A mining reseach contract report.

DECEMBER 1982

PERFORMANCE CRITERIA GUIDELINE FOR THREE EXPLOSION PROTECTION METHODS OF ELECTRICAL EQUIPMENT RATED UP TO 15,000 VOLTS AC

Contract J0318081
National Aeronautics and Space Administration

EAU OF MINES
ED STATES DEPARTMENT OF THE INTERIOR

50277-101

REPORT DOCUMENTATION PAGE

1. REPORT NO.

2.

3. Recipient's Accession No.

4. Title and Subtitle

Performance Criteria Guideline for Three Explosion Protection Methods of Electrical Equipment Rated Up to 15,000 Volts AC.

5. Report Date Date Approved:
11 April '83

6.

7. Author(s)

Larry Joe Linley, Alton B. Luper

8. Performing Organization Rept. No.

TR-WSTF-299-002

9. Performing Organization Name and Address

National Aeronautics and Space Administration, White Sands Test Facility
P.O. Drawer MM
Las Cruces, New Mexico 88004

10. Project/Task/Work Unit No.

F7000

11. Contract(C) or Grant(G) No.

(C) J0318081
(G)

12. Sponsoring Organization Name and Address

United States Department of Interior, Bureau of Mines
Pittsburgh Research Center
4800 Forbes Avenue
Pittsburgh, Pennsylvania 15213

13. Type of Report & Period Covered

Final
15 Aug '81 - 1 Dec '82

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The Department of the Interior, Bureau of Mines is reviewing explosion protection methods for use in gassy coal mines. This performance criteria guideline is an evaluation of three explosion protection methods of machines electrically powered with voltages up to 15 000 volts AC. A sufficient amount of basic research has been accomplished to verify that the explosion-proof and pressurized enclosure methods can provide adequate explosion protection with the present state of the art up to 15 000 volts AC. The routine application of the potted enclosure as a stand alone protection method requires further investigation or development in order to clarify performance criteria and verification-certification requirements. An extensive literature search, a series of high voltage tests, and a design evaluation of the three explosion protection methods performed at White Sands Test Facility indicates that the explosion- proof, pressurized, and potted enclosures can all be used to enclose up to 15 000 volts AC, if the performance criteria and verification-certification requirements recommended in this guideline are implemented.

17. Document Analysis a. Descriptors

Descriptors: safety devices, safety engineering, purging, potting, potted circuits, high voltage, performance evaluation, potting compounds, coal mines, excavating equipment, coal, coal dust, methane, enclosures, instructions, electric corona, electric arcs, flashover.

b. Identifiers/Open-Ended Terms

Open Ended Terms: explosion proof, pressurized, potted, enclosure, explosion protection, performance criteria.

c. COSATI Field/Group

18. Availability Statement

19. Security Class (This Report)
Unclassified

20. Security Class (This Page)
Unclassified

21. No. of Pages

22. Price

(See ANSI–Z39.18)

See Instructions on Reverse

OPTIONAL FORM 272 (4–77)
(Formerly NTIS–35)
Department of Commerce

FOREWORD

This report was prepared by the National Aeronautics and Space Administration, Johnson Space Center, White Sands Test Facility under USBM Contract number J0318081. Investigations were performed by Larry Joe Linley and Alton B. Luper with assistance from James H. Dunn. The contract was initiated under the Minerals, Health, and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Lawrence W. Scott acting as the Technical Project Officer. Joseph A. Gilchrist was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period 15 August 1981 to 15 November 1982. This report was submitted by the authors on 15 December 1982.

CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

The Department of the Interior, Bureau of Mines is reviewing explosion protection methods for use in gassy coal mines. This performance criteria guideline is an evaluation of three explosion protection methods of machines electrically powered with voltages up to 15 000 volts AC. A sufficient amount of basic research has been accomplished to verify that the explosion-proof and pressurized enclosure methods can provide adequate explosion protection with the present state of the art up to 15 000 volts AC. The routine application of the potted enclosure as a stand alone protection method requires further investigation or development in order to clarify performance criteria, verification, and certification requirements. An extensive literature search, a series of high voltage tests, and a design evaluation of the three explosion protection methods performed at White Sands Test Facility indicates that the explosion-proof, pressurized, and potted enclosures can all be used to enclose up to 15 000 volts AC, if the performance criteria, verification, and certification requirements recommended in this guideline are implemented.

EXECUTIVE SUMMARY

Introduction

The development of more efficient coal removal equipment for use in underground coal mines has resulted in a demand for more electrical power at the working face. This can be accomplished in a number of ways, however, the most cost effective method appears to be the increase of the supply voltage.

The Bureau of Mines is presently reviewing the effects of increasing the high voltage limit to 15 000 volts AC. One of the aspects of this review is the effect of the new voltage limit on explosion protection techniques. The National Aeronautics and Space Administration, Johnson Space Center, White Sands Test Facility has conducted an in depth review of three explosion protection techniques (explosion-proof, pressurized, and potted techniques) which is presented in this performance criteria guideline. The three explosion protection methods are based on an understanding of explosion protection theory, mine environment flammability characteristics, and the pertinent characteristics of high voltage systems.

Background

The theories behind explosion protection methods range from completely isolating an ignition source from the mine atmosphere to confining ignitions of the atmosphere to relatively small volumes. The application of each explosion protection method is also dependent on the flammability characteristics of the environment. Included in the mine environment are such materials as methane gas, coal dust, electrical insulators, and various materials used in the fabrication of machine enclosures. A number of environmental and material effects, which become more important as the voltage is increased, must also be considered. A corona discharge becomes more intense and the potential for a high voltage arc is increased as the supply voltage approaches 15 000 volts AC.

Performance Criteria for Explosion Protection Methods

The three explosion protection methods investigated have performance criteria which are dependent upon the theory of operation and potential failure modes of the machine and enclosure. The certification and verification procedures recommended will ensure that the design satisfies the performance criteria before it is placed in service and throughout the service life of the device.

Explosion-Proof Method

The explosion-proof method is a passive form of explosion protection, which is based on the containment of methane and coal dust deflagrations and electric arcs. This enclosure must isolate the ignition source by containing any flame generated within the enclosure, limiting the surface temperature to less than 423°K (150°C), and containing all electrical arcs. The explosion-proof enclosure must also contain any pressure generated within the enclosure which can not be vented through the flange gap. The potential failure modes include flame propagating to the exterior of the enclosure, surface overheating, and grounding circuit failure.

There are a number of verification and certification procedures recommended for the explosion-proof enclosure. The verification procedures include a visual inspection of the enclosure, measurement of the flange gap, and verification of the grounding circuit, high voltage conductor isolation, and any current limiting or safety devices. The tests described in Sections 18.60 through 18.62 of the Code of Federal Regulations Title 30, are sufficient to certify that an enclosure will contain a methane flame, however, high voltage machines must also be certified incapable of generating high energy arcs.

Pressurized Method

The pressurized method is an active form of explosion protection based on the isolation of the ignition source from the atmosphere in the mine. The enclosure integrity, ignition source isolation, and the purge supply requirements are critical performance criteria for the pressurized enclosure. The potential failure modes for this explosion protection method include flame propagating from the enclosure, loss of purge pressure, and the enclosure surface becoming an ignition source. The verification procedures, for this enclosure type involve testing the flange gap (if so equipped), the ground circuit integrity, and the isolation of the high voltage conductors as required for the explosion proof enclosure. The purge gas and gas supply system must also be verified. Certification tests involve an inspection of components, (per Sections 18.60 and 18.61 of the Code of Federal Regulations Title 30 except Section 18.61(b1)), tests of the effectiveness of the initial purge cycle, enclosure deflection, enclosure pressure indicator performance, spark/flame containment, and the functionality of safety switches specified for the enclosure.

Potted Method

The potted method is a passive form of explosion protection which isolates the electrical ignition source from the atmosphere in the mine with a solid barrier. The mining industry is not currently using potted enclosures as an independent explosion protection method at any voltage rating. Most of the performance criteria sited were established by the National Aeronautics and Space Administration for use in the outer space environment. These performance criteria involve material selection, the protective enclosure, and machine power dissipation. The evaluation of potential failure modes of this protection method involves the consideration of the failure modes of the potting compound, the enclosure integrity, and machine failures which generate heat or arcs. Adequate verification and certification procedures are not fully defined, at the present time, for the potted enclosure in a coal mining application.

High Voltage Explosion Protection Method Comparison

The effects of supply voltage on adequate conductor isolation, insulator selection, and power dissipation must be considered in comparing explosion protection methods. Potted protection presents more unanswered questions in the area of conductor isolation than either of the other two protection methods. The theory of operation for the potted method implies inherent isolation, while practical application requires definition of verification and certification procedures, potting compound specifications, and a protective enclosure specification. The explosion-proof and pressurized protection methods provide isolation by separation of conductors and insulation. It has been demonstrated that separation is not a reliable isolation technique for high voltage uninsulated conductors during methane combustion, which can occur in explosion-proof enclosures. Conductor separation is a viable isolation technique for the pressurized protection method due to the inherent lack of methane and other combustible materials. The harsh operating conditions and the high voltage environment make insulator selection most critical in the explosion-proof protection method . Insulators selected for use in pressurized and potted enclosures must survive the effects of the high voltage environment, and are not normally subjected to such harsh operating conditions as methane combustion. The potted enclosure is very sensitive to the power dissipation of the enclosed machine due to the natural thermal insulation of the potting compound. The pressurized and explosion-proof enclosures are relatively insensitive to the power dissipation of the machine due to forced air circulation and convection cooling.

Conclusion

The performance criteria recommended in this guideline are sufficient to provide adequate explosion protection with any of the three methods evaluated. The practical implementation of the criteria, verification and certification requirements may be difficult in some cases. The implementation of the potted enclosure presents the most difficult obstacles to overcome for high voltage applicatons. The explosion-proof enclosure can be utilized in high voltage applications if due consideration is given the selection of insulation materials. The pressurized enclosure can be directly applied to high voltage machines using the present state-of-the-art.

INTRODUCTION

The mining industry is developing more efficient coal removal techniques as the demand for coal increases. To this end the industry is using progressively larger and more powerful machines at the working face, which require more electrical power to be delivered (ref. 45 p.2-3). The past practice has been to increase the supply voltage and current to obtain the required power; however, the voltage which may be contained within a permissible enclosure is limited to 4 160 volts AC by Title 30 of the Code of Federal Regulations, Section 18.47(d). An alternative to increasing the voltage is to increase the current. However, an increase in current requires a corresponding increase in the cable size to maintain the cable voltage losses at an acceptable level, which limits the maximum power available at the face (ref. 45 p.1-1). This limiting effect on the maximum power available makes it necessary to investigate the merits of explosion protection techniques for electrical mine equipment, energized with up to 15 000 volts AC.

A technical investigation of the merits of utilizing several explosion protection techniques with applications up to 15 000 volts AC was conducted by the National Aeronautics and Space Administration, Johnson Space Center, White Sands Test Facility (NASA/WSTF), for the Department of the Interior Bureau of Mines. The investigation was initiated with an extensive literature search and review to determine the history and present state-of-the-art of explosion protection techniques. A design evaluation of three explosion protection methods at 15 000 volts AC was also conducted. An investigation of the critical effects of corona discharges and arcing faults on methane air mixtures was performed to provide data unavailable in the literature. The data compiled from the literature search, design evaluation, and the discharge/fault investigations is presented in the form of a design guideline.

The design guideline consists of explosion protection considerations and design philosophy; performance, verification, and certification requirements for each explosion protection method; and a comparison of the three explosion protection methods with respect to high voltage considerations. The design philosophy, performance criteria, and recommended verification and certification requirements provide a basis for selecting a method and designing an enclosure for use at up to 15 000 volts AC. The performance criteria discussion for each method establishes the minimum requirements for a successful enclosure method. Various concepts are recommended to verify and certify each enclosure for use up to 15 000 volts AC. Material and design considerations are also included to increase designer awareness of critical safety factors.

DEFINITIONS

Ignition Source - Any material, action, or process which can generate sufficient energy to ignite a combustible mine atmosphere containing a flammable gas and/or coal dust, and air (ref. 12 p.25).

Minimum Ignition Energy (MIE) - The minimum electric spark energy required to ignite a combustible gas or dust mixture (ref. 12 p.35). The actual ignition energy varies with the concentration of the constituents, pressure of the mixture, and configuration of the spark electrodes (ref. 66 pp.326-335).

Upper Flammability Limit - The maximum concentration of a gas or vapor in air above which the propagation of flame does not occur on contact with an ignition source (ref. 12 p.13).

Lower Flammability Limit - The minimum concentration of a gas or vapor in air below which the propagation of flame does not occur on contact with an ignition source (ref. 12 p.10).

Minimum Explosive Concentration - The minimum concentration of organic dust which, when ignited, will develop 14 000 to 21 000 pascals (ref. 12 p.137).

Autoignition temperature - The temperature at which vapors ignite spontaneously from the heat of the environment (ref. 12 p.25).

Deflagration - A propagating reaction in which energy transfer from the reacting zone to the unreacted zone is by ordinary heat and mass transport processes (ref. 49). The resulting flame travels slower than the local speed of sound (ref. 92). The overpressure is developed from the heating due to the chemical reaction (ref. 12 pp.47-49).

Detonation - A reaction in which the energy is transferred from the reacting zone to the unreacted zone on a reaction generated shock wave. This type of reaction always propagates faster than the local speed of sound (ref. 49 pp.4-6) (ref. 17 and ref. 66 pp.512-517) (ref. 65 and 77).

Enclosure Failure - An enclosure is considered to have failed when it allows the potentially combustible mine atmosphere to be exposed to an ignition source normally contained by the enclosure (ref. 74 p.16).

Machine - Any electrically powered equipment considered as a potential ignition source in a mine atmosphere is referred to as a machine.

Maximum Experimental Safe Gap (MESG) - The maximum gap of a joint of 25 mm width which prevents any transmission of flame from the combustion of a given gas (ref. 25 p. 5).

BACKGROUND

Implementation of explosion protection methods for use in coal mines requires a consideration of explosion protection theory, flammability characteristics of the mine environment, and characteristics of high voltage systems. Several explosion protection methods have been derived from these basic facts.

Explosion Protection Theory

The primary function of an explosion protection method is to prevent ignition of the atmosphere in a mine caused by machine operation or failure. This may be accomplished by isolation of ignition sources from the combustible atmosphere in the mine.

Ignition Sources

The ideal way to prevent the combustion of coal mine atmospheres is to isolate all potential ignition sources from the combustible atmosphere. This can be accomplished by either placing a barrier between the ignition source and the mine atmosphere or physically removing the ignition source from the mine. The physical barrier between the ignition source and the combustible atmosphere must be such that the two have no opportunity to interact. The barrier could be constructed of a solid, liquid, or gas, which must be inert to the ignition source as well as the mine environment. A small portion of the mine atmosphere around the ignition source may be allowed to burn if the combustion is confined to a volume of gas around the ignition source. The method of confining the combustion might be passive (enclose the ignition source in a box) or active (an automatic fire extinguishment system). Physical removal of electrical ignition sources would appear to require that a nonelectrical power source be used in the gassy areas of the mine. Hydraulics and compressed air are examples of the use of nonelectrical power sources. Both isolation and physical removal of the ignition source are applicable in certain situations involving known ignition sources.

Combustible Atmosphere

The actual removal of the methane contaminant from the mine atmosphere is not practical due to its inherent nature in coal. Mine ventilation is a method used to dilute the combustible atmosphere below the lower flammability limit. Regulations govern the amount, velocity, and quality of the air which is delivered to the face and specifies what actions must be taken when the methane concentration increases above a given level (ref. 89 Section 75). Flammable concentrations of methane are assumed to be in certain areas of the mine, and the law requires that appropriate measures be taken (ref. 89 Section 75.500).

Flammability Characteristics

The coal mine environment necessarily contains many flammable materials. The selection of an explosion protection method is dependent on the flammability characteristics of methane, coal dust, electrical insulation and other enclosure materials. The flammability characteristics of all the materials used in the construction of an explosion protection device must be evaluated.

Methane

Methane may be distributed throughout the coal seam or concentrated in areas of high porosity coal which rapidly vent into the mine when ruptured during the coal removal process. Mine ventilation is required to dilute the methane to less than 1.0 percent by volume (ref. 89 Section 75.308). However, in the event of rapid methane release or a ventilation failure, it is possible for the methane concentration to increase to within the flammability limits of 5.0 to 15.4 percent by volume in air (ref. 12 p.18 and ref. 16 p.441). Methane ignition sources are grouped into three general categories: electric sparks, open flame, and autoignition temperature (810°K or 537°C) (ref. 12 p.27 and ref. 16 p.441). The minimum spark ignition energy of these concentrations of methane range from 0.3 to 10 millijoules (ref. 66 p.333). An open flame will normally have sufficient energy to ignite flammable concentrations of methane.

Coal Dust

Coal dust is constantly generated during the mining process. The minimum ignition energy of coal dust is dependent on the concentration in air and the particle size. The smaller more easily suspended particles require the least amount of energy to be ignited for a given concentration of coal dust in air (ref. 12 p.139). The minimum spark ignition energy of coal dust is from 20 to 60 millijoules and the minimum explosive concentration is from 40 to 60 milligrams of coal dust per liter of air (ref. 35 pp.21-22). The ignition temperature of layered coal dust can be as low as 428°K (155°C) for deep (.10 to .20 m) layers of dust (ref. 12 p.143).

Electrical Insulation

The selection of an electrical insulating material in an explosion protection device is dependent on the flammability and the potential decomposition products of the material when exposed to the mine machine operating environment. Many organic insulating materials generate combustible products during decomposition as reported by Morley and Trutt (ref. 75 pp.35-39) and by Kratzer, Lee, Nakahara, and Paciorek (ref. 64 pp.127-133). Decomposition is accelerated and product distribution varies when the material is heated or burned. These decomposition products can have flammability characteristics which could exceed the capabilities of a protective enclosure designed for methane and coal dust combustion. For example, an explosion-proof enclosure designed to contain methane combustion will not contain hydrogen combustion due to the difference in MESG (ref. 75 p.11).

Enclosure Materials

The relative flammability of metals can be based on consideration of ease of ignition, combustion rate, character of combustion products, effect of combustion on other enclosure materials, and the character of any probable failure as recommended by McKinley (ref. 71 p.2). Explosion protection devices in the United States are generally constructed of metal with no stated specifications as to the composition of the metal. However, certain metals used in the construction of explosion protection devices can be ignited if exposed to high energy electric arcs (ref. 51 pp.B20, B35, and ref. 71 pp.26-29).

Plastics or ceramics may be considered for use as enclosure wall materials in some cases (ref. 24 Section 6 and ref. 25 Section 11.6). Ceramics are considered a noncombustible material. However, most plastics must be grouped with the organic insulators and have similar flammability characteristics.

General High Voltage System Characteristics

The characteristics of high voltage systems must be considered in the design of explosion protection devices for the mining envirnoment. The two characteristics of interest are corona and arc discharge since the probability of the occurance and effects of both is increased with supply voltage.

Corona Discharge

Corona discharge is defined as an electrical discharge of less than 0.1 ampere (ref. 33 p.207). It is caused by the ionization of gases under the influence of an electrical field (ref. 33 p.252). The intensity of a corona discharge depends on the voltage, size of the conductor, frequency of the voltage, conductor surface conditions (ref. 30 p.29), and atmospheric pressure and temperature (ref. 33 pp.256, 277, and 280).

A corona discharge will result in a certain degree of ionization of the local atmosphere and a corresponding decrease in the dielectric strength of the atmosphere (ref. 33 p.335). Corona has been shown to be an ignition source for methane in air mixtures (ref. 38). The dielectric strength of insulation material has been shown to degrade when exposed to corona discharge (ref. 84 p.562).

High Voltage Arcing

An arc is defined as a discharge current greater than 0.1 ampere which is self-sustaining (ref. 33 p.207). High voltage arcs occur when the source voltage exceeds the breakdown voltage of the gas separating the conductors. The combustion of a methane and air mixture generates free ions which decrease the dielectric strength of the resulting atmosphere (ref. 15 p.1). This decrease in dielectric strength can lead to an unpredictable arc discharge from exposed high voltage conductors (ref. 38).

The effects of high voltage arcs on the peak combustion pressure of methane has not been well described in the literature. Tests simulating low energy corona discharge faults and high energy (up to 1 408 kilojoules) arcing faults across a 0.15 meter (6 inch) gap in a 1.061 cubic meter chamber indicate that methane and air combustion pressures were approximately the same when ignited by a high energy arc as when ignited by corona. The combustion pressures of the corona tests and arc tests were repeatable within 5% given similar initial conditions (ref. 38). Ciok reports that tests conducted in a .250 cubic meter chamber where energies 25 times greater than those described above produced combustion pressures approximately 2 times greater (ref. 32 p4.6). This indicates that the peak combustion pressure is virtually independent of the energy which ignited the mixture, and very dependent on the volume of the enclosure.

PERFORMANCE CRITERIA FOR EXPLOSION PROTECTION METHODS

All methods of explosion protection must prevent ignition of the mine atmosphere, but each method has separate definable requirements in order to meet that objective. Three explosion protection methods (explosion-proof, pressurized, and potted) are evaluated for supply voltages up to 15 000 volts AC. The explosion protection methods are compared by evaluation of the theory of operation, performance criteria, failure modes, and certification-verification procedures.

Explosion-Proof Method

The explosion-proof method is a passive form of explosion protection. This method isolates the ignition source with an enclosure which is capable of containing ignitions of the mine atmosphere.

Theory of Operation

The explosion-proof enclosure must contain all events occurring within the enclosure and prevent an ignition of the atmosphere outside the enclosure. (ref. 89 Sections 18.50 and 18.62). This passive type of protection must be constructed to contain methane deflagration, coal dust deflagration and electric arcs since it is assumed that any combustible atmosphere entering the enclosure will be ignited.

Performance Criteria

An explosion-proof enclosure must isolate any ignition source from the atmosphere in the mine, and contain the pressure generated from combustion within the enclosure. An enclosure which meets this general performance criteria will protect the mine atmosphere from ignition sources in electrically powered machines contained within the enclosure.

Isolation of Ignition Source

The enclosure must not allow flame to propagate through the flange gap, (a specified separation between an enclosure body and a flange, the dimensions of which produce complete quenching of a flame) and must not allow ignition of the combustible atmosphere in the mine (ref. 89 Section 18.62). Materials used within the enclosure must not decompose into flammable by-products (ref. 89 Section 18.25). The decomposition products of many electrical insulators have a smaller MESG than methane. This could result in a flame propagating through the flange gap without being quenched (ref. 75 p.11).

The outside surface temperature of the explosion-proof enclosure must not exceed 423°K (150°C). This limit has been established in paragraph 18.23 of the Code of Federal Regulations to prevent the ignition of coal dust. Materials used within the enclosure should not continue to burn after an ignition source is removed (ref. 12 p.18 and ref. 89 Section 18.62(b3)). This requirement prevents excessive heat stress on the enclosure and minimizes pressure generated during combustion.

The explosion-proof enclosure must contain all electrical arcs. Electrical discharges must not occur on the exterior of the enclosure. Paragraph 18.50 of the Code of Federal Regulations requires that enclosures be connected to the mine grounding system to prevent the ignition of coal dust or methane by spark discharges. Electrical grounding and conductor isolation become more critical as the operating voltage is increased due to the unpredictability of the atmospheric dielectric strength during a methane deflagration (ref. 38). Electrical machines and conductors energized with voltages and currents of sufficient energy to mechanically damage enclosure walls due to arcing (ref. 38 and 62) should be insulated in a manner which is independent of the atmospheric dielectric strength. The failure of many electrically powered machines can produce an electrical arc capable of producing 3 937 008 joules per meter (100 000 joules per linear inch) which will melt a 0.0127 meter (1/2 inch) steel plate (ref. 68).

Pressure Containment

The explosion-proof enclosure must contain any pressure generated within the enclosure which cannot be vented through the flange gap. The Code of Federal Regulations requires that an enclosure contain at least 1 034 214 pascals (150 psig). The combustion of materials used in the enclosure must not produce pressures that exceed the overpressure caused by methane combustion in air (ref. 89 Section 18.31 (a1)).

Failure Modes and Design Considerations

Explosion-proof enclosures must meet the performance criteria in order to provide explosion protection from electrical machines. Failure modes for explosion-proof enclosures include flame propagating to the exterior of the enclosure, surface overheating, and ground circuit failure.

Flame Propagation

The combustion of gases other than methane, mechanical damage to the enclosure wall, or compromise of the MESG may allow a flame to propagate to the exterior of the enclosure. Flames which result from the combustion of gases such as hydrogen and acetylene can readily pass through a flange gap designed for methane (ref. 75 P.11). Currently, no materials are allowed within the enclosure which decompose to produce a combustible by-product (ref. 89 Section 18.25).

An explosion-proof enclosure can be mechanically damaged by a roof fall, metal fatigue, arc burn through, transportation and handling, etc. Visual observation is the only means of sensing such damage. The enclosure should be constructed with as much reinforcement as practical and installed in a location that provides as much protection from damage as possible. The prevention of mechanical damage in the form of fatigue failures begins with a strong design, with wide tolerances for thermal or mechanical stresses. King and Bollinger report independently the use of computer models to analyze proposed explosion-proof enclosures for stresses produced during methane deflagration (ref. 13 and 63). Arc burn through (as defined in the American Society for Testing and Materials test E390) is an important consideration for high voltage enclosures. The possibility of an arc from a high voltage conductor to the enclosure wall is not increased by the addition of methane to the atmosphere. However, a methane deflagration has been shown to greatly increase the probability for arcing to the enclosure wall. Tests conducted at NASA/WSTF indicate that the dielectric strength of the atmosphere between exposed high voltage (14 400 volts AC) conductors is very unpredictable during methane combustion. Arc gaps were shown to vary from 0.15 to 0.59 meter (6 to 23 inches) under these conditions (ref. 38). An arc within the enclosure that causes failure of a wall would result in an enclosure failure at the worst possible time, for it must be assumed that if a combustible mixture exists within the enclosure, a similar mixture is outside also. Fault clearing devices to sense the excessive current (ref. 86) or the phase change between current and voltage (ref. 48) could be used to prevent this failure mode.

The MESG can be exceeded in several ways. Particulate left on the flange during reassembly can increase the flange gap sufficiently to allow methane flames to escape. Heat or mechanical damage can cause the flange to warp or damage the flame quenching surfaces. An excessive gap may be caused by a temperature gradient across the flange or mechanical abuse. This is readily detectable with standard verification tests. However, a damaged quenching surface could remain undetected until the enclosure failed. Secured flanges with access limited to authorized personnel has been recommended (ref. 28) to prevent ignition sources from being exposed to the atmosphere in the mine by inadvertent removal of the flange while the machine is engaged.

Surface Overheating

The external surface temperatures of the enclosure are limited to 423°K (150°C) (ref. 89 Section 18.23). The design must prevent the normal operating temperature from exceeding this limit due to the ignition characteristics of coal dust. The insulating qualities of dusts which can be expected to accumulate on exposed surfaces must be considered when determining the maximum surface temperature of the enclosure (ref. 89 Section 75.800 and ref. 48). Abnormally high temperatures can be produced by some electrical fault conditions. Current sensing devices, to clear the fault, and fire retardent materials must be used to limit the heating in the enclosure. A temperature sensitive switch might be applicable in some cases to deactivate the machine and/or activate an alarm when the surface temperature exceeds 423°K (150°C).

Ground Circuit Failure

The circuit connecting the enclosure to the mine grounding system becomes more critical as the enclosure operating voltage is increased. The electric field of the voltage supply will charge an enclosure wall grounded through a high resistance to a voltage proportional to the capacitance between the enclosure and ground. This can cause a spark discharge from the surface of an explosion-proof enclosure which can ignite methane or coal dust and air mixtures. An effective grounding circuit does not allow a charge to accumulate on the enclosure wall with respect to ground. An arc to the enclosure wall can also raise the enclosure to voltages near the supply potential if the ground circuit is not sufficient in quality. A protected and monitored ground circuit is required to prevent grounding failures, as specified in sections 18.50 and 75.800 of the Code of Federal Regulations Title 30.

Verification and Certification

Verification tests are used to insure that an explosion-proof enclosure continues to meet the performance criteria in accordance with Section 75.503, Title 30 of the Federal Code of Regulations. Certification tests demonstrate that a new or reconditioned unit satisfies the performance criteria before being placed in service. The verification and certification tests now being conducted on explosion-proof enclosures are adequate for high voltage applications with some additions.

Verification

Visual inspection, flange gap verification, and routine maintenance are currently used to guarantee explosion-proof enclosure integrity. However, the use of high voltage requires verifying the integrity of the grounding circuit, high voltage conductor isolation, and any current limiting or safety devices.

Ground Circuit Integrity

The conductance of the ground circuit should be verified and recorded on a periodic basis. Adequate grounding should be verified by a measurement of the resistance from a defined point on the enclosure to a defined point on the mine ground system. The same measurement points should be used for each subsequent measurement on a given enclosure. These measurement points must be clean (wire brushed or polished) and dry so that they will provide low contact resistance each time a measurement is made. The ground wire should also be physically checked for corrosion, fraying, crimping, and tight contacts. The need for these verification tests has been reported by Towle (ref. 85).

Conductor Isolation

The conductor isolation verification test is used to determine the resistance between the high voltage conductor and the enclosure wall. This measurement should be recorded and observed for any downward trend in resistance over a period of time. A downward trend would indicate that the insulating medium between the conductor and ground is degrading; thus, eventual failure can be expected. Firm guidelines are not now available and will be required before this verification can be effectively implemented.

Safety Devices

Any device which increases the safety of using an explosion-proof enclosure must be routinely checked for proper operation. This should involve a visual and functional check to determine the operational status of the device. Part 75 of the Code of Federal Regulations Title 30 specifies the methods and procedures for verifying the operational status of the safety devices currently required. Verification procedures must be established for all safety devices approved for any explosion protection method.

Certification

The present certification tests, as specified in Title 30 Part 18, Subpart C, of the Code of Federal Regulations are adequate for enclosures powered with lower voltages. However, as the supply voltage approaches the corona transition, as defined by Lewis and Von Elbe, specific tests are required to guarantee that high energy arc failures do not occur (ref. 66 p.330). The corona transition voltage for a specific case depends on the orientation of the conductor relative to the ground or neutral conductor, the size, surface condition, type and composition of the conductor, and conditions and composition of the surrounding atmosphere.

Enclosure Integrity Tests

The certification tests described in Section 18.60 through 18.62 of the Code of Federal Regulations Title 30 certify that the explosion-proof enclosure will contain a methane flame. These tests consist of reviewing the design, comparing the enclosure configuration with the drawing, and subjecting the enclosure to methane flame tests.

High Voltage Certification Tests

It is recommended that a high voltage machine be certified to be incapable of generating a high energy arc. Any part of a machine which can generate a corona discharge must also be considered as a source for an arcing fault during a methane deflagration (ref. 38). A visual inspection of the unit should be conducted, and discrepancies which could increase the corona current must be eliminated (ref. 30 p29). The explosion-proof enclosure must be placed in a combustible atmosphere similar to that defined in Title 30 of the Code of Federal Regulations, Section 18.62, and tested as follows. The machine should be energized with the specified supply voltage in a manner which simulates the intended use (intermittent or continuous). The methane and air mixture should be ignited as required in the explosion test to certify the high voltage isolation is maintained during methane combustion. The enclosure configuration should be considered unacceptable if an arc is struck at any time during this test (assuming sufficient current is available for a damaging arc).

Pressurized Method

The pressurized method is an active form of explosion protection. This method requires an inert or noncombustible gas to replace combustible gas mixtures exposed to the ignition source.

Theory of Operation

Pressurized enclosures isolate an ignition source from a potentially combustible atmosphere by filling the enclosure with an inert gas or fresh air and maintaining a positive pressure within the enclosure. The positive pressure does not allow combustible gases to enter the enclosure; thus, the enclosure must be rated to contain only the purge pressure.

Performance Criteria

The enclosure integrity, ignition source isolation, and the purge supply requirements are critical in providing an effective pressurized enclosure. Enclosures which meet this performance criteria will isolate the coal mine atmosphere from ignition sources generated by the enclosed electrically powered machine.

Enclosure Integrity

The pressurized enclosure must be constructed to contain the purge pressure. The purge pressures required for this method are effective at differential pressures as low as 24.9 pascals (0.1 inch of water) (ref. 3). The enclosure design must be sufficiently rugged to withstand the handling procedures common to the mining industry and should comply with the ASME Pressure Vessel Code (ref. 1). A safety device must deactivate the machine if enclosure pressure is too low (ref. 3 p.14 and ref. 28 pp.23-24).

Ignition Source Isolation

All ignition sources associated with the machine and the pressurized enclosure must be isolated from the atmosphere in the mine. The pressurized enclosure must not provide a means of producing external arcs or sparks. The enclosure must be connected to the mine grounding system (as discussed for the explosion-proof method) such that the enclosure will not develop a static charge. The enclosure must be constructed to contain any sparks or flame which might be generated within the enclosure. The application of flange gaps, gaskets, and spark/flame arrestors is required to contain any sparks or flame generated within the enclosure (ref. 39 p.96). Combustion produces ions which increase the conductance of the local atmosphere and the possibility of a high voltage arc which could damage the enclosure and ignite the mine atmosphere (ref. 75 p.18). Therefore, materials selected for use within an enclosure must be fire retardent or noncombustible (ref. 75 p.22). Low flammability materials must be used to minimize the external surface temperatures during enclosure atmosphere combustion by reducing the availability of fuel to ignition sources. The temperature of all enclosure exterior surfaces as well as the enclosure exhaust air temperatures must not exceed 423°K (150°C) to prevent coal dust ignition (ref. 12 p.143).

Purge Supply

The purge supply for the pressurized method of explosion protection must be adequately specified and monitored in order to ensure that the machine is isolated from the combustible mine atmosphere. The design specification of the purge gas supply should include the type of gas (compressed air, bottled air, bottled nitrogen, etc.), the quality of the gas (allowable hydrocarbons, water content, etc.), and the volumetric flow rate of the gas required to maintain the minimum enclosure pressure. The purge gas supply must have provided at least 10 enclosure volume changes before the machine is energized (ref. 3 p.21). The purge must dilute any combustible gases generated by material decomposition to below the lower flammability limit. The purge must not allow accumulations of decomposition products. The allowable rate of combustible material generation must be specified for each material used in each application. This determination is primarily dependent on the amount of material used in the enclosure (ref. 75) and the purge specification.

The quantity and quality of the purge supply must be continuously monitored in order to assure that the purge specifications are met. All pressurized enclosures must be equipped with a pressure or flow switch capable of activating an alarm and de-energizing the enclosed machine when the internal pressure of the enclosure falls below 24.9 pascals (0.1 inch of water) (ref. 3 p.15). A methane monitor, similar to those used on continuous miners, must be located inside the pressurized enclosure to continuously monitor the purge supply. The monitor must activate an alarm and de-energize the machine if methane is detected. The alarm level should be set to 1% by volume of methane, as this quantity of methane in air is well established as a required action point (ref. 89 Section 75.307-8).

Failure Modes and Design Considerations

Pressurized enclosures which fail to meet the performance criteria will not provide adequate explosion protection. The method fails when flame propagates from the enclosure, purge pressure is lost, or the enclosure surface becomes an ignition source.

Flame Propagates From the Enclosure

Enclosure materials and contaminating gases can provide sufficient fuel for combustion in a pressurized enclosure. These materials and gases can be ignited by mechanical or electrical failures in the machine. The enclosure must be constructed to contain any flame or sparks generated within the enclosure during such failures. This requires the use of seals and/or flange gaps at access ports (ref. 3), spark/flame arrestors on the exhaust port(s) (ref. 80), and consideration of the geometry of the enclosure-machine combination (no potential spark sources in the plane of a flange gap or in line with an exhaust port) (ref. 75 p.9).

The use of flame retardent or noncombustible materials is also a necessary practice to minimize combustion possibilities (ref. 75 p.22). The pressurized explosion protection method prevents gases from entering the enclosure from the exterior; however, combustible gases can be generated from materials within the enclosure. For example, corona discharges and resistance heating of electrical insulators have been shown to generate flammable gases (ref. 64 pp.127-133 and ref. 75 pp.35-39). The offgassing rate of the enclosure materials must be such that the purge is sufficient to dilute the resulting combustible gas mixture below the lower flammability limit of the offgassed products.

Methane contamination of the purge supply is another potential source of fuel. However, this would be detected by the enclosure methane monitor and result in an alarm being activated and the machine being de-energized. The use of an inert gas purge would eliminate combustion within the enclosure by removing the oxygen source. This solution, however, would require that the enclosure be vented outside the mine.

Loss of Purge Pressure

The purge pressure can become ineffective when the purge source is interrupted or the enclosure integrity is compromised. The purge supply can be interrupted by damage to the supply duct or by depletion of the purge gas source. These failure modes must be detected by the enclosure pressure/flow sensor. The supply duct must be maintained to provide the required quantity of purge gas to the enclosure. The purge supply pressure should be routinely verified and maintained.

The enclosure integrity may be compromised through damage or improper access. Enclosure wall damage can be the source of a leak which allows the enclosure pressure to fall below 24.9 pascals (0.1 inch of water). The pressurized enclosure must be constructed to withstand the expected conditions of use (ref. 3 p.8) and contain any sparks or flame as previously noted. Any damage compromising the enclosure integrity must be immediately repaired. The effectiveness of the purge is lost immediately when any access port is opened while the machine is energized. An enclosure pressure switch or a purge flow safety switch is an effective element in preventing the ignition of the mine atmosphere when a purged system has been compromised. Safety switches that are used to guarantee the purge system integrity must be configured to address all modes of purge failure (ref. 3 p.16). An access port switch should be installed such that the machine is de-energized as soon as possible after the port begins to open (ref. 3 p.14). Additional security should be provided such as the locked or secured access currently used on explosion-proof enclosures (ref. 28 pp.23-24).

Surface Ignition Source

The surface of a pressurized enclosure can become an ignition source when the surface temperature exceeds 423°K (150°C) or when a static charge develops on the enclosure surface. A temperature switch as described for the explosion-proof enclosure may be required in equipment which may be overloaded (ref. 3 p.15). A grounding circuit failure can allow an enclosure surface to develop a static charge due to the moving purge gas. The pressurized enclosure must have ground circuit protection and monitoring devices as described for the explosion-proof enclosure.

Verification and Certification

Verification tests are required to guarantee that pressurized enclosures are providing explosion protection. These tests must be designed to verify the enclosure, purge system, and electrical system integrity. Certification testing must be performed to assure that the design and implementation of the pressurized enclosure performance criteria have been practically incorporated in the construction of the unit.

Verification

The flange gap (if the enclosure is so equipped), ground circuit integrity, and the isolation of the high voltage conductors should be verified for pressurized enclosures in the same manner as described for the explosion-proof enclosure. A pressure indicating device should be installed on pressurized enclosures to provide a readily available means of monitoring the purge supply, checking the operation of the pressure or flow safety switch, door safety switches, and detecting an enclosure failure (ref. 3 p.31). Flame arrestors must be routinely serviced to remove any foreign material which may clog the openings (ref. 28 p.11). The flame arrestor must be replaced if corrosion or other mechanical damage is observed during this service. The purge supply may consist of bottled gas or some means of forced air from outside the mine. The purge source must be routinely analyzed to guarantee that the purge supply is not contaminated with flammable or other unwanted gases. A periodic visual inspection of the purge system supply line must be conducted for damage and leaks to minimize the potential for contamination downstream of the source.

Certification

There are several tests of the pressurized enclosures which are required to guarantee that the design meets the performance criteria. However, an explosion test of the pressurized enclosure is not required (ref. 56 pp.72-73). The inspection of components of the complete machine are required as described in Sections 18.60 and 18.61 of the Code of Federal Regulations - Title 30 (except 18.61 (b1) which requires an explosion-proof enclosure). Additional tests must certify that the initial purge cycle, enclosure deflection, the enclosure pressure indicator, spark/flame containment, and the function of any safety devices specified for the enclosure are adequate to meet the performance criteria.

The purge cycle certification procedure recommended by Hinds is performed by purging the pressurized enclosure with pure nitrogen until the oxygen concentration is reduced below 1%. The enclosure is then purged with air at the specified pressure or flow rate until the oxygen concentration approaches that of air. The time required to return the oxygen concentration in the enclosure to that of air should be less than or equal to the purge cycle time specified by the enclosure designer (ref. 56).

The Pressure Vessel Code specifies that a given vessel must be equipped with a pressure relief device such that if the supply regulation fails so as to deliver a maximum flow, a hazardous pressure cannot occur within the enclosure (ref. 1 and ref. 3 p.35). A wall deflection test is recommended in order to certify compliance with this requirement. This test is performed by pressurizing the enclosure to the maximum pressure capable of being developed by a failure of the purge system and then measuring the resulting deflection. Any distortion over 3.333 millimeter per linear meter (0.040 inch per linear foot) is not acceptable (ref. 89 Section 18.62b5). The enclosure pressure indicator may be certified in conjunction with the wall deflection test. An acceptable indicator must display an accurate status of the enclosure pressure above and below 24.9 pascals (0.1 inch of water differential). A test to certify that an enclosure will prevent sparks or flame generated within the enclosure from igniting a combustible atmosphere outside the enclosure is required. However, there is insufficient documentation in the literature to define the requirements for such a test (ref. 3 p.14).

The certification of the enclosure safety devices can be accomplished using a simple series of tests. The enclosed machine is activated with the specified purge in progress. Each access port is opened to observe that each switch operates as designed. The enclosure pressure switch or flow switch is certified by reducing the flow of purge gas while monitoring the enclosure pressure. The switch must operate at 24.9 pascals (0.1 inch of water differential pressure), thereby de-energizing the equipment and activating the alarm. The methane monitor is certified by injecting a quantity of methane (dependent on the purge gas flow rate) sufficient to form a 1% mixture of methane in air within the enclosure and verify that the alarm is activated and equipment is de-energized by the monitor. The temperature switch, if so equipped, is certified by heating the local area of the switch to a temperature slightly greater than 150°C and observing that the switch is activated at 423°K (150°C).

Potted Method

The potted method is a passive form of explosion protection. This method isolates the electrical ignition source from the atmosphere in the mine with a solid barrier. This discussion is general due to the wide variety of potting compounds available and the small amount of research performed in explosion protection related areas. The critical characteristics of potted enclosures include long term mechanical and chemical stability of potting compounds and the effect of various aspects of the mining environment on the candidate compounds.

Theory of Operation

The solid material used in the potted enclosure must completely isolate the electrical ignition source from the combustible atmosphere. The potting compound must coat or encapsulate all electrical ignition sources in order to provide a hermetic seal and electrical isolation. A jacket or shield is provided to mechanically protect the potting and machine components.

Performance Criteria

Potted enclosures are not in common use as an independent explosion protection method in the mining industry at any voltage rating (ref. 45 p.32.2.2). Most of the performance criteria sited for encapsulating high voltage sources were originally established by the National Aeronautics and Space Administration for use in the outer space environment (ref. 30). The following performance criteria are adapted for application to the coal mine environment and are subject to refinement as more experience is gained in the use of these enclosures. The performance criteria concern the general areas of material selection, the protective enclosure, and the machine power dissipation.

Material Selection

The stability of the potting compound selected must be sufficient to guarantee that it will not degrade in service to the point of allowing exposure of an electrical ignition source to the mine atmosphere. The potting compound must be mechanically, chemically, and electrically stable over the expected lifetime of the machine it is to protect. These compounds must be applied in such a manner that no voids are formed during the pouring or curing process, and must have sufficient mechanical strength to withstand the stresses induced by normal machine operation. The chemical stability of these potting compounds must be such that the electrical and mechanical characteristics are not compromised when exposed to the mine environment, such as methane, coal dust, mine water, various oils and greases, and temperature extremes. The potting compound must provide electrical isolation of the supplied power under all use conditions.

Protective Enclosure

The protective enclosure for a potted or encapsulated machine must prevent the potting compound from being degraded by the mine environment. The protective enclosure must prevent the potting compound from being exposed to standing water, since most compounds absorb water to a certain extent resulting in degradation of various critical characteristics (ref. 64 p.35). The protective enclosure must be of sufficient strength to prevent damage to the compound due to mechanical stress while the enclosure is being moved. The enclosure should provide protection from abrasion and other forms of mechanical damage, and it should be constructed of a conductive material and connected to the mine grounding system as described for the explosion-proof enclosure. Section 18.31(b) in Title 30 of the Code of Federal Regulations specifies the thickness of materials and flange gaps to be used on the enclosure and the means of electrical access.

Machine Power Dissipation and Temperature

A machine to be installed in a potted enclosure should not dissipate enough heat to allow the surface temperature to exceed 423°K (150°C). The actual power dissipation limit depends on the thermal conductivity and heat capacity of the particular potting compound. The potting compound and protective enclosure combination must be capable of containing a machine failure.

Failure Modes and Design Considerations

The failure of the potted enclosure to meet the performance criteria could result in an ignition source being exposed to the mine environment. The potting material, the protective enclosure, or the enclosed machine could fail in a number of ways.

Material Failure

The potting compound may allow the ignition source to be exposed to a combustible atmosphere by failing mechanically or electrically. An electrical ignition source can be exposed through mechanical failure of the potting material in the form of voids, stress cracks, and compressive fracture. Voids can be formed in two ways. Air may be entrapped in the potting compound during the pouring process, or gases may evolve and become entrapped during the curing process. Voids and cracks increase the electrical stress across the gas/solid interface and lead to electrical discharges which over a period of time degrade the dielectric strength of the potting compound. Cracks may develop as the polymer chains are cut by either electrical discharges or the resulting by-products (ref. 30 pp.25 and 33) as reported by Sharbough and Devins (ref. 36). Roof fall damage could cause a compressive fracture or crack in the compound and expose an ignition source to the combustible atmosphere.

Little information is available concerning the degradation of electrical and mechanical characteristics of potting compound due to chemical interactions with low energy discharges (corona), methane, coal dust, etc. The reaction between methane or coal dust and a specific potting compound can generally be predicted by standard chemical evaluation; however, the effect of an energy source (corona, leakage current, etc.) on the chemical reaction is very difficult to determine (ref. 30 p.25).

The effect of water exposure on potting compounds is well documented and is the subject of a test standardized by the American Society for Testing and Materials (Procedure Number D570 - Water Absorption). The dielectric strength and tracking resistance decrease as water is absorbed into the potting compound resulting in an increase in the leakage current and resistive heating of the material. The degradation of either of these characteristics will lead to a potentially catastrophic failure of the enclosure due to the energy released by a high voltage arc (ref. 83). Variations in the dielectric strength are more likely to cause arcing as the voltage increases. Some hydrocarbons (oils, greases, etc.) found in the mining industry can attack potting compounds resulting in loss of mechanical and dielectric strength (ref. 73 p.109-160). The potting compound being considered should be carefully evaluated for compatibility with any reactive components that are found in the mine environment.

Protective Enclosure Integrity

The potting compound may expose an ignition source to the mine atmosphere if the protective enclosure fails to provide adequate protection. Compressive fracture, cracks or excessive exposure to water could compromise the potting compound to the point of electrical or mechanical failure. The protective enclosure may become a spark ignition source if the enclosure grounding circuit fails. The possibility of the protective enclosure coming into direct contact with the supply potential is minimal due to the inherent insulating qualities of the potting compounds. However, a protected ground circuit is necessary due to the capacitance between the machine and the enclosure wall.

Machine Failure

Machine failures generating heat or arcs can cause the potted enclosure to become an ignition source. A machine failure which generates heat can raise the potting compound temperature to a decomposition point (ref. 64) (ref. 75 p.35) and/or phase change (ref. 83). The probability of potting compounds attaining high temperatures is increased due to the natural thermal insulating qualities of good electrical insulators (ref. 81 p.296). Certain compounds have been found to generate combustible gases such as hydrogen and acetylene at elevated temperatures (ref. 75 p.35-29). The evaluation of current research indicates that these compounds should be strictly avoided (ref. 64 and 75). Applications in which the power dissipation of the machine approaches the limit allowed for the selected potting compound, may require the installation of a temperature sensitive switch (ref. 3 p.23). This switch would be located in an area of the enclosure expected to attain the highest operating temperature and would activate an alarm and de-energize the machine as the temperature exceeded 423°K (150°C). This surface temperature limit is now widely accepted and would require no retraining of personnel, and data reported by Kratzer and co-workers indicate that many compounds do not begin decomposition below the temperature range of 433°K to 473°K (160°C to 200°C) in air (ref. 64 pp.139-157).

Verification and Certification

The potted explosion protection method requires periodic verification tests to guarantee the integrity of the electrical circuit and potting compound. Potted enclosures must be certified to meet the performance criteria which includes the mechanical, thermal, and batch integrity of the potting compound. Adequate verification and certification test procedures for the potted explosion protection method cannot be fully defined at the present state of development.

Verification

Verification tests must confirm the electrical circuit integrity, mechanical stability, and chemical stability of the enclosure. Grounding circuit integrity and the conductor isolaton verification tests should be performed as described for the explosion-proof enclosure. Tests to determine if cracks, voids, and chemical breakdown have occurred in the potting material must be routinely performed to verify that the enclosure can function properly. The development of practical verification tests for potting compound electrical, chemical, and mechanical integrity are essential before this method of explosion protection can be successfully utilized.

Certification

A design review specification and certification test procedures must be developed before a potted enclosure can be certified. Certification tests must check for voids and cracks, determine batch sensitivity of the potting compound, and determine the stable operating temperature of the machine. Each enclosure should be certified at the time of manufacture to be free of voids and cracks in the potting compound. Batch sensitive testing should be accomplished to assure that each lot of potting compound is within specification. The batch certification tests should include parameters such as dielectric strength, tracking resistance, thermal conductivity, water absorption, and flexural modulus, which are critical to the potted enclosure method. The methods for testing each of these parameters for samples of the potting compound are well established by the American Society for Testing and Materials; however, testing the completed unit to certify a void and crack free potting compound requires the same development requirements described for verification tests. The potting compound temperature should be certified to remain below 423° (150°C). This could be accomplished by actual measurement or by calculations involving the maximum power dissipation of the machine and the heat capacity and conductivity of the potting compound. This measurement or calculation should be completed for the machine in the normal operating mode.

HIGH VOLTAGE EXPLOSION PROTECTION METHOD COMPARISON

Each of the three explosion protection methods presents varying degrees of difficulty in protecting the mine environment from ignition for applications up to 15 000 volts AC. The effects of the supply voltage on adequate conductor isolation, insulator selection, and power dissipation must be considered when comparing explosion protection methods.

Conductor Isolation

High voltage conductor isolation must be reliably accomplished within the selected enclosure due to the available energy and the potential for damage to enclosure materials during breakdown. The theory of operation for the potted enclosure assumes inherent conductor isolation. However, practical application of this method requires definition of various verification and certification tests (as discussed earlier), the potting compound specification, and the protective enclosure specification. The explosion-proof method provides conductor isolation by separation and insulation. It has been demonstrated that separation is not a reliable isolation technique at high voltages for uninsulated conductors during methane combustion. High voltage conductors should be insulated to provide reliable isolation in an explosion-proof enclosure. The pressurized enclosure provides conductor isolation by separation and insulation, also. However, the inherent lack of methane combustion within the enclosure greatly increases the reliability of the separation method of isolation.

Insulator Selection

A high voltage insulator must reliably isolate the conductor under any conditions anticipated for the enclosure. The selection of an insulation material is most critical in the explosion-proof enclosure due to the harsh conditions present during methane combustion. These insulators must not only survive these combustion episodes, but they must also resist the effects of corona discharge. The insulators selected for use in pressurized and potted enclosures are not required to survive methane combustion due to the lack of flammable gas concentrations within these enclosures. However, the insulators must be resistant to the effects of corona discharge.

Power Dissipation

The power dissipation of a given machine will naturally increase as the supplied power is increased. The potted enclosure is very sensitive to variations in the power dissipation due to the natural thermal insulation of the potting compound. Small changes in the power dissipated within this enclosure can produce large temperature gradients in the potting compound. The resultant temperature gradients are dependent on the heat capacity, conductivity, and thickness of the potting compound. The pressurized and explosion-proof enclosures provide air circulation around the machine by forced circulation or convection; thus, these two methods are relatively insensitive to changes in the machine power dissipation.

CONCLUSION

The performance criteria recommended in this guideline are sufficient to provide adequate explosion protection with any of the three methods evaluated. However, the implementation of these criteria, verification, and certification requirements may be difficult in some cases. The lack of definition, specifications, and basic research in the areas concerning potted encloures currently make this particluar enclosure method a difficult choice as a high voltage explosion protection device. The explosion-proof enclosure explosion protection method can be applied to high voltage machines if due consideration is given to the selection of the insulation materials. Certain materials are not acceptable for use in this explosion protection method due to their decomposition products and flammability characteristics. The pressurized enclosure provides considerably more flexibility in the selection of insulation materials, and can be directly applied to high voltage machines using the present state of the art.

BIBLIOGRAPHY

USBM PERFORMANCE CRITERIA GUIDELINE

1. American National Standard Institute/American Society of Mechanical Engineers. Boiler and Pressure Vessel Code Section VIII, Divisions 1 and 2.

2. American National Standards Institute/National Fire Protection Association. Intrinsically Safe Apparatus 1968. National Fire Protection Association No. 493-1978. Batterymarch Park, MA., 55p.

3. _____. Purged and Pressurized Enclosures for Electrical Equipment 1974. National Fire Protection Association No. 496-1974. Batterymarch Park, MA., 39p.

4. American Standard Compressed Gas Cylinder Valve Outlet and Inlet Connection. American Standards Association, B57.1-1957, Compressed Gas Association Pamphlet V-1, Compressed Gas Association, Inc., New York, 1978 Appended.

5. American Welding Society, Inc. Standard D14.4-77 Classification and Application Welded Joints for Machinery and Equipment. Available from Am. Welding Soc., Inc., 2502 N.W. 7th Street, Miami, Fl., 33125. PP.1310-1388.

6. Barbero, L.P., H. Lord. Problems Arising From the Use of Organic Plastics Materials in Flameproof Enclosures. Proc. 2nd Int. Conf. Electrical Safety in Hazardous Environments. London, England: IEEE, Dec. 9-11, 1975, pp.59-64.

7. Bartels, A.L. The Relationship Between Stress and Strain in Flameproof Enclosures. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 153-157.

8. _____. Ignition Energies of Methane/Air Mixtures as a Function of Electrical Discharge Type. In Proc. 2nd Int. Conference. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 148-152.

9. _____. The Revised United Kingdom Code of Practice for Electrical Apparatus in Potentially Explosive Atmospheres. In Proc. 2nd Int. Conference. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 157-164.

10. Bartels, A.L., A.G. Day. Insulation Requirements for Explosion-Protected Equipment. In Proc. 2nd Int. Conference. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 158-163.

11. Benz, F.J, C.V. Bishop, and R.P. Rollins. Flammability and Explosive Characteristics of Selected Aerospace Fluids. NASA Handbook.

12. Bodurtha, R.T. Industrial Explosion Prevention and Protection. McGraw-Hill Book Company, New York, 1980, 167p.

13. Bollinger, P.A. Optimizing the Design of a NEMA Type 7 "Explosion-Proof" Enclosure Used for Electromechanical Switching Devices. IEEE Trans. on Ind. Applications, v.IA-16, No. 1, January/February 1980, pp.44-50.

14. Bossert, J.A. Electric Arcing During Flammable Gas Explosions. Canadian Explosive Atmospheres Laboratory, Ottawa, Canada, Report 342, December 1974.

15. Bossert, J.A., G.K. Brown, P. Morgan. Electric Arcing at High Voltage During Methane/Air Explosions. 15th International Conf. on Safety in Mines Res., Korlovy Vary, Czechoslovakia, Report 293, September 1973.

16. Braker, W. and A.L. Mossman. Matheson Gas Data Book Sixth ed. Matheson Division Searle Medical Products USA, Inc., Lyndhurst, N.J, pp.441-445.

17. Brinkley, S.R. Jr., B. Lewis. On the Transition from Deflagration to Detonation. In Seventh Symp. (Int.) Combustion. London: Butterworth, 1959, pp.807-811.

18. British Standard 1259: 1958 Intrinsically Safe Electrical Apparatus and Circuits, March 1981. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

19. British Standard 4683: Specification for Electrical Apparatus for Explosive Atmospheres, Part 1: Classification of Maximum Surface Temperatures. 1971. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

20. British Standard 4683: Specification for Electrical Apparatus for Explosive Atmospheres, Part 2: The Construction and Testing of Flameproof Enclosures of Electrical Apparatus. 1971. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

21. British Standard 4683: Specification For Electrical Apparatus for Explosive Atmospheres, Part 3: Type of Protection N. 1972. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

22. British Standard 5126: Specification for Mining Type Flameproof Supply and Control Units for Use on Systems up to 1100V, Part 1: 160/250A Direct-on-line Motor Starters (For Use on Three Phase A.C. Circuits). 1974. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

23. British Standard 5126: Specification for Mining Type Flameproof Supply and Control Units for Use on Systems Up to 1100V, Part 2: 300A Circuit Breaker Units, 1976. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

24. British Standard 5501: Electrical Apparatus for Potentially Explosive Atmospheres, Part 1: General Requirements. December 30, 1977. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

25. British Standard 5501: Electrical Apparatus for Potentially Explosive Atmospheres, Part 5: Flameproof Enclosure 'd'. December 30, 1977; Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

26. British Standard 5501: Electrical Apparatus for Potentially Explosive Atmospheres, Part 6: Increased Safety 'e'. December 30, 1977. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

27. British Standard 5501: Electrical Apparatus for Potentially Explosive Atmospheres, Part 7: Intrinsic Safety "i'. December 30, 1977. Available from Publications Manager, 101 Pentonville Road, London N1 9ND.

28. Brunot, H.B., E.J. Gleim, and R.S. James. Explosion-Proof Design and Wiring for Permissible Mining Equipment. BuMines Bull. 541, 1955, 40p.

29. Bull, D.C., J.E. Elsworth, G. Hooper, and C.P. Quinn. A Study of Spherical Detonation in Mixtures of Methane and Oxygen Diluted by Nitrogen. J. Phys. D.: Appl. Phys., Vol. 9, 1976. Printed in Great Britain. pp.1991-2000.

30. Burrow-Bridge, D., and F.W. Paul. Prevention of Electrical Breakdown in Spacecraft. National Aeronautics and Space Administration Report, No. SP-208.

31. Butzler, E.W. and J.J. Jakowsky. Oxygen-Oil Explosions. Preliminary Report II, Spontaneous Ignitiion of Metals in Oxygen Under Pressure. BuMines RI 2521, 1923, 4p.

32. Ciok, J. Internal Short Circuits in Flameproof High-Voltage Equipment. Paper No. 14. Pres. at the 16th International Conference on Coal Mine Safety Research, Washington, D.C., September 1975, 9p.

33. Cobine, J.D. Gaseous Conductors Theory and Engineering Applications. Dover Publications, Inc. New York, 1958, pp.271-277, 606p.

34. Cook, F., W.G. Stiffler. Laboratory Evaluation and Performance Testing of High Voltage Sealed Insulation Systems for Large AC Motors. IEEE Petroleum and Chem. Ind. Conf. 25th Ann. Record of Conf. Papers, September 1978. Catalogue No. 78CH1322-7-IA, New York, pp.204-211.

35. Cooper, A.R., H.G. Dorsett, and J. Nagy. Explosibility of Carbonaceous Dusts. BuMines RI 6597. August 1964, 30p.

36. Devins, J.C., and A.H. Sharbaugh. Electrical Breakdown in Solids and Liquids. Electro-Technology, Science and Engineering Series, October 1961, pp.97-117.

37. Dolgos, J.G., and L.W. Scott. Electric Arcing at High Voltage Inside Explosion-Proof Enclosures During Methane-Air Explosions. Unissued BuMines TPR, 1981, 19p.

38. Dunn, J.H., L.J. Linley, and A.B. Luper. The Effects of Corona Discharge and High Voltage on the Combustion Characteristics of Methane, Coal Dust and Air Mixtures for the U. S. Bureau of Mines Reimbursable Agreement No. J0318081. TR-WSTF-299-001.

39. Ecker, H.W., B.A. James, and R.H. Toensing. Electrical Safety: Designing Purged Enclosures. Chemical Engineering, May 13, 1974, pp.93-97.

40. Eckhoff, R.K., G. Enstad. Why Are "Long" Electrical Sparks More Effective Dust Explosion Initiators Than "Short" Ones? Combustion and Flame, v.27, January 1976, pp.129-131.

41. Ellis, J.M. Inspection and Maintenance of Electrical Equipment in Hazardous Environments. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 138-142.

42. Engel, U. and H. Wickboldt. Special Types of Explosion Protected Electrical Machines of Type of Protection "Increased Safety". In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 118-123

43. Fleisig, D.J. The German Explosion-Proof Concept for Hazardous Atmospheres. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp 174-182.

44. Foster-Miller Associates, Inc. High-Voltage Arcing Faults in Explosion-Proof Enclosures. Proposed Experimental Program. BuMines Contract No. H0308093, October 14, 1981, 20p.

45. Foster-Miller Associates, Inc. Permissible Load Centers State-of-the-Art Review. Report on USBM Contract H0308093, May 1981. 132p.

46. Galambos, L.G. Corona: What It is; Damage It Causes; How To Avoid It. Electronic Products magazine, April 1965.

47. Gibson, N., and G.F.P. Harris. The Calculation of Dust Explosion Vents. Chem. Eng. Prog., v.72, No. 11, 1976, pp.62-67.

48. Gray, G.W. Phase Sensitive Short Circuit Protection. Mining Technol. April 1978, pp.133-136.

49. Grelecki, C. Fundamentals of Fire and Explosion Hazards Evaluation. New York: Am. Inst. Chem. Eng. 1972.

50. Gust, G., and D.F. Sansom. Flameproof Components in Hazardous Areas. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 113-117.

51. Handbook of Chemistry and Physics. The Chemical Rubber Co., Cleveland, OH., 62nd Edition.

52. Hashad, I.F.M., P.B. McGarth, and J.K. Nelson. A Comparison of the Electrical Breakdown Characteristics of Hydro- and Fluorocarbon Liquids. J. of Electrostatics, v.7, August 1979, pp.67-74.

53. Heinrich, O.X. Corona Measuring Techniques and Their Use in Insulation System Evaluation. 1964 Electronic Components Conference, Washington D.C.; available from Biddle Instruments, 510 Township Line Road, Blue Bell, Pa. 19422, Technical Bull. 66T1, 18p.

54. Hikita, M., M. Ieda, M. Nagao, and G. Sawa. Dielectric Breakdown and Electrical Conduction of Poly(vinylidene-fluoride) in High Temperature Region. J. of Phys. D: Applied Phys., v.13, No. 4, 1980, pp.661-666.

55. Hill, B. Electrical Equipment in Flammable Atmosphere - The Balance of Safety. Mining Technol. August 1979, pp.361-367.

56. Hinds, F.W. Safety Tests for Purged and Pressurized Machines. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 70-74.

57. Horenstein, M.N. and J. R. Mecher. Particle Contamination of High Voltage DC Insulators Below Corona Threshold. IEEE Trans. on Electrical Insulation, v.EI-14, No. 6, December 1979, pp.297-305.

58. Ichikawa, K., and R. Tanaka. Ignition of Flammable Solid materials by Electrical Discharges Under Artificial Atmospheres. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 65-69.

59. Imada, H., K. Isshiki, and K. Yahagi. Relation Between Electrical Impulse Breakdown Strength and Rate of Drawing in Polyethylene. Japanese J. of Applied Phys., v.18, No. 11, 1979, pp.2047-2049.

60. Ingue, Y. and H. Mitsui. Statistical Analysis on the Electrical Failure Properties of the Form-Wound Epoxy Micaceous Insulation Systems for Rotating Machines. IEEE Trans. Electrical Insulation, v.EI-12, No. 3, June 1977, pp.237-248.

61. Isobe, S. and K. Saito. Methods for Electrical Field Analysis of Insulation Structure with High Resistance Layer for Surface Corona Suppression. Electrical Engineering in Japan, v.*96*, No. 3, 1976, pp.1-9.

62. Killing, F. and M. Tielke. The Interference Short-Circuit With Arcing Phenomena in Electrical Equipment in Flameproof Enclosures With Special Reference to the So-Called Transmission of Ignition by Particles. Paper No. 13, Pres. at the 16th Internat. Conf. on Coal Mine Safety Res., Washington, D.C., September 1975.

63. King, R.L. Development of Performance Standards for Explosion-Proof Enclosures. IAS Conf. Record of the 14th Ann. Meeting. Paper Pres. September 1979. Pub. by IEEE, Catalogue No. 79CH1484-51A, New York, 1979, pp.1115-1119.

64. Kratzer, R.H., F.F.C. Lee, J.H. Nakahara, and K.L. Paciorek. Safe Organic Insulators and Fluids for Permissible Enclosures. Bureau of Mines Minerals Research Contract Report, Contract No. J0377075, June 1980.

65. Laderman, A.J., P.A. Urtiew, and A.K. Oppenheim. On the Generation of a Shock Wave by Flame in an Explosive Gas. In Ninth Symp. (Int.) Combustion. New York: Academic Press, 1963, pp.265-274.

66. Lewis, B. and G. Von Elbe. Combustion, Flames and Explosions of Gases. Academic Press Inc., New York, 1961, 731p.

67. Lloyd, M.R. Approval and Certification of Electrical Apparatus for Use in Hazardous Environments in Australia. In *Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments.* London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 101-106.

68. Lyman, T. Metals Handbook. 8th Ed., v.*6*, Am. Soc. for Metals, Metals Park, Ohio, 44073. Aug. 1971, 734p.

69. Magison, E.C. Electrical Safety Standards in the United States - A Status Report. In *Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments.* London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp.11-15.

70. Marinovic, N. Effect of Short Circuits Inside Explosion-Proof Enclosures on Propagation of Ignition. Paper No. 15. Pres. at the 16th International Conference on Coal Mine Safety Research, Washington, D.C., September 1975.

71. McKinley, C. Experimental Ignition and Combustion of Metals. Paper Pres. at the Compressed Gas Assoc. Oxygen Compressors and Pumps Symp. at the Regency Hyatt House, Atlanta, Georgia. November 9-11, 1971, 36p.

72. McMillan, A.J. Electrical Apparatus for Zones 2. In *Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments.* London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 85-90.

73. Miller, W.S. Machine Design, Pub. by Penton/IPC Inc., Cleveland, Ohio, v.52, No. 8, April 17, 1980, pp.109-160.

74. Morley, L.A., F.C. Trutt. Materials in Explosion-Proof Enclosures. Proceedings of The Third West Virginia University Conference on Coal Mine Electrotechnology, December 1976, pp.12-1 to 12-12.

75. _____. Materials Suitable for Use Inside Explosion-Proof Enclosures. BuMines Open File Rept. 76-78, 1976, 39p. Available from National Technical Information Service, Springfield, Va., PB 283 972.

76. Nagy, J. and D.J. Surincik. Thermal Phenomena During Ignition of a Heated Dust Dispersion, BuMines RI 6811, 25p.

77. Oppenheim, A.K. Gasdynamic Analysis of the Development of Gaseous Detonation and Its Hydraulic Analogy. In Fourth Symp. (Int.) Combustion. Baltimore, Md.: Williams and Wilkins, 1953, pp.471-480.

78. Peterson, M.D. Testing of Electrical Equipment for Use in Hazardous Locations. IEEE Trans. on Ind. and General Applications, v.IGA-6, No. 5, September/October 1970.

79. Rae, D., and W. Thompson. Experiments on Prevention and Suppression of Coal-dust Explosions by Bromochlorodifluoromethane and on Prevention by Carbon Tetrachloride. Combustion and Flame, v.35, 1979, pp.131-138.

80. Rogowski, Z.W. Protection of Electrical Equipment Using Flame Arrestors as Pressure Reliefs. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp.10-7-112.

81. Rusk, R.D. Introduction to College Physics. 2nd ed. Appleton-Century-Crofts, Inc., 1960, 944p.

82. Schram, P.J. New Facility for Testing Explosion-Proof Electrical Equipment. IEEE Petroleum and Chem. Ind. Conf. - 27th Ann. Record of Conf. Papers, September 1980, Pub. by IEEE, Catalogue No. 80CH1549-5-IA, Piscataway, N.J., pp.1-9.

83. Simon, K.F. Preliminary Investigation Into the Causes of the Bursting of Group I Flameproof Enclosures, In Which the Electric Current Caused Gases to Evolve From Plastic Material. SMRE Transl. No. 6012, Paper F5, Pres. at the 14th Internat. Conf. of Mine Safety Res. Estab., Donetsk, 1971.

84. Thomas, A.M. The Effect of Corona on Solid Insulating Materials. Inst. of Electrical Eng., London. Part 2: Power Eng., v.91, December 24, 1944, pp.549-562.

85. Towle, L.C. Earthing in Hazardous Atmospheres. In Proc. 2nd Int. Conf. Electrical Safety In Hazardous Environments. London, England: Inst. Elec. Eng., Dec. 9-11, 1975, pp. 96-100.

86. Underwriters' Laboratories, Inc. Standard 198C: High-Interrupting-Capacity Fuses, Current-Limiting Types. Chicago, Ill., 1981, 31p.

87. _____. Standard 698: Industrial Control Equipment for Use in Hazardous Locations, Class I, Groups A, B, C and D, Class II, Groups E, F and G. Chicago, Ill., 1981, 28p.

88. _____. Standard 1203: Explosion-Proof and Dust-Ignition-Proof Electrical Equipment for Use in Hazardous Locations. Chicago, Ill., 1973, 24p.

89. U.S. Code of Federal Regulations. Title 30 - Mineral Resources; Chapter I - Mine Safety and Health Admin., Department of the Interior; Subchapter D - Electrical Equipment, Lamps, Methane Detectors; Test for Permissibility; Fees.

90. Wilkens, W.D. and O.L. Willis. How to Prevent Failure of Electric Power Cables. Plant Engineering, Feb. 21, 1980, pp.87-90.

91. Wright, L.D. The Testing of Combination Starters in Explosion Proof Enclosures. Paper available from General Electric Co., P.O. Box 2913, Bloomington, Illinois 51701, 4p.

92 Zabetakis, M.G. Fire and Explosion Hazards at Temperature and Pressure Extremes. Pres. at the Assoc. of Ind. Chem. Eng. - Ind. Chem. Joint Meeting, London, England, June 13-17, 1965, 8p.

APPENDIX

TR-WSTF-299-001

Test Report

The Effects of Corona Discharge and High Voltage on the Combustion Characteristics of Methane, Coal Dust and Air Mixtures for the U. S. Bureau of Mines

Reimbursable Agreement No. J0318081

Issued by
Laboratories Test Office
White Sands Test Facility
Johnson Space Center

Prepared by: J Dunn
James H. Dunn
LEMSCO, Environmental Test Section

Prepared by: Alton B Luper
Alton B. Luper
LEMSCO, Environmental Test Section

Prepared by: Larry J Linley
RF/Larry J. Linley
NASA, Laboratories Test Office

Approved by: David L. Pipen
RF/David L. Pipen
Chief, NASA Laboratories Test Office

FOREWORD

This report was prepared by the National Aeronautics and Space Administration, Johnson Space Center, White Sands Test Facility under USBM Contract number J031801. The contract was initiated under the Minerals, Health, and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Lawrence W. Scott acting as the Technical Project Office. Joseph A. Gilchrist was the contract administrator for the Bureau of Mines. This report concerns the tests recently completed as a part of this contract during the period 15 August 1981 to 15 November 1982. This report was submitted by the authors on 31 January 1983.

ABSTRACT

The Department of the Interior, Bureau of Mines, is reviewing explosion protection methods for use in gassy coal mines. This test report describes an investigation into the effects corona discharge and high voltage arcing have on the combustion of various combinations of methane, coal dust and air mixtures. Corona discharge and high voltage arcing were found to enhance the reaction characteristics of methane, coal dust, and air mixtures. However, the observed increase in reaction rates was well within the rates expected by methane deflagrations. Corona discharge was observed to ignite concentrations of methane and air in some conditions. Increasing the distance between high voltage conductors and ground return paths in an air atmosphere did not reduce the susceptibility for high voltage arcing during methane deflagration. Varying the ignition energy from less than 10 millijoules to over 1500 kilojoules caused no significant increase in the combustion overpressure for the mixtures tested. These results have a direct bearing on the recommendations for the performance criteria of explosion protection devices as submitted on 15 December 1982.

INTRODUCTION

The United States Department of the Interior, Bureau of Mines (USBM) has requested the National Aeronautics and Space Administration, White Sands Test Facility (NASA WSTF) to evaluate means of extending present explosion protection methods to voltages up to 15,000 volts RMS AC. Explosion protection methods currently under consideration include explosion-proof, purged, and potted enclosures. The effects of corona discharge associated with high voltage and high energy arcing were examined in order to evaluate explosion protection methods. While the deleterious effects of corona on insulators and various materials are well known, the influence of alternating current corona on methane and air combustion has not been reported and a literature search has confirmed that little data exists on the effects of high energy arcing on methane and air combustion. This report describes an investigation into some of the effects that corona discharge and high energy arcing have on combustion of methane and air mixtures and coal dust suspensions in methane and air mixtures.

BACKGROUND AND OBJECTIVES

Corona discharge between electrodes is defined in numerous ways. Some definitions are based on current and potential characteristics, measurable current, visible appearance or manifestations, and levels or thresholds of electrical discharge up to and including complete breakdown. In this experiment, the term "corona" refers to a class of electrical discharges as a result of accelerated ionization of gas under the influence of the electrical field within a current range of 10^{-6} to 10^{-2} amperes. This general definition bounds all of the characteristics of corona discharge that are found throughout the literature except "dark current" or "dark discharge" corona which occurs at less current and complete breakdown which occurs at greater currents than the range specified. The term "high energy arc" or "arc" is defined as a high current (greater than 10^{-2} amperes), self-sustaining discharge.[1, 2, 3, 4]

Ignition of a flammable gas mixture is generally described as combustion which is more specifically broken down into deflagration and detonation type reactions.

1. The term deflagration is defined as a propagating reaction in which energy transfer from the reacting zone to the unreacted zone is by ordinary heat and mass transport process. The resulting flame travels slower than the local speed of sound and the resulting overpressure develops from the heating due to chemical reaction.

2. The term detonation is defined as a reaction in which the energy is transferred from the reacting to the unreacted zone on a reaction generated shock wave. This type of reaction always propagates faster than the local speed of sound.

The objectives of this experiment were: (a) Determine if exposure to 60 Hertz alternating current corona ignites, enhances ignition or enhances the reaction overpressure in methane and air environments; (b) Determine if exposure to high energy arcing enhances reaction rate or overpressure in methane and air and coal dust suspensions in methane and air environments.

EXPERIMENTAL APPARATUS

The test system used to characterize the effects of high voltage on methane combustion consisted of a test chamber (see Figure A-1), a corona discharge source, high energy arc equipment, an auxiliary ignition source, and data acquisition and instrumentation. (See Figures A-2, A-3, A-4, A-5, and A-6.)

The test chamber provided a controlled volume where the methane and air could be accurately mixed, exposed to the potential ignition sources, and monitored for combustion characteristics. The test chamber was a one cubic meter aluminum sphere with a one-quarter inch thick wall. The chamber was rated to a system working pressure of 250 psi. A flange equipped with two high tension feedthroughs and a glass window was mounted on the front of the chamber. A back flange had penetration ports to provide for mixing methane and air, purging with nitrogen and venting. Additionally, the back flange was fitted with a 500 psi strain gauge transducer to indicate test pressures on an oscillograph, a 1000 Torr capacitive manometer to monitor mixing pressures, and a feedthrough for instrumentation wiring. (See Figure A-1.)

The corona discharge source consisted of an 8,000 volt RMS AC 60 milliampere luminous tube transformer secondary connected to the high tension feedthroughs by high tension (40,000 volt maximum) cable. The pointed electrodes were constructed from 3/8 inch stainless steel rod and were mounted on the high voltage feedthroughs protruding inside the test chamber. The primary voltage was controlled by an autotransformer in order to provide a variable secondary voltage. (See Figure A-2.) Sources of undesired corona discharge were washed with Freon and coated with corona suppressant (Dielectric strength - 15,000 volts/.01 inch).

The high energy arc source was supplied by a 14,400 volts RMS AC public utility line through a 100 ampere fused cutout, a 100 ampere recloser, and a remotely controlled oil switch. A 264 ohm series resistor was used to limit the arc current to 55 amperes RMS. (See Figure A-3.)

An auxiliary ignition source placed within the test chamber was used in the corona discharge tests to ignite methane and air mixtures that had not been ignited by the corona. This spark ignition source consisted of a standard 12 volt oil-filled automotive ignition coil encased in a plexiglass protective box with two stainless steel electrodes connected to two high-tension feedthroughs mounted on the box. The igniter was activated externally by a switching circuit consisting of a 0.22 microfarad capacitor and a push button breaker switch connected to a 14 volt DC power supply. (See Figure A-4.) The spark igniter was secured to an instrumentation mounting frame which was constructed from angle iron and placed within the test chamber. (See Figure A-5). The igniter provided a spark of 1 to 1.5 microsecond duration with an average energy of 8 millijoules in a 3/32 inch gap.

A capacitive circuit was assembled by connecting two parallel plate capacitors in parallel. One capacitor was fixed to the instrumentation mounting frame inside of the test chamber. (See Figure A-5.) The second capacitor was external to the chamber. Connections were facilitated by the instrumentation feedthrough. Each capacitor was fabricated from two square, 1 3/4 x 1 3/4 inch copper plates separated by 1/16 inch. Together, the effective capacitance was 350 picofarads. A digital multimeter was used to measure the voltage across the plates. (See Figure A-6.) These two capacitors were used during corona testing to detect the electric field due to the igniter, indicate the strength of the field due to the corona discharge, and indicate the field generated by the increase in current as the flame front passed the corona discharge site.

In some of the corona discharge and high energy arc tests, open aluminum cans were placed in various locations in the chamber to observe if the differential pressure between the inside and outside of the can was sufficient to crush them. This can be regarded as evidence of a detonation.

An optical dust density monitor was constructed utilizing an infrared emitter and detector to assure repeatable coal dust suspension during one phase of arc testing. The dust density output was recorded on a strip chart recorder. A funnel was mounted in the test chamber and attached to the air inlet line which provided a means of dispensing the coal dust and a fan which was used to disperse the coal dust. (See Figure A-5.)

Four chromel-alumel type thermocouples were secured within the chamber in order to measure combustion temperatures. Three temperature outputs were recorded by the oscillograph and the fourth output was routed to the strip chart recorder.

Voltage applied to the electrodes was monitored by 1000X voltage probes and recorded by the oscillograph and a memory oscilloscope. Current measurements were made with a toroidal current pick-up coil with the output amplified and displayed on the oscilloscope and oscillograph. All tests were recorded on video tape by a closed circuit TV camera located in front of the glass window of the test chamber. (See Figure A-7.)

EXPERIMENTAL PROCEDURE

The corona discharge testing and high energy arc testing were conducted separately. The corona discharge source and high energy arc source were entirely independent of each other. Tests of coal dust combustion were conducted only with the high energy arc source.

Tests were conducted at two fuel-air ratios. A mixture of 8.3 percent methane in air was used as the most easily ignitable methane and air mixture. A 9.5 percent methane in air mixture was used as the stoichiometric concentration which burned most completely, thus leading to greater overpressures on ignition and the release of the maximum amount of free ions. (5, 6, 7)

A series of nine corona discharge tests were completed using a test mixture of 8.3 percent methane in air at an initial test pressure of 14.7 psia. Seven additional tests with test mixtures of 9.5 percent methane in air at the same initital test pressure were also performed. Test mixtures of methane and air were altered in some of the corona tests in the sense that the air source was a combination of bottled certified breathing air and atmospheric air with a higher relative humidity, while the other tests used the dry bottled air only.

A total of eight high energy arc tests were performed. Four of the tests were conducted in methane and air environments and four were in test environments which had coal dust suspensions. The methane and air tests had initial test pressures of 14.7 psia, two at fuel-air ratios of 8.3 percent methane in air and two at 9.5 percent methane in air. The coal dust suspension tests were comprised of two tests of coal dust suspensions in air and two coal dust suspensions in methane and air.

TEST PROCEDURE

The first phase of the corona discharge testing was performed in order to baseline the experiment by comparing the corona discharge characteristics exhibited in laboratory open air experiments to those achieved in air in the test chamber. The range of voltages applied to the electrodes was 5,000 volts peak to 11,000 volts peak. Electrode gap spacing was either 3/4 inches or 6 3/4 inches depending on the test.

The first phase of the high energy arc testing consisted of generating high energy arcs in air across electrode spacings of 6 3/4 inches to establish a system baseline.

The second phase of the corona discharge and high energy arc testing was to perform a series of similar tests in order to (a) Determine if exposure to 60 hertz alternating current corona discharge ignites or enhances ignition or the reaction overpressure; (b) Determine if exposure to high energy arcing enhances reaction rate or overpressure in methane and air and coal dust suspensions in methane and air environments.

The following procedure was used in the second phase of corona discharge and high energy arc testing, except as noted.

(i) The test chamber was evacuated to approximately 0.5 torr.

(ii) Methane (minimum 99 percent pure) and air (certified breathing air, except when otherwise noted on the test data sheet) were admitted into the chamber by using the method of partial pressures to obtain the required pressure and mixture.

(iii) The data acquisition and closed circuit television system was activated.

(iv) For the corona discharge tests:

(a) The test chamber environment was exposed to corona discharge for a specified time.

(b) The auxillary ignition source was activated to ignite the methane and air mixture after exposing the test chamber environment to corona discharge if no ignition had occurred.

(c) Tests were repeated without generating a corona discharge in the mixture utilizing the spark igniter as the only ignition source.

(v) For the high energy arc tests: A 14,400 volt RMS alternating current was applied to copper electrodes with a gap of 6 3/4 inches fusing a strand of 40 gauge wire which initiated an arc. The arc was allowed to continue for three seconds and then the voltage was removed.

(vi) The test chamber was then purged with gaseous nitrogen.

EXPERIMENTAL RESULTS

The results of the experiment are presented in two categories: the corona discharge testing phase of the experiment and the high energy arc testing phase. Results of the corona discharge experiments with 8.3 percent and 9.5 percent methane in air are shown in Tables A-1 and A-2 respectively. Table A-3 is a summary of data collected from the high energy arc tests.

Corona Test Results

A comparison between corona discharge experiments in the laboratory and the corona discharge in air tests performed in the test chamber revealed that the current and voltage measurements from both configurations were within one standard deviation when the testing circuit and measurement apparatus were identical.

Results of the corona discharge experiments with 8.3 percent and 9.5 percent methane in air are shown in Table A-1 and A-2 respectively. The pretest gas mixture temperature, the source of air, the length of the corona discharge electrode gap, the maximum corona current achieved, and the source of ignition are listed for each test. The maximum change in pressure and temperature is reported as ΔP and ΔT. The occurrence of sharp pressure and temperature peaks during the more general increasing trends is indicated for each test. The electric field measured at the point where the corona current was maximum and at the point of ignition is recorded as the voltage across the parallel plate capacitor. Comments concerning the deformation of open aluminum cans placed in the chamber give a qualitative view of the overpressure phenomena during the test. This data provides a basis for evaluating the combustion process during each test. The ignition of 8.3 percent methane in the humid atmospheric air mixture with the spark igniter was achieved only after the test mixture had been exposed to corona discharge across a 6 3/4 inch gap for 30 minutes (Test 3). These conditions exhibited the greatest peak pressure and fastest pressure rise of the tests performed in this phase of the experiment. In Tests 4 through 7, the spark igniter failed to ignite the same mixtures which had not been exposed to corona discharge. These tests indicate that the preconditioning of the test mixture with corona discharge enhances the likelihood of igniting the mixture.

Corona discharge generated through a 3/4 inch gap provided the only source of ignition in Test 9. The corona discharge was in the glow discharge regime (600 microamperes RMS) and evolved into a full brush discharge that can be essentially classified as self-sustaining (4.6 milliamperes).(1, 2, 3, 4) The corona current rapidly varied between values less than 1.0 and greater than 4.6 milliamperes which was verified on the video record which indicated occasional momentary extinction of the discharge. The video record also indicated that as the methane began to burn, the corona discharge intensified. As the corona discharge intensified more combustion occurred leading to a further increase of corona discharge current. This rise in current was due to the flame front of the methane and air mixture producing free ions that cause a large decrease in resistance of the gap between the electrodes.(5, 8) Two of the aluminum containers inside the test chamber during Test 9 were distorted forming a hemispherical surface at the end of one and the end partially expanded on the other. Two other containers had minor distortions. Even though the reaction rates in this and other tests were accelerated, no indication of detonation or extreme container deformation was observed.

The remaining tests at 8.3 percent methane in air (Tests 1, 2, and 8, Table A-1) were performed using only the bottled air source. Large distortions of corona discharge current were observed in Test 1. The current was almost twice as large as the corona discharge current observed through a gap of equal size (6 3/4 inches) in test 3 and the corona discharge current through a 3/4 inch gap which ignited the test mixture in Test 8. This larger current was probably due to residual ions attracted to the electrodes.(2, 3, 4) However, the larger corona discharge current observed in Test 1 did not ignite the test environment. The existence or creation of these ions may have been related in the difference of the water content of the air source. An unexpected ignition occurred during Test 8 even though the limit of corona discharge current (10^{-2} amperes) was not reached. The power was turned off immediately upon ignition. The auxillary ignition source ignited the environment in Test 2 with a single spark. These tests illustrate the great uncertainty of corona discharge effects on the ignition and combustion characteristics of methane.

Results of seven corona discharge tests in 9.5 percent methane in air mixtures are shown in Table A-2. Tests 6 and 7 were conducted with only the auxillary ignition source in order to establish a baseline of methane reaction characteristics in air at this gas mixture. Tests 1 through 3 were exposed to corona discharge for approximately 30 minutes and then ignited with the auxillary ignition source. Only slight variations in reaction rates were observed in these three tests with the exception that sharp peaks were recorded on the temperature and pressure curve during Test 2 and 3. The video record of Test 3 indicated bright glowing spots in the area of the corona discharge electrodes before the spark was initiated. This record also indicated some local ignition occurred before the auxillary ignition source ignitor was activated. The methane air mixture was exposed to the corona discharge for four hours before the spark ignitor was activated in Test 4. A significant increase in temperature change and rate of temperature and pressure change was observed after this longer 4 hour corona exposure when compared to the other tests in this series. A corona discharge across a 3/4 inch gap unexpectedly ignited the gas mixture in Test 5. The rate of reaction indicators are noticeably increased for this methane and air mixture with longer exposure to corona discharge.

High Energy Arc Testing

A summary of the data collected from the high energy arc discharge tests is included as Table A-3. The test atmosphere composition and pressure, power dissipated by the arc, arc energy, peak pressure attained and pressure rise rate are noted for each test.

The pressure profiles observed during the high energy arc and corona discharge methane and air tests are very similar in shape and magnitude. However, the incidental rapid pressure and temperature peaks observed during the reactions initiated by spark and corona discharge were not observed during the high energy arc tests. Aluminum containers exposed to the high energy arc initiated reactions were only slightly deformed during these tests. The high voltage arc was observed to be very unstable and unpredictable in the presence of methane combustion. The arc traversed gaps ranging from 6 3/4 inches (the gap between the electrodes) to 23 inches (distance from anode electrode to the angle iron instrumentation frame) during the methane and air ignitions. Thus the integrity of the electrode gap was not maintained during methane combustion.

Peak pressures and temperatures were lower in the tests which included the addition of coal dust to the methane and air mixtures. The elapsed time from arc initiation to attainment of peak pressure was decreased by a factor of 2.4 in the coal dust tests, indicating a cooler, faster reaction.

CONCLUSIONS

Corona discharge and high voltage arcing enhance the reaction characteristics of methane, coal dust, and air mixtures, however, the increase of reaction rates observed during these tests was well within the rates expected by methane deflagrations. Corona discharge can ignite concentrations of methane and air under some conditions. The seperation of high voltage conductors will not prevent high voltage arcing during methane deflagrations. Variation in energy of the ignition source caused no increase in overpressure during the combustion of the mixtures tested.

Corona Discharge

(i) Corona discharge served as an ignition source in methane and air environments. This was observed in two tests at 8.3 percent methane in air and one at 9.5 percent. In these cases, the geometric domain and voltage at the corona discharge site were manipulated to accelerate the corona discharge. The video record for Test 3, Table A-2 shows that even at gap sizes of 6 3/4 inch, corona discharge may ignite methane air mixtures.

(ii) Corona discharge enhanced conditions for ignition of methane in air environments. In one test using the 8.3 percent methane in air mixture, ignition occurred with a single spark generated by the spark igniter (Test 3, Table A-1) after the test environment had been exposed to corona for 30 minutes. In contrast, four tests using the same methane in air ratio that were not exposed to corona failed to ignite when the spark igniter was activated (Tests 4-7, Table A-1).

(iii) Corona discharge increased the possibilities of overpressure conditions. Test environments exposed to corona discharge showed higher rates of pressure rise. The greatest pressure rise rate occurred in a test in which the mixture had been exposed to corona for the longest time (4 hours). This test also had the highest peak pressure (Test 4, Table A-2).

High Energy Arc Testing

(i) The separation of conductors by the air gaps specified in these experiments did not prevent the high voltage system from arcing during the combustion of methane and air and coal dust. Other measures are necessary to guard against arcing at the voltages used (14,400 volts RMS AC) in these environments.

(ii) The methane and air environments had no greater tendency toward excessive overpressures when ignited by high energy arcs than the same environments ignited by low energy sparks in the presence of corona.

(iii) The addition of coal dust to the methane and air mixtures resulted in reactions with slightly higher pressure rise rates and lower temperature reactions compared to the arc initiated reactions in methane and air environments without coal dust.

Bibliography

1. Benedict and Maxfield, "Theory of Gaseous Conduction and Electronics", McGraw-Hill, 1941.

2. Loeb, "Electrical Coronas, Their Basic Physical Mechanisms", University of California Press, 1965.

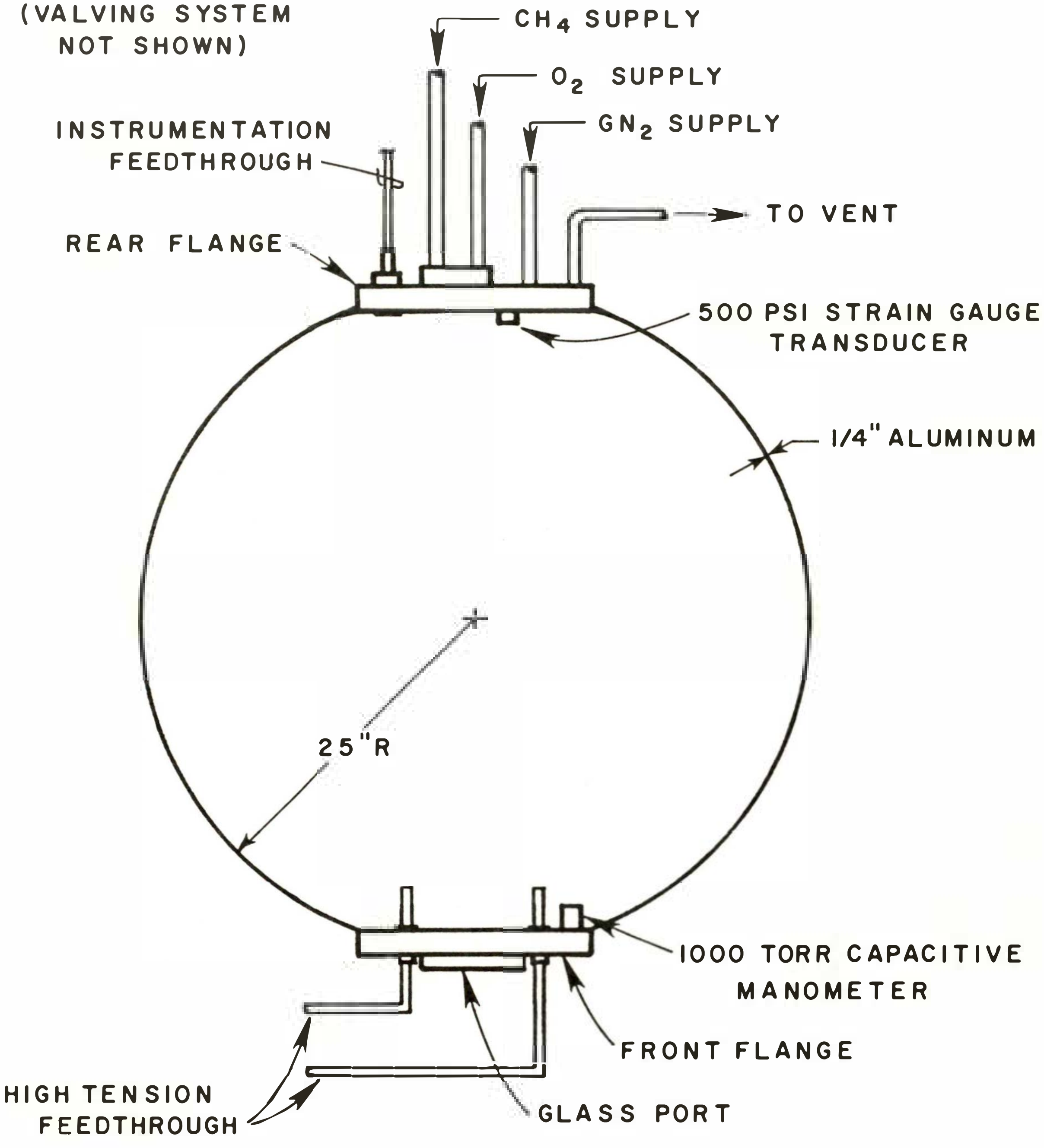
3. Nasser, "Fundamentals of Gaseous Ionization and Plasmas", Wiley, 1971.

4. Cobine, "Gaseous Conductors Theory and Engineering Applications", Dover, 1958.

5. Scott and Dolgos, "Electrical Arcing at High Voltage Inside Explosion-Proof Enclosures During Methane-Air Explosions", Technical Progress Report, U. S. Bureau of Mines, 1981.

6. Bodurtha, "Industrial Explosion Prevention and Protection", McGraw-Hill, 1980.

7. Fuhre and Eckhoff, "Pressure Development Due to Turbulent Flame Propagation in Large-Scale Methane-Air Explosions", Combustion and Flame, Vol. 47 (1:July 1982), The Journal of the Combustion Institute.



$V = \simeq 1 M^3$

SYSTEM WORKING PRESSURE = 250 PSI

Figure A-1 TEST CHAMBER

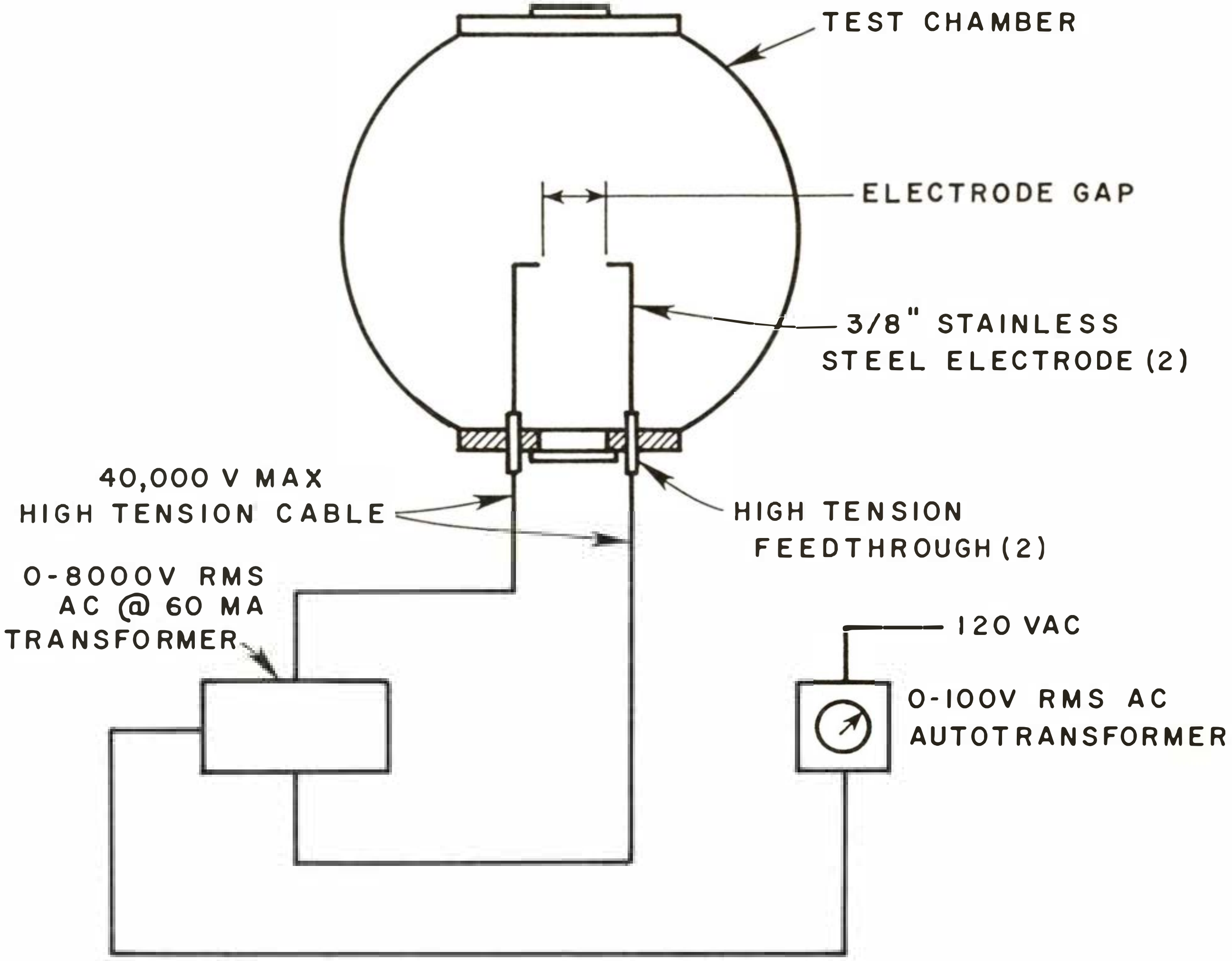


Figure A-2 CORONA DISCHARGE SOURCE

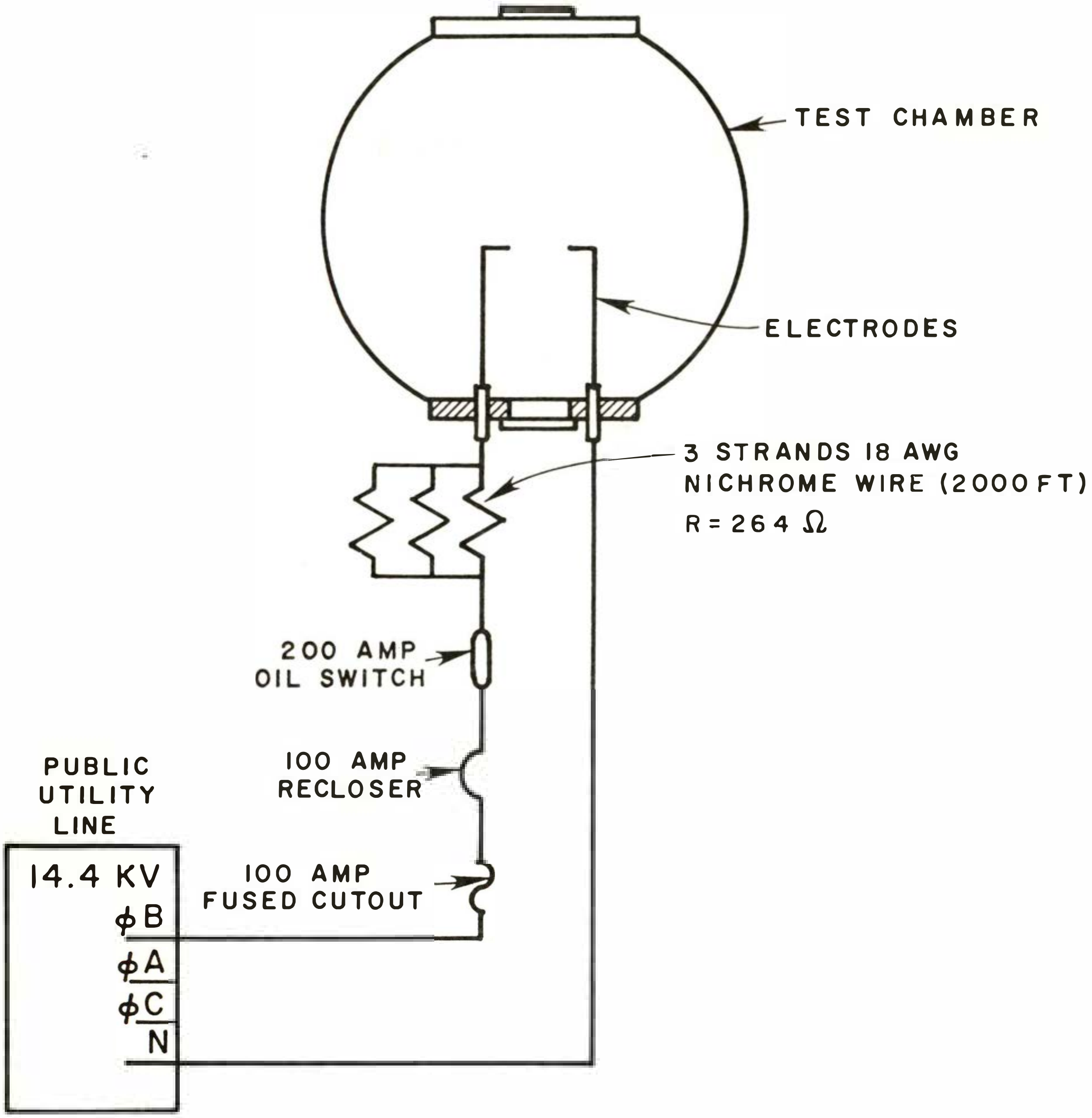
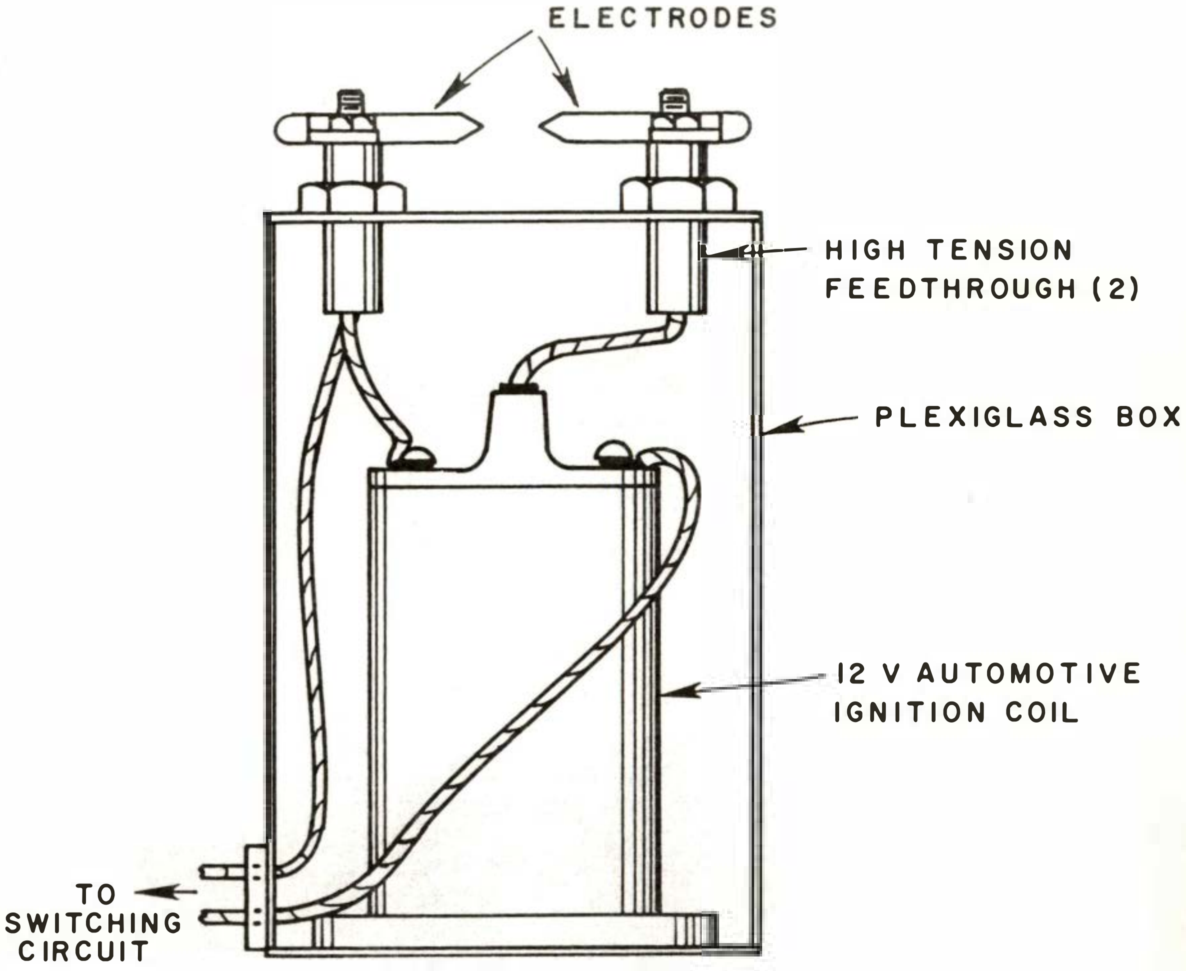
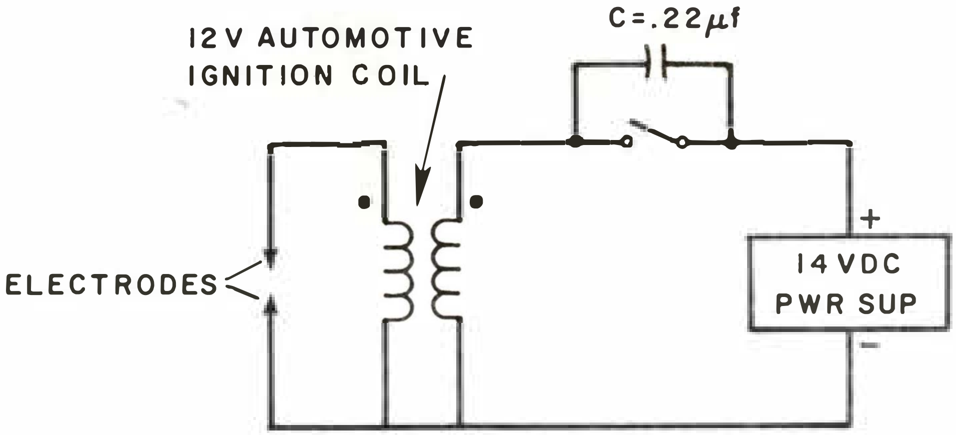


Figure A-3 HIGH ENERGY ARC SOURCE

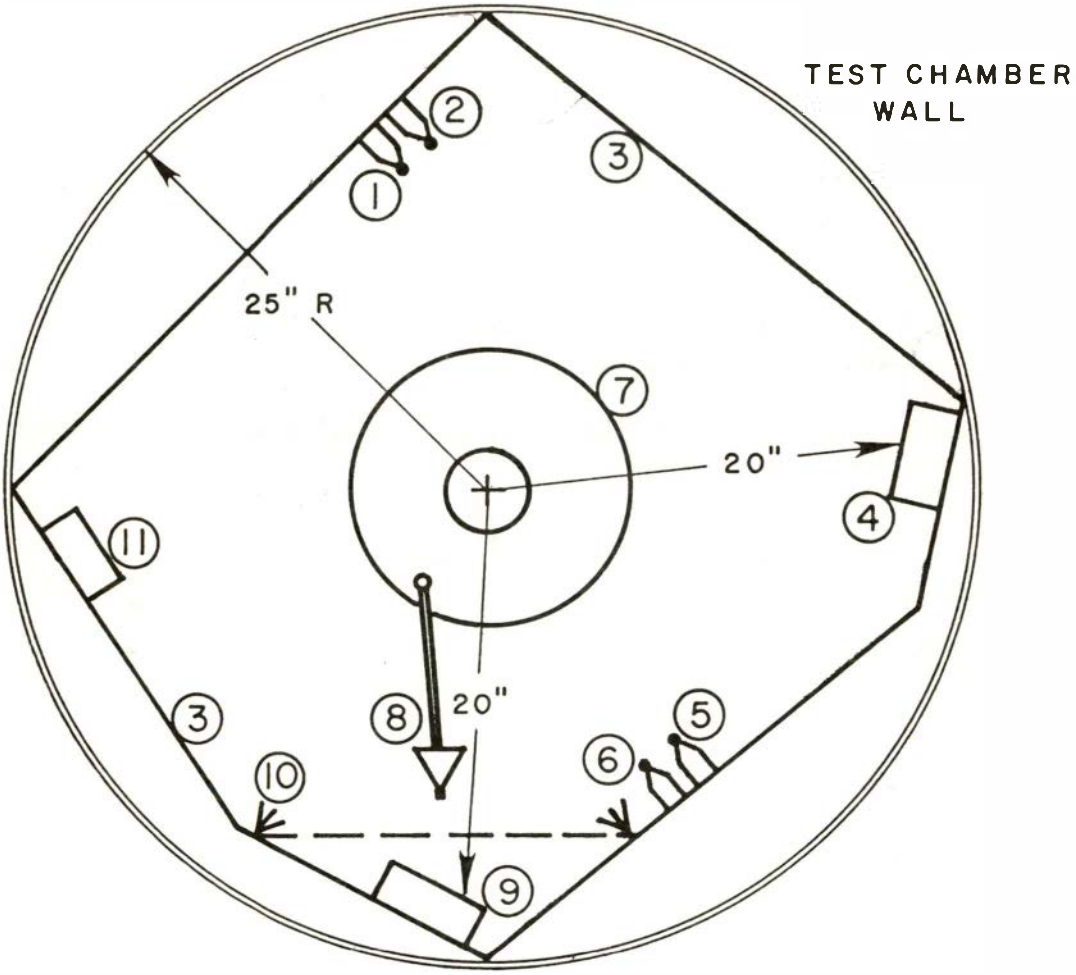


SPARK IGNITER



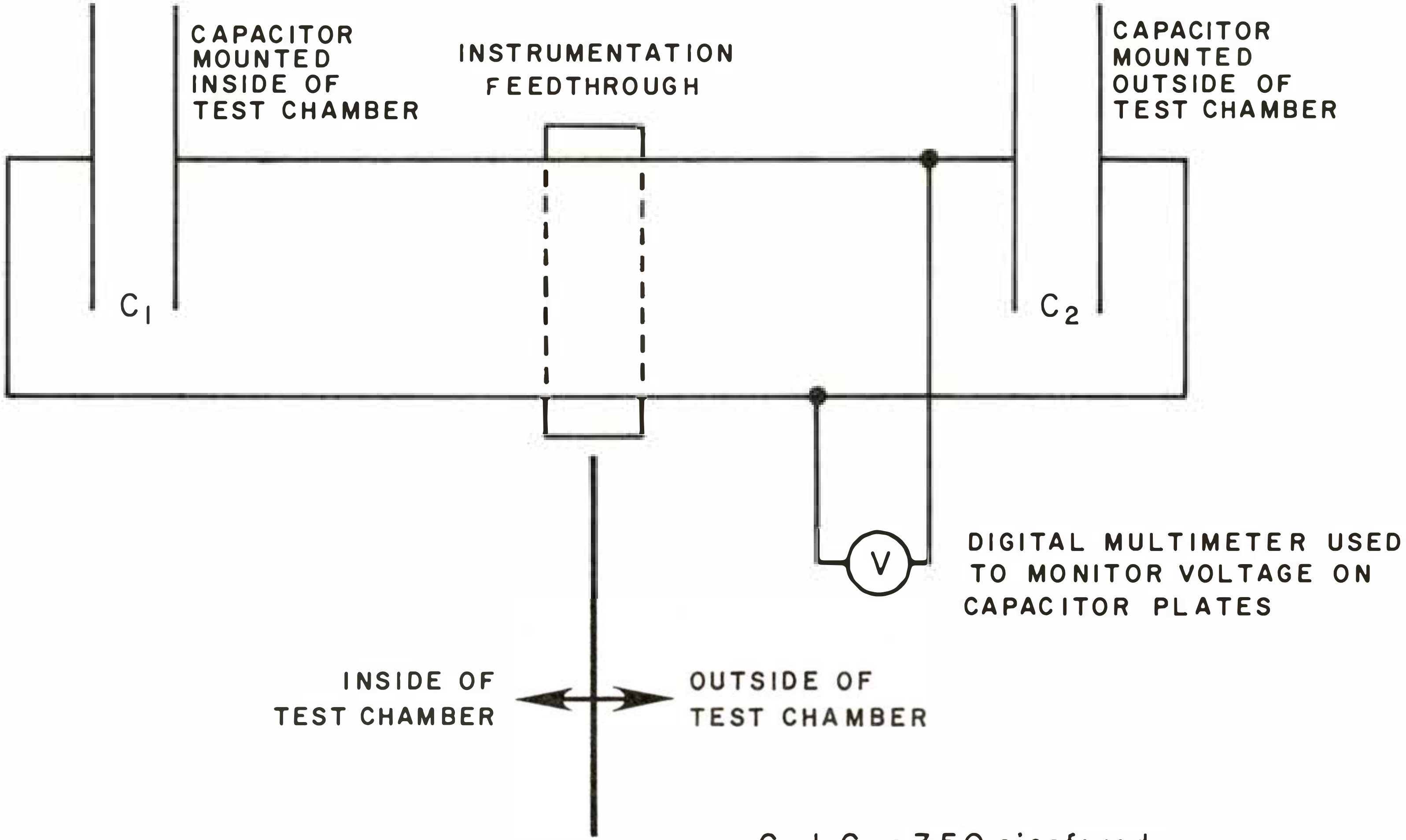
SCHEMATIC

Figure A-4 AUXILIARY SPARK IGNITION SOURCE AND SCHEMATIC



1,2. THERMOCOUPLES TC_1 & TC_2 (CORONA DISCHARGE AND HIGH ENERGY ARC TEST)
3. ANGLE IRON FRAME (CORONA DISCHARGE AND HIGH ENERGY ARC TEST)
4. CAPACITOR (CORONA DISCHARGE TEST)
5,6. THERMOCOUPLES (CORONA DISCHARGE AND HIGH ENERGY ARC TEST)
7. REAR FLANGE
8. COAL DUST DISPENSER (HIGH ENERGY ARC TEST)
9. AUXILIARY SPARK IGNITION SOURCE (CORONA DISCHARGE TEST)
10. COAL DUST DENSITY MONITOR (HIGH ENERGY ARC TEST)
11. COAL DUST DISPERSION FAN (HIGH ENERGY ARC TEST)

Figure A-5 INSTRUMENTATION DISTRIBUTION INSIDE OF TEST CHAMBER



$C_1 + C_2 = 350$ picofarads

Figure A-6 FIELD STRENGTH CIRCUIT USED IN CORONA DISCHARGE TEST

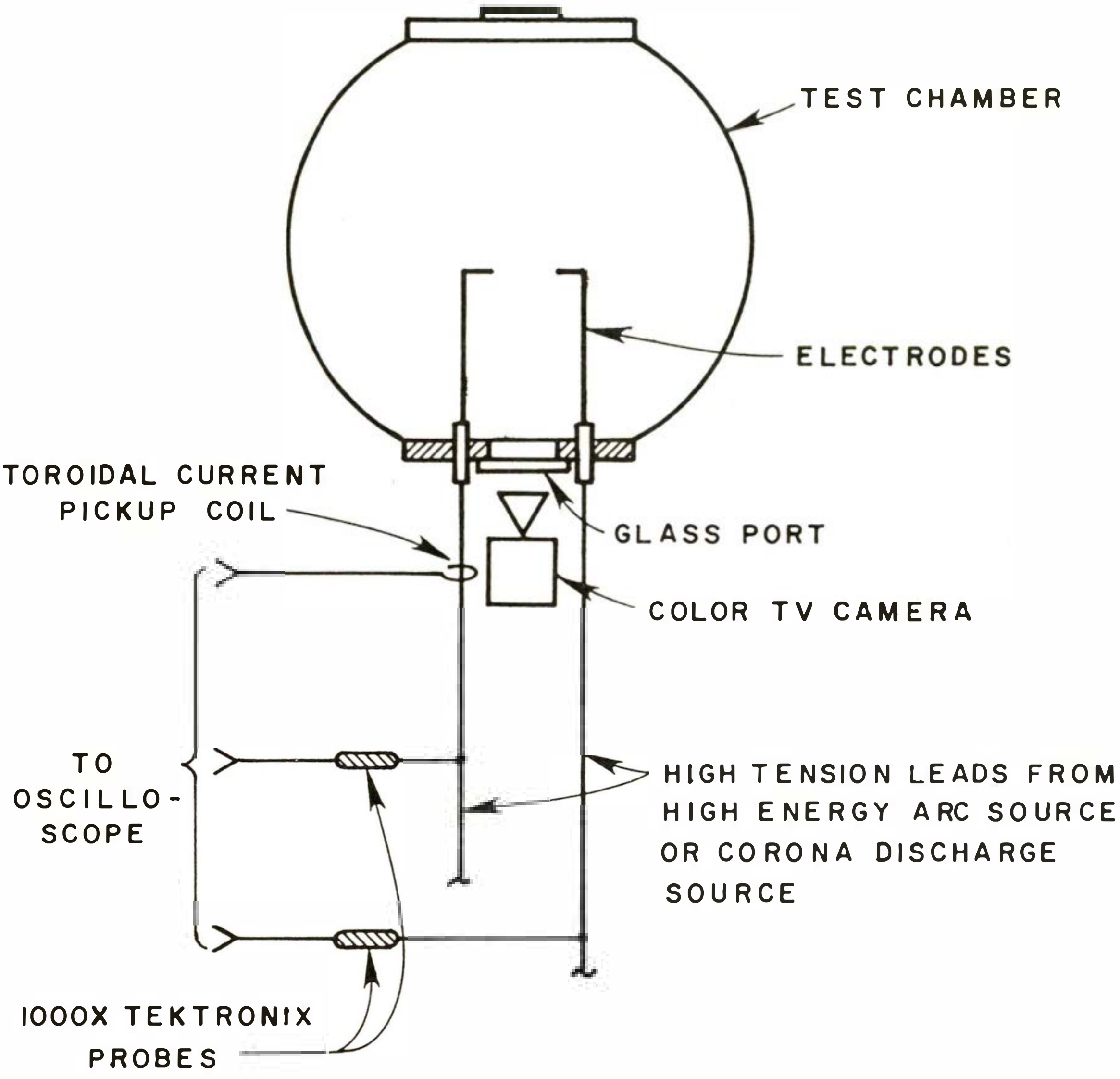


Figure A-7 DATA ACQUISITION EQUIPMENT EXTERNAL TO TEST CHAMBER

TABLE A-1
Corona discharge experiments
8.3 percent methane in air at 14.7 psia

Test Number	Preignition Temperature (°C)	Air Source (Bottled/ Atmospheric)	Exposure Time (seconds)	Maximum Current (ma RMS)	Ignition Source	ΔP (psi)	ΔT (°C)	Pressure/ Temperature Peaks	Maximum Field Strength (volts)	Can Deformation Comments
1	29	B	1800	0.9	Spark	78	1187	Yes	1	N/A
2	32	B	0	N/A	Spark	87	500	Yes	1	N/A
3	34	B and A	1800	0.4	Spark	89	660	Yes	102	N/A
4	28	B and A	0	N/A	N/A	0	0	No	1	N/A
5	31	B and A	0	N/A	N/A	0	0	No	1	N/A
6	29	B and A	0	N/A	N/A	0	0	No	1	N/A
7	30	B and A	0	N/A	N/A	0	0	No	1	N/A
8	41	B	1200	N/A	Corona	N/A	590	N/A	175	Moderate
9	44	B and A	1500	4.6	Corona	87	688	Yes	N/A	Slight to Moderate

TABLE A-2
Corona discharge experiments
9.5 percent methane in air at 14.7 psia

Test Number	Preignition Temperature (°C)	Air Source (Bottled/ Atmospheric)	Exposure Time (seconds)	Maximum Current (ma RMS)	Ignition Source	ΔP (psi)	ΔT (°C)	Pressure/ Temperature Peaks	Maximum Field Strength (volts)	Can Deformation Comments
1	20	B	1800	0.5	Spark	92	562	Yes	160	N/A
2	36	B	1800	0.6	Spark	91	640	Yes	108	N/A
3	39	B	1800	0.4	Corona/Spark	88	640	Yes	179	Slight
4	40	B	14,400	0.4	Spark	93	712	Yes	48	Slight
5	42	B	1200	N/A	Corona	N/A	540	N/A	N/A	Slight
6	40	B	0	N/A	Spark	88	640	Yes	1	None
7	39	B	0	N/A	Spark	88	640	Yes	1	Slight

TABLE A-3
High energy arc experiments

Test Number	Methane/Air Mixture (Percent Methane)	Coal Dust Concentration (mg/l)	Preignition Pressure (psia)	Preignition Temperature (°C)	ΔP (psi)	ΔT (°C)	Pressure/ Temperature Peaks	Peak Arc Power (KW)	Arc Energy (KJ)
1	8.3	0	14.7	31	N/A	N/A	N/A	315	N/A
2	8.3	0	14.7	35	93	603	Yes	285	925
3	9.5	0	14.7	34	99	537	Yes	315	903
4	9.5	0	14.7	30	101	497	Yes	315	1195
5	0.0	50	12.4	24	0	0	No	375	1155
6	0.0	200	12.4	25	8	58	No	175	608
7	9.9	50	13.8	34	99	212	Yes	320	1582
8	9.6	200	13.8	24	95	348	No	338	409