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DEVELOPMENT OF HIGH VOLTAGE PERMISSIBLE LOADCENTER

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16. Abstract

This report makes recommendations for new approval and testing criteria for high voltage permissible loadcenters (transformer and switchgear, greater than 4,160 V) for underground U.S. mines, and describes the development and testing of a prototype loadcenter to meet the criteria.

The recommended criteria (Chapters 2 and 3) included new findings in several areas: minimum clearances between live conductors, special precautions for using organic insulators, tests for dielectric strength and electrical stress, and explosion testing.

A research test program (Chapter 4) was conducted to evaluate the pressure rise caused by a high-energy arcing fault (10,000 A) with and without a simultaneous methane-air explosion inside the enclosure.

The prototype loadcenter (Chapter 5) included a 1,250 kV.A, 7,200 V - primary transformer inside a center compartment with separate, attached enclosures for high voltage switchgear on one end and low-voltage distribution and protection on the other end.

A state-of-the-art review (Chapter 6) is also included.

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FOREWORD

This report was prepared by Foster-Miller, Inc., (FMI), of Waltham, MA, under Bureau of Mines Contract No. H0308093. It was administered under the technical direction of the Pittsburgh Research Center. The Technical Project Officer was Mr. Lawrence W. Scott. Mr. Michael Nowicki was the Contracting Officer. This report is the result of work carried out during the period from July 1980 to December 1985.

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1. EXECUTIVE SUMMARY

This report documents the results of a 5-year program to develop recommended criteria for the Approval of High Voltage Permissible Loadcenters and to construct a loadcenter which was designed to meet this criteria. There were four major phases of this program:

a. Comprehensive Industry Survey, Literature Search, and State-of-the-Art Review

b. High Energy Arc Testing Program

c. Development of Recommended Criteria

d. Design, Construction and Testing of a High Voltage Permissible Loadcenter.

Section 2 presents the recommended criteria, and Section 3 provides a discussion of the criteria. These criteria were structured to provide recommendations which would address specific problems posed by the use of high voltages (greater than 1000 V) in areas where permissible equipment is required, with the assumption that all existing regulations for the approval of permissible equipment (less than 1000 V) would still apply. Major new findings and recommendations included the following:

a. Specification of minimum clearances between exposed electrical conductors, based upon in-house United States Bureau of Mines research

b. Special safety precautions governing the use of insulators such as organic plastics which can be decomposed by high heat and liberate highly explosive gases, based upon research conducted in other countries

c. Electrical tests for dielectric strength and electrical stress, based upon U.S. Bureau of Mines contract research programs

d. New explosion-testing recommendations, based upon arcing fault tests conducted during this program.

Section 4 discusses the high-energy arc testing which was conducted during this program in order to assess the hazards posed by the pressure increase caused by a high energy arcing fault, with and without a simultaneous methane-air explosion. The following major points were covered:

a. Arcing faults up to maximum power of 15,000 V, 10,000 A for 250 msec duration

b. Enclosure free volumes from 0.1 m^3 to 1 m^3

c. With and without explosive concentrations of methane

d. Maximum pressure rise of 138 psi.

Section 5 contains a discussion of the design, construction, and testing of a prototype permissible high voltage loadcenter. Major items of interest were as follows:

a. 1250 kV.A rating, 7200 V primary, 1000/440 V secondaries

b. Size and weight comparable to nonpermissible load centers

c. Insulators which are highly resistant to electrical tracking and decomposition are difficult or impossible to find for some components

d. The existing regulations and the recommended criteria may be interpreted differently than we had assumed, in areas such as protection from organic plastic insulators and the definition of trailing cable.

Section 6 contains a report on the literature search and state-of-the-art review. Although this was the first phase of the program, it is placed at the back of this report to serve as a reference text or appendix. This review provided background information on specific problems and solutions which are unique to the application of high voltage to permissible enclosures, including the following items:

a. Different methods for safe use of high voltages inby the last open crosscut, including explosion-proof enclosures, potted transformers, and sealed or specially ventilated enclosures

b. Special hazards posed by high voltages, such as volatilization or decomposition of insulating materials and pressure rises due to high energy arcing faults

c. Proposed solutions for the above hazards, including insulator testing, special sensing devices, and special protective devices such as current limiting fuses

d. Existing regulations which contain requirements which are relevant to high-voltage permissible systems, such as United States mining regulations (30 CFR 18 and 30 CFR 75), foreign regulations (British Standards and European standards such as EN 50018) and United States testing standards (ASTM, UL, IEEE, NFPA, etc.).

2. RECOMMENDED APPROVAL AND TESTING CRITERIA FOR HIGH-VOLTAGE PERMISSIBLE LOADCENTERS

2.1 PURPOSE

The purpose of these criteria is to specify the design and testing requirements to be used by MSHA in approving loadcenters, transformers, and switchgear containing high voltage components as permissible for use in gassy mines or tunnels. These criteria are a supplement to the existing requirements of 30 CFR 18, all of which apply unless specifically modified or replaced by parts of these criteria. These provisions are applicable to loadcenters, transformers, switchgear, and related equipment operating at maximum voltages of 15 kV.

2.2 DEFINITIONS

a. Corona (partial discharge) - A type of localized discharge resulting from the ionization of gas in an insulation system when the voltage stress exceeds a critical value. The ionization is localized over only a portion of the distance between the electrodes of the system

b. Corona inception voltage - The lowest voltage at which corona occurs as the applied voltage is gradually increased

c. Corona extinction voltage - The highest voltage at which corona no longer occurs as the applied voltage is gradually decreased from above the corona inception voltage

d. High voltage - High voltage means greater than 1000 V

e. Phase segregation - The isolation of each phase conductor of an electrical circuit by means of a surrounding grounded metallic covering or enclosure.

2.3 QUALITY ASSURANCE

The following quality assurance items apply specifically to high voltage equipment:

a. Requirements for outby circuit protection (overcurrent and short circuit) marked on the equipment

b. Insulation resistance tests (section 2.11).

c. Adequate clearance between exposed conductors (section 2.5)

d. Corona tests (section 2.17)

2.4 LIMITATION OF EXTERNAL SURFACE TEMPERATURES

The temperature of the external surfaces of mechanical or electrical loadcenter components shall not exceed 150° C (302° F) under normal operating conditions.

2.5 ELECTRICAL CLEARANCES

Minimum clearances between exposed electrical conductor surfaces, or between exposed conductor surfaces and grounded metal surfaces, within enclosures shall be as listed in table 1.

Bus bars must be physically braced to prevent movement which would decrease the required clearances.

TABLE 1. - Minimum clearances

Voltage range (rms volts)	Clearance (in.)
8,001 to 15,000	7
5,001 to 8,000	4
2,001 to 5,000	3
1,001 to 2,000	2

2.6 INSULATING MATERIALS USED IN ENCLOSURES CONTAINING HIGH VOLTAGE COMPONENTS

Organic plastics or other insulating materials that give off highly explosive gases when decomposed by heat shall not be used within enclosures containing more than one phase of a high voltage circuit where they might be subjected to destructive electrical arcing, unless one of the following conditions are met:

a. The materials shall be highly resistant to electrical tracking if they have a Comparative Tracking Index (CTI) of not less than 250 as measured by the standard test method described in ASTM Standard No. D3638-77

   Materials will be deemed highly resistant to electrical arcing if they pass the Fuse Wire Arc Test - described in the Electrical Research Association Report No. 5078, 1964 - or an equally effective test recognized by MSHA

b. A detection device shall be provided within the enclosure that will operate to remove the power incoming to the enclosure before decomposition of insulating materials leads to hazardous conditions. The detection device may operate on pressure rise, temperature rise, detection of the products of insulator decomposition, or other effective means. Detection of temperature rise is recommended. If a detection device is provided, the applicant must state how it works, how it will sense and limit insulator decomposition, and the operating range of the device (including temperature and pressure limits).

2.7 EXPLOSION-PROOF ENCLOSURES

a. The requirements of 30 CRF 18.31, 18.32, and 18.33 must be met by all enclosures containing high voltage components. All welds shall be made in accordance with American Welding Society Standard AWS D14.4-77

b. MSHA may impose additional requirements for the use of high-voltage components in sealed enclosures, potted enclosures, or enclosures designed to vent gases rapidly enough to avoid pressure rises above 50 psi.

2.8 ACCESS OPENINGS AND COVERS

Access openings in enclosures containing high-voltage components will be permitted for proper maintenance such as tap changing and circuit breaker adjustment. The provisions of 30 CFR 18.29 must be met.

2.9 LEAD ENTRANCES; CABLE CONNECTORS AND PLUGS

a. The provisions of 30 CFR 18.42 - explosion-proof distribution boxes - shall apply to enclosures containing high-voltage components

b. High-voltage cable connectors and plugs used in areas where permissible equipment is required shall meet the requirements of 30 CFR 18.41 and the test requirements in table 2, using the testing procedures of IEEE 48-1975

TABLE 2. - Standard dielectric tests for high-voltage cable plugs and connectors used in areas where permissible equipment is required

Tests	Insulation voltage class	
	8.7 kV	15 kV
1-min withstand value	27 kV	35 kV
6-h withstand value	15 kV	25 kV
Impulse withstand peak value	75 kV	95 kV
Corona (partial-discharge) extinction value	7 kV	11 kV
15-min dc withstand value	40 kV	50 kV
Test procedure IEEE 48-1975		

c. Tests specified in paragraph (b) shall be performed on each high-voltage connector or plug intended for use on permissible equipment or on approved cables in areas where permissible equipment is required. These tests may be conducted by the mine or the shop after the assembly of each connector or plug. Equipment shall be designed so that plugs and receptacles can be completely assembled and tested before mounting on permissible enclosures. Cable connectors which have been tested for use in permissible areas shall be clearly marked and identified.

2.10 LEADS THROUGH COMMON WALLS BETWEEN EXPLOSION-PROOF ENCLOSURES

Insulated bushings or studs will be acceptable for use in the common wall between two explosion-proof enclosures. When insulated wires or cables extend though a common wall between two explosion-proof enclosures, the techniques described in 30 CFR 18.38 shall be employed to prevent propagation of an explosion from one enclosure to the other. Wires and cables shall be mechanically secured in open areas of enclosures and in passageways between enclosures to prevent excessive movement.

2.11 OPENINGS THROUGH COMMON WALLS BETWEEN EXPLOSION-PROOF ENCLOSURES; COMPONENT PLACEMENT

a. As provided in 30 CFR 18.38 (e), unsealed openings though common walls between explosion-proof enclosures shall be large enough to prevent pressure piling. Partitions subdividing single enclosures shall not be used

b. High voltage electrical components located in explosion-proof enclosures shall not be placed in the same plane as the flange gap

c. Internal components shall be arranged so as not to effectively divide the interior of the enclosure into separate compartments joined by restricted passages. Successful completion of the explosion tests required by section 19 of these criteria shall be indicative of compliance with this requirement.

2.12 VOLTAGE LIMITATION

Equipment with nameplate ratings in excess of 4,160 V, but less than 15,000 V, may be approved as permissible if the applicable requirements of 30 CFR 18 and the additional requirements contained in these criteria are met.

2.13 ELECTRICAL PROTECTIVE DEVICES

a. High-voltage circuits connected to permissible loadcenters shall be protected by circuit breakers equipped with devices to provide protection against undervoltage, grounded phase, short circuit and overcurrent. Ground fault test circuits shall also be provided

b. Overcurrent protection shall be provided in the primary circuit of power transformers. Such protection may be physically located either on the outby end of the portable cable supplying power to the transformer, or on the inby end of the portable cable in a permissible enclosure. In either case, the specifications for the transformer overcurrent protection shall be furnished along with other information required by 30 CFR 18.35

c. Upon detection of ground fault in a circuit supplying power to high-voltage, permissible equipment, the circuit shall be de-energized and remain so until the ground fault is cleared. In no instance shall such a circuit be energized while a phase conductor remains grounded

d. All equipment which breaks current at fault levels shall have an interrupting rating sufficient for the system voltage and the current which is available at the line terminals of the equipment. Equipment intended to break current at other than fault levels shall have an interrupting rating at system voltage sufficient for the current that must be interrupted

e. The circuit protective devices, the total circuit impedance, the component short circuit withstand ratings, and other characteristics of the circuit to be protected shall be so selected and coordinated as to permit the circuit protective devices to clear a fault without the occurrence of extensive damage to the electrical components of the circuit.

2.14A MAXIMUM AVAILABLE SHORT CIRCUIT FAULT CURRENT

The maximum short circuit fault current available at the terminals of high-voltage components located in permissible enclosures shall be 10,000 A or less.

2.14B MINIMUM INTERNAL FREE VOLUME

An enclosure containing more than one phase of a high-voltage circuit shall have a minimum internal free volume of 0.125 m^3.

2.15 INSPECTIONS

Inspections specified in 30 CFR 18.60 and 18.61 shall be required for permissible enclosures containing high-voltage components. Additional inspections which take into account the requirements of Paragraphs 1-14 of these criteria shall also be performed. These include:

a. Examination of items listed on the factory inspection form

b. Examination for the use of proper insulating materials, as defined in paragraph 6

c. Examination for adequacy and proper installation and operation of all electrical and mechanical protective devices.

2.16 TESTS TO DETERMINE EXPLOSION-PROOF CHARACTERISTICS

a. All enclosures containing high-voltage components must pass the explosion tests specified in 30 CFR 18.62

b. When a pressure exceeding 100 psi (gage) is developed in an enclosure containing nonsegregated high-voltage components during the explosion tests required by paragraph (a), MSHA reserves the right to reject the enclosure unless (1) constructional changes are made that result in a reduction of pressure to 100 psi (gage) or less, or (2) the enclosure passes the explosion tests required by paragraph (c).

c. When required by the provision of paragraph (b), enclosures containing more than one phase of a high-voltage circuit must meet the requirements of 30 CFR 18.62 when the methane/air mixture in the enclosure is ignited by a high-voltage, phase-to-phase arcing fault. The fault used in this test shall have the following specifications:

(1) Fault duration - 15 cycles (0.250 s)

(2) Source voltage - rated system voltage

(3) Fault arc length - fault arc length (electrode spacing) shall be equal to the minimum clearances specified in paragraph 5 of these criteria for the appropriate system voltage

(4) Fault current - the power source shall be adjusted prior to the test so as to deliver a current of approximately 10,000 A to a bolted fault.

2.17 CORONA (PARTIAL DISCHARGE) TESTS

a. The manufacturer shall submit to MSHA the results of a Corona Detection Test performed on the insulation system of high-voltage equipment submitted for approval or certification. This test shall be performed in accordance with ASTM Standard D 1868-73 or IEEE Standard 454-1973 or other equivalent test method acceptable to MSHA. The corona extinction voltage measured in this test shall exceed the values listed in table 3 when the corona detecting apparatus is adjusted to a sensitivity of 3.0 picacoulombs.

TABLE 3. - Minimum corona extinction voltages

System voltage (line-neutral rms, kV)	Minimum corona extinction voltage (kV)
2.4	3
3	5
8	10

3. DISCUSSION OF RECOMMENDED CRITERIA

3.1 PURPOSE

Self-explanatory.

3.2 DEFINITIONS

Self-explanatory.

3.3 QUALITY ASSURANCE

Self-explanatory.

3.4 LIMITATION OF EXTERNAL SURFACE TEMPERATURE

No change is recommended to the present requirements of 30 CFR 18.23. Loadcenters must be designed so as to adequately dissipate the heat generated by the transformer without exceeding the surface temperature requirements.

3.5 ELECTRICAL CLEARANCES

The clearances in table 1 are based on experimental work by researchers at the Canadian Explosive Atmospheres Laboratory(1) and the U.S. Bureau of Mines (USBM) (2). These clearances take into account the possible exposure of conducting surfaces to the ionized flame front resulting from a methane/air ignition in the enclosure. The recommended clearances in this document are 50% larger than the minimum experimental clearances reported in the above references.

3.6 INSULATING MATERIALS USED IN ENCLOSURES CONTAINING HIGH-VOLTAGE COMPONENTS

One of the biggest safety concerns in explosion-proof high-voltage equipment is that high electrical stress can break down insulation. Some insulators, particularly organic insulators, can decompose (or volatilize) producing highly flamable gasses such as hydrogen, acetylene, etc. The safest way to protect against this hazard is not to use such insulators. In part (a) we have listed two options for identifying satisfactory insulating material: the CTI Test (3) and the Fuse Wire Arcing Test (4). It should be noted that no single test developed to date provides an absolute measure of satisfactory insulator performance. The CTI Test was chosen because it is a well-known American test.

The British equivalent (5) has been used for some time by the National Coal Board, with a minimum CTI specification of 250. Although the CTI Test is the best-known of the tests available today, we suggest that MSHA may want to consider other tests which may eventually prove more useful, such as the Fuse Wire Arc Test. Thus, section (a) is meant to recommend that one standard test be used -- but this standard may be substituted by another depending upon future experience and research.

Part (b) provides the manufacturer with another option if it proves impossible to utilize only materials which are approved under part (a). This option is to provide means of detecting the low-energy arcing faults which lead to decomposition of organic insulators. Research (6-10) has indicated that this condition is associated with a substantial temperature rise, and we feel that sensing temperature rise is the most practical, protective measure. Temperature measurements in controlled experiments typically ranged from 500° to 1200° C. Thus, it is possible to use a temperature switch which is set to trip at temperatures well below 500° C but well above normal operating temperatures of the air inside the enclosure. Our tests on a 1250 kV.A permissible transformer operating at simulated full load conditions established a 110° C setting which provided an ample margin to avoid nuisance trips.

It should be noted that pressure sensors could prove unreliable because of the high temperatures created during arcing.

3.7 EXPLOSION-PROOF ENCLOSURES

Sealed enclosures, potted enclosures, or highly-vented enclosures (designed to keep pressure rises low) are all unique solutions to explosion-proof requirements. While they have never been used in the mining industry, we do not want to preclude their further development or use. However, each of these approaches will have unique problems, which may have to be considered on a case-by-case basis and are outside the scope of this program.

3.8 ACCESS OPENINGS AND COVERS

Self-explanatory.

3.9 LEAD ENTRANCES; CABLE CONNECTORS AND PLUGS

The recommendations contained in table 2 are based on the work performed under USBM Contract HO377043(11), which concluded that a high voltage plug or connector presented special problems that were not evident at lower voltages. The biggest problem was that an improperly assembled plug or connector can have high electrical stress even though it may look all right and initially perform properly. This high stress can lead to eventual catastrophic failure of the plug. The best way to prevent these problems is for the assembler of the plug or connector to perform the recommended dielectric test on each unit immediately after assembly.

3.10 LEADS THROUGH COMMON WALLS BETWEEN EXPLOSION-PROOF EXPLOSURES

Self-explanatory.

3.11 OPENINGS ThOUGH COMMON WALLS BETWEEN EXPLOSION-PROOF ENCLOSURES; COMPONENT PLACEMENT

Pressure piling is a complex phenomenon that can occur when gas in a portion of an explosion-proof enclosure is compressed before being ignited. The resulting pressure rise may be much greater than would normally be expected from a methane/air ignition. Subdividing enclosures into compartments connected by narrow passages, either intentionally or by careless component placement, can result in pressure piling and must be avoided.

It is not always possible to predict exactly when, or to what degree, pressure piling may occur. However, its presence can be detected in the explosion tests specified in 30 CFR 18.62. Pursuant to this section, when a pressure exceeding 125 psi (gage) is developed during explosion tests (which would indicate that pressure piling has occurred), MSHA will reject the enclosure unless constructional changes are made. These changes should result in a reduction of pressure to 125 psi or less, or else the enclosure must withstand a dynamic pressure of twice the highest value recorded in the initial test. Experience has shown that this approach provides an adequate level of protection against the hazards of pressure piling in enclosures containing low voltage components and circuits.

3.12 VOLTAGE LIMITATION

The following changes to 30 CFR 18.47 are recommended:

a. In 30 CFR 18.47(d), delete the words "but not exceeding 4160V"

b. 30 CFR 18.47(d)(3) should be changed to read: "All high-voltage switchgear and controls for equipment having a nameplate rating exceeding 1000V are approved (permissible) for use in gassy mines or tunnels, or are certified as suitable for incorporation in a machine to be submitted for approval, or are located remotely and operated by remote control at the main equipment. Potential for remote control shall not exceed 120V"

c. 30 CFR 18.47(d)(5) should be changed to read: "Portable (trailing) cable for equipment with nameplate ratings greater than 1OOOV shall include grounding conductors, a ground check conductor, and grounded metallic shields around each power conductor and shall be adequately constructed and insulated for the applied voltage."

It seems likely that MSHA could adopt the recommendations contained in these criteria, using their authority to modify the design, construction, and test requirements of Part 18 in recognition of unforeseen equipment designs (30 CFR 18.20 (b)), without making the above recommended changes to 30 CFR 18.47. However, it seems clear that §18.47(d) does not contemplate approval or certification of equipment or components having voltage ratings in excess of 4160 V. Accordingly, we recommend that the above changes to §18.47(d) be incorporated in the next general revision.

30 CRF 18.47(d)(6) reserves the right for MSHA to require "additional safeguards" for high-voltage equipment. These criteria represent those additional safeguards for high-voltage loadcenters (up to 15 kV and 2000 kV.A). Similar criteria should be developed, as needed, for other types of high-voltage, permissible equipment (for example, motors and motor starters).

3-13 ELECTRICAL PROTECTIVE DEVICES

Self-explanatory.

3.14a MAXIMUM AVAILABLE SHORT CIRCUIT FAULT CURRENT

The maximum available short circuit fault current was set at 10,000 A because that is the highest current level at which tests were conducted during the high-energy arcing fault test program.

3.14b MINIMUM INTERNAL FREE VOLUME

The smallest volumes tested during the high-energy-arcing fault test program were 0.125 m^3.

3.15 INSPECTIONS

Self-explanatory.

3.16 TESTS TO DETERMINE EXPLOSION-PROOF CHARACTERISTICS

Placement of high-voltage components and circuits in explosion-proof enclosures creates the possibility that ignition of methane/air mixtures in such enclosures will be caused by high-energy arcing faults. Tests performed in the course of this program revealed that such ignitions can result in substantially higher pressure rises than would be expected from methane/air mixtures ignited by low energy sources. For this reason, it is recommended that MSHA adopt the requirements set forth in paragraph 19 (b) of these criteria for enclosures containing more than one phase of a high-voltage circuit. These requirements would reduce the maximum allowable pressure in the initial (low energy ignition) explosion test from 125 psi. Development of pressures in excess of 100 psi would require constructional changes that result in a reduction of pressure to 100 psi or less, or additional tests verifying that ignition of the gas mixture with a high energy source does not result in pressures exceeding 125 psi.

3.17 CORONA (PARTIAL DISCHARGE) TESTS

One danger of high-voltage equipment is that higher electrical stresses can cause premature breakdown of insulating materials. We therefore recommended a standard test which is designed to detect the presence of excessive electrical stress in a high-voltage enclosure. Table 3 is based on the research done under USBM Contract No. H0377043 (11).

4. HIGH-ENERGY ARC TESTING PROGRAM

4.1 SUMMARY

Part 18 requires that all explosion-proof enclosures must be subjected to an internal methane-air explosion. However, it was known that high-power electrical arcs, such as might occur in a permissible loadcenter, can sometimes produce additional pressures equivalent to those generated by methane-air explosions. Therefore, any approval criteria for high voltage loadcenters would have to recognize the possibility of pressures caused by arcing faults. A test program was therefore undertaken to measure the effects of high energy arcing faults inside sealed enclosures, both with and without the presence of explosive concentrations of methane.

Tests were made in which high voltage arcs were produced inside a closed pressure vessel (test enclosure) containing either air or a combustible methane-air mixture initially at atmospheric pressure. The test volume was adjusted from 1.05 to 0.123 m^3 by means of displacer blocks. Because copper is the likely material to be involved in a fault, parallel copper electrodes were used and the spacing between them, 6 in., approximated the spacing recommended for high voltage conductors in permissible enclosures. The source voltage for all tests was 15,000 V, single-phase, 60 cycles, and the arc was initiated by a fuse wire. The fault currents were 2,500, 5,000, and 10,000 A applied for 10 or 15 cycles. The magnitude and duration of these fault currents are commensurate with the maximum fault currents expected in the actual permissible loadcenters.

The highest pressure for a combined high energy arc and a methane-air explosion was 138 psi. The highest pressure for an arc alone was 96 psi and for a methane-air explosion alone (ignited by a hot wire) was 68 psi. The test enclosure results are considered conservative because, in general, a permissible loadcenter will have a larger internal surface area to volume ratio than the test chamber, resulting in increased energy losses to the enclosure and components. The reduced amount of energy available to heat the air will result in lower pressures. This was demonstrated by replacing some of the displacer blocks with loosely stacked bricks to provide increased internal surface area. Lower pressures were observed when this was done.

The following sections describe the test program in more detail, organized as follows:

Test Design (section 4.2)
Test Results and Conclusions (section 4.3)
Recommendations for Future Work (section 4.4)

4.2 TEST DESIGN

This section describes the major features of the test program, organized as follows:

a. Source voltage

b. Test current

c. Selection of single phase arc

d. Fault duration

e. Arc length

f. Arc initiation

g. Test enclosure

h. Test implementation.

4.2.1 Source Voltage

Results of previous 60 Hz high energy arc tests at large electrode separations indicated that source voltage is not of prime importance in determining the voltage drop across the sustained arc. That is, once an arc has been initiated and has continued for a few cycles, the arc length, the current, the ionizing materials present and other factors are more important than source voltage. However, the source voltage must be sufficient to sustain the arc and overcome other circuit losses at high current levels. Tests powered from a lower voltage level source would have produced fully representative arcs. Nonetheless, to erase any doubt as to the validity of the test results, the test voltage was set at 15,000 V (the maximum covered by the recommended criteria) for all tests, and the facilities of the Westinghouse High Power Laboratory were used to ensure that adequate current would be available at this voltage.

4.2.2 Test Current

The maximum current available to a short-circuit arcing fault will depend upon the characteristics of the power system and the location of the fault. The maximum test current used should exceed the maximum current expected to result from an actual fault in a mine power system. An estimate of this maximum current is made below.

The energy released by an arcing fault depends on its magnitude and duration. Because the arc has a finite resistance, the fault current will be less than the current possible in a "bolted" (zero resistance) short circuit. Thus, it would be conservative to test with a current equal to the maximum current which would result from a bolted fault at the input terminals of the loadcenter. A study, reported in reference (12), established that 4,160 V would probably be the minimum input voltage which would be considered for a 2,000 kV.A permissible loadcenter (PLC). The limitation is the current carrying capacity of the largest size cable normally used in mine distribution systems.

To calculate the maximum current to a 4,160 V, 2,000 kV.A PLC, the substation was assumed, as is usually the case, to be dedicated exclusively to the PLC and to have a capacity of 2,000 kV.A. Then, assuming that the substation transformer is connected to an infinite bus at the point of supply from the electric utility, and that its impedance is five percent of the impedance that would yield rated load current, and neglecting cable impedance, a maximum current of 5560A rms (7855A peak) is calculated. Thus, the maximum test current was set at 10,000 A rms with additional tests at 2,500 A and 5,000 A to provide further data concerning the relationship between arc energy, enclosure volume, and internal pressure rise.

4.2.3 Fault Duration

The worst case fault duration would not normally occur at the maximum current because the circuit protection mechanisms would operate most rapidly at this level. Instead, the worst case duration, assuming no protective device failure, would occur at currents sufficient to inject high energy into the ionized path, but small enough to exist for several cycles before actuating the inverse time delay relay.

High voltage circuit breakers are available which typically will clear a faulted circuit in one to eight cycles. Accordingly, fault times of 10 and 15 cycles (0.17 and 0.25 s) were used in the tests. These time periods provide a safety factor over the maximum time expected for detection and clearance under actual operating conditions when the protective equipment at the substation is in good working order.

4.2.4 Selection of Single Phase Arc

A single phase fault is the type most likely to occur in permissible high-voltage enclosures. Constructional requirements should all but preclude the possibility of an instantaneous three-phase fault. Accordingly, it was decided to perform the tests with single-phase arcs. These arcs are easier to control than a thee-phase arc; and measurement of arc voltage, current and energy dissipation is greatly simplified.

4.2.5 Arc Length (Electrode Separation)

A 6-in. parallel electrode spacing was used which is representative of the recommended separation between exposed conductors at the 15,000 V level. It is conservatively based on the spacing required to prevent arcing when the electrodes are bridged by ionized gas resulting from a methane-air explosion (2).

4.2.6 Arc Initiation

Since a very high voltage would be required to initiate an arc between electrodes spaced at 6 in. in air, a copper fuse wire was used to initiate the arc in all tests. Vaporization of this wire provided a low resistance ionized metal path between the electrodes. The use of a copper fuse wire is realistic because copper is the material most likely to act as an electrode, and hence as a source of ions, in any real fault.

4.2.7 Test Enclosure

Existing experimental data and theoretical calculations suggested that arcs in the voltage and current ranges of interest to this program would not produce excessive pressure rises in enclosures with a free volume of at least 1 m^3. These data and calculations were not conclusive, and a major goal of this test program was to verify, or revise, this conclusion. Accordingly, the maximum volume of the test enclosure was chosen to be 1 m^3. Smaller volumes were obtained by partially filling the enclosure with specially-shaped concrete blocks.

A drawing of the test enclosure is shown in figure 1. The enclosure was fabricated from standard 30-in. diam pipe, designed and built according to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, 150-lb class. The final assembly had a maximum working pressure of 275 psi and was static-tested at 420 psi. The bottom cover was a standard 30-in. bolted blind flange. The top cover was a special quick-release design, described in the next paragraph. All of the joints in the enclosure were designed to be airtight. Although leakage is expected through the flange gap of normal explosion-proof enclosures, it was felt that for this test program a sealed enclosure would provide the most conservative case for the measurement of peak pressures. This involved the development of two special-design features: a quick-release cover and airtight cable feed-throughs.

The quick-release cover is shown in figure 2. The cover assembly was a modification of a standard industrial quick-opening pipe closure. It consists of a removable domed flange and a mating flange welded to the pipe section, with an O-ring seal. The two flanges are clamped together with a split yoke, driven by lead screws which are driven by a single hand crank. Using this system permitted removing the cover in less than a minute, compared to 30 min or more for the removal of a standard bolted flange of the same size.

The electrical cable feed-throughs are shown in figure 3. Several types of commercially available explosion-proof glands and stuffing boxes were laboratory tested; it was found that although they prevented flame propagation, they did permit air leakage. A special-purpose feed-through was therefore developed, as shown in figure 4. The electrical cable was potted inside a 1-1/2-in. pipe nipple, using a two-part flexible adhesive sealant. This assembly is then theaded into a 1-1/2-in. pipe coupling in the enclosure cover. This system was hydrostatically tested to 400 psi and found to be leak-free.

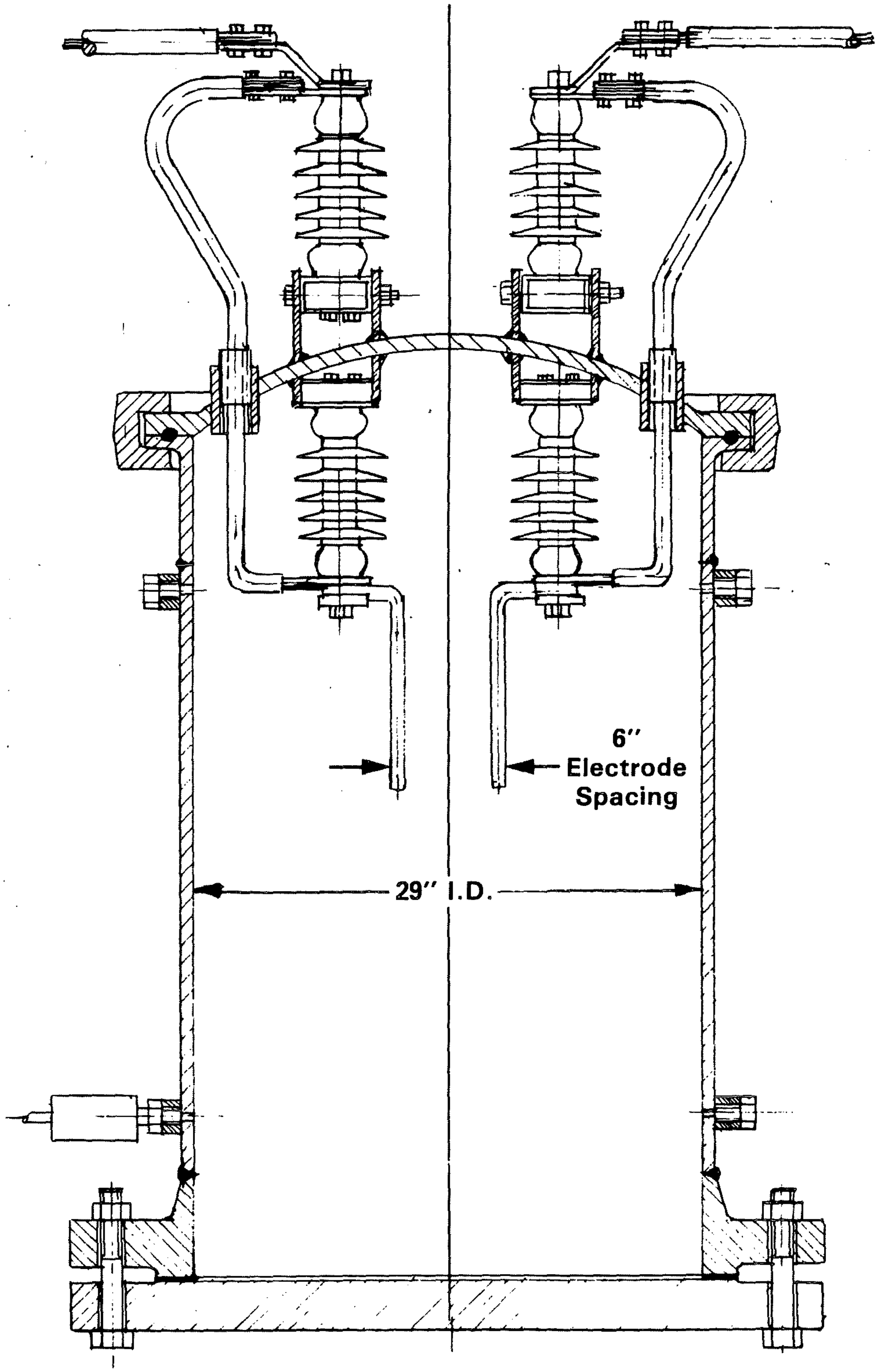


FIGURE 1. - Test enclosure.

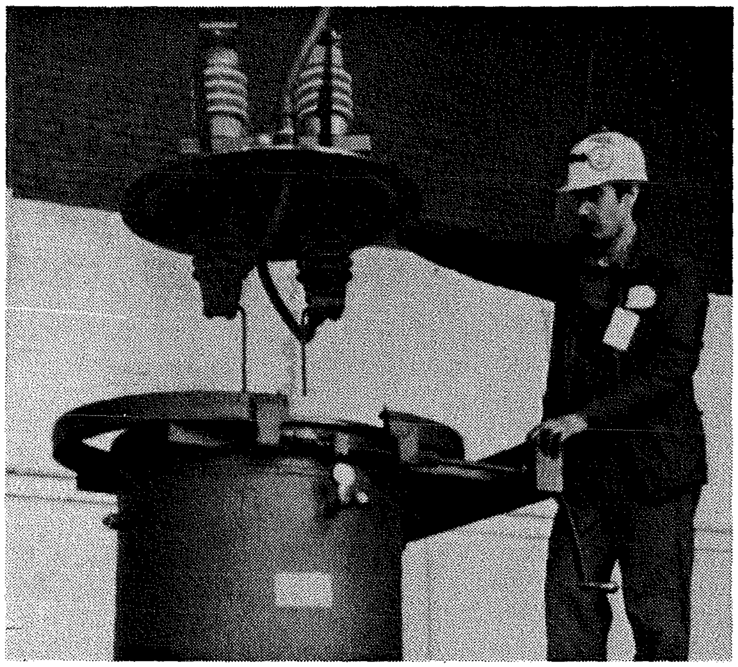


FIGURE 2. - Quick-release cover.

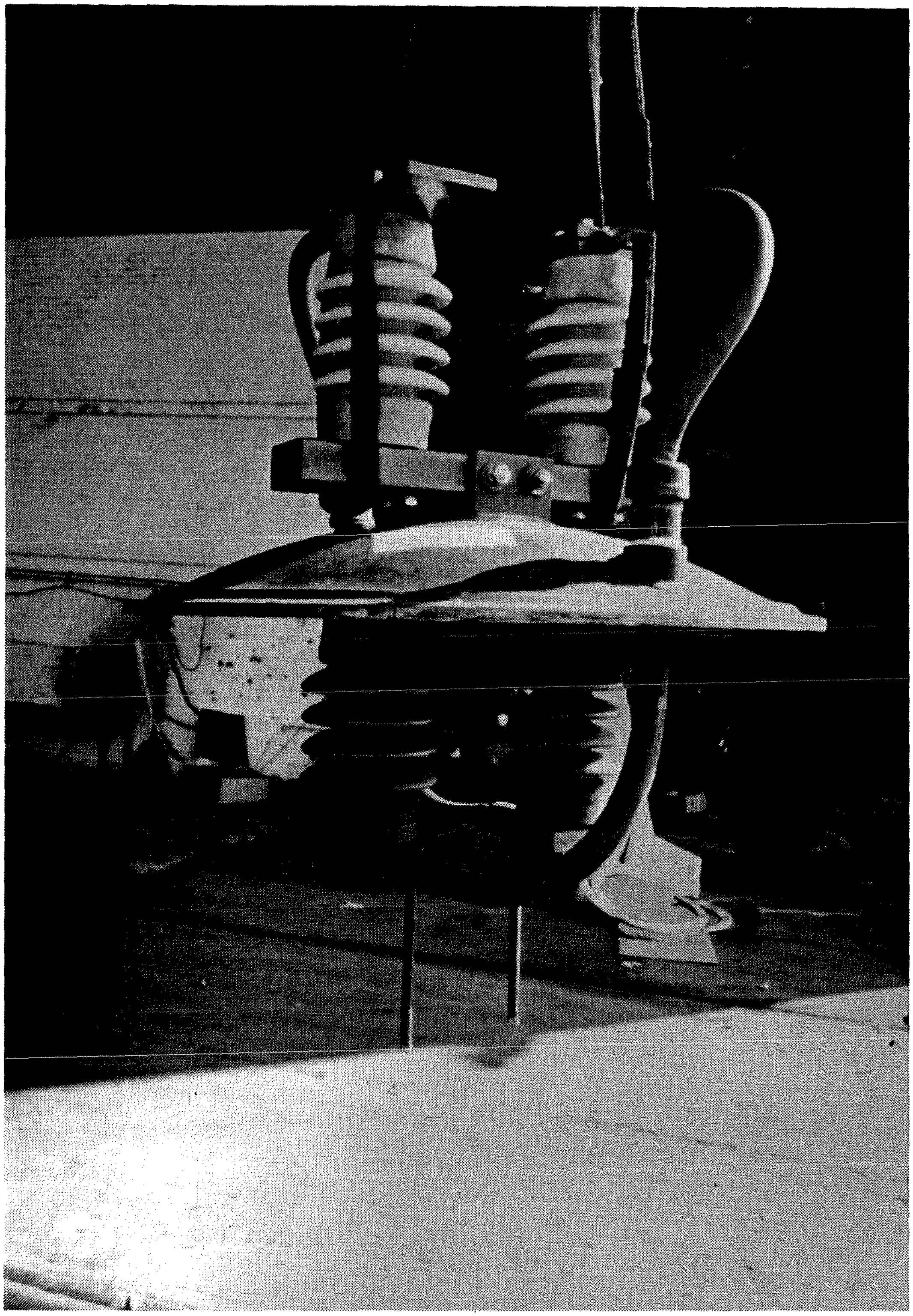


FIGURE 3. - Enclosure cover, showing electrical feed-throughs.

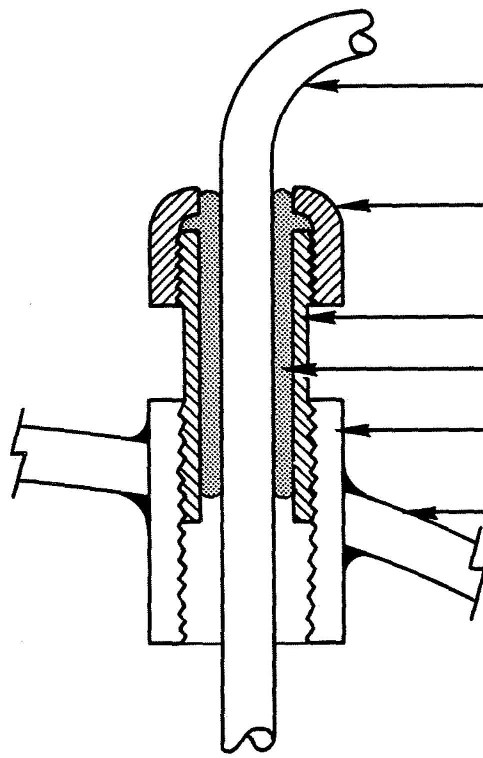


FIGURE 4. - Sketch of cable feed-through.

Current to the electrodes was led into the enclosures by way of two short lengths of insulated cable which entered the enclosure through the previously described seals. The parallel 1/2 in. diam copper rod electrodes were isolated from the enclosure walls by two ceramic insulators mounted on the inside of the cover. Outside of the chamber, the cables were supported by two ceramic insulators, also mounted on the cover.

The enclosure shown in figure 1 provided an internal free volume of 0.53 m^3. Figure 5 shows how other volumes were achieved by bolting on a second section of pipe and/or by adding specially-shaped concrete blocks to decrease the internal free volume. Figure 6 shows the test enclosure with the cover removed, and figure 7 shows the double-size maximum volume enclosure of 1.05 m^3. Figure 8 shows the cast concrete blocks used to reduce the volume. The minimum volume of 0.125 m^3 was achieved by stacking bricks on top of the concrete block in such a way that the electrodes and insulators would still fit down into the enclosure, as shown in figure 9.

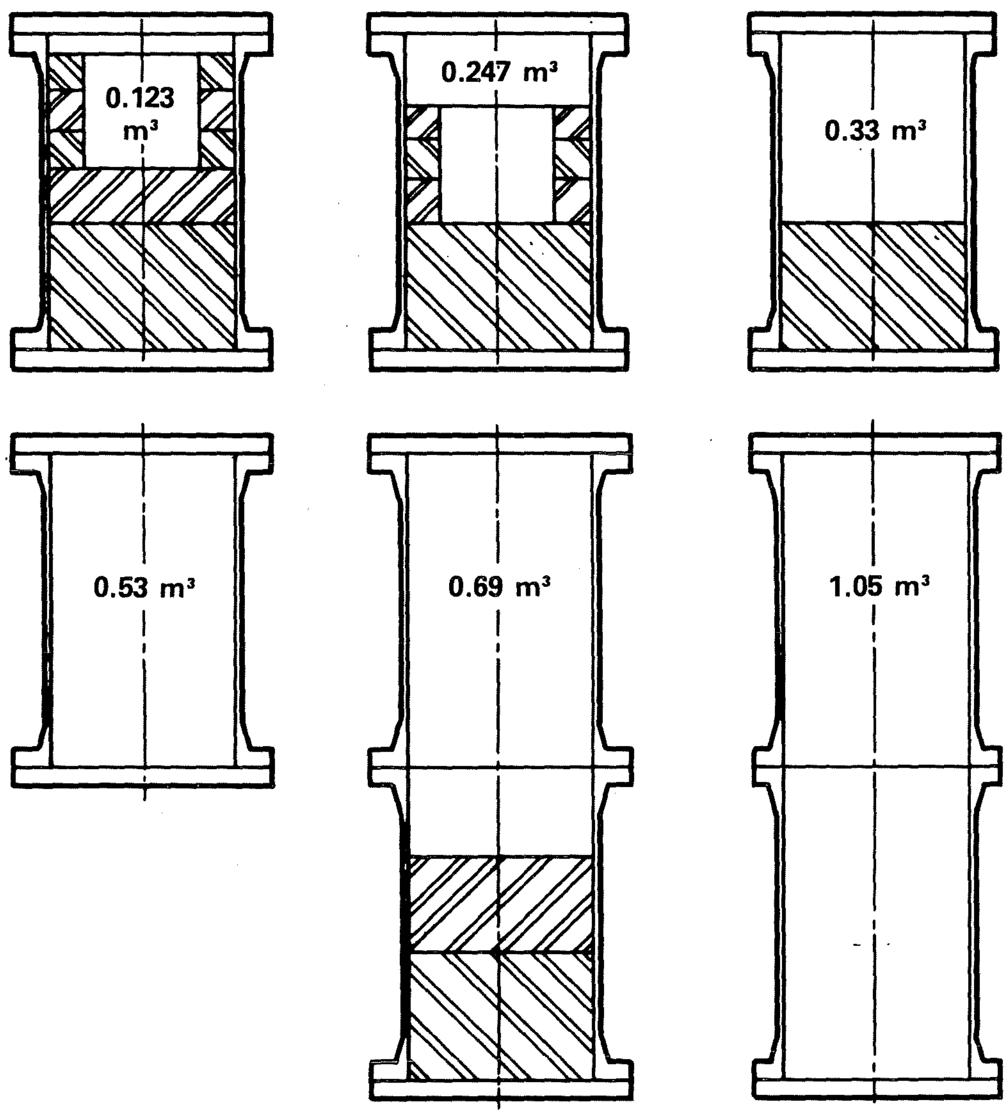


FIGURE 5. - Variable test volumes.

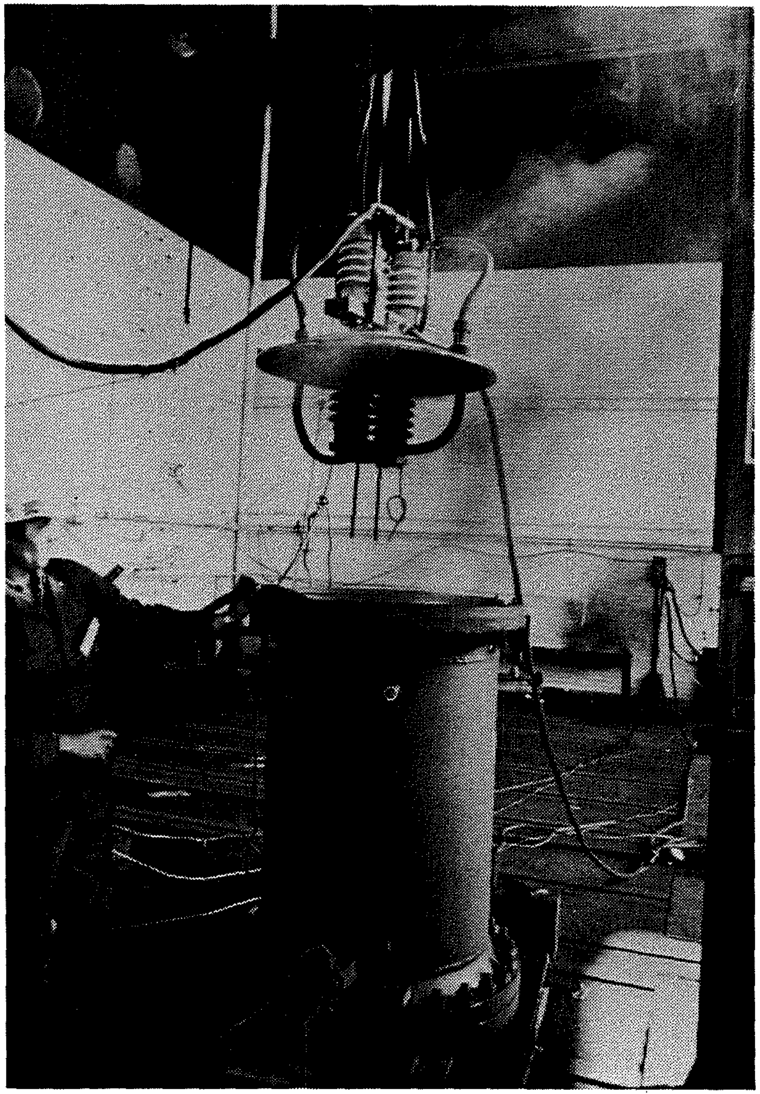


FIGURE 6. - Enclosure with cover removed.

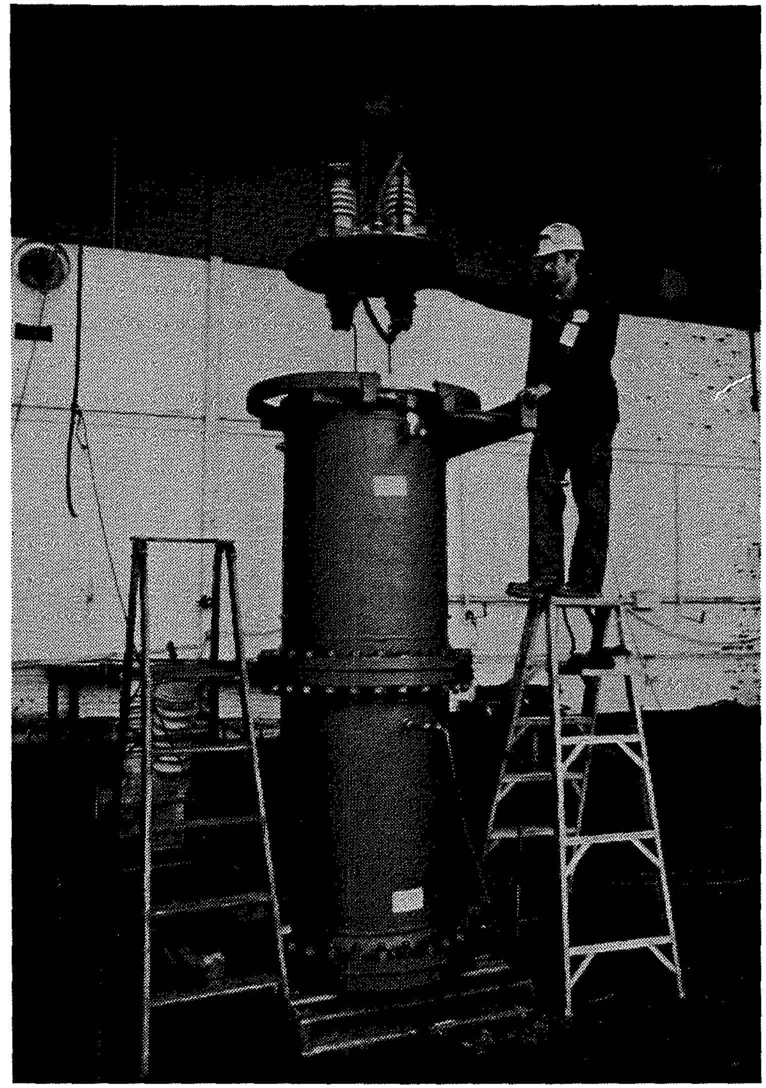


FIGURE 7. - Double-size enclosure.

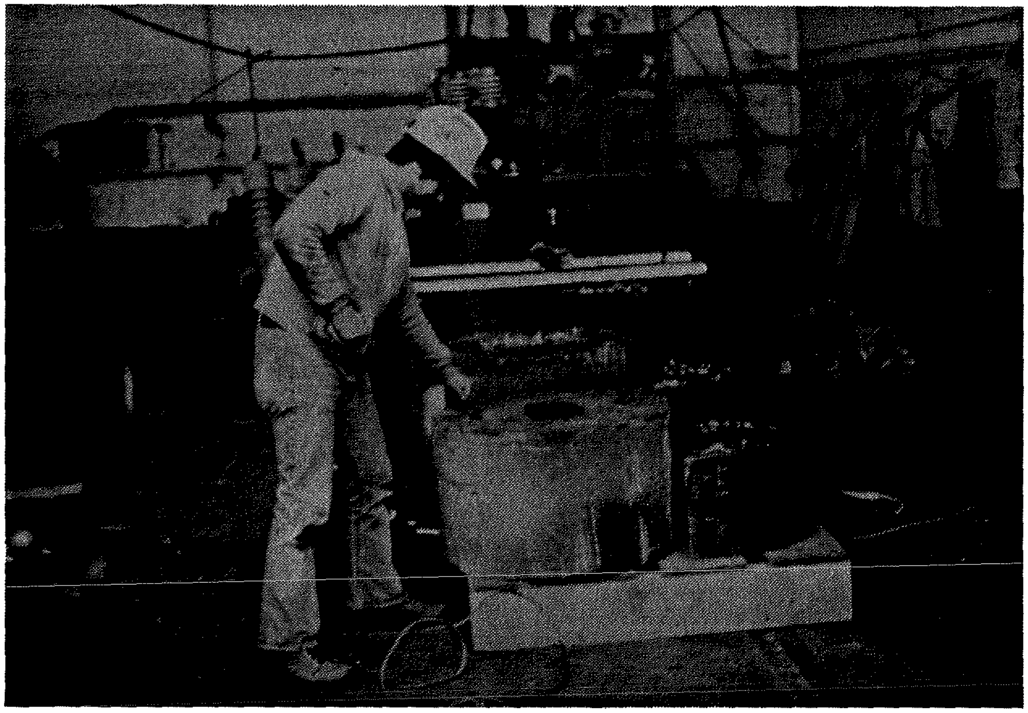


FIGURE 8. - Cast concrete blocks for internal volume reduction.

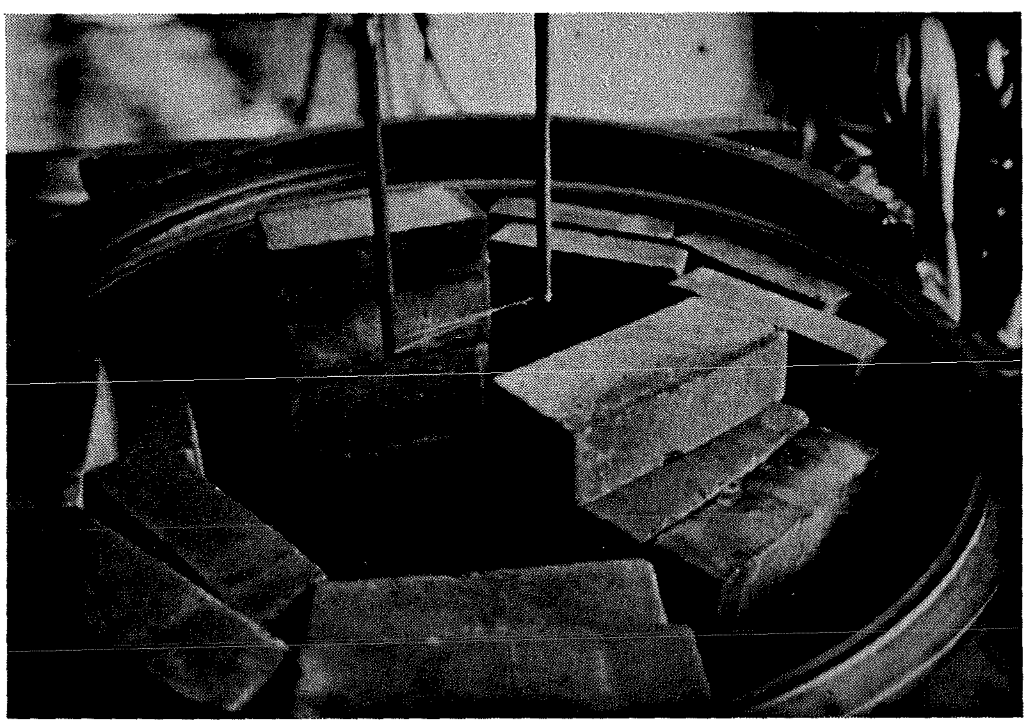


FIGURE 9. - Minimum internal free volume.

4.2.8 Test Implementation

The tests were conducted at the Westinghouse High Power Laboratory at East Pittsburgh, PA. The test enclosure was installed in an outdoor test bay where testing could be observed from the building which housed the control and data logging facilities. Westinghouse facilities included instrumentation for monitoring the arc current and voltage, pressure transducers and recording equipment, and a 15,000 V power source capable of sustaining faults of the desired magnitude and duration.

One series of tests required a very short duration low energy arc (to measure methane-air ignition pressures with minimal contribution of electrical energy). For these tests, special high voltage contactors, supplied by Westinghouse, had to be used, so that power to the enclosure could be cut off after 2-1/2 cycles. This contactor assembly is shown in the background of figure 10.

The photo recorder facilities of the Westinghouse High Power Laboratory were used to provide two traces of enclosure pressure from two different transducers, one trace of arc voltage and one trace of arc current. Arc voltage and arc current traces were stored in computer memory which also provided output traces with scale factor indicated. The computer calculated peak and rms volts, rms amperes, total energy input in joules, and average kV.A. Examples of these traces and computer outputs are reproduced later in this report.

A special-design mobile control station was used to inject methane into the enclosure and measure the concentration. This equipment was developed and operated by MSHA personnel. The trailer-mounted control station, shown in figure 11, was parked in a bay next to the test cell, and 100% methane was piped into the test enclosure. The methane concentration in a return line was monitored in the trailer, until the desired concentration was reached - at which time the methane was shut off by solenoid valves such as those shown in figure 12. Methane concentrations and ignition pressures were monitored inside the trailer, using some of the instrumentation shown in figures 13 and 14.

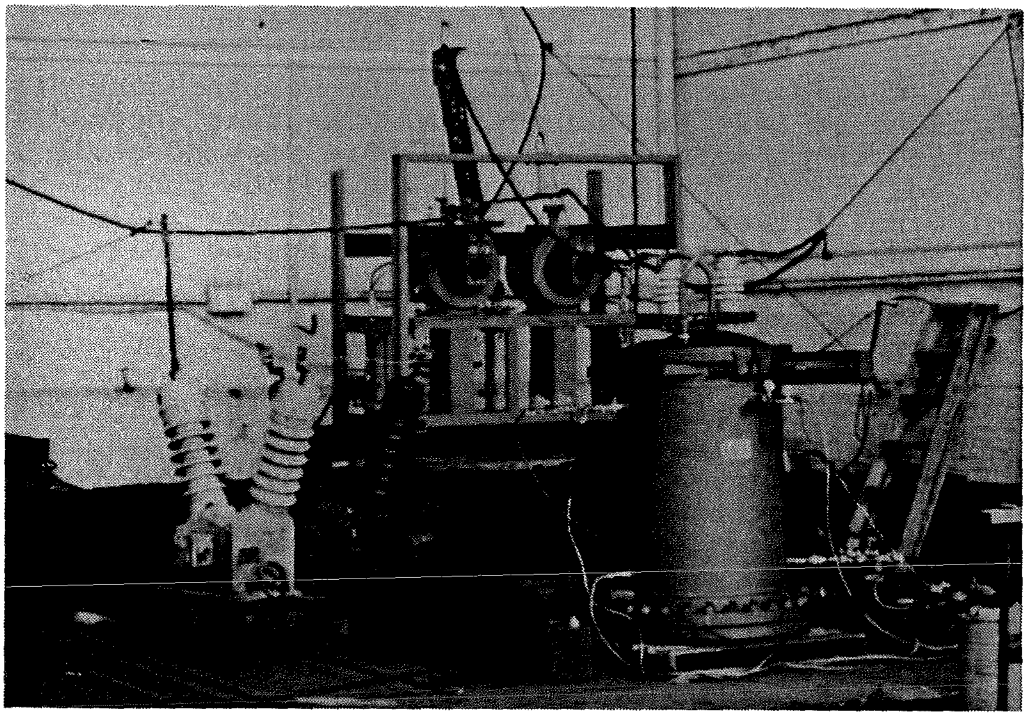


FIGURE 10. - Contactor assembly used for short-duration arc tests.

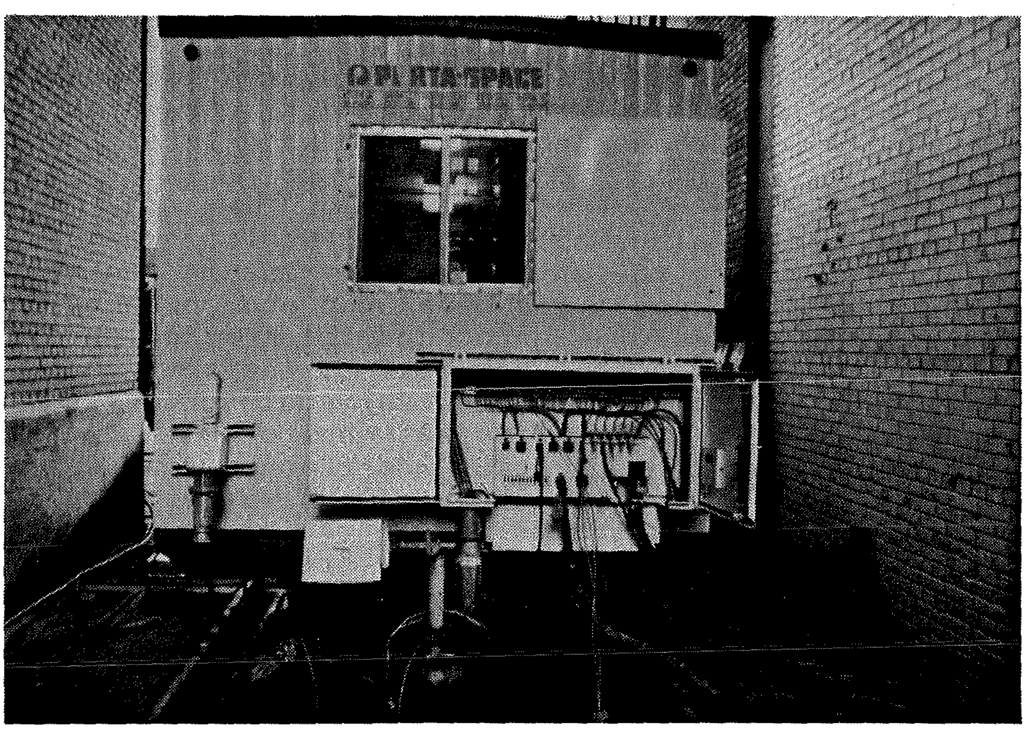


FIGURE 11. - MSHA mobile control station for methane tests.

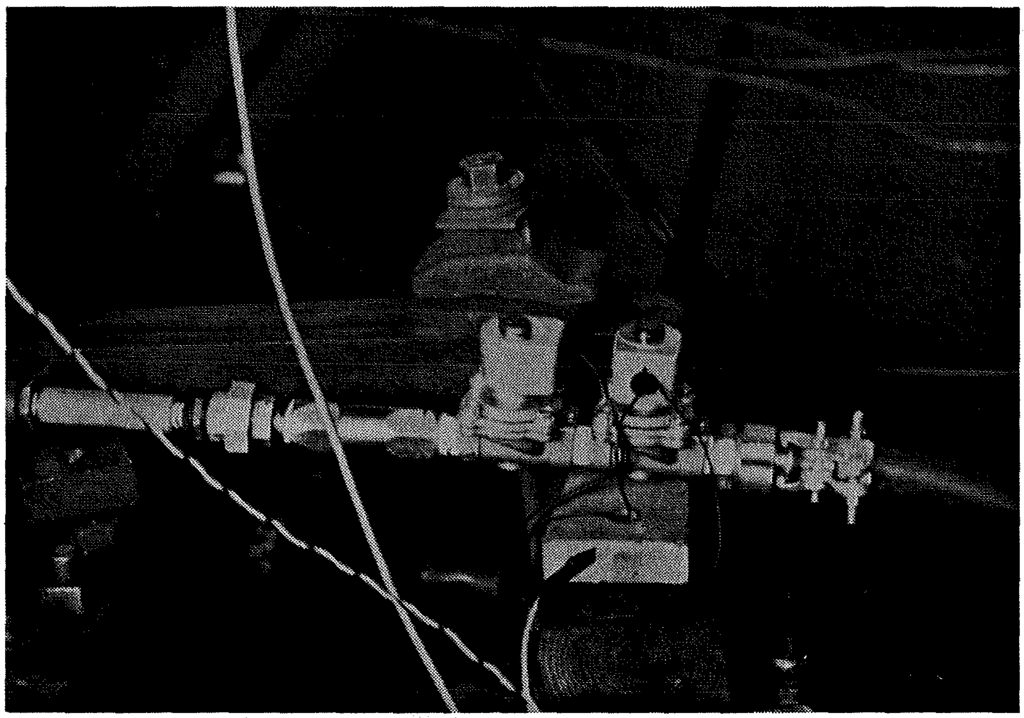


FIGURE 12. - Solenoid valves to control methane flow.

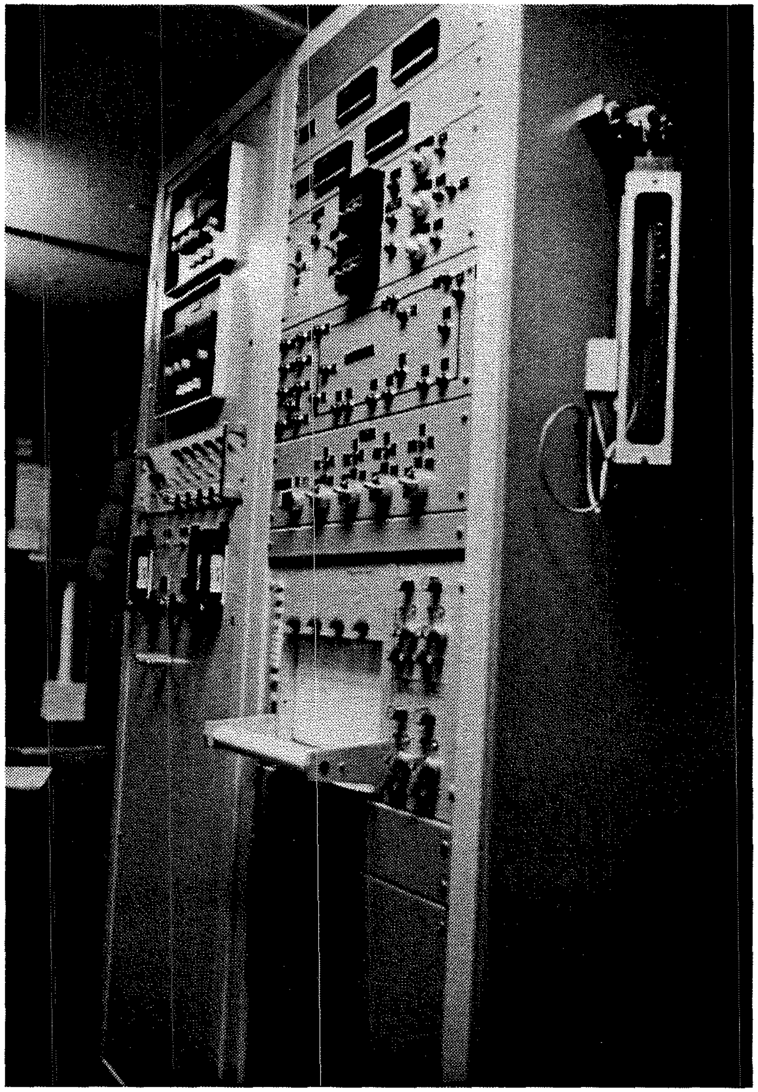


FIGURE 13. - Instrumentation in MSHA trailer, left side.

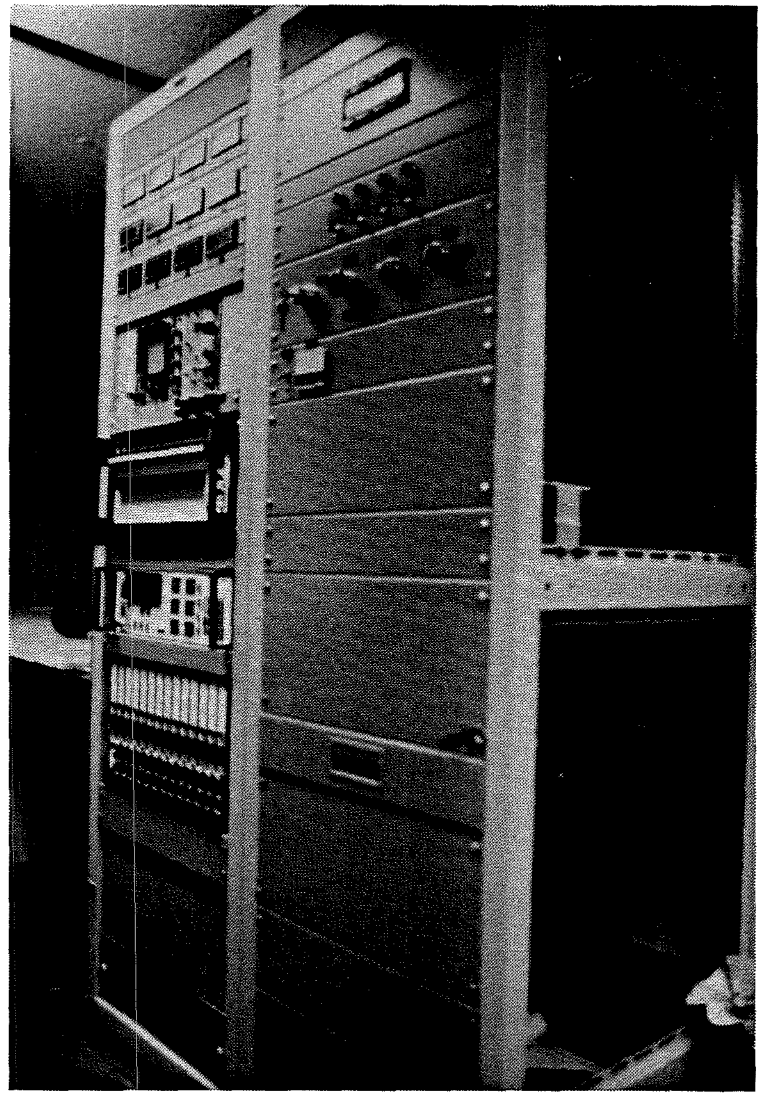


FIGURE 14. - Instrumentation in MSHA trailer, right side.

For the most part, all of the equipment worked as planned, with the following exceptions:

a. On 2 of the 76 tests, a puff of smoke was seen escaping from the enclosure, between the cover and the upper flange. This was attributed to inadequate tightening of the quick-release cover. When those two tests were repeated, it was found that the peak pressure obtained did not change

b. On the sixth and final day of testing, the ceramic insulators inside the enclosure cracked. They were replaced with spare units on hand

c. Some difficulties were experienced with the methane plumbing and solenoid valves. New solenoid valves were purchased and check valves were added to protect the low pressure solenoid valves. It is recommended that air-operated high pressure ball valves be used in the future

d. Long after these tests were concluded, it was discovered that there was a calibration error in the methane sampling system. Because of this, it appears that all of the methane/air ignitions were performed with an estimated 6% methane concentration, rather than the desired 9% range.

4.3 TEST RESULTS AND CONCLUSIONS

Table 4 lists the number of tests performed, with and without methane-air mixtures, for each value of current, fault duration, and enclosure volume, and the resulting peak, or maximum pressure.

The results from two of the 76 tests performed are shown in figures 15 and 16. Arc voltage, arc current, and pressure data from two transducers were recorded for each test.

In the arc-in-air tests, pressure rises at a relatively constant rate from the beginning to the end of the arc. When the current ceases, pressure immediately begins to decline. In the arc-in-methane-air tests, pressure begins to rise in the same fashion, but, after a few cycles, rapidly increases to peak pressure. This rapid pressure rise is thought to result from nearly simultaneous ignition of the methane throughout the enclosure by energy supplied by the arc.

TABLE 4. - Test plan as executed

Test current/ duration (kA)/(cycles)	Enclosure volume (m^3)	Maximum pressure (psi)	
		Arc-in-6% methane-air	Arc-in-air
2.5/10	0.247		11
2.5/10	0.333		20
2.5/10	0.530		20(2)
2.5/10	0.691		16
2.5/10	1.051		11
2.5/15	0.123		18
2.5/15	0.247	54	16
2.5/15	0.333	70	36
2.5/15	0.447		33
2.5/15	0.530	101(3)	27
2.5/15	0.691	93	23
2.5/15	1.051	93	15(2)
5/10	0.333		42
5/10	0.530	114	45
5/10	0.530(1)		35
5/10	0.691		33
5/10	1.051		22
5/15	0.247	58	23
5/15	0.330	112	49(3)
5/15	0.530	119(3)	55(5)
5/15	0.530(1)		43
5/15	0.691		35
5/15	1.051	106	26
10/10	0.247		41(2)
10/10	0.333		66(2)
10/10	0.530	134	64
10/10	0.530(1)		55
10/10	0.691		55(2)
10/10	1.051		28
10/15	0.123		49
10/15	0.247	84	54
10/15	0.330	119	85
10/15	0.447		70
10/15	0.530	132	88(3)
10/15	0.530(1)		62
10/15	0.691	126	78(2)

TABLE 4. - Test plan as executed - Continued

Test current/ duration (kA)/(cycles)	Enclosure volume (m^3)	Maximum pressure (psi)	
		Arc-in-6% methane-air	Arc-in-air
10/15	1.051	112	34
0.5/2.5	0.247	50(2)	
0.5/2.5	0.530	65(2)	
0.5/2.5	1.051	64	

Notes: (1) Increased internal surface area, see text
(2) Average pressure in 2 tests with same conditions
(3) Average pressure in 3 tests with same conditions
(5) Average pressure in 5 tests with same conditions

For the test in figure 16, peak pressure was reached after approximately 7 cycles, following which the curve flattens and the pressure remains constant for the duration of the fault. This behavior was observed in all arc-in-methane-air tests in which the pressure exceeded 80 psi. This suggests that a state of equilibrium was achieved in which the electrical energy dissipated by the arc was equaled by the thermal energy losses to the enclosure. This phenomenon is further discussed in the next section.

Figures 15 and 16 also illustrate the dramatic increase in arc voltage observed during arc-in-methane-air test. The voltages of arc-in-methane-air were typically 75% to 90% higher than the voltages of arcs in air-only. A possible explanation for this occurrence has to do with the relatively large amounts of moisture generated by the methane-air reaction. This moisture will exist as steam in the enclosure due to the high temperatures produced. It is known that the presence of steam will cause arc voltages to increase (13). Hydrogen (H_2), if present, will also cause an increase in arc voltage. The presence of Methane (CH_4) in the ionizing arc path may have led to the production of some free hydrogen, causing a rise in arc voltage. Finally, it is known that arc voltage is a function of pressure (13). The higher pressures observed in the arc-in-methane-air tests may, themselves, have contributed to the arc voltage increases.

The increases in arc voltages observed resulted in increases in electrical energy dissipated by the fault. An increase in arc resistance will cause a corresponding decrease

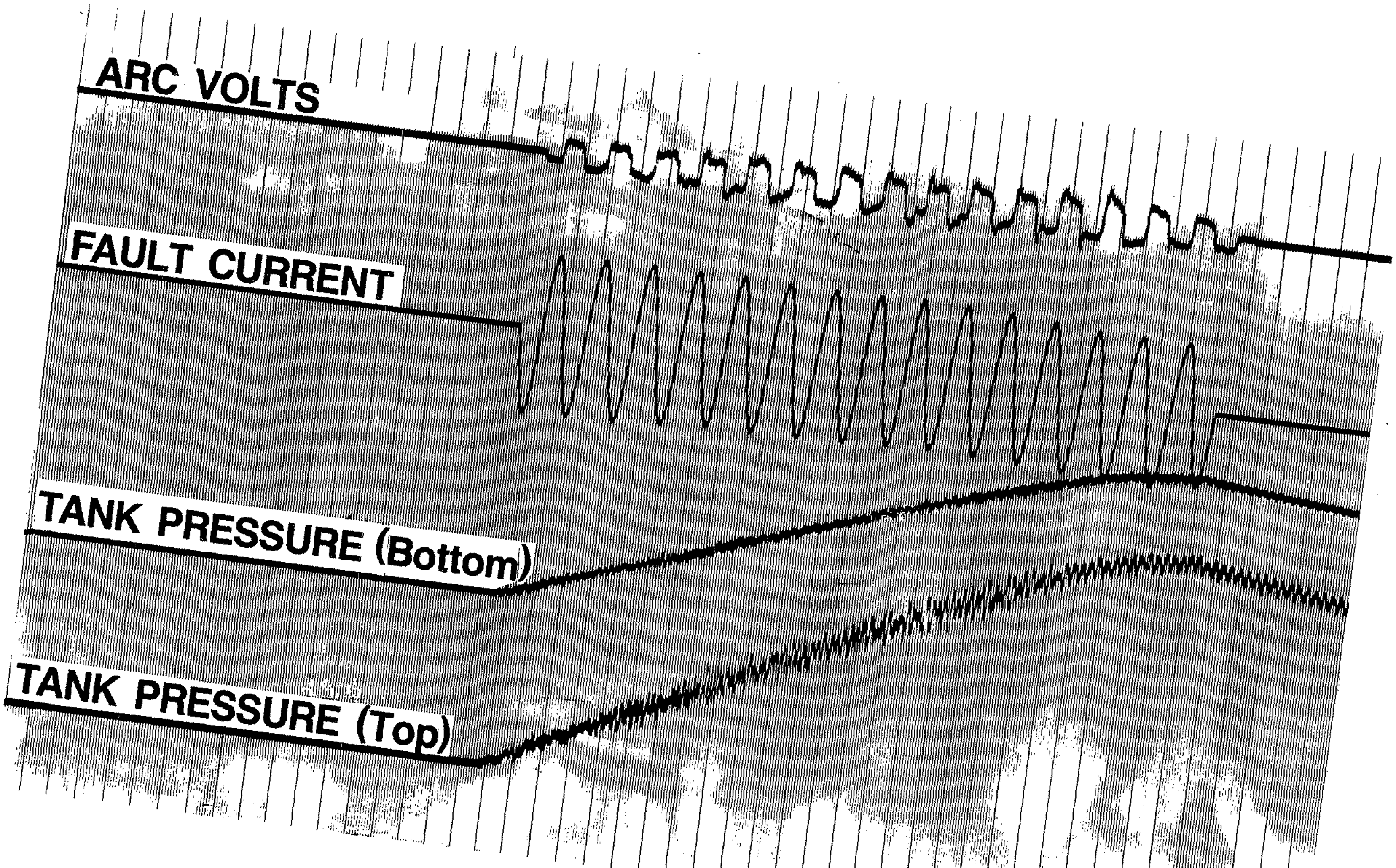


FIGURE 15. - Arcing fault without CH_4.

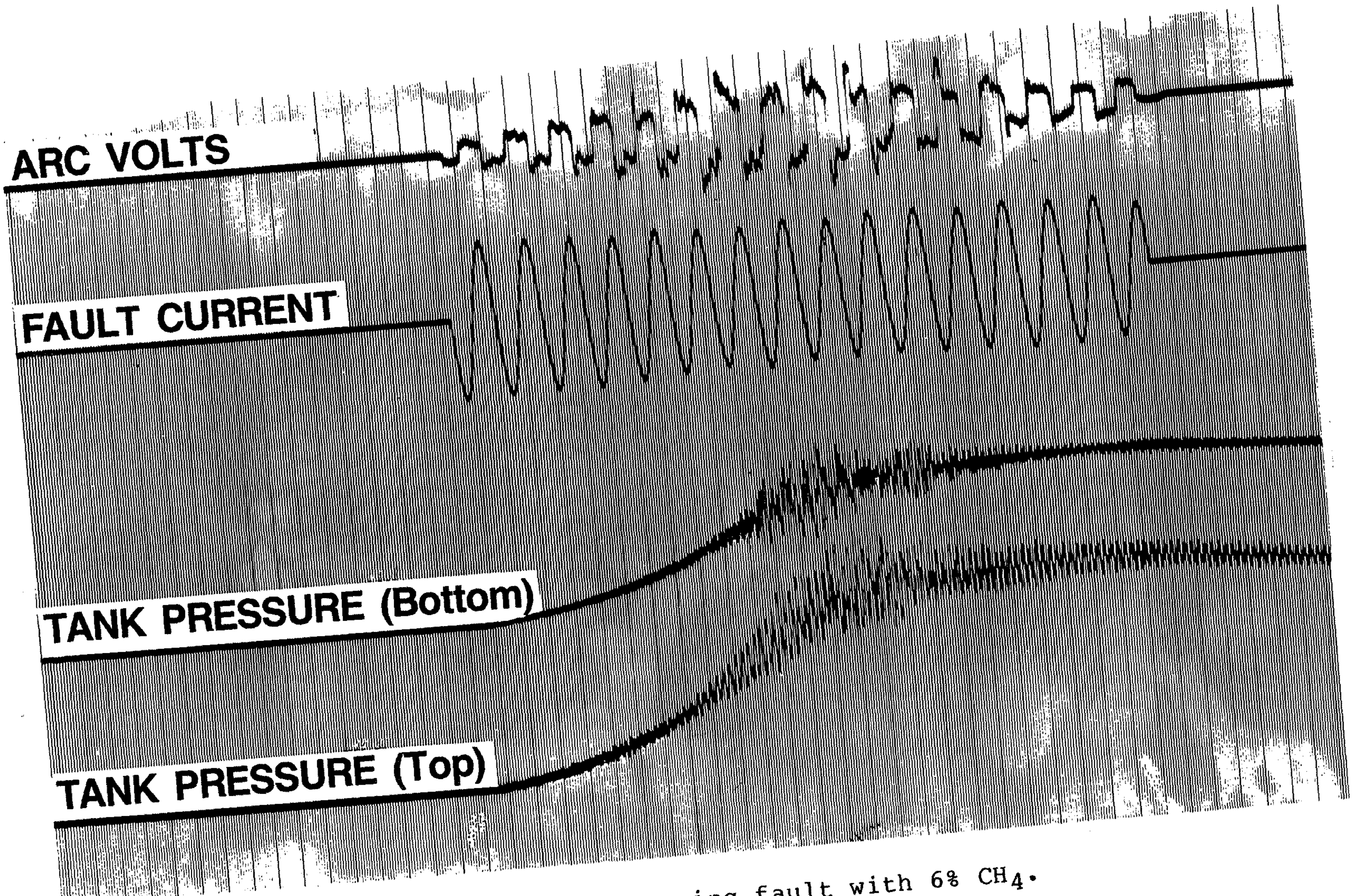


FIGURE 16. - Arcing fault with 6% CH_4.

in arc current in proportion to the impedance of the power source. Only a slight decrease in current was observed in these tests. This is attributed to the impedance characteristics of the power source at the Westinghouse facility. For the 10 kA tests, the generating station impedance was 1.375 ohms, of which 1.373 was inductive reactance and 0.081 was resistance. The impedance of the arc, which can be assumed to be entirely resistive, was approximately 0.24 ohms for the 10 kA arc-in-methane-air and 0.12 ohms for the 10 kA arc-in-air. When added vectorially to the station impedance, an almost imperceptible change in total impedance results. In a power system operating at a higher power factor, a comparable increase in arc resistance would result in larger decreases in fault current. Lower arc voltages would, in turn, be required to maintain the lower current levels. This suggests that a lesser amount of electrical energy would be dissipated by an arc-in-methane-air occurring in an enclosure supplied by a mine power system.

4.3.1 Effects of Increasing Arc Current Methane-Air Ignitions

Figure 17 shows the pressure traces from 4 methane-air ignitions using progressively higher arc currents. In the lowest energy arc, approximately 0.75 s elapse before all of the methane has burned. More energetic arcs cause the methane to burn more rapidly. For example, it is clear that when a 5 kA arc is applied, all of the methane has burned in the first 0.25 s, as evidenced by the fact that the pressure starts to decrease after 0.25 s (i.e., after 15 cycles when the arc is extinguished). In the highest-energy case, a 10 kA arc, peak pressure is reached long before the arc is extinguished. As mentioned earlier, a state of equilibrium has been achieved in which the electrical energy liberated by the arc is offset by heat transfer to the walls of the enclosure. In other words, peak pressures will not increase without limit as electrical energy increases, because the enclosure starts to absorb the energy as fast as it is produced.

This phenomenon is well illustrated in figure 18, in which peak pressures observed in the 0.530 m^3 enclosure are plotted against the arc current. Note that in these arc-in-methane tests, increasingly higher arc currents produce smaller and smaller pressure increases. The test sequence shown would appear to be approaching an asymptotic boundary of approximately 140 psi. The peak pressure of 138 psi measured in the 0.53 m^3 enclosure with a 10 kA arc was the highest pressure measured in all of the tests.

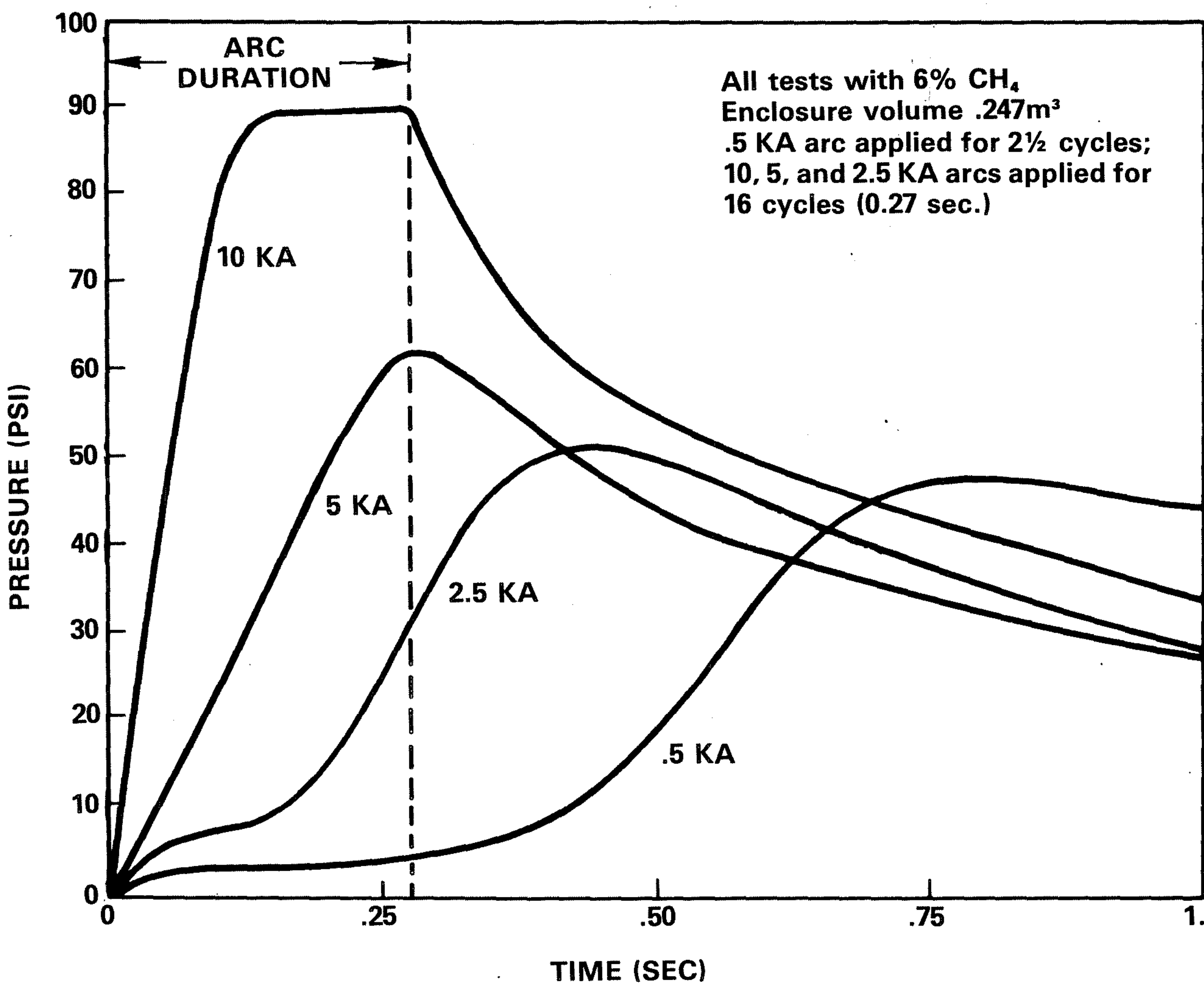


FIGURE 17. - Pressure traces from 4 methane-air ignitions.

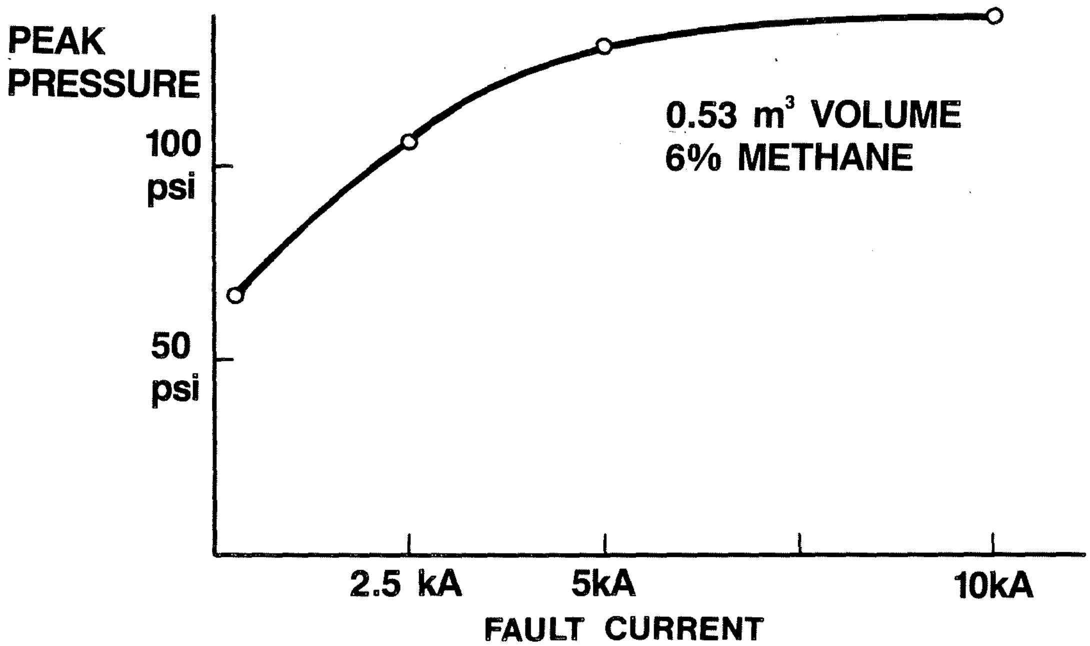


FIGURE 18. - Peak pressure versus fault current.

4.3.2 Effects of Enclosure Geometry on Peak Pressures

Figures 19 and 20 show the pressure/volume relationships observed for all tests. Pressures increased with decreasing volumes from 1.05 m^3 down to 0.53 m^3. Further decreases in volume, however, produced sharp decreases in observed pressures. A possible explanation for this behavior lies in the mechanisms by which energy is dissipated by an arc. Those mechanisms include radiation, head conduction, and the removal of energy of ionization by escaping ions (14). The blocks used to reduce enclosure volume effectively moved the enclosures walls closer to the arc and provided increased surface area upon which the recombination of ions could take place. Thus, a larger percentage of total energy was absorbed by the enclosure as the volume was reduced. A decrease in arc voltage was also observed in these smaller volumes. This decrease, which may have been caused by decreasing pressures, resulted in dissipation of lesser amounts of electrical energy by the arcs in smaller enclosures.

One would expect that a perfectly spherical shell would provide the least heat transfer because it has the least surface area for any given volume and because the entire wall

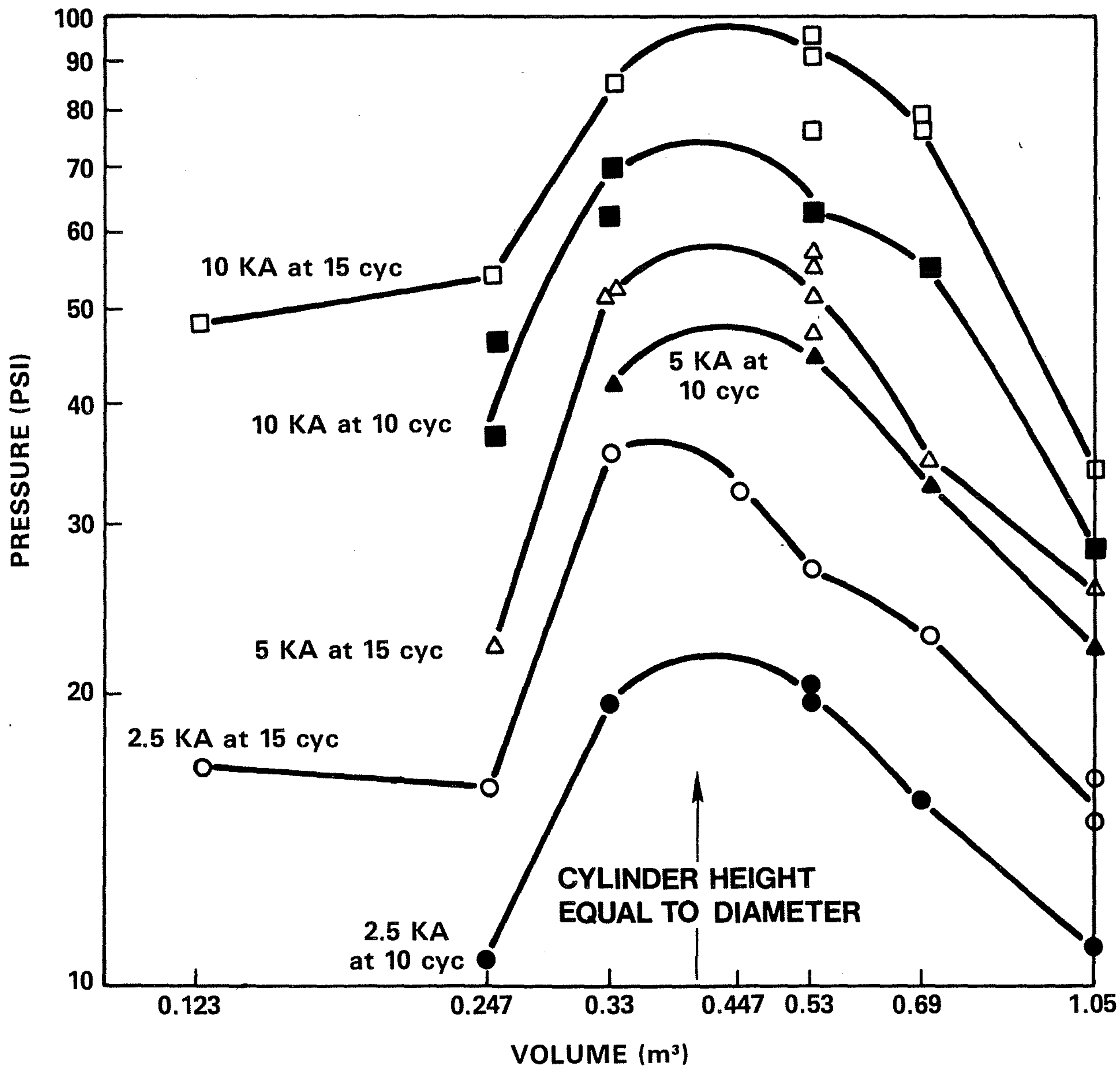


FIGURE 19. - Peak pressure versus volume, for arcs in air only.

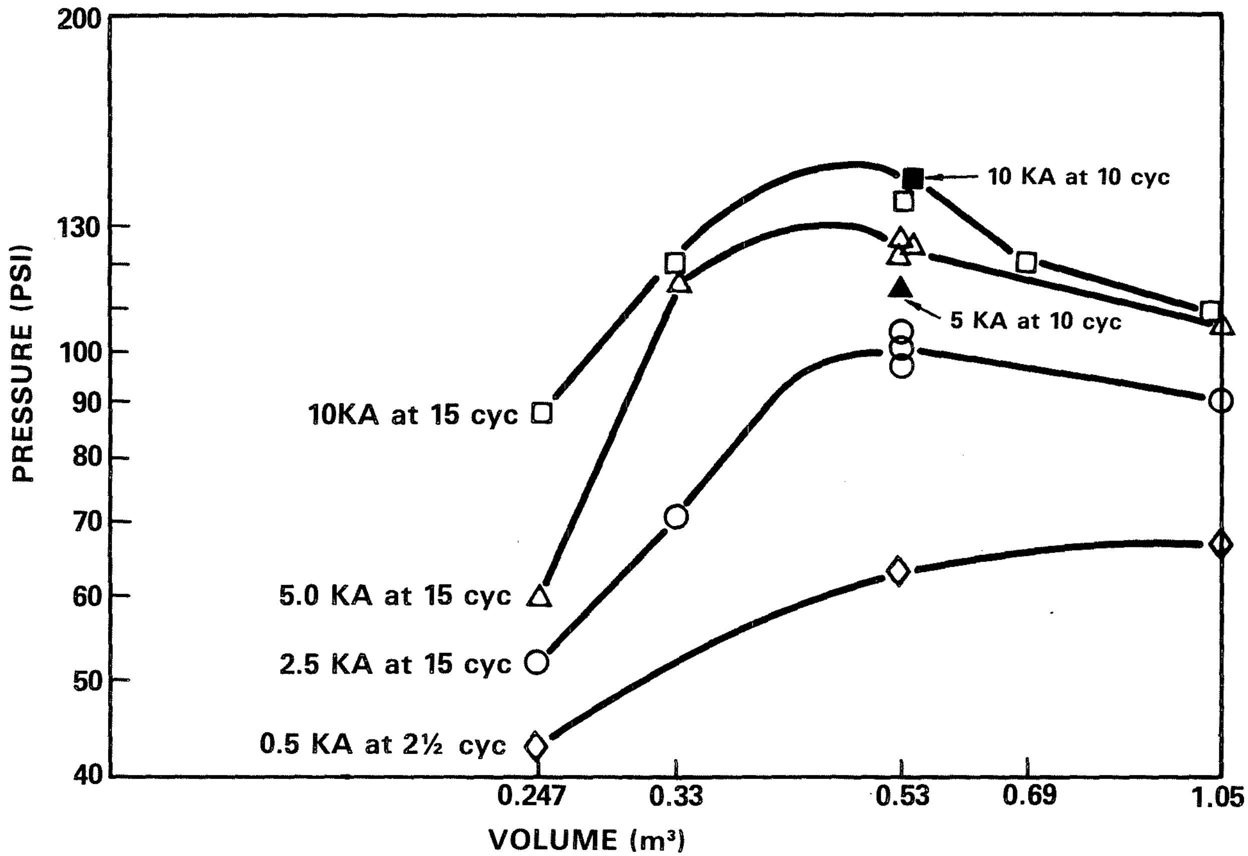


FIGURE 20. - Peak pressure versus volume for arcs in 6% methane.

surface would be equidistant from a centrally located arc. For the test enclosure (which was a right circular cylinder), the condition most closely approximating a sphere is when the enclosure height equalled the diameter, which occurs at a volume of about 0.4 m^3. It is interesting to note that the peak pressures did, in fact, occur at about this volume.

To further test the importance of surface area, four additional tests were run. In these extra tests, an internal free volume of 0.53 m^3 was achieved by using the double pipe enclosure with one concrete block insert (net free volume 0.69 m^3) and then filling this enclosure with 70 loose bricks. Thus, the same free volume of 0.53 m^3 used in earlier tests was achieved but with a much higher internal surface area (because of all the loose bricks). Table 5 shows the results of these tests compared with the results from the standard (i.e., lower internal surface area) 0.53 m^3 enclosure. It should be noted that for every current level, substantially lower pressures were achieved in the enclosure with the higher internal surface area, although the internal free volumes were the same.

TABLE 5. - Comparison of peak pressures in 0.53 m enclosures with different internal surface areas

	Low internal surface area	High internal surface area
5 kA, 10 cycles	45	35
5 kA, 15 cycles	53	43
10 kA, 10 cycles	63	55
15 kA, 15 cycles	94	62

4.3.3 Effect of Adding Methane to Arc-In-Air Enclosure

Referring again to figures 19 and 20, a comparison of the highest pressure recorded in the arc-in-air tests (98 psi) with the highest pressure recorded in the arc-in-methane-air tests (138 psi) reveals an increase of approximately 40% when the gas mixture is present. However, in addition to the energy contributed by the methane, almost twice as much electrical energy was dissipated in the enclosure during the arc-in-methane-air tests due to the increase in arc voltage noted earlier. The relatively small increase in pressure resulting from such a large increase in total energy is attributed to the pressure limiting effect imposed by the thermal mass of the enclosure, as discussed previously.

4.4 RECOMMENDATIONS FOR FUTURE RESEARCH

4.4.1 Additional Data Analysis

A great deal of data was collected during the course of this test program. As explained in the introduction, we are primarily interested in the results of this program as they relate to the development of criteria to be used for the approval of permissible loadcenters. However, this data may well be of use to other researchers in other areas. For each of the 76 tests conducted, there exists voltage, current, and pressure trace records such as those shown in figures 15 and 16. In addition, there are computer-generated plots showing instantaneous voltage and current plus computer-calculated values of rms voltage, fault current, energy, and total power. An example of these plots is shown in figure 21. All of this data has been preserved and is available to interested researchers. The special-design test enclosure is also available for future testing.

4.4.2 Interaction of High-Energy Arcing Faults and Pressure-Piling

A major area of concern in the approval of explosion-proof enclosures is the effect of pressure piling. Pressure piling is an increase in explosion pressure caused by precompression of the methane-air mixture before ignition (15). The classic pressure piling case occurs in an enclosure consisting of two separate volumes connected by a pipe. When an ignition starts in one of the volumes, expanded combustion products push unburned gas through the pipe into the second volume, thereby precompressing or "supercharging" the methane-air mixture. When this supercharged mixture is ignited by the advancing flame front, the resulting pressure rise can be substantially higher (and the rise time faster) than in single volumes not subject to precompression. Although this effect may be most pronounced in the classic case just described, some degree of pressure piling will be in evidence in any enclosure with irregular geometry, such as a long thin tube or even a large regular box in which the placement of internal components may cause restrictions.

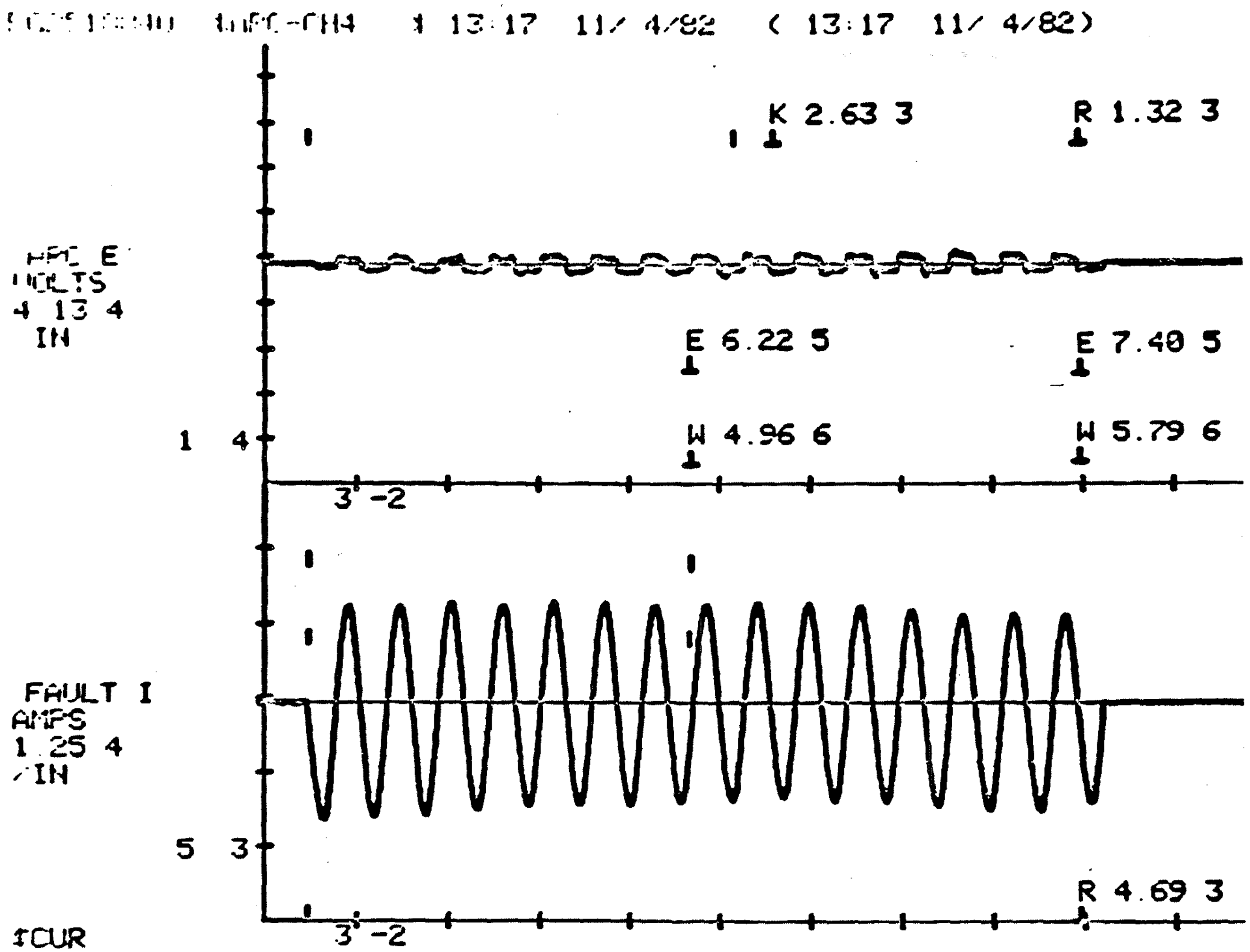


FIGURE 21. - Example of computer-generated data.

Pressure piling was <u>not</u> investigated in the arcing fault test program previously described; in fact, the test enclosure and the test program were planned to minimize pressure piling so that the peak pressures would be a result only of arc energy and methane-air ignition energy. However, results of this test program do provide some hints that pressure piling may actually be mitigated by a high-energy arcing fault. The arcing fault, with its large plasma ball and high radiant energy, appears to ignite methane almost "simultaneously" throughout the enclosure, rather than starting at one end; and pressure piling is most prevalent when the ignition starts at one end of an enclosure. Figure 9, previously referred to, shows how much faster the methane burns when a high-energy arc is applied (less than 1/4 s burn time) than when a low-energy spark ignites the methane (3/4 s burn time).

The preceding discussion will remain somewhat speculative until experimental data can be obtained. Minor modifications could be made to the test enclosure in order to conduct a test program which would investigate the interaction between pressure piling and arcing faults. The proposed modified enclosure is shown in figure 22. A flange, with a hole bored through its center, has been inserted between the upper and lower portions of the enclosure. A variety of hole sizes could be quickly achieved by using orifice plates (with different size orifices) which are clamped to the flange. This test arrangement will provide a classic pressure piling situation: methane air is ignited at the top end of the enclosure and the flame front will then travel through the restricting orifice to the lower half of the enclosure. The resultant pressures in the lower half of the enclosures will indicate the degree of pressure piling, when compared to existing data for the same enclosure without the flange/orifice combination. A one-day test-plan might look as shown in table 6.

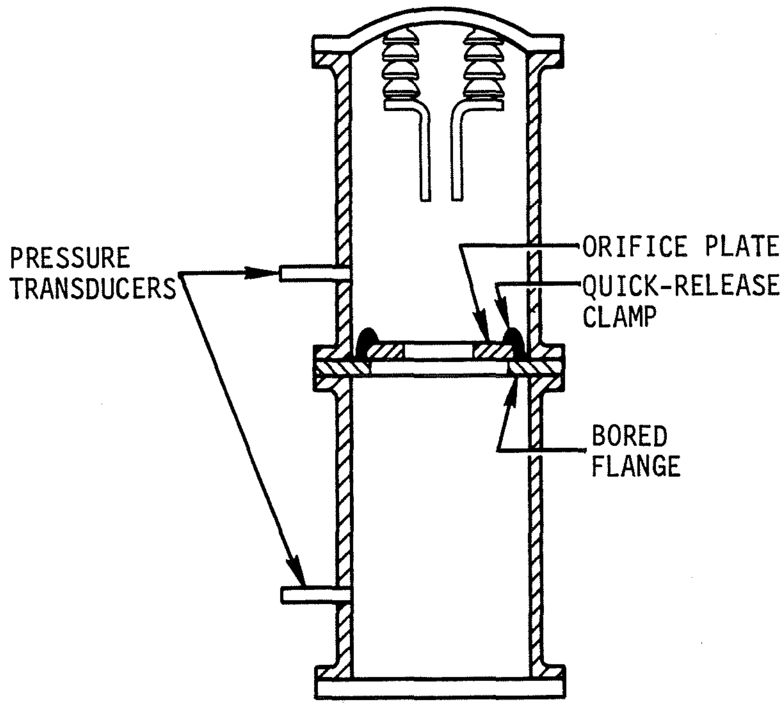


FIGURE 22. - Proposed test enclosure.

TABLE 6. - Proposed test plan

Test no.	Test current/duration (kA/cycles)	Orifice diameter (in.)
1	0.5/2.5	20
2	5/10	20
3,4	10/15*	20
5	0.5/2.5	10
6	5/10	10
7,8	10/15*	10
9	0.5/2.5	5
10	5/10	5
11,12	10/15*	5

*One test with methane, one test without methane

5. DESIGN, CONSTRUCTION & TESTING OF A HIGH-VOLTAGE LOADCENTER

5.1 SUMMARY

One of the major objectives of this program was to "reality-test" the criteria outlined in section 2 and discussed in section 3. This "reality-testing" was accomplished by constructing a loadcenter which was specifically designed to meet the recommended criteria and then making application to MSHA for Approval of the loadcenter. This approach produced the following benefits:

a. Insight into the practical application of the criteria

Having to design and fabricate a loadcenter which would meet the recommended criteria gave us a good perspective on how realistic and how sensible the criteria was

b. Better understanding of the impact on design of hardware and selection of components

By actually designing a loadcenter and having to choose specific components, we gained an appreciation of what manufacturers will have to face, what type of construction techniques will have to be used, and the special requirements which are placed on the internal components

c. Appreciation of how the recommended criteria might be interpreted by others

We knew what we meant when we wrote the criteria, and we designed the loadcenter according to our own understanding. But when we began the Approval process with MSHA, we gained a much better understanding of what the criteria would mean to an independent user.

The balance of this section is divided into two major areas, a description of the design and construction of the loadcenter, and a discussion of the application of the criteria to the loadcenter during the Approval Process.

The design and construction of the loadcenter is described in section 5.2, which discusses the following key issues:

a. The size and weight of the explosion-proof loadcenter are not significantly greater than those of conventional non-explosion-proof loadcenters used in American mines today

b. The loadcenter is constructed of three separate enclosures: a high voltage chamber with cable inlet and high voltage protection, a large central chamber containing the transformer, and a low-voltage chamber containing circuit breakers, protection equipment, and low-voltage explosion-proof plugs for distribution to face equipment

c. The largest chamber, containing the transformer core and coils, has corrugated steel sides, which improve heat dissipation and provide more strength for less weight

d. Several features are provided specifically to minimize the hazard of volatilization of organic insulators, such as the use of special-order components to minimize the use of such insulators, and thermal and pressure sensors to sense conditions which can lead to the decomposition of the organic insulators which still have to be used.

Factory testing of the loadcenter is discussed in section 5.3.

The interpretation of the criteria during the approval process is discussed in section 5.4, where the following major issues are raised:

a. Specification of protective measures to minimize volatilization of insulators is a difficult task, and the requirements in the criteria might lead to confusion. It was the intent of the criteria to provide several alternatives, but MSHA may require that <u>all</u> of the alternatives be employed, rather than <u>any one</u> of them

b. The criteria assumed that electrical cables supplying power to an explosion-proof loadcenter would be treated as a feeder-cable; however, MSHA may choose to define it as a trailing cable, which would put severe limitations on the maximum lengths which could be used

c. The criteria recommended a corona-extinction test, based upon a recommendation from another USBM program. However, as of this writing, the corona-extinction test has not been performed and we therefore could not do an independent evaluation of the performance and/or value of this test.

5.2 DESCRIPTION OF THE DESIGN AND CONSTRUCTION OF AN EXPLOSION-PROOF LOADCENTER

5.2.1 General Description

As discussed in more detail in section 6, the United States mining industry has had little experience with the manufacture or use of high-voltage explosion-proof loadcenters. Furthermore, there is no requirement for explosion-proof loadcenters in U.S. mines, and American manufacturers have therefore shown little or no interest in the development of such equipment. For this and other reasons, Brush Transformers, Ltd.* of the United Kingdom was chosen as the manufacturer of the explosion-proof loadcenter which was especially designed and fabricated for this program. The design and parts specification was a joint effort with FMI. Brush manufactured the enclosures and the transformer and Foster-Miller supplied all of the low-voltage components such as breakers, ground-fault system, and explosion-proof receptacles (all purchased from United States suppliers).

The complete explosion-proof loadcenter is shown in the mechanical drawing of figure 23. Photographs of the loadcenter with the top covers removed are shown in figures 24 and 25. Technical specifications for the unit are shown in table 7. One of the interesting features of this load-center is that it is no bigger in size and only about 20% heavier than comparable units used in the United States which are not explosion-proof. This may come as something of a surprise to many of the people with whom we communicated during the course of this program; the popular perception in the United States seemed to be that to explosion-proof a conventional loadcenter would necessitate a tremendous increase in mass.

*Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

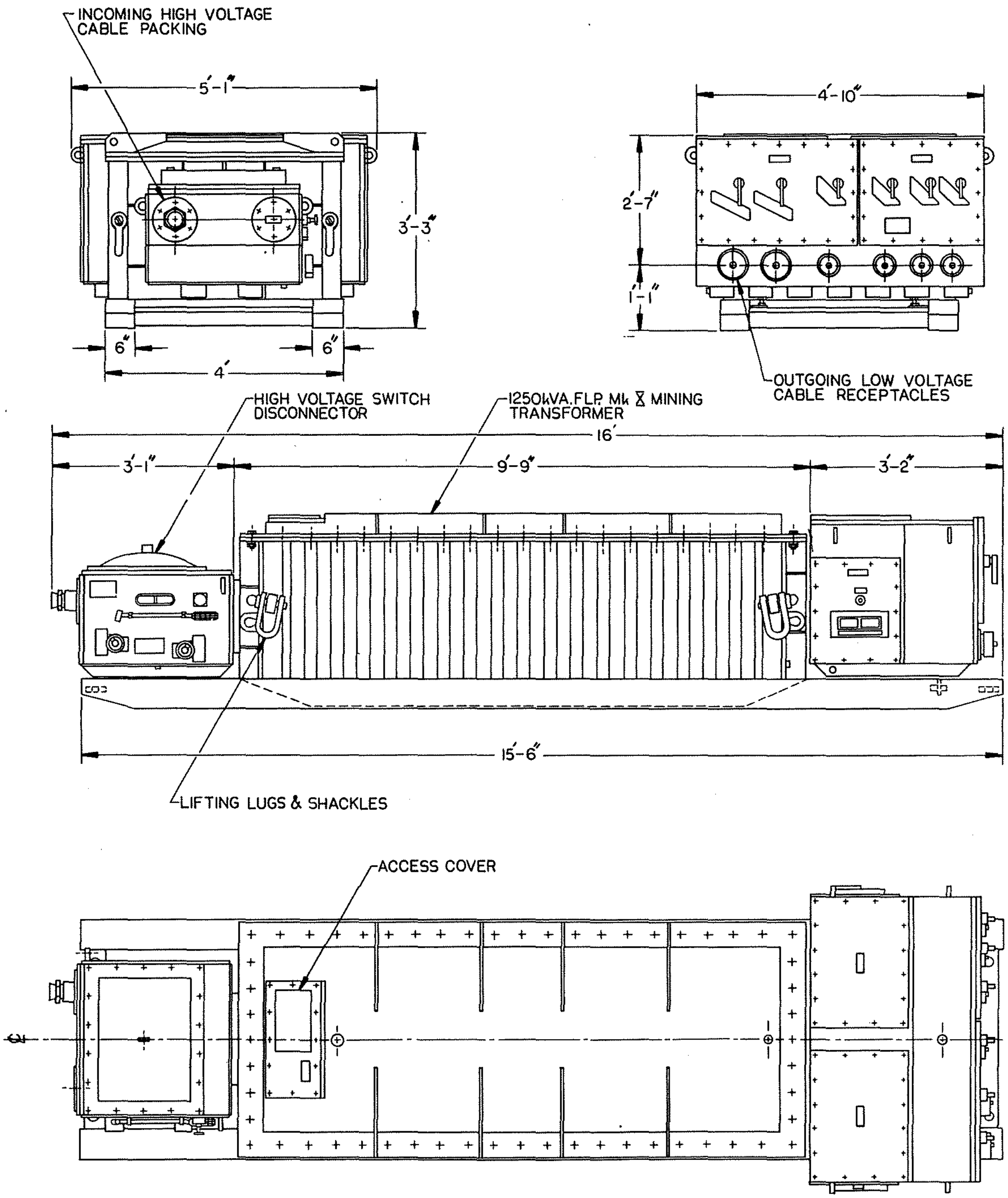


FIGURE 23. - Drawing of loadcenter enclosure.

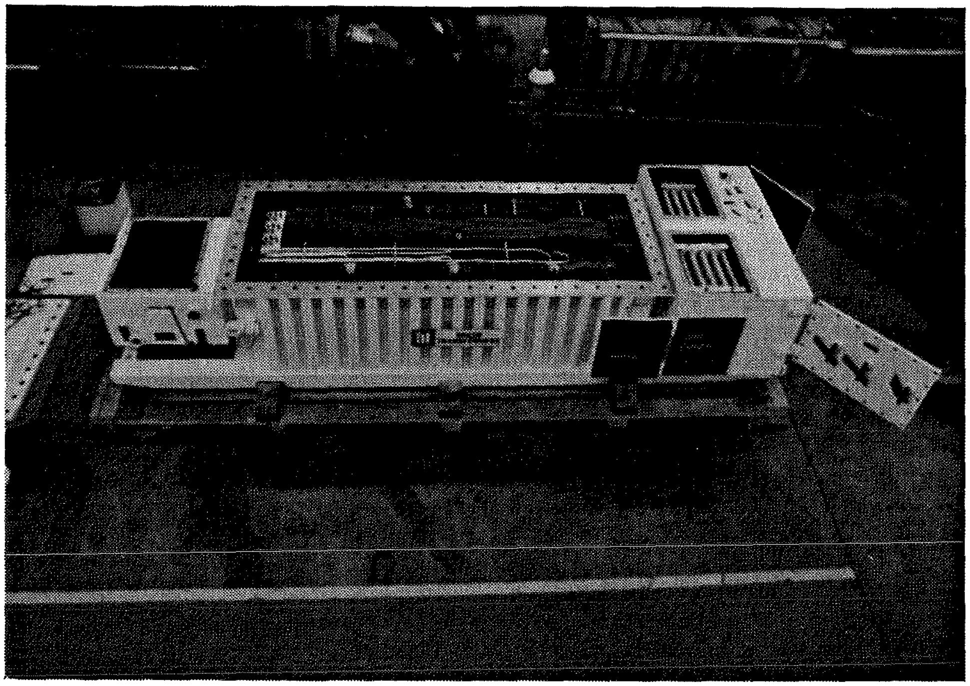


FIGURE 24. - Top view of loadcenter.

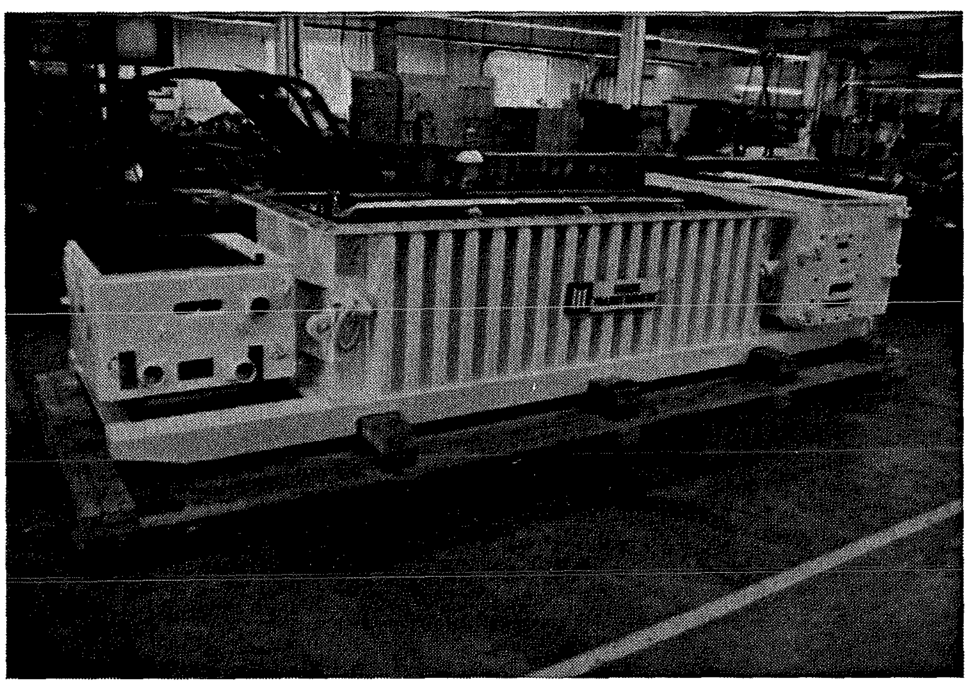


FIGURE 25. - Side view of loadcenter.

TABLE 7. - Technical specification of prototype high voltage permissible loadcenter

Mechanical	Electrical
Length 16 ft 3 in.	Power 1250 kV.A
Width 5 ft 2 in.	Voltage 7200 V input thru cable gland
Height 3 ft 3 in.	(2) 1000/V receptacles
Weight 18,600 lbs.	(4) 440 V receptacles
	Impedance 4.2%

As could be seen in figures 23, 24, and 25, the loadcenter actually consists of three separate enclosures. Looking from left to right in figure 24, the individual units consist of the high voltage enclosure, the transformer tank, and the low-voltage enclosure. The following three sections (5.2.1.1 - 5.2.1.3) describe each of these enclosures and its contents in more detail. Following that, section 5.2.2 contains a discussion of specific hardware components which were designed or purchased in order to satisfy the recommended criteria.

5.2.1.1 High-Voltage Enclosure

The high-voltage enclosure is shown in figure 26, consisting of a rectangular box approximately 3 x 3 x 2 ft high. There are five major external components:

a. Top cover

b. Cable entrance and cable

c. Switch disconnect

d. Window

e. Panic button.

The top cover provides the only access to this chamber. It is of conventional design and is bolted on to the enclosure; the photograph in figure 26 shows the enclosure with the cover removed. Limit switches inside the enclosure are tripped when the cover is removed, thus breaking continuity of the ground monitoring circuit and activating the outby protection to interrupt electrical power to the loadcenter.

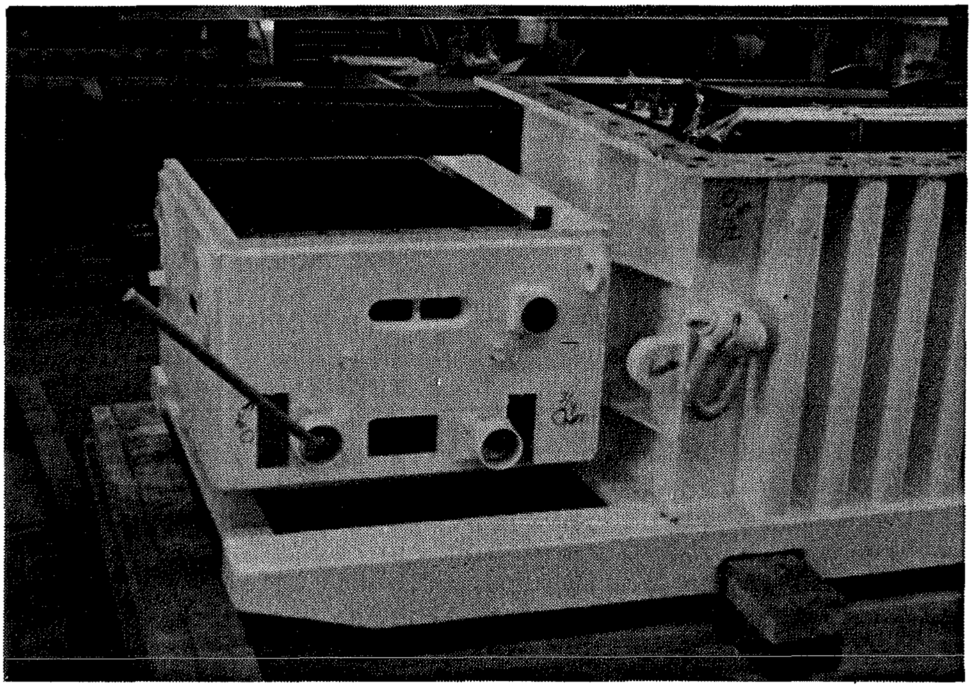


FIGURE 26. - High-voltage enclosure.

The cable entrance is at the far left in figure 26. It is a conventional packed asbestos gland and was purchased from an American supplier to fit the cable, which was specified as 4/0 3-conductor shielded with ground check, rated 8000 V, 90°C.

The switch disconnect in this chamber was a standard knife-blade type arrangement actuated by a lever outside the enclosure. Figure 26 shows the lever engaged in the left hand shaft, which makes and breaks contact with the 7200 V supply voltage from the cable. The right-hand shaft is used to earth-ground the output side of the switch. The switching mechanism is mechanically interlocked so that the grounding switch cannot be actuated unless the make/break switch is open. Likewise, the make/break switch cannot be closed unless the grounding switch is open. During normal operation, the lever arm is stored on the side of the enclosure, held in place by small spring clips visible in the photograph.

The small oval window provides a visible means of verifying the switch positions. The window itself is made of polycarbonate, with a steel backing plate which is secured by bolts from the inside of the enclosure. Thus, to remove the window one must first remove the top cover, tripping the ground monitoring circuit as previously described.

The red panic button on the right hand end of the circuit is also wired into the ground monitoring circuit, to provide an instantaneous means of tripping out the outby breaker, as required by existing regulations.

The high-voltage enclosure is mounted to the transformer tank with bolts which are attached from the inside of the h-v enclosure once again assuring that the limit-switch-protected top cover must be removed before any other portion of the enclosure is disassembled. The 7200 V supply is transmitted from the h-v enclosure to the transformer tank through insulated studs such as the one shown in figure 27. These studs fit into bored holes in the enclosure wall and are held in place by steel plates bolted from the inside. Thus, the two chambers are physically isolated from one another and actually form two separate explosion-proof enclosures which share a common wall when they are bolted together.

The internal components of the high-voltage enclosure are shown schematically in figure 28. The major components are as follows:

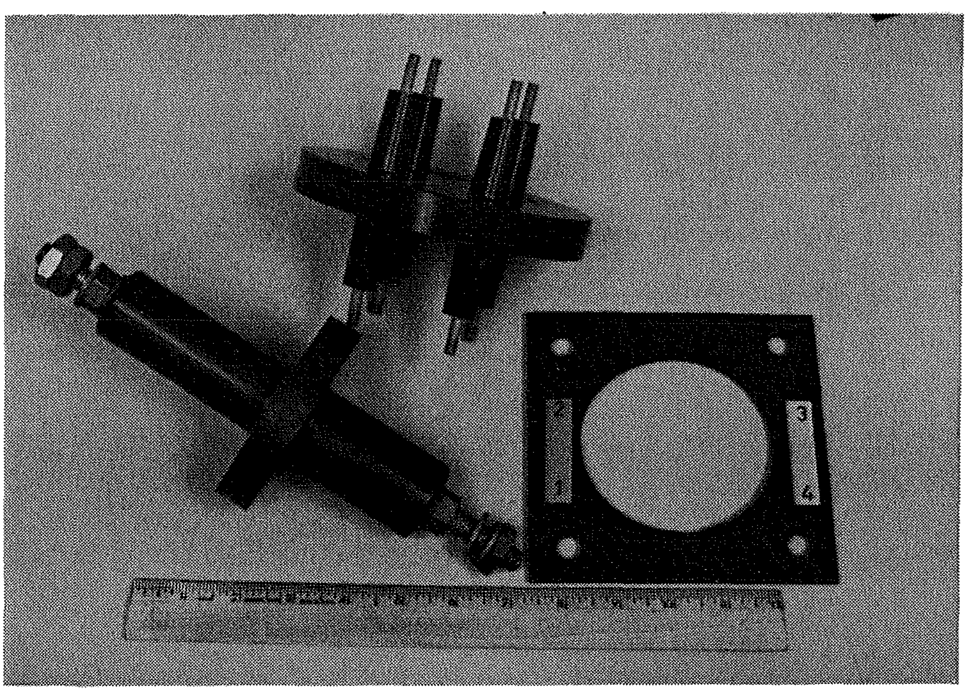


FIGURE 27. - Insulated feed-through stud.

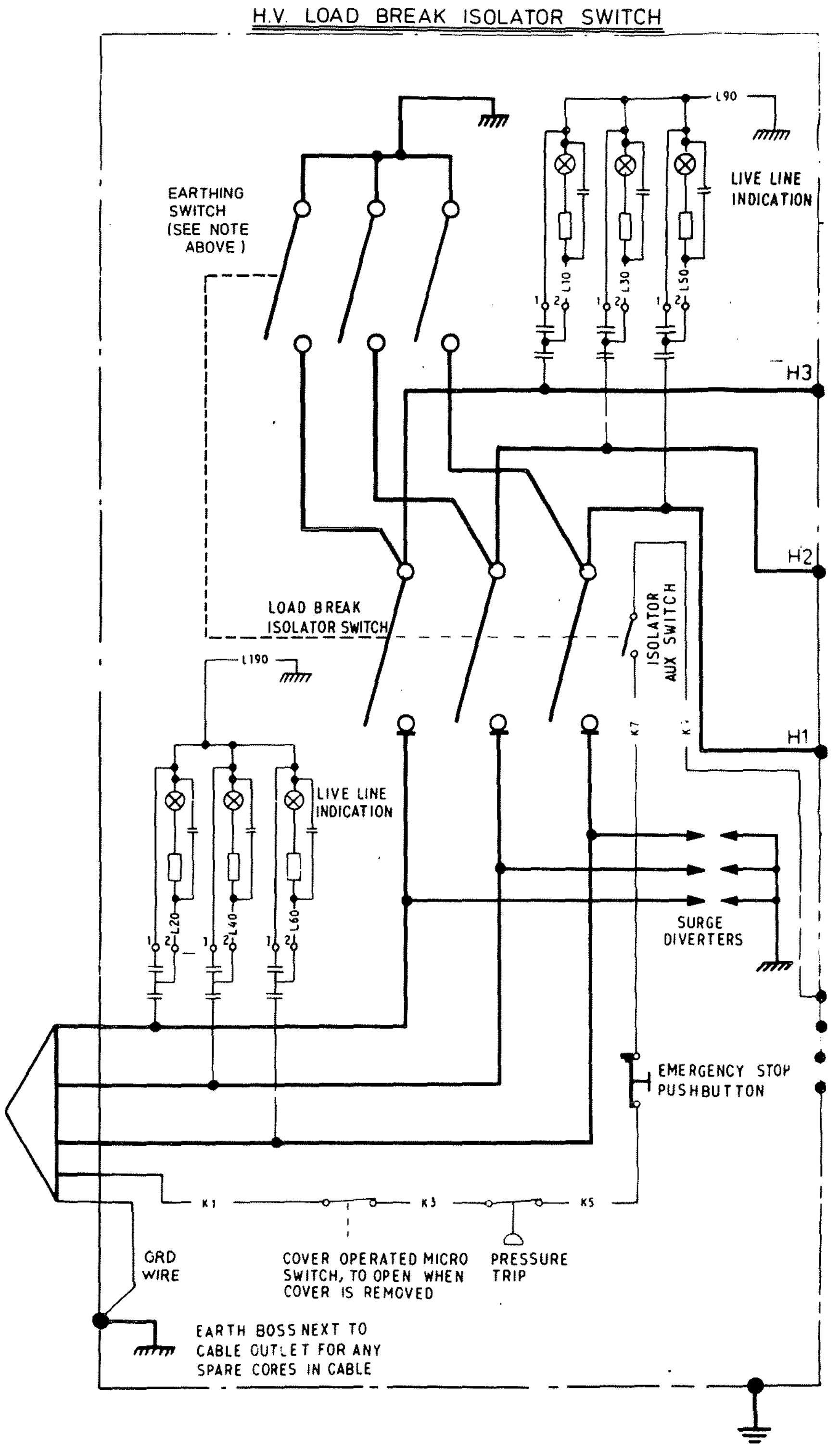


FIGURE 28. - Electrical schematic of high-voltage enclosure.

a. Disconnect and grounding switch

b. Ground monitor interlocks

c. Entrance cable and associated wiring.

The operation of the disconnect and grounding switch was previously described, as was the function of some of the ground monitor interlocks, namely the cover limit-switches and the panic button. Also included in this circuit is a pressure switch, whose function is to sense conditions (i.e., pressure rise) which may indicate that catastrophic breakdown of organic insulators may be occurring. This system is more fully discussed in section 5.2.2. All insulating components in the high-voltage enclosure have a minimum Comparative Tracking Index (CTI) of 250.

Note that there are no self-actuating breakers or contactors in the high-voltage enclosure, excluding the manually-operated disconnect. The design of this loadcenter requires that outby protection be provided, and specified, as the recommended criteria suggests.

5.2.1.2 Transformer Tank

The transformer tank, the largest part of the loadcenter, is a rectangular enclosure 3 ft high, 5 ft wide and 10 ft long. It was shown in the center part of figures 24 and 25 with the slightly domed cover removed. The large cover has a smaller cover on top of it, allowing access to the inside without removing the large main cover. Like all of the other covers on the loadcenter, these covers are secured by bolts and make contact with limit switches which trip the ground monitoring circuit if the cover is removed.

The two long sides of the transformer tank are fabricated from 1/4 in. steel plate which has been folded back and forth to form a corrugated wall, with "ripples" about 5 in. deep and 5 in. wide. This feature provides two distinct advantages:

a. The side walls can be made significantly lighter than a flat wall designed for the same strength

b. Heat transfer is improved, allowing better cooling of the transformer, lower surface temperatures, and a more compact arrangement of interior components.

Electrical feed through and attachment to the low-voltage enclosure is the same as that described in section 5.2.1.1.

The internal components of the transformer tank are shown schematically in figure 29. The major part of this system is of course the transformer unit itself. The transformer is an air-cooled wound core-and-coils type with an impedance of 4.2%. It is rated at 1250 kV.A, with a 7200 V primary and two secondary voltages of 1000 and 440 V. The 1000 V secondary can supply 700 kV.A and the 440 V system supplies 550 kV.A. Because this was a prototype unit designed for application to the recommended criteria, the two secondary voltages were selected as being most representative of the requirements of U.S. coal mines.

Other components inside the tank include the limit switches previously alluded to and temperature switches to trip the ground monitor system. Like the pressure switch in the high-voltage compartment, the temperature switches were installed to detect conditions (in this case, excessive temperature rise) which might lead to, or be caused by, the volatilization of organic insulators. The temperature switches in this enclosure were set at 110° C after extensive factory testing showed that the maximum temperature at the switch locations was less than this setting. This data was obtained after the temperature had stabilized in a simulated long-term full-power test, as further discussed in section 5.3.

All insulating components in the transformer tank have a minimum CTI of 250.

5.2.1.3 Low-Voltage Enclosure

The low-voltage enclosure is pictured in figures 30 through 33, shown from the end, front side, and back side. A welded rectangular box is used, measuring 5 ft wide, 3 ft long, and 3 ft high. It has the following features:

a. Two bolt-on top covers for access to power-resistor chamber

b. Bolt-on-and-hinged front cover for access to ground-fault monitor

c. Window and external reset lever for ground fault monitor

d. Bolt-on-and-hinged back cover for access to meters

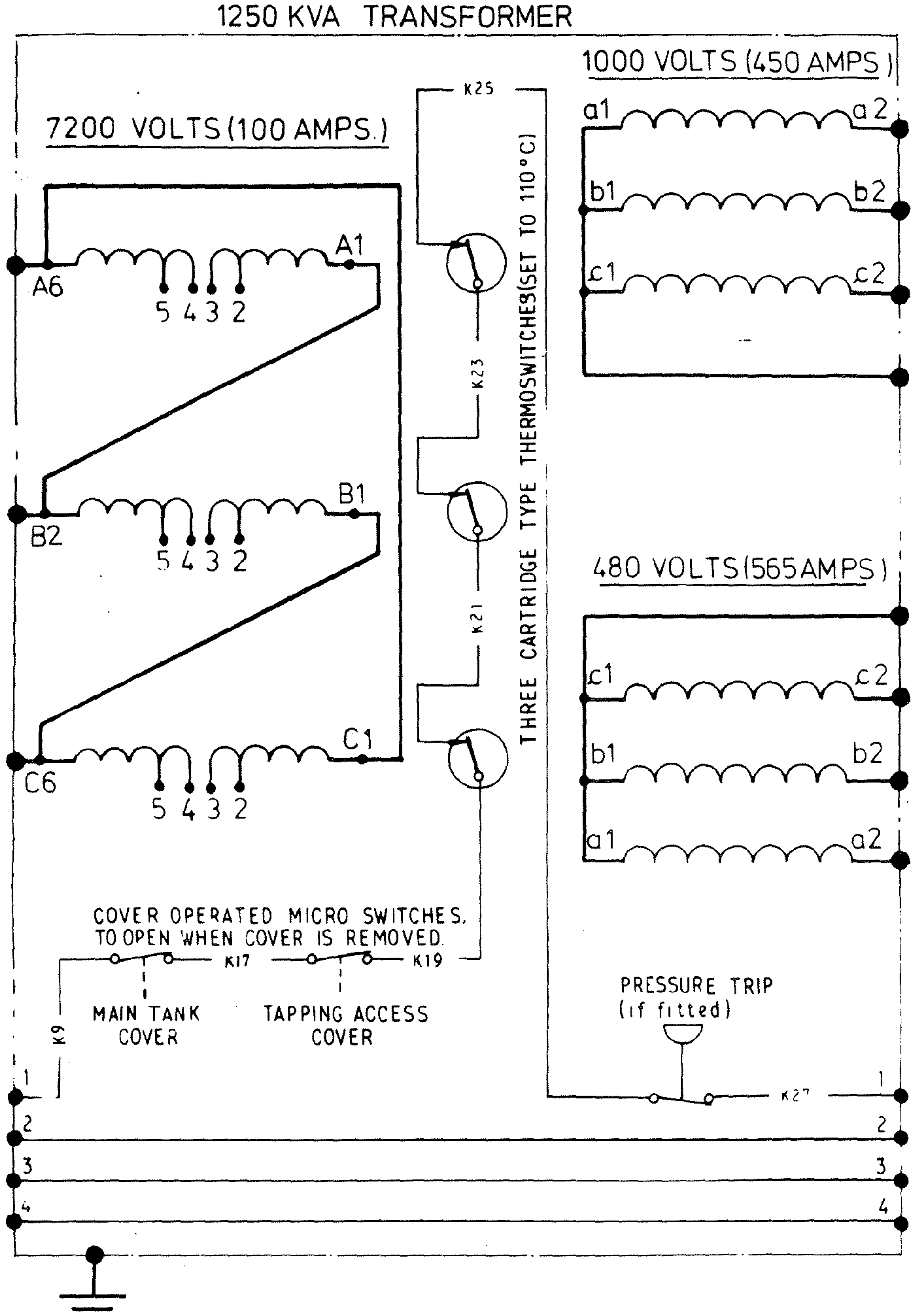


FIGURE 29. - Electrical schematic of transformer enclosure.

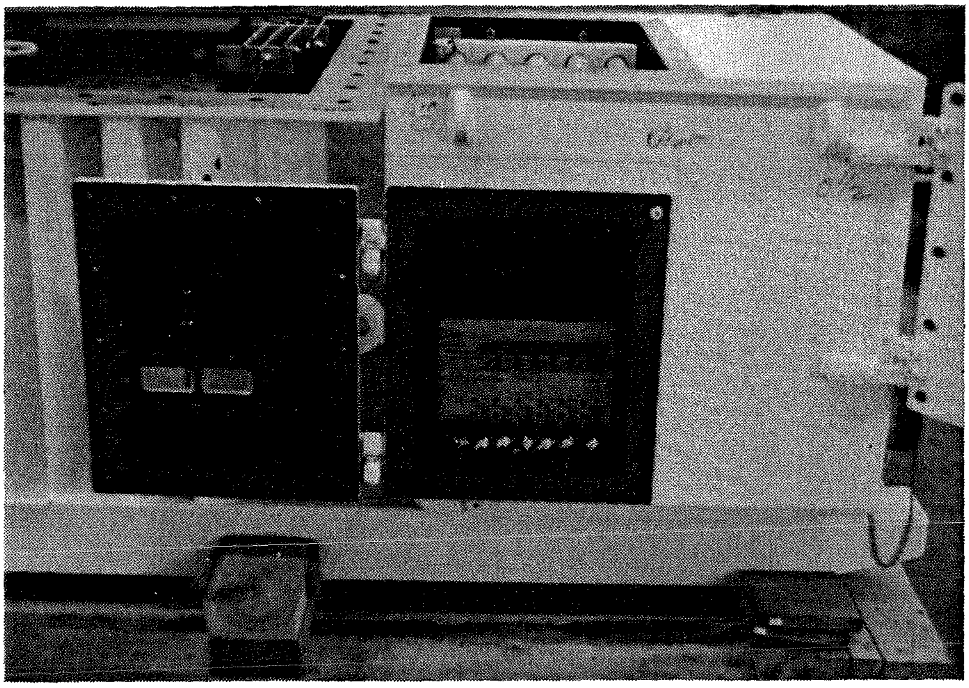


FIGURE 30. - Front view of low-voltage enclosure.

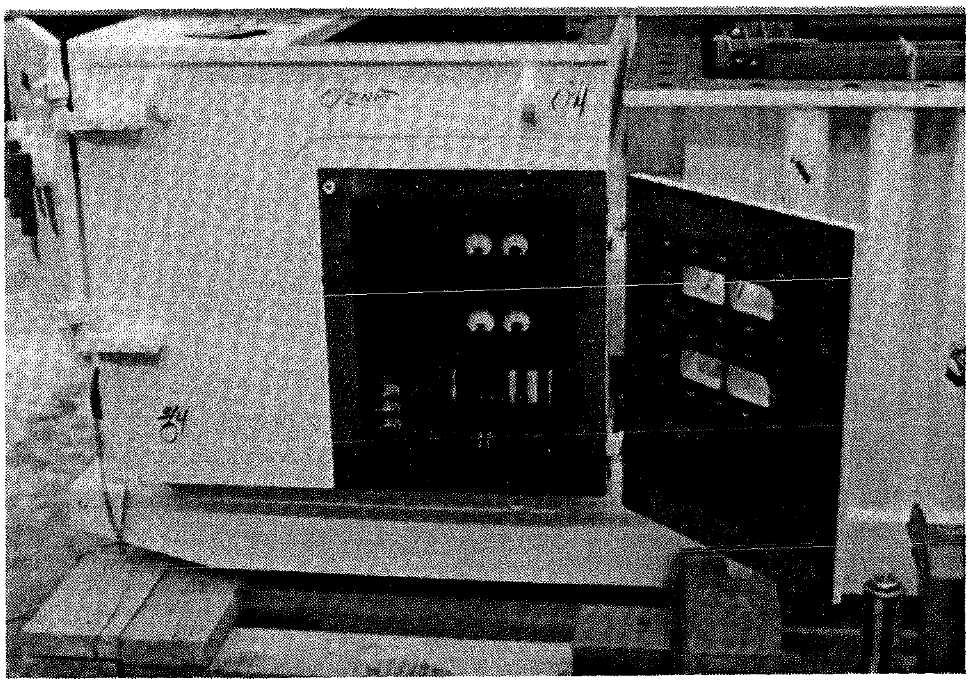


FIGURE 31. - Back view of low-voltage enclosure.

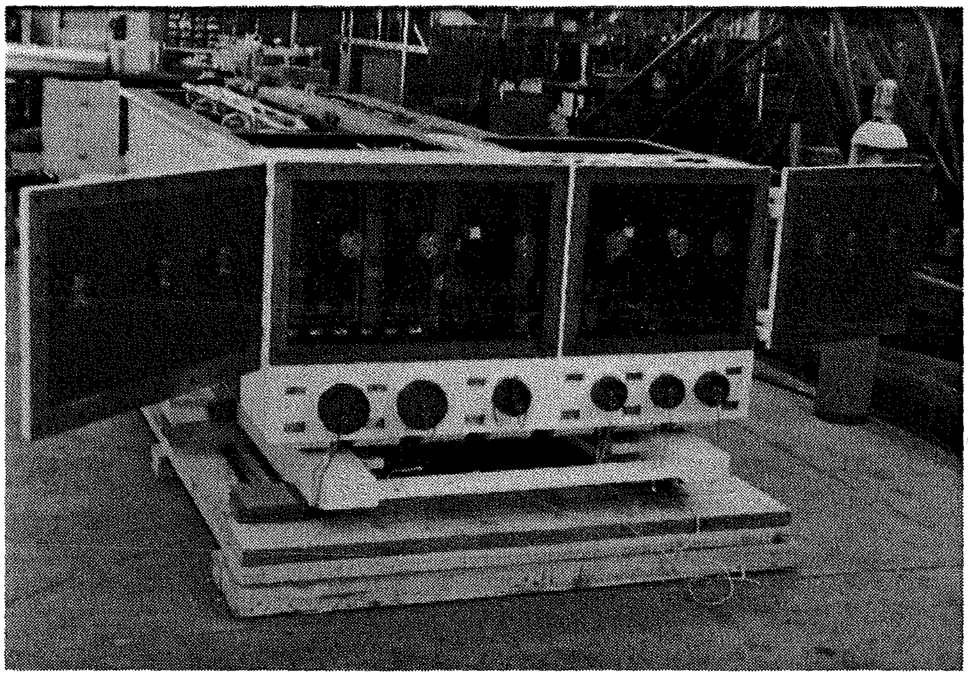


FIGURE 32. - End view of explosion-proof enclosure, covers open.

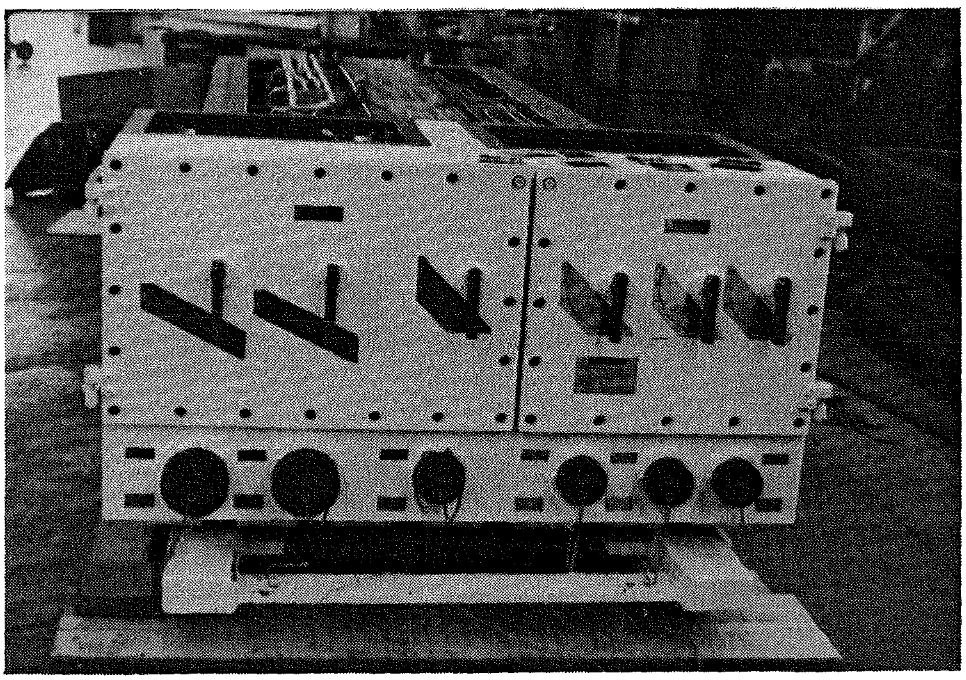


FIGURE 33. - End view of explosion-proof enclosure, covers close.

e. Window for meters

f. Two bolt-on-and-hinged end covers for access to circuit breakers

g. External levers for resetting circuit breakers

h. Six explosion-proof receptacles - (2) 1000 V and (4) 440 V.

The two bolt-on covers on the top of the enclosure (shown with covers removed in the photographs) provide access to a separate explosion-proof chamber built into the top of the low-voltage enclosure. This compartment contains the power resistors used in the back-up ground fault circuit described later. Electrical feed-throughs are similar to those previously described.

The front, rear, and end walls of the enclosure also have bolt-on covers. In addition to being bolted-on, these covers are hinged, so that they will swing open once the bolts have been removed. The front and rear views (figure 30 and 31) show the covers swung open, while the two rear views show the rear covers open in one photograph (fig. 32) and closed (fig. 33) in the other.

The front cover contains a window which provides a view of the ground fault monitor installed inside. This window is identical in design to that on the high-voltage enclosure. The front cover also contains a lever which allows the monitor to be reset from outside the enclosure. Removing the bolts and swinging the cover open permits access to the monitor and other components located on the front side of the enclosure.

The rear cover also contains an identical window which provides a view of the voltage and current meters, associated with the transformer outputs and the back-up ground fault lights. An external lever permits resetting the back-up ground-fault system without opening the cover.

The end cover contains the six levers which are used to set the six low-voltage circuit breakers corresponding to the six explosion-proof receptacles located immediately below the covers. Two 1000 V receptacles and four 440 V receptacles are provided. These receptacles are commercially available; the key to the explosion-proof design is that when unscrewing the collar of the mating plug, the live plug connections break contact with the receptacle contacts while the collar is still partially threaded onto the receptacle, maintaining a flame-proof path. These units have already received Certification from MSHA, although their use in this application raised some new issues which are further discussed in section 5.4.

As in the other sides of the enclosure, the covers can be unbolted and hinged open to provide access.

The internal components of the low-voltage enclosure are shown schematically in figure 34. Major components in the system include the following:

a. Control transformer

b. Ground fault monitor

c. Ground monitor

d. Back-up ground fault monitor

e. Circuit breakers

f. Receptacles.

The control transformer is included in the system in order to provide 110 V for other system components which require that voltage for operation, including the ground fault monitor and annunciator lights.

The ground fault system is of conventional design. The trip point for the ground leakage current was set at 10 A.

A back-up ground fault system is not presently required by Part 18, Part 75, or the recommended criteria. However, discussions held with MSHA during the design phase of this program indicated that such a system was highly desirable; it was therefore included in the design. The need for such a system is discussed further in section 5.4.

The ground monitoring system utilized a commercially available prepackaged unit. There are two basic designs available in the market today. One system, the "pilot" system, requires an additional ground wire in the cable so that continuity can be checked by monitoring the end of the normal ground wire and the extra ground wire which is also earth grounded at the far end of the cable. The other system, the "wireless" system, superimposes a high frequency

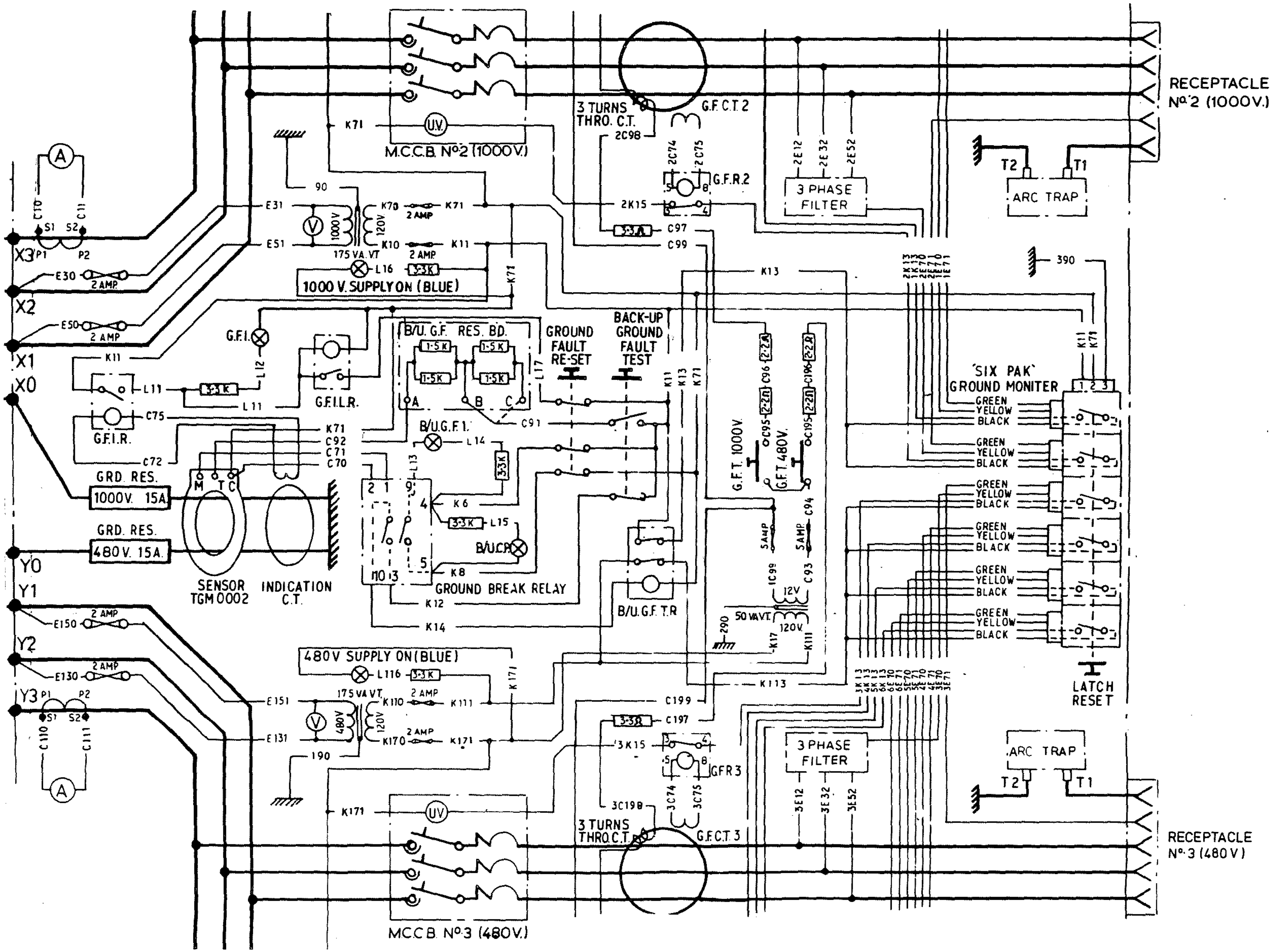


FIGURE 34. - Electrical schematic of low-voltage enclosure.

signal on one of the hot phases, places a coupling unit between the phase and ground at the far end of the cable, and senses the return of the signal on the ground wire back at the monitor. This system is more flexible because it can be used with any power cable because the extra wire is not required; we therefore chose it for our system. A major complication had to be resolved in using this system with the explosion-proof receptacle and plug assembly. This issue is discussed further in section 5.4. The design of the explosion-proof receptacle was discussed earlier in this section.

The circuit breakers were standard mine circuit breakers equipped with thermally-tripped overload protection. However, although the breakers themselves were standard, the molded cases were made from a special-order plastic, for reasons discussed in the next section.

5.2.2 Special Components Selected to Meet the Criteria

There were a number of components in the loadcenter that were especially chosen for their application to high-voltage permissible systems and/or to comply with some of the recommendations in the criteria. This section summarizes our experiences in the selection, acquisition, use, and approval of these components, which included the following items:

a. Temperature switches

b. Pressure switches

c. Special-order insulating materials

d. Cable insulation.

All of these components were included in the system because of our concern about the potential for high voltage to volatilize organic insulators and thereby create some highly explosive gases. Protective measures to guard against this hazard are outlined in Paragraph 6 of the criteria, in which the following procedures are recommended:

a. Do not use organic insulators

b. Where possible, use insulators which either pass the Fuse Wire Arc Test or have a minimum Comparative Tracking Index (CTI) of 250

c. If the above measures cannot be achieved, provide a protective device which can sense conditions which lead to decomposition of insulators and interrupt the incoming electrical power.

In the design of the loadcenter, we tried all of the above approaches in order to gain a better understanding of how easily each of those measures could be implemented.

Using only materials which have either passed the fuse wire arc test or have a minimum CTI of 250 is virtually impossible at this time, for the following reasons. First, the Fuse Wire Arc Test has not been widely used; therefore, test data is available on only a very limited number of insulating materials. The Bureau has developed some test apparatus, and we believe that in the future this test, or similar test, may be more widely used. However, for the present, other means must be used to minimize the chance of insulator volatilization. The Comparative Tracking Index is more widely known and used. For example, it was possible to obtain assurances from Brush that all of the insulating components which they used in the enclosures containing high voltages did in fact have a minimum CTI of 250. However, this was not necessarily the case with some of the other components purchased in the American market. For example, the electrical power cable which feeds through the flame-proof gland and into the high-voltage enclosure contained a number of different insulating materials for which the manufacturer was unable to supply any CTI information.

Another example of places where unknown or suspected low-CTI insulators exist is in the molded cases of purchased parts such as meters and circuit breakers. We were able to obtain, on special order and at almost twice the price, special-order circuit breakers with a different case which offered much superior insulation. However, we discovered that some of the smaller, internal parts of the breaker still contained some molded plastic parts of the same material which we had tried to eliminate by specifying the special cases. Strictly speaking, the higher CTI insulators would not be required in the low-voltage enclosure because the enclosure does not contain "more than one phase of a high-voltage circuit." However, these examples do tend to illustrate the difficulty in eliminating all questionable insulators in the near future.

The recommended criteria suggests using detection devices to sense conditions which can lead to decomposition in enclosures in which low-CTI insulators are used. We therefore investigated sensor/switches for both temperature and pressure, because volatilization of insulators is caused by arcing faults (usually at low enough power levels that do not trip circuit breakers or fuses) which will cause a rise in pressure or temperature. The major disadvantage of pressure sensors was that we were unable to find one which would be certain of operating properly at the elevated temperatures which might also be expected. Temperature switches, on the other hand, were available in any temperature range in which we were interested. The only remaining concern was that the temperature switch could be set low enough to sense a dangerous condition but high enough to avoid nuisance trips caused by the normal heat load of the transformer operating at full power. This problem was solved by fitting the transformer enclosure with thermocouples during a simulated full-load heat test. We found that in three internal locations where we wanted to place the temperature switches, maximum operating temperatures would not exceed approximately 85° C. Research papers (6,7,8) have reported that temperatures associated with insulator decomposition typically range from 500° C to 1200° C. We therefore specified a temperature switch setting of 110° C, which placed us comfortably above normal operating temperatures and yet well below the temperatures we would expect to see before volatilization started to occur.

5.3 FACTORY TESTING OF THE ASSEMBLED LOADCENTER

The manufacturer conducted numerous tests on the loadcenter prior to shipment. Although all of this testing was necessary and informative, we will discuss only three tests which were particularly relevant to this program:

a. Hydrostatic pressure test of enclosures

b. Heat rise test

c. Electrical tests.

The hydrostatic pressure test was conducted to ensure that the fabricated unit would indeed be able to withstand the explosion-testing for which it was designed. From past experience with similar enclosures, the manufacturer knew that the typical maximum pressure rise in a methane-air explosion test would probably be in the 75 to 90 psi range; but in any case, it would be unlikely for the pressure to exceed 100 psi. Since British regulations require that every enclosure be hydrostatically tested to 150% of the peak pressure recorded in the explosion-testing of the first model, it was decided that the loadcenter enclosures would be hydrostatically tested at 150 psi. This value would also coincide with design pressure according to Part 18 of the United States regulations. Each separate explosion-proof enclosure of the loadcenter was therefore tested to 150 psi, with no evidence of failure or permanent deformation.

The heat rise test was conducted with at least three major objectives in mind:

a. Verification of design calculations for proper cooling of the transformer

b. Determination of maximum surface temperature

c. Determination of minimum temperature set-point for temperature switches.

The heat rise test was conducted by operating the transformer at simulated full electrical power according to recognized testing standards until all temperatures had stabilized or a minimum of 12 h. At least 50 thermocouples were placed around the inside and outside of the transformer tank and within the transformer itself. The following results were obtained:

a. Adequate cooling of the transformer was achieved

b. Surface temperatures of the enclosure did not exceed 150° C

c. Temperature switches located in the transformer tank along the top front edge could be set at 110° C with no risk of tripping during normal operation.

Electrical tests included the following:

a. Voltage withstand

b. Insulation testing.

One test which was not conducted was the corona extinction test recommended in Paragraph 17 of the criteria. As of this writing, MSHA has acquired the loadcenter for Approval testing and for other research purposes; we expect that they will conduct this test at a future date. However, this is one section of the criteria that has not been checked out by actually applying it to the prototype loadcenter. We therefore do not have any insight into the utility or practicality of this test.

5.4 APPLICATION OF THE CRITERIA DURING THE APPROVAL PROCESS

The loadcenter had not been explosion-tested by MSHA as of this writing, however, the Approval Process had been initiated about 18 months earlier, and there was a great deal of discussion with MSHA concerning the design, the hardware, the drawing package and application of the criteria. This discussion gave us a preview of some of the issues which will be raised when others pursue the Approval of high voltage equipment in the future, as well as some insight into how the recommended criteria might be interpreted by others. Most of the Approval process was straightforward; however, there were five major issues which required some clarification and where future applicants for Approval may find some divergence of opinion as to how the criteria and/or Parts 18 and 75 are interpreted:

a. Protection against volatilization of insulators

b. Test conditions for explosion testing

c. Definition of "trailing cable" and maximum allowable lengths

d. Use of ground monitor with explosion-proof receptacles

e. Requirement for back-up ground fault protection.

The following five paragraphs discuss these five issues.

We feel that proper protection against volatilization of insulating material is the single-most important factor in designing a safe high-voltage explosion-proof enclosure. We therefore provided a two-part "protection package." The first choice was to avoid using any insulator which did not pass one of two tests. If the use of such insulators was unavoidable, or if test results on some insulators were unavailable, then safety devices should be used to detect potentially unsafe conditions and interrupt electrical power before the insulators underwent significant decomposition and the resultant release of highly-explosive gases. As of this writing, MSHA seemed to be leaning toward requiring that all insulators be passed by both test methods. This was not our intent in proposing the recommended criteria. As discussed in section 5.2.2, very little test data is presently available in this country; the intent of the criteria was to encourage more work in the area, with the option of using protective devices instead, until the time when high-voltage permissible equipment can be built using only insulating material which minimizes the risk of volatilization.

Another major concern in this program was the potential for excessively high pressures which might be caused by a methane-air ignition in combination with a high-energy arcing fault. We felt that the results of the test program discussed in section 4 adequately justified a limitation of 100 psi for the maximum explosion pressure in a methane-air ignition, thus allowing a 50 psi margin (before reaching the 150 psi design pressure mandated by Part 18) for any increase in pressure due to a simultaneous arcing fault. MSHA's final position on this issue has not yet been established, but they might well reach a different conclusion.

During the Approval process, MSHA chose to define the electrical cable supplying power to the loadcenter as a "trailing cable." This meant that, according to existing regulations, it could have a maximum length of 1000 ft. This interpretation could severely limit the utility of an explosion-proof loadcenter; one of the reasons an operator might want to use an explosion-proof loadcenter is that he wants to locate it thousands of feet from the breaker which feeds it. At this writing, this issue remains unresolved.

The explosion-proof plug-and-receptacle used on the prototype loadcenter has a metal shell on the plug. Existing regulations require that this shell be grounded. As long as the plug is attached to the receptacle, the shell is grounded through the receptacle housing and thus the frame of the transformer. However, when the plug is disconnected, this grounding path is lost. Thus, it is common to connect the shell of the plug to the ground wire in the cable so that it is always grounded. However, if a "wireless" ground monitor is used with this arrangement, then the ground wire in the cable is then tied directly to the frame ground of the loadcenter, effectively shorting out the high frequency signal from the monitor. A "wireless" monitor would therefore continuously trip out because it cannot "hear" the return signal coming back on the ground wire. The easiest way to solve this problem is to avoid bonding the plug shell to the ground wire of the cable, and rely instead on the shell being grounded through the threads of the shell to the threads of the receptacle. Note that as the plug is unscrewed, the design of the explosion-proof plug/receptacle combination is such that the live phase pins in the plug disengage from the receptacle before the coupling is fully un-threaded, as described in section 5.2.1.3. Thus the cable is totally deenergized before the ground between the plug shell and the loadcenter frame is lost. This arrangement seems to be acceptable to MSHA, but it is subject to a different interpretation which would make the use of a "wireless" monitor somewhat difficult. Note that the pilot-wire-type monitor operates on a different principle and would not have this potential problem.

The use of a back-up ground fault system is not, strictly speaking, an issue that relates only to high-volate equipment. However, we have included it because it is a topic which is not required in the existing regulations but has become increasingly widespread. During the design phase of this program, we discussed our plans for the loadcenter with MSHA personnel involved with Part 75 as well as Part 18. They indicated a strong preference to see back-up ground fault protection included in future designs, even though it was not required in the regulations. We therefore included such a system in the loadcenter; future applicants for Approval might wish to consider doing likewise.

6. LITERATURE SEARCH AND STATE-OF-THE-ART REVIEW

6.1 SUMMARY

The first phase of this program included a comprehensive literature search and state-of-the-art review of research and industrial experience with high-voltage explosion-proof transformers. The results have been organized into four major areas:

a. United States Mining Practices (section 6.2)

b. Mining Industry Literature (section 6.3)

c. Related (Utility Industry) Literature (section 6.4)

d. Relevant Regulations (section 6.5).

Detailed information is contained in sections 6.2 through 6.5, which are summarized in the remaining paragraphs of this section.

United States mining practices have included at least five different methods for safely locating transformers inby the last open crosscut:

a. Explosion-proof enclosures

b. Potted transformers

c. Sealed dry-type transformers

d. Purged and pressurized enclosures

e. Enclosures with special ventilation precautions.

Mining industry literature revealed at least four major problem areas associated with high-voltage equipment:

a. Volatilization of insulating materials

b. High energy arcing faults

c. High voltage faults induced by methane/air ignitions

d. Particle ignition.

Related literature showed that the utility industry has had considerable experience and done extensive research on fault-induced overpressurization of oil-filled transformers, with the following results:

a. Critical parameters have been identified and analytical models developed

b. A testing standard has been adopted for enclosures to withstand a specified arcing fault

c. Protective measures have been developed, such as elimination of the oil and use of current-limiting fuses.

Relevant regulations which were of interest to this program included the following:

a. 30 CFR 18 and 75, the United States Coal Mining Standards, which currently limit explosion-proof enclosures to 4160 V, and require 125 psi maximum pressure in explosion testing with no electrical fault testing

b. EN 50018, the European Mining Standards, which have no voltage limit, no electrical arc testing, and require that all enclosures be hydrostatically tested to 150% of pressure recorded during explosion testing of first unit

c. NFPA 70-1981 and U.L. 698, the standards for United States industry, have a nominal 600 V limitation (higher on request) and explosion-test one unit while it is operating at full electrical load.

6.2 U.S. MINING PRACTICES

6.2.1 Introduction

This section contains a brief review of high-voltage power distribution in United States mines (section 6.2.1), followed by a detailed discussion of the different types of available high-voltage equipment for hazardous locations (section 6.2.2 through 6.2.6), including the following enclosure types:

a. Explosion-proof enclosures

b. Potted transformers

c. Sealed, dry-type transformers

d. Purged and pressurized enclosures

e. Ventilated enclosures, with active controls.

Historically, when dc electrical systems predominated in underground mines, transformers and rectifiers were typically located along the main haulageway. Power was distributed to sections via the trolley wire. These transformers, like the rest of the haulage system, were not of permissible (explosion-proof) construction. As larger equipment, particularly continuous miners, came into use, transformers moved onto the section, often supplying both ac and dc power. They remained, however, nonpermissible in construction.

At one time, liquid-filled, sealed dry-type (gas-filled), and ventilated dry-type transformers were available for use in mines. However, the ventilated dry-type predominates today, due largely to economic reasons.

Until recently, coal mine power systems in the United States seldom varied from the requirements set by Parts 18 and 75 of Title 30, CFR (16). A typical mine power system is shown in figure 35. Power enters the mine through the 500 MCM shielded borehole cable. After passing through a disconnect switch near the bottom of the borehole, power travels through shielded cables to transformers located on sections or near conveyor belt drives. These transformers are typically ventilated dry-types of cast coil construction, housed in light sheet metal enclosures and mounted on skids. Secondary voltages range from 110/220 Vac, for utility applications and lighting, to 440 to 1000 Vac for equipment.

None of the transformers shown in figure 35 are classified as face equipment used inby the last open crosscut. Therefore, none are required to be constructed to the standards set by 30 CFR Part 18, and approved as permissible or explosion-proof. All are required to be ventilated by fresh intake air flowing over the loadcenter to the return.

The use of single entry mining systems is not compatible with the power system described above. The power requirements of large machines make it important to keep the transformer

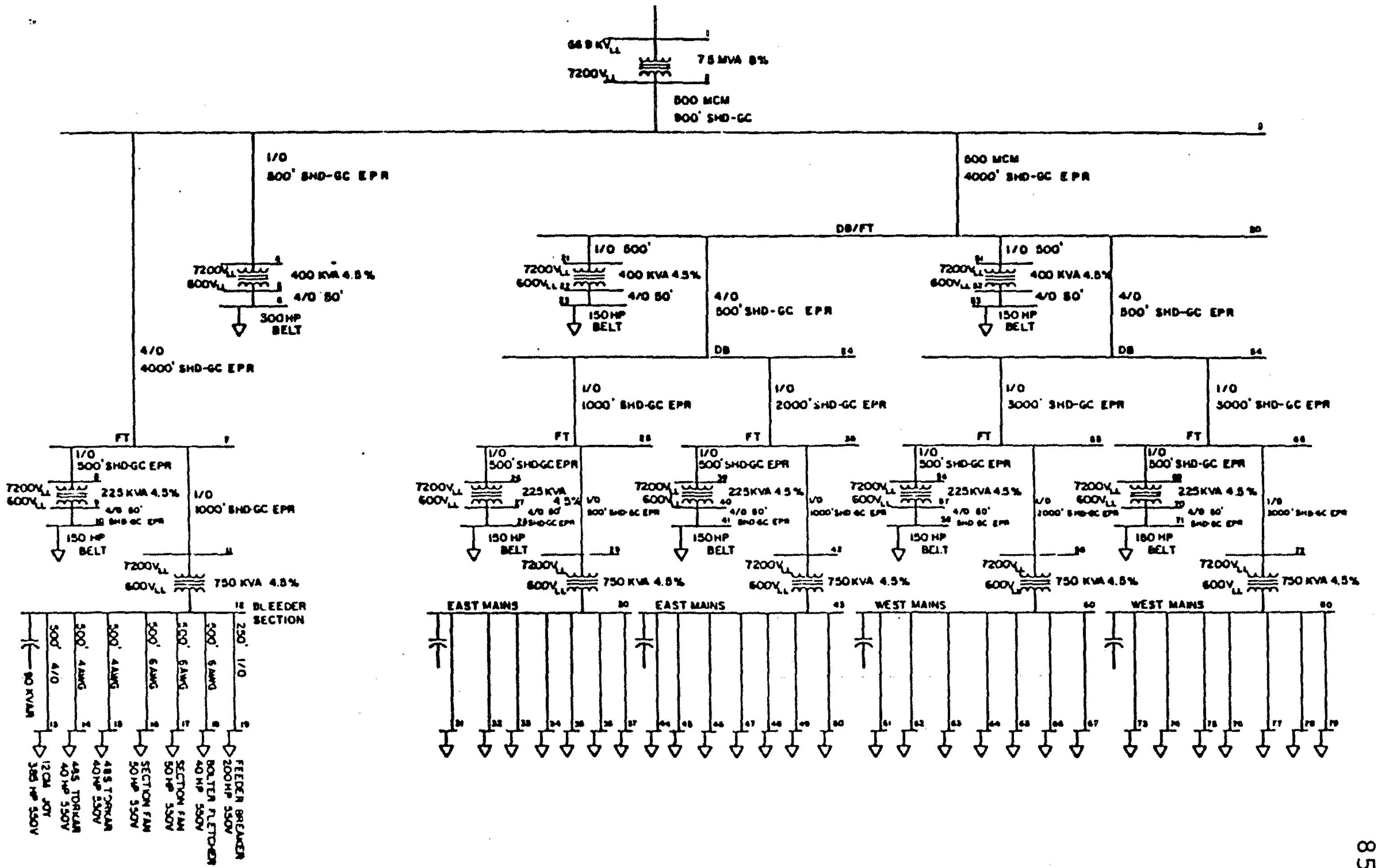


FIGURE 35. - A typical mine power system (21).

reasonably close to the face. Thus, in a long entry or tunnel, it becomes impossible to keep the loadcenter outby the last open crosscut. The next five sections look at five separate approaches aimed at solving this problem.

6.2.2 Explosion-Proof Enclosures

As explained in the previous section, United States coal mines have not used permissible or explosion-proof high-voltage transformers.

Furthermore, although explosion-proof testing and approval is available from Underwriter's Laboratories, Inc. (17), no references were found of instances in which large power transformers were enclosed in tight, explosion-proof enclosures of the type required in the mining industry (18-22). Although no reasons were firmly advanced for this fact, some possibilities are:

a. The ease of maintaining other types of protection in nonmining environments

b. The lower costs associated with some of the alternative techniques

c. The necessity of coping with a variety of hazardous vapors and dusts having different characteristics than CH_4 and coal dust

d. Differences in historical development.

The rest of the western world, with the exception of Australia, have for a number of years, required all electrical equipment, including high-voltage transformers, used in coal mines to be protected by explosion-proof enclosures. The problems arising when this type protection is applied to large, high-voltage transformers are discussed in detail in section 6.3. Many of these problems were first recognized as European equipment grew in response to increased power requirements at the face. An example of a large transformer, with high- and low-voltage switchgear, housed in an explosion-proof enclosure, is shown in figure 36.

Certification tests in the United States have been conducted on one high-voltage explosion-proof transformer enclosure. This work is discussed in the next subsection.

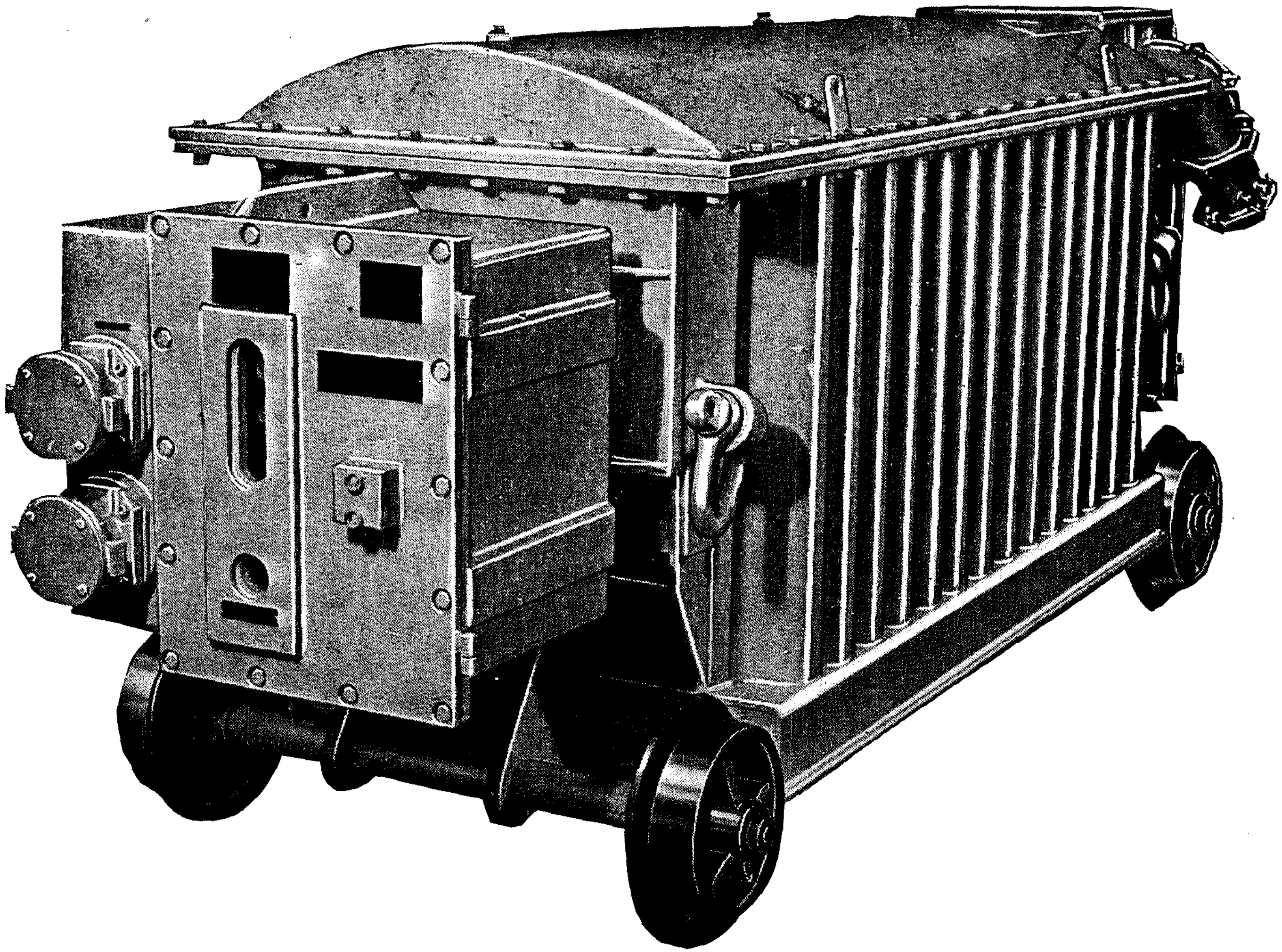


FIGURE 36. - Brush transformers ltd. 750 kVA flameproof mining substation incorporating a dry-type transformer with integral 6.6 kV/SF_6 high-voltage switchgear and low-voltage protection chamber.

6.2.3 Potted Transformers

High-voltage potted transformers, although seldom used, are sometimes proposed for hazardous atmospheres with the theory that the potting compound - be it a resin, sand, or something else can prevent the gassy atmosphere from coming in contact with the high-voltage components. The literature search uncovered one use of such a transformer - an experimental application for a tunnel boring machine. Although this transformer was also housed in an explosion-proof enclosure, the test procedures and results described in the balance of this subsection seem to relate to the nature of the potted transformer rather than the enclosure.

In 1974, Eastern Associated Coal Corporation (EACC) requested MESA (MSHA) approval of a 7200-V tunnel boring machine intended for use in Federal No. 2 Mine. On February 4, 1977, MSHA issued an Experimental Permit for the machine and tunnel project. Included on this machine was a 7200-V primary-potted transformer, housed in an explosion-proof enclosure.

This review is restricted to key decisions involving the boring-machine transformer and associated circuits. This information was compiled from files made available by MSHA's Pittsburgh Technical Support Center, Approval and Certification Center, and Coal Mine Safety and Health District 3. The reader should be aware in considering those decisions that MSHA did not, and still does not, have the authority or the mechanism by which it could "approve" equipment operated at voltages greater than 4160. Further, the mining industry had neither experience nor technology sufficient to define the potential seriousness of electrical and shock hazards with 7200-V mobile systems in underground coal mines; and, nothing was known of the potential fire and toxic product hazards of the potting compound proposed to contain electrical arcing within the transformer. The decisions summarized herein were intended to mitigate those hazards as well as ensure the structural integrity of the transformer enclosure.

Following considerable design changes by the boring machine manufacturer, MSHA, on October 20, 1975, conducted four tests at the Westinghouse High Power Laboratory (West.) to determine if the 7200-V enclosure would maintain its integrity during a short circuit fault. The enclosure failed; it was not of substantial construction. MSHA considered withdrawal of its "approval" for the 4160-V version of the tunnel boring machine. The tests and results are shown in table 8.

TABLE 8. - Test results, 20 October 1975

Test	Fault Current Amperes Peak-Peak	Cycles, No.	
1. Arc in top section of enclosure	6250 to 8000	14-1/2	One lid permanently deformed approximately 3 in. Flames came out through a joint between the lid and the case.
2. Arc in bottom section of enclosure	7500	1/2	Arc quenched
3. Repeat of 2	7500	1/2	Arc quenched
4. Repeat of 1	5500 to 7500	31-1/2	Five bolts on side cover plate broke; plate warped.

MSHA then stated preliminary requirements for its further consideration were that the transformer had to be in a case which would withstand at least four phase-to-phase short circuits at the maximum available fault current. The duration of the current was a minimum of eight cycles or twice the breaker clearing time, whichever was greater. While being subjected to these tests there was to be no: discharge of flame or sparks; rupture of any part of the enclosure; permanent distortion exceeding 0.040 in./linear foot; surface area temperature in excess of 302° F; or, ignition of a surrounding explosive methane-air mixture. Additionally, the enclosure was to have overcurrent protection using two independent circuit breakers in series, one of which was to be outside the mine. Both were to be set at 50% of the available phase-to-phase short circuit current and clear the fault within one-half the test time. The transformer was to have thermal overload protection set to remove the primary power before the insulation temperature rating was exceeded.

In November 1975, EACC and MSHA agreed high-voltage, current-limiting type fuses could be used in an attempt to limit the energy in the transformer case during a fault. The fuses were expected to decrease the duration of the short circuit time from eight to three cycles.

The transformer was tested February 28, 1976, at Westinghouse; this transformer (shown on McGuire Corporation's drawing No. 09-08-006A) had these new features: wide steel flanges on the external surfaces of the lower and top compartments; 1/2 x 3-in. web stiffeners added to the web of the 15-in. channel that formed the top compartment; a mating surface gap of 0.020 in. between the lid and the channel; no gasket in the gap; and, to increase the length of flame path a 1-1/4-in.^{2} box was attached to the bottom of the lid. Additionally, 3 in. at the top of the case were potted with GE RTV. The test schedule to determine if the enclosure could contain a short circuit fault with the coordinated circuit protection device is shown in table 9.

TABLE 9. - Test schedule, 28 February 1976

1. Four tests at three cycles at maximum amperes

2. Two faults in the upper compartment and two faults in the lower compartment

3. A current limiting fuse in the upper compartment in the first test

4. A 2-in.^{3} air void between the terminals for one test in the upper and in a second test in the lower compartment.

No flame was observed during the tests. The external temperature of the enclosure was below 140° F and there was no detectable distortion of the transformer case. MSHA believed the transformer construction was adequate.

The tests were repeated in March 1976, to evaluate further the reduced clearing times of the current-limiting fuses. Again, the transformer enclosure endured the four prescribed phase-to-phase short circuit faults. It was agreed to make the following changes:

a. Four independent circuit breakers in series to provide backup overcurrent protection for the transformer in addition to 125 E current limit fuses

b. All four were to be set at or less than 50% of the available 3500-A fault current. All breakers were to clear the fault within 0.2 s; the current limiting fuses within one cycle

c. Transformer thermal overload protection (290° F) was to be provided by a temperature relay which would open the ground check circuit to the first outby switch house

d. Emergency deenergizing device connected into the trip circuit of the first outby circuit breaker. Two Kirk Key locks on two high-voltage cable couplers; a third lock was on the high-voltage oil-circuit breaker.

The in-mine interconnection between the transformer and the main circuit breaker enclosure was sealed. Rope asbestos packing prevented the sealing compound from running into the main circuit breaker enclosure. Crouse-Hinds Chico A-5 sealing compound was poured into the interconnection filling completely the cavity between the two enclosures. The filling-pipe tee was plugged to prevent moisture and dust from entering.

Dielectric resistance and protective device operation tests conducted underground are described in Investigative Reports No. H050477 and No. C011377 (MSHA Pgh. T.S.). The result of these changes and tests was the Experimental Permit granted by MSHA on February 4, 1977; the Permit limited the use of the 7200-V tunnel boring machine to the conduct of work given in the Bureau Contract No. J0144075.

6.2.4 Sealed Dry-Type Transformers

This technique involves sealing the transformer in a welded enclosure, pressurized (10 to 12 psi) with an inert gas. Nitrogen filled transformers have been available since the 1940s. Other gases, notably C_2F_6, are generally used today due to advantageous combinations of dielectric strength, cooling effectiveness, and cost. Use of the welded enclosure is justified by the fact that faulted transformers are generally not repairable in the field. The high-voltage switchgear can be located upstream in nonhazardous areas and low-voltage gear can be protected by other techniques allowing field access. This type transformer was marketed by Westinghouse to the mining industry in the two decades prior to 1970. An example is shown in figure 37.

The safety of Westinghouse's sealed dry-type transformer was established in Tipton's work (23). In those experiments, a transformer was severely overloaded for long periods (hours) until failure, without fire or explosion, eventually

mine power centers

75 to 750 kva • 3 phase • 60 cycle
ventilated or sealed dry type • Inerteen

descriptive bulletin
47-355
page 3

(1) **high voltage terminal compartment**

(2) **transformer compartment**

(3) **low voltage panelboard compartment**

(5) **lighting outlet receptacles**

(6) **low voltage power outlet receptacles**

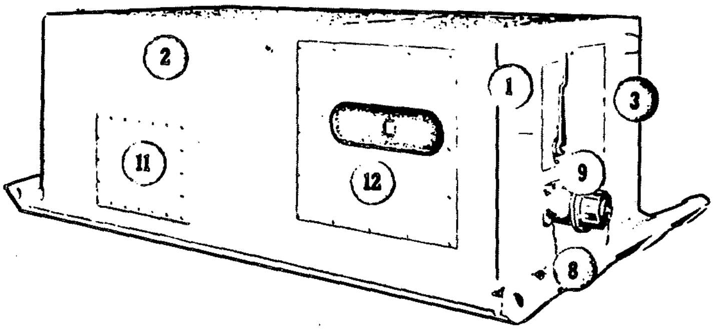
(8) **skid base**

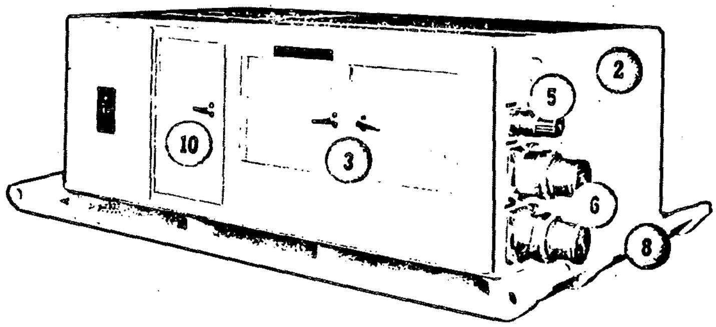
(9) **high voltage cable connectors**

(10) **equipment compartment**

(11) **tap changer access plate**

(12) **switch housing**





high voltage
2400 through 13800 delta

low voltage
240Y/138, 480Y/277

sealed dry type

Shown above is a back and front view of a typical sealed dry type mine power center.

Instead of being completely enclosed in one cabinet like the ventilated construction—page 2—the sealed unit is compartmented. The individual welded on high voltage compartment, transformer compartment, low voltage compartment, and such miscellaneous compartments as capacitor compartment are mounted on a rugged sled base assembly. The individual compartments are braced by the interconnecting flanges, throats, etc.

The core and coils of the transformer are hermetically sealed in a rugged nitrogen-filled case and are completely protected against any water damage or effects of extremely high humidity (even when de-energized during prolonged shutdowns), dust and other contaminants. The panelboard and associated equipment is mounted in a dust tight compartment separate from the transformer compartment and connected by means of a throat to the transformer compartment. Capacitors are mounted in ventilated compartments for adequate cooling. The same high voltage and low voltage accessories are available for the sealed as for the ventilated dry type unit described on page 2.

November, 1959
new information
mailed to: E/384/PL; C/414/DB

FIGURE 37. - Sealed dry-type transformer.

occurred. Arcing faults initiated inside the enclosure with fault currents of four-times full load current were maintained for first 85, and then 238, cycles. Neither fault resulted in a pressure rise within the transformer enclosure.

Use of these transformers in mining applications was highly recommended by Westinghouse engineers. However, based on Westinghouse's earlier experience manufacturing mine power centers, their personnel do not feel the mining industry is willing to bear the added costs of these transformers. A C_2F_6 filled, sealed dry-type is about 200% more costly than a comparable oil-filled transformer. A ventilated dry-type with a cast coil, typically used in mining power centers, costs about 160% to 170% of an oil-filled.

The largest customer for transformers of this type is General Motors Corporation (GMC). GMC typically buys 2000 kV.A, 15 kV units, costing approximately $38,000 to $40,000 each for indoor use in assembly plants. Although added safety is a consideration, the primary reason GMC selects this transformer is its extremely high reliability (19,20).

6.2.5 Purged and Pressurized Enclosures

Another technique commonly employed is purging or pressurizing instruments, small enclosures, control rooms, or large power equipment enclosures. In other words, instead of sealing the enclosure to prevent contact with dangerous gases, a positive air-pressure is maintained so that leakage is always out of the enclosure, never in. Standards for this technique are set forth in National Fire Protection Association Publication No. 493 (24). Requirements include:

a. Specification of a minimum allowable positive pressure of 0.1 in. of water

b. Maximum temperature levels for enclosures and egress air

c. Provision of system failure alarm devices

d. Guidelines for pressurizing and purging air sources and delivery systems.

Application of this standard in mining environment would result in systems very much like those described in the MSHA Modification Petitions (25,26) discussed below.

The Mandatory Safety Standard, 30 CFR 77.1914(a), provides as follows:

> "Electric equipment employed below the collar of a slope or shaft during excavation shall be permissible and shall be maintained in a permissible condition."

In 1978, a modification of this standard was granted to United States Steel Corp., allowing for use of a nonpermissible loadcenter to power a blind shaft boring machine (25). A similar modification was granted to United Pocahontas Coal Company in 1979 (26). Following is a review of the major features of these modifications.

The United States Steel Modification (25) involves the use of a standard mine power center located on the galloway stage of a vertical boring machine. The power center is fed at 7200 V from a surface circuit breaker through shielded high-voltage cables. Three methane monitors and three emergency stop stations are located at strategic points, all of which are capable of causing the surface breaker to open.

The ventilation system consists of two 100-hp Joy fans connected, respectively, to a blowing and an exhausting system. The blowing system directs ~26,000 CFM down the shaft through a 36-in. duct terminating ~10 ft below the galloway platform. The exhausting system draws ~19,000 CFM from the face area to the surface. The excess air goes up the shaft.

A separate duct taps the intake tubing as it passes the transformer and directs ~1500 CFM through the transformer and into the exhausting duct. Transformer pressure is approximately 2 in. of water. Flow through the transformer is regulated by placing a gate valve in the exhausting (transformer) duct. Additional interlocks and safeguards include:

a. A surface interlock preventing power from being switched on until the intake fan has been running for a minimum of 1 min

b. A pressure switch on the transformer which will deenergize the system when pressure drops below 0.1 in. of water and prevent it from being energized until pressure exceeds 0.1 in. of water

c. A surface interlock which will deenergize the system if the intake fan stops.

The United Pocahontas Coal Company system is similar except that the nonpermissible power center is located 80 ft behind a permissible Armco-Jarva Tunnel Boring Machine, which is boring a 15-deg inclined slope. Ventilation for the power center is activated by an air mover powered by compressed air. The mover circulates 1500 cfm through the power center, maintaining a pressure of 1.0 in. of water while the system is energized. The power supply for the compressed air is separate from the mine power. In addition, a diesel-powered backup compressor is stationed at the mouth of the slope, equipped with "quick-connect" couplings.

Interlocks like those in the United States Steel modification are required. In addition:

a. The ground check circuit is required to be intrinsically safe

b. Thermocouples in the core of each transformer are interlocked with the ground check system and set at 150° C

c. Weekly and daily examinations of the system must be performed and recorded

d. Electrical circuits shall not be energized following a fan failure until the slope has been examined by a certified person and tested for methane.

6.2.6 Ventilated Enclosures with Active Controls

A recent development in United States mining has been the use of nonpermissible transformers in single-entry systems provided that air flow and methane sensors are utilized such that operation is allowed only when a safe atmosphere (ventilation) is present at the loadcenter.

In 1980, a modification of 30 CFR 75.500(a)[1] was granted to Keystone Coal Mining Corporation (27,28). A nonpermissible transformer in an open enclosure, coupled with a

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[1]"All junction or distribution boxes used for making multiple power connections inby the last open crosscut shall be permissible;"

secondary permissible enclosure containing all arc producing equipment, such as relays and circuit breakers, is proposed for use in powering a permissible Jarva tunneling machine. Requirements of the modification include:

a. Provision of a separate switch house located at the outby end of the tunnel, equipped with appropriate protective devices (overloads, undervoltage, ground check, ground fault)

b. The transformer must be kept at least 150 ft behind the tunneling machine

c. Air flow switches will be provided at the auxiliary fan supplying air to the tunnel and near the transformer (set at 100 fpm). These switches will deenergize all circuits coming into the tunnel if ventilation is lost, and will prevent power from being restored until air flow resumes

d. Methane monitors and emergency stop switches will be provided at both tunneling machine and transformer, capable of deenergizing all power in the tunnel.

Air will be exhausted from the tunnel through a 24-in. duct suspended from the roof. Approximately 14,000 cfm will be drawn into the tunnel moving across the transformer and up to the face. The primary sources of protection from a methane ignition caused by the exposed transformer appear to be the air flow switch and the methane monitor provided at the transformer.

An identical modification petition has been submitted by Jim Walter Resources and is likely to be granted soon (29).

6.3 MINING INDUSTRY LITERATURE REVIEW

This section is based on a review of the foreign and domestic literature concerning the use of explosion-proof equipment in mine electrical systems. Particular emphasis is given to works addressing the problems associated with the use of high voltage components in explosion-proof enclosures. Although some of the most significant works are discussed in detail, no attempt is made to summarize each source. The purpose of this section is to integrate the data and information contained in these references, organize it by subject area, and evaluate it for its usefulness in specifying design, testing, and approval criteria.

Many of the works reviewed come from foreign sources. The only work done in the United States has been sponsored by USBM. This is no doubt due to the fact that most countries require that all electrical equipment used underground be protected with explosion-proof enclosures. Thus, the problems associated with enclosing large pieces of high-voltage equipment (such as loadcenters) were encountered earlier abroad than in the United States. No units are reported operating at the uppermost limits of voltage and power of concern to this program, 15 kV and 2000 kV.A. However, explosion-proof enclosures operating at 11 kV and 1250 kV.A are commercially available and not uncommon.

The mining industry literature and test data on explosion-proof enclosures of this size can be classified into four major areas:

a. Volatilization of insulating materials (section 6.3.1)

b. High-energy arcing faults (section 6.3.2)

c. Electrical clearances; effects of flame fronts (section 6.3.3)

d. Particle ignition (section 6.3.4).

6.3.1 <u>Volatilization of Insulating Materials</u>

Virtually all researchers investigating explosion-proof enclosure failures devote either all or a part of their attention to volatilization of insulating materials. This phenomenon is thought to be responsible for all reported incidents of enclosure failure due to overpressurization (6-10, 30-37). Failure can occur when the high temperature of an electrical arc decomposes solid material and drives the volatile material into the air, thereby increasing the pressure in the enclosure. Most researchers were concerned with volatilization in the presence of a low-current fault (less than 500 A), as discussed in this subsection. Volatilization in the presence of high current faults is part of section 6.3.2.

6.3.1.1 Classification of Insulating Materials

Low current phase-to-phase arcing faults are particularly hazardous in explosion-proof enclosures due to the difficulty involved in their detection. If these faults, which can last for long periods (several seconds), are supported by or come in contact with certain materials such as organic plastics, large amounts of gas may be evolved resulting in enclosure failure (7,10,31). This phenomenon has been duplicated experimentally in several of the references noted above.

The most significant work done abroad on this problem is that of Lord and Barbero (6,7) and later extended by Pearson (9). In these experiments, the authors used a 440 V ac, 400 A arc to evaluate the suitability of several plastic insulating materials. This work resulted in the division of the materials into three groups:

a. Those found to be self-extinguishing

b. Those allowing an arc to burn while the voltage was applied, but did not allow restriking after a momentary shutoff

c. Those allowing both the arc to burn and to restrike.

The authors tabulated test results for several plastics and other insulating materials (listed by common and trade names), identifying phenolic resins and epoxides as being particularly hazardous. The comparative tracking index (CTI) is also listed for these materials. CTI has been used by some manufacturers in screening materials.

Pearson evaluated several standard arc tests, selecting one that most closely resembles the experimental conditions of Lord and Barbero's work, and applying it to the same materials. This test, called the fuse wire arc test, is described in appendix I of reference 26. While not totally successful in grading all the materials in the three groups, Pearson found that all those placed in the first group by Lord and Barbero passed the test, while those placed in the second and third groups failed. Thus, Pearson concludes that this test is a simple and effective method of selecting arc-resistant materials.

Domestically, the approach has been more general. USBM, alerted to this problem by the incidents and experiments described in the foreign literature, has sponsored work which identifies available sources of information on insulating materials (32-35,37): Two of these works (32,35) present extensive bibliographies from the scientific literature.

In summary, the literature shows that:

a. Certain materials have been identified as hazardous when exposed to arcs in explosion-proof enclosures, such as phenolic resins

b. Certain materials have been identified as safe for use in enclosures, such as polyester dough molding compounds

c. There exist testing techniques and classification schemes to aid in material selection. In addition, new techniques are being developed.

6.3.1.2 Protective Measures

Several protective measures are currently employed or under consideration by manufacturers and users of large, high-voltage, explosion-proof machines. Some of these measures are:

a. Material restrictions

b. Phase sensitive short circuit protection

c. Adequate insulation and clearances

d. Active controls

e. Pressure relief devices.

Each of these measures is discussed in more detail on the following pages.

Material restrictions - Certain materials are totally excluded, wherever possible, from the interior of enclosures. If total exclusion is not possible, components containing undesirable materials are located so as to minimize the possibility of contact with arcs. The trend by electrical equipment manufacturers toward increased use of organic plastics makes it highly unlikely that all offending materials can be totally excluded (34).

Phase sensitive short circuit protection - One of the conditions aggravating this problem is the use of more powerful machinery fed by longer cables, resulting in short circuit protective devices being set at levels too high to detect high impedance (low current) arcing faults. Thus, one response was the development of a protective device that can distinguish between a fault current and a motor starting current. Such a device is described by Gray (38) and is currently required in the United Kingdom.

This protective device depends upon the difference in phase angle existing between motor starting voltage and current (fig. 38a) and short circuit voltage and current (fig. 38b). As can be seen from the figures, the in-phase component of the current is much larger for the short circuit than for the motor starting. Figure 39 shows a circuit designed to detect only the in-phase component of current. A typical application in a 120 hp motor circuit allows the short circuit trip setting to be reduced to 240 A, even though motor starting current is 750 A without causing spurious tripping.

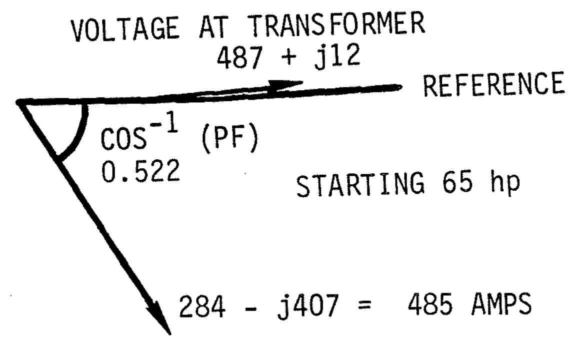
An even more sensitive device has since been developed and is currently undergoing field trials. This device, described by Lord and Pearson (39), is capable of detecting faults in an induction motor circuit at levels of only half the maximum full load current. When fully developed and applied, this device will give a factor of 18 reduction in trip settings compared with conventional instantaneous short circuit fault protection systems.

Phase segregation - In order to take advantage of the relative ease with which ground faults can be detected and controlled, phase segregation is practiced. This technique consists of placing grounded, metallic shields and barriers between each of the phases, thus precluding the possibility of a direct, short circuit fault.

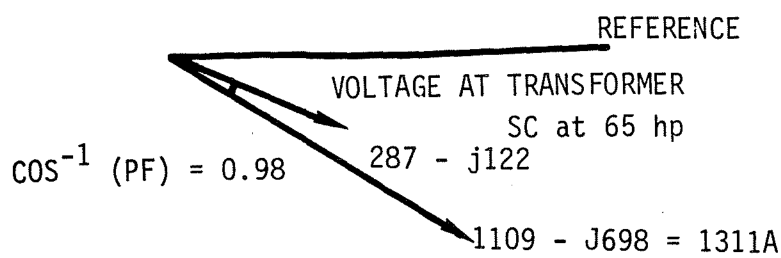
Adequate insulation and clearances - To prevent the occurrence of faults, particularly in high-voltage applications, adequate attention is paid to provide proper insulation and clearances. Corona detection tests are performed at critical points in the manufacturing process to identify areas of high electrical stress.

"Active" controls (for example, pressure and temperature sensors) have been proposed for use in enclosures. In particular, a temperature sensor has been developed for this application (see Lord and Davidson (8)). However, such devices are generally not used in Europe for the following reasons:

a. The other measures described are believed to give adequate protection from this hazard



a) MOTOR STARTING CURRENT AND VOLTAGE



b) SHORT CIRCUIT CURRENT AND VOLTAGE

FIGURE 38. - Current and voltage (38).

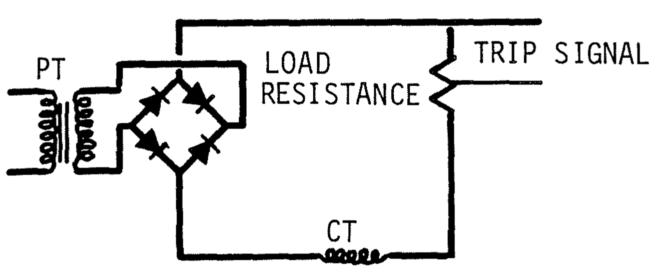


FIGURE 39. - Diagram of single phase, phase sensitive short circuit protection; for a three-phase circuit this is repeated three times (38).

b. While the devices themselves are relatively inexpensive, modifying many existing mine power systems to allow for their use would be very costly.

The disadvantage existing abroad concerning the application of temperature and/or pressure sensors (that is, expense of modifying existing power systems) does not apply in the United States. The universal existence of ground check ("pilot") circuits in United States mine electrical systems simplifies the control aspects of using these devices. The relatively small cost of this added protection would seem to make it difficult to justify their exclusion from explosion-proof enclosures.

Pressure relief devices are available and have been shown to be effective against overpressurization of enclosures due to methane/air explosions. However, their use does not appear to be appropriate for this hazard. Unlike the gases generated by a methane/air explosion, those generated by volatilization of insulation materials can include H_2, CO, C_2H_2, C_2H_4 and other hydrocarbons. When expelled from the enclosure they may be hot enough to ignite in the surrounding atmosphere.

6.3.2 High Energy Arcing Faults

Internal pressure rises can also occur due to the energy dissipated by arcing faults in tight enclosures. Low-energy (current) arcs (without materials volatilization) can, given time, deposit excessive amounts of energy in an enclosure. However, the precautions described in section 3.1 should be more than adequate in guarding against this possibility. Therefore, the following discussion focuses on the problems associated with high-energy (current) faults in explosion-proof enclosures. High current faults are those which are presumed to activate the circuit protective devices.

In the simplest situation, the arc occurs in air and the pressure rise is due entirely to heating of the enclosure atmosphere. The following sections discuss the important variables affecting the pressure rise (section 3.2.1), an analysis of the relationship between these variables (section 3.2.2), and protective measures to prevent overpressurization due to arcing faults (section 3.2.3).

6.3.2.1 Important Variables

Enclosure failure due to high-energy arcing faults does not appear to be a major problem in countries requiring the use of explosion-proof enclosures. The enclosure failure produced by MSHA testing of the transformer used at Eastern Associated's Federal No. 2 mine appears to be the only recorded failure of this type. Thus, little experimental work is found in the foreign literature. A review of the industry references (30,33,34,36,37,40,41), the additional references (13-42), and the analogous utility industry work discussed in section 6.4, indicates that pressure rise in the enclosure due to a high energy arcing fault depends on the following important variables:

a. Arc characteristics (length, resistance, pressure and temperature, orientation - that is, vertical or horizontal, etc.

b. Fault location (more energy transfer would be expected from an arc between two exposed terminals than from an arc confined by the transformer windings)

c. Available energy (fault power available and system clearing time)

d. Characteristics of the enclosure (volume, flange gap width and length, and other pressure relief devices)

e. Presence of methane, water, or volatile insulator and conductor materials.

The effects of these variables are discussed in more detail in the following paragraphs.

Ciok (30), Killing and Tielke (33), and Marinovic (41) all used high current arcs in their experiments. Marinovic was primarily concerned with MESGs.[2] His work shows that high fault currents can lower the MESG for methane significantly. However, the lowest value found was 0.25 mm (0.010 in.), which is still well above the 0.004 in. MSHA standard. Killing

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[2]Maximum experimental safe gap: methane/air explosions are vented between a mating pair of flanges to determine the maximum gap which prevents the escaping flame from igniting a surrounding methane/air mixture.

and Tielke were also primarily concerned with the effects of flange gaps, with emphasis on the particle ignition phenomenon (see subsection 3.4).

Ciok's experiments involved the initiation of high-power (10 to 150 mVA) three-phase arcs inside enclosures of 0.06, 0.25, and 0.5 m^3. He was able to identify several of the important variables:

a. Pressure rise increases with short circuit power (or increasing fault current)

b. Pressure rise decreases with increasing volume

c. The use of epoxide, rather than porcelain insulators resulted in significantly higher pressure rises

d. The presence of methane resulted in higher pressure rises (slightly greater than 20%).

Ciok also attempted to determine the effect of the presence of water in the enclosure, but his results are inconclusive.[3] The effect of the flange gap, in both decreasing (venting) enclosure pressure and in allowing emission of hot particles, was also studied. Under all test conditions the minimum gap found to insure non-propagation was again much larger than 0.004 in.

Ciok's work is significant in that it gives some idea as to the magnitude of pressure rise one might expect for several values of fault current and other variables. However, there are certain questions left unanswered. For instance, arc length has been shown to be a significant factor in determining arc resistance, which, in turn, will affect the power dissipated by the arc. However, Ciok does not refer to this variable in describing most of his experiments. A variation in arc length may very well explain why Ciok's data shows only a 25% pressure decrease resulting from a greater than 800% increase in enclosure volume.

Another question is raised by the manner in which Ciok initiates his arc. Van Warrington (43,44) has shown that the presence of copper vapor in an arc initiated by fusing a

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[3]The Bureau-sponsored research at Pennsylvania State University has shown that the presence of water in the arc path causes the pressure rise to decrease. See references (40) and (34).

copper wire, as Ciok did, significantly lowers the arc resistance. This affects the power dissipated by the arc.

Similarly, an arc initiated by, or in the presence of, a methane/air flame front may be lower in resistance than an arc in air. This may explain why Ciok's data shows only a 2.5 bar pressure rise increase for a fault in the 0.25 m^3 enclosure with 8.5% methane present, when one might normally expect to see two or three times that pressure increase if a simple additive relationship were assumed (that is, total pressure rise equals contribution of the arc plus contribution of the CH_4 explosion).

6.3.2.2 Protective Measures

As mentioned, failure of enclosures due to high energy faults is not common among European makers or users of explosion-proof loadcenters. Since such failures are theoretically possible, particularly in small enclosures, credit for their absence must go to the protective measures utilized. These measures are discussed below.

6.3.2.2.1 Protective Measures Currently Utilized by European Manufacturers

These measures focus on adequate component and enclosures design. Such measures include:

a. Adequate insulation and clearances

b. Proper design to eliminate areas of high electrical stress

c. Proper selection of insulating materials (that is, nonvolatilizing)

d. Use of appropriate circuit protective devices

e. Provision of adequate free volume in enclosures.

Free volume in transformer enclosures is usually dictated by size specifications needed for adequate cooling and proper electrical clearances. The gross and net volumes for units currently manufactured by Brush Transformers are shown in table 10. For smaller enclosures, where adequate volumes cannot be provided, phase segregation is practiced.

TABLE 10. - Gross and net volumes for explosion-proof transformers currently manufactured by Brush Transformers, Ltd.

(kV A)	Net volume (m^3)	Gross volume (m^3)	Ratio net volume/ gross volume
300	0.421	0.981	0.43
500	0.961	1.367	0.70
750	1.087	1.827	0.59
1000 (6.6 kV)	1.197	2.061	0.58
1000 (11 kV)	1.449	2.239	0.65

These measures have resulted in extended operating periods without experiencing failure from high current arcing. However, additional safeguards are available for use as situations demand.

6.3.2.2.2 Additional Measures

Current European practice is to design for the pressure rise expected from a methane/air explosion (plus safety factor). Thus, the most obvious additional safeguard is specification of a higher design pressure. This may sometimes be practical, but factors of size and weight are often critical in mining situations.

A second possibility is to limit the available fault energy. This may be done by the addition of impedance into the circuit (that is, use of longer cables), or specification of faster fault interrupting devices. Both of these solutions, while adequate in certain situations, may sometimes be inappropriate.

A third alternative is the use of the current limiting fuse. Figure 40 illustrates the current limiting effect of these fuses. Figure 41 shows a typical oscillogram of a current limiting fuse operation on a short circuit in a 15-kV circuit.

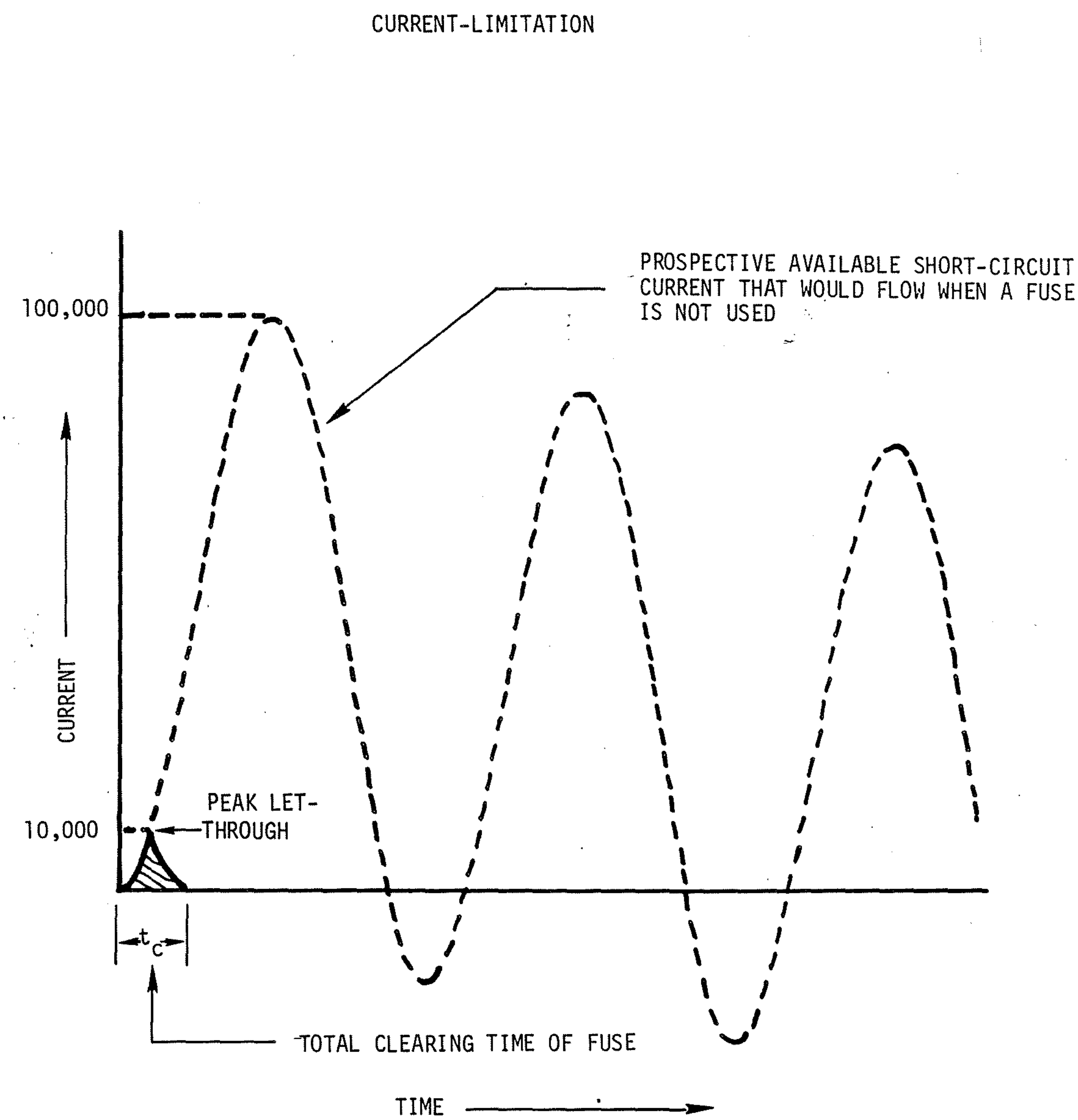


FIGURE 40. - Current limiting effect of a current limiting fuse (44). (See additional sources in the bibliography in Appendix B.)

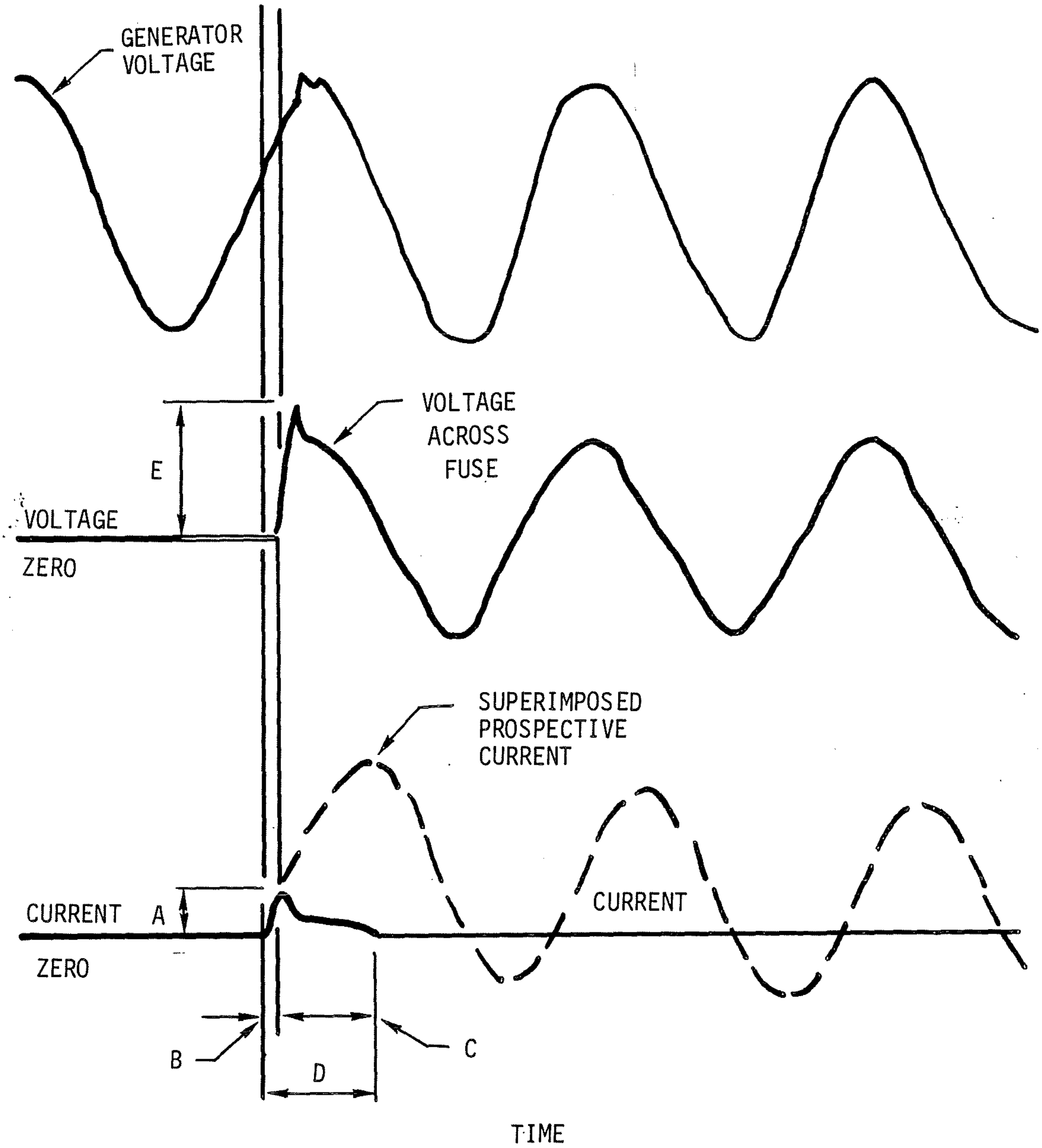


FIGURE 41. - Typical oscillogram of fuse operation on short circuit (100E14) (45). (See additional sources in the bibliography in appendix B.)

As will be discussed in section 6.4, these fuses are often used in the utility industry for an analogous purpose - that is, prevention of overpressurization due to high energy faults in pad and pole-mounted utility distribution transformers.

Although current limiting fuses have not been applied in European equipment, they were successfully used in the Federal No. 2 transformer discussed in section 2.1. Results of the MSHA tests performed with these fuses in the circuit verify their effectiveness in limiting both current availability and fault duration.

Another possible protective measure involves use of the enclosure itself to absorb the energy from a fault. As will be discussed in section 6.4, this measure is often employed by the utility industry to prevent rupture of oil-filled transformer enclosures. However, this results in a permanent deformation of the enclosure and would thus not be allowable under current Part 18 Requirements. Due to the necessity of ruggedness and structural integrity in mining equipment, it is probably best if measures other than plastic deformation of the enclosure are used if at all possible.

6.3.3 High Voltage Faults Induced by Methane/Air Explosions (Adequacy of Electrical Clearances)

A methane/air flame produces free ions which cause a current to flow whenever the flame bridges two electrodes of different polarity. As voltage levels in explosures increase, so too does the possibility that such currents will result in the initiation of self-sustaining electrical arcs.

Researchers at the Canadian Explosive Atmospheres Laboratory (1) investigated this problem for voltages up to 5000 V ac. Figure 42 shows the results of this work. It is noted that for a pointed electrode, a substantially larger gap is required at a given voltage to prevent arcing than for a rounded electrode. Thus, attention must be paid to the shape of exposed conductors in an explosion-proof enclosure.

This work was extended to 15 kV by USBM in-house experimental work using 12-mm diam spherical electrodes (2). These results are presented in figure 43. The researchers recommend a safety factor of 50% for use in actual spacing. Figure 44 extrapolates the Canadian data for round electrodes to 15 kV (assuming linearity) and compares the two sets of data. The Canadian work is clearly the most conservative.

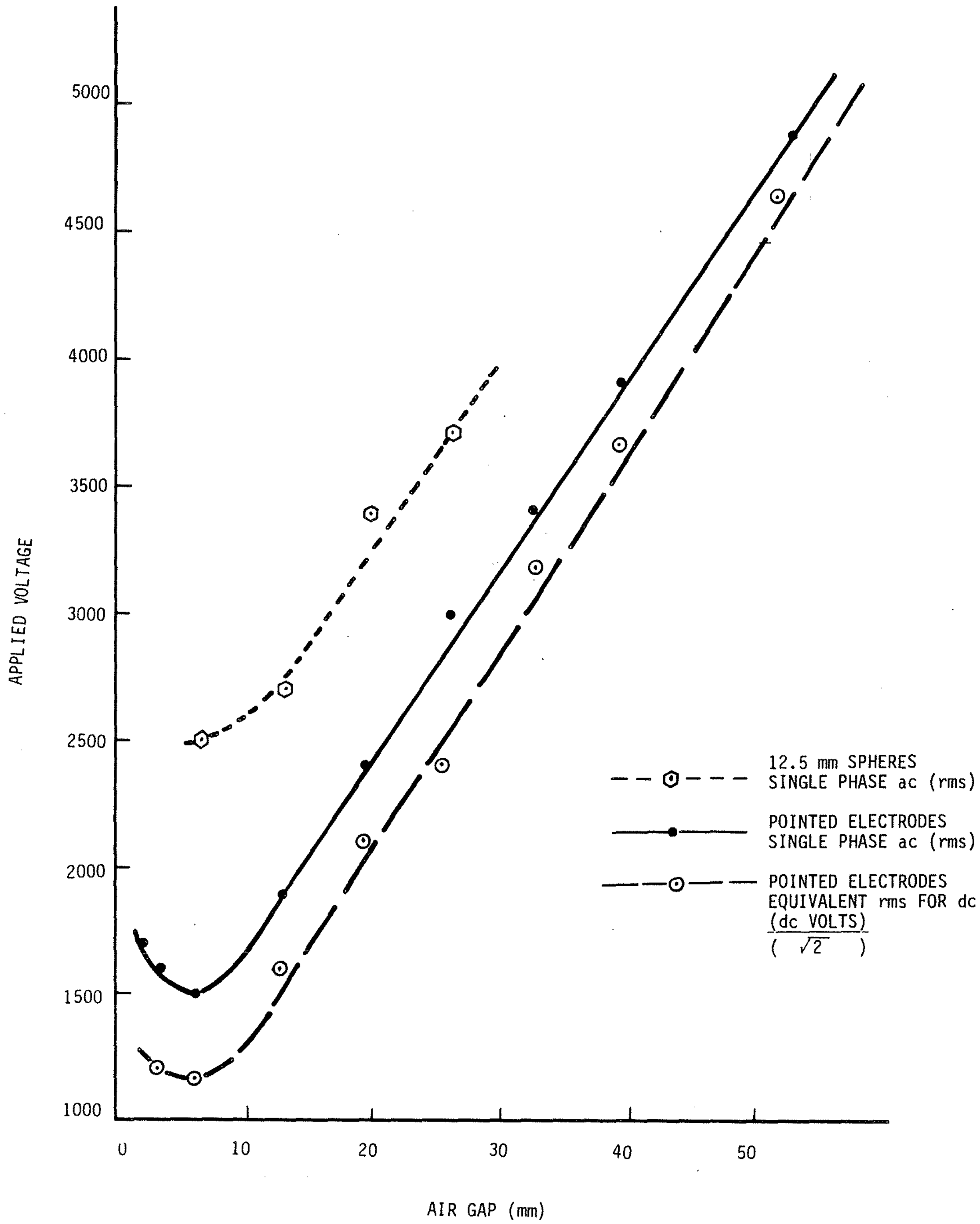


FIGURE 42. - Minimum arc voltage versus air gap for 9.8% methane/air mixtures (1).

However, addition of the 50% safety factor to USBM data essentially equalizes the two sets. For example, both would then require 6.75-in. spacing at 15 kV.

For a large, complex piece of equipment with varying conductor shapes and sizes, spacing recommendations based on the above data may be difficult to apply. One solution is to explosion-test each enclosure with power applied to the components (perhaps operating at full load, or even overload, capacity). Any arcing between phases or phase to ground would be indicative of inadequate clearances. The manufacturer would then be required to increase the spacing between the affected parts, or cover and/or shield the exposed conductors from contact with the methane/air flame front.

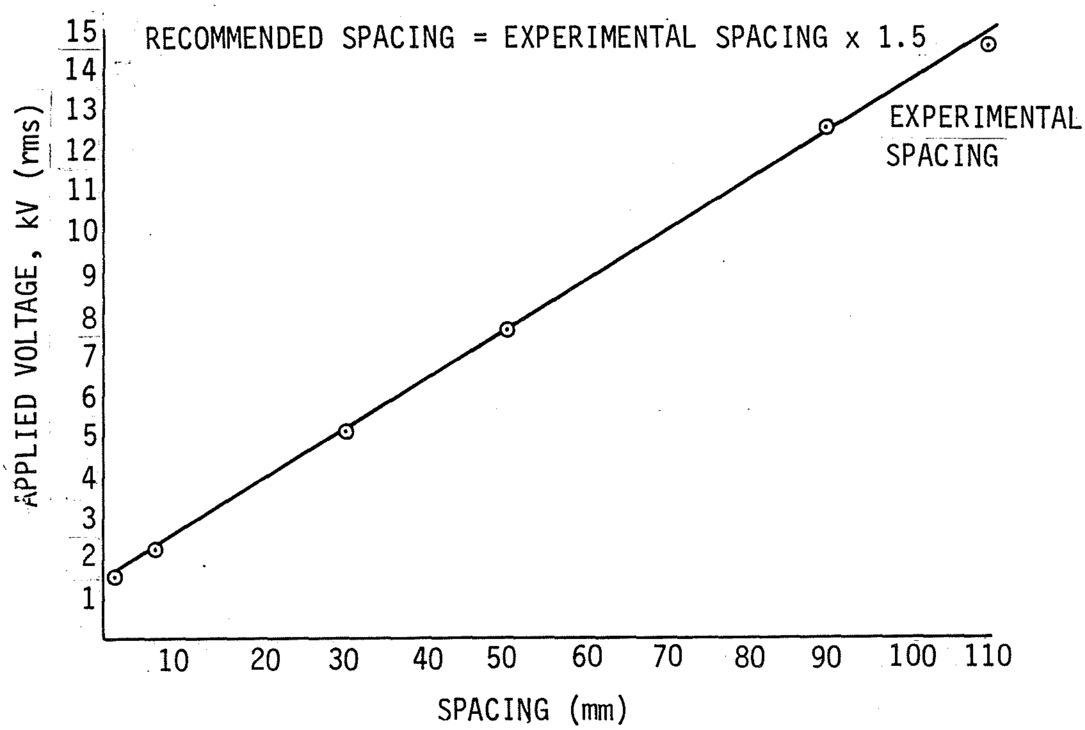


FIGURE 43. - Minimum arc voltage versus air gap spacing (9.8% CH_4-air mixture).

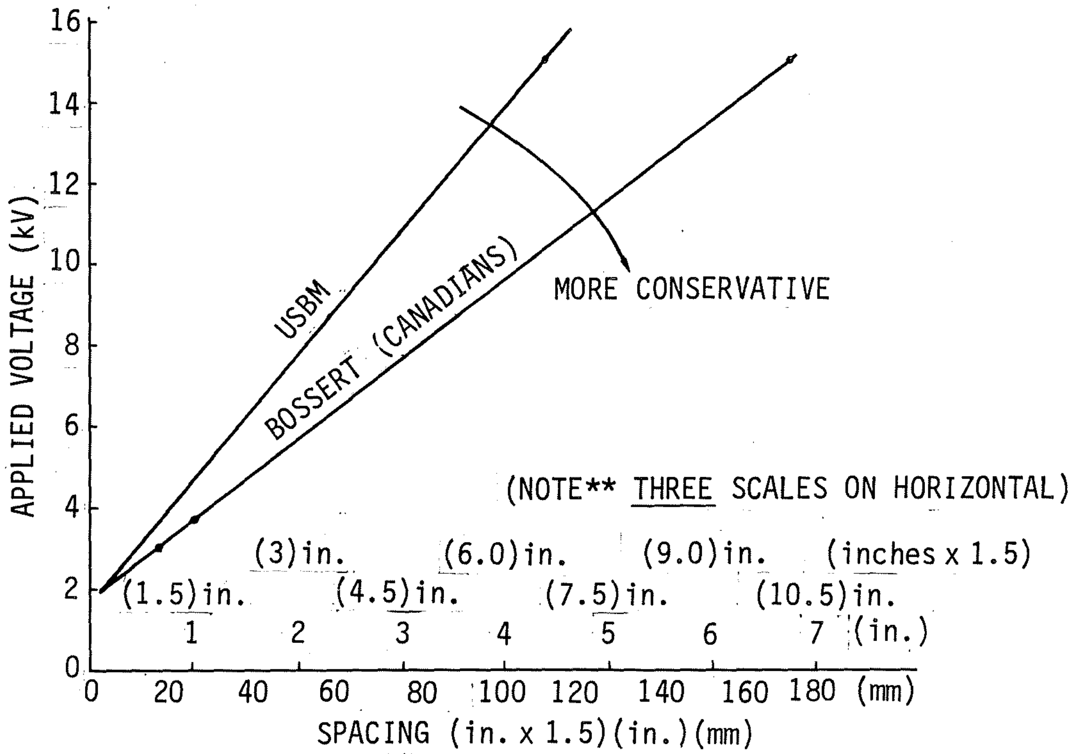


FIGURE 44. - Comparison of the Bureau and Canadian data for rounded electrodes.

This is a more rigorous test than currently required by either United States or European mining regulations. Before requiring such a test, an investigation seems in order to determine, among other things:

a. The likelihood of such an explosion

b. The consequences (damage, hazards) resulting

c. Alternative methods of protection (such as, internal CH_4 monitoring).

If the likelihood of explosion is small, and the consequences are limited to equipment damage only, the manufacturer/operator may want to risk smaller clearances for the sake of size and weight. On the other hand, care must be taken to ensure that such trade-offs do not introduce new or increase existing hazards in the workplace. Until more experience is gained with equipment of this type, a case-by-case approach may be advisable.

6.3.4 Particle Ignition

When a short circuit occurs between two electrodes, particles of the conductor material (usually copper) are "thrown" into the surrounding area. If the short circuit is in an explosion-proof enclosure and is accompanied by a pressure rise, some of these particles may be expelled through the flange gap and, if an explosive atmosphere is present, cause an ignition. This phenomenon, of course, defeats the protective purposes of an explosion-proof enclosure.

This problem has been noted by several researchers and was the main objective of the work done by Marinovic (41) and Killing and Tielke (33). These researchers found that, given the right experimental conditions, particle ignition can lower the MESG for methane significantly. Killing and Tielke found that the safe gap decreased as fault current increased, reaching a minimum at 7.5 kA. Marinovic found a similar minimum at 10 kA of fault current.

The experimental conditions under which this phenomenon occurs are significant. The electrodes (or shorting wire) must be located in the same plane as, and in close proximity to, the flange gap before particle ignition occurs. The researchers mentioned above conducted their experiments in this fashion inside two explosion-proof enclosures bolted together at the flange.

These conditions suggest a possible solution. That is, conductors should not be located in the same plane as, or in close proximity to, the flange gap. This solution is employed by European manufacturers. The same protection can be afforded through use of step, labyrinth, or threaded gaps. The considerable extra expense associated with this approach is not thought to be justified, considering the effectiveness of proper component placement used in conjunction with a flat gap.

The minimum safe gaps found in References (33) and (39) were 0.32 mm (0.012 in.) and 0.25 mm (0.010 in.), respectively. While these gaps are significant for European users (since the maximum gap allowed by law is 0.020 in.), they are well in excess of the maximum allowable United States gap of 0.004 in. Thus, the ignition process described should not be a problem for equipment built to a 0.004-in. standard.

The combination of a tight flange gap and proper component placement should be sufficient protection against an ignition caused by emission of hot particles. The additional protection offered by use of special flange designs, while available, should not be necessary.

6.4 RELATED LITERATURE

In searching the scientific literature for data on faults in explosion-proof enclosures, a related body of work was discovered. This work is directed at the utility industry problem of fault-induced failure of oil-filled pad and pole-mounted distribution transformers. Compared to the information available on explosion-proof, or enclosed, dry-type transformers, this literature is extensive. A sample of abstracts obtained through Computerized Engineering Index (Compendex) is presented in appendix B. Several of these papers were obtained and reviewed. They can be roughly divided into two groups:

a. Those dealing with transformer failure (46-52)

b. Those describing protective devices, particularly current limiting fuses (45,53-62)

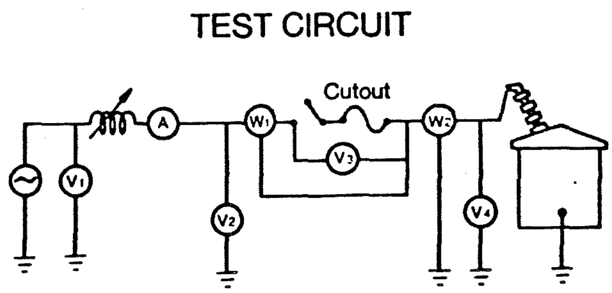
The papers in the first group are described in section 6.4.1. Unfortunately, this work is not directly applicable to the problems disclosed in section 6.3, because the failure modes for oil-filled transformers are quite different than those of dry-types. However, important variables are identified, as are experimental and practical approaches to solutions for the fault-induced enclosure failure problem.

Section 6.4.2 discusses the protective measures suggested by the papers in both groups. Special attention is given to current limiting fuses, which were highly recommended by several authors (47-49,51) and which seem well-suited to some of the analogous problems in explosion-proof enclosures.

6.4.1 Arcing Faults in Oil-Filled Distribution Transformers

An "eventful failure" of an oil-filled distribution transformer has been defined as "a reaction to an internal arcing fault in which either fire occurs, components are ejected, or excessive oil is expelled" (47). Benton, in a paper prepared in 1979, summarizes the research done by Westinghouse Electric Corporation regarding such failures.

A typical test circuit is shown in figure 45. The failure modes that have been identified through these tests are illustrated in figure 46 and are briefly described below.



V_1 = Generator Voltage
A = Line Current
V_2 = Recovery Voltage (Cathode Ray OSC.)
W_1 = Cutout Power
V_3 = Cutout Voltage
W_2 = Arc Power
V_4 = Arc Voltage

FIGURE 45. - A typical test circuit used to investigate arcing faults in oil-filled transformers (47).

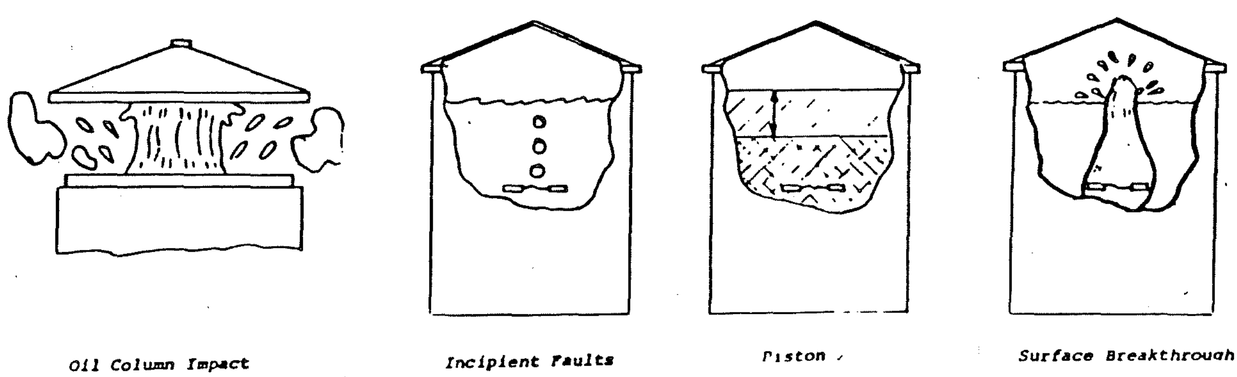


FIGURE 46. - Failure modes accompanying faults in distribution transformers (47).

Incipient Faults

Most arcing faults in distribution transformers are progressive in nature and usually begin as short, low current arcs known as incipient faults. This arc volatilizes the oil and causes pressure in the gas space to increase slowly. Most transformers are equipped with pressure venting devices that will prevent failure unless the gas generation rate exceeds the pressure relief flow rate.

Oil Column Impact

A high energy fault located deep in the oil can cause a column of oil to be forcefully projected into the transformer top cover.

Piston

Under several arcing conditions, a piston of oil may oscillate between the gas space and the arcing gas bubble, behaving like a spring mass system, and exerting pressure on the top cover.

Surface Breakthrough

An arc near the surface will create a large enough bubble to break through the oil and pressurize the gas space.

The critical parameters in an arcing fault in oil are:

a. Current level

b. Fault symmetry

c. Arc length

d. Gas space volume

e. Arc depth

f. Fault duration.

The amount of gas generated by a fault is proportional to the arc energy. Arc energy is the time integral of the arc voltage times current. Arc voltage usually expressed in volts/per centimeter, is affected strongly by arc length and, to a lesser degree, pressure and temperature.

The many variables involved makes theoretical analysis of pressure rise difficult. Attempts have been made by Mahieu (51) and Goodman (50), among others, but their results are usually limited. Mahieu's equation for peak pressure, for instance, depends on four empirically derived constants which, according to the author, may change with arc length, arc depth, tank diameter and other geometric changes. Mahieu, Benton, and others point out that arc location and characteristics are not predictable. Goodman's work, which was supported by the Electric Power Research Institute, applies only to static pressure increases such as might occur from an incipient fault. The dynamic forces (impact forces, such as oil column impact) are not accounted for in his analysis.

Despite these difficulties, a testing standard has been adopted by the National Electrical Manufacturers Association (NEMA). Standard TR-P7-1975 specifies that an enclosure must withstand two 8000 A, 1/2 to 1 cycle duration arcing faults located 1 in. below the core clamps of the transformer (typically 1/3 to 1/2 of the way down from the top). Arc length is specified as 1 in.

According to Benton (47), the fault specified is not claimed to be typical, most probable, or even worst case, as there is much uncertainty and difference of opinion as to each of these. Rather, this test serves as a reasonably uniform test condition to allow comparison between units on an equal basis.

6.4.2 Protective Measures Employed

Several protective measures have been recommended and employed by manufacturers and utility operators (47). These include:

Tank Construction Enhancements

These include strengthening the tank, redesign of top cover clamps, allowances for pressure venting, increase gas space volume, etc. Utility transformer tanks are typically designed to lower pressures than are mining enclosures; the limiting factors are weight, size and cost. Almost all are provided with pressure relief devices set in the 7 to 10 psi range.

Fault Current Limitation

Available fault current is a function of the existing electrical system. While it is not always practical to limit fault current availability, it is advisable to recognize when a high level exists so appropriate protection may be installed.

Oil Elimination

According to Benton, many of the hazards associated with arcing faults in distribution transformers would go away if the oil were eliminated. However, dry-type transformers with overload capacities suitable for utility service are not available. This protective measure has special significance for this program since an enclosed dry-type transformer is to be the end product. Thus, unlike the utility industry, we are able to utilize this form of protection.

Current Limiting Fuses

These devices are highly recommended ("the best method" by Benton and "nearly ideal" by Mahieu) by all researchers as an important solution to the problem of fault-induced tank failure. As reported earlier, application of a CLF allowed the potted transformer used at Federal No. 2 to pass MSHA testing, despite the severity of the tests, presence of the volatile potting compound, and the restricted volume. Several papers describing construction and application of these fuses were collected and reviewed and some representative operating characteristics were presented in section 3. Current limiting fuses are not universally applied by utility companies, where, due to the number of units involved, economic considerations weigh heavily in the selection of protective devices. However, they are available and are applied when conditions warrant.

Similarly, CLF use would not be necessary for all dry-type explosion-proof mining transformers, particularly since the evidence indicates that the hazards produced by a fault would be less, and enclosure strength and free volume would be greater, than in the utility industry case. However, they are available for use in appropriate situations.

6.5 REGULATIONS

In addition to the technical areas discussed in the previous sections, an equally important goal of the state-of-the-art review included an examination of the foreign and domestic regulations affecting the use of high-voltage explosion-proof equipment. This section presents the results of this examination. In section 6.5.1, Title 30 Part 18 CFR (Schedule 2G) and applicable portions of Part 75 are discussed and compared to various international standards. European standards and test procedures are reviewed in section 6.5.2. The National Electric Code and Underwriters Laboratories, Inc., requirements in this area are briefly reviewed in section 6.5.3.

6.5.1 United States Regulations - Title 30, Parts 18 and 75

The review of United States regulations is divided into three parts. The first (section 6.5.1.1) is a review of Part 18 (2G), comparing it with various international standards. This task was facilitated by the existence of prior USBM-supported efforts in this area. The second part (section 6.5.1.2) reviews applicable portions of Part 75, identifying those affecting this program. The third part (section 6.5.1.3) consists of an effort to identify areas of inadequate or inconsistent coverage likely to need special attention in drafting approval and testing criteria.

6.5.1.1 Comparison of Part 18 (Schedule 2G) to International Mining Regulations

Title 30, Part 18 (2G) of the Code of Federal Regulations specifies design, construction, inspection, testing, and approval requirements which must be met by electrically powered mining equipment used in United States mines. Because manufacturers, operators, and the participants of this program are generally very familiar with the requirements of Schedule 2G, effort was concentrated on the comparison with other mining standards.

Work on this task was facilitated by the existence of a prior USBM effort. Stefanko and Morley (63) conducted an extensive literature search in this area, obtaining and reviewing mining regulations from various countries, as well as other pertinent information sources. A decision was made early in this program to build on, rather than attempt to duplicate, this effort. Thus, a summary of the results of this study is presented below.

The results of Stefanko's literature search are presented in the form of an extensive list of references and an associated bibliography. Standards were obtained from Japan, Poland, United Kingdom, and many other nations. However, the authors point out the trend toward alignment of the various standards with those of the International Electrotechnical Commission (IEC) Recommendations Publications Series 79. Primary concern is then given to comparison of Schedule 2G with these standards.

The authors discuss specific sections of Part 18 in the context of three general areas vital to all explosion-proof classifications. These are:

a. Limitations on external surface temperature

b. Enclosure mechanical strength and internal pressures

c. Explosion transmission.

The major differences between various standards can be grouped in one of these three areas.

Limitations on External Surface Temperature

The authors identify the limiting factor on surface temperature requirements to be the ignition point of layered coal dust (63). They also point out that most world mining standards specify a maximum surface temperature of 200° C. The current United States requirement is specified by 30 CFR 18.23 to be 150° C. Work is cited suggesting a justification for the lower temperature requirement (ignition temperatures as low as 160° C for high volatile Illinois coal). Current European standards permit a maximum surface temperature of 150° C (64). High-voltage explosion-proof transformers, of the kind pictured in Section 2 of this report, are designed by Brush Transformers to meet a 100° C standard without difficulty. This consideration, however, is a major determinate of enclosure volume (size) requirements and an adequate, but not excessive, safety factor should thus be determined.

Enclosure Mechanical Strength and Internal Pressure

Schedule 2G specifies that the enclosure be designed to withstand a pressure rise of 150 psig. This conservative standard is justified by experimental work described by the authors (68, p. 17). This testing is usually performed on a single sample (that is, serial no. 1) of each enclosure design. The enclosure under test must survive a series of methane/air explosions without rupture or permanent deformation exceeding 0.04 in./linear ft. Pressure rises exceeding 125 psig lead to rejection of the enclosure unless it can withstand a dynamic pressure of twice the highest value recorded in the initial test. Static pressure tests (150 psig or 1.5 times the maximum recorded explosion pressure) are performed only on enclosures with suspected welding defects not discernible by visual inspection.

In contrast, the widely followed IEC approach is to perform the series of explosion tests on the first model and record pressure rises. Subsequent static or dynamic pressure testing is required on each enclosure manufactured, at a level of 1.5 times the maximum explosion pressure recorded during acceptance testing. If pressure rise time (see fig. 47) recorded in the explosion tests is less than 5 ms, the static pressure test levels are increased to three times maximum recorded pressure. For enclosures that will not be individually tested, a prototype must withstand a static pressure of four times the maximum recorded. Pressure must be maintained for not less than 1 min and are termed successful if the enclosure shows no damage or deformation which would weaken the enclosure or enlarge the flange gap.

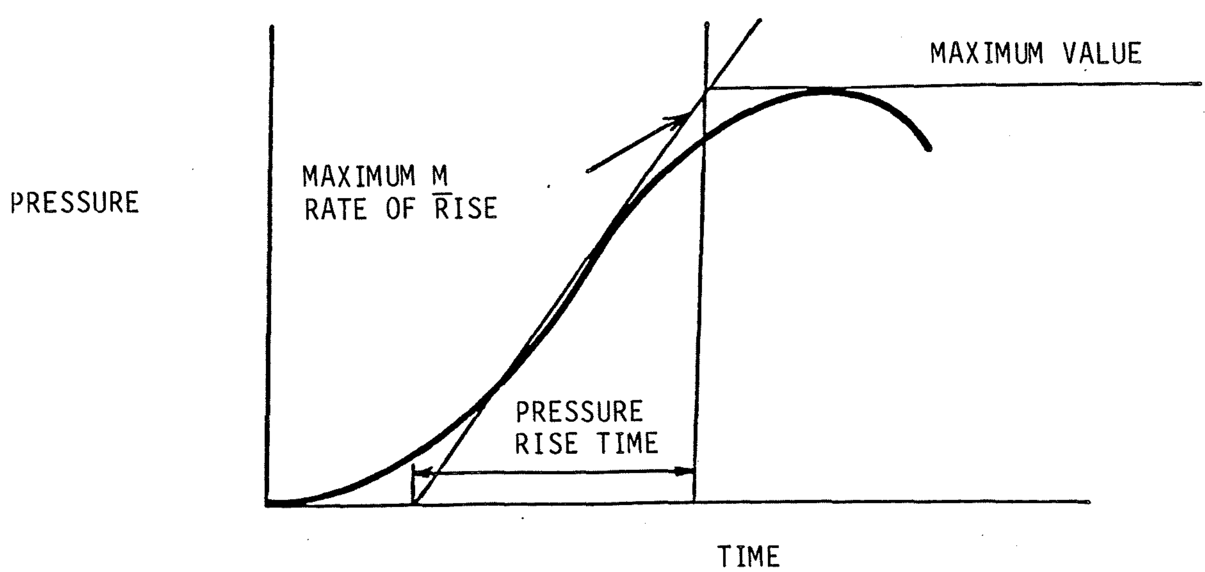


FIGURE 47. - Definition of pressure rise time.

The IEC test described is clearly more performance oriented than 2G. This is also apparent in the parts of 2G which specify metal wall thicknesses, cover thicknesses, bolt spacings and other physical dimensions. The IEC standards, for the most part, lack these kind of design specifications.

Differences also exist in the area of lenses and windows. The 2G testing standard appears to be more rigorous than IEC requirements. Differences in mounting requirements (external mount in the United States versus internal mount in Europe) are also apparent.

Explosion Transmission

The major differences in this area are two:

a. Specification of a maximum United States flange gap of 0.004 in. versus a maximum European gap of 0.020 in.

b. The United States requirement forbidding the transmission of visible flame versus the European requirement which is concerned only with transmission of explosions.

The two are not independent, as the tighter gap is necessary to prevent flame transmission. Flame discharge occurs with gaps as small as 0.006 in., whereas explosion propagation for methane does not occur for gaps smaller than 0.040 in. (1-in. flange). In practice, however, European manufacturers produce equipment with gaps usually built very close to the United States requirement. If the gap deteriorates (widens) in the field, the equipment is removed for refurbishment long before the 0.020-in. maximum is reached. Testing is performed both with covers fitted tightly and shimmed to the 0.020-in. gap. The authors tabulate gap requirements of the United States, IEC, Japanese and Polish standards across the full range of enclosure sizes.

Additional differences in the standards noted in the course of the state-of-the-art review were:

a. United States testing requires the addition of coal dust to the enclosure during explosion testing

b. International standards have restrictions on the use of certain percentages of aluminum, titanium, and magnesium in the construction of enclosures

c. The latest international standards call for the shrouding or protection of all exposed bolt heads

d. Allowable voltage levels for equipment vary from country to country.

Of particular interest to this program is the fact that no foreign standards currently require the initiation of a short circuit arcing fault in explosion-proof enclosures, regardless of the voltage level. Explosion-proof loadcenters are operating in several countries in the 11- to 12-kV range.

6.5.1.2 Title 30, Part 75

Certain mandatory safety standards set forth in Part 75 affect the mine electrical system in such a way as to be of concern to this program. Some of these are listed in table 11.

These and other applicable safety standards may affect the choice of protective measures selected to combat the hazards discussed in section 6.3. For instance, the existence of a resistance grounded system eliminates the danger of a high current fault to ground and possible damage to the enclosure wall. The existence of the ground check circuit facilitates application of monitoring and sensing devices capable of interrupting power under appropriate conditions. Use of shielded cables is a phase segregation technique that may prove desirable to extend into the loadcenter itself.

6.5.2 European Standards and Test Procedures

As noted in section 6.5.1.1 the trend among foreign nations is toward harmonization of standards for equipment used in hazardous locations. This trend is particularly apparent in Europe. On 1 March 1977, CENELEC, the European Committee for Electrotechnical Standardization accepted the texts of seven harmonized standards detailing methods of explosion protection. The 17 member nations[4] are required to accept these standards without modification. Table 12 lists the CENELEC standard and the corresponding national standard for 11 nations. The seven standards (electrical apparatus for potentially explosive atmospheres) are:

[4]Austria, Belgium, Denmark, Finland, France, West Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

TABLE 11. - Safety standards from part 75

Part No.	Requirement
75.500	Requires junction and distribution boxes used inby the last open crosscut be permissible
75.507	Requires nonpermissible loadcenters used outby the last open crosscut to be located in intake air
75.601	Short circuit protection of trailing cables, maximum allowable circuit breaker settings and fuse ratings are specified
Subpart H	Specifies grounding requirements for underground power distribution systems
75.801	High-voltage power systems must be resistance grounded
75.803	Requires ground check circuits on high-voltage systems
75.804	Requires high-voltage cables to be shielded in construction
75.807	High-voltage cable must be installed in regularly inspected airways or haulageways

TABLE 12. - CENELEC and corresponding national standards
Source: unidentified publication from D.G. Eastwood, Brush Transformers, Ltd.

CENELEC Standard	EN 50014	EN 50015	EN 50016	EN 50017	EN 50018	EN 50019	EN 50020
Belgium	NBN C23-001	NBN C23-104	NBN C23-105	NBN C23-106	NBN C23-103	NBN C23-102	NBN C23-101
Denmark	AFSNIT 50	AFSNIT 50-1	AFSNIT 50-2	AFSNIT 50-3	AFSNIT 50-4	AFSNIT 50-5	AFSNIT 50-6
Finland	SFS4094	SFS4095	SFS4096	SFS4097	SFS4098	SFS4099	SFS4100
France	NF C23-514	NF C23-515	NF C23-516	NF C23-517	NF C23-518	NF C23-519	NF C23-520
German Federal Republic	VDE 0170/0171 Pt 1/5.78	VDE 0170/0171 Pt 2/5.78	VDE 0170/0171 Pt 3/5.78	VDE 0170/0171 Pt 4/5.78	VDE 0170-0171 Pt 5/5.78	VDE 0170/0171 Pt 6/5.78	VDE 0170/0171 PT 7/5.78
Italy	CEI 31-8: 1978	CEI 31-5: 1978	CEI 31-2: 1978	CEI 31-6: 1978	CEI 31-1: 1978	CEI 31-7: 1978	CEI 31-9: 1978
Netherlands	NEN-EN 50014	NEN-EN 50015	NEN-EN 50016	NEN-EN 50017	NEN-EN 50018	NEN-EN 50019	NEN-EN 50020
Norway	NEN-110	NEN-111	NEN-112	NEN-113	NEN-114	NEN-115	NEN-116
Spain	UNE 21814	UNE 21815	UNE 21816	UNE 21817	UNE 21818	UNE 21819	UNE 21820
Switzerland	SEV 1068	SEV 1069	SEV 1070	SEV 1071	SEV 1072	SEV 1073	SEV 1074
United Kingdom	BS 5501 Part 1	BS 5501 Part 2	BS 5501 Part 3	BS 5501 Part 4	BS 5501 Part 5	BS 5501 Part 6	BS 5501 Part 7

Notes:
- o National standards unknown for Austria, Greece, Ireland, Luxembourg, and Portugal
- o Sweden has adopted only EN 50020
- o Dates given with German and Italian standards to avoid confusion with earlier standards
- o Spanish standards as yet unpublished.

a. EN 50014 - General Requirements

b. EN 50015 - Oil Immersion 'o'

c. EN 50016 - Pressurized Apparatus 'p'

d. EN 50017 - Powder Filling 'q'

e. EN 50018 - Flameproof Enclosure 'd'

f. EN 50019 - Increased Safety 'e'

g. EN 50020 - Intrinsic Safety 'i'.

The major differences in United States and international standards described in section 6.5.1.1 are valid for EN 50014 and 50018, the standards dealing with explosion-proof enclosures (64,65). These standards specify flange widths and gaps, various joint dimensions and details, and maximum surface temperature. However, they are for the most part performance standards. For example, the test for mechanical strength (explosion test described in section 6.5.1.1) is successful if the enclosure survives with "neither damage nor permanent deformation liable to weaken any of its parts" and "the joints shall in no place have been enlarged permanently to values greater than those permitted in (table 1, 0.020-in.)."

Although alignment of standards is progressing, it is far from complete. Most European nations operate under more than one standard. For instance, the United Kingdom applies its own standards (66-68), applicable CENELEC standards (64,65) and IEC standards (69).

6.5.3 National Electric Code/Underwriters Laboratories Standards and Test Procedures

The National Electric Code (NFPA 70-1981) divides hazardous locations into classes and divisions based on the nature of the hazard and its probability of occurrence (70,71). In this scheme a coal mine atmosphere would be classified as Class I, Division 1, Group D (for methane) and Class II, Division 1, Group F (for coal dust). Underwriters Laboratories, Inc., publishes a standard (UL No. 698) for industrial equipment operating in these atmospheres (17). Following is a brief discussion of that standard.

UL 698 is both a design and performance standard. Minimum wall thicknesses, joint and flange dimensions and maximum surface temperature (200° C) are specified. Indeed the minimum flange gap, determined by the relationship shown in figure 48, is tighter than that required by Part 18. The strength test, however, is performance oriented, with the enclosure required to withstand an explosion test and a hydrostatic pressure test without rupture, permanent deformation, or loosening of the joints. (The hydrostatic test may be bypassed if calculations indicate the existence of an acceptable safety factor).

Explosion testing is performed much like MSHA testing, with one important exception - tests are conducted with the equipment energized and under load. If arcing occurs due to insufficient clearances, the enclosure is rejected. Ignition is by spark plug or operation of a spark producing component in the enclosure. Criteria for a successful test are:

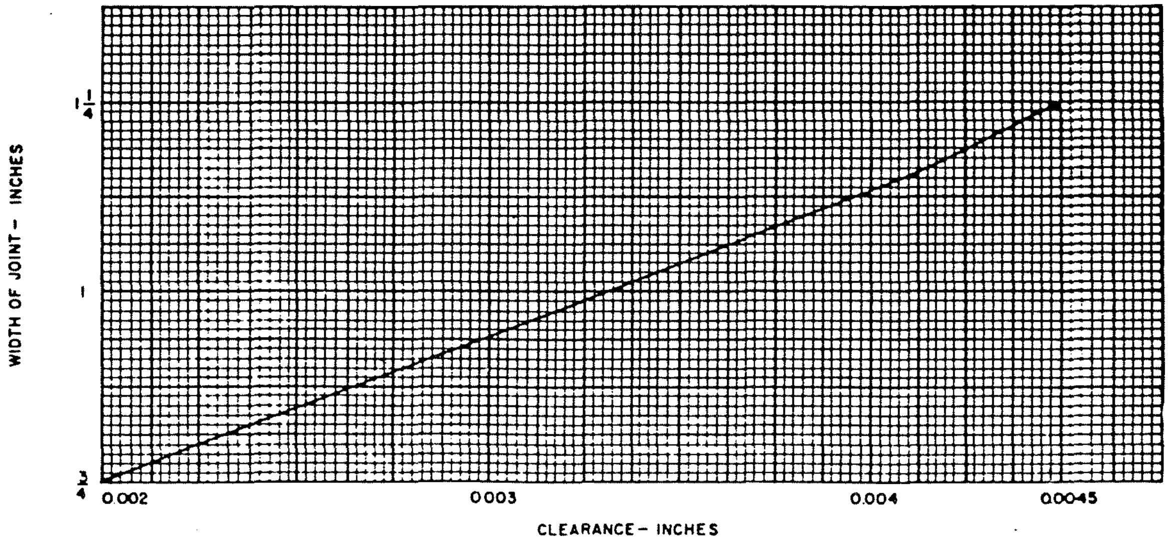


FIGURE 48. - Relation between clearance and width of joint.

a. Survival of the enclosure

b. Nonpassage of flame

c. The nonfailure of electrical devices having contacts located in the enclosure.

This standard is nominally applicable for a maximum voltage level of 600 V. However, Underwriters Laboratories will test higher voltage equipment, relying on the engineering judgement of their test engineers to recognize situations warranting special consideration.

For higher voltage equipment, no internal arcing fault test is performed. However, when a fuse or circuit breaker is located in an enclosure, overload or bolted short circuit tests are run to determine the electrical and pressure effects caused by interruption of the fault current. Testing experience indicates that for a fault current of less than 10,000 rms symmetrical amperes, the arc has little effect on pressure rise or explosion violence. However, at fault current levels greater than 10,000 A, increases in pressure are often observed (22).

7. REFERENCES

1. BOSSERT, J. A., BROWN, G. K., and MOGAN, P.
   Canadian Explosive Atmospheres Laboratory. Electric Arcing at High Voltage During Methane/Air Explosions. Presented - 15th International Conference on Safety in Mines Research, Karlovy, Vary, Czechoslovakia, September 1973. DOE Mines & Resources, Mines Branch, Ottowa, Canada.

2. SCOTT, L. W., and DOLGOS, J. G.
   "Electric Arcing at High Voltage During Methane-Air Explosions Inside Explosion-Proof Enclosures," BuMines TRP 115, 1982.

3. AMERICAN NATIONAL STANDARD D3638-77,
   "Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials"

4. HARDWICH, J. N.
   "An Improved Fuse Wire Arc Test Including a Proposed Specification," Electrical Research Association Report No. 5078, United Kingdom, 1964.

5. BRITISH STANDARDS INSTITUTION BS3781:1964,
   "Comparative Tracking Index"

6. BARBERO, L. P., DAVIS, E. H., and LORD, H.
   Hazards Resulting From the Volatilization By Electric Arcing of Insulating Materials in Flameproof Equipment. Presented to XV International Conference on the Safety in Mines Research, Karlovy, Vary, Czechoslovakia, 18-21 September 1973. Department of Trade & Industry Safety in Mines Research Establishment.

7. LORD, H. and BARBERO, L. P.
   Problems Arising from the Use of Organic Plastics Materials In Flameproof Enclosures. Proc. 2nd International Conference on Electrical Safety in Hazardous Environments. IEEE, December, 1975.

8. LORD, H. and DAVIDSON L.
   Fault Arc Detection Within Flameproof Enclosures. Electrical Review Vol. 208 No. 3, January 23, 1981.

9. PEARSON, F. K.
Health and Safety Executive, Health and Safety Laboratories. Arc Resistance of Plastics Electrical Insulating Materials Used Within Flameproof Enclosure. Issue authorized by: Dr. H. Lord. 16 February 1978. (U.K.)

10. SIMON, K. E.
Preliminary Investigation into the Causes of the Bursting of Flameproof Enclosures in Which the Electric Current Caused Gases to Evolve from Plastic Materials. 14th International Conference of Mine Safety Research Establishments, Donetsk, 1971 (English Translation). (U.S.S.R.)

11. BISE, C. J., and MORLEY, L. A.
"Evaluation of High-Voltage Cable-Coupler Performance for Underground Mine Power Systems"

12. CONROY, George, BERRY, Randy, and GILLENWATER, Robert
"High-Voltage, Explosion-Proof Load Centers," BuMines IC 8893, 1982.

13. COBINE, J. D.
Gaseous Conductors: Theory and Engineering Applications. Dover Publications, Inc. New York, NY, 1958.

14. DOW, W. G.
"Fundamentals of Engineering Electronics," John Wiley and Sons, New York, 1952.

15. MAGISON, E. C.
"Electrical Instruments in Hazardous Locations," Instrument Society of America, Research Triangle Park, North Carolina, 1980.

16. CODE OF FEDERAL REGULATIONS
Title 30, Parts 18 and 75.

17. UNDERWRITERS' LABORATORIES, INC.
Standard for Safety. Industrial Control Equipment for Use in Hazardous Locations, Class I, Groups A, B, C, and D Class II, Groups E, F, and G. UL 698. August 6, 1980.

18. BRAUNSTEIN, H. R.
Electrical Engineer, Westinghouse Electric Corporation, Athens, GA, Personal Communication

19. FOLEY, ED
Electrical Engineer, Westinghouse Electric Corporation, Sharon, PA., Personal Communication

20. ROWTRUCK, JAMES
Electrical Engineer, Westinghouse Electric Corporation, Sharon, PA., Personal Communication

21. SHEFKA, DAVE
Brown Baverra Electric Company, Bland, VA., Personal Communication

22. VAICKAUSKI, RONALD
Engineering Group Leader, Casualty and Chemical Hazards Department, Hazardous Equipment Division, Underwriters Laboratories, Northbrook, Il., Personal Communication

23. TIPTON, E. W.
"Sealed Dry-Type Transformers Proved Safe by Test." Reprint from October, 1953.

24. NATIONAL FIRE PROTECTION ASSOCIATION
Intrinsically Safe Apparatus for Use in Division 1 Hazardous Locations 1978. NFPA #493. Boston, MA., 1979.

25. DEPARTMENT OF LABOR
Petition for Modification. Docket No. M-78-31. United States Steel Corp. versus Mine Safety and Health Administration. Mine Safety and Health Administration. January 15, 1981.

26. DEPARTMENT OF LABOR
Notice of Proposed Decision of Petition for Modification - In the Matter of United Pocahontas Coal Co. Docket No. 79-102-C. Mine Safety and Health Administration. January 4, 1980.

27. DEPARTMENT OF LABOR
Notice of Investigative Report Submitted in Reference to Petition for Modification - In the Matter of Keystone Coal Mining Corporation. Docket No. M-79-14-C. Mine Safety and Health Administration. April 14, 1980.

28. DEPARTMENT OF LABOR
Notice of Proposed Decision on Petition for Modification - In the matter of Keystone Coal Mining Corporation. Docket No. M-79-14-C. Mine Safety and Health Administration. June 26, 1980.

29. WOODS, JOSEPH A.
Mine Safety and Health Administration, Arlington, VA., Personal Communication

30. CIOK, J.
Internal Short Circuits in Flameproof High-Voltage Equipment. Central Mining Institute, Experimental Mine Barbara, Mikolaw, Poland. Paper No. 14 Presented at the 16th International conference on Coal Mine Safety Research. Washington, D.C. September 1975.

31. DAVIDSON, L. and LORD, H.
Safety in Mines Research Establishment, Department of Energy. Some Aspects of Fire and Explosion Hazards In Enclosure-Protected Electrical Apparatus. Reprinted from Fire Prevention Science & Technology No. 10. London, England.

32. HERRERA, W. R. and ADAMS, L. M.
Recommended Acceptance Criteria for Potting Materials Used in Explosion-Proof Enclosures in Coal Mines. U.S. Bureau of Mines Interim Technical Report. August 22, 1980.

33. KILLING, F. and TIELKE, H.
The Interference Short-Circuit With Arcing Pheonomena in Elecrical Equipment in Flameproof Enclosures With Special Reference to the So-Called Transmission of Ignition By Particles. Westfalische Bergwerkschaftskasse Bergwerkshaftlich Versuchsstrecke. Federal Republic of Germany. Paper No. 13. Presented at the 16th International Conference on Coal Mine Safety Research. Washington, D.C. September 1975.

34. MORLEY, L. A., ROBINSON, J. W., and TRUTT, F. C.
Electrical Materials Analysis - Arcing. Penn State University, Department of Electrical Engineering. USBM Grant - Annual Progress Report, December 30, 1977.

35. MORLEY, L. A. and TRUTT, F. C.
Materials Suitable for Use Inside Explosion-Proof Enclosures. Department of Mineral Engineering, Penn State University. USBM Grant Final Report, dated April 7, 1976.

36. ROBINSON, J. W. and TRUTT, F.C.
Arcing Faults in Coal Mine Enclosures. Mine Power Systems Research - Part 4. U.S. Department of Interior - Bureau of Mines, 1979.

37. ZAHN, P. M.
Analyses of Pressure and Temperature Rises in an Enclosure Due to Volatization of Insulation from Electrical Arcing. MS Thesis, Pennsylvania State University 1977, 97 pages.

38. GRAY, G. W.
Phase Sensitive Short-Circuit Protection. Mining Technology, April, 1978, pp. 123-126.

39. LORD, H. and PEARSON, F. K.
Ultra-Sensitive Instantaneous Fault Protection For Cage Induction Motor Supplies. Mining Technology, May, 1980, p. 219.

40. FORTE, T. P.
Energy Dissipation & Pressure Rise Due to Capacitor Discharge Arcing Thru Water In A Sealed Container. MS Thesis. The Pennsylvania State University. November, 1976.

41. MARINOVEC, N.
Effect of Short Circuits Inside Explosion-Proof Enclosures On Propagation Of Ignition. "Rade Koncar" Electrotechnical Institute, Zagreb, Yugoslavia. Paper No. 15. Presented at the 16th International Conference on Coal Mine Safety Research. Washington, D.C. September 1975.

42. WARRINGTON, A. R. van C.
Reactance Relays Negligibly Affected by Arc Impedance. Electrical World, 98, No. 12, September 19, 1931, pp. 502-505.

43. WARRINGTON, A. R. van C.
Protective Relays: Their Theory and Practice. Vol. 1 and 2, John Wiley & Sons. New York, NY, 1969. (Volume 2, Third Edition, 1977.)