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Underground Coal Mine Power Systems

Proceedings: Bureau of Mines Technology Transfer Seminar, Pittsburgh, Pa., September 16, 1982

Compiled by Staff—Bureau of Mines

UNITED STATES DEPARTMENT OF THE INTERIOR

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BUREAU OF MINES
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PREFACE

This Information Circular summarizes recent Bureau of Mines research results concerning improved mine electrical power systems for America's underground coal mines. The papers are only a sample of the Bureau's total effort to improve coal mine safety, but they do delineate the major concerns of the mine electrical power programs. Some of the technology discussed has applications in other types of mining.

The six technical presentations reproduced here were made either by Bureau researchers or by personnel representing Bureau contractors at the Technology Transfer Seminar on Underground Coal Mine Power Systems given in September 1982 in Pittsburgh, Pa. The content of the other presentation not included here can be found in the Bureau of Mines Handbook, "Application Notes--Mine Electric Power Systems." Those desiring more information on the Bureau's mine electrical power safety programs in general, or information on specific situations, should feel free to contact the Bureau of Mines Division of Health and Safety Technology, 2401 E Street, NW, Washington, D.C., 20241, or the appropriate author.

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UNDERGROUND COAL MINE POWER SYSTEMS

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ABSTRACT

This Bureau of Mines publication presents an overview of mine electrical power systems research currently being conducted by the Bureau. The papers, given at a Technology Transfer Seminar, emphasize the increasing importance of research related to the safety considerations of underground coal mine electrical systems. Selected topics are included that summarize results of research in the areas of electrical shock prevention, explosion-proof enclosures and load centers, discriminating circuit breakers, and trailing cables. Other topics discussed at the seminar are published as separate sections of the Bureau of Mines Handbook "Application Notes--Mine Electrical Power Systems."

INTRODUCTION

Mine power systems (MPS) research encompasses the following areas: permissible equipment, power distribution, dc power systems, cable usage problems, and intrinsic safety. In general terms, MPS research attempts to identify and attack electrical problems which pose a significant hazard to the safety of the individual miner. This is accomplished by one of several methods.

In studying shock prevention, for example, the problem must be correctly identified. To this end, Mine Safety and Health Administration (MSHA) accident statistics were studied to build a history of electrical accidents both fatal and nonfatal; then innovative but practical solutions were proposed and evaluated. Some of these solutions are contained in the first paper. Shock prevention research will continue to receive a high priority in future MPS research.

A recent MSHA publication[1] attributes 60 pct of the mine fires investigated through 1972 and 21 percent of all methane ignitions to electrical ignition sources and inadequate design of electrical equipment. A Bureau study[2] of electrical violations cited by MSHA indicated that the second most common electrical violation was failure to comply with regulations for permissible electrical face equipment maintenance. In fact, the improper use of permissible equipment accounted for 17 pct of the total electrical violations studied.

The study of permissible equipment and enclosures is an area requiring investigation into materials, methods of construction, and testing criteria. At present, the explosion-proof enclosures used in underground mines are constructed to rigid design requirements that contribute to the difficulties in maintaining the enclosures in a permissible condition. If designers were permitted more freedom, it would be possible to construct enclosures that are easier to maintain in a permissible condition, and to eliminate aluminum alloys if they are deemed a safety hazard. These new enclosures would be submitted to performance tests to insure that they offer the same degree of safety as the enclosures presently being constructed to the design requirements. It is the objective of this research area to determine the safety factors in the present design requirements, and to develop and demonstrate the feasibility of performance tests. The second paper deals with the results to date of this research area. Another paper deals with the need for ever-increasing power requirements of larger and larger face equipment. The paper on explosion-proof load centers presents tentative specifications and a request for interested persons to comment.

At least 80 of the 127 coal mine fires involving the trolley system, which were investigated by Federal personnel from 1952 to 1977, could have been prevented if circuit protection systems capable of responding to low-current arcing faults had been available and universally installed. If one considers only nonreportable fault conditions on haulageways, the annual worth of a low-level fault protection scheme is estimated at $21,000 to $52,000 per mine. Thus, even on a cost-saving basis, without mentioning saved lives, sensitive trolley wire protection can be shown to be of value to mine operators. This does, however, require physical demonstration that the method performs as required. To meet this objective, the Bureau sponsored research that led to the development of the discriminating circuit breaker (DISCB) described in the fourth paper. This device may find future applications in electrified mass transit systems. The DISCB can distinguish between low level ground fault currents and legitimate high-current loads on a mine haulageway,

[1]MSHA IR-1018, "Electrical Hazards in Underground Bituminous Coal Mines," 1975, 5 pp.

[2]BuMines IC 8726, "Mine Inspection Records Study," 1976, 11 pp.

responding (instantaneously) only to the former. It can be employed in any existing haulageway with a minimum amount of modification of the haulage equipment. A scaled demonstration is described in the paper.

Cables contribute more to downtime and to personnel injury than any other electrical component used in mines. Accident classification by injured activity from 1975 to 1979 has shown that in 19 pct of all accidents contact with energized cables occurs while splicing a supposedly dead line. Proper ratings, construction, and application of cables is very important. The last two papers discuss these subjects in more detail.

The increased use of electrical power in the mining environment dictates that research into specific mine electrical hazards be focused on those areas which will most significantly reduce fatal and nonfatal accidents among miners. MPS research will continue to identify electrical hazards and propose innovative, yet practical, solutions to alleviate those hazards.

DESIGN PRACTICES TO MINIMIZE THE PROBABILITY OF SHOCK DURING CONTROL BOX MAINTENANCE

By Thomas Novak[1] and George J. Conroy[2]

ABSTRACT

The use of dead-front construction and other means of segregating higher-voltage portions of control box circuitry with carefully planned use of test points, an in-place schematic diagram, and indicator lights, are explained in this paper. Sensitive circuitry for personnel protection is discussed. The reception by manufacturers and mine personnel of the ideas as embodied in a demonstrator unit is summarized. Recommendations to improve maintenance safety are listed and discussed.

INTRODUCTION

Mine Safety and Health Administration (MSHA) accident statistics for both coal and metal-nonmetal mines show that maintenance personnel have the highest frequency of electrical accidents. These statistics might be expected since repairworkers have the greatest exposure to electrical hazards. Yet electrical-safety features of equipment have been directed primarily toward protecting the electrical wiring, the machine, and the mine from heat and fire damage. Considering the evidence, present emphasis should be placed on protection of maintenance personnel.

The harsh operating conditions common to most mining processes contribute greatly to the electric shock hazard. As mineral or rock is extracted, the electrical machines must advance, followed by their sources of power. During these moves, both equipment and cables are frequently stressed by pulling over rough surfaces and being twisted or impacted. As all those who work in mines can attest, gentle handling of equipment is not the rule but the exception. The extreme abuse increases the amount of maintenance while at the same time it renders insulating qualities, etc., questionable, all of which increases the repairworker's exposure to electric shock.

The environmental conditions of the mine also enhance the probability of electrical accidents. Wet conditions are often encountered which decrease the contact resistance between a person and earth. Thus, a person becomes more susceptible to electrocution from contacting an energized conductor.

Space on mining machines is extremely limited, and electric control boxes and panels are crowded with parts. Troubleshooting with the circuit energized is permitted under present regulations, leading to a distinct probability that, either through ignorance, inattention, or an inadvertent slip, an elbow or hand will contact an energized member.

If normal production is interfered with by a breakdown, which is frequently the case, the repairworker will probably be rushed. Especially in mines where roof and rib might be unstable because the machine cannot do its roof-bolting job, the cramped working conditions and the foreman's frequent encouragement to complete the repair, can create sufficient confusion to add to existing potential hazards.

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[2]Supervisory electrical engineer (retired), Bureau of Mines, Pittsburgh Research Center, Pittsburgh, Pa.

There is not much hope that the working conditions will change; nevertheless, the accident statistics can be improved. Electric shock prevention can be afforded to the maintenance worker as follows:

1. Minimizing exposure to energized members.

2. Providing sensitive, rapid-response electrical protective devices.

Both of these approaches will be discussed.

The first approach can be implemented by having the machine manufacturer or, in some cases, the mine maintenance group itself, incorporate certain physical-mechanical design modifications that are simple in concept but so beneficial in their consequences that their added first cost can easily be shown to be balanced by reduced maintenance costs and improved safety. The second approach is, in some cases, only now becoming fully realizable, with the entry into the mining field of rugged, reliable solid-state devices.

PHYSICAL DESIGN MODIFICATIONS

The design concepts to be considered in this paper are dead-front construction, interlocks, segregation of high-voltage circuits, and lockouts. They may be employed singly or in combination, with the objective of avoiding inadvertent contact with energized members by introducing elements which, while restraining from contact, facilitate or at least do not significantly hinder rapid troubleshooting. The designer should also give consideration to secondary aspects of protection, as explained when discussing interlocks which remain, even when the primary protective elements are bypassed.

Dead-Front Construction

It is possible to perform a large number of troubleshooting operations without making a manual approach of any kind to the vicinity of the high voltage (600 V, 480 V, etc.) portions of a control circuit, if test points are supplied on a panel that is interposed as a physical barrier between the circuit and the external world. For application to explosion-proof enclosures, a hinged panel can be installed in a position slightly recessed behind the outer cover of the enclosure. The test points are installed to penetrate the surface of the hinged panel to allow important voltage measurements. The concept requires little or no increase in overall size of the control case.

The dead-front, troubleshooting concept can be applied to almost any type of electrical-control case. A simplified unit was constructed to demonstrate the concept and is shown in figure 1. The internal components comprise a simple, two-motor starting circuit. Since this prototype was built for use as a demonstration unit, the electrical components are housed in a portable, lightweight, aluminum enclosure rather than a heavy, explosion-proof box; however, the ultimate usage was kept in mind at all times.

The unit is designed to simplify troubleshooting procedures, as well as to reduce the hazards of electrical shock. Figure 1 shows the dead-front panel with the outer lid of the enclosure removed. The incorporation of test points into an actual diagram of the circuit schematic is an important aspect. This feature could greatly simplify troubleshooting techniques and possibly reduce machine downtime. In addition, the schematic provided on the panel is more permanent than paper schematics, which deteriorate quickly in the moist mine atmosphere and are susceptible to being mislaid and lost. The hinged panel provides a complete barrier between the repairworker and the electrical components. The test points are pin jacks and therefore restrict access to dangerous voltages requiring the use of test probes. A key is required to gain access to the internal

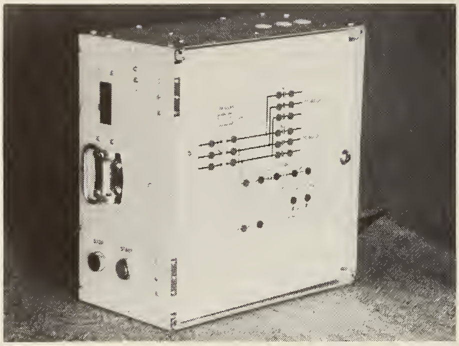

FIGURE 1. - Dead-front panel with outer lid of enclosure removed.

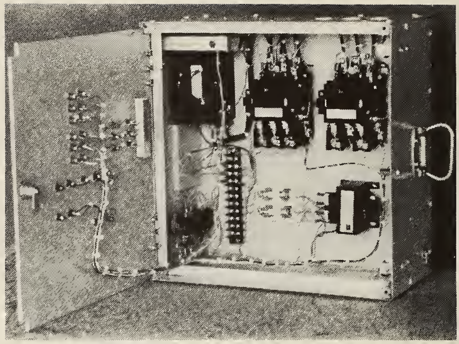

FIGURE 2. - Panel as removed after internal electrical controls are unlocked.

electrical controls. After being unlocked, the panel can be opened, as shown in figure 2; however, opening the panel results in the operation of two interlock switches which are in series with the undervoltage release of the circuit breaker. The opened interlock switches interrupt power to the undervoltage release, tripping the circuit breakers. Thus, all internal components, with the exception of the incoming leads of the circuit breaker, are deenergized. A guard with a warning light is placed around the incoming connectors of the breaker to prevent accidental contact should the repairworker fail to deenergize the incoming line. On an actual ac machine used in coal mining, the interlock switches would usually be connected in series with the pilot circuit of the ground-check system rather than to an internal circuit breaker. Opening the panel would trip the upstream circuit breaker, located in the section power center; thus all power to the control case would be shut off. In that application, the warning light would be retained, whether or not the internal circuit breaker was included.

Many variations of the basic dead-front concept can be applied to control centers. One possibility is to use a dead-front panel made of transparent plastic, such as polycarbonate. Since the electrical controls are located directly behind the panel, the physical movement of line starters, relays, and contactors can be observed while voltage measurements are made at the isolated test points. The transparent panel can be so constructed that permissibility is not compromised, with only intrinsically safe test points used if any are needed. With this design, a relatively thin, steel-hinged outer cover protects the plastic panel from most sources of scratching or other damage. Whether or not the transparency of an unprotected panel can be maintained under actual operating conditions depends upon the individual application.

A further refinement of the dead-front concept is to replace or supplement the test points with visual indicators, such as LED's or lamps. In effect, the built-in indicators would serve in place of a voltage tester for many routine troubleshooting observations, and a quick assessment of the condition of the control circuit could be accomplished simply by visual inspection of the panel.

Testing and changing control-circuit fuses are among the most frequent electrical-maintenance procedures. For a dead-front approach, the fuses can be mounted behind a separately interlocked explosion-proof cover. The interlock would operate an internal contactor which, because of its very low duty cycle with regard to circuit interruption, could be relatively small. The fuses could thus be removed and replaced with no risk of having personnel contact energized metal clips. A refinement of this idea is to include test points under the interlocked cover connected to each end of each fuse. With the circuit opened by the interlock, fuse continuity can be checked with an ohmmeter without removing the fuse.

Interlock Disable Precautions

Interlock design should always be oriented toward prevention of accidental reclosure of the interlock. Where the interlock is a simple jump-link arrangement, the energized contacts should be female, recessed in insulating plastic. If a sensitive switch is used, the pressure to close the switch should be applied by a protrusion operating through a hole in the panel behind which the switch is mounted. Any safety feature can be circumvented by a determined maintenance worker if it interferes with his or her troubleshooting function. Since some interference by an interlock is unavoidable, the means to circumvent the device should be thought out beforehand by the designer and not left to be jury-rigged in a manner that permanently damages or disables the interlock. In its most desirable form, the disabling means will automatically clear once the necessity for its use is over. An example would be a latched interlock switch arranged so that cover closure results in mechanically resetting of the latch. Also, a highly visible warning should be included telling when an interlock has been disabled, to remind the repairworker that circuits remain energized.

Segregation of Different Voltages

For some controls, isolation of the entire circuit with a physical barrier may not be possible or desirable. One means of improving electrical safety in these situations is to include one or more terminal strips for use as test points. The terminal strips should be located such that accidental contact with energized conductors would be minimized. Each test point on a terminal strip must be numbered to correspond with the circuit's schematic, and all components within the case should be labeled for easy identification. The test points should also be segregated according to their voltages. In other words, control-circuit test points of 120 V should be located in an area away from the power-circuit test points of 440, 550, or 950 V. The repairworker would then know the approximate level of the voltage with which he or she is dealing. The color coding of conductors might also be helpful in distinguishing different voltage levels.

The main disadvantage of using isolated test points or voltage indicators for troubleshooting is that the amount of wiring is increased. The additional wiring increases as the size of the circuit increases. With very large circuits it may not be feasible to isolate all possible test points. A circuit analysis would have to be performed to determine which test points are the most critical. The critical test points would then be brought out to the dead-front panel or terminal strips.

The preceding discussions primarily deal with machine circuitry. However, the concepts are not limited to this application. Dead-front, troubleshooting panels can also be applied to the low- and medium-voltage circuits of power-distribution equipment in a similar fashion.

Lockout Features

The following example illustrates a maintenance-related electrical accident that has occurred numerous times:

A repairworker deenergizes the faulty circuit at the power center prior to performing repair work. While he or she works on the faulty circuit, another worker, who is unaware of the situation or mistakes the cable of the faulty circuit for another cable, energizes the faulty circuit and thus subjects the repairworker to electrical shock or electrocution.

Mine power center manufacturers have made available lockout features on cable couplers to prevent this situation. Locking-type dust covers on equipment-mounted receptacles along with keyed couplers are supplied as a means of reducing the possibility of this hazard. With keyed couplers, the plug of each outgoing circuit is matched to fit only one receptacle. The dust covers are connected to the coupler or the equipment by a chain in order to prevent their loss while not in use. A loosely hinged cover would serve the same purpose with increased operational facility and greater assurance against damage.

Locking-type dust covers for the cable-mounted plug can afford even more protection for maintenance personnel. Once the plug is locked, connection to any receptacle is impossible. Chain-connected, locking-type dust covers are presently available for high voltage plugs. However, consideration should be given to the development of hinged dust covers for all plugs energized at higher than 30 or 40 V.

Electrical lockout features utilizing the ground monitor circuit can also be incorporated to give the mechanic working at the machine the ability to prevent reestablishment of power from the load center, until he or she is fully ready to allow it. A typical circuit would employ an interval timer, a small relay, and a reset switch.

When lockout features--and strict procedures for their employment--are combined with other cable and machine-related safety provisions, a very significant improvement in the count of fatalities and injuries may be observed.

Sensitive Electrical Protection

This subject will be summarized here rather than explored in detail, as a very thorough treatment will become available in the final report of a Bureau contract (J0113009) during November 1982. Many aspects of the foregoing discussion are also included in the report. The present discussion will center on the physiological basis for relying on sensitive electrical protection and will simply mention a few of the findings of that study and other research projects.

Electric Shock Threshold

Ventricular fibrillation is usually the most dangerous shock hazard, as it occurs at relatively low values of current. Disabling or fatal burns require larger currents, and cardiac arrest due to high current flow can, in some cases, be countered by appropriate physical action by another person after the current has been turned off. When fibrillation occurs the pumping motions of the heart become disorganized and, finally, the pulse ceases. Death occurs within minutes. Dalziel (1)[3] presented an equation extrapolating statistical data obtained from experiments on animals, which predicts the minimum threshold for fibrillation for a body weight of 110 lb (50 kg) at a power-line frequency of 60 Hz

$$I = \frac{116}{\sqrt{t}} \qquad 8.3 \text{ msec} \leq t \leq 5 \text{ sec},$$

where I = minimum current in milliamperes through major extremities,

and t = duration of the shock, in seconds.

The equation is represented graphically by the solid curve of figure 3. According to Dalziel (1), the area underneath and to the left of the solid curve is considered the "safe area" with respect to fibrillation.

Although it is impossible to eliminate fatal reactions to electrical shock for all cases, a reasonable degree of safety can be achieved by limiting the maximum ground-fault current to a low value (say 500 mA) and by matching the characteristics of a ground-fault relay to the

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

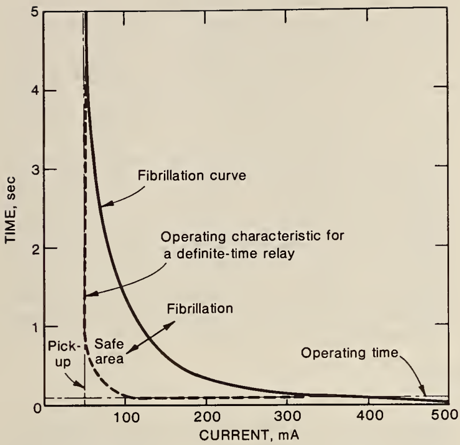

FIGURE 3. - Fibrillation curve.

fibrillation curve. If the Dalziel equation is accepted, a definite-time relay with an operating characteristic similar to the dashed line of figure 3 would be required to meet the necessary sensitivity. The pickup current of 50 mA was selected since this value is generally considered the minimum threshold of fibrillation. The operating time of 0.1 sec is based on worst-case conditions and takes into account system capacitance and the reaction time of molded-case circuit breakers.

Ventricular fibrillation can also be caused by direct current, but related research has not been nearly as comprehensive when compared with alternating currents. However, Daziel (1) indicates that the fibrillation level for dc currents is approximately five times the threshold of ac currents. Therefore, the pickup current of 250 mA at an operating time of 0.1 sec is suggested for dc applications.

Ground Fault Current Interrupters (GFCI)

The GFCI concept was originally developed by Fuchs-Westinghouse, Ltd.[4] in South Africa, for use in residential wiring, and is presently commercially available from a number of sources in the United States. It is being increasingly incorporated into single-phase systems in both residences and industrial buildings. The system depends on having a toroid with a "square" hysteresis loop, through which all power conductors pass, so that the flux created by the current out the one conductor can be balanced by the flux generated by return current in the other conductor. Any unbalance indicates the presence of a leakage current through the earth or external grounding circuits and if the output of a secondary winding on the toroid is utilized to trip a sensitive relay circuit, leakage currents as small as 5 mA will result in circuit interruption.

In the investigation conducted under Bureau of Mines contract J0113009, no commercially manufactured GFCI was found for the high-current applications peculiar to mining. Generally, the highly sensitive response to fault currents was accompanied by a similarly high sensitivity to electrical "noise" pulses conducted through the mine wiring or transmitted through space. Frequent nuisance tripping resulted, which would make the devices intolerable to operating personnel. It is possible, however, to include devices of this type in control boxes, to be enabled when the outer cover is opened but bypassed in normal operation. In this way, the maintenance worker would have highly sensitive protection at the expense of susceptibility to nuisance

[4]Reference to specific manufacturers does not imply endorsement by the Bureau of Mines.

tripping, whereas the noise immunity of the machine would not be compromised during routine operation.

Sensitive Earth Leakage (SEL) System

The SEL system has been used for over 10 years in the United Kingdom, and has been recently introduced into the U.S. mining operations by the Consolidation Coal Co., a subsidiary of DuPont Industries (2). Full details of the fundamental circuit have not been revealed. For U.S. mines, the British circuit was modified by adding an input filter, shielding the current transformer, and providing a short time delay, all to minimize nuisance tripping. The modified system limits the maximum ground-fault current to 500 mA, while the relay picks up at 140 mA, operating about 0.17 sec (10 cycles of 60-Hz current) after initiation. While these values of fault current and time are not yet comparable to the safe levels indicated in figure 3, there is a strong promise that future improvements will result in a relaying system that matches the desired characteristic. Meanwhile, the use of the system improves the probability that permanent damage will not result from contact with energized members.

CONCLUSION

MSHA statistics show that maintenance personnel are the primary victims of electrical accidents in the mining industry. This high incidence can be attributed to the worker's frequent exposure to electrical hazards. Reduced electrical exposure, through the use of dead-front construction and other physical barriers between the control circuit and the troubleshooter, in combination with test points, interlocks, and circuit lockout features, can play a significant role in decreasing electrical accidents. Sensitive ground-fault relaying, which is capable of detecting and isolating a ground-fault prior to electrocution, should be developed to provide protection if preventive measures fail. Dalziel's (1) ventricular fibrillation curve could define the ultimate time-current characteristic of such a relaying system. It is hoped that the illustrated examples provided in this paper serve as a starting point in a campaign to enhance electrical safety and that new approaches suggest themselves as these few suggestions are tried.

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2. Dolinar, K. D. Improved Ground Fault Protection System for Low and Medium Voltage Trailing Cables. IAS of IEEE Proc., 1982, pp. 122-127.

A DESIGN GUIDE FOR EXPLOSION-PROOF ELECTRICAL ENCLOSURES

By P. A. Cox[1] and Lawrence W. Scott[2]

ABSTRACT

A guide is being prepared for the design of explosion-proof electrical enclosures. It will address those aspects of design which affect enclosure strength and ruggedness. Material selection will be covered only for materials such as polycarbonates, adhesives, and sealants which can be seriously degraded by the mine environment. The guide will not address electrical function, nor will it duplicate or supplant the requirements set forth in the Code of Federal Regulations (CFR), Title 30, Part 18 (Schedule 2G). If followed, the design guide should assure that the strength and ruggedness requirements of Schedule 2G are met.

INTRODUCTION

This paper represents a status report on the preparation of a design guide for explosion-proof electrical enclosures. It is proposed that the guide be published under the auspices of the Federal Bureau of Mines and that it be made available to both the Mine Safety and Health Administration (MSHA) and enclosure manufacturers. Use of the design guide will be optional. Its purpose is to provide guidelines for the design of explosion-proof enclosures which, if followed, will assure that the enclosure will both pass MSHA certification testing and fulfill its intended service life underground. The guide will cover only those aspects of design that affect enclosure strength, ruggedness, and service life. It will not address electrical function such as connector design, lighting, electrical leads, or electrical penetrations. An attempt has been made to keep the guide general, rather than specific, so that it will continue to be useful as MSHA requirements evolve. For example, ruggedness is not now a specific requirement in Schedule 2G. Ruggedness has been achieved in the past by minimum thickness requirements and by design to withstand internal explosions of methane and air; however, future regulations may eliminate minimum thickness requirements and also permit the venting of enclosures to reduce internal overpressures. If this occurs, a ruggedness requirement may be imposed to insure that the enclosure will withstand the mine environment. Thus, a section on ruggedness will be included in the design guide.

The concept for the design guide and much of the material in it originated under Bureau of Mines contract H0377052. This contract included a survey of design and fabrication practice in the manufacture of explosion-proof enclosures. The survey showed that a design guide could be useful to the mining industry to unify and formalize procedures already being followed and to introduce to the industry new data and procedures generated in this contract. Data are also being taken from other related research, such as Bureau contract H0387009 (4)[3] and from numerous other sources as cited in the bibliography of this paper.

[1]Senior research engineer, Southwest Research Institute, San Antonio, Tex.

[2]Technical project officer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[3]Underlined numbers in parentheses refer to items in the bibliography at the end of this paper.

ORGANIZATION AND CONTENTS OF THE GUIDE

The guide is organized to address the various steps in the design process in the approximate order in which they usually occur. It is divided into many chapters, each of which covers a separate topic. It is hoped that through this organization of material the designers can easily locate and use the parts that they need or follow step by step through the entire design process. To facilitate the use of the guide by designers, as well as by analysts, many of the design process steps will be given in graphical format.

When the guide is first used, it is recommended that the designer review each chapter for content and then read carefully or work through examples (to be presented in the guide). The examples will cover the procedures described in the guide and will acquaint the designer with proper use of the equations, graphs, and data.

Because the guide will cover a number of different topics, some extensively, not all of the material can be presented in this paper. Instead, a brief review of the contents of the guide by topic is given, and following sections give details on three of the topics: "Design Pressures," "Design for Static Pressure," and "Design for Dynamic Pressure." Graphical solutions, which will be part of the completed design guide, have not yet been developed.

Design Requirements. - This chapter will cite MSHA requirements that affect the strength of explosion-proof enclosures and discuss new requirements that are being considered for adoption by MSHA at the time the guide is published. MSHA requirements are subject to change, and current regulations must always be checked.

Design Pressures. - This chapter will give procedures for choosing static and dynamic design pressures. Usually the static pressure will control the design, but dynamic effects must be checked also. Methods will be given for estimating the maximum value, rise time, and decay time of the dynamic pressure. The design procedure assumes that pressure piling does not occur, and guidelines will be given that will help the designer avoid pressure piling in his or her enclosure. The "Design Pressures" section of this paper gives the major details of this chapter except for those which pertain to pressure piling.

Design for Static Pressure. - Procedures will be given for sizing rectangular plates, circular plates, and cylinders to withstand the design static pressures without excessive distortion. Much of this chapter is included in this paper.

Design for Dynamic Pressure. - Procedures will be given for checking dynamic effects of the loading for both elastic and elastic-plastic material behavior. For small deformations, such as now permitted by MSHA, the elastic procedure can be used with good accuracy even though plastic behavior is ignored. For larger permanent deformations, the elastic-plastic procedure is recommended. This material is covered in the related section of this paper.

Design for Ruggedness. - MSHA does not now have an explicitly stated ruggedness requirement; however, a ruggedness test is being considered for adoption. This chapter will contain procedures for designing the enclosure to withstand external impact loads that can occur in the mine and which will most likely be included in a ruggedness requirement if one is adopted.

Guidelines for Windows and Lenses. - This will be an extensive chapter that covers the design of windows and their mounting arrangements for use in explosion-proof enclosures (9). Design procedures will be given for both glass and polycarbonate windows and lenses.

Thermal Stresses in Windows. - This brief chapter will give procedures for evaluating thermal stresses that are produced in glass and polycarbonate windows and lenses by the MSHA thermal shock test with one-side quenching. Window mounting arrangements for minimizing thermally induced stresses will also be given.

Welded Connections. - Weld joint design and joint efficiency will be covered in this chapter. Material is taken primarily from American Welding Society (AWS) Welding Code DW14.4, and this code is referenced for welding procedures, welder qualification, and weld joint inspection.

Bolted Connections. - This chapter will contain design procedures for bolted connections, primarily for enclosure covers. Cover restraint associated with external loads and prying action produced by internal loads will be treated. Connections will be designed to avoid permanent deformation in the bolts which could increase the flange gap.

Reinforcement of Openings. - Simple formulas for area replacement and stiffness continuity will be given for use in designing reinforcement around openings in the enclosure.

Materials of Construction. - This chapter will list materials that are suitable for explosion-proof enclosures. It will include metals, polycarbonates, glasses, and adhesives. Service life restrictions will be noted where applicable, and procedures will be given for qualifying new polycarbonates, adhesives, and sealants.

Examples. - Examples that demonstrate the use of the material in the guide will be included in this chapter. These examples will not cover the steps a designer must follow which lead up to the selection of an enclosure geometry, but they will address the design details that assure proper enclosure strength.

DESIGN PRESSURES

Static Pressures

Unless higher than expected pressures occur during the explosion test, the structural performance test will subject the enclosure to 150 psig. Because the magnitudes of pressures that can result from pressure piling cannot be predicted, it is proposed that the enclosure be designed under the assumption that pressure piling will not occur and that the guidelines for avoiding pressure piling (to be given in the design guide) will be followed. Using this approach, the design static pressure will be 150 psig.

Dynamic Pressures

Dynamic pressures are produced in an enclosure during the explosion test. These pressures are routinely measured by MSHA during testing and have also been measured by other investigators. For a spherical enclosure, a typical pressure-time history is given by Zabetakis (12) and shown in figure 1. Comparison between experiment and theory is also given from the work of Perlee (7). To analyze the response of an enclosure for the explosion pressure, the pressure's magnitude, rise time, and duration must be known. Methods for estimating the magnitude and rise time of the pressure are contained in following sections. Because the enclosure is usually tightly closed during the explosion test and in service, the pressure does not decay rapidly; therefore, its duration can be treated as long relative to the response time of the enclosure.

Peak Pressure

The peak pressure that theoretically can occur in a closed volume from the ignition of a mixture of methane and air at the stoichiometric[4] ratio is 117 psig.

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[4]Ratio at which there is, theoretically, just sufficient oxygen in the air for complete combustion of all of the methane. This ratio is 9.5 pct for methane and air.

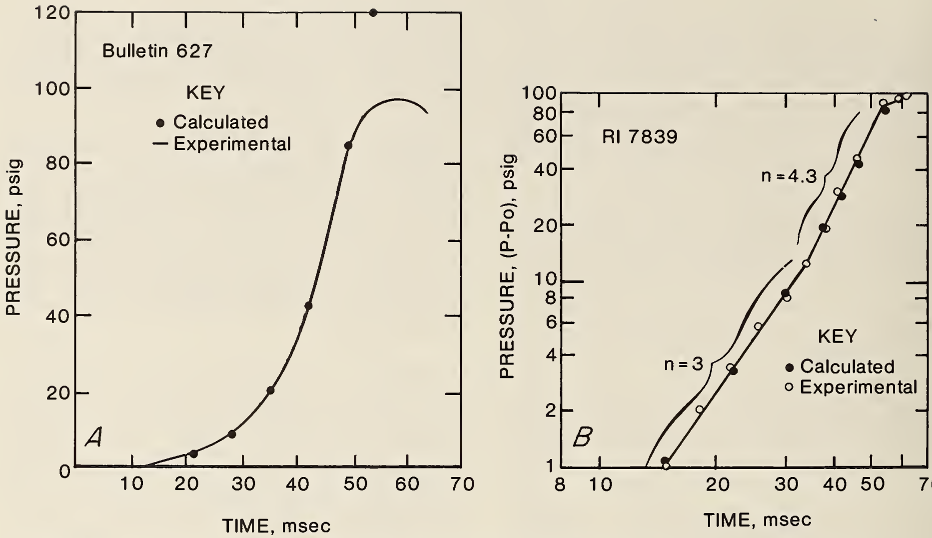


FIGURE 1. - Pressure in a 9-liter spherical chamber produced by ignition of a 9.6 vol-pct CH_4-air mixture.

This pressure is produced by complete combustion and assumes that no heat loss to the walls of the enclosure and, of course, no pressure piling occur. A more realistic upper limit for the pressure is the measured value shown in figure 1. This pressure is for a 9.6 vol-pct methane-air mixture, which is slightly rich and in practice gives the highest measured value of the explosion pressure. Also, this pressure was measured in a spherical chamber with central ignition, which is an idealized condition relative to most enclosure tests. Typical values of pressure measured by MSHA in the explosion test are 60 to 80 psig. Thus a peak explosion pressure of 100 psig is suggested as a reasonable design value unless the designer has valid reasons for increasing its magnitude. For example, the dynamic design value might be increased if the particular geometry of the enclosure is expected to produce pressure piling.

Rise Time

The rise time of the explosion pressure, as well as its magnitude, is needed to calculate the response of the enclosure to these dynamic loads. Further, a short rise time generally produces a greater response in the enclosure than a long one. Therefore, an estimate of the minimum rise time is made for design purposes.

To determine the minimum rise time, it is convenient to use the maximum rise rate of the pressure. Again, the data in figure 1 for spherical enclosures will be used. Using the minimum rise rate determined for spherical enclosures will not guarantee that a minimum rise time for all enclosures will be obtained, but using a minimum estimated rise time is conservative, and so the approach is appropriate for design of nonspherical enclosures.

An approximate relationship between the time from ignition to peak pressure and the enclosure volume is given by Zabetakis (12) as

$$t = 75\ \sqrt[3]{V},\ \text{msec}, \qquad (1)$$

where V is in cubic feet and t is in milliseconds. This is not a minimum rise time, but equation 1 can be used to scale a minimum rise time or maximum rise rate determined for one enclosure to enclosures with different volumes. A minimum rise rate for a 9-liter enclosure can be estimated from figure 1. Taking the tangent to the steepest part of the curve in figure 1*A* gives a pressure rise rate of

$$\dot{P}_{MAX} = \frac{97\ \text{psi}}{10.5\ \text{msec}} = 9.2\ \text{psi/msec}. \qquad (2)$$

This same rate is given by the upper part of the curve in figure 1*B*. Combining equations 1 and 2, the maximum rise rate for enclosures of other volumes is

$$\dot{P}_{MAX} = 9.2\ \text{psi/msec}\ \frac{75\ \sqrt[3]{0.1352\ \text{ft}^3}}{75\ \sqrt[3]{V\ \text{ft}^3}}$$

$$= \frac{4.72}{\sqrt[3]{V}},\ \text{psi/msec}. \qquad (3)$$

Thus, the minimum rise time is

$$t_{r_{min}} = \frac{P_{MAX}}{\dot{P}}$$

$$= \frac{P_{MAX}\ \sqrt[3]{V}}{4.72},\ \text{msec} \qquad (4)$$

where P_{MAX} is in pounds per square inch, gage, and V is in cubic feet,

or for a maximum explosion pressure of 100 psig

$$t_{r_{min}} = 21\ \sqrt[3]{V},\ \text{msec} \qquad (5)$$

where V is in cubic feet.

Equation 5 is used unless the expected dynamic pressure is other than 100 psig.

DESIGN FOR STATIC PRESSURE

The sizes and shapes of enclosures can vary greatly, but basically the geometry of the sides, bottom, and cover can be categorized as rectangular, circular, and cylindrical. Approximate design procedures are given in the following paragraphs for treating each of these basic geometries. Some of these procedures include provisions for permanent deformations; others do not. If permanent deformations are included in the design, they must not exceed the limits set by MSHA. Use of these procedures will be illustrated by example problems in the design guide, but ultimately the designer must use his or her own judgment in the application of these methods.

Rectangular Plates

Solutions for rectangular plates under uniform static loads are taken from the work of Jones and Walters (5). These solutions are based on rigid-perfectly plastic theory and give the relationship between the applied pressure, P, and permanent normal deflections of the plate, w_o. For the geometry of figure 2, equations 6 through 11 give the solutions for clamped and simply supported plates.

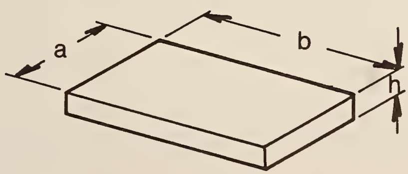


FIGURE 2. - Geometry of rectangular plates.

Clamped Plates

$$\frac{P}{P_c} = 0.618 + \frac{1.236\ w_o}{h}\left[\frac{(1+\beta^2)\sqrt{3+\beta^2} - \beta(2+\beta^2)}{\sqrt{3+\beta^2}}\right], \tag{6}$$

where $P_c = \dfrac{3\sigma_y}{\frac{a^2}{4h^2}(3 - 2\xi_o)}$, (7)

$\beta = a/b \leq 1,$ (8)

and $\xi_o = \beta(\sqrt{3+\beta^2} - \beta).$ (9)

Simply Supported Plates

$$\frac{P_c}{P} = 1 + \frac{4\ w_o^2}{3h^2}\left\{\frac{\xi_o + (3 - 2\xi_o)^2}{(3 - \xi_o)}\right\} \text{ for } \frac{w_o}{h} \leq \frac{1}{2}, \tag{10}$$

where $P_c = \dfrac{3\sigma_y}{\frac{a^2}{2h^2}(3 - 2\xi_o)}$. (11)

The solution for clamped plates has been shown by Jones and Walters (5) to give good agreement with experimental results for plates with β in the range of 1/3 to 1 and a/h in the range of 57 to 161. Equations 6 and 10 both should be applied to conditions for which w_o/h is less than 1/2. The current MSHA requirement that the permanent deformation be less than 0.040 in/ft will usually give $w_o/h \ll 1/2$.

Boundary conditions for the walls and covers of typical enclosures are not well known. This occurs because some junctions between side walls are formed by bending the plate and some are produced by welding. Further, the strength of the weld joint will vary depending upon the weld joint design; so the designer must use his or her own judgment in defining the boundary conditions of the plate and, thus, the proper equations to be used. If there is uncertainty about the proper choice of boundary conditions, the assumption of simple support will give a conservative results. (The choice of boundary conditions will be further illustrated in the design guide by the use of worked examples.)

Circular Plates

Solutions for circular plates are based on rigid-perfectly plastic theory and define the pressure for which a fully plastic collapse mechanism first develops in the plate. Lower bound collapse pressures for uniformly loaded plates of radius R and thickness h are given by Wood (11), and are as follows:

Clamped Edges

$$P_c = \frac{1.877\ \sigma_y h^2}{R^2}. \qquad (12)$$

Simply Supported Edges

$$P_c = \frac{\sigma_y h^2}{R^2}, \qquad (13)$$

where σ_y is the yield stress of the material. Note that these equations are independent of displacement. They do not include the stiffening effects of membrane forces produced by large displacements and in-plane restraint at the boundaries. The stiffening effects of displacements have been accounted for in simply supported plates by Sawezuk (8). For plates with in-plane restraint at the boundary, he gives

$$\frac{P}{P_c} = 1 + \frac{4}{3}\left(\frac{w_o}{h}\right)^2, \qquad (14)$$

where w_o is the center displacement of the plate and P_c is given by equation 13. As stated for rectangular plates, the permanent deformation now permitted by MSHA is so small that membrane effects are negligible. Thus equations 12 and 13 are satisfactory for enclosure design. Also, in sizing the cover, it is recommended that the clamping effect of the bolts be neglected and that equation 13 for simple support be used to determine cover thickness.

Cylinders

Cylinders designed for 150 psig will have thin walls, so that standard elastic formulas for thin wall cylinders can be used for design. Stresses will be uniform across the wall thickness, t, and the design conditions can be based on the circumferential wall stress just reaching some prescribed design stress. For cylinders, a design stress just below the yield stress (95 pct σy) is chosen because, once yielding occurs, the deformations cannot be accurately predicted. Beyond the yield stress, the deformations will be controlled only by the effect of end restraints and the increase in strength of the material produced by strain hardening. Thus, the following pressure-thickness relationship is recommended for cylinders with a mean radius, R:

Thin Wall Cylinder

$$P = \frac{0.95\ \sigma_y y}{R}. \qquad (15)$$

This formula should be used with the minimum yield stress of the material to assure that permanent deformations do not occur. Local yielding may occur at the ends of the cylinder or around penetrations, but the deformations will be well within the current MSHA requirement of 0.040 in/ft. (The design of penetrations will be covered in another part of the guide.)

DESIGN FOR DYNAMIC PRESSURES

Dynamic effects produced by transient loads can be important when the rise time of the loading is less than three times the fundamental period of the structural element. Methods for including dynamic effects in the design of enclosures for the explosion pressures are given in this section.

Elastic Behavior

If the response is elastic, that is, no permanent deformations occur, the effect of the dynamic loads can be estimated from figure 3. This figure gives the dynamic effect in terms of a dynamic load factor (DLF). $(DLF)_{MAX}$ is the maximum deflection produced by the dynamic loading divided by the deflection produced by a static load of the same magnitude.

To determine the DLF, one must know the rise time of the loading and the fundamental frequency of the structural element. (The rise time of the explosive loading is determined from data given in "Design for Dynamic Pressures" section.) In general, the shortest rise time will produce the greatest dynamic effect; however dips in the DLF do occur at even multiples of t_r/T_N. Because the rise times can vary, the minimum rise time should be estimated and the largest DLF for this rise time or any *longer* rise time should be chosen as the appropriate value. The fundamental frequency of the structural component can be calculated from equations in figures 4 and 5. These figures contain formulas for the fundamental frequencies of rectangular plates, circular plates, and cylinders. Note that for a cylinder, the fundamental mode corresponds to a uniform radial expansion and is not a bending mode. A uniform radial expansion is the type of response that a uniform internal pressure will produce in the cylinder. The next section also contains procedures for estimating fundamental frequencies of structural components.

Once the DLF has been determined from figure 3, equations 6 through 15 can be used to calculate the required plate or wall thickness. Note that the design pressure is now the maximum explosion pressure as shown in the section "Design Pressures" multiplied by DLF. This procedure is approximate because the formulas for plates in the "Design for Static Pressure" section are based on some material plasticity and thus the response is not completely elastic. The error will be small. A method that accounts for material plasticity, and which can be used if larger permanent deformations are permitted, is given in the next section.

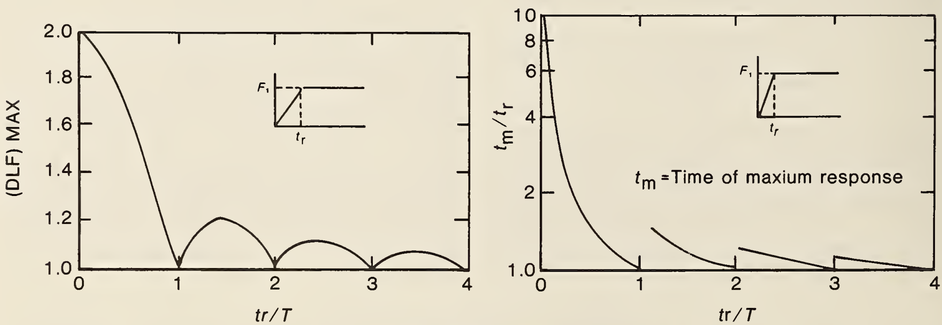
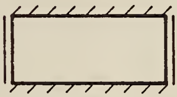
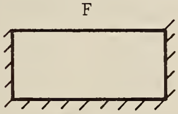
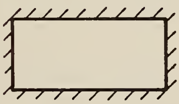
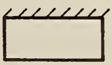
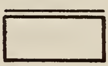


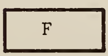
FIGURE 3. - Maximum response of 1-degree elastic systems (undamped) subjected to constant force with finite rise time (9).

BOUNDARY CONDITIONS*	$\omega b^2\sqrt{\rho h/D}$ FOR VALUES OF b/a				
	0.4	0.6667	1.0	1.5	2.5
	11.45	14.26	19.74	32.08	71.56
F  $\nu = 0.3$	10.13	10.67	11.68	13.71	18.80
	12.13	17.37	28.95	56.35	145.50
F  $\nu = 0.3$	22.58	23.02	24.02	26.73	37.66
	23.65	27.01	35.99	60.77	147.80

KEY

 CLAMPED

 SIMPLE SUPPORT



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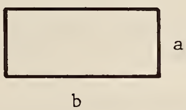
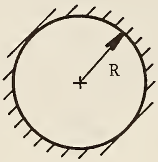
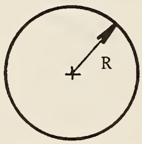
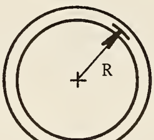


$D = \frac{Eh^3}{12\,(1-\nu)}$ ρ = mass density

FIGURE 4. - Fundamental circular frequencies for rectangular plates (derived from data in reference 3).

GEOMETRY	CIRCULAR FREQUENCY
	$\omega = \frac{10.22}{R^2} \sqrt{\frac{D}{\rho h}}$
S.S.  $\nu = 0.3$	$\omega = \frac{4.98}{R^2} \sqrt{\frac{D}{\rho h}}$
	$\omega = \frac{1}{R} \sqrt{\frac{E}{\rho(1-\nu^2)}}$ (breathing zone)

$$D = \frac{Eh^3}{12\,(1-\nu^2)} \qquad \rho = \text{mass density}$$

FIGURE 5. - Fundamental frequencies of circular plates and long cylinders (derived from data in reference 3).

Elastic-Plastic Behavior

For elastic-plastic behavior, particularly if larger permanent deformations are permitted, procedures developed by Biggs (2), Nemark (6), and Beck (1) are recommended. These methods are based upon the assumption of a deformation pattern for the structural element. The usual assumption for elastic behavior is the static deformed shape under the same distribution of loading. For plastic behavior, a hinge mechanism is postulated. Once the deflected shape has been chosen, the system (beam or plate) can be transformed into a one-degree-of-freedom (dof) system for which the dynamic response can be easily computed.

Based on the assumption of the static deformed shape and the formation of plastic hinges, figures 6 through 10 give transformation factors, resistance functions, spring constants, and shear reactions for uniformly loaded rectangular and circular plates. These quantities are given for different boundary conditions, plate aspect ratios, and material behavior. Definitions of these quantities follow.

Maximum Resistance. - This is the total load at which the plate will develop a fully plastic hinge mechanism. For the elastic solution of a clamped rectangular plate, it is the load at which a plastic hinge forms at the fixed boundary. For elastic-plastic and fully plastic behavior, it corresponds to the development of a hinge at the center as well as the fixed edge. The moments used to calculate the maximum resistance are

M°_{psb} = negative plastic bending moment capacity *per unit width* at the center of edge b,

M_{psb} = *total* negative plastic bending moment capacity along edge b,

M_{pfb} = *total* positive plastic bending moment along the midspan section parallel to edge b,

M°_{psa}, M_{pfa} = same as above, but for edge a.

M_{pc} = positive plastic bending moment capacity *per unit length* at the center of the circular plate,

and M_{ps} = negative plastic bending moment capacity *per unit length* at the edge of the circular plate.

Positive and negative moments need be considered only for concrete slabs in which these values may differ from each other. For homogeneous materials, there is no distinction between the positive and negative values.

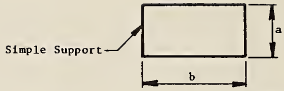
Spring Constant. - This is the spring constant for the plate expressed in terms of the elastic modulus, E, and the moment of inertia per unit width, I_a. It is calculated as the total load on the plate divided by the static center deflection.

Dynamic Reaction. - The dynamic reaction is the shear at the boundaries expressed as a fraction of the instanteous values of the applied load, F, and the resistance, R. To accurately determine the maximum shear, the time-history of the one-dof system must be calculated; however, because the loading from internal explosions is idealized as a ramp function to a constant load, calculating the shear reaction at t_m when the response is a maximum, and after the load has peaked, should give the maximum value. An upper limit is found by taking the peak value of F and R to calculate the dynamic shear.

Load Factor, K_L. - The load factor is the ratio of the load applied to the equivalent one-dof system to the total load applied to the plate. When the static deformed shape is assumed for the deformation pattern (as it is in figs. 6-10), it is also the ratio of the spring constant of the equivalent system to the spring constant of the plate as given in the figures.

Mass Factor, k_m. - This is the ratio of the mass of the equivalent one-dof system to the total mass of the plate.

Load-Mass Factor, k_{LM}. - The load-mass factor is the ratio k_m/k_L.



Strain Range	a/b	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}	Maximum Resistance	Spring Constant k	Dynamic Reactions V_A	Dynamic Reactions V_B
Elastic	1.0	0.45	0.31	0.68	$\frac{12}{a}\left(M_{pfa} + M_{pfb}\right)$	$252\ EI_a/a^2$	0.07 F + 0.18 R	0.07 F + 0.18 R
	0.9	0.47	0.33	0.77	$\frac{1}{a}\left(12.0\ M_{pfa} + 11.0\ M_{pfb}\right)$	$230\ EI_a/a^2$	0.06 F + 0.16 R	0.08 F + 0.20 R
	0.8	0.49	0.35	0.71	$\frac{1}{a}\left(12.0\ M_{pfa} + 10.3\ M_{pfb}\right)$	$212\ EI_a/a^2$	0.06 F + 0.14 R	0.08 F + 0.22 R
	0.7	0.51	0.37	0.73	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.8\ M_{pfb}\right)$	$201\ EI_a/a^2$	0.05 F + 0.13 R	0.08 F + 0.24 R
	0.6	0.53	0.39	0.74	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.3\ M_{pfb}\right)$	$197\ EI_a/a^2$	0.04 F + 0.11 R	0.09 F + 0.26 R
	0.5	0.55	0.41	0.75	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.0\ M_{pfb}\right)$	$201\ EI_a/a^2$	0.04 F + 0.09 R	0.09 F + 0.28 R
Plastic	1.0	0.33	0.17	0.51	$\frac{12}{a}\left(M_{pfa} + M_{pfb}\right)$	0	0.09 F + 0.16 R_m	0.09 F + 0.16 R_m
	0.9	0.35	0.18	0.51	$\frac{1}{a}\left(12.0\ M_{pfa} + 11.0\ M_{pfb}\right)$	0	0.08 F + 0.15 R_m	0.09 F + 0.18 R_m
	0.8	0.37	0.20	0.54	$\frac{1}{a}\left(12.0\ M_{pfa} + 10.3\ M_{pfb}\right)$	0	0.07 F + 0.13 R_m	0.10 F + 0.20 R_m
	0.7	0.38	0.22	0.58	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.8\ M_{pfb}\right)$	0	0.06 F + 0.12 R_m	0.10 F + 0.22 R_m
	0.6	0.40	0.23	0.58	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.3\ M_{pfb}\right)$	0	0.05 F + 0.10 R_m	0.10 F + 0.25 R_m
	0.5	0.42	0.25	0.59	$\frac{1}{a}\left(12.0\ M_{pfa} + 9.0\ M_{pfb}\right)$	0	0.04 F + 0.08 R_m	0.11 F + 0.27 R_m

FIGURE 6. - Transformation factors for two-way slabs. Simple supports—four sides, uniform load; for Poisson's ratio = 0.3 (10).

The purpose of the transformation factors is to define a one-dof system that can be easily solved for its response to dynamic loads. The resulting equation is

$$K_M K\ddot{x} + K_L kx = K_L F\ (t), \qquad (16)$$

where M, F, and k are the total mass, total load, and spring constant, respectively, of the plate, and K_L and K_M are the transformation factors. Dividing equation 16 by K_L yields

$$K_{LM} M\ddot{x} + kx = F(t). \qquad (17)$$

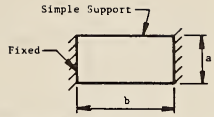
Equation 17 shows that only K_{LM} is needed to obtain an equivalent one-dof system.

The fundamental period of the plate, T_N, is also given by the one-dof system because the system is kinematically equivalent to the plate. The period is calculated as

$$T_N = 2\pi \sqrt{\frac{K_M M}{K_L k}} = 2\pi \sqrt{\frac{K_{LM} M}{k}}. \qquad (18)$$

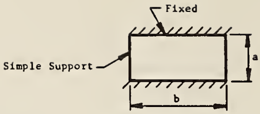
Thus, only K_{LM}, the spring constant from the figures, and the plate mass are needed to calculate T_N.

Numerical or closed-form solutions can be obtained easily for equation 17, but graphical solutions are also available. The solution for a ramp loading to a



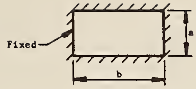
Strain Range	a/b	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}	Maximum Resistance	Spring Constant k	Dynamic Reactions V_A	Dynamic Reactions V_B
Elastic	1.0	0.39	0.26	0.67	$20.4\ M^\circ_{psa}$	$575\ EI_a/a^2$	$0.09\ F + 0.16\ R$	$0.07\ F + 0.18\ R$
	0.9	0.41	0.28	0.68	$10.2\ M^\circ_{psa} + \frac{11.0}{a} M_{pfb}$	$476\ EI_a/a^2$	$0.08\ F + 0.14\ R$	$0.08\ F + 0.20\ R$
	0.8	0.44	0.30	0.68	$10.2\ M^\circ_{psa} + \frac{10.3}{a} M_{pfb}$	$396\ EI_a/a^2$	$0.08\ F + 0.12\ R$	$0.08\ F + 0.22\ R$
	0.7	0.46	0.33	0.72	$9.3\ M^\circ_{psa} + \frac{9.7}{a} M_{pfb}$	$328\ EI_a/a^2$	$0.07\ F + 0.11\ R$	$0.08\ F + 0.24\ R$
	0.6	0.48	0.35	0.73	$8.5\ M^\circ_{psa} + \frac{9.3}{a} M_{pfb}$	$283\ EI_a/a^2$	$0.06\ F + 0.09\ R$	$0.09\ F + 0.26\ R$
	0.5	0.51	0.37	0.73	$7.4\ M^\circ_{psa} + \frac{9.0}{a} M_{pfb}$	$243\ EI_a/a^2$	$0.05\ F + 0.08\ R$	$0.09\ F + 0.28\ R$
Elasto-Plastic	1.0	0.46	0.31	0.67	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 12.0\ M_{pfb}\right]$	$271\ EI_a/a^2$	$0.07\ F + 0.18\ R$	$0.07\ F + 0.18\ R$
	0.9	0.47	0.33	0.70	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 11.0\ M_{pfb}\right]$	$248\ EI_a/a^2$	$0.06\ F + 0.16\ R$	$0.08\ F + 0.20\ R$
	0.8	0.49	0.35	0.71	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 10.3\ M_{pfb}\right]$	$228\ EI_a/a^2$	$0.06\ F + 0.14\ R$	$0.08\ F + 0.22\ R$
	0.7	0.51	0.37	0.72	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.7\ M_{pfb}\right]$	$216\ EI_a/a^2$	$0.05\ F + 0.13\ R$	$0.08\ F + 0.24\ R$
	0.6	0.53	0.37	0.70	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.3\ M_{pfb}\right]$	$212\ EI_a/a^2$	$0.04\ F + 0.11\ R$	$0.09\ F + 0.26\ R$
	0.5	0.55	0.41	0.74	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.0\ M_{pfb}\right]$	$216\ EI_a/a^2$	$0.04\ F + 0.09\ R$	$0.09\ F + 0.28\ R$
Plastic	1.0	0.33	0.17	0.51	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 12.0\ M_{pfb}\right]$	0	$0.09\ F + 0.16\ R_m$	$0.09\ F + 0.16\ R_m$
	0.9	0.35	0.18	0.51	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 11.0\ M_{pfb}\right]$	0	$0.08\ F + 0.15\ R_m$	$0.09\ F + 0.18\ R_m$
	0.8	0.37	0.20	0.54	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 10.3\ M_{pfb}\right]$	0	$0.07\ F + 0.13\ R_m$	$0.10\ F + 0.20\ R_m$
	0.7	0.38	0.22	0.58	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.7\ M_{pfb}\right]$	0	$0.06\ F + 0.12\ R_m$	$0.10\ F + 0.22\ R_m$
	0.6	0.40	0.23	0.58	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.3\ M_{pfb}\right]$	0	$0.05\ F + 0.10\ R_m$	$0.10\ F + 0.25\ R_m$
	0.5	0.42	0.25	0.59	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.0\ M_{pfb}\right]$	0	$0.04\ F + 0.08\ R_m$	$0.11\ F + 0.27\ R_m$

FIGURE 7. - Transformation factors for two-way slabs. Short edges fixed, long edges simply supported; for Poisson's ratio = 0.3 (10).



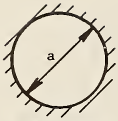
Strain Range	a/b	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}	Maximum Resistance	Spring Constant k	Dynamic Reactions V_A	Dynamic Reactions V_B
Elastic	1.0	0.39	0.26	0.67	$20.4\ M^{\circ}_{psb}$	$575\ EI_a/a^2$	0.07 F + 0.18 R	0.09 F + 0.16 R
	0.9	0.40	0.28	0.70	$19.5\ M^{\circ}_{psb}$	$600\ EI_a/a^2$	0.06 F + 0.16 R	0.10 F + 0.18 R
	0.8	0.42	0.29	0.69	$19.5\ M^{\circ}_{psb}$	$610\ EI_a/a^2$	0.06 F + 0.14 R	0.11 F + 0.19 R
	0.7	0.43	0.31	0.71	$20.2\ M^{\circ}_{psb}$	$662\ EI_a/a^2$	0.05 F + 0.13 R	0.11 F + 0.21 R
	0.6	0.45	0.33	0.73	$21.2\ M^{\circ}_{psb}$	$731\ EI_a/a^2$	0.04 F + 0.11 R	0.12 F + 0.23 R
	0.5	0.45	0.34	0.72	$22.2\ M^{\circ}_{psb}$	$850\ EI_a/a^2$	0.04 F + 0.09 R	0.12 F + 0.25 R
Elasto-Plastic	1.0	0.46	0.31	0.67	$\frac{1}{a}\left[12.0\ M_{pfa} + 12.0\left(M_{psb} + M_{pfb}\right)\right]$	$271\ EI_a/a^2$	0.07 F + 0.18 R	0.07 F + 0.18 R
	0.9	0.47	0.33	0.70	$\frac{1}{a}\left[12.0\ M_{pfa} + 11.0\left(M_{psb} + M_{pfb}\right)\right]$	$248\ EI_a/a^2$	0.06 F + 0.16 R	0.08 F + 0.20 R
	0.8	0.49	0.35	0.71	$\frac{1}{a}\left[12.0\ M_{pfa} + 10.3\left(M_{psb} + M_{pfb}\right)\right]$	$228\ EI_a/a^2$	0.06 F + 0.14 R	0.08 F + 0.22 R
	0.7	0.51	0.37	0.73	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.8\left(M_{psb} + M_{pfb}\right)\right]$	$216\ EI_a/a^2$	0.06 F + 0.13 R	0.08 F + 0.24 R
	0.6	0.53	0.39	0.74	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.3\left(M_{psb} + M_{pfb}\right)\right]$	$212\ EI_a/a^2$	0.04 F + 0.11 R	0.09 F + 0.26 R
	0.5	0.55	0.41	0.74	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.0\left(M_{psb} + M_{pfb}\right)\right]$	$216\ EI_a/a^2$	0.04 F + 0.09 R	0.09 F + 0.28 R
Plastic	1.0	0.33	0.17	0.51	$\frac{1}{a}\left[12.0\ M_{pfa} + 12.0\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.09\ F + 0.16\ R_m$	$0.09\ F + 0.16\ R_m$
	0.9	0.35	0.18	0.51	$\frac{1}{a}\left[12.0\ M_{pfa} + 11.0\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.08\ F + 0.15\ R_m$	$0.09\ F + 0.18\ R_m$
	0.8	0.37	0.20	0.54	$\frac{1}{a}\left[12.0\ M_{pfa} + 10.3\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.07\ F + 0.13\ R_m$	$0.10\ F + 0.20\ R_m$
	0.7	0.38	0.22	0.58	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.8\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.06\ F + 0.12\ R_m$	$0.10\ F + 0.22\ R_m$
	0.6	0.40	0.23	0.58	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.3\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.05\ F + 0.10\ R_m$	$0.10\ F + 0.25\ R_m$
	0.5	0.42	0.25	0.59	$\frac{1}{a}\left[12.0\ M_{pfa} + 9.0\left(M_{psb} + M_{pfb}\right)\right]$	0	$0.04\ F + 0.08\ R_m$	$0.11\ F + 0.27\ R_m$

FIGURE 8. - Transformation factors for two-way slabs. Short sides simply supported, long sides fixed; for Poisson's ratio = 0.3 (10).

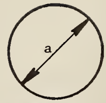


Strain Range	a/b	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}	Maximum Resistance	Spring Constant k	Dynamic Reactions V_A	Dynamic Reactions V_B
Elastic	1.0	0.33	0.21	0.63	$29.2\ M^{0}_{psb}$	$810\ EI_a/a^2$	0.10 F + 0.15 R	0.10 F + 0.15 R
	0.9	0.34	0.23	0.68	$27.4\ M^{0}_{psb}$	$742\ EI_a/a^2$	0.09 F + 0.14 R	0.10 F + 0.17 R
	0.8	0.36	0.25	0.69	$26.4\ M^{0}_{psb}$	$705\ EI_a/a^2$	0.08 F + 0.12 R	0.11 F + 0.19 R
	0.7	0.38	0.27	0.71	$26.2\ M^{0}_{psb}$	$692\ EI_a/a^2$	0.07 F + 0.11 R	0.11 F + 0.21 R
	0.6	0.41	0.29	0.71	$27.3\ M^{0}_{psb}$	$724\ EI_a/a^2$	0.06 F + 0.09 R	0.12 F + 0.23 R
	0.5	0.43	0.31	0.72	$30.2\ M^{0}_{psb}$	$806\ EI_a/a^2$	0.05 F + 0.08 R	0.12 F + 0.25 R
Elasto-Plastic	1.0	0.46	0.31	0.67	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 12.0\left(M_{pfb} + M_{psb}\right)\right]$	$252\ EI_a/a^2$	0.07 F + 0.18 R	0.07 F + 0.18 R
	0.9	0.47	0.33	0.70	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 11.0\left(M_{pfb} + M_{psb}\right)\right]$	$230\ EI_a/a^2$	0.06 F + 0.16 R	0.08 F + 0.20 R
	0.8	0.49	0.35	0.71	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 10.3\left(M_{pfb} + M_{psb}\right)\right]$	$212\ EI_a/a^2$	0.06 F + 0.14 R	0.08 F + 0.22 R
	0.7	0.51	0.37	0.73	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.8\left(M_{pfb} + M_{psb}\right)\right]$	$201\ EI_a/a^2$	0.05 F + 0.13 R	0.08 F + 0.24 R
	0.6	0.53	0.39	0.74	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.3\left(M_{pfb} + M_{psb}\right)\right]$	$197\ EI_a/a^2$	0.04 F + 0.11 R	0.09 F + 0.26 R
	0.5	0.55	0.41	0.75	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.0\left(M_{pfb} + M_{psb}\right)\right]$	$201\ EI_a/a^2$	0.04 F + 0.09 R	0.09 F + 0.28 R
Plastic	1.0	0.33	0.17	0.51	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 12.0\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.09\ F + 0.16\ R_m$	$0.09\ F + 0.16\ R_m$
	0.9	0.35	0.18	0.51	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 11.0\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.08\ F + 0.15\ R_m$	$0.09\ F + 0.18\ R_m$
	0.8	0.37	0.20	0.54	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 10.3\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.07\ F + 0.13\ R_m$	$0.10\ F + 0.20\ R_m$
	0.7	0.38	0.22	0.58	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.8\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.06\ F + 0.12\ R_m$	$0.10\ F + 0.22\ R_m$
	0.6	0.40	0.23	0.58	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.3\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.05\ F + 0.10\ R_m$	$0.10\ F + 0.25\ R_m$
	0.5	0.42	0.25	0.59	$\frac{1}{a}\left[12.0\left(M_{pfa} + M_{psa}\right) + 9.0\left(M_{pfb} + M_{psb}\right)\right]$	0	$0.04\ F + 0.08\ R_m$	$0.11\ F + 0.27\ R_m$

FIGURE 9. - Transformation factors for two-way slabs. Fixed supports, uniform load; for Poisson's ratio = 0.3 (10).



Fixed Edges



Simple Supports

Edge Condition	Strain Range	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}	Maximum Resistance	Spring Constant	Dynamic Reaction
Simple Supports	Elastic	0.46	0.30	0.65	$18.8\ M_{pc}$	$216\ EI/a^2$	$0.28\ F + 0.72\ R$
	Plastic	0.33	0.17	0.52	$18.8\ M_{pc}$	0	$0.36\ F + 0.64\ R_m$
Fixed Supports	Elastic	0.33	0.20	0.61	$25.1\ M_{ps}$	$880\ EI/a^2$	$0.40\ F + 0.60\ R$
	Elasto-Plastic	0.46	0.30	0.65	$18.8\left(M_{pc} + M_{ps}\right)$	$216\ EI/a^2$	$0.28\ F + 0.72\ R$
	Plastic	0.33	0.17	0.52	$18.8\left(M_{pc} + M_{ps}\right)$	0	$0.36\ F + 0.64\ R_m$

FIGURE 10. - Transformation factors for circular slabs. Poisson's ratio = 0.3 (10).

constant value is given by figure 11. Figure 11*A* gives the maximum displacement, x_m, relative to the displacement at yielding, x_e, and figure 11*B* gives the time, t_m, at which the maximum response is reached relative to the rise time of the load, t_r. Both of these quantities are given as functions of the maximum resistance, R_m, the maximum total applied load, F, and the fundamental period of the plate, T_N. To use figure 3, one must determine the following quantities:

T_N - calculated by equation 18,

t_r - the rise time of the load,

F - the maximum value of the load on the plate which is the product of the maximum value of the pressure and the plate area,

R_m - maximum resistance from figures 6 through 10.

X_e - deflection at which the plate yields. It is calculated as the maximum resistance for elastic behavior divided by the spring constant from figures 6 through 10.

Note that to use figure 4, the only transformation factor that is needed is K_{LM}, used in equation 18 to calculate T_N. Also, it is necessary to know in advance how the structure will respond; that is, will the structure remain elastic, experience mild plasticity, or undergo gross deformations? This determines the choice of parameters from the figures. If elastic behavior is expected, choose the parameters that correspond to elastic behavior; if gross plasticity is

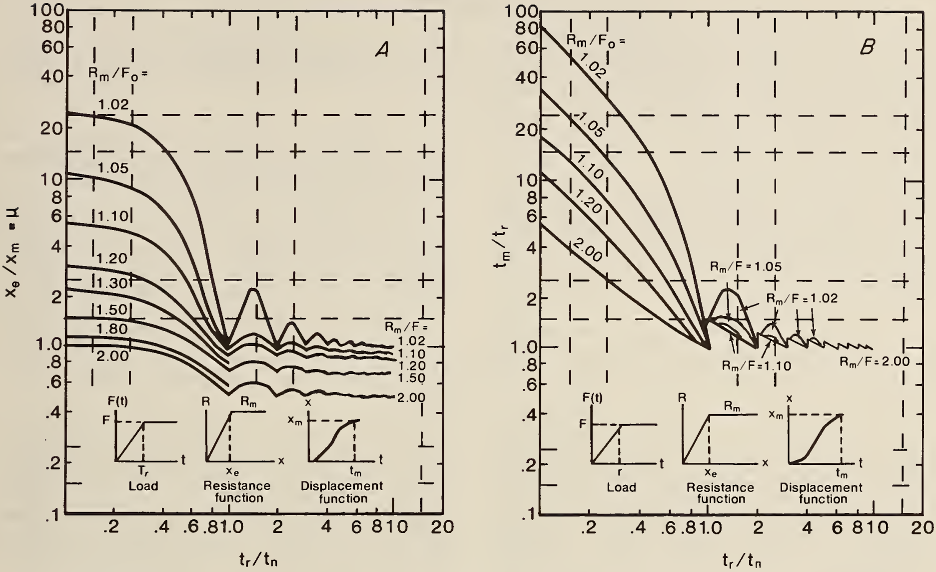


FIGURE 11. - Maximum response of undamped single-degree-of-freedom elastic-plastic system to step pulse with finite rise time (10).

expected, choose the parameters for plastic behavior; if mild plasticity is expected, average the values for elastic and plastic behavior. Another alternative is to solve equation 17 for the response of the structural element. When solving equation 17, note that the parameters that define the one-dof approximation must change as the system yields.

As explained previously, the maximum response is usually produced by a loading with the shortest rise time; however, dips in the response do occur at even multiples of the t_r/T_N ratio. Therefore, it is recommended that the response be taken as the maximum value that occurs for all rise times equal to or greater than the minimum rise time as determined in the "Design Pressures" section.

CONCLUSIONS

The authors hope that the design guide that is being developed by the Federal Bureau of Mines will be of great benefit to the manufacturers of explosion-proof enclosures. This can only happen if the guide contains the appropriate information in a suitable format and if the guide is accepted and used by the industry. Although this paper does not show the final format of the guide, it does give an overview of its contents. The format will be similar to that used in this paper, but it will be complemented by charts in some areas to make the solutions simpler. Comments on the scope, contents, and format of the guide are solicited by the authors in order to tailor the guide to the mining industry.

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HIGH-VOLTAGE, EXPLOSION-PROOF LOAD CENTERS

By George Conroy,[1] Randy Berry,[2] and Robert Gillenwater[2]

ABSTRACT

To attain future underground mine production considered to be necessary by the Department of Energy, voltages higher than the presently permitted 4,160 V must be carried to the close vicinity of the mining machines; otherwise, trailing cable size and weight creates handling problems. A project has been running for the past year to delineate approval tests and acceptance criteria for explosion-proof load centers that will permit operation inby the last open crosscut. The investigation includes fabrication and testing of a load center. Tentative specifications are presented in this report.

INTRODUCTION

Present methods of developing some underground coal mines and some extensive noncoal mines require the transfer of large amounts of electric power through long lengths of trailing cable. A practical alternative to specifying very large diameter cables, used to reduce voltage drop, is to transfer the power at high voltage and relatively low current levels. The voltage might then be transformed to a working level by equipment located near the mining machine. In certain circumstances, either inherent in the mode of operation or because uncontrollable methane "bursts" can occur, the stepdown transformer and associated switching apparatus may become surrounded by methane-air atmosphere, leading to the possibility of a mine explosion if the equipment has not been constructed to be permissible.

Verifying permissibility is the responsibility of Mine Safety and Health Administration's (MSHA) Approval and Certification Center in Triadelphia, W. Va. The most important guidelines for the determination are the set of regulations contained in Title 30, Code of Federal Regulations (CFR), Part 18. Part 18 gives very little guidance for test and acceptance of equipment to be energized at voltages from 1,000 to 4,160 V, and does not even consider voltages above 4,160 V. In an effort to facilitate the use of higher voltages, the Department of Energy (DOE) funded a Federal Bureau of Mines project to develop acceptance tests and criteria that MSHA could use to supplement current Part 18 regulations. At the same time, DOE has funded MSHA to develop an explosion test gallery capable of accommodating and testing the large enclosures necessary for high-voltage transformers and switchgear. At MSHA's option, this gallery could be transported to a high-power test facility to conduct explosion tests on load centers using a high-voltage source ranging up to the 15-kV maximum now contemplated. These tests would measure the internal pressures and temperatures resulting from the occurrence of an arcing electrical fault in the presence of an explosive methane-air mixture. At other times, the MSHA gallery would be utilized at Triadelphia, W. Va., for explosion testing as presently conducted on all permissible equipment.

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This paper examines the following special considerations concerning high voltage load centers:

- Power rating: maximum levels
- Maximum current to an arcing fault
- Maximum arc duration
- Electrical clearances
- Insulating materials

Each of these five topics is discussed separately in the following sections.

SPECIAL CONSIDERATIONS CONCERNING APPROVAL AND TESTING CRITERIA FOR HIGH-VOLTAGE PERMISSIBLE LOAD CENTERS

Power Rating of Load Centers

Maximum power requirements for underground coal mine section load centers, whether or not permissible, are estimated to be within the 2,000-kVA upper limit addressed in the ongoing Bureau program. One limiting factor is the physical size of such equipment as compared with the dimensions of existing mine entries. Load centers capable of delivering more than 2,000 kVA are likely to pose major mobility problems in underground coal mines. This may be less of a problem in such noncoal settings as oil shale mines. However, the question of permissibility has not yet been resolved in that application, nor have particular equipment rating and size requirements been specified.

Another limiting factor for lower voltage permissible load centers is cable size. Present Part 18 requirements for three-conductor trailing cable for use at voltages up to 5 kV specify a maximum ampacity of 305 A for 350 MCM shielded cable. This places an upper limit on the power rating of permissible load centers, assuming power input through a single trailing cable, as shown in figure 1. As indicated by the curve, a 2,000-kVA load center could be supplied at any line voltage level above 3.8 kV. No more than 500 kVA could be utilized in a load center designed for 1.0-kV operation. However, a 350 MCM cable is much larger than most mines would care to use for supplying power to individual sections. Supposing the use of a 4/0 cable, with a maximum ampacity of 220 A, yields the lower curve shown in figure 1. Using this cable, a 2,000-kVA permissible load center could be supplied at any line voltage level above 5.1 kV. A 500 kVA load center would require a minimum operating voltage of 1.3 kV. Adoption of cable rating tables that allow a higher conductor temperature would result in higher current levels and correspondingly higher allowable kilovoltampere ratings. This is not likely to occur without

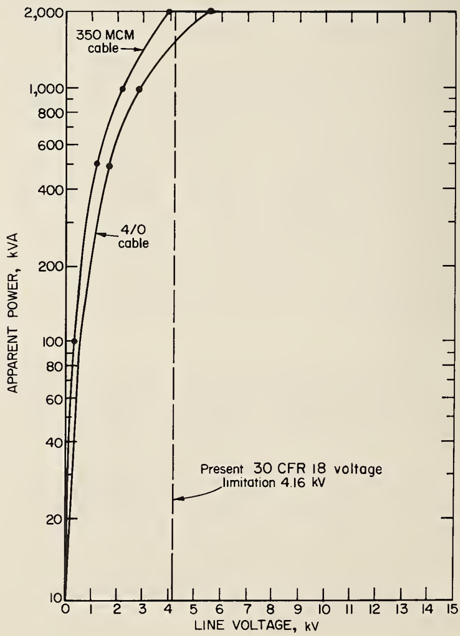

FIGURE 1. - Regions of practical interest, high-voltage permissible load centers.

substantial justification. Therefore, the practical range of interest in preparing special acceptance criteria for very high voltage permissible load centers includes input powers from 500 to 2,000 kVA, and line voltages from 1.0 kV to a maximum of 15 kV, the highest voltage expected to be used underground in the forseeable future. Although load centers operating at less than 4.16 kV could supposedly be examined under the existing regulations, a dearth of precedents in the region above 1 kV justifies interest with regard to new test and acceptance criteria.

Maximum Current to an Arcing Fault

One of the principal questions regarding permissible load centers is whether or not their explosion-proof characteristic can be compromised if the energy released by an arcing electrical fault is added to that generated by a simultaneous methane-air explosion within the enclosure. The energy contributed by the arcing fault depends on the fault current. Because the arc has a finite resistance, this fault current will be less than the current possible in a "bolted" (zero resistance) short circuit. Thus, the worst case situation can be conservatively considered as the occurrence of an arcing fault with a current flow equal to the maximum available current through a bolted fault at the internal terminations of the trailing cable. The shortest length of trailing cable connecting the load center to the substation supplying its power would usually be 500 to 1,000 ft, while the maximum might be 21,000 ft. The cable impedance at the shortest distance is so small as to be a negligible factor in limiting the fault current, so that substation transformer impedance must provide the worst case limit. At the longest distance, trailing cable impedance along with the arc voltage might limit fault current to a rather low value, thus creating a sensitive situation with regard to the ability of primary circuit protection devices to interrupt the current rapidly enough to prevent a serious buildup of pressure in the enclosure. This problem is explored in more detail in the next subsection.

Continuing the conservative approach, the substation is assumed to be connected to an "infinite bus" at the point of supply from the utility. This substation is presumed to be dedicated to the single load center concerned so that its transformer impedance may be related directly to this circuit. This impedance is assumed to be 5 pct of the impedance that would yield rated load current, and therefore rated apparent power, for any given line voltage. Taking some discrete values of line voltage and power rating, transformer phase-to-phase impedance would appear as shown in table 1. This value can be used to calculate the current available to a bolted fault (neglecting cable impedance). The impedance per thousand feet of the smallest size cable that could be used for the selected values, per Part 18, is also listed in table 1. This value will be used for estimating the current limiting effect of long lengths of cable.

Table 2 and figure 2 show the current available to bolted faults as calculated using the preceding assumptions. The largest available fault current is 8,175 A in the 1-kV, 500-kVA unit. The available current in the 4.16-kV, 2,000-kVA unit is only slightly less. A worst-case test as suggested by the analysis is to be one with 10,000 A available from a 4.16-kV source, supplying an arcing fault in a 2,000-kVA load center. As the intent is to verify only that the enclosure can withstand any developed internal pressures and temperatures, actual testing would be performed using separately introduced test electrodes rather than actual component members. An arbitrary electrode spacing of 6 in is recommended, with the arc being started by means of a connecting filament.

TABLE 1. - Primary cable values

Line voltage, kV	Power rating, kVA	Line current at rated power, A	Transformer 5 pct impedance, ohms	Mine cable size	Cable impedance, ohms per 1,000 ft
1.0	500	289	0.173	350 MCM	0.116
2.3	500	126	.916	AWG 2	.386
	1,000	251	.458	300 MCM	.125
4.16	1,000	139	1.499	AWG 1/0	.255
	1,500	208	.999	AWG 4/0	.151
	2,000	278	.749	350 MCM	.116
7.2	1,000	80	4.490	AWG 4	.296
	1,500	120	2.993	AWG 1	.153
	2,000	160	2.245	AWG 2/0	.102
12.5	1,000	46	13.351	[1]AWG 6	.468
	1,500	69	9.021	AWG 4	.296
	2,000	92	6.794	AWG 3	.237
15	1,000	38	19.485	AWG 6	.468
	1,500	58	12.990	AWG 6	.468
	2,000	77	9.742	AWG 4	.296

[1]Smallest size permitted by 30 CFR 18.

TABLE 2. - Peak available current to a bolted fault

Line voltage, kV	Power rating, kVA	Bolted fault available peak current, A
1.0	500	8,175
2.3	500	3,551
	1,000	7,102
4.16	1,000	3,925
	1,500	5,889
	2,000	7,855
7.2	1,000	2,268
	1,500	3,402
	2,000	4,536
12.5	1,000	1,306
	1,500	1,960
	2,000	2,602
15	1,000	1,089
	1,500	1,633
	2,000	2,177

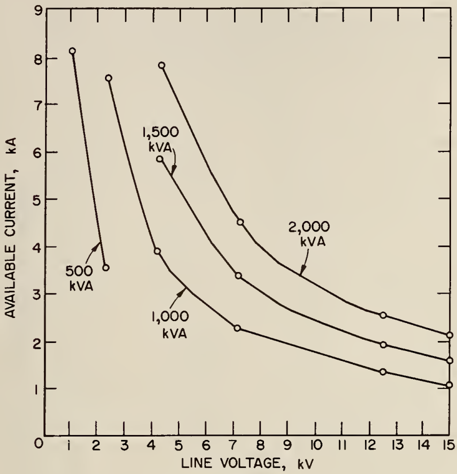

FIGURE 2. - Peak available current for various power ratings.

Maximum Arc Duration

Modern industrial practice with regard to power systems in the 1- to 15-kV range calls for the use of circuit protection devices capable of interrupting the circuit within 50 msec (3 cycles at 60 Hz). Circuit interruptions in this short interval would occur after a fault to ground activates a sensing relay, which signals the circuit interrupter to initiate action. The total interrupting time on a ground fault might therefore be as much as 83 msec (5 cycles). If, for any reason, the ground fault relay should fail to act, it is important that circuit overcurrent protection can act to interrupt the current; otherwise, an arc of long duration and extreme destructiveness could result. The question therefore arises as to whether or not the combined effect of transformer impedance, impedance of the longest trailing cable likely to be used, and arc voltage drop can limit the circuit current to a value that is too low to permit reliable setting of overcurrent relays without nuisance tripping on motor startup.

Arc voltage is known to be a decreasing function of arc current, becoming fairly constant for currents lower than about 300 A. Arc voltage then slowly increases with increasing current, probably never exceeding 1,000 V under the conditions described. Some additional investigation is justified in this area. If an arc voltage of 1,000 V is assumed (except in the case of the 1.0-kV load center), this value can be used together with the impedances listed in table 1 to calculate the ratio of minimum overcurrent to rated current for various line voltages and power ratings. These ratios are listed in table 3. The ratio at 1.0 kV line voltage is uncertain, as 1,000-V arc voltage obviously cannot be assumed. However, this value of line voltage is already covered by 30 CFR 18, and no instances of long-continued arcing have been reported.

From table 3, the smallest calculated I_F/I_R ratio is 3.5, where I_F is the fault current and I_R is the rated current. This occurs for a 2.3-kV, 500-kVA load center. In order for this value to be reached by a motor startup current, a motor larger than 425-hp must be started directly online, under load, to give a starting current that is 5.5 times rated current. The more common starting currents for mine equipment are about 2.5 times rated current. Motors larger than 400-hp powered from a 2.3-kV line can certainly be equipped with step starters, if necessary, to avoid nuisance interruptions even when started under full load. Therefore, the overcurrent protection for the load center primary circuit can be set below 3.5 times rated current, with only a very small time delay--less than 2 cycles--to allow for unavoidable line transients.

From this analysis, circuit protective devices can be presumed capable of interrupting an arcing fault, either by ground fault relaying or by the circuit overcurrent relaying, within 7 cycles. This permits calculation of the maximum energy in the fault as shown in the last column of table 3. The free volume within the enclosure should be sufficient to avoid excessive buildup of pressure when this energy is combined with that released by a methane explosion.

TABLE 3. - Arc currents and energies at various line voltages

Line voltage, kV	Power rating, kVA	Calculated arc current, A	Ratio, I_F/I_R	Maximum fault energy, kJ
1.0	500	(1)	(1)	(1)
2.3	500	440	3.5	118
	1,000	1,162	4.6	312
4.16	1,000	992	7.1	481
	1,500	790	3.8	383
	2,000	1,600	5.8	776
7.2	1,000	577	7.2	485
	1,500	996	8.3	837
	2,000	1,409	8.8	1,184
12.5	1,000	491	10.7	715
	1,500	753	10.9	1,098
	2,000	975	10.6	1,422
15	1,000	476	12.5	833
	1,500	612	10.5	1,071
	2,000	875	11.3	1,531

[1]Value uncertain, 1,000-V arc voltage cannot be assumed.

Electrical Clearances

A special laboratory investigation[3] was conducted to determine the effect of a methane-air explosion in facilitating the occurrence of an arc between electrodes sustaining a high potential difference. The mixture at which arcing is most likely to occur is 9.8 pct methane, the same mixture that gives maximum pressure and highest flame temperature. Using this mixture, the critical voltages for arc initiation were determined for a number of gap distances. A linear relationship was found to exist between electrode spacing and the minimum initiation voltage under explosion conditions. As presented in figure 3, curve B indicates that arcing can occur during the explosions at a gap distance more than 18 times as great for a given voltage as the spacing for an arc in air, shown by curve A. For design purposes, a factor of 1.5 times the curve B spacing is considered to be the minimum recommended clearance between energized members.

[3]Scott, L. W., and Joseph G. Dolgos. Electrical Arcing at High Voltage During Methane-Air Explosions Inside Explosion-Proof Enclosures. BuMines TPR 115, 1982, 9 pp.

Insulating Materials Used in Explosion-Proof Enclosures

It has long been known that certain organic insulating materials, when decomposed by the action of an electrical arc, can liberate large quantities of hazardous gases. This has never been a problem in the United States for permissible equipment operating at less than 1,000 V. However, incidents of enclosure failure caused by this phenomenon have been reported in Canadian and European mines where the use of high-voltage equipment in explosion-proof enclosures is commonplace.[4]

[4]Barbero, L. P., E. H. Davis, and H. Lord. Hazards Resulting From the Volatilization by Electric Arcing of Insulating Materials in Flameproof Equipment. Pres. at 15th Internat. Conf. on the Safety in Mines Research, Karlovy, Vary, Czechoslovakia, Sept., 18-21, 1973, 8 pp.; available for consultation at Bureau of Mines Pittsburgh Research Center, Pittsburgh, Pa.

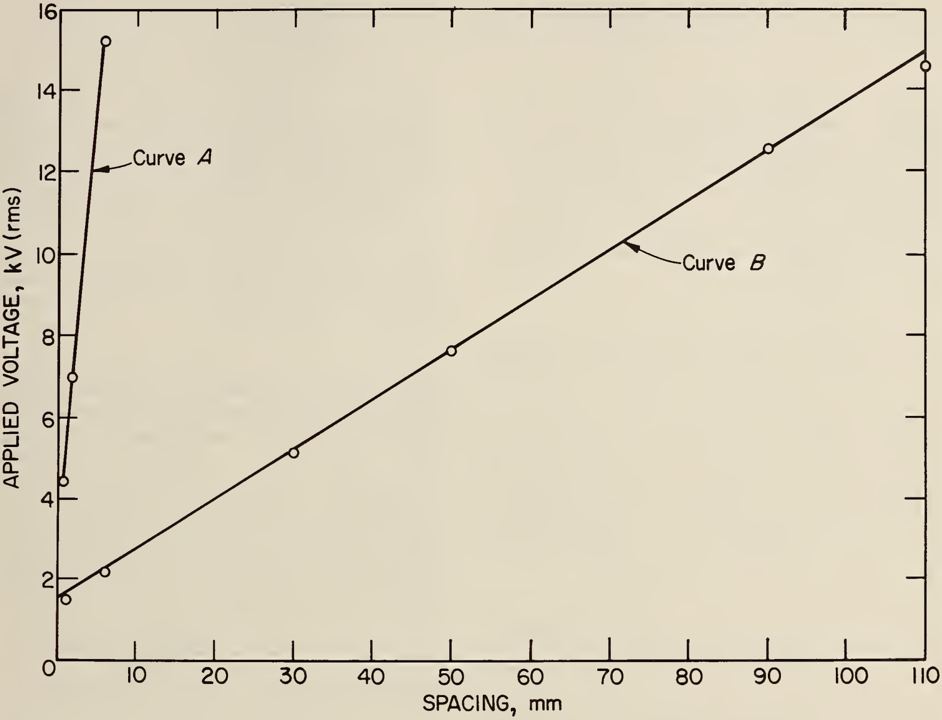

FIGURE 3. - Minimum arc of voltages versus air-gap spacings of electrodes. Curve *A*, in air; Curve *B*, in 9.8 pct methane-air mixtures.

Owing to the widespread use of organic plastic insulating materials in the electrical industry, a complete ban of such materials in high-voltage explosion-proof enclosures is not practical. However, the use of such insulators must be accompanied by special efforts that minimize the amount of such material used and insure that the materials that are used have been tested and found highly resistant to the destructive effects of electrical arcs. In addition, protective devices inside a permissible enclosure can be used to detect arcing, overpressure, or excessive temperatures and disconnect incoming power before a hazardous condition develops.

CONCLUSIONS

The preceding discussion describes some of the problems and reasoning involved in the development of acceptance criteria for high voltage permissible load centers. The product of this development to date is the document attached as appendix A. This document has been reviewed by various government and industry personnel and comments received up to now have been incorporated. Further views and comments are invited as the opportunity for revision will continue for some time.

APPENDIX A.--RECOMMENDED APPROVAL AND TESTING CRITERIA FOR HIGH-VOLTAGE PERMISSIBLE LOAD CENTERS[1]

INTRODUCTION

The objective of phase I of this program is the development of criteria for use by the Mine Safety and Health Administration (MSHA) in testing and approving permissible load centers with maximum voltage ratings of 15 kV and maximum power capacities of 2,000 kVA. A draft of the recommended criteria follows this brief introduction.

The distinguishing feature between the existing requirements of Title 30, Code of Federal Regulations (CFR), Part 18, and the requirements of 30 CFR 18 as supplemented by these criteria, is that the latter permits approval of permissible equipment consisting, in full or in part, of high-voltage circuits and components. The criteria address only those factors that are influenced by the higher voltage. These factors are discussed in numbered paragraphs that follow.

The organization of the recommended criteria follows closely that of Part 18. This organization has the obvious advantage of familiarity and is the natural result of "extending" Part 18 to cover the type of equipment of interest in this program.

For ease of reference, selected sections of Parts 18 and 75 are reproduced in appendix B. These sections are applicable to permissible load centers with one recommended change. That change is to Section 18.47--Voltage Limitation. It is recommended that the 4,160-V limitation found in Section 18.47(d) be deleted. Recommended changes to the texts of Sections 18.47(d), 18.47(d) (3), and 18.47(d)(5) can be found in the comment following paragraph 14.

With the 4,160-V limitation removed, Part 18 will continue to be the sole source of requirements for approval of low- and medium-voltage permissible electrical equipment. However, Section 18.47(d)(6) reserves for MSHA the right to require additional safeguards for high-voltage equipment. These criteria represent those additional safeguards required for the approval of load centers, transformers, switchgear, and related equipment with maximum voltage ratings of 15 kV and maximum power capacities of 2,000 kVA. Similar criteria should be developed for other high-voltage applications, as needed.

Comments and suggestions from interested persons are welcomed. Written comments are especially appreciated.

PART A--GENERAL PROVISIONS

1. Purpose

The purpose of these criteria is to specify the design and testing requirements to be used by MSHA in approving load centers, transformers, and switchgear 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 load centers, transformers, switchgear, and related equipment operating at maximum voltages of 15 kV. For transformers, the maximum secondary voltage is 4.16 kV, and the maximum power rating is 2,000 kVA.

[1]This work was performed under Bureau of Mines contract H0308093.

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

3. Quality Assurance

The factory inspection form required by 30 CFR 18.6(k) shall specify a systematic checking sequence designed to assure the quality of each load center. The form shall include, but not be limited to, a detailed checklist in the following areas:

- Explosion-proof construction--with special attention paid to flange gap dimensions, surface finishes, cable entrances, plugs and receptacles, joints, covers, fasteners, and welding quality.

- Components--a visual inspection for damaged or faulty components prior to assembly.

- Assemblies--insure that all components, subassemblies, and assemblies are fitted in accordance with appropriate drawings and specifications.

- Operation--check for proper operation of all mechanical devices and linkages. Also check for proper installation and operation of pressure relief, ventilation and drainage devices, pressure rise detectors, over-temperature sensors, and other protective devices.

- Ancillaries--where applicable, all preceding checks will be carried out on ancillary components, assemblies, and enclosures.

Emphasis should be placed on systematic organization of the inspection form to insure that all checks are made at appropriate times.

PART B--CONSTRUCTION AND DESIGN REQUIREMENTS

4. Limitation of External Surface Temperatures

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

COMMENT: No change is recommended to the current requirements of 30 CFR 18.23. Load centers must be designed so as to adequately dissipate the heat generated by the transformer without exceeding the surface temperature requirements.

5. Electrical Clearances

Minimum clearances between exposed electrical conductor surfaces in explosion-proof enclosures shall be as listed in Table A-1.

TABLE A-1. - Minimum clearances

Voltage range, V	Clearance, in
8,000 to 15,000...........	7
5,000 to 8,000...........	4
2,000 to 5,000...........	3
1,000 to 2,000...........	2

6. Insulating Materials Used in Explosion-Proof Enclosures

a. Inorganic insulating materials shall be used, where feasible, in preference to organic plastic insulating materials.

b. Insulators composed of organic plastic materials shall not be used as bushings or supports for bus bars or in other locations where potentially dangerous short circuits might occur.

c. Where the use of organic plastic insulating materials cannot be avoided, the following conditions shall be met:

(1) The volume of such materials used shall be kept to a minimum.

(2) Those materials used shall be highly resistant to electrical tracking and arcing.

(3) A detection device shall be provided that will operate to remove the power incoming to the enclosure before decomposition of the insulating material due to an electrical fault leads to hazardous conditions.

COMMENT: A material will be deemed highly resistant to electrical tracking if it has a comparative tracking index (CTI) of not less than 250. Materials will be deemed highly resistant to electrical arcing if they pass the fuse wire arc test--described by J. N. Hardwich in "An Improved Fuse Wire Arc Test Including a Proposed Specification," The Electrical Research Association, Report No. 5078, 1964--or an equally effective test recognized by MSHA.

The detection device specified in paragraph c(3) may operate on pressure rise, temperature rise, detection of the products of insulator decomposition, or other effective means. In either case, the ground monitor circuit can be used to remove the power incoming to the enclosure.

7. Gaskets and Sealed Enclosures

a. Gaskets shall be used in accordance with 30 CFR 18.27.

b. Hermetically sealed (welded) enclosures, pressurized with inert gas or other special atmosphere, may be used for transformers if

(1) Means are provided for sensing the loss of an effective seal and automatically disconnecting the power supply from the enclosure if the seal is lost. The methods selected for this purpose shall prevent reapplication of power to the transformer until the proper atmosphere and an effective seal are restored.

(2) Means are provided for preventing or relieving overpressurization of the enclosure caused by accidental overfilling with gas, operation at high temperatures, or internal electrical fault.

(3) The enclosure is of substantial design and construction so as to prevent damage that may lead to a loss of seal. The minimum thickness of material for the walls shall be 1/4 in.

c. Enclosures designed in accordance with paragraph 7(b) need not be designed to withstand the minimum internal pressure of 150 psig as specified in 30 CFR 18.31(a)(1).

d. Enclosures designed in accordance with paragraph 7(b) need not be explosion tested as specified in 30 CFR 18.62 and paragraph 19 of these criteria.

8. Explosion-Proof Enclosures

a. The requirements of 30 CFR 18.31, 18.32, and 18.33 must be met by all explosion-proof load center and auxiliary component enclosures. 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 potted enclosures.

COMMENTS: The problems associated with placing high-voltage components in potted enclosures should be explored, and adequate testing and approval criteria developed, before this type of equipment is accepted.

9. Access Openings and Covers

Access openings in explosion-proof load center enclosures will be permitted where necessary for proper maintenance such as tap changing and circuit breaker adjustment. The provisions of 30 CFR 18.29 must be met.

10. High-Voltage Power Cables

High-voltage power cables used as portable cables, or located where the use of permissible equipment is required, shall conform to the following:

a. Have each conductor of a current-carrying capacity consistent with the Insulated Cable Engineers Association (ICEA) standards (see table A-2).

b. Have current-carrying conductors not smaller than No. 6 (AWG).

c. Have flame-resistant properties (see 30 CFR 18.64).

d. Have short-circuit protection at the outby (circuit-connecting) end of underground conductors. The fuse rating or breaker trip setting shall be included in the assembler's specifications.

e. Have nominal outside dimensions and tolerances consistent with ICEA standards.

f. ICEA standards for derating ampacities for cables wound on reels, and ICEA recommended minimum bending diameters, shall be observed.

g. No temporary splices shall be used. All permanent splices and terminations shall be made in accordance with manufacturer's specifications by qualified personnel familiar with the techniques required for proper high-voltage cable installation, operation, and maintenance.

11. Lead Entrances; Cable Connectors and Plugs

a. The provisions of 30 CFR 18.42--Explosion-proof distribution boxes--shall apply to explosion-proof load centers.

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 specified in table A-3.

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. Equipment shall be designed so that plugs and receptacles can be completely assembled and tested before mounting on the permissible enclosure. Cable connectors that have been tested for use in permissible areas shall be clearly marked and identified.

COMMENTS: The tests listed in table A-3 are based on work performed under Bureau of Mines contract H0377043.

TABLE A-2. - Ampacities for portable power cables, amperes per conductor

Power conductor size	Single conductor		Three-conductor, round and flat, 0 to 5,000 V, nonshielded	Three conductor, round	
	2,001 to 8,000 V,[1] shielded	8,001 to 15,000 V,[1] shielded		0 to 8,000 V, shielded	8,001 to 15,000 V, shielded
AWG, copper:					
8	NAp	NAp	59	NAp	NAp
6	112	NAp	79	93	NAp
4	148	NAp	104	122	NAp
3	171	NAp	120	140	NAp
2	195	195	138	159	164
1	225	225	161	184	187
1/0	260	259	186	211	215
2/0	299	298	215	243	246
3/0	345	343	249	279	283
4/0	400	397	287	321	325
MCM, copper:					
250	444	440	320	355	359
300	496	491	357	398	NAp
350	549	543	394	435	NAp
400	596	590	430	470	NAp
450	640	633	460	503	NAp
500	688	678	487	536	NAp
550	732	NAp	NAp	NAp	NAp
600	779	NAp	NAp	NAp	NAp
650	817	NAp	NAp	NAp	NAp
700	845	NAp	NAp	NAp	NAp
750	889	NAp	NAp	NAp	NAp
800	925	NAp	NAp	NAp	NAp
900	998	NAp	NAp	NAp	NAp
1,000	1,061	NAp	NAp	NAp	NAp

NAp Not applicable.
[1]Based on single isolated cable in air operated with open-circuited shield.

NOTE.--These ampacities are based on a conductor temperature of 90° C and an ambient temperature of 40° C.

TABLE A-3. - Standard dielectric tests for high-voltage cable plugs and connectors used in areas where permissible equipment is required

Test	Test voltage, kV	
	8.7-kV class	15-kV class
1-min withstand value..........kilovolts..	27	35
6-hr withstand value..............do......	15	25
Impulse withstand peak value......do......	75	95
Corona (partial-discharge) extinction value.........................kilovolts..	7	11
15-min dc withstand value.........do......	40	50

12. Leads Through Common Walls Between Explosion-Proof Enclosures

Insulated bushings with proper voltage rating and current-carrying capacities may be used in the common wall between two explosion-proof enclosures. When insulated wires or cables are extended through a common wall between two explosion-proof enclosures, the techniques described in 30 CFR 18.38 may be employed provided the seal between the two enclosures is sufficient to prevent propagation of an explosion from one enclosure to the other. Wires and cables shall be mechanically secured in open areas of the enclosure and in passageways between enclosures to prevent excessive movement in the event of high current flows.

13. Openings Through Common Walls Between Explosion-Proof Enclosures

As provided in 30 CFR 18.38(e), unsealed openings through common walls between explosion-proof enclosures shall be large enough to prevent pressure piling. Partitions subdividing single enclosures shall not be used. Internal components shall be arranged so as not to effectively divide the interior of the enclosure into pockets joined by restricted passages.

COMMENTS: 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 placements, can result in pressure piling and should 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. When a pressure exceeding 125 psig is developed during explosion tests (which would indicate that pressure piling has occurred), MSHA can reject the enclosure unless constructional changes are made that result in a reduction of pressure to 125 psig or less, or the enclosure withstands a dynamic pressure of twice the highest value recorded in the initial test.

14. Voltage Limitation

Load centers 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.

COMMENT: The following changes to 30 CFR 18.47 are recommended:

- In 30 CFR 18.47(d), delete the words "but not exceeding 4,160 V."

- 30 CFR 18.47(d)(3) should be changed to read: "All high voltage switchgear and controls for equipment having a nameplate rating exceeding 1,000 V 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 120 V."

- 30 CFR 18.47(d)(5) should be changed to read: "Portable (trailing) cable for equipment with nameplate ratings greater than 1,000 V 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."

30 CFR 18.47(d)(6) reserves the right for MSHA to require "additional safeguard" for high-voltage equipment. These criteria represent those additional safeguards for high-voltage load centers (up to 15 kV and 2,000 kVA). Similar criteria should be developed, as needed, for other types of high-voltage, permissible equipment (for example, motors and motor starters).

15. Electrical Protective Devices

a. High-voltage circuits connected to permissible load centers shall be protected by modern, high-speed circuit breakers equipped with devices to provide protection against undervoltage, grounded phase, short circuit, and overcurrent.

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

c. All equipment intended to break current at fault levels shall have an interrupting rating sufficient for the system voltage and the current that 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.

d. The overcurrent protective devices, the total 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.

e. Additional coordination shall be provided between the electrical circuit characteristics and protective devices and the design parameters (for example, strength, free volume) of the explosion-proof enclosure to prevent damage to the enclosure should an electrical fault occur. Precautionary measures may include

(1) Limitation of available fault energy,

(2) Provision of adequate free volume within the enclosure,

(3) Inclusion of devices which detect hazardous pressure and temperature rises, ozone, or visible arc radiation, and/or

(4) Use of devices or techniques designed to vent or limit internal pressure.

COMMENT: High-voltage ac circuit breakers are available with interrupting speeds of 1, 2, 3, 5, and 8 cycles. A description of various types and a history of the development of such breakers can be found in the "Standard Handbook for Electrical Engineers," Fink and Beaty, 11th ed. In addition, vacuum circuit breakers with interrupting speeds of less than 1 cycle are available in the voltage range of interest to this program. These breakers are in common use throughout the mining industry today and offer other advantages (for example, compact size, low maintenance, enclosed contacts) which are desirable for mine electrical equipment in general, and permissible equipment in particular.

Paragraph 15(b) is included in recognition of the fact that some mine electrical systems have, in the past, been allowed to operate for long periods (hours) with one phase of the power system grounded. This is usually done to avoid shutdown of an entire mine while a single ground fault is being located and repaired. However, continued operation with a grounded phase increases the electrical stress on the system insulation and, with the occurrence of a second fault, can give rise to a double phase-to-ground fault situation. This defeats the purpose of ground shields, barriers, and other forms of phase segregation provided in shielded cables and permissible high-voltage enclosures. If permission is ever granted to energize and operate a power system before clearing a ground fault, it should be conditioned on the removal from the circuit of equipment of the type covered by these approval criteria.

Devices other than high-speed breakers are available to limit fault energy. Most notable of these is the current-limiting fuse. This type of protection is used extensively in the utility industry to prevent overpressurization of transformer enclosures due to internal faults. However, the current-limiting characteristics of these fuses does not come into play unless several (20 to 30) multiples of rated current is available from the circuit in the event of a fault. In most mine high-voltage power systems, the overall impedance of the circuit will limit fault current availability to a few thousand amps. Only in locations where abnormally high fault currents are available (for example, very close to the main mine substation) would current-limiting fuses actually provide the kind of protection for which they are designed.

Data from testing to be performed later in this program may shed additional light on proper coordination of circuit electrical characteristics and enclosure design specifications.

16. High-Voltage Circuit Design

a. High-voltage circuits and components in permissible enclosures shall conform with accepted practices and standards of high-voltage design for the appropriate voltage class.

b. Ground barrier and shields shall be used when possible to minimize the occurrence of phase-to-phase faults within enclosures.

17. Component Placement

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

b. Components located in tight, explosion-proof enclosures shall not be placed in such a way as to effectively subdivide or create "compartments" or "pockets" within the enclosure which might give rise to pressure piling upon ignition of a methane-air mixture.

PART C--INSPECTIONS AND TESTS

18. Inspections

Inspections specified in 30 CFR 18.60 and 18.61 shall be required for permissible load centers. Additional inspections which take into account the requirements of parts A and B 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.

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

d. Examination for areas of possible excessive electrical stress.

COMMENT: In examining for areas of possible excessive electrical stress, MSHA may want to use one of a number of standard corona (partial discharge) detection and measurement techniques (for example, IEEE Standard 454--1973 or ASTM Standard D 1868-73). Such testing might also be required by the manufacturer as part of the quality assurance provisions (see paragraph 3 of these criteria).

19. Tests To Determine Explosion-Proof Characteristics

a. With exception of the hermetically sealed enclosures referred to in paragraph 7 (b, c, and d) of these criteria, all permissible enclosures used with load centers or related equipment must pass the explosion tests specified in 30 CFR 18.62.

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 sec).

(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--fault current shall be increased in successive increments of 1,000 A until an excessive pressure rise (>125 psig) is measured in the enclosure, or to a maximum of 10,000 A. The enclosure shall be approved for use in circuits with available fault currents less than the maximum fault current used in this test.

c. All or any part of the additional tests specified in paragraph 19 (b) may be waived by MSHA for equipment meeting all other requirements of these criteria and of 30 CFR 18, if such equipment is provided with one or more of the following design features:

(1) An enclosure containing more than one phase of a high-voltage circuit is designed and constructed so as to preclude the possible occurrence of a phase-to-phase arcing fault (for example, complete phase segregation or shielding is provided).

(2) An enclosure is equipped with approved vents or pressure relief devices such that no pressures greater than 15 psig are measured in the methane-air explosion tests required by 30 CFR 18.62.

(3) An enclosure containing more than one phase of a high-voltage circuit is provided with a minimum free internal volume of 1 m^3.

COMMENT: The design of high-voltage, metal-enclosed switchgear so that each phase is enclosed in a separate metal housing, with an air space provided between the housings, is considered to be the safest, most practical, and most economical way of preventing phase-to-phase short-circuit faults through construction methods. Therefore, the additional testing described in paragraph 19(b) is required only for enclosures containing more than one phase.

Other design techniques may also provide a high degree of safety; they are listed in paragraphs 19(c) 1, 2, and 3. Paragraph 19(c) gives MSHA the prerogative to waive arc tests for such designs. It should be noted, however, that MSHA retains the right to verify, by testing, the degree of protection afforded by these design features, and is free to exercise that right until sufficient experience with such testing is gained.

The minimum free volume specified in paragraph 19(c)(3)--1 m^3--is subject to revision, pending receipt of data from testing to be performed later in this program.

The use of pressure relief vents [paragraph 19(c)(2)] makes field inspection more difficult than the simple feeler-gage test now used for explosion-proof housings. It may be desirable to develop a new test to insure that the vents have not become clogged once the unit is in operation.

APPENDIX B.—CFR 30, SUBCHAPTER D—ELECTRICAL EQUIPMENT, LAMPS, METHANE DETECTORS; TESTS FOR PERMISSIBILITY, FEES; PARTS 18 AND 75

PART 18—ELECTRIC MOTOR-DRIVEN MINE EQUIPMENT AND ACCESSORIES

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Subpart A—General Provisions

§ 18.1 Purpose.

The regulations in this part set forth the requirements to obtain MSHA: (a) Approval of electrically operated machines and accessories intended for use in gassy mines or tunnels, (b) certification of components intended for use on or with approved machines, (c) permission to modify the design of an approved machine or certified component, (d) acceptance of flame-resistant cables, hoses, and conveyor belts, (e) sanction for use of experimental machines and accessories in gassy mines or tunnels; also, procedures for applying for such approval, certification, acceptance for listing; and fees.

§ 18.2 Definitions.

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"Approval" means a formal document issued by MSHA which states that a completely assembled electrical machine or accessory has met the applicable requirements of this part and which authorizes the attachment of an approval plate so indicating.

"Approval plate" means a metal

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"Certification" means a formal written notification, issued by MSHA, which states that an electrical component complies with the applicable requirements of this part and, therefore, is suitable for incorporation in approved (permissible) equipment.

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"Component" means an integral part of an electrical machine or accessory that is essential to the functioning of the machine or accessory.

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"Distribution box" means an enclosure through which one or more portable cables may be connected to a source of electrical energy, and which contains a short-circuit protective device for each outgoing cable.

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"Explosion-proof enclosure" means an enclosure that complies with the applicable design requirements in Subpart B of this part and is so constructed that it will withstand internal explosions of methane-air mixtures: (1) Without damage to or excessive distortion of its walls or cover(s), and (2) without ignition of surrounding methane-air mixtures or discharge of flame from inside to outside the enclosure.

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"Flame-arresting path" means two or more adjoining or adjacent surfaces between which the escape of flame is prevented.

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"Gassy mine" means a coal mine classed as "gassy" by MESA or by the State in which the mine is situated.

"Incendive arc or spark" means an arc or spark releasing enough electrical or thermal energy to ignite a flammable mixture of the most easily ignitable composition.

"Intrinsically safe" means incapable of releasing enough electrical or thermal energy under normal or abnormal conditions to cause ignition of a flammable mixture of methane or natural gas and air of the most easily ignitable composition.

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"Permissible equipment" means a completely assembled electrical machine or accessory for which a formal approval has been issued, as authorized by the Administrator, Mining Enforcement and Safety Administration under the Federal Coal Mine Health and Safety Act of 1969 (Pub. L. 91-173, 30 U.S.C. 801 or, after March 9, 1978, by the Assistant Secretary under the Federal Mine Safety and Health Act of 1977 (Pub. L. 91-173, as amended by Pub. L. 95-164, 30 U.S.C. 801).

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"Portable cable", or "trailing cable" means a flame-resistant, flexible cable or cord through which electrical energy is transmitted to a permissible machine or accessory. (A portable cable is that portion of the power-supply system between the last short-circuit protective device, acceptable to MSHA, in the system and the machine or accessory to which it transmits electrical energy.)

"Portable equipment" means equipment that may be moved frequently and is constructed or mounted to facilitate such movement.

"Potted component" means a component that is entirely embedded in a solidified insulating material within an enclosure.

"Pressure piling" means the development of abnormal pressure as a result of accelerated rate of burning of a gas-air mixture. (Frequently caused by restricted configurations within enclosures.)

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§ 18.6 Applications.

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(e) Drawings, drawing lists, specifications, wiring diagram, and descriptions shall be adequate in number and detail to identify fully the complete assembly, component parts, and subassemblies. Drawings shall be titled, numbered, dated and shall show the latest revision. Each drawing shall include a warning statement that changes in design must be authorized by MSHA before they are appliea to approved equipment. When intrinsically safe circuits are incorporated in a machine or accessory, the wiring diagram shall include a warning statement that any change(s) in the intrinsically safe circuitry or components may result in an unsafe condition. The specifications shall include an assembly drawing(s) (see Figure 1 in Appendix II) showing the overall dimensions of the machine and the identity of each component part which may be listed thereon or separately, as in a bill of material (see Figure 2 in Appendix II). MSHA may accept photographs (minimum size 8" × 10½") in lieu of assembly drawing(s). Purchased parts shall be identified by the manufacturer's name, catalog number(s), and rating(s). In the case of standard hardware and miscellaneous parts, such as insulating pieces, size and kind of material shall be specified. All drawings of component parts submitted to MSHA shall be identical to those used in the manufacture of the parts. Dimensions of parts designed to prevent the passage of flame shall specify allowable tolerances. A notation "Do Not Drill Through" or equivalent should appear on drawings with the specifications for all "blind" holes.

(f) MSHA reserves the right to require the applicant to furnish supplementary drawings showing sections through complex flame-arresting paths, such as labyrinths used in conjunction with ball or roller bearings, and also drawings containing dimensions not indicated on other drawings submitted to MSHA.

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(j) The applicant shall submit a sample caution statement (see Figure 3 in Appendix II) specifying the conditions for maintaining permissibility of the equipment.

(k) The applicant shall submit a factory-inspection form (see Figure 4 in Appendix II) used to maintain quality control at the place of manufacture or assembly to insure that component parts are made and assembled in strict accordance with the drawings and specifications covering a design submitted to MSHA for approval or certification.

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§ 18.11 Approval plate.

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(c) The approval plate identifies as permissible the machine or accessory to which it is attached, and use of the approval plate obligates the applicant to whom the approval was issued to maintain in his plant the quality of each complete assembly and guarantees that the equipment is manufactured and assembled according to the drawings, specifications, and descriptions upon which the approval and subsequent extension(s) of approval were based.

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§ 18.12 Letter of certification.

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(b) A letter of certification will be accompanied by a list of drawings, specifications, and related material covering the details of design and construction of a component upon which the letter of certification is based. Applicants shall keep exact duplicates of the drawings, specifications, and descriptions that relate to the component for which a letter of certification has been issued; and the drawings and specifications shall be adhered to exactly in production of the certified component.

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Subpart B—Construction and Design Requirements

§ 18.20 Quality of material, workmanship, and design.

(a) Electrically operated equipment intended for use in coal mines shall be rugged in construction and shall be designed to facilitate inspection and maintenance.

(b) MSHA will test only electrical equipment that in the opinion of its qualified representatives is constructed of suitable materials, is of good quality workmanship, based on sound engineering principles, and is safe for its intended use. Since all possible designs, circuits, arrangements, or combinations of components and materials cannot be foreseen, MSHA reserves the right to modify design, construction, and test requirements to obtain the same degree of protection as provided by the tests described in Subpart C of this part.

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(d) Flange joints and lead entrances shall be accessible for field inspection, where practicable.

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§ 18.23 Limitation of external surface temperatures.

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

§ 18.24 Electrical clearances.

The clearance between live parts and casings shall be sufficient to minimize the possibility of arcs striking the casings. Where space is limited, the casing shall be lined with adequate insulation.

§ 18.25 Combustible gases from insulating material.

(a) Insulating materials that give off flammable or explosive gases when decomposed electrically shall not be used within enclosures where the materials are subjected to destructive electrical action.

(b) Parts coated or impregnated with insulating materials shall be heat-treated to remove any combustible solvent(s) before assembly in an explosion-proof enclosure. Air-drying insulating materials are excepted.

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§ 18.27 Gaskets.

A gasket(s) shall not be used between any two surfaces forming a flame-arresting path except as follows:

(a) A gasket of lead, elastomer, or equivalent will be acceptable provided the gasket does not interfere with an acceptable metal-to-metal joint.

(b) A lead gasket(s) or equivalent will be acceptable between glass and a hard metal to form all or a part of a flame-arresting path.

§ 18.28 Devices for pressure relief, ventilation, or drainage.

(a) Devices for installation on explosion-proof enclosures to relieve pressure, ventilate, or drain will be acceptable provided the length of the flame-arresting path and the clearances or size of holes in perforated metal will prevent discharge of flame in explosion tests.

(b) Devices for pressure relief, ventilation, or drainage shall be constructed of materials that resist corrosion and distortion, and be so designed that they can be cleaned readily. Provision shall be made for secure attachment of such devices.

(c) Devices for pressure relief, ventilation, or drainage will be acceptable for application only on enclosures with which they are explosion tested.

§ 18.29 Access openings and covers, including unused lead-entrance holes.

(a) Access openings in explosion-proof enclosures will be permitted only where necessary for maintenance of internal parts such as motor brushes and fuses.

(b) Covers for access openings shall meet the same requirements as any other part of an enclosure except that threaded covers shall be secured against loosening, preferably with screws having heads requiring a special tool. (See Figure 1 in Appendix II.)

(c) Holes in enclosures that are provided for lead entrances but which are not in use shall be closed with metal plugs secured by spot welding, brazing, or equivalent. (See Figure 10 in Appendix II.)

§ 18.30 Windows and lenses.

(a) MSHA may waive testing of materials for windows or lenses except headlight lenses. When tested, material for windows or lenses shall meet the test requirements prescribed in § 18.66 and shall be sealed in place or provided with flange joints in accordance with § 18.31.

(b) Windows or lenses shall be protected from mechanical damage by structural design, location, or guarding. Windows or lenses, other than headlight lenses, having an exposed area greater than 8 square inches, shall be provided with guarding or equivalent.

§ 18.31 Enclosures—joints and fastenings.

(a) Explosion-proof enclosures:

(1) Cast or welded enclosures shall be designed to withstand a minimum internal pressure of 150 pounds per square inch (gage). Castings shall be free from blowholes.

(2) Welded joints forming an enclosure shall have continuous gas-tight welds. All welds shall be made in accordance with American Welding Society standards.

(3) External rotating parts shall not be constructed of aluminum alloys containing more than 0.5 percent magnesium.

(4) MSHA reserves the right to require the applicant to conduct static-pressure tests on each enclosure when MSHA determines that the particular design will not permit complete visual inspection or when the joint(s) forming an enclosure is welded on one side only (see § 18.67).

(5) Threaded covers shall be designed with Class 1 (coarse, loose fitting) threads. The flame-arresting path of threaded joints shall conform to the requirements of paragraph (a)(6) of this section.

(6) Enclosures shall meet the following requirements based on the internal volumes of the empty enclosure.

	Volume of empty enclosure		
	Less than 45 cu in.	45 to 124 cu. in., inclusive	More than 124 cu. in.
Minimum thickness of material for walls	1/8"	3/16"	1/4".
Minimum thickness of material for flanges	1/4" [1]	3/8" [2]	1/2" [2]
Minimum thickness of material for cover	1/4" [1]	3/8" [2]	1/2" [2].
Minimum width of joint—all in one plane	1/2"	3/4"	1".
Maximum clearance—joint all in one plane	0.002"	0.003"	0.004".
Minimum width of joint, portions of which are in different planes—cylinders or equivalent.	3/8" [3]	5/8" [3]	3/4" [3].
Maximum clearances—joint in two or more planes, cylinders or equivalent:			
(a) Portion perpendicular to plane	0.008" [4]	0.008" [4]	0.008" [4].
(b) Plane portion	0.006"	0.006"	0.006".
Maximum bolt [5] spacing—joints all in one plane	6" with minimum of 4 bolts.	6" with minimum of 4 bolts.	6"
Maximum bolt spacing—joints, portions of which are in different planes.	[6]	[6]	[6].
Minimum diameter of bolt (without regard to type of joint).	1/4"	1/4"	3/8".
Minimum thread engagement [7]	1/4"	1/4"	3/8".
Maximum diametrical clearance between bolt body and unthreaded holes through which it passes [8].	1/64"	1/32"	1/16".
Minimum distance from interior of enclosure to the edge of a bolt hole:			
Joint—minimum width 1"			7/16".[9]
Joint—less than 1" wide	1/8"	3/16"	
CYLINDRICAL JOINTS			
Shafts centered by ball or roller bearings:			
Minimum length of flame-arresting path	1/2"	3/4"	1".
Maximum radial clearance	0.010"	0.0125"	0.015".
Shafts through journal bearings: [10]			
Minimum length of flame-arresting path	1/2"	3/4"	1".
Maximum radial clearance	0.003"	0.004"	0.005"
Other than shafts:			
Minimum length of flame-arresting path	1/2"	3/4"	1".
Maximum radial clearance	0.0015"	0.002"	0.003".

[1] 1/32-inch less is allowable for machining rolled plate.
[2] 1/16-inch less is allowable for machining rolled plate.
[3] If only two planes are involved, neither portion of a joint shall be less than 1/8-inch wide, unless the wider portion conforms to the same requirements as those for a joint that is all in one plane. If more than two planes are involved (as in labyrinths or tongue-and-groove joints) the combined lengths of those portions having prescribed clearances will be considered.
[4] The allowable diametrical clearance is 0.008 inch when the portion perpendicular to the plane portion is 1/4 inch of or greater in length. If the perpendicular portion is more than 1/8 inch but less than 1/4 inch wide, the diametrical clearance shall not exceed 0.006 inch.
[5] Where the term "bolt" is used, it refers to a machine bolt or a cap screw, and for either of these studs may be substituted provided the studs bottom in blind holes, are completely welded in place, or the bottom of the hole is closed with a secured plug. Bolts shall be provided at all corners.
[6] Adequacy of bolt spacing will be judged on basis of size and configuration of the enclosure, strength of materials, and explosion test results.
[7] In general, minimum thread engagement shall be equal to or greater than the diameter of the bolt specified.
[8] Threaded holes for fastening bolts shall be machined to remove burrs or projections that affect planarity of a surface forming a flame-arresting path.
[9] Less than 7/16-inch (1/4-inch minimum) will be acceptable provided the diametrical clearance for fastening bolts does not exceed 1/32 inch.
[10] Shafts or operating rods through journal bearings shall be not less than 1/4-inch in diameter. The length of fit shall not be reduced when a pushbutton is depressed. Operating rods shall have a shoulder or head on the portion inside the enclosure. Essential parts riveted or bolted to the inside portion will be acceptable in lieu of a head or shoulder, but cotter pins and similar devices will not be acceptable.

(b) Enclosures for potted components: Enclosures shall be rugged and constructed with materials having 75 percent, or greater, of the thickness and flange width specified in paragraph (a) of this section. These enclosures shall be provided with means for attaching hose conduit, unless energy carried by the cable is intrinsically safe.

(c) No assembly will be approved that requires the opening of an explosion-proof enclosure to operate a switch, rheostat, or other device during normal operation of a machine.

§ 18.32 Fastenings—additional requirements.

(a) Bolts, screws, or studs shall be used for fastening adjoining parts to prevent the escape of flame from an enclosure. Hinge pins or clamps will be acceptable for this purpose provided MSHA determines them to be equally effective.

(b) Lockwashers shall be provided for all bolts, screws, and studs that secure parts of explosion-proof enclosures. Special fastenings designed to prevent loosening will be acceptable in lieu of lockwashers, provided MSHA determines them to be equally effective.

(c) Fastenings shall be as uniform in size as practicable to preclude improper assembly.

(d) Holes for fastenings shall not penetrate to the interior of an explosion-proof enclosure, except as provided in paragraph (a)(9) of § 18.34, and shall be threaded to insure that a specified bolt or screw will not bottom even if its lockwasher is omitted.

(e) A minimum of ⅛ inch of stock shall be left at the center of the bottom of each hole drilled for fastenings.

(f) Fastenings used for joints on explosion-proof enclosures shall not be used for attaching nonessential parts or for making electrical connections.

(g) The acceptable sizes for and spacings of fastenings shall be determined by the size of the enclosure, as indicated in § 18.31.

(h) MSHA reserves the right to conduct explosion tests with standard bolts, nuts, cap screws, or studs substituted for any special high-tensile strength fastening(s) specified by the applicant.

§ 18.33 Finish of surface joints.

Flat surfaces between bolt holes that form any part of a flame-arresting path shall be plane to within a maximum deviation of one-half the maximum clearance specified in § 18.31(a)(6). All metal surfaces shall be finished in manufacture to not more than 250 microinches. A thin film of nonhardening preparation to inhibit rusting may be applied to finished steel surfaces.

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§ 18.35 Portable (trailing) cables and cords.

(a) Portable cables and cords used to conduct electrical energy to face equipment shall conform to the following:

(1) Have each conductor of a current-carrying capacity consistent with the Insulated Power Cable Engineers Association (IPCEA) standards. (See Tables 1 and 2 in Appendix I.)

(2) Have current-carrying conductors not smaller than No. 14 (AWG). Cords with sizes 14 to 10 (AWG) conductors shall be constructed with heavy jackets, the diameters of which are given in Table 6 in Appendix I.

(3) Have flame-resistant properties. (See § 18.64.)

(4) Have short-circuit protection at the outby (circuit-connecting) end of ungrounded conductors. (See Table 8 in Appendix I.) The fuse rating or trip setting shall be included in the assembler's specifications.

(5) Ordinarily the length of a portable (trailing) cable shall not exceed 500 feet. Where the method of mining requires the length of a portable (trailing) cable to be more than 500 feet, such length of cable shall be permitted only under the following prescribed conditions:

(i) The lengths of portable (trailing) cables shall not exceed those specified in Table 9, Appendix I, titled "Specifications for Portable Cables Longer Than 500 Feet."

(ii) Short-circuit protection shall be provided by a protective device with an instantaneous trip setting as near as practicable to the maximum starting-current-inrush value, but the setting shall not exceed the trip value specified in MSHA approval for the equipment for which the portable (trailing) cable furnishes electric power.

(6) Have nominal outside dimensions consistent with IPCEA standards. (See Tables 4, 5, 6, and 7 in Appendix I.)

(7) Have conductors of No. 4 (AWG) minimum for direct-current mobile haulage units or No. 6 (AWG) minimum for alternating-current mobile haulage units.

(8) Have not more than five well-made temporary splices in a single length of portable cable.

(b) Sectionalized portable cables will be acceptable provided the connectors used inby the last open crosscut in a gassy mine meet the requirements of § 18.41.

(c) A portable cable having conductors smaller than No. 6 (AWG), when used with a trolley tap and a rail clamp, shall have well insulated single conductors not smaller than No. 6 (AWG) spliced to the outby end of each conductor. All splices shall be made in a workmanlike manner to insure good electrical conductivity, insulation, and mechanical strength.

(d) Suitable provisions shall be made to facilitate disconnection of portable cable quickly and conveniently for replacement.

[33 FR 4660, Mar. 19, 1968; 33 FR 6343, Apr. 26, 1968]

§ 18.36 Cables between machine components.

(a) Cables between machine components shall have: (1) Adequate current-carrying capacity for the loads involved, (2) short-circuit protection, (3) insulation compatible with the impressed voltage, and (4) flame-resistant properties unless totally enclosed within a flame-resistant hose conduit or other flame-resistant material.

(b) Cables between machine components shall be: (1) Clamped in place to prevent undue movement, (2) protected from mechanical damage by position, flame-resistant hose conduit, metal tubing, or troughs (flexible or threaded rigid metal conduit will not be acceptable), (3) isolated from hydraulic lines, and (4) protected from abrasion by removing all sharp edges which they might contact.

(c) Cables (cords) for remote-control circuits extending from permissible equipment will be exempted from the requirements of conduit enclosure provided the total electrical energy carried is intrinsically safe or that the cables are constructed with heavy jackets, the sizes of which are stated in Table 6 of Appendix I. Cables (cords) provided with hose-conduit protection shall have a tensile strength not less than No. 16 (AWG) three-conductor, type SO cord. (Reference: 7.7.7 IPCEA Pub. No. S-19-81, Fourth Edition.) Cables (cords) constructed with heavy jackets shall consist of conductors not smaller than No. 14 (AWG) regardless of the number of conductors.

§ 18.37 Lead entrances.

(a) Insulated cable(s), which must extend through an outside wall of an explosion-proof enclosure, shall pass through a stuffing-box lead entrance. All sharp edges that might damage insulation shall be removed from stuffing boxes and packing nuts.

(b) Stuffing boxes shall be so designed, and the amount of packing used shall be such, that with the packing properly compressed, the gland nut still has a clearance distance of ⅛ inch or more to travel without meeting interference by parts other than packing. (See Figures 8, 9, and 10 in Appendix II.)

(c) Packing nuts and stuffing boxes shall be secured against loosening.

(d) Compressed packing material shall be in contact with the cable jacket for a length of not less than ½ inch.

(e) Special requirements for glands in which asbestos-packing material is specified are:

(1) Asbestos-packing material shall be untreated, not less than 3/16-inch diameter if round, or not less than 3/16 by 3/16 inch if square. The width of the space for packing material shall not exceed by more than 50 percent the diameter or width of the uncompressed packing material.

(2) The allowable diametrical clearance between the cable and the holes in the stuffing box and packing nut shall not exceed 75 percent of the nominal diameter or width of the packing material.

(f) Special requirements for glands in which a compressible material (example—synthetic elastomers) other than asbestos is specified, are:

(1) The packing material shall be flame resistant.

(2) The radial clearance between the cable jacket and the nominal inside diameter of the packing material shall not exceed 1/32 inch, based on the nominal specified diameter of the cable.

(3) The radial clearance between the nominal outside diameter of the packing material and the inside wall of the stuffing box (that portion into which the packing material fits) shall not exceed 1/32 inch.

§ 18.38 Leads through common walls.

(a) Insulated studs will be acceptable for use in a common wall between two explosion-proof enclosures.

(b) When insulated wires or cables are extended through a common wall between two explosion-proof enclosures in insulating bushings, such bushings shall be not less than 1-inch long and the diametrical clearance between the wire or cable insulation and the holes in the bushings shall not exceed 1/16 inch (based on the nominal specified diameter of the cable). The insulating bushings shall be secured in the metal wall.

(c) Insulated wires or cables conducted from one explosion-proof enclosure to another through conduit, tubing, piping, or other solid-wall passageways will be acceptable provided one end of the passageway is plugged, thus isolating one enclosure from the other. Glands of secured bushings with close-fitting holes through which the wires or cables are conducted will be acceptable for plugging. The tubing or duct specified for the passageway shall be brazed or welded into the walls of both explosion-proof enclosures with continuous gas-tight welds.

(d) If wires and cables are taken through openings closed with sealing compounds, the design of the opening and characteristics of the compounds shall be such as to hold the sealing material in place without tendency of the material to crack or flow out of its place. The material also must withstand explosion tests without cracking or loosening.

(e) Openings through common walls between explosion-proof enclosures not provided with bushings or sealing compound, shall be large enough to prevent pressure piling.

§ 18.39 Hose conduit.

Hose conduit shall be provided for mechanical protection of all machine cables that are exposed to damage. Hose conduit shall be flame resistant and have a minimum wall thickness of 3/16 inch. The flame resistance of hose conduit will be determined in accordance with the requirements of § 18.65.

§ 18.40 Cable clamps and grips.

Insulated clamps shall be provided for all portable (trailing) cables to prevent strain on the cable terminals of a machine. Also insulated clamps shall be provided to prevent strain on both ends of each cable or cord leading from a machine to a detached or separately mounted component. Cable grips anchored to the cable may be used in lieu of insulated strain clamps. Supporting clamps for cables used for wiring around machines shall be provided in a manner acceptable to MSHA.

§ 18.41 Plug and receptacle-type connectors.

(a) Plug and receptacle-type connectors for use inby the last open crosscut in a gassy mine shall be so designed that insertion or withdrawal of a plug cannot cause incendive arcing or sparking. Also, connectors shall be so designed that no live terminals, except as hereinafter provided, are exposed upon withdrawal of a plug. The following types will be acceptable:

(1) Connectors in which the mating or separation of the male and female electrodes is accomplished within an explosion-proof enclosure.

(2) Connectors that are mechanically or electrically interlocked with an automatic circuit-interrupting device.

(i) *Mechanically interlocked connectors.* If a mechanical interlock is provided the design shall be such that the plug cannot be withdrawn before the circuit has been interrupted and the circuit cannot be established with the plug partially withdrawn.

(ii) *Electrically interlocked connectors.* If an electrical interlock is provided, the total load shall be removed before the plug can be withdrawn and the electrical energy in the interlocking pilot circuit shall be intrinsically safe, unless the pilot circuit is opened within an explosion-proof enclosure.

(3) Single-pole connectors for individual conductors of a circuit used at terminal points shall be so designed that all plugs must be completely inserted before the control circuit of the machine can be energized.

(b) Plug and receptacle-type connectors used for sectionalizing the cables outby the last open crosscut in a gassy mine need not be explosion-proof or electrically interlocked provided such connectors are designed and constructed to prevent accidental separation.

(c) Conductors shall be securely attached to the electrodes in a plug or receptacle and the connections shall be totally enclosed.

(d) Molded-elastomer connectors will be acceptable provided:

(1) Any free space within the plug or receptacle is isolated from the exterior of the plug.

(2) Joints between the elastomer and metal parts are not less than 1 inch wide and the elastomer is either bonded to or fits tightly with metal parts.

(e) The contacts of all line-side connectors shall be shielded or recessed adequately.

(f) For a mobile battery-powered machine, a plug padlocked to the receptacle will be acceptable in lieu of an interlock provided the plug is held in place by a threaded ring or equivalent mechanical fastening in addition to the padlock. A connector within a padlocked enclosure will be acceptable.

§ 18.42 Explosion-proof distribution boxes.

(a) A cable passing through an outside wall(s) of a distribution box shall be conducted either through a packing gland or an interlocked plug and receptacle.

(b) Short-circuit protection shall be provided for each branch circuit connected to a distribution box. The current-carrying capacity of the specified connector shall be compatible with the automatic circuit-interrupting device.

(c) Each branch receptacle shall be plainly and permanently marked to indicate its current-carrying capacity and each receptacle shall be such that it will accommodate only an appropriate plug.

(d) Provision shall be made to relieve mechanical strain on all connectors to distribution boxes.

§ 18.43 Explosion-proof splice boxes.

Internal connections shall be rigidly held and adequately insulated. Strain clamps shall be provided for all cables entering a splice box.

• • •

§ 18.47 Voltage limitation.

• • •

(d) An alternating-current machine shall not have a nameplate rating exceeding 660 volts, except that a machine may have a nameplate rating greater than 660 volts but not exceeding 4,160 volts when the following conditions are complied with:

(1) Adequate clearances and insulation for the particular voltage(s) are provided in the design and construction of the equipment, its wiring, and accessories.

(2) A continuously monitored, fail-safe grounding system is provided that will maintain the frame of the equipment and the frames of all accessory equipment at ground potential. Also, the equipment, including its controls and portable (trailing) cable, will be deenergized automatically upon the occurrence of an incipient ground fault. The ground-fault-tripping current shall be limited by grounding resistor(s) to that necessary for dependable relaying. The maximum ground-fault-tripping current shall not exceed 25 amperes.

(3) All high voltage switch gear and control for equipment having a nameplate rating exceeding 1,000 volts are located remotely and operated by remote control at the main equipment. Potential for remote control shall not exceed 120 volts.

(4) Portable (trailing) cable for equipment with nameplate ratings from 661 volts through 1,000 volts shall include grounding conductors, a ground check conductor, and grounded metallic shields around each power conductor or a grounded metallic shield over the assembly; except that on machines employing cable reels, cables without shields may be used if the insulation is rated 2,000 volts or more.

(5) Portable (trailing) cable for equipment with nameplate ratings from 1,001 volts through 4,160 volts shall include grounding conductors, a ground check conductor, and grounded metallic shields around each power conductor.

(6) MSHA reserves the right to require additional safeguards for high-voltage equipment, or modify the requirements to recognize improved technology.

§ 18.48 Circuit-interrupting devices.

(a) Each machine shall be equipped with a circuit-interrupting device by means of which all power conductors can be deenergized at the machine. A manually operated controller will not be acceptable as a service switch.

(b) When impracticable to mount the main-circuit-interrupting device on a machine, a remote enclosure will be acceptable. When contacts are used as a main-circuit-interrupting device, a means for opening the circuit shall be provided at the machine and at the remote contactors.

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§ 18.49 Connection boxes on machines.

Connection boxes used to facilitate replacement of cables or machine components shall be explosion-proof. Portable-cable terminals on cable reels need not be in explosion-proof enclosures provided that connections are well made, adequately insulated, protected from damage by location, and securely clamped to prevent mechanical strain on the connections.

§ 18.50 Protection against external arcs and sparks.

Provision shall be made for maintaining the frames of all off-track machines and the enclosures of related detached components at safe voltages by using one or a combination of the following:

(a) A separate conductor(s) in the portable cable in addition to the power conductors by which the machine frame can be connected to an acceptable grounding medium, and a separate conductor in all cables connecting related components not on a common chassis. The cross-sectional area of the additional conductor(s) shall not be less than 50 percent of that of one power conductor unless a ground-fault tripping relay is used, in which case the minimum size may be No. 8 (AWG). Cables smaller than No. 6 (AWG) shall have an additional conductor(s) of the same size as one power conductor.

(b) A means of actuating a circuit-interrupting device, preferably at the outby end of the portable cable.

Note: The frame to ground potential shall not exceed 40 volts.

(c) A device(s) such as a diode(s) of adequate peak inverse voltage rating and current-carrying capacity to conduct possible fault current through the grounded power conductor. Diode installations shall include: (1) An overcurrent device in series with the diode, the contacts of which are in the machine's control circuit; and (2) a blocking diode in the control circuit to prevent operation of the machine with the polarity reversed.

§ 18.51 Electrical protection of circuits and equipment.

(a) An automatic circuit-interrupting device(s) shall be used to protect each ungrounded conductor of a branch circuit at the junction with the main circuit when the branch-circuit conductor(s) has a current carrying capacity less than 50 percent of the main circuit conductor(s), unless the protective device(s) in the main circuit will also provide adequate protection for the branch circuit. The setting of each device shall be specified. For headlight and control circuits, each conductor shall be protected by a fuse or equivalent. Any circuit that is entirely contained in an explosion-proof enclosure shall be exempt from these requirements.

(b) Each motor shall be protected by an automatic overcurrent device. One protective device will be acceptable when two motors of the same rating operate simultaneously and perform virtually the same duty.

(1) If the overcurrent-protective device in a direct-current circuit does not open both lines, particular attention shall be given to marking the polarity at the terminals or otherwise preventing the possibility of reversing connections which would result in changing the circuit interrupter to the grounded line.

(2) Three-phase alternating-current motors shall have an overcurrent-protective device in at least two phases such that actuation of a device in one phase will cause the opening of all three phases.

(c) Circuit-interrupting devices shall be so designed that they can be reset without opening the compartment in which they are enclosed.

(d) All magnetic circuit-interrupting devices shall be mounted in a manner to preclude the possibility of their closing by gravity.

§ 18.52 Renewal of fuses.

Enclosure covers that provide access to fuses, other than headlight, control-circuit, and handheld-tool fuses, shall be interlocked with a circuit-interrupting device. Fuses shall be inserted on the load side of the circuit interrupter.

Subpart C—Inspections and Tests

§ 18.60 Detailed inspection of components.

An inspection of each electrical component shall include the following:

(a) A detailed check of parts against the drawings submitted by the applicant to determine that: (1) The parts and drawings coincide; and (2) the minimum requirements stated in this part have been met with respect to materials, dimensions, configuration, workmanship, and adequacy of drawings and specifications.

(b) Exact measurement of joints, journal bearings, and other flame-arresting paths.

(c) Examination for unnecessary through holes.

(d) Examination for adequacy of lead-entrance design and construction.

(e) Examination for adequacy of electrical insulation and clearances between live parts and between live parts and the enclosure.

(f) Examination for weaknesses in welds and flaws in castings.

(g) Examination for distortion of enclosures before tests.

(h) Examination for adequacy of fastenings, including size, spacing, security, and possibility of bottoming.

§ 18.61 Final inspection of complete machine.

(a) A completely assembled new machine or a substantially modified design of a previously approved one shall be inspected by a qualified representative(s) of MSHA. When such inspection discloses any unsafe condition or any feature not in strict conformance with the requirements of this part it shall be corrected before an approval of the machine will be issued. A final inspection will be conducted at the site of manufacture, rebuilding, or other locations at the option of MSHA.

(b) Complete machines shall be inspected for:

(1) Compliance with the requirements of this part with respect to joints, lead entrances, and other pertinent features.

(2) Wiring between components, adequacy of mechanical protection for cables, adequacy of clamping of cables, positioning of cables, particularly with respect to proximity to hydraulic components.

(3) Adequacy of protection against damage to headlights, push buttons, and any other vulnerable component.

(4) Settings of overload- and short-circuit protective devices.

(5) Adequacy of means for connecting and protecting portable cable.

§ 18.62 Tests to determine explosion-proof characteristics.

(a) In testing for explosion-proof characteristics of an enclosure, it shall be filled and surrounded with various explosive mixtures of natural gas and air. The explosive mixture within the enclosure will be ignited electrically and the explosion pressure developed therefrom recorded. The point of ignition within the enclosure will be varied. Motor armatures and/or rotors will be stationary in some tests and revolving in others. Coal dust, produced by grinding coal from the Pittsburgh coal bed to a fineness of minus 200 mesh, will be added to the explosive gas-air mixtures in some tests. At MSHA's discretion dummies may be substituted for internal electrical components during some of the tests. Not less than 16 explosion tests shall be conducted; however, the nature of the enclosure and the results obtained during the tests will determine whether additional tests shall be made.

(b) Explosion tests of an enclosure shall not result in:

(1) Discharge of flame.

(2) Ignition of an explosive mixture surrounding the enclosure.

(3) Development of afterburning.

(4) Rupture of any part of the enclosure or any panel or divider within the enclosure.

(5) Permanent distortion of the enclosure exceeding 0.040 inch per linear foot.

(c) When a pressure exceeding 125 pounds per square inch (gage) is developed during explosion tests, MSHA reserves the right to reject an enclosure(s) unless (1) constructional changes are made that result in a reduction of pressure to 125 pounds per square inch (gage) or less, or (2) the enclosure withstands a dynamic pressure of twice the highest value recorded in the initial test.

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§ 18.67 Static-pressure tests.

Static-pressure tests shall be conducted by the applicant on each enclosure of a specific design when MSHA determines that visual inspection will not reveal defects in castings or in single-seam welds. Such test procedure shall be submitted to MSHA for approval and the specifications on file with MSHA shall include a statement assuring that such tests will be conducted. The static pressure to be applied shall be 150 pounds per square inch (gage) or one and one-half times the maximum pressure recorded in MSHA's explosion tests, whichever is greater.

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§ 18.69 Adequacy tests.

MSHA reserves the right to conduct appropriate test(s) to verify the adequacy of equipment for its intended service.

Subpart D—Machines Assembled With Certified or Explosion-Proof Components, Field Modifications of Approved Machines, and Permits To Use Experimental Equipment

§ 18.80 Approval of machines assembled with certified or explosion-proof components.

(a) A machine may be a new assembly, or a machine rebuilt to perform a service that is different from the original function, or a machine converted from nonpermissible to permissible status, or a machine converted from direct- to alternating-current power or vice versa. Properly identified components that have been investigated and accepted for application on approved machines will be accepted in lieu of certified components.

(b) A single layout drawing (see Figure 1 in Appendix II) or photographs will be acceptable to identify a machine that was assembled with certified or explosion-proof components. The following information shall be furnished:

(1) Overall dimensions.

(2) Wiring diagram.

(3) List of all components (see Figure 2 in Appendix II) identifying each according to its certification number or the approval number of the machine of which the component was a part.

(4) Specifications for:

(i) Overcurrent protection of motors.

(ii) All wiring between components, including mechanical protection such as hose conduits and clamps.

(iii) Portable cable, including the type, length, outside diameter, and number and size of conductors.

(iv) Insulated strain clamp for machine end of portable cable.

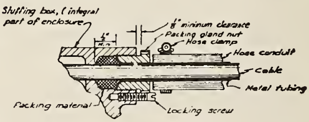
(v) Short-circuit protection to be provided at outby end of portable cable.

(c) MSHA reserves the right to inspect and to retest any component(s) that had been in previous service, as it deems appropriate.

(d) Fees for testing under this subpart shall be consistent with those stated in § 18.7.

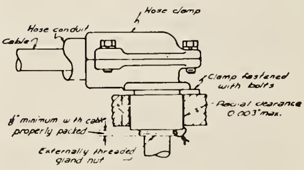
(e) When MSHA has determined that all applicable requirements of this part have been met, the applicant will be authorized to attach an approval plate to each machine that is built in strict accordance with the drawings and specifications filed with MSHA and listed with MSHA's formal approval. A design of the approval plate will accompany the notification of approval. (Refer to §§ 18.10 and 18.11.)

(f) Approvals are issued only by Approval and Certification Center, Box 201B Industrial Park Road, Dallas Pike, Triadelphia, W. Va. 26049.

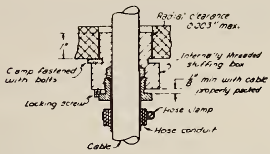


Typical Threaded Straight Stuffing Box and Packing Gland Lead Entrance with Provision For Hose Conduit

Figure 8

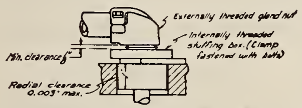


Typical Slip Fit Angle Type Stuffing Box Packing Gland Lead Entrance with Hose Clamp



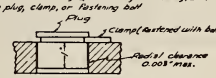
Typical Slip Fit Straight Type Stuffing Box and Packing Gland Lead Entrance

Figure 9.



Typical Slip Fit Angle Type Stuffing Box and Packing Gland Lead Entrance

Plugs shall be secured by spot welding or brazing, weld may be on plug, clamp, or fastening bolt



Typical Plug For Spare Lead Entrance Hole

Figure 10

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PART 75—MANDATORY SAFETY STANDARDS—UNDERGROUND COAL MINES

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Subpart I—Underground High-Voltage Distribution

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Subpart I—Underground High-Voltage Distribution

§ 75.800 High-voltage circuits; circuit breakers.

[Statutory Provisions]

High-voltage circuits entering the underground area of any coal mine shall be protected by suitable circuit breakers of adequate interrupting capacity which are properly tested and maintained as prescribed by the Secretary. Such breakers shall be equipped with devices to provide protection against under-voltage grounded phase, short circuit, and overcurrent.

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§ 75.800-2 Approved circuit schemes.

The following circuit schemes will be regarded as providing the necessary protection to the circuits required by § 75.800:

(a) Ground check relays may be used for undervoltage protection if the relay coils are designed to trip the circuit breaker when line voltage decreases to 40 percent to 60 percent of the nominal line voltage;

(b) Ground trip relays on resistance grounded systems will be acceptable as grounded phase protection;

(c) One circuit breaker may be used to protect two or more branch circuits, if the circuit breaker is adjusted to afford overcurrent protection for the smallest conductor.

§ 75.800-3 Testing, examination and maintenance of circuit breakers; procedures.

(a) Circuit breakers and their auxiliary devices protecting underground high-voltage circuits shall be tested and examined at least once each month by a person qualified as provided in § 75.153;

(b) Tests shall include:

(1) Breaking continuity of the ground check conductor, where ground check monitoring is used; and

(2) Actuating at least two (2) of the auxiliary protective relays.

(c) Examination shall include visual observation of all components of the circuit breaker and its auxiliary devices, and such repairs or adjustments as are indicated by such tests and examinations shall be carried out immediately.

§ 75.800-4 Testing, examination and maintenance of circuit breakers; record.

The operator of any coal mine shall maintain a written record of each test, examination, repair, or adjustment of all circuit breakers protecting high voltage circuits which enter any underground area of the coal mine. Such record shall be kept in a book approved by the Secretary.

§ 75.801 Grounding resistors.

[Statutory Provisions]

The grounding resistor, where required, shall be of the proper ohmic value to limit the voltage drop in the grounding circuit external to the resistor to not more than 100 volts under fault conditions. The grounding resistor shall be rated for maximum fault current continuously and insulated from ground for a voltage equal to the phase-to-phase voltage of the system.

§ 75.802 Protection of high-voltage circuits extending underground.

(a) Except as provided in paragraph (b) of this section, high-voltage circuits extending underground and supplying portable, mobile, or, stationary high-voltage equipment shall contain either a direct or derived neutral which shall be grounded through a suitable resistor at the source transformers, and a grounding circuit, originating at the grounded side of the grounding resistor, shall extend along with the power conductors and serve as a grounding conductor for the frames of all high-voltage equipment supplied power from that circuit.

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§ 75.803 Fail safe ground check circuits on high-voltage resistance grounded systems.

[Statutory Provisions]

On and after September 30, 1970, high-voltage, resistance grounded systems shall include a fail safe ground check circuit to monitor continuously the grounding circuit to assure continuity and the fail safe ground check circuit shall cause the circuit breaker to open when either the ground or pilot check wire is broken, or other no less effective device approved by the Secretary or his authorized representative to assure such continuity, except that an extension of time, not in excess of 12 months, may be permitted by the Secretary on a mine-by-mine basis if he determines that such equipment is not available.

§ 75.803-1 Maximum voltage ground check circuits.

The maximum voltage used for ground check circuits under § 75.803 shall not exceed 96 volts.

§ 75.803-2 Ground check systems not employing pilot check wires; approval by the Secretary.

Ground check systems not employing pilot check wires will be approved only if it is determined that the system includes a fail safe design causing the circuit breaker to open when ground continuity is broken.

§ 75.804 Underground high-voltage cables.

(a) Underground high-voltage cables used in resistance grounded systems shall be equipped with metallic shields around each power conductor with one or more ground conductors having a total cross sectional area of not less than one-half the power conductor, and with an insulated external conductor not smaller than No. 8 (A.W.G.) or an insulated internal ground check conductor not smaller than No. 10 (A.W.G.) for the ground continuity check circuit.

(b) All such cables shall be adequate for the intended current and voltage. Splices made in such cables shall provide continuity of all components.

§ 75.805 Couplers.

[STATUTORY PROVISIONS]

Couplers that are used with medium-voltage or high-voltage power circuits shall be of the three-phase type with a full metallic shell, except that the Secretary may permit, under such guidelines as he may prescribe, no less effective couplers constructed of materials other than metal. Couplers shall be adequate for the voltage and current expected. All exposed metal on the metallic couplers shall be grounded to the ground conductor in the cable. The coupler shall be constructed so that the ground check continuity conductor shall be broken first and the ground conductors shall be broken last when the coupler is being uncoupled.

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§ 75.808 Disconnecting devices.

[STATUTORY PROVISIONS]

Disconnecting devices shall be installed at the beginning of branch lines in high-voltage circuits and equipped or designed in such a manner that it can be determined by visual observation that the circuit is deenergized when the switches are open.

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§ 75.810 High-voltage trailing cables; splices.

[STATUTORY PROVISIONS]

In the case of high-voltage cables used as trailing cables, temporary splices shall not be used and all permanent splices shall be made in accordance with § 75.604. Terminations and splices in all other high-voltage cables shall be made in accordance with the manufacturer's specifications.

§ 75.811 High-voltage underground equipment; grounding.

[STATUTORY PROVISIONS]

Frames, supporting structures and enclosures of stationary, portable, or mobile underground high-voltage equipment and all high-voltage equipment supplying power to such equipment receiving power from resistance grounded systems shall be effectively grounded to the high-voltage ground.

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DEMONSTRATION OF THE DISCRIMINATING CIRCUIT BREAKER (DISCB)

By Michael R. Yenchek[1]

ABSTRACT

The evolution of the DISCB concept and theory of operation are described briefly. Laboratory test results with a simulated mine haulageway are included and illustrate detector operation, and the effects of rectifier ripple, arcing, and deteriorating track bonding. Future Federal Bureau of Mines laboratory and fieldwork plans are outlined in conclusion along with an appendix containing important points for consideration during in-mine installation.

INTRODUCTION

Track haulage systems in United States underground coal mines operate at 300 to 600 V dc, one side of which returns to the source through grounded rails. Electrical faults on these systems are a major cause of mine fires, and once having caused a fire, can also block egress from the mine and contaminate the fresh air supply.

From 1952 to 1977, Federal personnel investigated 127 such fires. At least 80 would have been prevented if suitable electrical protection had been available.

The simple overcurrent sensing devices commonly used in haulage systems date back to the 1920's despite advances in electrical and electronic technology. What is needed is a protection scheme that permits the flow of thousands of amperes of normal motor currents, but responds rapidly to the low-level ground fault currents associated with incendiary arcing.

THE DISCB CONCEPT

In the early 1960's, French researchers (8)[2] successfully developed a scheme for accomplishing the required discrimination by impressing an audio frequency tone on the trolley line at each rectifier station and monitoring its magnitude. The need for modification of the system, to accommodate the heavier rolling stock prevalant in U. S. mines, led to Bureau of Mines research contract H0122058 with Westinghouse Electric Corp. in 1972.

Through the DISCB concept, arcing and other types of faults are detected as illegitimate loads because of the low impedance they present to 3-kHz-ac current. This frequency was chosen because it gives good signal transmission on underground trolley wires, yet is high enough to permit a clean separation of the signal from normal system noise.

Many small mobile loads such as jeeps have sufficient motor inductance to prevent significant 3-kHz current from flowing, however, larger haulage locomotives must be equipped with filters to raise their impedance at 3 kHz as shown in figure 1. Applying this technique, Westinghouse (13) found it possible to detect illegitimate impedances of 20 Ω or less, corresponding to fault currents of 15 A or more on a 300-V system. However, during underground tests the filtering devices needed on most mine vehicles presented a problem. This equipment had to be mounted in exposed areas and was subjected to severe mechanical stress. Because of this a simplified method was sought that significantly reduced the number of filters needed.

[1]Electrical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

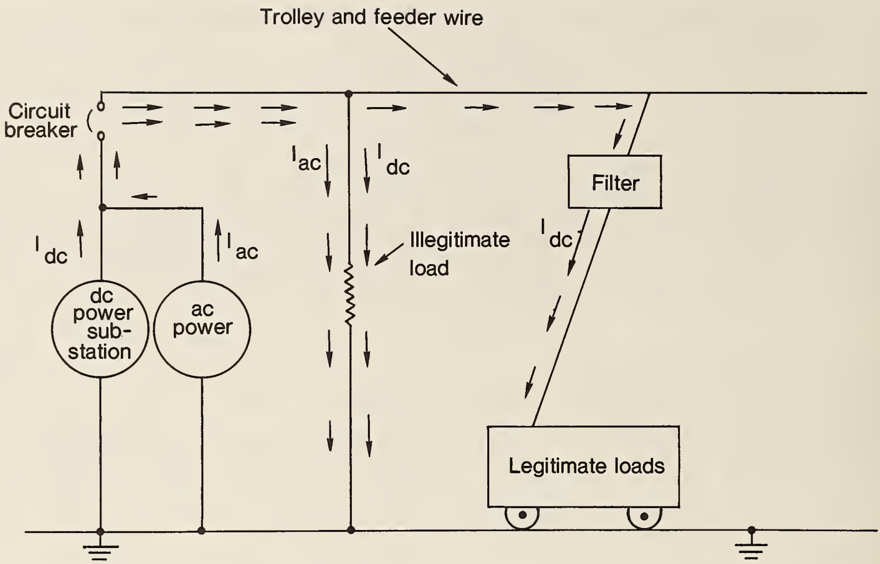

FIGURE 1. - DISCB current flow.

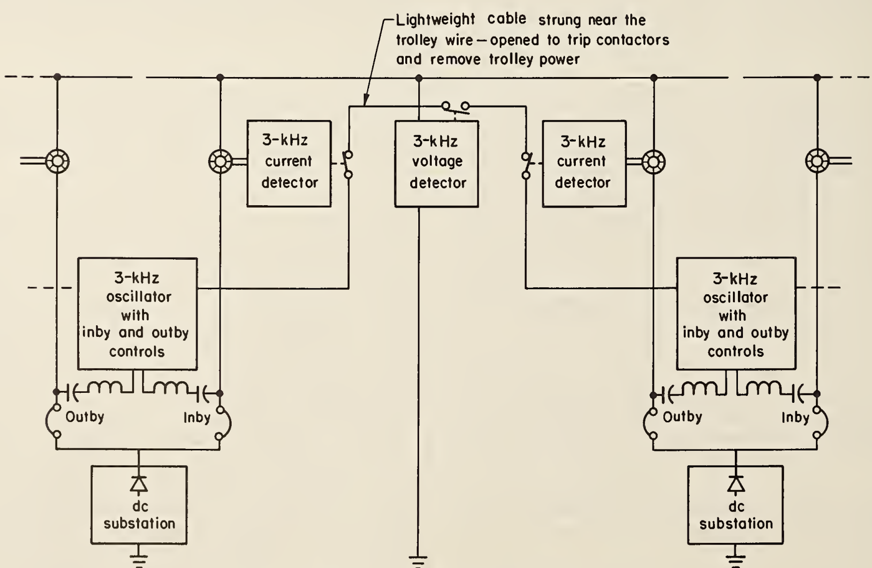

FIGURE 2. - Simplified DISCB system.

Work by Mine Safety and Health Administration (MSHA) personnel (4) indicated that arcing faults on 300-V trolley systems are much less likely to be sustained at current levels smaller than 200 A. Below this limit arc voltage increases rapidly and the arc easily extinguishes itself. Thus a discriminating circuit breaker system capable of detecting any faults in excess of 150 A will provide substantial protection.

In the final modified design, 3-kHz-ac current detectors are used to detect illegitimate loads up to 1,200 ft from the substation. For more remote faults the inductance of the trolley wire prevents adequate high frequency current from flowing; however, the same inductance causes a substantial high frequency voltage drop which can be recognized by a 3-kHz-ac undervoltage detector remote from the substation (see fig. 2). This combination of voltage and current detectors provides detection of any illegitimate load in excess of 150 A, without recourse to filters on other than the largest vehicles.

In operation a lightweight pilot wire alongside the trolley wire carries signals to coordinate the operation of dc breakers at the various sources to interrupt all lines feeding the fault. This wire also provides additional protection, in that if the cable is broken by a roof fall, the dc power is interrupted and cannot be energized until repairs have been made.

System Benefits

If those fault conditions on coal mine track haulageways which are usually not reported are considered, it is found that there is a probable continuous benefit to be derived from discriminating circuit breakers. Not all short circuits start fires but they often stress and damage equipment. This damage can be significantly reduced with the quick response of the discriminating circuit breakers. Inquiries within the industry indicate that such incidents may occur about two to five times a year. Inby production stops for an average of 4 hours while repairs are made. If a 150-worker-per shift mine with one-third the workers idled by the outage is assumed, and equating 1 man-hour of labor to 1 ton of coal at $40 per ton, the annual worth of a trolley wire protection scheme is estimated as 2 to 5 (mishaps) × 4 (hours to repairs) × 50 (workers) × 40 ($ man-hour) = $16,000 to $40,000.

If the initial cost of a discriminating circuit breaker system is estimated to be in the range of $35,000 to $70,000, the payback time is of the order of 2 years, an acceptable period. Thus trolley wire protection appears justified on economic grounds alone (11, p. 12).

Of all the protection schemes proposed to date, the DISCB offers the best hope of functioning well, given proper installation. It does not depend on uncontrolled characteristics such as rectifier ripple, transient waveforms, or dI/dt level sensing for its basic operation. Also, the DISCB can be employed on any existing haulageway with minimal modifications to the haulage equipment. Finally, it utilizes low-power solid-state electronics (fig. 3) that can give virtually maintenance-free performance for many years.

After the development of the discriminating circuit breaker, a system was installed underground and exposed to typical haulage conditions including electrical power system fluctuations for over 5 years (see fig. 4). It performed satisfactorily but operated event counters in lieu of tripping circuit breakers. What remains to be demonstrated is that the system, in the long term, will work reliably and safely when actually protecting a mine haulageway. The appendix to this paper provides recommendations for field installation.

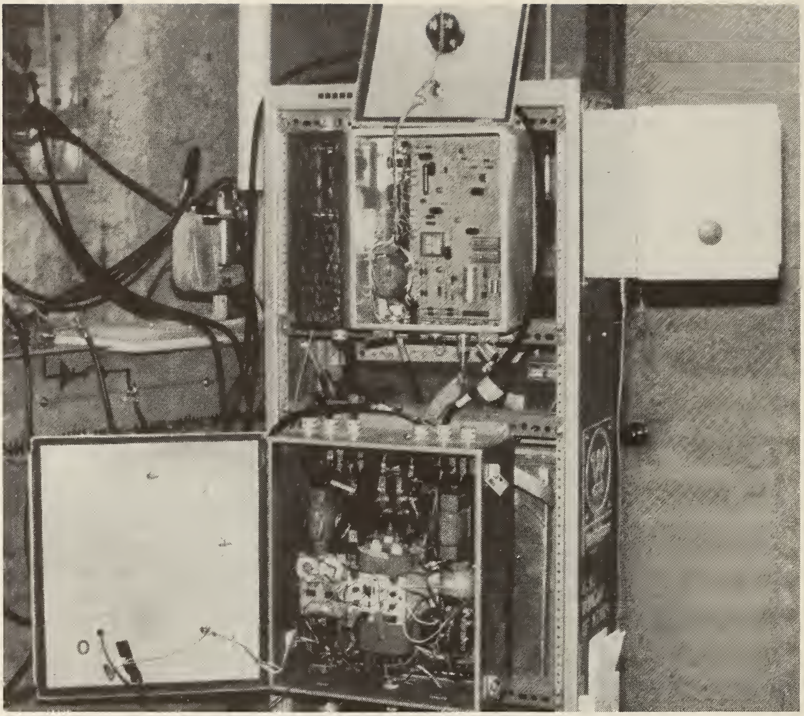

FIGURE 3. - DISCB internal components.

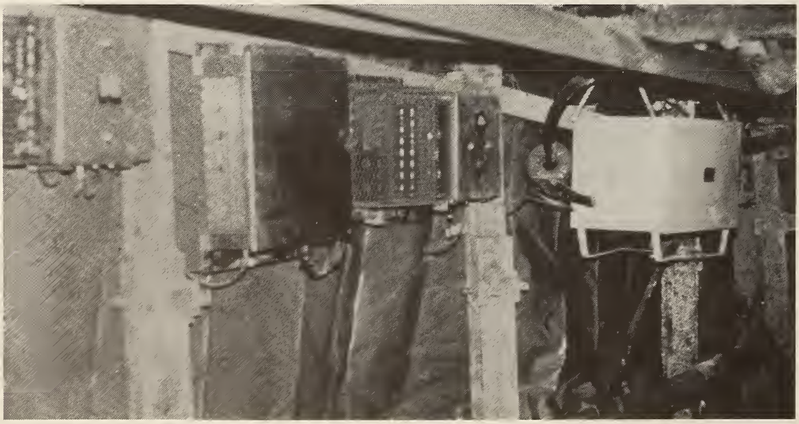

FIGURE 4. - DISCB control installed underground.

HAULAGEWAY MODEL

Background

The management of Federal No. 1 Mine of Eastern Associated Coal Co., Grant Town, W. Va., expressed an interest in utilizing the system to protect a 1-mile section in the oldest but still actively used area of the mine. Prior to commitment they requested a laboratory demonstration of the DISCB basic functions using prototype hardware and a simulation of the particular haulage section. The Bureau of Mines, therefore, has recently constructed and successsfully operated a lumped parameter simulation of the rail section, protected by the actual DISCB equipment.

Federal Haulageway

The Federal No. 1 Mine was visited to gather data on a portion of the rail haulage fed from a single 300-V source shown in figure 5. Two parallel track entries, one for loads and the other for empties, connect the rotary dump area with the active sections of the mine. At the No. 1 substation a 500-kW mercury arc hewittic rectifier was tied into the system through a circuit breaker having an overcurrent setting of 2,500 A. It has since been replaced with a solid-state unit.

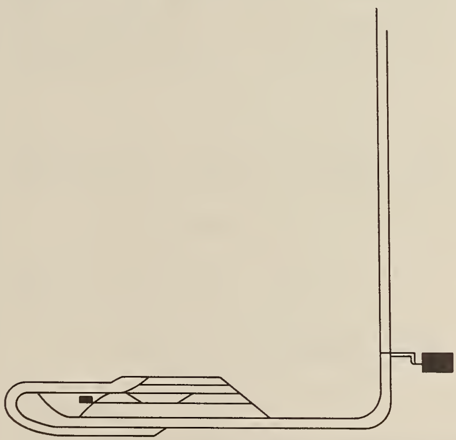

FIGURE 5. - Portion of Federal No. 1 haulage used for model.

The positive No. 9 section copper trolley is paralleled part of the way by a 1,590 kcmil aluminum feeder cable, tied to the trolley at 200-ft intervals. The track conductors consist of 85-lb double-bonded rails. The distance between trolley and feeder is 12 in; between trolley and rail it averages 72 in.

The available locomotive loads are: Two 50-ton locomotives with four 160-hp motors, six 37-ton locomotives with four 120-hp motors, and two 15-ton locomotives with two 150-hp motors. Numerous utility vehicles of 150 hp and less are also used.

Theoretical Analysis

The rectifier can be represented by the equivalent circuit shown in figure 6.

Mine rectifiers generally are found in one of two configurations: The three-phase bridge and the six-phase double wye (12). It can be shown that the operation of both of these circuits is equivalent (14). The steady-state regulation curve of either circuit is shown in figure 7.

The effective source resistance, V/I, is not constant but is lower in the overload range than for the short circuit. The source resistance, R_s, may be calculated given the per-unit reactance and resistance of the transformer rectifier. For a 500-kW unit, typically percent R equals 1.1, percent X equals 7.5, and percent Z equals 7.6.

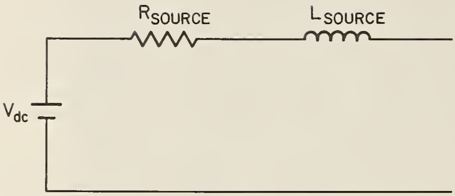

FIGURE 6. - Direct current mine power supply.

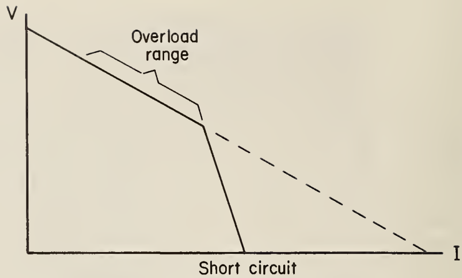

FIGURE 7. - Rectifier voltage regulation.

Assuming an infinitely stiff source feeding a 500-kW three-phase bridge rectifier, the ac impedance can be calculated as (3, pp. 12-17)

$$V_{LINE - NEUTRAL} = \frac{V_{DC}}{1.35\sqrt{3}} = \frac{300}{1.35\sqrt{3}} = 128 \text{ V},$$

$$I_{LINE} = 0.816\ I_{DC} = 0.816\ (1{,}666) = 1{,}360 \text{ A},$$

and

$$Z_{BASE} = 128/1{,}360 = 0.094\ \Omega.$$

Therefore,

$$R_{AC} = (0.11)(0.094\ \Omega) = 1.03\ m\Omega,$$

$$Z_{AC} = (0.076)(0.094\ \Omega) = 7.14\ m\Omega,$$

$$X_{AC} = (0.075)(0.094\ \Omega) = 7.05\ m\Omega,$$

and

$$L_{AC} = X/377 = \frac{7.05\ (10^{-3})}{377} = 18.7\ \mu\text{H}.$$

For the overload range the equivalent dc circuit impedance is (14)

$$R_{SOURCE} = 6\ fL_{AC} + 2\ R_{AC} = (360)(18.7)10^{-6} + 2(1.03)(10^{-3})$$

$$= 8.79\ m\Omega.$$

For the short-circuit case

$$R_{SOURCE} = \sqrt{3}\ Z_{AC} = \sqrt{3}\ (7.14)(10^{-3})$$

$$= 12.37\ m\Omega$$

The equivalent source inductance is essentially constant and equal to (14)

$$L_{SOURCE} = 1.65\ L_{AC} = 1.65(18.7)10^{-6} = 31\ \mu\text{H}.$$

Since the DISCB detects relatively low levels of fault current, the equivalent source resistance for the overload range was chosen for the model.

The theoretical dc resistance at 20° C for 400 kcmil, figure 9 hard-drawn copper trolley wire is (1) 0.02687 Ω/1,000 ft. For the 1,590 kcmil aluminum feeder it is (10) 0.01091 Ω/1,000 ft, or roughly equivalent to 1,000 kcmil copper. So the paralleled trolley and feeder resistance is 0.00755 Ω/1,000 ft

The resistance of two 85-lb rails cross-bonded at 200-ft intervals and having 33 bonded joints per rail per 1,000 ft is (6) 0.0064 Ω/1,000 ft.

Actual measurements (9) of unbonded joints indicate that their resistance averages 50 times that of a well-bonded joint. Resistances of unbonded 85-lb rail joints have been measured (2) to be 0.025 Ω. In simulating poor bonding for a pair of 85-lb rail it is assumed that 70 pct of the joints are unbonded. Thus the dc resistance becomes 0.335 Ω/1,000 ft.

Because the DISCB imposes a 3-kHz signal directly onto the haulage system conductors, the importance of skin effect was considered. Let R' be the effective ac resistance for a linear cylinderical conductor and R the dc resistance; then

$$R' = kR,$$

where k can be determined from standard references (3, p. 4-29) in terms of

$$x = 0.0636 \sqrt{\frac{f\mu}{R}}$$

where f = frequency in hertz,

μ = magnetic primability of the conductor (assumed constant),

and R = dc resistance at 20° C.

For the 9-section copper trolley at 3,000 Hz,

$$x = 0.0636 \sqrt{\frac{3(10^3)(1)}{0.142}} = 9.25, \ K = 3.60,$$

so the resistance of the trolley to a 3-kHz voltage is 0.09734 Ω/1,000 ft. For the aluminum feeder x = 14.92, k = 5.53, so ac resistance is 0.0637 Ω/1,000 ft and, for trolley and feeder is parallel, R'_{3kHz} = 0.0373 Ω/1,000.

For steel rails the value of μ, and thus R', will vary and should be determined by test. Measured (16) values of ac resistance versus current indicate that between 500 and 800 A, R' is almost constant and a maximum. As this range is of interest for the DISCB, an approximate extrapolation of the curves yielded

$$R'_{3kHz} = 0.3273 \ \Omega/1,000 \text{ ft}$$

for 85-lb double-bonded track.

The inductance of any trolley system configuration may be calculated theoretically by several methods (2, 7) with the following assumptions:

1. All conductors are nonmagnetic.

2. All conductors are cylindrical.

3. Constant spacing exists between conductors.

4. Rail self-inductance is negligible.

5. The cross-sectional area of feeder is added to trolley and/or rails.

Accurate field measurements of system inductance yields results in substantial agreement with the theoretical values. Therefore, it was not considered necessary to choose inductance values for the haulage model based upon rigorous theoretical calculations; instead, they are reasonable estimates from field surveys (5, pp. 9-1, 9-13) of systems similar to Federal No. 1. Thus

$$L_{9S\&85\#} \simeq 0.5 \text{ mH}/1,000 \text{ ft}, \ X_L = 9.3 \ \Omega/1,000 \text{ ft at 3 kHz}$$

and

$$L_{9S||A1\&85\#} \simeq 0.3 \text{ mH}/1,000 \text{ ft}, \ X_L = 5.7 \ \Omega/1,000 \text{ ft at 3 kHz}.$$

In general, the use of parallel feeder conductors decreases inductance while greater conductor separation increases it.

The shunt capacitance between the system conductors can be determined by individually calculating capacitance to neutral points and combining the resultant values in series and parallel as necessary. The equation that is used is (15, pp. 77-83)

$$C_N = \frac{0.0388}{\log (D_i/R_i)} \ \mu f/\text{mile},$$

where C_N = the capacitance of a conductor to a neutral point,

R_i = the radius or equivalent radius of the conductor,

and D_i = the distance to the neutral point between conductors.

The values arrived at by these calculations are, for the trolley and or feeder and track, C_N equals 0.016 µF/1,000 ft; and for the trolley and track, C_N equals 0.005 µF/1,000 ft. The respective shunt capacitive reactances at 3 kHz are X_c equals 3.3 kΩ/1,000 ft and X_c equals 10.6 kΩ/1,000 ft. For modeling purposes the shunt capacitance was neglected.

Large mobile haulage loads on dc mine systems utilize series field dc motors. Empirical relationships for 300-V-dc motors show that the effective inductance can be approximated by (12, pp. 4-18)

$$La = 190/\text{hp rating (mH)}.$$

The circuit simulation is shown in figure 8. The starting resistance, R_s, can be varied to produce up to triple full load current. Stationary loads (11, p. 16)

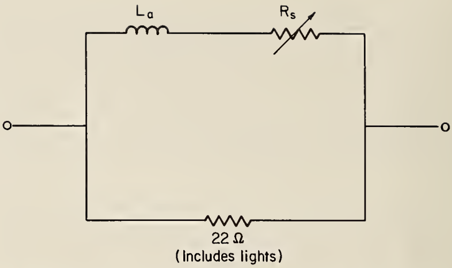

FIGURE 8. - Electrical model of mine haulage locomotive.

such as pumps and lights distributed along the haulage were simulated using 90 Ω per 500 ft.

Construction of the Model

The actual haulage system routing was rearranged, as shown in figure 9, to fit on a 4- by 8-ft plywood board. It was subdivided into sections and simulated as shown in figure 10 where L is the system inductance per section length. The parallel combination of R_{AC} and R_{DC} in series with R simulates dc resistance, and R_{AC} + R, the ac resistance; L_{SK} is sufficiently large to approximate skin effect at 3 kHz. R_s represents distributed stationary loading and R_B, the high resistance of poor bonding (normally jumpered).

Owing to power source limitations in the lab, loading and fault simulations did not exceed 100 A dc. Number 8 square copper magnet wire was wound on the lathe to form inductors. Appropriate resistance values were obtained with nickel-chromium wire noninductively wound.

The demonstration board is shown in figure 11.

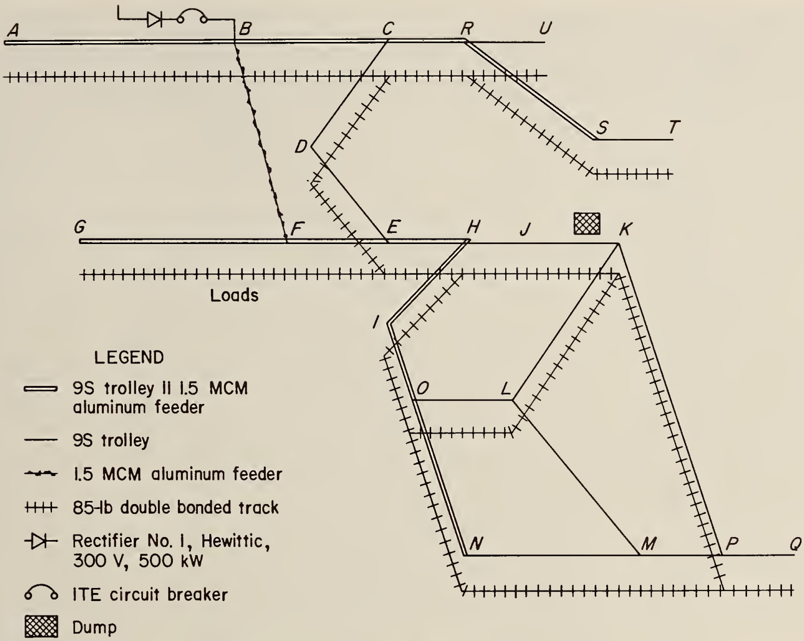

FIGURE 9. - Federal No. 1 haulage model.

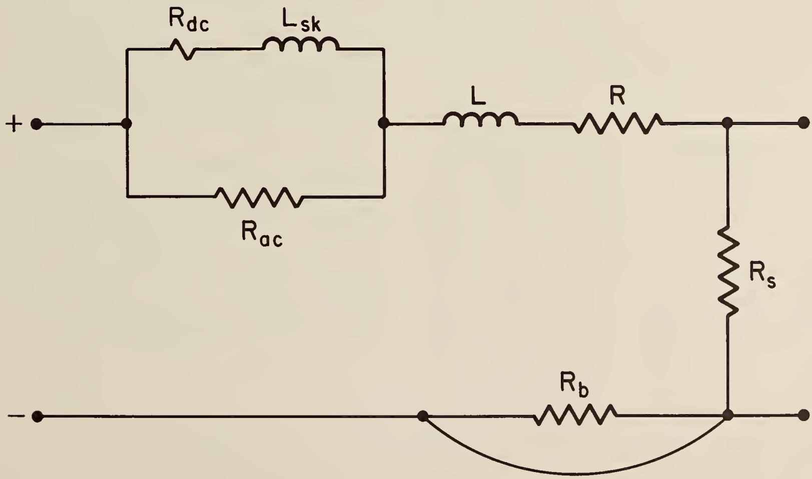

FIGURE 10. - Lumped haulage simulation.

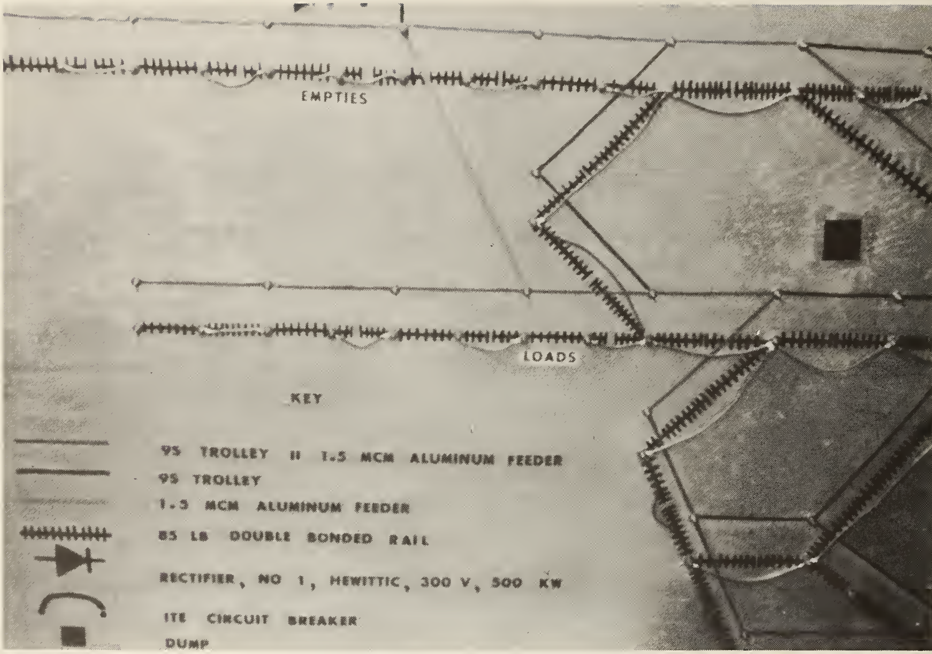

FIGURE 11. - Haulageway model.

LAB DEMONSTRATION

Current and Voltage Detection

Upon completion of the model the discriminating circuit breaker controls were connected to impress the 3-kHz signal on the system at the rectifier location as shown in figures 12 and 13. The 3-kHz current flow with no external mobile load or faults connected was 1.17 A as measured by the current detector. Referring to figure 9, with a 1.5-Ω resistive fault at point B, the rectifier, the 3-kHz current increases to 4.42 A; the current detector relay is activated and the circuit breaker trips. A simulated 15-ton locomotive placed at B drew 2.30 A at 3 kHz and did not trip the breaker.

Applying the fault at point A, 3,450 ft from the source, the total high frequency current increases slightly over the no-load value, to 1.24 A. This point is past the protective range of the current detector where audio current magnitude remains relatively unchanged for resistive faults remote from the substation.

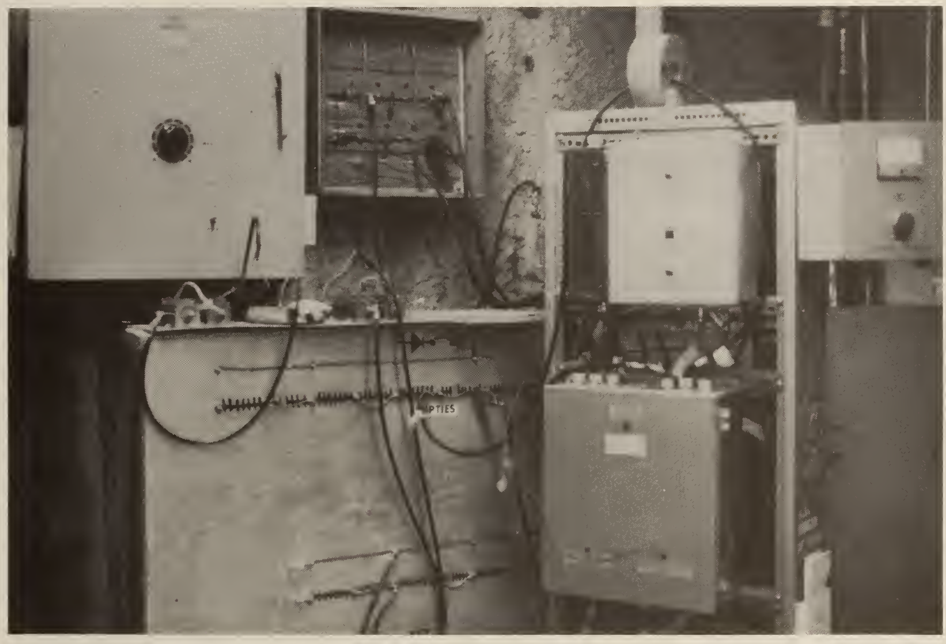

FIGURE 12. - Laboratory setup.

It is here that the DISCB voltage detector is needed and a simple example will illustrate this. Referring to table 1 the high frequency voltage was monitored (fig. 14) at six locations under normal, abnormal, and no-load conditions. Location B is at the substation while A, G, U, T, and Q are remote from it.

TABLE 1. - 3 kHz voltage variations

Load condition	Location					
	B	A	G	U	T	Q
No-load....................	8.0	6.7	6.3	6.8	6.9	7.1
1.5-Ω fault at B..........	6.1	5.0	4.8	5.2	5.3	5.4
15-ton locomotive at B....	7.1	5.9	5.7	6.0	6.1	6.3
1.5-Ω fault at A..........	7.8	.2	6.1	6.6	6.7	6.9
15-ton locomotive at A....	7.9	1.4	6.1	6.7	6.8	7.0
1.5-Ω fault at G..........	7.9	6.6	.1	6.7	6.8	7.0
15-ton locomotive at G....	7.9	6.6	1.3	6.7	6.8	7.0

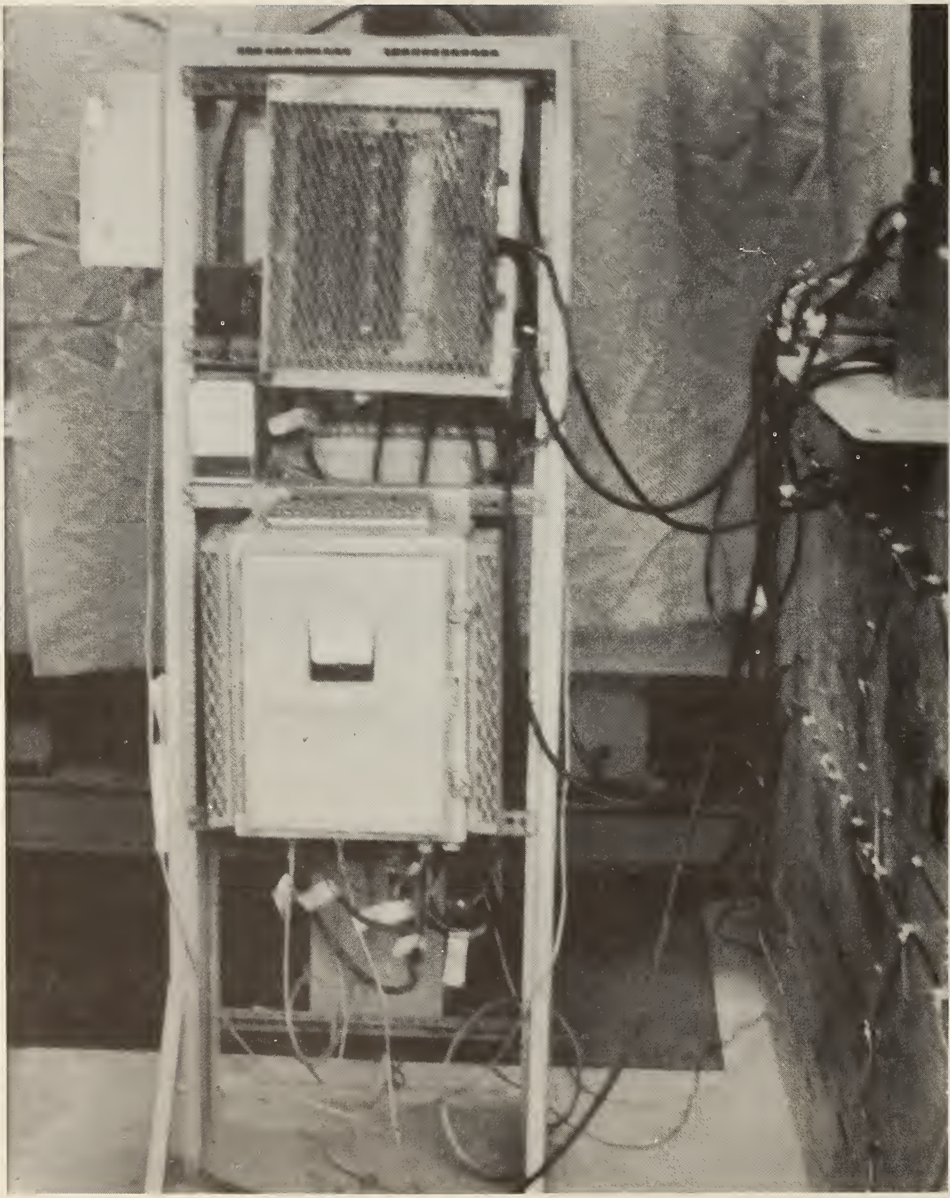

FIGURE 13. - DISCB controls at substation.

FIGURE 14. - Voltage measurements on model.

No-load is defined as that time when only distributed stationary loads such as pumps and lights are connected on the system. The high frequency voltage is a maximum at the rectifier and drops by 22 pct at the remotest point. With a fault near the rectifier the 3-kHz voltage throughout the system decreases 24 pct from the no-load value. The voltages at B for a fault or a locomotive differ by 15 pct. Since this margin between legitimate and illegitimate loads is insufficient for discrimination a voltage detector located near the source serves no purpose.

Away from the substation, high current loads and faults substantially alter the 3-kHz voltage distribution. With the fault at A the signal voltage there drops to 3 pct of the no-load value. It also drops substantially with a legitimate locomotive load there. However, now there is an 86-pct difference in the two voltages, large enough to adjust the setting of the voltage detector to protect against resistive faults. It is of interest to note that the voltage magnitude remains relatively unchanged at locations remote from the fault and the rectifier.

DISCB worst-case performance is illustrated in figure 15 with a voltage detector located 2,875 ft away from the rectifier at A. Through judicious placement of the voltage detectors it is possible to protect the entire system.

Active Impedance Multiplier

As described in the first section, the 3-kHz impedance of vehicles rated 25 tons and larger must be raised sufficiently to prevent nuisance tripping. This is accomplished by mounting an active impedance multiplier (fig. 16) on board large mobile loads. Laboratory testing of the multiplier with a simulated 37-ton locomotive yielded satisfactory results.

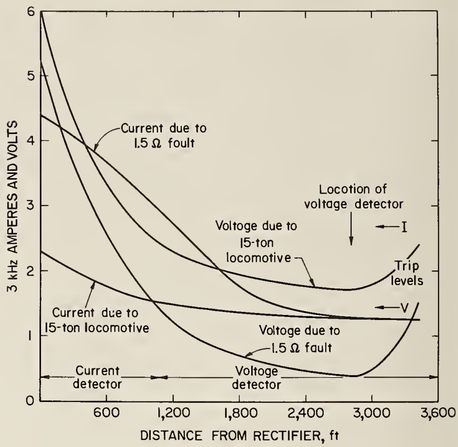

FIGURE 15. - DISCB protection.

FIGURE 16. - Active impedance multiplier (AIM) with power supply.

Signal currents and voltages were measured with the load at the rectifier. Using the multiplier the current drawn was 1.3 A. Without it current increased to 2.5 A. The voltage at remote points remained unchanged.

Moving the locomotive to point A the current level was not changed by the multiplier's exclusion. However, the voltage decreased from 5.0 to 1.0 V. Figure 17 illustrates the effect graphically.

Poor Track Bonding

Poorly maintained or disconnected track bonds will insert an additional impedance in the rail circuit and slightly reduce the 3-kHz voltage measured at remote points. For example, with a poorly bonded track simulated between the rectifier and G, and the 15-ton locomotive at G, there was a 10-pct reduction in the signal voltage at G over the good bonding value.

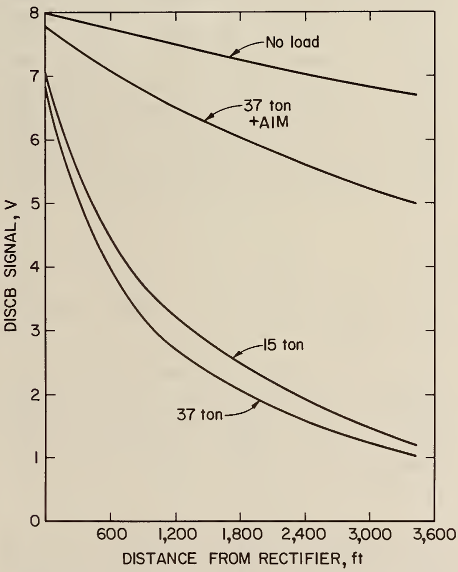

FIGURE 17. - Effects of active impedance multiplier (AIM).

Effects of Arcing

A series of arcing fault tests were conducted to note any effect on DISCB operation. A resistive fault was applied at G in series with two steel electrodes, 0.5 inch in diameter and separated by an air gap. Arcing was initiated by bridging the gap with several strands of a 19-strand No. 12 AWG wire that vaporized upon energization. The air gap was varied from 3/32 to 5/8 in. The presence of the arc did not affect the flow of 3-kHz current or DISCB operation.

Rectified Versus Generated Input

The DISCB and the demonstration board have been used with both a 30-kW generator and a 200-kW rectifier. No difference in operation could be detected. Satisfactory operation was obtained for input voltage fluctuations from 200 to 350 V dc.

Further Study

At present sufficient hardware is available in prototype form for small-scale demonstrations to interested coal operators or for consideration by a manufacturer as a marketable product.

It is intended to install the system at the Federal No. 1 Mine on the portion of rail haulage modeled in the laboratory. Technical advice will be furnished by the Bureau as required throughout the installation and initial demonstration phases of the single-section system. The equipment will remain installed for a sufficient time to accumulate an extended performance history. The Bureau intent is to show that the unit can be operated for a 3-month period with no more than one nuisance interruption and no instance of any failure permitting the trolley line to remain energized for a sustained ground fault greater than 200 A.

Typical trolley haulage systems in coal mines are powered by multiple dc sources, typically about 1 mile apart. The 3-kHz DISCB signal is impressed upon the system at these substations through an oscillator and power amplifier. Since the signal can be applied at several separate locations, means is provided to minimize circulating audio frequency currents by selection of a master frequency and phase. The power amplifier contains a synchronizing unit that locks onto the nearest outby oscillator and disengages its own master oscillator. If for any reason the outermost master oscillator controlling the system is unavailable the next outby oscillator automatically takes over the master role and sets the frequency and phase of the 3-kHz voltages. By this means the integrity of the discriminating system is maintained even when several substations are out of commission. It is this interaction of DISCB power source controls that remains to be demonstrated in the Bureau's laboratory with a multisource system.

Upon agreement with a cooperating mine, the DISCB system will be installed to protect a haulage system having at least three branches protected by separate circuit breakers and fed from more than one dc source. This larger demonstration and long-term usage test will prove to the mining industry that the system is fail-safe, reliable, and effective.

The present design requires that a lightweight cable comprising three twisted pairs of insulated 20 gage wire be strung alongside the trolley wire to carry signals for the system. For the substation breaker to close, proper data must be received through the cable. For example if the cable is broken by a roof fall the dc power cannot be energized. Also, if the detector units indicate a faulty condition, both inby and outby breakers are prevented from closing. The pilot wire carries signals to synchronize the master oscillators and provides the power to operate relays contained in the voltage detectors. Finally, it can be used to reintroduce the high frequency tone onto the trolley at points remote from the substation. Thus, the wire serves a number of vital functions. However, it does require additional labor expenditures for installation and maintenance. So it is desirable to explore substitute techniques, such as multiplexing, to eliminate the pilot wire.

As the 3-kHz voltages and currents are present on the system even when dc power is interrupted it is possible to detect the location of a fault by walking along the wire with ac voltmeter and noting where a minimum occurs. It appears feasible that the fault location can be pinpointed automatically by sampling data from the current and voltage detectors. Ultimately, this information could be fed into a computerized mine monitoring system for readout on the surface.

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APPENDIX.--RECOMMENDATIONS FOR FIELD INSTALLATION

At present, there are no guidelines covering the installation of the DISCB in an underground mine. Since haulage systems vary in size and shape, they must be analyzed individually.

Once a cooperative agreement is reached with mine mangagement, an up-to-date mine electrical map should be obtained. It should show the routing and size of the trolley haulage conductors and the locations of all power sources and circuit breakers.

Additional design data and special system features can be determined on the initial mine visit during a nonproduction shift. Incandescent lamp distribution and pump locations should be noted as well as modifications to enhance trolley phone performance such as coiled leads at substations or capacitors across dead blocks. The number of active impedance multipliers needed can be determined by tabulating the sizes and horsepower ratings of the larger locomotives. The heavy current welders for bonding rails must use inductive resistors to prevent nuisance tripping.

During this initial visit, installation details of the DISCB system can be discussed. The controls will be located nearby the rectifiers so these areas should be inspected. The pilot wire can be conveniently supported using existing communication wire hooks if available.

Typically, electrical noise on mine trolley systems is less than 0.1 V at 3 kHz (11, p. 6).[1] However, since substantially higher values occasionally have been recorded measurements should be made.

Resistance and inductance can be approximated theoretically, given conductor size and separation. Underground tests can yield more exact values. In the technique (12, pp. 2-21) shown in figure A-1*A*, the oscillator frequency is adjusted for resonance (V_s is in phase with V_o) and the values of C, f, V_o, and V_s are recorded. Another approach (5, p. 9-5) is shown in figure A-1*B*. The current is recorded upon fault through the test resistor. The time constant of the system can be determined by measuring the time it takes the current to reach 0.637 of the peak value.

By connecting a portable 10-V, 3-kHz oscillator and monitoring the current, the no-load effects of pumps and lights can be measured. A signal voltage distribution similar to figure 17 can be obtained by taking voltage readings on board a small vehicle of about 100 hp as it traverses the system. Battery powered voltage recorders can be installed at key locations underground and left running during production time. This information is helpful for establishing voltage detector protection zones and settings.

Finally, a computer model of the system can reinforce the analysis and can be

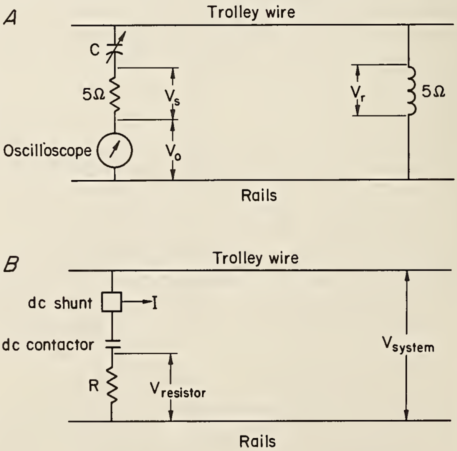

FIGURE A-1. - Testing high frequency characteristics.

[1]Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

updated as the system changes. In this manner simultaneous loads and faults can be simulated easily. Including the effects of distributed stationary loading the circuit consists of lumped π sections representing 500 ft of trolley wire and incorporating nodes for calculation purposes as shown in figure A-2.

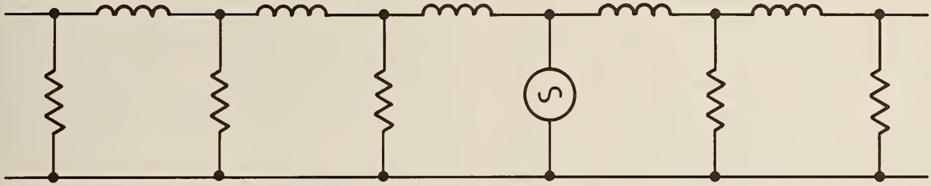

FIGURE A-2. - Computer simulation.

INTERMITTENT DUTY RATING OF TRAILING CABLES

By George J. Conroy[1] and Herman W. Hill[2]

ABSTRACT

Federal Bureau of Mines sponsored research conducted at Penn State University and West Virginia University has resulted in recommendations to the Mine Safety and Health Administration (MSHA) concerning the maximum current ratings for trailing cables used at various duty cycles. If approved, the ratings would permit smaller size cables than those presently required by 30 CFR 18, yet would provide equivalent safety when protected by circuit breakers which include overload trip capabilities. Computer and calculator programs for calculating allowable ampacity (current capacity) are presented.

INTRODUCTION

If conductor size for a continuous miner cable is chosen on the basis of continuous-duty ampacity, the result is a very large-diameter, and consequently, very heavy trailing cable. This is a hardship in the manual handling of the trailing cable, particularly as the miner backs out to permit cleanup and roof bolting. The usual solution has been to use as small a cable as the local inspector will permit, down to AWG 4/0 or smaller, without resorting to any particular references or guidelines other than a general idea as to what acceptable insulation temperature should be. This temperature depends on the duty cycle of the machine. Consequently, an enforcement and compliance problem exists in that changes in mining pattern or strata, or even changing the machine operator, can transform a safe cable choice to an unsafe one without there being any standard available by which the unsafe condition can be judged. This paper describes a method of determining an intermittent-duty ampacity for trailing cables. The ampacity value can be updated with changing mine conditions so that dangerous situations can be anticipated.

At the request of MSHA, a 2-year series of cable tests were performed by the Pennsylvania State University (PSU) to study the effects of varying duty cycles on cable temperatures and to find what modifications of the circuit protection devices would be necessary in order to maintain safe operation if intermittent-duty ratings higher than the continuous-duty ampacities were permitted. The data from these tests were analyzed by both PSU and West Virginia University (WVU), and specific conclusions have been reached. An effective summation of the findings concerning circuit protection is to be found in the doctoral dissertation of George Luxbacher of PSU entitled "Evaluation of the Effectiveness of Molded-Case Circuit Breakers for Trailing-Cable Protection," November 1980. An important conclusion is that by including thermal overload elements in the breakers it is possible, with proper adjustment, to adequately protect the cable despite large variations in the duty cycle. Please note that the inclusion of these elements is essential for safety, if ratings are based on intermittent duty in a situation where the duty cycle can vary.

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METHODS OF CALCULATION

WVU's analysis of the PSU data, in combination with previous Bureau research on conductors by Derek Paice of Westinghouse and others, provided recommendations for sizing conductors, in the form of equations, nomographs, and a calculator program. A good representation of the thermal data, within the limits of experimental error, is given by the equation:

$$C = 0.13 \sqrt{A} \qquad (1)$$

where A = the cross-sectional area of the copper conductor,[3] in circular mils,

and C = the thermal constant, in minutes.

A single time constant is considered sufficiently accurate with regard to both heating and cooling.

The relationship which yields a new cable rating for intérmittent duty is then

$$I_{\substack{int\\duty}} = I_{\substack{cont\\rating}} \sqrt{\frac{1 - \exp(-T_1/C)}{1 - \exp(-T_2/C)}}, \qquad (2)$$

where T_1 = the total time in minutes of a cycle of operation,

T_2 = the operating time in minutes or "on" time within a cycle, during which the current flows;

C = the time constant from equation 1,

$I_{\substack{cont\\rating}}$ = the continuous current rating,

and $I_{\substack{int\\duty}}$ = the intermittent duty rating.

Further explanation is required regarding the flow of current during a particular operating time. It is rare that a mining machine would be operated in a manner such that current drain would behave as a step function, as shown in figure 1. The more usual behavior is as seen in figure 2, where many peaks and valleys of current drain occur and there

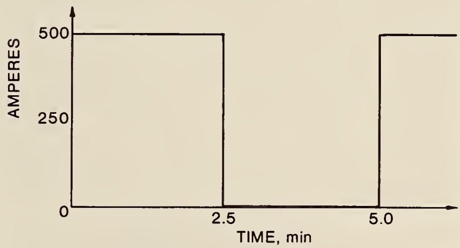

FIGURE 1. - Ideal 50 pct duty cycle.

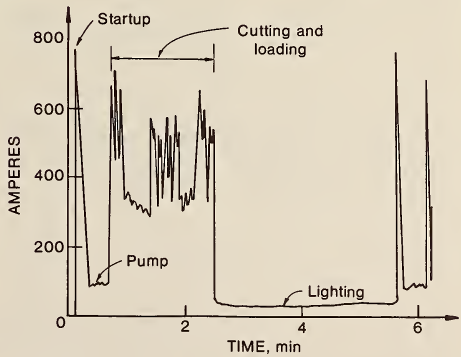

FIGURE 2. - Realistic current trace for continuous miner.

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[3]A convenient relationship, relating AWG size to conductor area, is the expression:

$$A = 105500 \exp(-0.232\ W)$$

where W is the wire size and A is the area in circular mils. This holds true for all AWG wire sizes with the proviso that the larger sizes are represented as

1/0:	0	3/0:	-2
2/0:	-1	4/0:	-3

are also multiple levels of even the average current, during each cycle. Therefore, while the preceding calculations yield an intermittent duty rating for any given on time, it may not be a simple matter to determine whether this rating is being exceeded, on the average, during the on time. The choice of an on time, itself, may not be totally simple, as there may be low current drains, such as from headlights or idling pump motors, throughout the cycle. These small currents contribute almost insignificantly to the heating of the trailing cable; yet their presence complicates the defining of the operating cycle. Some arbitrary ground rules become necessary, such as deciding that a single root-mean-square (rms) average current will represent the drain and that the machine will be considered to be on whenever the short-term average current exceeds 25 pct of the continuous-duty rating of the trailing cable. Thus, for a machine powered by an AWG 4/0 cable (continuous current rating of 180 A) and yielding the current drains shown in figure 2, T_2 would be 2.25 min out of a total cycle time of 5.0 min. This would result in a cable current maximum rating of

$$I_{\substack{int\\duty}} = 180\sqrt{\frac{1 - \exp(-5.0/60)}{1 - \exp(-2.25/60)}} = 265 \text{ A}$$

by equation 2.

It is possible to instrumentally determine the true rms value of the current. However, it is probably adequate for present purposes to take the envelope of the peak reading at each major step, as they appear on an instrument having inertia in its movement, and estimate an "average" value from this. Then

$$I_{rms} = \frac{\Sigma\,(I_N^2 T_N)}{\Sigma\,T_N} \qquad (3)$$

$$I_{rms} = \sqrt{\frac{800^2 \times 0.05 + 65^2 \times 0.35 + 575^2 \times 0.20 + 275^2 \times 0.85 + 475^2 \times 0.8 + 15^2 \times 2.75}{5.0}} = 263 \text{ A}$$

by equation 3.

Note that all of the current drains have been included in the average, even though the duration of the on time was set by ignoring the lowest values of drain.

Comparing this true value with the calculated rating, it appears that the cable is adequate for the observed load.

A simple assumption for the initial calculation of the rating might be to agree that intermittent duty will be arbitrarily defined for the rating purpose as some cycle such as 60 min comprised of 50 pct on time, 50 pct off time. For the preceding example, this would have yielded an intermittent duty rating of 252 A. It would still be necessary to use the rms averaging technique on the actual usage data in order to check operation against the calculated cable rating. Just what the most representative arbitrary cycle might be--50-50, 25-75, etc.--has never been decided.

INSTANTANEOUS TRIP SETTINGS

Thermal-magnetic trip circuit breakers with the thermal overload units sized at or below the cable's continuous duty ampacity may allow use of higher currents with providing adequate protection with regard to routine loading at all intermittent duties. However, nothing in this paper should be construed as suggesting that the size of fuses or the instantaneous trip setting of circuit breakers may be increased above the values permitted by present regulations for a particular size of cable. These values are determined by short-circuit considerations, not by long-term thermal effects.

NOMOGRAPHS

Figures 3 and 4 comprise a set of nomographs that may be used to determine the thermal time constant of the cable and then, directly, a cable rating factor, K, which is equivalent to the entire radical expression in equation 2, such that

$$I_{\substack{int \\ duty}} = K\, I_{IPCEA}, \qquad (4)$$

where I_{IPCEA} is the continuous ampacity rated by the Insulated Power Cable Engineers Association (IPCEA).

Equation 4 can be used to find cable rating factors directly. Nomograph 1 (fig. 3) is used with the on time, t_2, and the cable time constant (or the cable heating time constant) to determine a heating factor, H. The total cycle-time, t_1, is used with the cable time constant (or the cable cooling time constant) to determine a cooling factor C on the same nomograph. Using the values of H and C on nomograph 2 (fig. 4), one obtains the cable rating factor, K. One example is worked out on figures 3 and 4 for No. 6 round cable with t_2 = 4 min, t_1 = 20 min, and time = 30 min, thus K = 1.97.

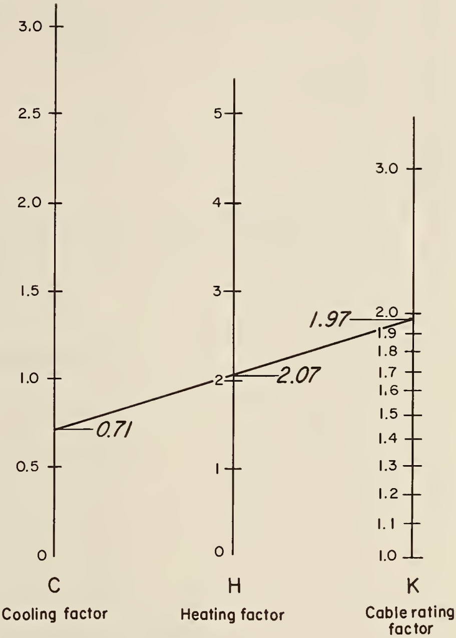

FIGURE 3. - Intermittent duty rating nomograph 1.

PROGRAMS

The appendix to this paper gives HP41C[4] and HP97 programs for calculating individual rating values. In addition, it gives a BASIC program listing for obtaining tabulated intermittent duty ampacities applicable to 30 CFR 18 appendix I rating tables.

DRAG CABLES

The rating factors obtained by applying the described techniques, with 30 CFR 18 continuous ratings as a base, are not at this time approved by MSHA but do represent Bureau of Mines best judgment on realistic values for cables that may or may not be on reels during part of the working cycle. If only drag cables are considered, the Title 30 continuous duty ampacities are probably excessively conservative, and even higher intermittent-duty ratings for drag cables would be possible, if based on revised 30 CFR 18 tables. This exception is important because the greatest need for higher ratings may occur as handling difficulties are experienced with large-diameter drag cables, and it may be possible to use smaller cables for the given currents. The solution to this problem must be in modification of the continuous duty tables of 30 CFR 18, not in altering the intermittent-duty calculations.

[4]Reference to specific programs does not imply endorsement by the Bureau of Mines.

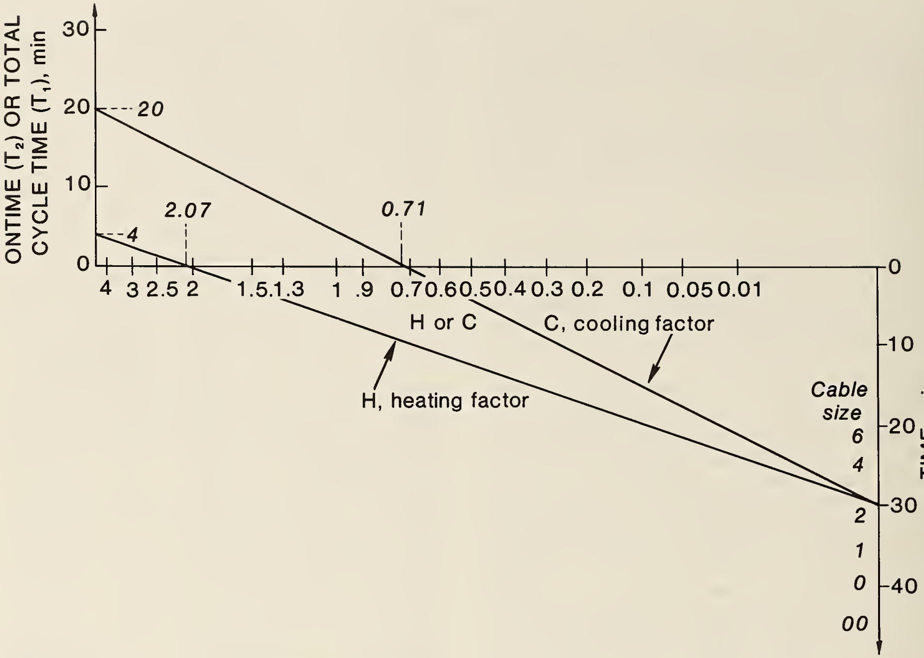

FIGURE 4. - Intermittent duty rating nomograph 2.

VOLTAGE DROP

As the stated calculations are based on thermal considerations (that is, maximum permitted temperature) and do not take into account the effect of the higher currents on voltage drop in the cable and other circuit elements, it is recommended that the trailing cable intermittent-duty current not exceed about 250 pct of the continuous rating, whatever the calculations may give.

CONCLUSIONS

This discussion has presented a practical method of determining an acceptable intermittent-duty loading of trailing cables, although further consideration by MSHA would be required before ratings which result from the calculations could be considered as applicable to the coal mining industry.

APPENDIX.--PROGRAMS

HP41C Program, Cable Ampacity Rating Table Buildup--Cycle Time in Minutes, Operating Time in Percent

```
01     LBL AMP
02     LBL 00
03     CYCLE T?
04[1]  AVIEW
05[1]  STOP
06     LBL A
07     STO 03
08     PCT ON?
09     AVIEW
10     STOP
11     LBL B
12     ENTER↑
13     .01
14     *
15     STO 01
16     WIRE?
17     AVIEW
18     STOP
19     LBL C
20     STO 02
21     249
22     ENTER↑
23     RCL 02
24     X≤Y?
25     GTO c'
26     ENTER↑
27     1000
28     X<>Y
29     X>Y?
30     GTO 05
31     *
32     GTO 05
33     LBL b
34     SQRT
35     .13
36     *
37     STO 04
38     RATED?
39     AVIEW
40     STOP
41     LBL D
42     STO 05
43     2.5
44     *
45     STO 06
46     RCL 05
47     EXECUTE
48     AVIEW
49     STOP
50     LBL E
51     RCL 03
52     RCL 01
53     *
54     STO 09
55     FIX 1
56     ON T=
57     ARCL 09
58     AVIEW
59     RCL 09
60     RCL 04
61     /
62     CHS
63     E^X
64     CHS
65     1
66     +
67     1/X
68     ENTER↑
69     RCL 03
70     RCL 04
71     /
72     CHS
73     E^X
74     CHS
75     1
76     +
77     *
78     SQRT
79     RCL 05
80     *
81     STO 11
82     ENTER↑
83     RCL 06
84     X≤Y?
85     GTO e
86     RCL 11
87     GTO a
88     LBL e
89     RCL 06
90     GTO a
91     LBL c'
92     .232
93     *
94     CHS
95     E^X
96     105500
97     *
98     LBL 05
99     FIX 0
100    STO 02
101    AREA=
102    ARCL 02
103    AVIEW
104    PSE
105    GTO b
106    LBL a
107    STO 07
108    FIX 0
109    NEW I=
110    ARCL 07
111    AVIEW
112    PSE
113    PSE
114    PSE
115    PSE
116    NEXT?
117    AVIEW
118    STOP
119    GTO 00
120    END
```

Input Values

A - Cycle time
B - Percent on
C - Wire size[2]
D - 30CFR18 rating
E - Execute

[1]Steps 04 and 05 and all similar instructions throughout the program may be replaced by the single instruction, "Prompt".

[2]8 through 0, -1, -2, -3 (representing 2/0, 3/0, 4/0); 250 through 750 (for 250,000 MCM, etc.).

HP97 Program, Cable Ampacity Rating Table Buildup--Cycle Time in Minutes, Operating Time in Percent

001	*LBLA	21 11	050	ENT↑	-21
002	PRTX	-14	051	RCL3	36 03
003	STO3	35 03	052	RCL4	36 04
004	R/S	51	053	÷	-24
005	*LBLB	21 12	054	CHS	-22
006	ENT↑	-21	055	e^x	33
007	.	-62	056	CHS	-22
008	0	00	057	1	01
009	1	01	058	+	-55
010	x	-35	059	x	-35
011	DSP2	-63 02	060	X	54
012	PRTX	-14	061	RCL5	36 05
013	DSP0	-63 00	062	x	-35
014	STO1	35 01	063	STO6	35 06
015	R/S	51	064	ENT↑	-21
016	*LBLC	21 13	065	RCL2	36 02
017	X=0?	16-43	066	X>Y?	16-34
018	GSB5	23 05	067	RCL6	36 06
019	PRTX	-14	068	PRTX	-14
020	X	54	069	SPC	16-11
021	.	-62	070	SPC	16-11
022	1	01	071	R/S	51
023	3	03	072	*LBL5	21 05
024	x	-35	073	R/S	51
025	STO4	35 04	074	.	-62
026	R/S	51	075	2	02
027	*LBLD	21 14	076	3	03
028	PRTX	-14	077	2	02
029	SPC	16-11	078	CHS	-22
030	STO5	35 05	079	x	-35
031	2	02	080	e^x	33
032	.	-62	081	1	01
033	5	05	082	0	00
034	x	-35	083	5	05
035	STO2	35 02	084	5	05
036	RCL5	36 05	085	0	00
037	R/S	51	086	0	00
038	*LBLE	21 15	087	x	-35
039	RCL3	36 03	088	RTN	24
040	RCL1	36 01	089	R/S	51
041	x	-35			
042	RCL4	36 04			
043	÷	-24			
044	CHS	-22			
045	e^x	33			
046	CHS	-22			
047	1	01			
048	+	-55			
049	1/X	52			

Input Values

A - Cycle time
B - Percent on
C - Cable area[1]
D - 30CFR18 rating
E - Execute

SAMPLE RUNS

5-min cycle time	5.	*** A
50 pct on (enter 50")	0.50	*** B
"0" then 2" for AWG 2	66335.	***C,R/S
90 A from 30CFR18	90	*** D
New I value		*** E 125.
"0" then "1"	83656.	***C,R/S
30CFR18 value	100.	*** D
New I value	239.	*** E
"0" then ")"	105500.	***C,R/S
30CFR18 value	120.	***D
New I value		***E 167.
Same cycle	5.	***
Vary percent on to "10"	0.10	*** B
AWG #0 (same)	105500.	*** C
30CFR18 (same)	120.	*** D
New I value		*** E 300.
Vary AWG # to "4"	83656.	*** C
30CFR18	100.	*** D
New I value		*** E 250.
250 pct of 30CFR18 rating		
.1 pct on	1.000000000-03	*** B
AWG #1	83656.	*** C
30CFR18	100.	*** D
New I value		*** E 250.

(NOTE: 250 pct is maximum allowed.)

For additional values, enter only the changed parameters, depress proper letter, then "E".

[1]If only AWG number is known, enter "0" (zero), depress "C," then enter AWG number, depress "R/S".

Computer BASIC Program

```
AMPCAP    19-FEB-81    08:06:03

  5 DIM I2(60,10)
  6 REM  CALCULATES AREA FROM WIRE SIZE OR USES AREA DIRECTLY, TO OBTAIN AVERAGE
  7 REM THERMAL TIME CONSTANT OF CONDUCTORS.
 10 PRINT "AMPACITY TABLE CALCULATION"
 11 PRINT "THERMAL RATING ONLY.  VOLTAGE DROP SHOULD ALSO BE CONSIDERED."
 20 PRINT " "
 30 PRINT " "
 40 PRINT "ENTER WIRE SIZE, RATING FROM 30CFR18, AND MAX TIME IN MINUTES."
 41 PRINT "FOR SIZE 00 USE   -1, FOR SIZE 000 USE   -2, FOR SIZE 0000 USE   -3"
 50 INPUT W,R,L
 55 R1-2.5*R
 60 IF W<250 GO TO 190
 70 A1=1000*W
 80 C=.13*SQR(A1)
 90 FOR T=1 TO L
100 FOR P=1 TO 10
110 P2=.1*P
120 N1=1-(2.71828^(-T/C))
130 D1=1-(2.71828^(-P2*T/C))
140 K=SQR(N1/D1)
150 I2(T,P)=INT(K*R)
155 IF I2(T,P)>R1 THEN 12(T,P)=INT(R1)
160 NEXT P
170 NEXT T
180 GO TO 240
190 REM CALCULATES AREA
200 A1=105500*(2.71828^( .232*W))
210 GO TO 80
220 REM PRINTING FORMAT MAY BE IMPROVED BY BASIC 'PRINT USING' STATEMENT
230 REM IF YOUR COMPUTER SUPPORTS IT.
240 PRINT "CYCLE";"  ";"     PERCENT OPERATING TIME"
245 IF R<90 GO TO 250
246 PRINT "(MIN)";"  10";"  20";"  30";"  40";"  50";"  60";"   70";"  80";"
                  90";"  100"
247 GO TO 255
250 PRINT "(MIN)";"  10";"  20";"  30";"  40";"  50";"  60";"  70";"  80";"
                  90";"  100"
255 PRINT " "
260 FOR T-1 TO L
270 PRINT T;"  ";I2(T,1);I2(T,2);I2(T,3);I2(T,4);I2(T,5);I2(T,6);I2(T,7);I2(T,8);
            I2(T,9);I2(T,10)
280 NEXT T
290 PRINT " "
300 PRINT " "
310 PRINT "next?( Y or N )"
320 INPUT Q$
330 IF Q$="Y" GO TO 20
340 PRINT " SIGN OFF"
```

SEMICONDUCTING RUBBER AS A LOW-VOLTAGE SHIELD FOR PERSONNEL PROTECTION

By J. N. Tomlinson[1] and L. A. Morley[2]

ABSTRACT

Semiconducting rubber insulation is used in high-voltage distribution cable to provide a gradual transition of potential, in order to avoid the occurrence of harmful corona. Metallic shielding is used in both distribution and trailing high-voltage cables to assure that any fault to a phase conductor will be a relatively low current phase-to-ground fault through the shield rather than a highly energetic phase-to-phase fault. A strong desire of users of mining machines employing cable reels has been to find a way to make a cable with semiconducting shielding take the place of metallically shielded cable, which is so much heavier, larger, and less flexible. Research shows no semiconducting formulation capable of conducting the fault current of several amperes that is usually considered necessary for operations of current-operated ground fault protection devices. A voltage-sensing protection method has been found, however, employing an additional conductor in the cable. This method is so sensitive that, as discussed in this paper, the circuit can be interrupted before the semiconducting rubber in the vicinity of a phase-to-ground fault is carbonized. Therefore, it should be possible to provide cable reel installations with short-circuit protection almost equivalent to that provided by metallic shielding.

INTRODUCTION

Shielding of low-voltage trailing cables, such as those used on shuttle cars, offers improved personnel safety but is not easily implemented simply because the usual shield designs cannot withstand the excessive flexing. Under Federal Bureau of Mines Contracts G0188306[3] and J0199106,[4] evaluations have been made of shield designs using copper-copper, copper-cotton, and copper-nylon braid combinations as well as copper stranding with semiconductive rubber materials. None of those proved to be satisfactory mainly because of copper fatigue. However, semiconductive rubbers are able to withstand the flexing and might provide a suitable shield if materials having sufficient electrical conductivity can be used. This paper is based on a portion of the research conducted under Bureau of Mines contract J0199106 in which the authors have addressed the resistivity requirements for conductive-rubber shielding materials in conjunction with fault-sensing equipment sensitivities and power-interruption times.

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[2]Professor of Mining Engineering, Pennsylvania State University, University Park, Pa.

[3]King, R. H., B. L. Fisher, and L. A. Morley. Mine Trailing Cables and Cable Splices: Shielded Cables (Contract 60188036, Pennsylvania State Univ.). BuMines OFR 81-80, Feb. 29, 1980, 69 pp.; NTIS PB 80-208135.

[4]Pennsylvania State University. Mine Trailing Cables and Cable Splices. September 1979, 109 pp.; available for consultation at the Bureau of Mines Pittsburgh Research Center, Pittsburgh, Pa.

THE PHYSICAL CASE

A typical example of how shielding might improve personnel safety is illustrated in figure 1. In this highly simplified case, a nail has pierced the cable and made contact with an energized conductor. At the same instant, a person is in contact with the nail and also with the grounded machine frame. The result is current flow through the person as well as through the shield to the grounding conductor. (A similar situation could result if, for instance, a mechanic were to cut into an energized cable in preparation for making a splice repair.) For this simplified and strictly resistive case, the portion of current through the worker is

$$I_m = \frac{R_s V}{(R_s + R_m)\, R_g + R_s R_m}, \qquad (1)$$

where V is the phase-to-neutral voltage, R_s is the resistance through the shield from the nail to the grounding conductor, R_g is the ohmic value of the grounding resistor, and R_m is the worker's effective resistance which can vary appreciably depending on contact resistance, body weight, and so forth.

SHIELD RESISTANCE

The situation for the nail piercing the semiconducting sheath is shown in figure 2, and also in figures 3 and 4 when the sheath is unwrapped from the insulated conductor to form a uniform layer of semiconducting material as illustrated. The condition of the current flow in figure 4 between the nail and one side of the grounding conductor is equivalent to the heat flow from a heated cylinder[5] to an exposed wall as illustrated in

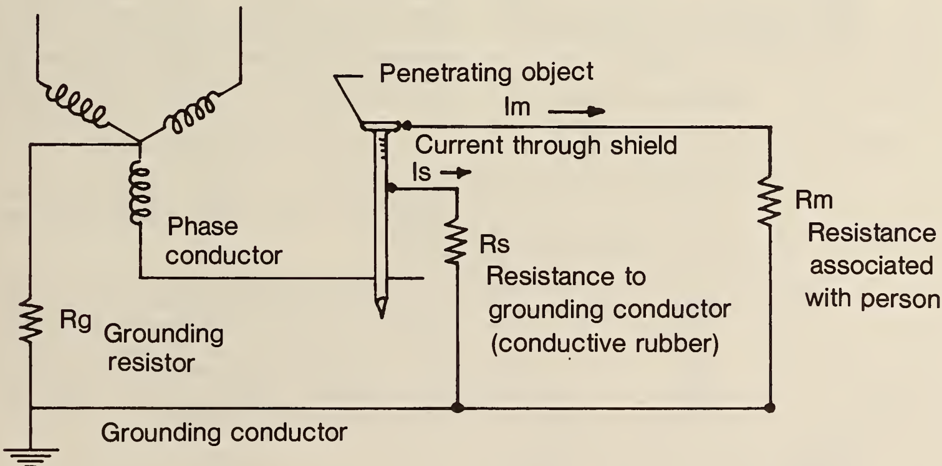

FIGURE 1. - Parallel current paths through person and shield for a simplified circuit.

[5] Incropera, F. P., and D. P. Dewitt. Fundamentals of Heat Transfer. John Wiley & Sons, New York, 1981, p. 140.

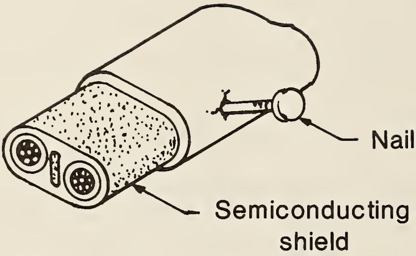

FIGURE 2. - Nail piercing cable and shorting semiconducting shield to power conductor.

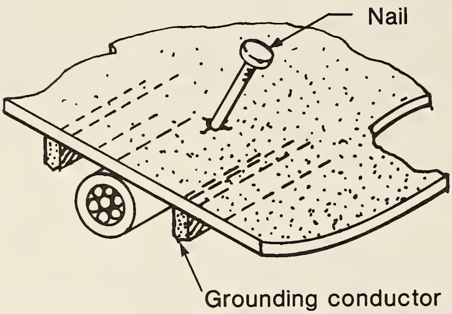

FIGURE 3. - Shielding material unwrapped from insulated conductor.

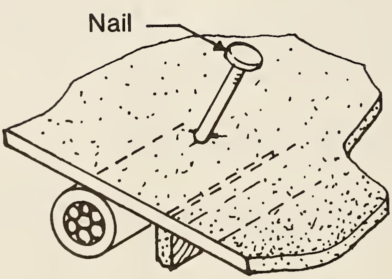

FIGURE 4. - Shielding further simplified for analysis of current between power and grounding conductors.

figure 5. The analogy for electrical resistance, R, is thus

$$R = \frac{\rho_v}{2\pi L} \ln\left(\frac{4h}{D}\right), \tag{2}$$

where ρ_v is the volume resistivity, L is the thickness of the semiconducting layer, h is the distance from the center of the cylindrical probe (or nail) to the grounding conductor, and D is the probe diameter.

Empirical and theoretical values of the resistance, R, have been obtained and are plotted in figure 6 as a function of h where h is given in terms of probe diameters. The difference between the two curves is attributed to the finite limits used in the experimental evaluations. The curves in the figure have been normalized for $\rho_v = 1$ Ω-cm and L = 1 cm.

Since the piercing object will in effect be somewhere between two grounding conductors (fig. 3), the resistance is more like that shown in figure 7 and a value on the order of 6 Ω might be approximated if ρ_v were equal to 1 Ω-cm and the shield thickness, L, were on the order of 1 mm.

MAXIMUM CURRENTS VERSUS TIME

Values for I_m from equation 1 are plotted in figure 8 for three different voltages.

The concern in electrical shock is that the victim's heart will lose its normal rhythm and go into ventricular fibrillation. The current level and time exposure at which this statistically occurs for a typical human has been given by Dalziel[6] as

$$I = \frac{116}{\sqrt{t}}$$

where I is in minimum current in milliamperes and t is duration of shock in

[6]Dalziel, D. F. Electric Shock Hazard. IEEE Spectrum, February 1973, pp. 44-50.

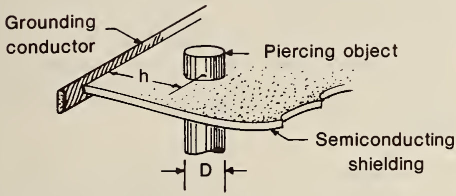

FIGURE 5. - Electrical path from piercing object to grounding conductor via the semiconducting shield material.

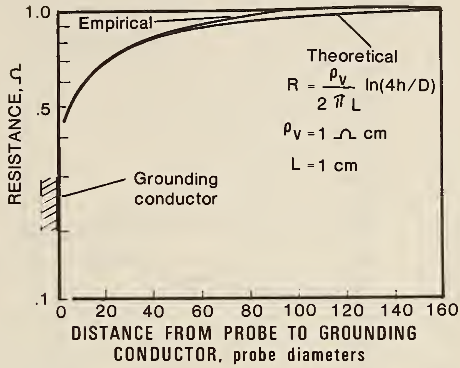

FIGURE 6. - Theoretical versus experimental resistances between probe and grounding conductor in a conductive medium.

seconds. The values of t are scaled against I_m in figure 8 and provide an indication of the time requirements for power interruption in order that the shield is effective for the operating conditions considered.

VOLUME-RESISTIVITY TEST DATA

Volume-resistivity measurements were made on semiconducting shield materials used in three prototype cable designs and another cable used in a similar mining application in the United Kingdom. Also, measurements were made on the conductive material used in a high-voltage cable application, and some semiconducting tape was also evaluated. The sample configurations are illustrated in figures 9 and 10. Table 1 presents the laboratory values.

TABLE 1. - Volume resistivity values for various semiconducting material samples

Sample	Typical volume resistivities (Ω-cm)	
	Along extrusion direction	Across extrusion direction
Prototype 1..........	750	415
Prototype 2..........	600	500
Prototype 3..........	280	180
Drill cord...........	300	130
High-voltage cable...	12,500	5,600
Semiconducting tape..	240	610

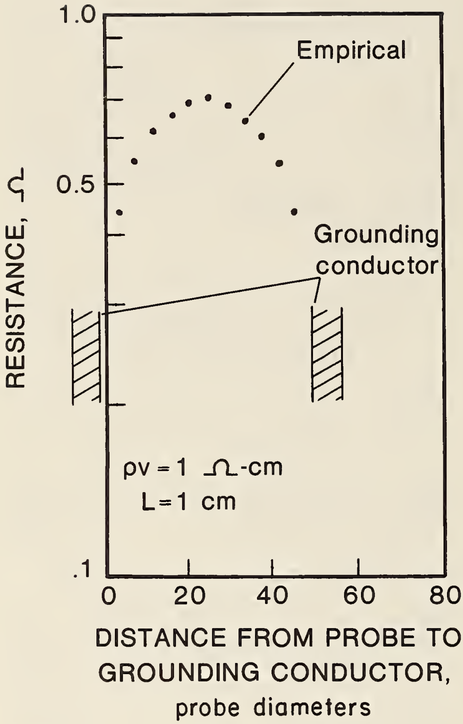

FIGURE 7. - Resistances with probe placed between two conductors.

Applying some of the values from table 1 to the curves in figure 8, it is obvious that power-interruption times would have to be extremely short for the high system voltages where the maximum ground-fault current is limited to 25 A. If R_g was set to limit maximum ground-fault current to 750 mA, the required power-interruption times might be more practical, especially in the low-voltage cases. Materials with volume resistivities orders of magnitude lower than the best values listed in table 1 would, of course, provide a much better safety margin for the shield design.

The advantage of higher-ohmage grounding resistors is quite obvious from the curves presented in figure 8. The higher values also limit ground-fault current in the shield which might otherwise volatize the shield material and provide no shunt protection for the victim. This latter advantage is also true should copper braid be used rather than semiconducting materials.

The curves in figure 8 are generated using a resistance value of 500 Ω for the victim. Volume resistivities of 100 Ω-cm would produce about equal current flow through the shield and through the victim, all other resistances being equal. It is also important to note that while the shield is actually being cut into, the contact resistance is much higher, and this would reduce the initial shunting effect even more.

FAULT-TEST EXPERIMENTS

Numerous tests were conducted in which a nail was driven into prototype cables having semiconducting rubber shields of the SHD configuration. Both ac, 295-V line-to-neutral and dc, 245-V line-to-neutral systems were used. Grounding resistors limited the maximum current to 15 A. Fault sensing used a zero-sequence method for the ac system and saturable-reactor sensing for the dc system.

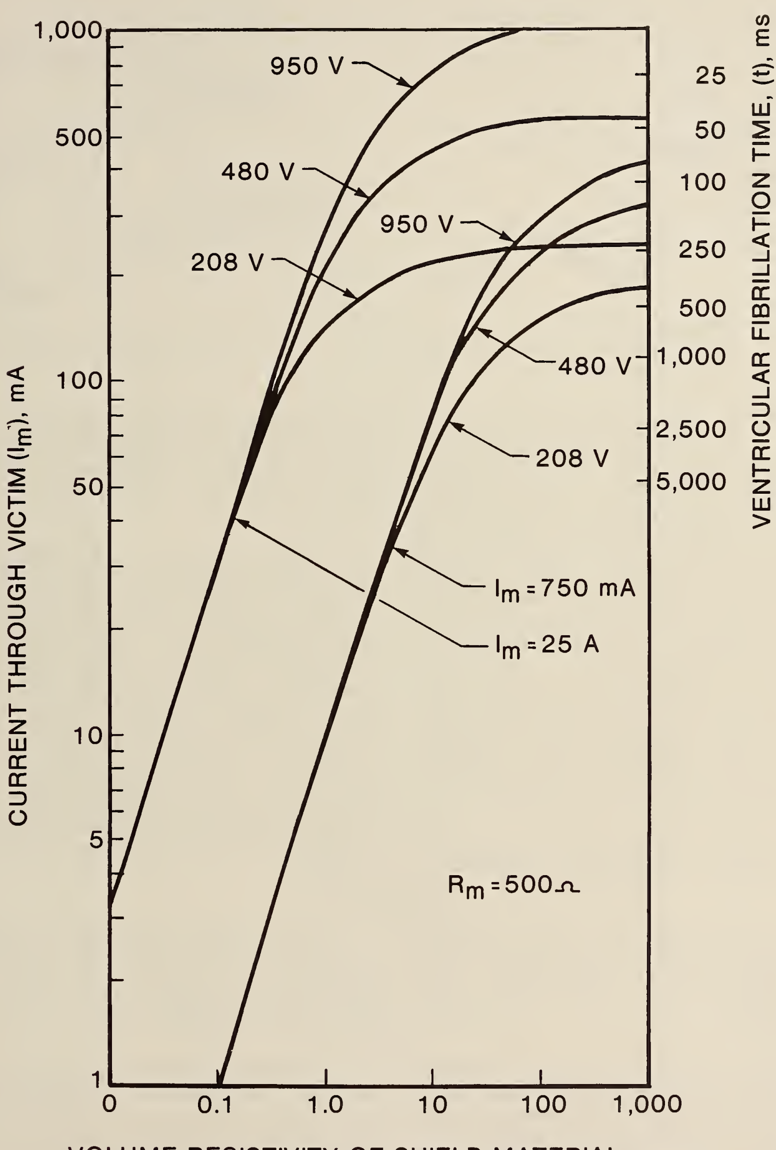

FIGURE 8. - Currents and ventricular fibrillation times versus shield resistivities for various operating voltages and ground resistor.

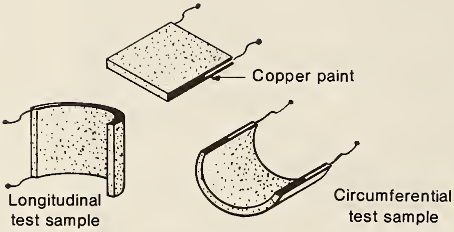

FIGURE 9. - Sample configurations taken from semiconducting shielded cable used to determine volume resistivity, ρv.

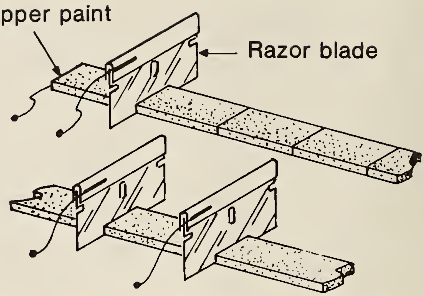

FIGURE 10. - Sample configurations used in measuring ρv for semiconducting tape samples.

The results were in two general categories. For the first group, the time required to interrupt the power ranged from slightly less than 1 sec to as high as 2.5 sec, depending on sensing method, puncture location, and so forth. The resistance between the nail and the grounding conductor was time dependent and decreased as the I^2R heated the material. In most cases, the semiconducting material actually carbonized before the power was interrupted. In the second group, the immediate current flow volatized the semiconducting shield material in contact with the nail, and the power was not interrupted at all. Approximately 1 out of every 10 experiments produced this result.

The second group in which the shield was volatized obviously provided no personnel protection. However, a higher grounding resistance would limit the current to a less destructive value and so provide an improvement for these cases.

A higher grounding resistance for the first group would tend to lengthen the already-too-long time between initial contact and power interruption since the I^2R dissipated in the semiconducting shield would decrease; thus, the rate of resistance change between the nail and the grounding conductor would be lessened. The solution here is high-resistance grounding along with low-resistivity shielding materials. Safety limitations would simply be the current-sensing abilities of the ground-fault system and associated power-interruption delays.

CONCLUSIONS

The results of this work suggest the semiconducting shielding might have application in low-voltage trailing cables under the following circumstances.

(1) Volume resistivities on the order of 1 Ω-cm must be applied to the cables of interest. It is important to note that volume resistivities measured on laboratory slab samples are usually much lower than that measured for samplings taken from an actual extruded shield.

(2) High-ohmage grounding resistors are required to allow more time to sense and interrupt the power and to limit current levels which might otherwise volatize the shield material.

(3) High-sensitivity ground-fault detectors are needed. Combining semiconductive shielding of trailing cables, very low ground-current limits, and high-sensitivity ground-fault relaying should substantially reduce electrocution hazards on portable or mobile mining equipment.

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