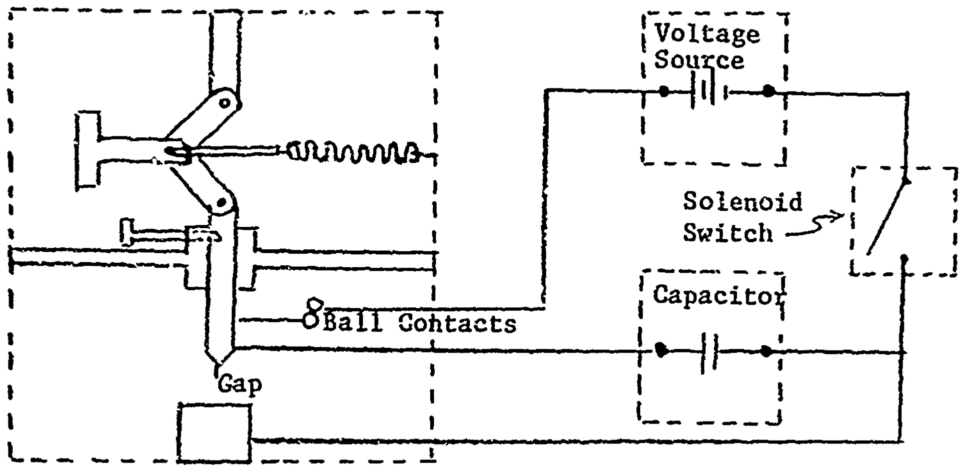
Locations employing the slow gap-closure method have relatively simple operations. In all cases, one side of the capacitor is disconnected from the charging circuit prior to discharging. At the Allegany Ballistics Laboratory, Cumberland, Maryland, the needle is released from a holding device and lowered by a well-insulated handle. At Frankford Arsenal [10] the needle is lowered by a calibrated knob, and Lake City Army Ammunition Loading Plant uses an apparatus quite similar to the Frankford Arsenal type.

General Circuitry

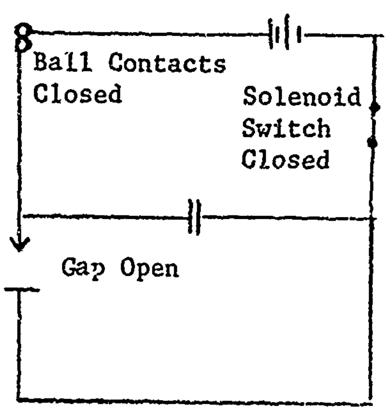
In the design of electrostatic sensitivity testing equipment, attention must be given to reduce leakage problems associated with the high voltages involved. The fact that the voltage is static and not dynamic gives rise to the need of even greater leakage protection. Leakage occurs principally in three ways: conduction through inadequate insulators or through surface films accumulated on them; corona discharges through the atmosphere, separating a charged object from a ground or opposite charge; and induction between parallel conductors, such as lead wires.

Designers of such equipment are usually aware of these problems, but often tend to underestimate their significance. In most instances care has been taken to keep the circuit portions leading to the opposite sides of the capacitor isolated from one another. Also, the charging and discharging portions of the circuit are usually separated, as indicated in the discussion concerned with gap-closure methods. These steps should eliminate the induction problems and most of the corona problems.

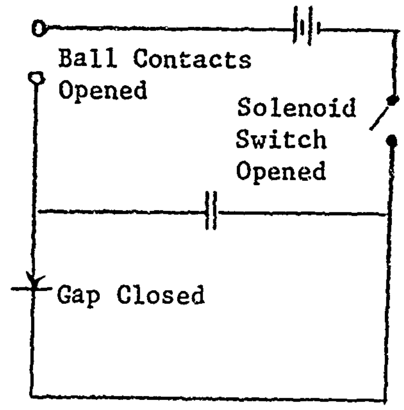
As a further step toward the suppression of the corona problem, some designers have arranged all parts and connections so that no radius of curvature of less than a set value (usually 1/8 or 1/4 inch, depending upon voltage used) is obtained. These components are usually kept smooth and clean, as well, for sharp corners and points or rough spots seem to provide focal points for corona discharges. Films of dirt also create leakage paths along the surfaces of materials which are otherwise good insulators. A further practice is usually observed, that of controlling the atmosphere to a comfortable working temperature and the relative humidity to less than about 50 percent.



Apparatus



Charge Circuit



Discharge Circuit

Figure 4. Diagram showing Operation of Naval Ordnance Test Station Apparatus

Operator Safety

A final design consideration is that of the safety of the equipment operator. The practice in the more elaborate devices is to place all components in a case, or cases, and to equip all access doors or openings with a system of interlocking switches to short circuit or ground immediately all capacitors upon opening. Various safety lights are often used to indicate which portions of the circuit are actuated.

Precautions normally employed when handling explosive or inflammable materials (such as the wearing of safety shoes, safety glasses, and special work uniforms) are generally required.

It is the opinion of Mr. Wiebke of the Naval Ordnance Test Station that, because of the small quantities of explosives handled for each sample and the high voltages produced to evaluate them, it might be safer to have the operator highly insulated, rather than grounded as is the usual practice.

TEST PROCEDURES

General

The test procedures followed vary considerably in mathematical aspects, but are basically the same with regard to the physical operations performed. Explosive handling methods are those commonly established by the safety departments of the various organizations. In general, if a dry powder is to be tested, it is usually conditioned in the test room or equivalent environment for 24 hours unless the moisture content is one of the variables under consideration.

Sample Placement

The size of the sample is usually selected by the investigator. The most common amount used for flammable materials is 50 milligrams. For very high explosives, however, a smaller sample size may be required for safety's sake.

Before the test is conducted, the sample is placed on the proper location of the lower electrode, or plate, to be in the line of closure with the upper point electrode. Some agencies use lower electrodes having detachable and replaceable sections to permit loading prior to sample conditioning and/or for ease of operation when conducting tests.

Discharging Operation

After the sample has been placed in position and the equipment engaged properly, the power supply is activated to charge the preselected capacitor to the appropriate voltage and then, occasionally, the capacitor is isolated from the charging and discharging circuits to check for leakage rates and operating voltages. When the capacitor contains the appropriate charge, the discharge triggering devices are actuated and the equipment is deactivated. At this point, the operator records the results, cleans the electrodes, and replaces components as required. Most investigators require a change of samples after each test, even when no ignition or detonation occurs, but the needle electrode is usually used repeatedly until it appears burned to the naked eye.

Mathematical Analysis

When equipment is used in which either or both the capacitance and voltage can be varied, a series of "up-and-down" trials is usually made until a threshold of sensitivity is established.

Some investigators are interested in the insensitivity level; i.e., the maximum energy discharged without obtaining detonation or ignition. Other investigators are interested in the 50 percent sensitivity point. This is usually easier to obtain and/or calculate, and generally requires less testing.

It has been found by most investigators that, by varying both the voltage and capacitance at random, poor results are obtained, so the most popular procedure seems to be to vary the capacitance and keep the voltage constant. The reverse procedure can be used; i.e., the voltage can be varied and the capacitance kept constant, but in either approach the realistic values of both capacitance and voltage expected for electrostatic discharges should be used.

In either approach, a series of trials is conducted at each energy level, usually ten at an interval, and the percentage results are plotted to obtain data desired.

Types of Discharge

There are two general types of discharge employed. One is the discharging of the energy in the form of a spark through the air and the material to be tested, and the other is a discharge through the material by direct contact. The type used is usually dependent upon type of material to be tested, the energy range being investigated, and the limitations of the equipment. In any event, rapid closure equipment is required to use very low energy discharges.

Confinement

When very high voltages (over 5000 volts) are employed, the sample is often surrounded by a plastic cylinder to prevent the spark from jumping around, rather than through, the sample. This confinement has an influence upon sensitivity, and it will be discussed in another section of this report.

Safety Applications

Results obtained with the various electrostatic sensitivity testing devices are applied in a variety of ways. Some are used in conjunction with planned programs having well established specifications, while others are used to obtain empirical comparisons with convenient standards.

Most programs are conducted to establish the zero ignition probability of a material under consideration with an energy level considered as the maximum hazard for acceptability. The value most often used is the one obtained by the Bureau of Mines, [6] 0.015 joule. The Allegany Ballistics Laboratory has deviated slightly from this figure, to 0.01375 joule to comply with capacitance and voltage levels available on their equipment. [7]

Frankford Arsenal uses a level of 0.045 joule which was found to be the zero ignition point of grade "B" magnesium obtained on the apparatus shown in Figure 5. This standard was used since it was considered to be the most sensitive metal powder being safely handled at the time. Others have set similar or comparable levels of acceptance, either formally or informally.

The Naval Ordnance Test Station deviates from this procedure by using the 50 percent functioning point to set up categories of relative sensitivity ranges. These categories are then correlated

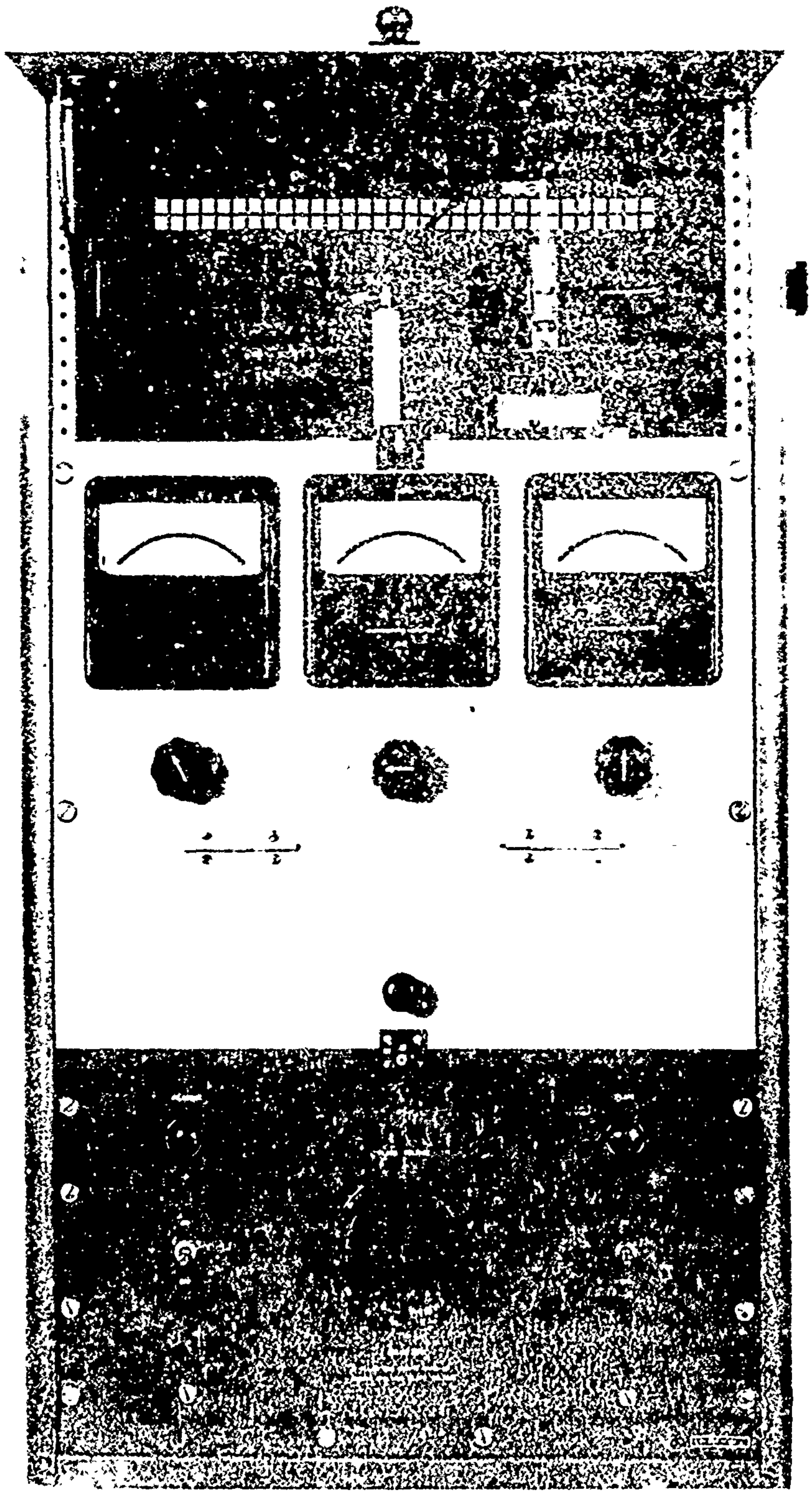


Figure.5. Frankford Arsenal Electrostatic Discharge Tester

with handling and accident experiences, and each is handled accordingly rather than limiting efforts to materials complying with an exact safety specification.

It is in this aspect of electrostatic sensitivity testing that knowledge is most lacking and inconsistent.

RESEARCH ON ELECTROSTATIC SENSITIVITY

Work Completed

The design and fabrication of any testing equipment mentioned in this report can be considered a form of research since, to some extent, it is original work. In addition to this applied phase, some agencies have attempted to study the basic physics involved in sparking and arcing, and in discharges resulting in the detonation or ignition of materials. Because of the complex nature of problems being considered, the most useful source of data obtained from these experiments must still be considered empirical.

Early work in this area was conducted at the Bureau of Mines. This research led to the fabrication of a testing device as well as an analysis of some of the variables, including voltage, degree of confinement, particle size of the sample, moisture in the sample, and electrode polarity. [6] These tests have been substantiated and, in some cases, supplemented by other investigators. Further empirical studies were carried out by the Naval Ordnance Laboratory, leading to an improved design of the equipment and an analysis of fundamental variables. [12,13]

A statistical study of the effects of voltage, series resistance, gap distance, humidity, and sample size, was conducted by Picatinny Arsenal on equipment designed by them. [9] The Allegany Ballistics Laboratory has done some work on new methods for testing and on fundamentals to substantiate existing information. [7] Other organizations have benefited from the pioneering of this small group.

Several other groups have approached the problem with a trend toward basic research, rather than applied research. Construction of equipment was, of course, necessary but its design was fairly simple, although very carefully built.

Morris, Taylor, and Hall (mentioned in Reference 1) did some work to determine the dependence of ignition probability on the voltage, capacitance, and energy. Ubbelohde et al did a similar study and, also, considered the effect of series resistance (also mentioned in Reference 1). These studies were further elaborated upon by Moore, Sumner, Wyatt, and Scaife, of the Explosives Research and Development Establishment of the British Ministry of Supply. [1,2,3,4,5] This source of information is probably the most complete available with regard to the theory of ignition by electrostatic discharge.

The first [1] of these reports deals with the mathematical basis of condenser sparks and the application of the principles to situations of air gaps and explosions. The most important tool in this study was an oscilloscope, used for the purpose of obtaining voltage and current traces of sparks in several situations.

Part two [2] of this study describes both the approaching and fixed electrode apparatus and draws a comparison of the two. The effects of capacitance, voltage, series resistance, and inductance, on ignition probability are discussed and the effects of electrode shape and comparison were studied. For the fixed electrode apparatus, the gap length variable was studied.

Parts three [3] and five [5] deal with the application of the spark theory to actual "factory" conditions. Factors considered include electrical characteristics of the human body and the modification of the capacitance and electrodes of the test equipment to simulate these characteristics. This included the comparison of finger electrodes with other common materials, studies of spark splitting as a result of high series resistance, and further studies of capacitance effects upon sensitivity.

A closely related topic, the sensitivity of certain materials to the radiation energy of the spark was studied in part four. [4]

The mathematical evaluations of electrostatic hazards can also be considered as basic research, and notable contributions were made in this area by the Bureau of Mines, [6] Franklin Institute, [9] and Explosives Research and Development Establishment. [3]

Work Planned or In Process

A considerable amount of attention is being given to electrostatic sensitivity problems at many agencies, but only a few are known to have any actual research projects in progress. The Explosives Research and Development Establishment [5] has completed and is about to report further on the magnitude of electrostatic hazards and the physical characteristics involved. Both the Naval Ordnance Laboratory at White Oak and the Naval

Ordnance Test Station at China Lake attack the various aspects of this problem as specific questions arise, and it is expected that results obtained will be reported subsequently. The Carneys Point Process Laboratory of E. I. duPont de Nemours & Company, Inc., is conducting some long range studies to investigate spark characteristics by the oscillographic method. The Denver Research Institute of the University of Denver, in Denver, Colorado, is beginning work on a project to investigate further the electrostatic sensitivity problem.

Relative to research on closely related subjects, it is noted that the American Petroleum Institute has sponsored programs with Massachusetts Institute of Technology and John Hopkins University related to problems of the petroleum industry. Royal Dutch Shell is also a center of research in this line. The Bureau of Mines is actively investigating hazards posed by dust dispersions in air and attempting to relate the findings to those concerning layers of dust in a nondispersed state.

VARIABLES INVOLVED IN ELECTROSTATIC SENSITIVITY EVALUATIONS

Energy

When a spark in the discharge occurs, energy is dissipated in four ways, mainly: as heat in the spark channel; as shock-wave energy; as electron beam energy; and as radiation. [4] Heat is probably the main cause of ignition, while the shock-wave and electron beam energies are thought to have very little effect. Some recent work done by D. B. Scaife [4] has shown that radiation may account for as high as from 10 to 15 percent of the energy dissipated in a spark under some conditions, but normally it is probably much smaller than that.

Energy is the most important single value to be considered in an electrostatic determination. Sensitivity is usually reported in terms of the energy level at which the ignition probably reaches zero, fifty percent, or some other convenient level. Energy, therefore, could be considered the dependent variable in the system, with the more basic principles which are used to determine energy becoming the independent variables.

When a discharge, or spark, is produced, its tendency to cause ignition is probably largely dependent upon the rate at which the energy is delivered. This rate is influenced by the charged voltage and the resistance and inductance through which the energy must pass to be completely discharged. The voltage determines the time taken to dissipate the energy, while the nature of the discharge path and the shape of the voltage-vs-time are indicative of method of delivery. Conditions should be controlled to produce a discharge having a maximum temperature by positioning the electrode and providing surroundings such that heat losses are minimized.

It should be recognized that this approach is making the assumption that the most important cause of electrostatic actuation is thermal energy, but it is recognized that there are exceptions which make generalizations complex and less than 100 percent accurate. In the following sections, a more complete assessment of factors will be attempted.

Voltage and Capacitance

To determine the effects of voltage on sensitivity, a series of curves was drawn to show the relationship of the ignition probability of certain materials to discharge energy, with each plot representing a particular capacitance.[3] Energy, when capacitance is kept constant, is proportional to the square of the voltage, i.e., $E = 5\ CV^2$.

For extremely sensitive organic salts of metals, the ignition probability rises from zero to a maximum value as the discharge energy is increased, and then falls back to a low value of probability with further increases. In still higher energy ranges another increase in ignition probability is noted, eventually reaching 100 percent. In the lower energy ranges, the curves for the various capacitance levels nearly coincide, suggesting that the sensitivity may be independent of capacitance over a fairly wide range of values. The initial zero point on the curve is the energy value that would normally be considered to establish the sensitivity of the material.

For a particular material, the maxima of a series of curves all lie at about the same voltage.[3] For different materials, this voltage appears to increase with the resistance of the test material. The voltage at which maximum probability occurs is considered to be the voltage at which a transition from a contact discharge to a spark discharge occurs if an approaching electrode apparatus is used. This transition voltage increases for more resistant materials because of a higher potential required to overcome the combined resistance of the air and the crystals of the sample. The majority of the transition voltages lie between 200 and 500 volts, with some exceeding 1000 volts.

Another phenomenon which may influence the behavior of ignition sensitivity is the movement of the particles as a result of the electrostatic field. At higher voltages the movement of some materials toward either the positive or negative electrode becomes quite significant.

The two maxima of the probability curves are considered to be due to (1) low voltage contact discharges, and (2) higher voltage spark discharges. [2]

When the same sort of curves were plotted using capacitance levels such that the voltage remained in the gaseous spark region, a temporary maximum was again observed when a series resistance was placed in the path of the discharge. [3] This behavior was studied by placing a conductive rubber covering on the lower electrode of the approaching electrode apparatus, and it produced a phenomenon known as "spark splitting." This is a condition in which only a portion of the discharge energy is contained in the initial spark and, as the electrode continues to approach, additional discharges are obtained.

Since at high capacitance levels, the energy level at which voltage splitting occurs is very high, the initial spark possesses sufficient energy to produce a high ignition probability, thus minimizing or even eliminating the premature maximum in the energy-vs-probability curve. At the lower capacitances, the curve attains a prominant peak as the voltage becomes high enough to cause splitting, and rises a second time as the portion of the remaining energy becomes sufficient to supplement the initial discharge to increase the ignition probability. At very low capacitances, splitting apparently occurs before the minimum ignition energy is reached, and energy remaining is not sufficient to supplement the initial discharge to produce ignition.

From this it can be inferred that there is a minimum capacitance for ignition. It follows that there is an optimum capacitance at which the ignition probability reaches its lowest point under conductive rubber (or series resistance) conditions, as opposed to that of the minimum ignition energy found to be independent of capacitance over a limited range using metal electrodes with no added resistance.

With metal electrodes, if the minimum energy is determined over a wide range of capacitances, the value rises at both ends in which it is independent of capacitance. [5] The rise at the lower capacitance levels is caused by the increase in voltage to the gaseous spark range; the rise at the high capacitance level is marked by some peculiar and largely unexplained discontinuities. At high capacitances the voltage necessary for minimum ignition falls to a limiting value of the order of 10 volts, which is somewhat less than the voltage necessary to set up an arc discharge between two metal electrodes.

None of the foregoing generalizations on the dependence of sensitivity on voltage and capacitance can be considered applicable to all materials. If the sensitivity of a material lies in a higher energy range than those studied, the low voltage and capacitance effects will never be noted, and the ignition probability will vary with energy in a relatively simple manner, showing a marked dependence upon voltage.[6] Widely different materials such as metal powders, primary explosives, and secondary explosives, may vary significantly with regard to such properties as conductivity and particle size, and their sensitivities may not even be of the same order of magnitude.[14]

Series Resistance and Inductance

The charge remaining on a capacitor at any time during the discharge is dependent upon the resistance and inductance in the discharge circuit in a rather complex way.[1] Essentially, there are two characteristics in such a discharge - an exponential decay and an oscillation of the charge between the capacitor plates. When the resistance is kept near zero, the self-inductance of the circuit causes an oscillatory type discharge, the peaks of which decay exponentially. Addition of resistance lengthens the oscillation period and decreases the total discharge time, which reaches a minimum when

$$R = 2 (L/C)^{1/2}$$

where R is the resistance,

L is the inductance, and

C is the capacitance.

As the resistance increases, the oscillations disappear, forming a unidirectional discharge, the total time of which again increases. Discharge times may range from about 0.1 to 10,000 microseconds for these non-gap apparatus.

The inclusion of a gap in the test circuit results in a variable resistance.[1] The duration of the discharge appears to decrease considerably when a gap is present, but other characteristics remain similar. Addition of resistance in a gap circuit produces about the same effects as those described for the non-gap circuits described above. In addition, that portion of the energy contained on the capacitor which is actually dissipated in the initial discharge varies greatly with series resistance. With no resistance, virtually 100 percent of the energy available is discharged through the gap. According to Riddlestone (quoted in Reference 1), this figure drops to about 50 percent at one ohm resistance and to less than 10 percent at about 50 ohms. The tests run at constant capacitance showed these percentages to rise slightly with decreasing voltages at a given resistance level. At higher resistances, the energy in the gap again increased and decreased slightly, reaching a maximum of about 30 percent at approximately 50,000 ohms, according to Llewellyn.[1]

The change from oscillatory to unidirectional discharges appears to occur at a resistance value of 100 to 500 ohms, with the minimum time occurring in the vicinity of 100 ohms.[1] The resultant of these two effects produces a minimum in an ignition probability-vs-resistance curve or an optimum series resistance for sensitivity, all other conditions being constant. A change in inductance produces a shortening of the oscillation period at low resistances, but the effect on sensitivity is not large. At high resistances, inductance has practically no effect.

When a sample layer is included in the gap, little difference in spark characteristics is observed.[1] An explosion in the gap seems to increase the gap resistance and lengthens the spark duration.

A more detailed study of ignition probability at various resistances shows a slightly more complex behavior.[2] The probability drops to a minimum, as previously discussed, but rises again to a maximum, followed by a second drop at very high resistances. This maximum occurs over a range in which the proportion of energy dissipation in the gap is about constant. Other studies have shown that this variation may be the result of: (1) a variable time delay from spark initiation to the beginning of ignition, which reaches a minimum in this resistance range, and (2) a decrease with increasing resistance in the amount of energy in the gap that is dissipated before ignition begins. These effects point to the likelihood of a thermal ignition process, and appear to be similar for both contact and gaseous discharges.

The most widely used test modification involving inclusion of resistance is that of the conductive rubber covering over the lower electrode. This creates a resistance which may range from 100,000 to 2,000,000 ohms in series with the gap.[3] This rubber surface closely approximates the texture and resistance of human skin and, in oscillographic studies, produces a spark comparable in waveform to that produced by discharging the static charge from a human body through a finger. An important effect of this sort of resistance is spark splitting, which produces a double-peaked probability curve and gives rise to a minimum capacitance for ignition, as discussed in the preceding section of this report.

It was questioned whether a group of capacitors, interconnected through a group of resistances, more closely simulated the human body rather than a single capacitor and a single resistor.[3] It was found that a single 500 pf capacitor discharging through a 39,000-ohm resistance produced a probability-vs-energy curve similar to that produced by the human body.

Electrode Effects - Geometry and Composition

When a departure is made from the usual metal point-metal plane electrode arrangement, measurable differences in ignition probability and sensitivity are often noted. These changes may be in shape or composition.

In low voltage discharges, a pointed electrode is necessary to penetrate the layer of sample crystals so that a discharge will occur. The two forms used were a sharp needle and a "plumb bob" (a sphere which has been turned down to a point on one side).[2] The plumb bob resulted in greater ignition probability under all conditions and, in many cases, a lower minimum ignition energy (i.e., greater sensitivity). An attempt was made to determine this effect more specifically by using plumb bobs of various cone angles and tip radii. The results showed no significant variation.

At high voltages, the needle creates a problem because of corona discharges.[3] The plumb bob modifies the problem while a sphere electrode practically eliminates it below voltages of 10,000 volts. For overall use, however, the needle has been found to give the most reliable discharges.

The most probable reason given for these effects of electrode shape is a variation in effective confinement of the sample while the discharge is taking place.

The variation of sensitivity with the composition of the electrode seems to depend almost entirely upon the resistivity of the material involved. Therefore, the biggest effect is found upon comparing a metal electrode with a nonmetallic material, such as rubber, the effects of which were discussed in the section dealing with resistance. Comparisons between a rubber electrode of approximately 100,000 ohms resistance and a metal electrode in a circuit containing 100,000 ohms series resistance show parallel results for the two cases.[5] This would indicate that the effects of replacing metal with a nonmetal would depend upon resistance alone.

When electrodes are brought to very small gaps, voltages greater than the ionization potential of the atmosphere (about 15 volts) may cause discharge.[2] At very low voltages a portion of the energy seems to go to the heating and subsequent vaporization of the metal electrode surfaces, at times creating a welding effect. Therefore it was thought that the use of materials having different melting and boiling points might affect the sensitivity of the test sample. Upon trial, no discernible effect was observed. This effect, however, may give rise to the sensitivity at extremely low energy ranges in some materials.

In the gaseous discharge region, no metal vaporization was observed.[2]

Confinement

When high voltages are employed, the sample is often surrounded by a ring of nonconductive material to keep the discharge from by-passing the sample, giving rise to a condition of partial confinement. For most materials, greater sensitivity is noted for unconfined than for confined samples. [8] Primary explosives are the noted exceptions to this trend. This change in sensitivity may be caused by fine dust dispersions occurring in the air in the vicinity of the sample, caused by the passage of a spark. These dispersions would be expected to be more susceptible to ignition than the main dust layer.

Polarity

The use of a positive point and a negative plane results in greater apparent sensitivity than the reverse situation. [6] This is probably because a negative point is more susceptible to a corona discharge, requiring higher capacitor energy to produce the required energy to negate it.

Gap Length

At constant capacitance, resistance, and charged voltage, an increase in gap distance causes an increase in the voltage in the gap. [1] This is caused by a change in the gap resistance and the resulting reapportionment of the voltage in the various parts of the circuit. This variation appears to be linear. It could be expected that the slope of such a curve would be less as the series resistance in the gap is increased.

Circuit Design and Maintenance

Leakage

One of the biggest variations in electrostatic sensitivity is introduced by the dispersion of the charged energy through conductive paths other than the gap circuit. These paths result, usually, from improper insulating materials or, more often, from the deposition of conductive foreign materials upon these insulators. These depositions come from either dirt accumulations or condensations under high humidity conditions.

The other big leakage problem is that brought about through corona discharge. Corona discharge becomes greater at high voltages and occurs most frequently at points having abrupt surface changes, such as points, corners, metal burrs, and dirt particles. High humidity also seems to increase corona discharge. All of these leakage effects tend to make the test material appear to be less sensitive.

Measurements with the approaching electrode apparatus at the Explosives Research and Development Establishment showed a voltage drop ranging from 8 percent at 600 volts to 36 percent at 5000 volts during a 2 to 3 second lapse when a 100 pf capacitor was employed. [2] The use of a larger capacitor reduced these losses considerably. Other sources have noted changes in sensitivity with increasing humidity, being most apparent in the 50 to 60 percent relative humidity range.

Resistance and Inductance

A characteristic of circuitry which could have an effect upon electrostatic sensitivity is resistance. In a preceding section it was stated that a one-ohm series resistance in the discharge circuit could reduce the amount of energy in the gap by 50 percent. If no other resistance is included in the circuit, the placement, composition and size of conductors, and cleanliness of contacts may be critical. The placement of leads to avoid inductance effects may also be important. Capacitance variation methods must be arranged so that the resistance does not vary.

Test Sample Variables

There are many properties of the sample to be tested which may effect the sensitivity. Since the test is often designed to determine the effect of these variables rather than the opposite case (in which the variables influence the test procedure itself) it is felt that they lie largely outside the scope of this report. Therefore, only a brief mention will be given to each.

The size of the sample tested seems to have little influence upon sensitivity. This has been explored by Picatinny Arsenal [5] and noted by others during routine tests. No variations can be definitely attributed to sample size.

The particle size of the sample has a great influence on its sensitivity, but none on general testing procedures. Basically, material with smaller particles is much more sensitive than material with coarser particles. [6] This effect tends to minimize with increasing degrees of confinement for some materials.

The conductivity of the sample influences its sensitivity. This influence shows to the greatest extent at the transition voltage from contact to gaseous discharge, as explained in greater detail under "Voltage and Capacitance."

Moisture content has an effect upon sensitivity too. For "dry" samples, the moisture content usually depends upon the humidity of the place of storage prior to the test. The direction and degree of variation in sensitivity with moisture content may differ for each material, so no general statements can be made.

A variable which depends upon the type of material being tested, but which is directly involved in testing procedures, is the effect of repetitive testing upon the same sample. According to the Naval Ordnance Laboratory, White Oak, some materials appear to undergo a change such that ignitions cannot be obtained at energies far above normal sensitivities after undergoing tests of one or more sparks having energies too low for ignition. Other materials will eventually ignite upon repetitive exposure to discharges of far lower energy than the normal zero probability level. These effects are probably caused by a physical altering and rearrangement of the particles in the discharge channel.

It was concluded that there are some materials existing for which these generalizations do not apply. For a thorough assessment of the electrostatic hazards of these unknown materials, their specific properties would have to be established in a comprehensive investigation.

CONCLUSIONS

There does not seem to be any "standard" apparatus currently in use to establish the electrostatic sensitivity of solids. The types of equipment and techniques being used by the various investigators are somewhat similar, with differences usually a function of the materials being tested and the applicability of the results.

It was the concensus of the investigators that

1. Electrostatic discharges should be of the high voltage-low capacitance type, with

    a. Voltages controlled in the 5,000 to 15,000 volt range, and

    b. Values of the capacitors to be in the 300 to 500 pf range.

2. Electrodes be the metal point-to-metal plane type, with the point electrode being negative in polarity.

There appeared to be no majority opinion concerning other variables, such as circuit switches and discharge triggers, as well as the movability of the electrodes, size and confinement of the sample, and circuit resistances.

The electrostatic discharge energy most often quoted as being the maximum tolerated without undue hazard was 0.015 joule, obtained by the Bureau of Mines.

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APPENDIX

ORGANIZATIONS AND PERSONNEL VISITED

The following organizations were visited and personnel contacted to observe electrostatic sensitivity testing and equipment.

Atlas Chemical Industries Incorporated
Reynolds Experimental Laboratory
Tamaqua, Pa.
    Dr. F. W. Cox, Jr.
    Mr. W. D. Trevorrow
    Mr. T. Ball

E. I. duPont de Nemours & Co, Incorporated
Carneys Point Process Laboratory
Penns Grove, N. J.
    Mr. H. Lewis
    Mr. K. Betts

The Franklin Institute*
Philadelphia, Pa.
    Mr. V. Goldie

Hercules, Incorporated
Allegany Ballistics Laboratory
Cumberland, Md.
    Mr. R. H. Richardson
    Mr. J. Maybury

Lake City Army Ammunition Loading Plant
Independence, Mo.
    Mr. B. Kelly

U.S. Naval Ordnance Laboratory
White Oak, Maryland
    Mr. J. N. Ayres

U.S. Naval Ordnance Test Station
China Lake, Calif.
    Mr. A. T. Wiebke
    Mr. E. Kuletz
    Dr. E. D. Besser

*The Franklin Institute has no electrostatic sensitivity testing equipment, but was able to supply information on the electrification of the human body.

Picatinny Arsenal
Dover, N. J.
    Mr. D. E. Crane

Sylvania Electric Products, Incorporated
Montoursville, Pa.
    Dr. W. C. Fink
    Mr. Bennett

U.S. Bureau of Mines
Bruceton, Pa.
    Mr. F. C. Gibson
    Mr. N. Hanna

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	MUCOM

13. ABSTRACT

During the processing of ordnance items involving explosive or pyrotechnic materials, accidental explosions or fires are occasionally reported which are attributed to electrostatic discharges.

To augment studies being conducted at Frankford Arsenal, a survey of literature and visits to other governmental and nongovernmental agencies were made to obtain information related to electrostatic considerations of solids which are explosive or inflammable. The findings include a description of potential problems and the measurement of their magnitude, along with a description of the various designs of equipment employed and methods used to conduct tests.

Although the approaches and methods differ as influenced by materials and applications considered, in general, solids that cannot be initiated by electrostatic discharges with energies less than 0.015 joule are considered safe to handle.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electrostatic Energy						
Hazards						
Safety						
Test Equipment						
Circuitry						
Discharge Gaps						
Electrode Geometry						
Polarity						
Series Resistances						

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