Information Circular 8802

Mine Power Systems Research

(In Four Parts)

4. Transients and Enclosures

Compiled by Staff—Mining Research

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES
Lindsay D. Norman, Acting Director

This publication has been cataloged as follows:

United States. Bureau of Mines

Mine power systems research (In four parts) : 4. Transients and enclosures / by staff–Mining Research. [Washington] : U.S. Dept. of the Interior, Bureau of Mines, 1979.

69 p. : ill., diagrs. ; 27 cm. (Information circular - Bureau of Mines ; 8802)

Includes bibliographical references.

1. Transients (Electricity). 2. Electricity in mining. 3. Mining machinery - Electric equipment. 4. Electric apparatus and appliances - Protection. 5. Electric switchgear, Explosionproof. I. Title. II. Title: Transients and enclosures. III. Series: United States. Bureau of Mines. Information circular - Bureau of Mines ; 8802.

TN23.U71 no. 8802 622.06173

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CONTENTS

MINE POWER SYSTEMS RESEARCH

(In Four Parts)

4. Transients and Enclosures

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ABSTRACT

This Bureau of Mines report concerns two subjects important in the application of electric power in mining systems. Electrical transients and their suppression are discussed, and several considerations are explored with regard to the use of explosionproof or other electrical enclosures.

INTRODUCTION

The switching of high currents in mine power systems leads to the occurrence of damaging electrical transients, as evidenced by the destruction of a large number of solid state devices in recent years. The problem of defining the limits of these transients and that of reducing their effects have been the subject of considerable research. The first of four papers presented in this report discusses the factors contributing to the formation of transients and some general rules for reducing them, and describes a low-cost apparatus for measuring amplitude, rise time, and total pulse duration.

The second paper provides results of an evaluation of several types of transient suppressor and gives some criteria for testing circuits and components. The paper also describes test results of a current-limiting device and suggests an analytical method of determining suppression capacitance for a particularly rapid switching device. The device is one that eliminates arcs across circuit-breaker contacts.

Electric arcs occurring within enclosures can build up high pressures if uncontrolled. The formation of such arcs is discussed in the third paper, in which the effects of the presence of water and organic insulators are described.

The fourth paper describes a method to significantly reduce the pressure in an enclosure during an internal explosion, and also describes a cable entry gland that eliminates problems occurring with asbestos stuffing boxes.

The papers presented in this report are intended for possible immediate application rather than as a description of Bureau of Mines research programs. Further information is available in the annual and final reports of the various projects or through the technical project officer. Throughout this report, reference to specific companies or trade names is made for information only and does not imply endorsement by the Bureau of Mines.

A PRACTICAL APPROACH TO MINE POWER TRANSIENTS

by

L. A. Morley,[1] J. L. Kohler,[2] and J. G. Bredeson[3]

ABSTRACT

Presented is a summary of an investigation of power-system transients in underground coal mines. Descriptions of inexpensive transient-detection devices are included, as well as measurement techniques. Recommendations are provided for reducing hazardous transients on distribution systems.

INTRODUCTION

As defined by Greenwood, an electrical transient "is the outward manifestation of a sudden change in circuit conditions, as when a switch opens or closes, or a fault occurs on a system." The circuit parameters of inductance and capacitance are, to some extent, found in any power system. When the system is changed, the quantities of current, voltage, magnetic flux, and so on do not instantly assume new values, rather, they go through a transition to reach the new steady-state condition (11).[4] It is this transition period that gives rise to the transient voltages and currents, some of which are extremely destructive.

While transients are a fact of life on every power system, careful design within the technical and economic constraints of a system can result in a reduction of transient-related component failures. However, the underground coal mine power system is particularly vulnerable to transient-induced failures because its operation and arrangement are extremely dynamic. As the mining activity advances, the electrical system is expanded, often on a weekly basis. Although this expansion is normally designed into the system, circumstances underground can call for modifications. In some cases, these modifications are not completely known by the engineering personnel, and may not be pursuant to sound engineering principles.

A lack of knowledge about transients has resulted in power-system requirements that are considered vague by many mine power engineers. Furthermore, in the process of maintaining the system, faulty components can be replaced with devices of different specifications or even total incompatibility. These two factors increase the vulnerability of the mine power systems.

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

Under U.S. Bureau of Mines Grant G0155003, the Mine Electrical Research Group at the Pennsylvania State University has been investigating transient voltages and their causes and effects in underground coal mines. Because in-mine measurement of transients presents peculiar instrumentation problems, a large amount of effort has been expended to develop suitable detection devices. Using these measurement systems, enough data have been collected on distribution systems so that conclusions about the effect of system arrangement on transient severity can be drawn. A summary of the research is presented in this paper. Application of the ideas and techniques presented will result in increased electrical safety.

TRANSIENT SOURCES

There are several discrete sources of transient overvoltages. The Institute of Electrical and Electronic Engineers (IEEE) standards catalog the following seven types: Lightning, switching surges, static, contact with an high-voltage system, line-to-neutral faults, resonant conditions, and restriking ground faults (5). Switching operations account for the majority of all transient phenomena, and data collected through the present research indicate that the most destructive mine-power-system transients occur from this source. (This statement has been substantiated as true for industrial applications other than mining through conversations with prominent power engineers specializing in transients.) Although switching can be separated into several categories, there are only two relevant to this discussion--transformer switching and circuit-breaker operations.

Switching Transients

Transformer switching is simply divided into two primary categories--energizing and deenergizing the transformer. Energizing will cause a transient of up to two times the nominal secondary voltage to appear on the secondary side. This type of transient is harmless within the framework of present component design and construction practice, and is, in fact, characteristic of the proper operation of the transformer. Hence, it is classified as a "normal" transient. There are various other sources of normal transients which are usually of no consequence.

"Abnormal" transients (those that exceed two times the nominal secondary voltage) are not the result of correct component operation or system design. Hence, they are of primary interest because severe damage can follow their occurrence. Deenergizing a transformer, as well as other examples to follow, can cause an abnormal-transient overvoltage. If the transformer secondary is connected to a high-impedance load, transients in excess of 10 times line voltage may result (2).

The second type of switching transient involves the application of switchgear, especially vacuum circuit breakers (VCB's). Only a brief explanation of these events follows; a theoretical analysis of switching and the resulting transients is given by Rudenberg (11).

Switchgear has evolved from the hand-operated knife switch to the VCB's of today, which are capable of interrupting large fault currents in less than one cycle. (The actual interruption may take four or more cycles under fault conditions.) Many of the more recent advances in circuit-breaker technology have resulted from the use of vacuum as the dielectric between the contacts of the breaker.

In addition to their ability to interrupt large currents at the first zero-current crossing, VCB's are relatively maintenance free and reliable. This, coupled with small size, has made them very attractive to the mining industry; their employment is now universal on high-voltage systems.

Chopping

The high efficiency of VCB's, which has, in part, led to their wide application, is ironically the characteristic that can cause severe transients. Transients can occur when small currents such as transformer exiting currents are interrupted. In this case, the small current is forced to zero before the natural current zero, thereby trapping magnetic energy in the power system that is spontaneously released as a large voltage distribution (3). "Current chopping" is the name of this effect.

The level of current drop (di/dt) at the instant of chopping is greatly influenced by the contact material, primarily the cathode (8). At this writing, most VCB contacts are of a copper-bismuth material. Bismuth in minor amounts is employed to make the copper brittle and thereby reduce its weld strength. Therefore, any welding of the contacts during operation can be easily broken by the breaker mechanism. Copper, however, does not generate enough vapor in the vacuum bottle on small currents to sustain arcing until the natural current zero. Consequently, small currents are usually chopped.

It is beyond the scope of this paper to derive the equations governing chopping transients; rather eloquent developments can be found in the literature (3). Without describing the origin, it is instructive to state the simplified equation that yields the transient voltage due to a current chop:

$$V_p = I(L/C)^{1/2} = IZ_0 , \tag{1}$$

where V_p = peak transient voltage,

I = prechop current,

L = lumped inductance,

C = lumped capacitance,

and Z_0 = system surge impedance.

This relationship does not account for resistance but, since resistance is usually very small for power systems, it can be ignored without grave consequence.

From equation 1, it is apparent that the peak transient voltage will be determined by the current flow at the time of chopping and the characteristic impedance of the circuit in question. A typical mining application in which transients could present problems is a switchhouse connected to an energized, but unloaded, load center. In such a situation, the current would be about 0.03 to 0.05 per unit (pu) (a typical transformer magnetizing current). The transformer surge impedance would be large, so chopping transients of up to 10 times nominal line voltage may be expected. However, the system exhibits losses, and modern, dry-type transformers limit energy storage to about 40 pct. As a result, actual transients are usually limited to approximately 60 pct of that given in equation 1. Even so, transients of five to seven times line voltage can frequently occur.

If the cable length between the switchhouse and load center is increased, the cable capacitance will be proportionally increased. This will reduce the surge impedance and, therefore, the severity of the chopping transient. Voltage value too large for the system capacitance can result in other transient phenomena such as prestrike.

Prestrike

Although mine-power-system capacitance can reduce the effects of chopping, large capacitance can cause severe transients upon energization. Pflantz (10) has shown that during initial energization of system capacitance, prestriking (an arc ignition) will occur across the VCB's contacts prior to their closure. In such instances, overvoltages may reach substantial levels if the initial inrush current (that going into the circuit being energized) is momentarily stopped, then followed by a prestrike or contact closure. The magnitude is dependent on the ratio of capacitance, inductance, and resistance existing on both sides of the interrupter. However, transients of three to seven times peak system voltage are possible, depending on the voltage existing on the capacitance prior to energizing. Furthermore, these voltage transients, transmitted through conductors or cables (in the form of traveling waves), may be amplified as power system discontinuities by reflection and refraction.

The high-voltage, shielded cables abundant in underground coal mines can create such a capacitance problem. For example, the complex of feeder cables throughout the mine can reach thousands of feet and present a significantly large capacitance on the outby side of the switchhouse. The inby cable length, however, may only be a few tens or hundreds of feet. Therefore, a high ratio of outby-to-inby capacitance across the circuit breaker can exist, setting the stage for a probable prestrike-type transient. This capacitance ratio can be further increased by additional system capacitance beyond that of the cables (such as surge capacitors).

Transients in Direct-Current Systems

The theory developed for ac power systems is valid for the dc case if it is remembered that the forced frequency is zero, and, therefore, the capacitive reactance is infinite (except after a transient occurrence). The mining industry does not presently use VCB's to protect dc systems, so the chopping transients described in the previous section are no problem. However, the dc system is subject to abnormal transients. Large amounts of energy can be stored in the system inductance, and any sudden current decrease will result in an overvoltage. The magnitude of this overvoltage is proportional to the product of circuit inductance and the time rate of current change (L di/dt).

TRANSIENT-INDUCED FAILURES OF ELECTRICAL INSULATION

Deteriorating electrical insulation affects the entire mine power system and may jeopardize its safe operation. Whether the dielectric is in a transformer winding, motor winding, portable cable, or rectifier, it is a critical factor in the safe, economical, and reliable operation of any mine power system. Disturbances which threaten to compromise the integrity of the power system must be eliminated at the source; therefore, the causes of electrical transients and their elimination are addressed in the present research. It may be helpful to examine the effect of abnormal voltages on dielectrics.

Each type of dielectric insulation is designed for a safe maximum applied voltage and a transient overvoltage. The transient overvoltage rating is given in terms of BIL (basic insulation impulse level). The most common BIL measurement is the "1.2 x 50" wave test, in which the voltage impressed across the dielectric reaches its peak in 1.2 μsec and decays in 50 μsec (4). Thus a dielectric with a 95 kv BIL rating can safely withstand a "1.2 x 50" (7) pulse of 95 kv. This wave test is considered more severe than the transients found in mine power systems.

The event of dielectric deterioration is largely determined the rise time of the transient, as well as the peak magnitude. Of course, the greater the overvoltage pulse width (duration), the greater the probability of failure. These voltage anomalies break molecular bonds in the dielectric, which reduces its effectiveness. If the overvoltage contains sufficient energy, the dielectric can fail immediately, but this is usually not the case. Rather, the insulation is progressively weakened until it finally fails.

If the weakened insulation is in a portable cable or splice, a considerable personnel safety hazard exists because the insulation "appears" to be functional, when in reality a lethal potential may exist on the cable surface. Although the deteriorating dielectric may not present a direct safety hazard, complete failure may do so from an explosion or arcing. In any case, a serious hazard exists for the equipment in terms of repair, replacement costs, and downtime.

The physical construction of equipment may increase its susceptibility to transient failure. For instance, motor and transformer windings often fail at the end of a coil due to the increased electrical gradient. When the dielectric has deteriorated to a critical point, a line-to-neutral or line-to-line fault may occur. Corona may also occur, thereby hastening the failure (6-7).

MEASURING TRANSIENTS IN THE MINE

Transient Recorder

The easiest way to assess the occurrence of transient voltages is to measure them at various points of the mine power system. Under this research grant, an instrumentation package for the measurement of transients was assembled. The heart of this system as shown in figure 1, is a Biomation transient recorder. The complete system is the subject of a report by Morley (9).

The input signal to the transient recorder is the output from the transducer, which is a resistive voltage divider. When a transient defined by setting appropriate levels and controls on the recorder appears, it is "frozen" in a digital memory. It may then be viewed on an oscilloscope and strip chart recorder. If desired, the operator can then store the transient waveform on a digital tape. Transients recorded on digital tape may be directly analyzed by a computer. After the transient has been displayed or recorded, the operator can rearm the transient recorder for the next event. When a new transient is "captured," the procedure can be repeated according to the operator's wishes. The system can also be operated automatically so that every captured transient will be dumped onto digital tape and stored for future analysis.

This system was used in approximately 25 different mines to collect transient data. Although an excellent piece of equipment, it was expensive and was adversely affected by heat, dust, moisture, and vibration. Consequently, this system was utilized only at certain select locations in the mines. More ruggedly constructed transient recorders were evaluated but proved to be inadequate with regard to measurement response.

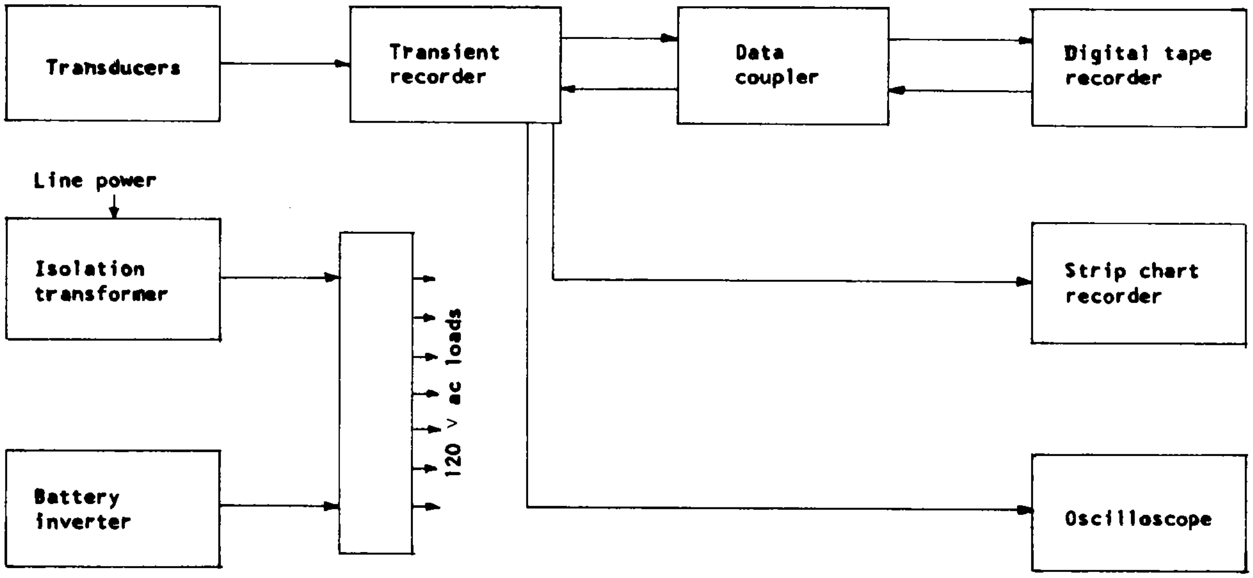


FIGURE 1. - Block diagram of transient recorder system.

Concurrently, a problem with lightning-induced transients on ground systems in midwestern strip mines necessitated the development of a rugged and portable detector to record the amplitude of a lightning-induced transient. The resulting "homemade" detector design was seen to be potentially useful for capturing the amplitude of any line transient, and, as the units could be fabricated at relatively low cost, several could be installed to provide simultaneous readings at various points in a distribution system.

Some basic design criteria were established for the transient detector.

1. It must not be affected by the hostile mining environment.

2. It must be portable and contain its own power supply.

3. It must be inexpensive (hundreds of dollars as compared with many thousands for commercial units) and be constructed from easily available and off-the-shelf components.

The two detectors that have resulted from this work are described below.

Transient Peak Detector

This circuit, assembled only to measure the amplitude of a lightning transient, is more correctly called a peak-detector circuit, as shown in figure 2. It is composed of a 10,000:1 resistive voltage divider, a precision detector, and an integrator. It is designed around a type 747 dual operational amplifier. The voltage divider is mounted on standoff insulators fastened to the top of a plastic box (3 inches by 6 inches by 1 inch), which contains the circuitry and batteries. The output from the detector is fed to a strip chart recorder. The chart is easily calibrated, allowing the amplitude of the transient to be directly read.

The voltage divider reduces the transient spike to a level compatible with the operational amplifier circuits. Amplifier A1 acts as a sample-and-hold circuit; that is, it samples an incoming signal and holds that level until it receives a higher signal, is reset, or finds a discharge path. Because of the lightning-discharge application, the circuit is designed to respond to only positive spikes. Diode D1 prevents amplifier A1 from being saturated if the input does become negative and provides feedback after a positive signal is detected. The feedback circuit for the detector is comprised of R5, R6, C1, and A2. The A2 circuit is also an integrator circuit with C1 holding the charge. In the lightning application, C1 has time to discharge through A2 before

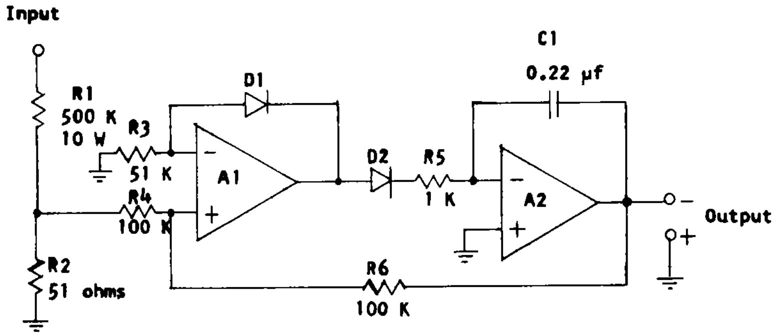


FIGURE 2. - Schematic of the transient peak detector. (K = kilohms.)

another spike occurs. Diode D2 assures that C1 will charge in one direction only. A2 is connected as an inverter, which results in a negative output. It is, therefore, necessary to connect the positive terminal of the strip chart recorder to the ground side of the detector circuit.

Application of Transient Peak Detector

This peak-detector circuit was successfully used to measure lightning transients on the ground system at a strip mine and to measure dc transients on trolley lines of underground coal mines. In the former application, the detector was connected to the power system for approximately 1 month. Mine personnel wound the recorder's drive mechanism every other day; the unit required no other attention and performed correctly giving a record of all transients. By reducing the voltage divider ratio to 1,000:1, the detector was also successfully used on a 300-volt dc trolley system.

The small size and light weight of the detector are convenient, although partially offset by the bulkiness of the strip-chart recorder. For general application, it is desirable to know more about the transient than its amplitude. Consequently, except for "ball-park" approximations, the detector is of greatest utility as an auxiliary unit in combination with the most expensive transient recorder, to provide widened coverage of the distribution system at low cost.

Transient Detector

Utilizing the experience gained with the first detector, the development of a second-generation detector was undertaken. In addition to the general requirements listed in the previous section, specific requirements were--

1. The detector should have its own built-in printer.

2. The detector should measure rise time, pulse width, and amplitude.

The measured parameters shown in figure 3 have the following constraints: The rise time must be between zero and 99 µsec, the pulse width must be between zero and 99 µsec, and the signal amplitude (from the voltage divider) must be less than 10 volts. These constraints were set within the limits of the type of transients known to occur on mine power systems, and were necessary to maintain the low cost and portability.

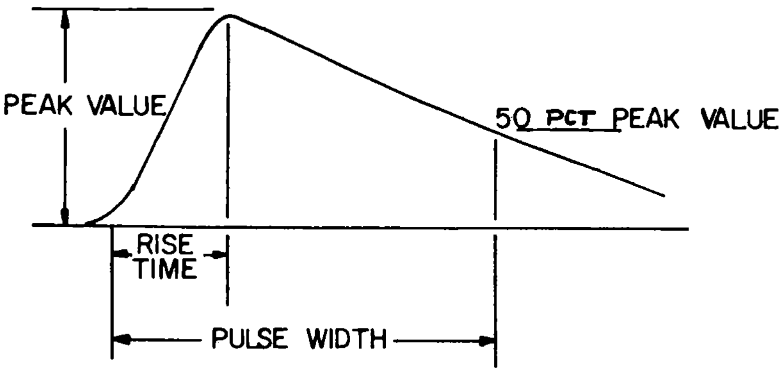


FIGURE 3. - Important transient parameters to measure.

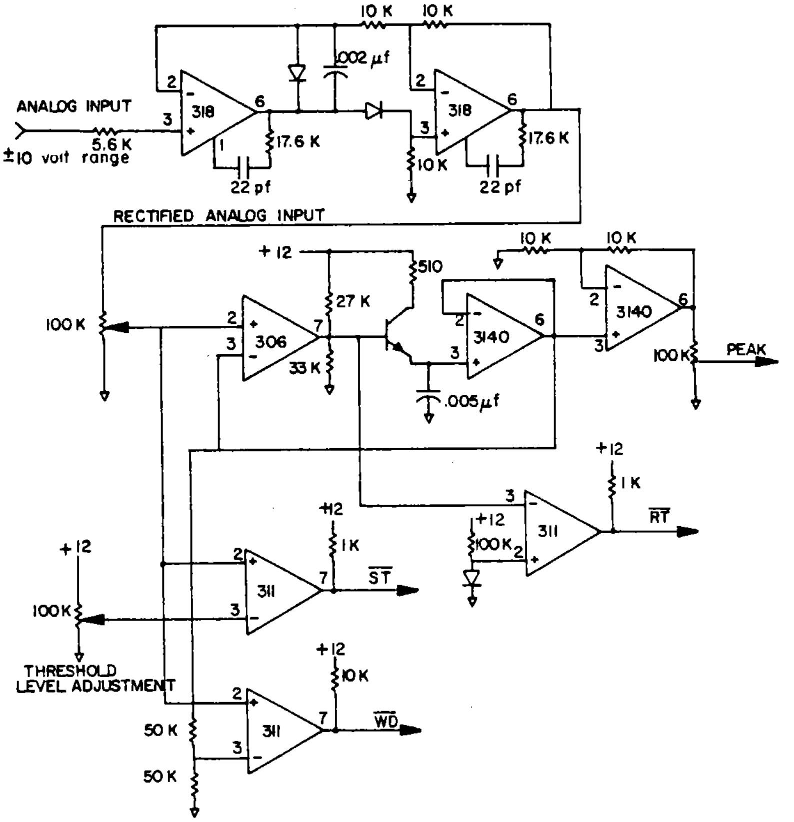


FIGURE 4. - Analog-input circuitry of the transient detector. (K = kilohms.)

Circuit Description

The analog-input circuit accepts the analog signal and generates control signals to the input control logic. The input control logic contains a control logic counter and analog-to-digital converter, from which the required parameters are extracted and computed. The output control logic contains shift registers, decoders, and analog multiplexors to condition the data for the calculator input. The clocks are generated with three inverters each. The various blocks of the circuit are described in detail below.

Analog Input Circuit

The analog-input circuitry, shown in figure 4, can accept voltages ranging from -10 to +10 volts. The 318 operational amplifiers are used to rectify the incoming pulse, and the rectified voltage is scaled before it reaches the inputs of the 306 comparator. This comparator works well only in the ±5-volt range. The 306 comparator and the 3140 bi-FET op-amp are used for a high-speed analog peak detector. The output of the peak detector is fed to a noninverting 3140 op-amp circuit to boost the voltage into the 0- to 10-volt range for the analog-to-digital converter.

The three 311 comparators are used to drive the digital logic. The typical timing diagrams are given in figure 5 for these signals. The ST (start) signal changes state when the threshold level is exceeded. The WD (width) signal produces a 1 → 0 transition on the falling edge of the pulse at 50 pct of initial peak value. The RT (rise time) signal produces negative pulses every time the 306 comparator dumps more charge onto the holding capacitor during the period the analog pulse is rising. This signal can be used to measure rise time. The PEAK signal of figure 4 is proportional to the peak of the analog pulse shown in figure 5.

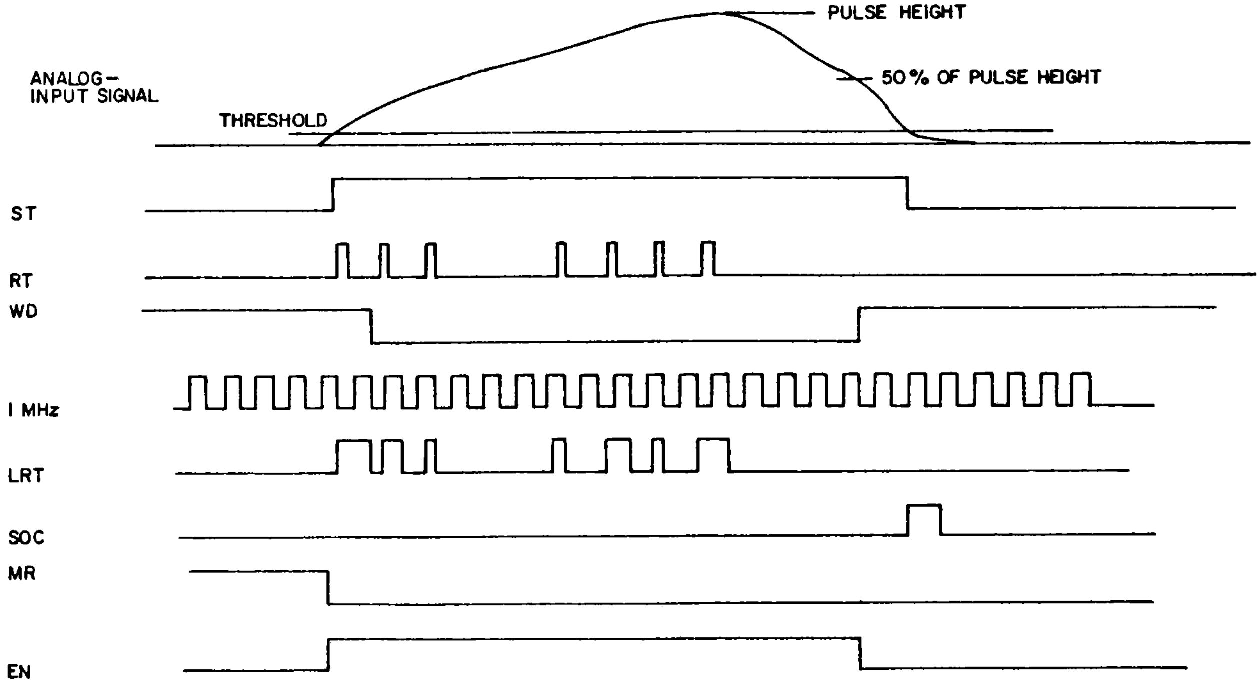


FIGURE 5. - Digital logic typical timing diagrams.

Input Control Logic

The peak detector is designed to function under battery power. Therefore, all digital logic uses CMOS circuits. All integrated circuits (IC's) are the 4000 series unless specified otherwise. Most IC's in the figures list only the last two or three digits. The number within the circle represents the location of the IC. The input control circuit is given in figure 6.

The inverters (4049), the D flip-flops (4013), and the AND gates (4073 and 4081) are the logic IC's that accept signals from the (start time) $\overline{RT}$ (rise time), and $\overline{WD}$ (width) input signals and generate control signals. The EN (enable) signal insures that the 14518 dual decade counter counts during the appropriate range of the analog pulse. The MR (master reset) signal resets the entire system. The LRT (load rise time) loads the count from the dual decade counter into a shift register in the data-output circuit every time a RT pulse is generated. The SOC (start-of-conversion) signal is a pulse which will activate the analog-to-digital converter (MM5357). The EOC (end-of-conversion) signal enables the output control logic. The typical timing diagram for these signals is also given in figure 5.

Data Output Logic

The data output logic is given in figure 7. The data output logic contains shift registers (4021's and 4013) that will serialize the data into four bits. The decoder (4028) controls the three analog multiplexer switches (4016's), which will simulate contact closures on the TI 5050 calculator keyboard.

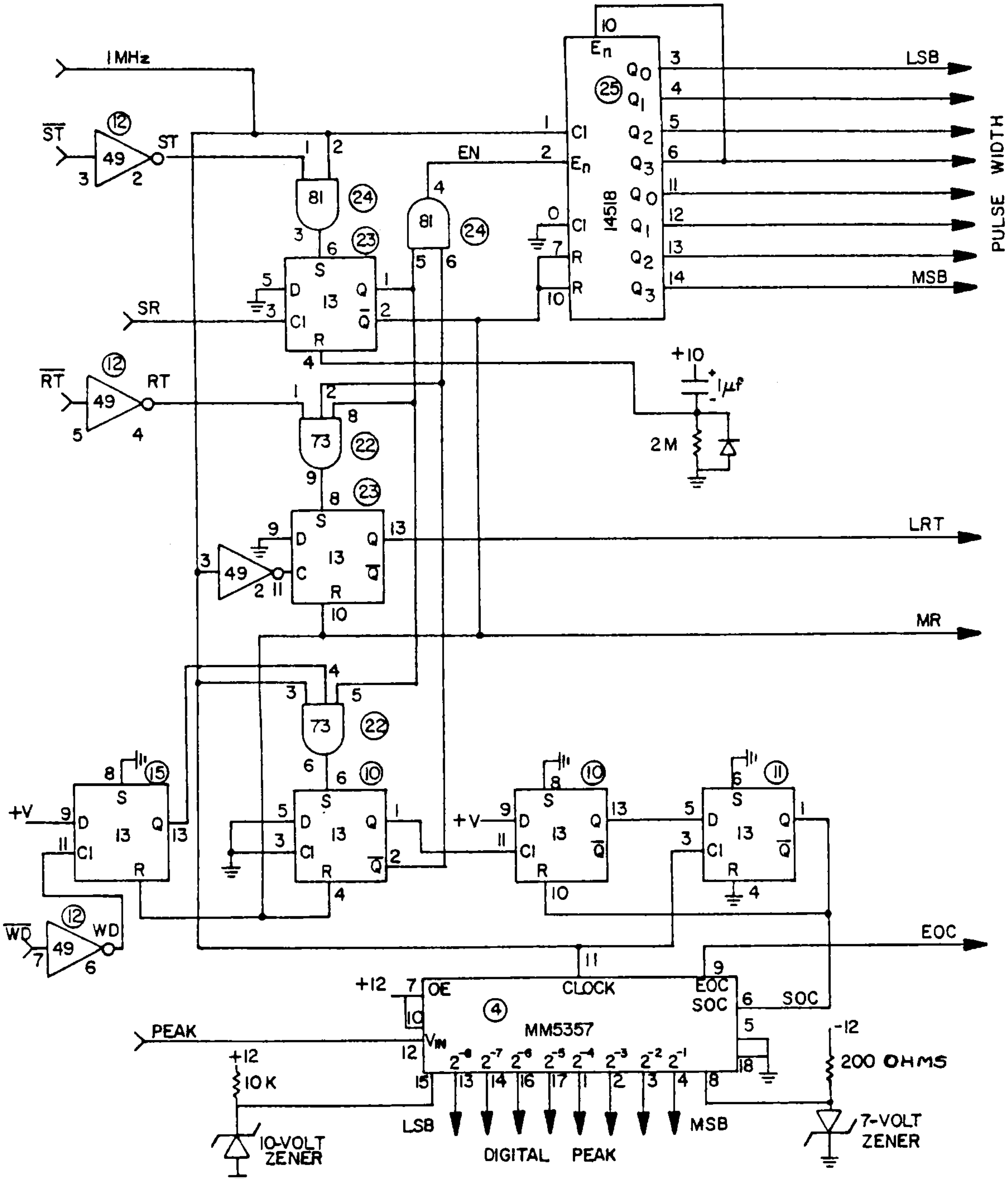


FIGURE 6. - Input control circuit of the transient detector. (K = kilohms.)

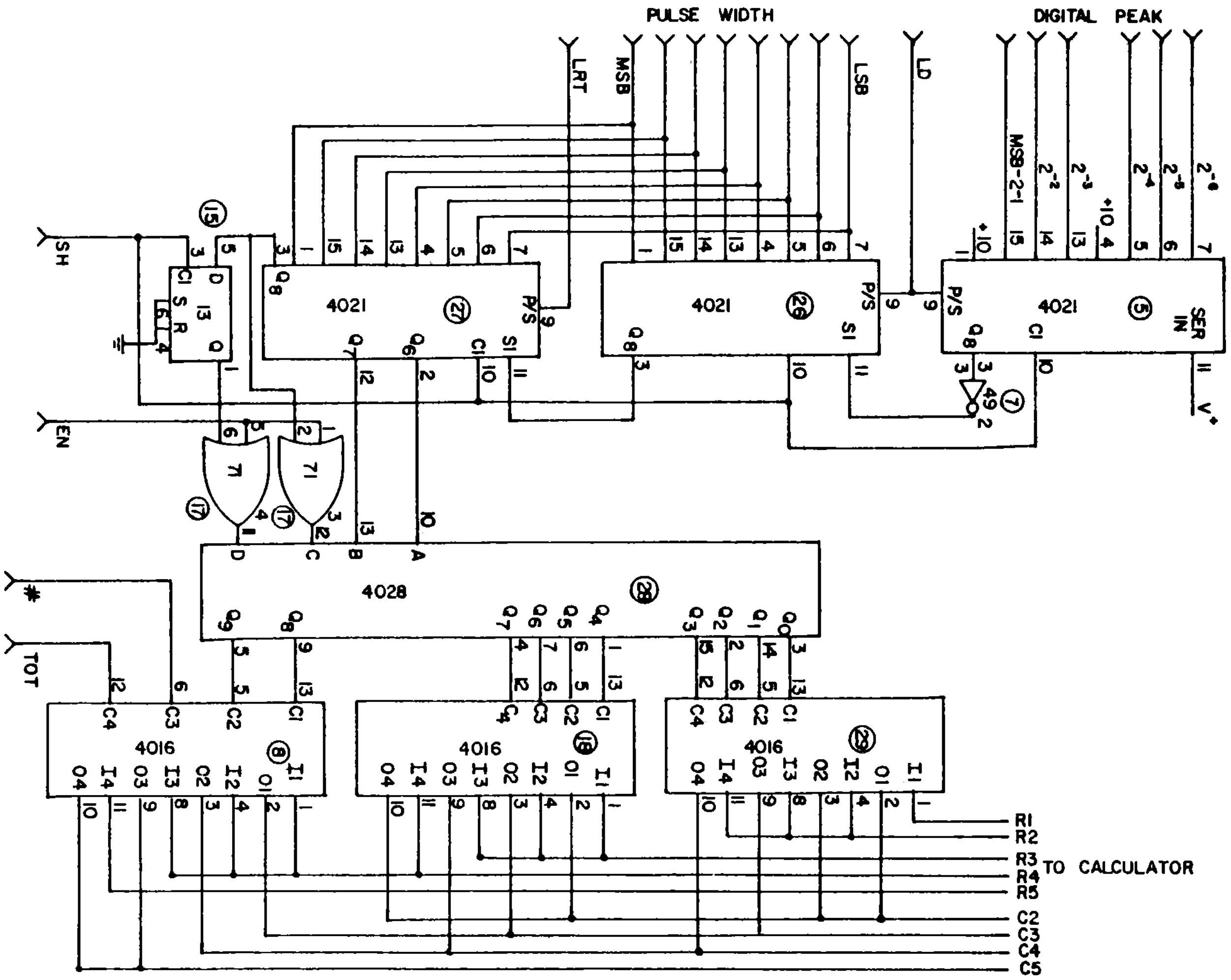


FIGURE 7. - Data-output logic of the transient detector.

Output Control Logic

The output control logic is given in figure 8 with the associated timing diagram in figure 9. The output control logic provides the appropriate control signals to the data output logic (fig. 7) to serialize and print each character.

The D flip-flops (4013) are used to generate the LD (load) signal and the counter (4024) after the data conversion is complete in response to a 0 → 1 transition on EOC. The states of the counter are decoded to provide shift pulses (SH), enable pulses (EN), identifying pulses (#), and total pulses (TOT) in the proper time sequence.

The system reset pulse (SR) resets a D flip-flop in the input control logic, which, in turn, resets the entire systems via the MR. This insures that no false resetting will occur. The peak detector will also ignore any new analog pulse until the peak detector is reset.

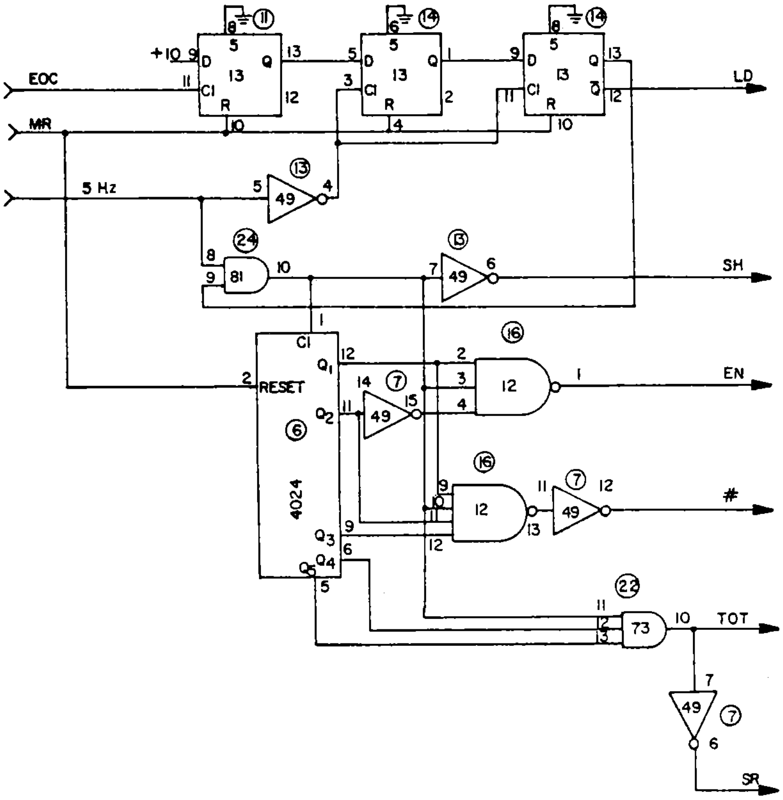


FIGURE 8. - Output control logic of the transient detector.

Calculator (TI 5050)

An inexpensive, digital-printing device with low power requirements was needed, and a thermal printer met these requirements. Most thermal printers print each character one at a time with a 5- by 7-dot matrix. This requires a significant amount of logic to sequence all of these signals to control a thermal printer. Therefore, it was decided to use the logic that already existed in the calculator (TI 5050) to perform the printing task.

A general interface to a thermal printer would allow the printing of special headings and characters. The interface directly to the keyboard of the calculator restricted the data format to the form which is indicated in figure 10.

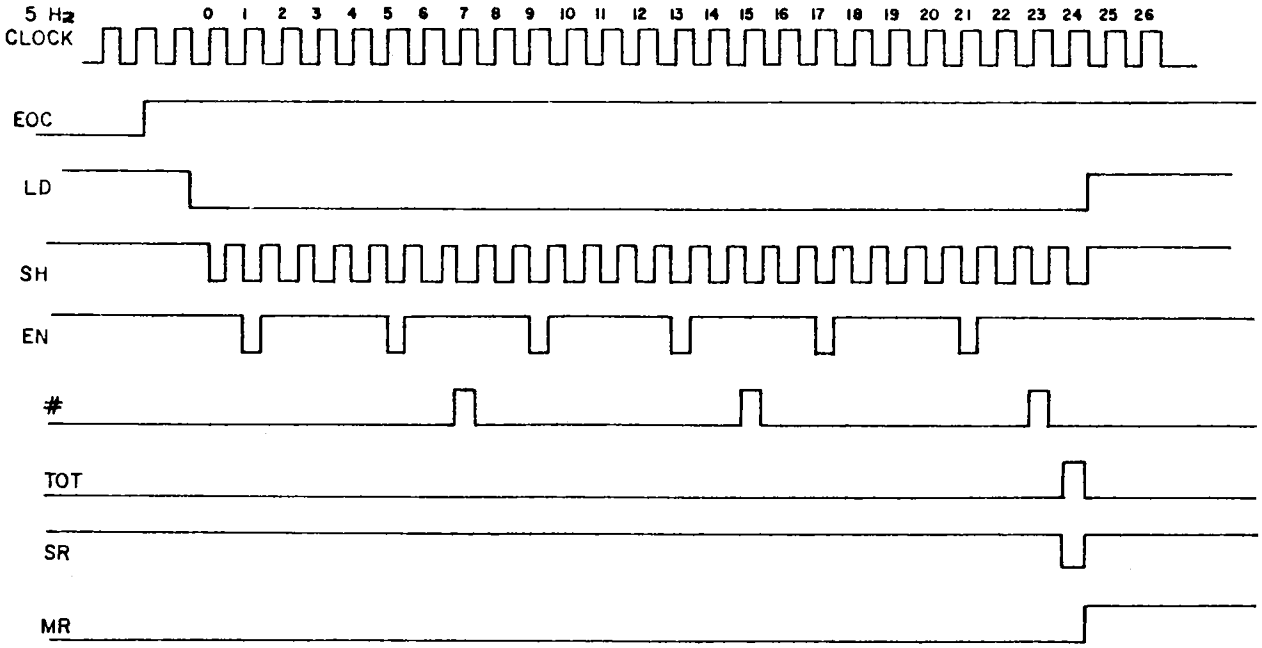


FIGURE 9. - Associated timing diagram for output control logic.

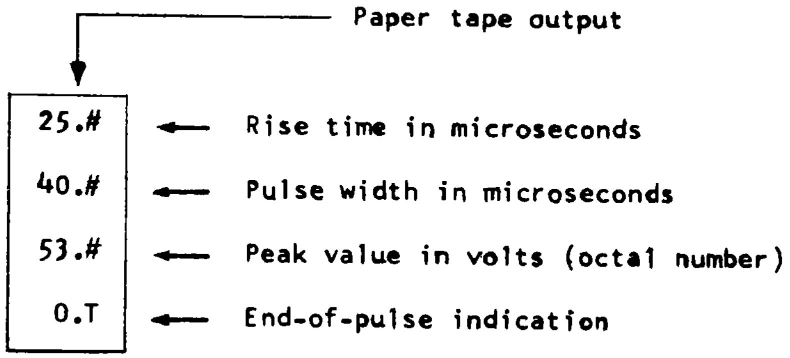


FIGURE 10. - Data output format for the transient detector.

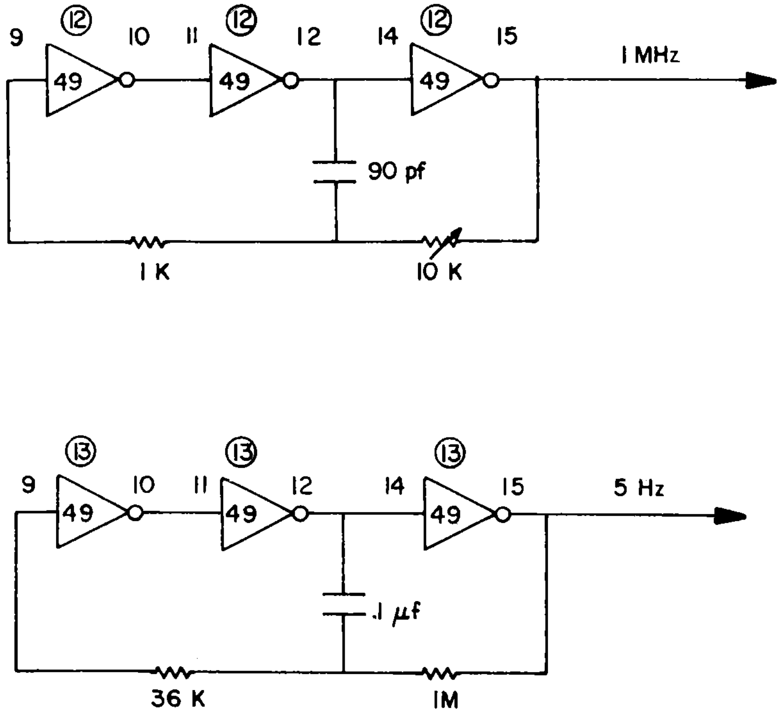


FIGURE 11. - Transient-detector clocks. (K= kilohms).

Clocks

Each clock (fig. 11) was built from three inverters plus resistors and capacitors. This design was chosen because it is relatively immuned to power-supply variations. A variable resistor was used to provide frequency adjustment on the 1-MHz clock.

The detector subsystems are connected together as shown in figure 12.

Voltage Dividers

The measured signal on a mine power system may range from a few hundred volts up to 14,000 volts, under normal conditions. Under transient conditions, the signal may be as high as 120,000 volts. Obviously, the amplitude of this signal must be reduced before it is supplied to the instrumentation. This is accomplished by using a resistive voltage divider with a ratio of 10,000:1. Thus, a 50,000-volt transient would cause 5.0 volts to appear on the instrumentation input.

Although this type of divider is constructed only from resistors, capacitive coupling creates problems. The capacitance of the lead terminals and stray capacitance form a low-impedance path around the divider. Consequently, the high-frequency transients can be recorded at an incorrectly higher value. Other problems, such as "ringing," may also occur. The subject of voltage-divider construction is discussed by Greenwood (3).

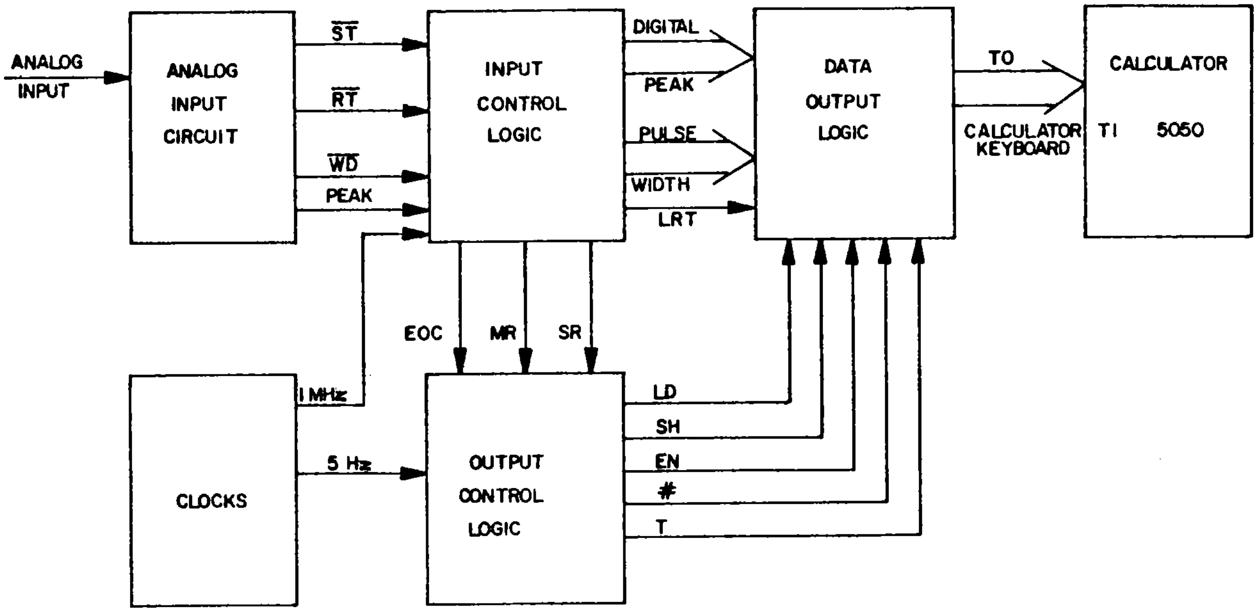


FIGURE 12. - Transient-detector block diagram.

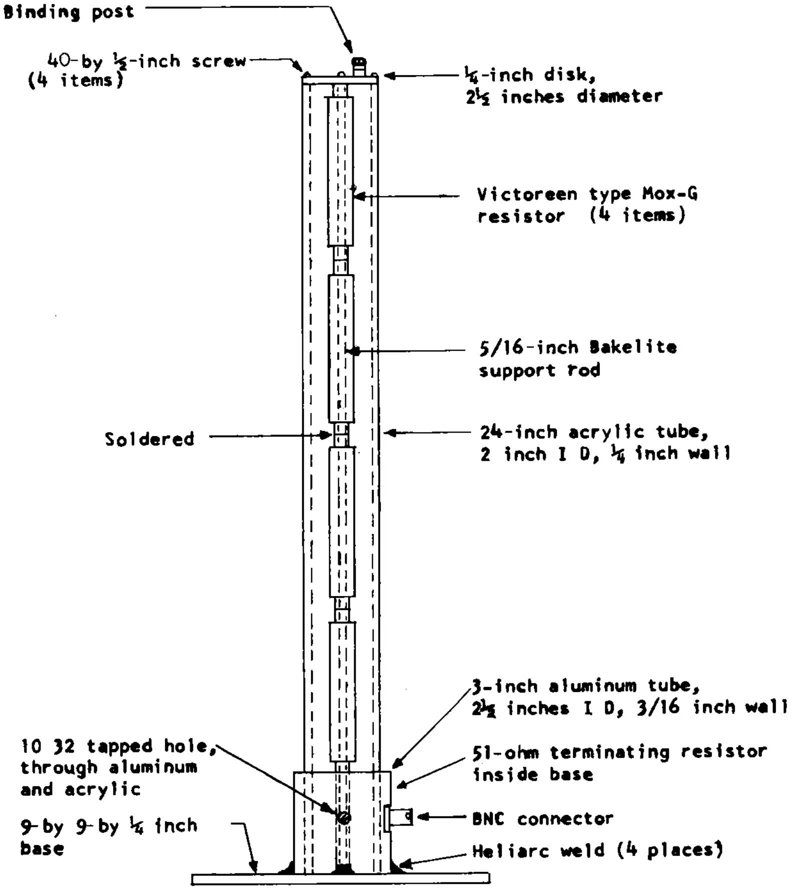


FIGURE 13. - A voltage divider for transient measurements.

If care is exercised in construction, a divider similar to that shown in fig. 13 can be used with minimal problems. More sophisticated versions, with capacitors that cancel the stray capacitance, can be built if desired. Where size is a factor, a more compact divider can be constructed by mounting the resistors in a straight line on a piece of perf board. Also, the resistor lead lengths should be minimized. The assembly should be mounted in a nonmetallic box. The divider should then be tested to insure that the division ratio is the same at 60 hertz as it is at 100 kHz.

The construction and use of voltage dividers is fairly simple, as indicated in this section, but there are disadvantages to their use. A reference such as Greenwood (3) should be reviewed before operation is attempted.

REDUCING TRANSIENT HAZARDS

Classical Approaches

Elimination of transient voltage problems is best started with an excellent power system design applying time-tested principles (12). In terms of ac systems, additional overvoltage control can be obtained by using surge arresters, surge capacitors, or shielding.

Surge arresters, formerly called lightning arresters, clip the peak of a voltage transient and divert the excess current to ground. Typically, they consist of two major parts--a spark gap and a valve section. The spark gap is designed to spark over, thus diverting the excess energy to ground at a given voltage level. The valve unit is designed to stop the current flow after the overvoltage is past. Although surge arresters are available for clipping as low as 50 volts, they are generally used only on high-voltage systems in mining.

Surge capacitors limit the rate of rise of the transient voltage. (As discussed earlier, the faster the pulse rise time, the greater the probability for damage.) If a capacitor is connected into the circuit, it will have to be charged by the transient before the overvoltage can be impressed upon system dielectric. The pulse rise time then will be largely determined by the capacitor charging rate. Surge capacitors (normally 0.25 μf in wye connection) can be located either at switchgear or at equipment to be protected, or both.

Faraday shields have some application for protecting the low side of a transformer against surge voltages. Transients can be coupled to the low side through primary-to-secondary transformer capacities at per-unit voltage levels much higher than those on the high side (1). Grounded Faraday shields between the primary and secondary winding destroy the interwinding capacitance and, thereby, substantially reduce the transfer to surge conditions. However, such shields can cause transformer breakdowns because their presence produces a dielectric-stress concentration at the edge of the shield. This tends to strain insulation locally and can result in destruction of the high-voltage winding. Even with the reported failures, several manufacturers appear to have solved the Faraday shield problem, or the interwinding-capacitance problem, through improved construction practices.

Research Findings

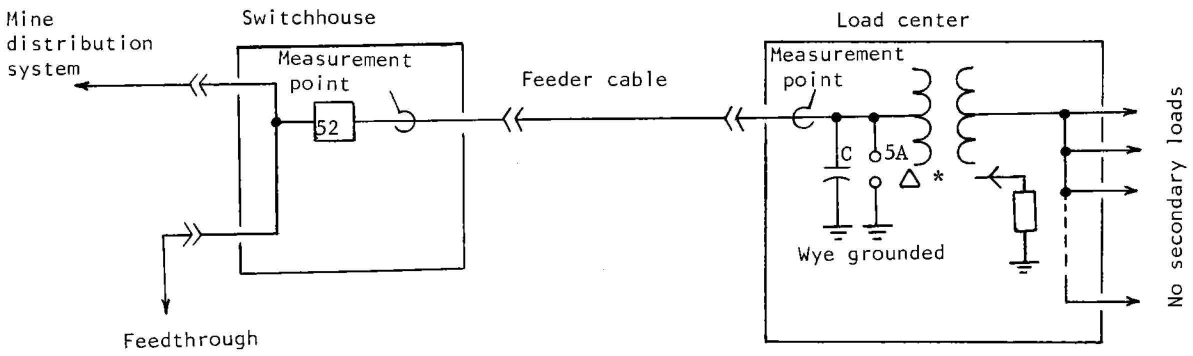
Extensive measurements were made to clarify the severity of transients existing in underground coal mine distribution systems (9). For the most part, these involved recording staged transients on unloaded and loaded systems by chopping (tripping the switchhouse) and prestrike (engaging the interrupter). In every instance, the system segment consisted of a VCB-equipped switchhouse with various lengths of feeder cable supplying a load center. Beyond the principal goal of uncovering the nature of these transients, the effort was aimed at providing recommendations for reducing any hazards encountered.

The effort commenced in-mine with the selected system segment shown in figure 14. With no secondary loads, the VCB was closed and tripped several times. Therefore, the breaker would basically chop only the transformer existing current during opening, while it would just look at inrush current upon closing. There was almost no abnormal transient activity during tripping, but many large transients, some obtaining 8.0 pu nominal or 60 kv line-to-neutral, were observed on closure practically every time.

Considering the large system capacitance (500-foot SHD-GC cable and 0.25-μf surge capacitors), the results for chopping were not surprising. The high peak transient voltages, upon closure, were rather unexpected but explainable by the aforementioned prestrike phenomena. Surge capacitors have long been recommended as a preventative for severe VCB chopping transients. The mine visited was employing them at the high side of every distribution transformer. Such extensive use, in conjunction with cable capacitance, might have caused prestrike transients. In other words, the high overvoltages might have been created by a high outby-to-inby capacitance ratio as seen by the VCB and described by Pflantz (10).

To verify the destructive quality of the transients observed in the preceding example, two field exercises were conducted. The work was performed on the surface to gain control over system variables, but, for comparison, actual 12.47-kv mine power equipment was employed to simulate the circuit arrangement shown in figure 14. The overall objective was to see if surge capacitors were necessary to limit chopping voltage transients and what effect they have on prestrike events.

For the first exercise, the system comprised a 600-kv, 12.47-kv Y/Δ load center, with either 60 feet of No. 4/0 aluminum or 1,000 feet of No. 2 copper



KEY

C	Surge capacitor, usually 0.25 μf
5A	Low sparkover distribution - surge arrester
*	Most load center transformers were delta-wye; some were wye-delta or delta-delta. Common capacity was 750 kva; other capacities included 650 and 1,000 kva

FIGURE 14. - Simplified sketch of a power system segment.

SHD-GC feeder cable, and a VCB. The power source was a 5,000-kva, 34.5-kv/12.47-kv substation transformer. Variations in system configuration during testing included--

1. The source power transformer either totally isolated from mine complex (minimum source capacitance), powering test setup only, or tied to underground mine complex (maximum source capacitance of 6.6 μf per phase), carrying normal mine load and test setup.

2. Load-center surge capacitors (0.25 μf per phase) either in normal wye grounded, wye ungrounded, or disconnected.

3. Switchhouse to load-center cable length at 60 feet or 1,000 feet.

4. Two VCB switchhouses, one with copper-bismuth contacts, the other with copper-chromium contacts.

With each possible combination, 10 trips and closures of the VCB were made, and measurements taken at either the VCB outgoing side or the high side of the load center. The surge arresters remained in the circuit and were verified as operational.

The results of these tests (line-to-neutral voltage, based on nominal) are summarized in table 1. Some combinations of system arrangements are not shown, because they resulted in recording no abnormal transients, as is also the case for some of the listed combinations.

TABLE 1. - Summary of controlled transient data at the first surface exercise

Test series	Surge capacitor connection	Cable length, feet	Measure point	Mine system	Prestrike (VCB closure)		Chopping (VCB tripped)	
					Number >1.0 pu	Maximum value, pu	Number >1.0 pu	Maximum value, pu
1.....	Disconnected	1,000	VCB	Isolated	(1)	(1)	(1)	(1)
2.....	...do.......	1,000	LC	...do....	(1)	(1)	(1)	(1)
3.....	...do.......	60	LC	...do....	1	2	4	2
4.....	Wye grounded	60	LC	Connected	2	2.1	(1)	(1)
5.....	Disconnected	60	LC	...do....	5	3	5	4.5
[2]6.....	...do.......	60	LC	...do....	2	1.7	10	5
7.....	Wye grounded	60	LC	...do....	10	4.7	(1)	(1)
[3]8.....	...do.......	60	LC	...do....	5	1.7	(1)	(1)

[1] No abnormal values.

[2] Repeat of test 5 using a different voltage divider.

[3] Repeat of test 7 using an engine driven generator for instrumentation power.

The second test site for controlled transient measurements on the surface consisted of an 1,000-kva, 12.47-kv Δ/Y load center, 1,000 feet of number 2 SHD-GC feeder cable, and a switchhouse employing copper-chromium contact VCB. The power source was an overhead 12.47-kv powerline from the mine's substation and was not modified during the tests. The same three surge capacitor arrangements were used as previously described, but two load-center-loading situations were used--either no loading, or loading by a continuous miner and shuttle car, causing 8 to 10 amp of high-side current. Again, measurements were made at the switchhouse on one end of the 1,000-foot cable and at the load center on the other end. Twenty openings and closings of the switchhouse VCB were made to get a reasonable sample of resulting transients for each position and loading situation. Table 2 summarizes the results obtained; the values given are again line-to-neutral referenced to nominal.

TABLE 2. - Summary of controlled transient results from the second surface exercise

Test	Surge capacitor connection	System loading	Prestrike		Chopping	
			Number >1.0 pu	Maximum value, pu	Number >1.0 pu	Maximum value, pu
1.....	Wye grounded	Unloaded	(1)	(1)	17	[2]9.1
2.....	...do.......	...do...	(1)	(1)	16	7.5
3.....	Disconnected	...do...	3	3.7	(1)	(1)
4.....	...do.......	Loaded..	(1)	(1)	(1)	(1)

[1] No abnormal values.

[2] 9.1 pu occurred twice; next highest peaks (on other events) were 3.8 pu.

The data contained in tables 1 and 2 provide some interesting information. For the first controlled exercise, there was no significant difference between the two VCB types (copper-bismuth and copper-chromium). For both test exercises, the only abnormal transients existed in the following combinations:

1. When surge capacitors were removed from the load center, thus allowing chopped currents to trap energy.

2. When the surge capacitors were installed, and the source feeding the switchhouse had significant capacitance.

All the configurations that had no abnormal events substantiated the findings of the first distribution example described previously. Although the peak transient voltages were not as great, the prestrike activity also matched that found in the in-mine test.

These measurements throw suspicion on the use of surge capacitors in mine power distribution systems. The effect of surge capacitors on chopping-created transients is obvious, but when the capacitors are removed, the peak-voltage levels are not extremely high. However, surge capacitors appear to create substantial prestrike transient voltages.

Distribution Recommendations

The research performed during this project has led to some specific suggestions to minimize electrical transients on distribution systems. From the information presented in this paper it can be concluded that minimization of transients will increase electrical safety and electrical component availability.

First, short cables should not be used between VCB switchhouses and transformers. Because the capacitance of 1/0 to 4/0 SHD cables is approximately 0.1 μf per 1,000 feet, the minimum length should be around 500 feet. This can decrease possible peak transient voltages from chopping by around 60 pct for most mining applications (as compared with very short cable lengths). Additionally, it seems unwise to specify VCB's in the same enclosure as a power transformer without stringent precautions.

It now appears that extensive surge capacitor use, which adds significant capacitance to that inherent in mine power distribution, can cause severe prestrike transients from VCB operation. Surge capacitors do readily correct transient problems from VCB chopping, but prestrike transients appear to be much more serious than chopping events (under normal system arrangements) and are dependent upon capacitive inrush current during contact closure. The magnitude of inrush current is controlled by the amount of capacitance inby the VCB, not just the capacitance ratio across the breaker contacts. Therefore, use of surge capacitors could result in more severe transients than those they are installed to correct.

Excessive system capacitance can definitely pose other problems in the coal mine's high-resistance grounding system. Most high-voltage distribution systems have a ground-current limit of 50-amp or less. Yet, each time a 0.25-μf surge capacitor is added to the system, the capacitive ground charging current is increased by approximately 5 amp (of course, dependent upon the voltage level). This charging current is around 0.2 amp per 1,000 feet for typical high-voltage feeder cables. Therefore, with just 10 capacitors on the distribution system, charging currents exceed a 50-amp limit. If a phase-to-neutral fault occurs in the complex, this capacitance can discharge feeding the fault with capacitive ground current in excess of current limit. This could happen within the ground system, and there is a possibility that the ground resistor and its protective circuitry will not see it. As a result, surge capacitors might be adding more problems to the mine power system than they are protecting against.

Even with these problems, surge capacitors cannot be unilaterally removed without constraint. The worries are twofold--BIL's and surge arresters.

Present standard transformer BIL's are 25 kv for 5 kv insulation class distribution, 35 kv for 8 kv, and 50 kv for 15 kv. From theoretical and observed levels, these appear too low for mine power systems. In mines employing VCB's, it is suggested that any new transformers purchased have 95-kv BIL. This is sufficient for any of the common high-voltage distribution systems, especially 8 kv and 15 kv classes, and appears a minimum protection level for units switched less than once per week. However, insulation class alone cannot provide adequate transient protection.

Excessive overvoltage problems can be readily fixed with the proper application of distribution-class surge arresters. It is mandatory, however, that these be sized to the system's distribution voltage; Smith (12) provides the necessary information. With 95-kv transformer BIL and distribution-class surge arresters across each high-voltage load and in every switchhouse, there appears to be no reason that surge capacitors cannot be removed. The result should be adequate protection with a mine-power-system improvement both in transients and capacitive charging currents. However, with lower BIL, such removal cannot be recommended unless minimum cable lengths are maintained.

Because too many surge capacitors can be harmful, the number of these devices should not exceed more than one per vacuum switchhouse. The capacitors should be installed in the switchhouse immediately inby the vacuum bottles, because the best location to suppress switching transients is at the source. This recommendation differs from other industry applications, in which the best placement is at the load.

Since overvoltages are dependent upon vacuum-breaker contact material, improved contacts would reduce switching transients. For this reason some VCB manufacturers are now using a copper-chromium alloy contact material instead of the common copper-bismuth. Measurements in the research are inconclusive, but the new contacts reportedly produce one-third less transient overvoltages from chopping or prestrike. This is an aspect of VCB design that is sure to receive more attention in the near future, and it would behoove the mine power engineer to make specific inquiries before purchasing new switchgear.

The last recommendation is tied to a common mining practice. Often, typical mine operations interrupt unloaded transformers from vacuum switchhouses no less than twice per week and up to once per day. Obviously, all unnecessary switching should be eliminated.

CONCLUSIONS

The foregoing presentation has had two primary objectives--the description of two inexpensive, transient-detection devices, and recommendations to reduce transient-related hazards on mine distribution systems.

In-mine measurements of transients would be a worthwhile endeavor at any mine. The peak detector or the transient detectors described here can be easily and economically constructed. The choice of which to use depends upon the information desired, but either would be adequate for locating transient sources and correcting them.

The use of the ideas and techniques presented on distribution-system transient reduction will increase mine-power-system reliability and electrical safety.

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TRANSIENT SUPPRESSION

by

E. K. Stanek[1] , A. Kunjara[2] , G. P. Russell[3]

ABSTRACT

Transient problems have plagued mine power systems for many years. An understanding of the sources of transient voltages and currents in power circuits or control-communications circuits and means of suppressing or eliminating transients are vital to the mine electrical engineer. This paper will present test results on several commercially available surge suppression devices, guidelines on the placement of surge suppression devices, sources of abnormal transients, and recommendations on preventive measures. It will also define worst-case transients that can be used for the purposes of design.

INTRODUCTION

Every power system experiences transients to a certain extent. The severity of the transient problem can be measured, at least in part, in terms of the statistical distribution of peak voltage magnitudes and the frequency of repetition. Simple circuit analysis shows that excursions up to twice the peak system voltage can occur every time a system is energized or deenergized. Transient voltages in excess of twice the peak system line-to-neutral voltage are considered abnormal (2).[3]

Generally, one is more concerned with voltage transients than current surges in an industrial-type power system. The duration of a transient is not usually long enough to cause heating and temperature rise sufficient to damage equipment, but a short spike of voltage can cause insulation to breakdown, p-n junctions to be damaged, etc. Therefore, this paper will concentrate on voltage transients, and, in most cases, it will express their magnitudes as multiples of the system's peak line-to-neutral voltage.

If a system is experiencing transient problems, there are several things that one might consider to alleviate the problem. The system could be rebuilt with better or stronger insulation, but this may not be economically feasible. The system could be redesigned to eliminate some of the sources of transients, but this might be practical only in a new system. Or one could take certain corrective measures involving either the use of surge suppression devices or the modification of operating procedures to minimize the magnitude and repetition rate of transients. This last approach is the most practical from an economical point of view and will be emphasized in this paper.

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[3] Numbers in parentheses refer to references at the end of this paper.

EVALUATION OF COMMERCIALLY AVAILABLE SUPPRESSION DEVICES

There are several devices available commercially that can be used to limit the amount of voltage that appears across a vulnerable piece of equipment. These devices work on the following two basic principles: (1) nonlinear impedance such that the shunt impedance to ground decreases with increasing voltage; and (2) frequency selection in which advantage is taken of the prominence of high-frequency components in a transient. The second type of suppression device is basically a low pass filter. In both cases, series impedance is needed to create a voltage divider between the system series impedance and the suppression device's effective impedance at the voltage level or frequency of the transient. The system impedance level at which the suppression device operates is a key parameter is determining its effectiveness in protecting vulnerable equipment.

Direct Injection Tests Versus TNA-type Injection Tests

One method of testing surge suppression devices is to apply transients to the devices from a surge generator through an impedance matching network so that the surge generator operates with the correct impedance at its terminals. This test does not take into account the system surge impedance level, but it offers the advantage of simplicity of construction and ease of testing.

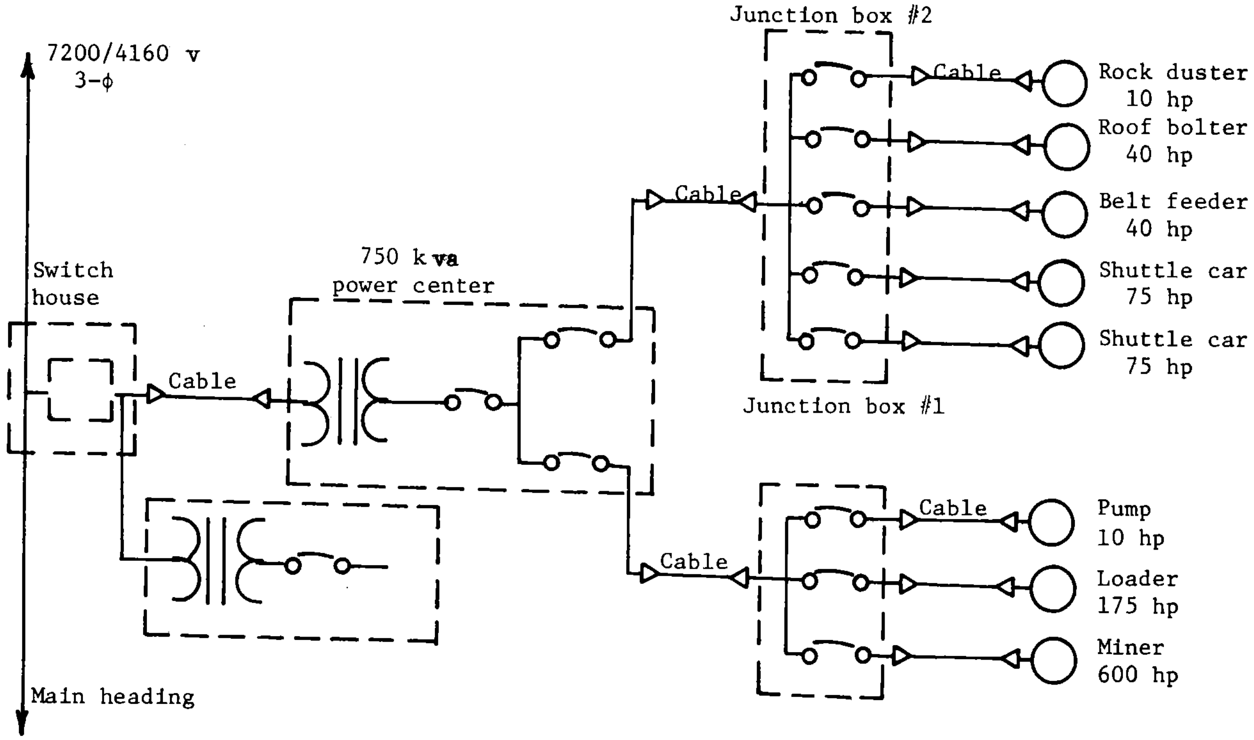

FIGURE 1. - Typical section distribution system.

The second method of surge-suppression-device testing is to place the surge device in an analog representation or model of an industrial-type power system. The model (transient network analyzer or TNA) is constructed of lumped resistance, inductance, and capacitance (RLC) elements and represents various bulk power system elements found in the typical power system (cables, transformers, rotating machines, etc.). The latter arrangement is clearly more realistic, but it requires significant effort to develop the models, wind coils, assemble stocks of capacitors, potentiometers, etc., and to construct the single-phase model. The network that was modeled is shown in figure 1 in one-line diagram form. The electrical equivalent of this model is shown with parameter values in figure 2.

Regardless of network type used to perform the tests, it is interesting to examine three separate characteristics of the surge suppression devices--energy capability, voltage capability, and frequency or rate-of-rise capability.

All of the surge suppression devices operate by diverting the energy of the transient away from the vulnerable element. In the case of nonlinear resistors, this energy turns up as joule-type heating. In the case of snubber circuits, the energy is stored in the electric field of a capacitor. Clearly, there are limits to the energy that can be dissipated before excessive heat destroys the suppression device, or stored before the electric field strength becomes so great that the dielectric materials of the device breakdown.

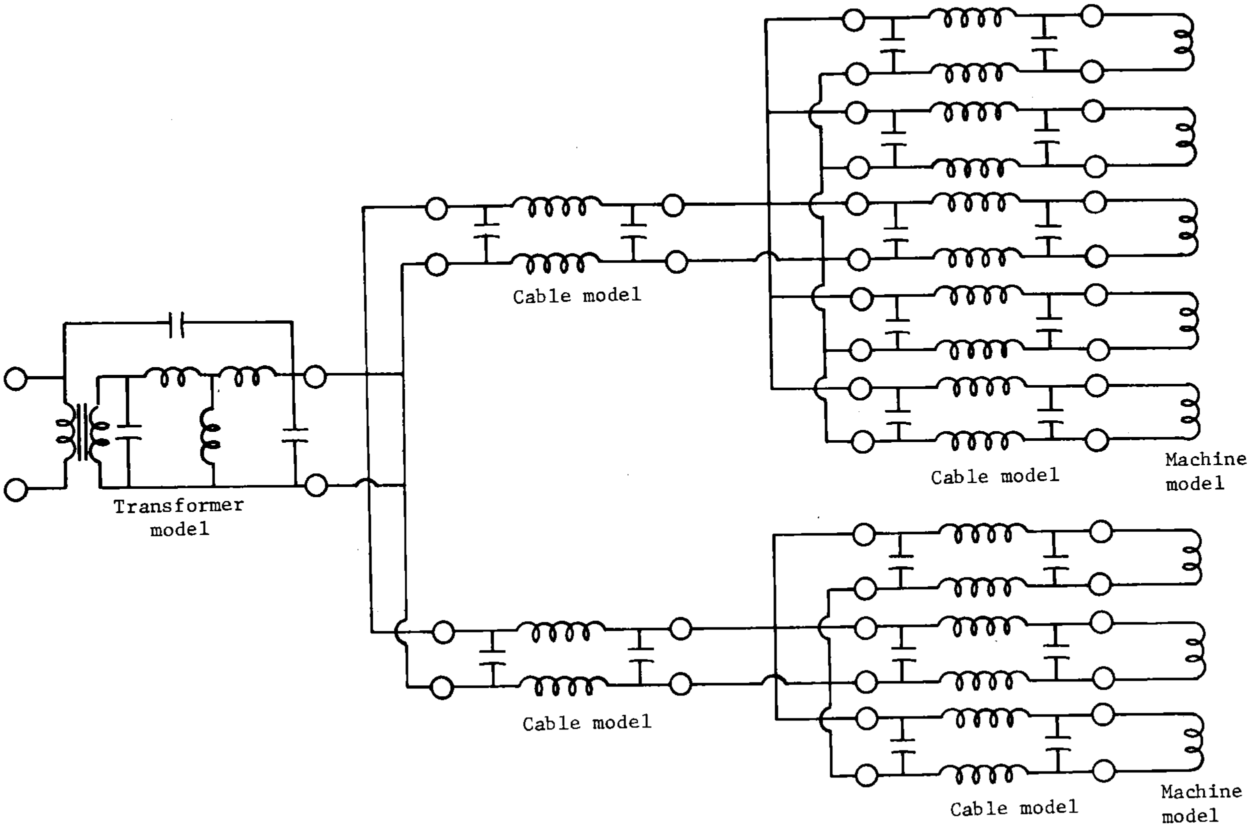

FIGURE 2. - Per-phase TNA for a typical mine section.

Suppression devices operate to clamp the voltage across the terminals by presenting a lower impedance. An ideal device would present an infinite impedance to the system until the device reached its operation threshold, at which point it would present zero incremental impedance; that is, the device would act like an ideal voltage source with zero internal impedance. The degree to which the suppression devices duplicate this ideal behavior can be tested by stressing the device with higher and higher voltages to draw larger and larger currents. The peak voltages, which are always proportional to current, across terminals are a measure of the degree of protection the these suppression devices offer to vulnerable circuits.

The last important characteristic of surge suppression devices is their ability to start conduction rapidly when a transient occurs. This is especially important when the transient has a rapid rate of rise. If the device starts to conduct too slowly and the transient rises to its peak value rapidly, a significantly transient voltage will be impressed across the vulnerable device for a short period of time before the suppression device reaches its conduction state.

These three characteristics were tested using the direct injection test setup described above with an unsuppressed voltage, v. The results are summarized in tables 1-3(6). While these results may not be based on conditions as realistic as those of the TNA-type tests, they do allow one to make comparisons of the performance of one device with that of another in identical situations. The voltage and energy tests were performed using a Velonex surge generator, which produces a square wave of voltage and hence is not useful for the rate-of rise test. A surge generator of the Marx type was used to perform the rate-of-rise test.

TABLE 1. - Direct injection test setup

Device	Peak clamping voltage, volts	Peak device current, amp	Energy dissipated by device, joules
		Energy test 1	
GE MOV-Varistor.............	1,275	11.10	2.75
IR Thyrector................	1,300	10.10	2.63
MCG Transient Suppressor.....	1,200	11.50	2.76
Westinghouse Voltrap.........	1,300	10.50	2.73
15-μf surge capacitor........	400	17.50	1.40
		Energy test 2	
GE MOV-Varistor.............	1,300	11.25	14.63
IR Thyrector................	1,250	10.00	12.50
MCG Transient Suppressor.....	1,200	13.50	14.43
Westinghouse Voltrap.........	1,350	10.50	14.18
15-μf surge capacitor........	900	19.00	9.21
		Energy test 3	
GE MOV-Varistor.............	1,350	12.00	135.00
IR Thyrector................	1,400	10.00	94.54
MCG Transient Suppressor.....	-	-	-
Westinghouse Voltrap.........	1,400	11.00	121.53
15-μf surge capacitor........	1,800	18.00	29.00

TABLE 2. - Voltage test

Device	Peak clamping voltage, volts		
	V_0 = 2,000 volts	V_0 = 5,500 volts	V_0 = 9,000 volts
GE MOV-Varistor.........	800	825	900
IR Thyrector............	490	500	800
MCG Transient Suppressor	780	800	810
Westinghouse Voltrap....	400	600	800
15-µf surge capacitor...	>100	>100	>100

TABLE 3. - Rate-of-rise

Device	V_0, volts	V_{clamp}, volts
Rise time = 0.12 msec (8.3 kHz):		
GE MOV-Varistor......................	5,500	1,300
IR Thyrector.........................	5,500	1,600
MCG Transient Suppressor.............	5,500	1,000
Westinghouse Voltrap.................	5,500	1,300
15-µf surge capacitor................	5,500	300
Rise time = 1 msec (1 kHz):		
GE MOV-Varistor......................	5,500	1,000
IR Thyrector.........................	5,500	1,000
MCG Transient Suppressor.............	5,500	600
Westinghouse Voltrap.................	5,500	1,050
15-µf surge capacitor................	5,500	350
Rise time = 9 msec (110 Hz):		
GE MOV-Varistor......................	5,700	800
IR Thyrector.........................	5,700	600
MCG Transient Suppressor.............	5,700	1,300
Westinghouse Voltrap.................	5,700	900
15-µf surge capacitor................	5,700	350

The basic conclusion drawn from the first series of tests was that all of the devices tested (the GE MOV-Varistor, IR Thyrector, MCG Transient Suppressor, Westinghouse Voltrap, and the 15-µf surge capacitor) clamped the transient well below their specified values of 800 to 1,350 volts. The MCG suppressor showed the most overshoot on the rate-of-rise test, but it still limited voltage to less than the 1,200 volts specified. The 15-µf capacitor clamped the voltage at the lowest value of 350 volts. This low clamping voltage (V_{clamp}) probably resulted from the high system surge impedance level. All of the devices were able to handle rated energy. In fact, only the MCG Transient Suppressor was tested to failure, and it failed only when tested at twice rated energy (16 joules compared with 8 joules rated). Extremely large voltages leaked through the suppressors during the energy tests when the devices were tested at large multiples of rated energy. Typical oscillograms from the energy, voltage, and rate-of-rise tests are shown in figures 3-5.

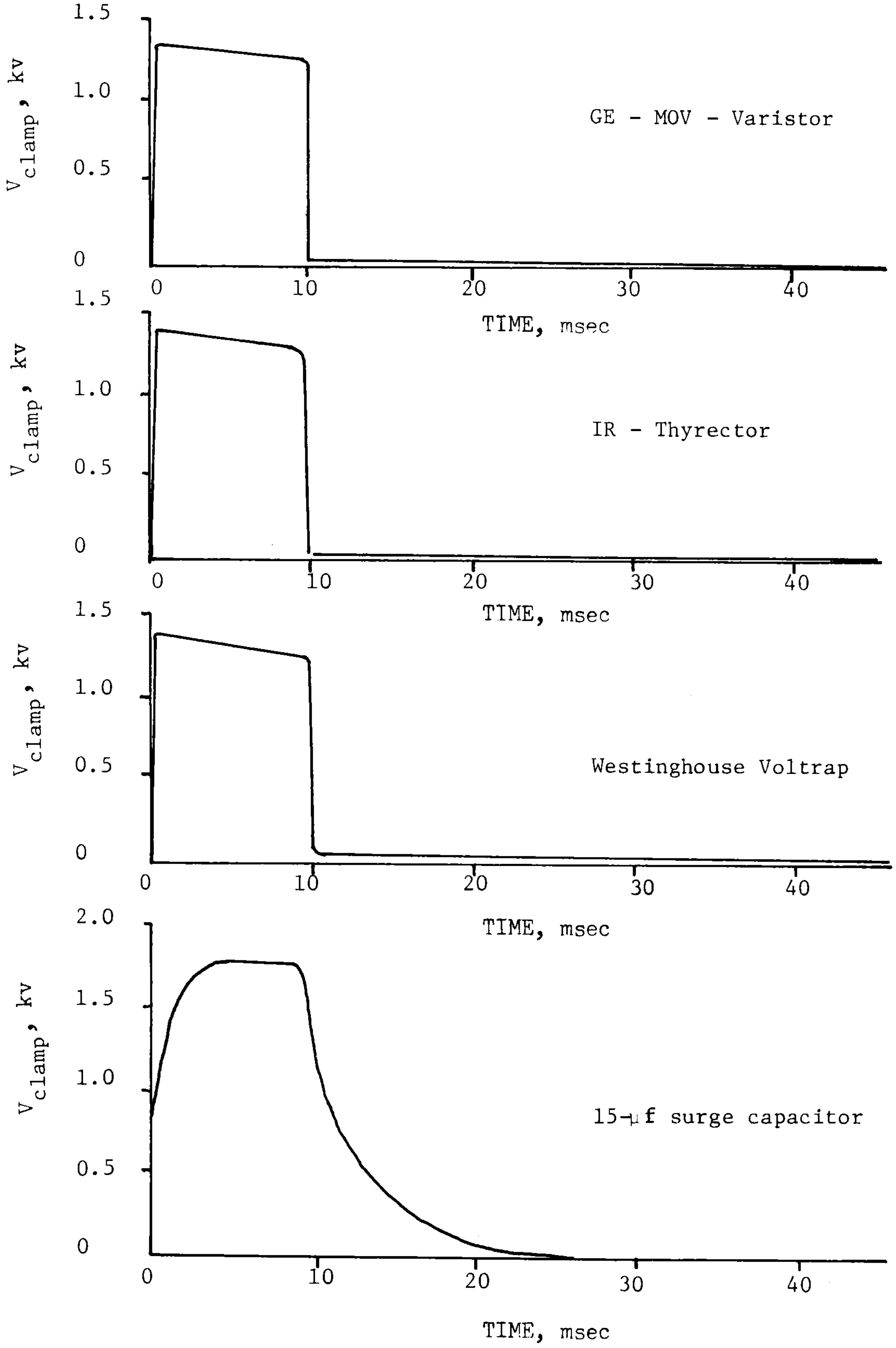

FIGURE 3. - Comparison of device clamping voltage (V_{clamp}) when subjected to energy test 3.

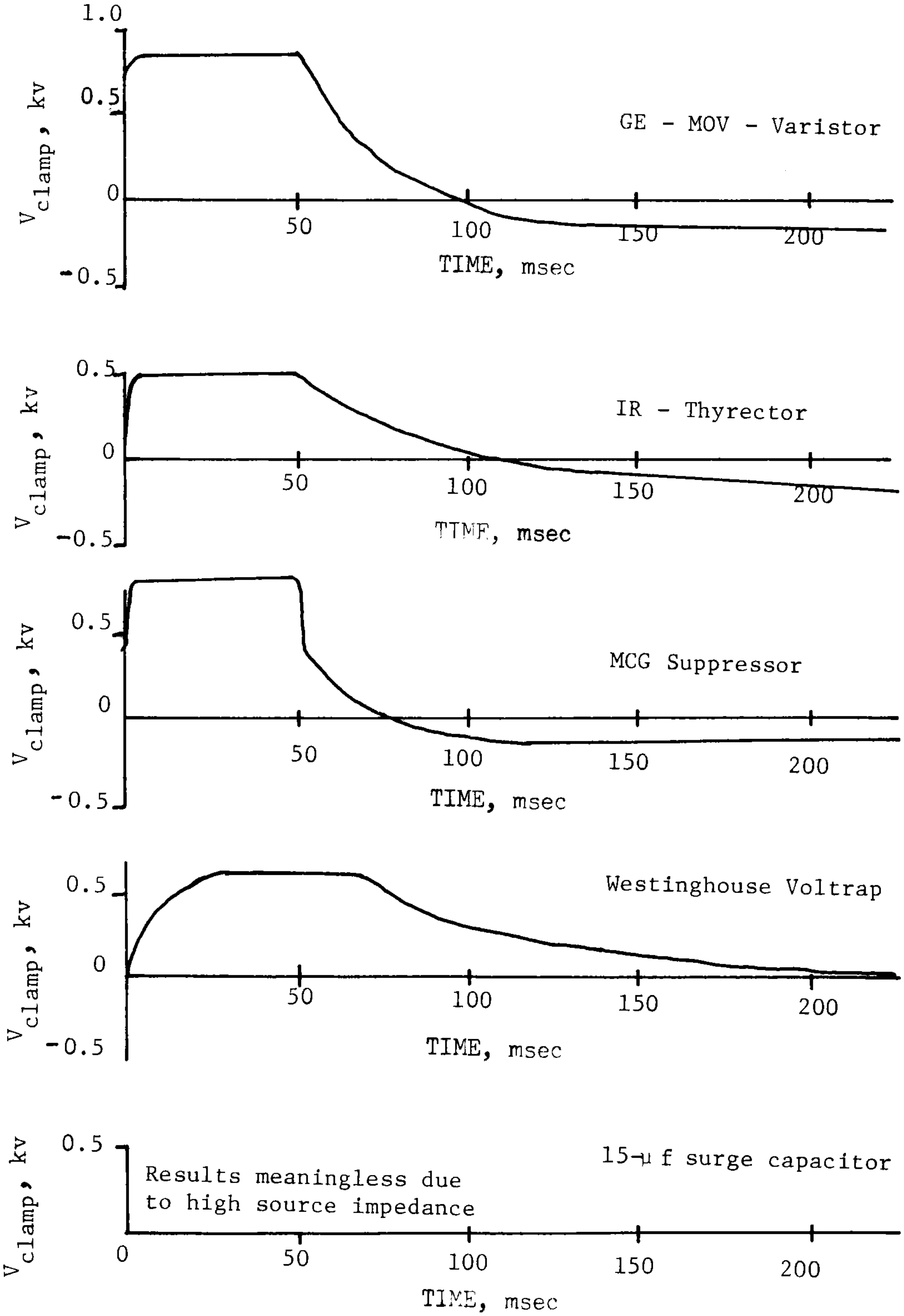

FIGURE 4. - Comparison of clamping voltage when subjected to voltage test. (V_o = 5,500 volts.)

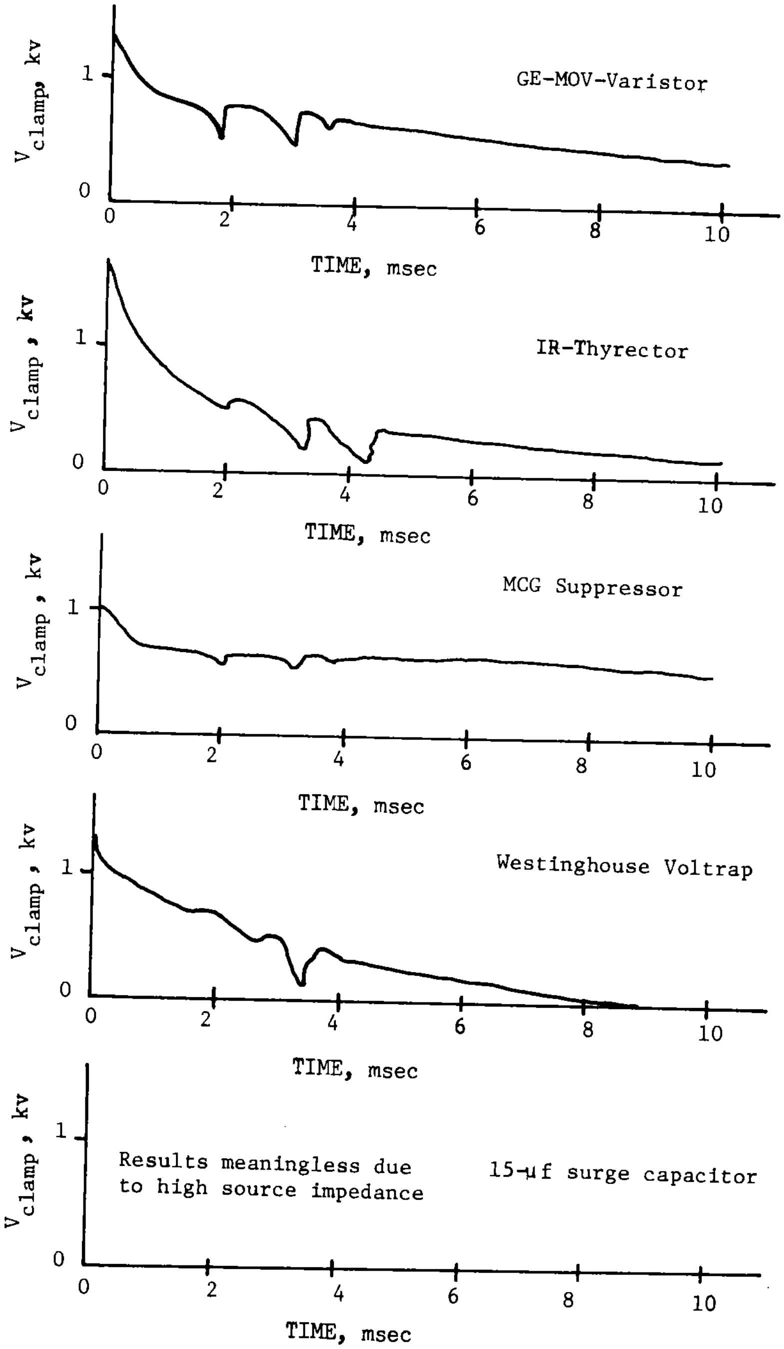

FIGURE 5. - Comparison of device clamping voltage (V_{clamp}) when subjected to high-frequency test.

Similar tests were performed using the TNA-type circuit described in figures 1 and 2. The results basically confirm the data from the direct injection tests.

PLACEMENT OF SURGE SUPPRESSION DEVICES

The generally accepted procedure in applying surge suppression devices is to connect the suppression devices directly across vulnerable items of power system equipment (1). The reason for this is as follows: Suppose one connects a suppression device at point A in the circuit of figure 6. Assume a transient occurs that creates a current of 100 amp with a rate of rise of 10 amp/usec. This will create a possible transient voltage at the protected equipment equal to the suppression device clamping voltage of 1,200 volts plus the (L di/dt) voltage of the series inductance. Thus, the protected equipment could experience a voltage of $1{,}200 + 0.1 \times 10^{-3} \times 10^{7} = 2{,}200$ volts.

It may be possible in some cases to place suppression devices at the sources of transients rather than across vulnerable devices. For example, when lightning surges are transmitted from the surface system to the underground system, suppressors can be placed from each phase to ground. This will limit the voltage surges entering the underground system. An example of a system for which it is not possible to suppress the transient at its source is in the case of a steep front surge entering a transformer from the high-voltage side. If one places a surge suppression device on the high side of

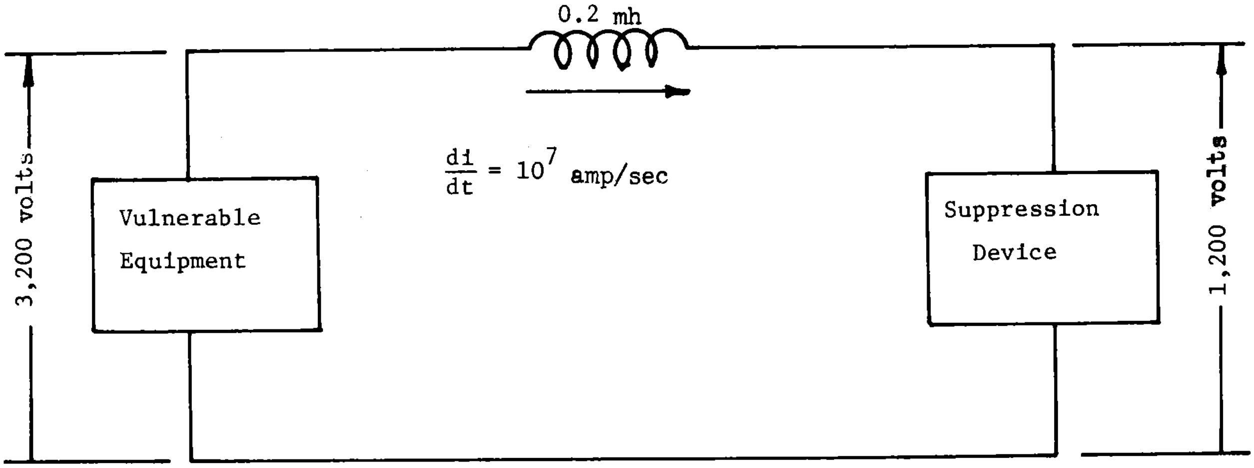

FIGURE 6. - System demonstrating differences in transient voltages at various locations.

the transformer to clamp the surge to an acceptable level from the point of view of the transformer's insulation level, there is no assurance that an intolerably large surge will not appear on the secondary. The reason is that the surge may not be reduced by the transformer turns ratio in passing through the transformer. The mode of coupling to the secondary, especially for steep front surges, is a capacitor divider utilizing the transformer's interwinding capacitance and its secondary-to-ground capacitance. This effect may allow one-third to one-half of the primary voltage to appear on the secondary. If the turns ratio is high (as in a 4,160-to 480-volt transformer), then the secondary surge may have a very high per-unit value. This problem could be remedied by placing another surge suppression device on the low side of the transformer.

The simplest method of assuring that the suppression devices are effective in protecting vulnerable equipment is to place the devices directly across the vulnerable equipment. In some cases, it is possible to limit surges at their source. The greatest problem is that of series impedance between the suppression device and the vulnerable equipment. This series impedance can produce inductive or resistive drops that add to the clamping voltage of the surge suppression devices so that the voltage at the terminals of the vulnerable equipment is much higher than the clamping voltage. Specific guidelines will be presented below.

Two series of simulations have been done to assess the placement of surge suppression devices in mine power systems. The two-pronged approach consisted of digital computer simulation (3) and analog simulation with the TNA model used in the suppression device evaluation. In both cases, a standard transient was either applied to the TNA model or simulated in the computer model. Then the voltage at key locations was either measured (TNA model) or computed (digital model). By comparing the transient voltages, one can assess the merits of placing suppression devices at various locations in the mine power system.

The conclusions drawn are summarized as follows:

1. Place surge capacitors on the high-voltage side of transformers.

2. Place suppression devices across the most vulnerable item of equipment on the high-voltage system.

3. Placement of suppression devices on the utilization system is not critical.

4. Large, energized motors tend to suppress slow transients at their terminals.

The above general conclusions about surge device placement require some additional comments. Both transient network analyzer and digital simulations verify that surge capacitors are more effective when placed on the high-voltage side of equipment; the reason is that a high-frequency (fast-rise-time) transient on the high-voltage system can be diverted to ground by the surge capacitor through a process similar to a low pass filter. However, when the surge capacitor is on the low-voltage side, a significant portion of the surge voltage appears across the leakage inductance of the transformer so that the line-to-neutral voltage is not effectively limited on the high side.

On the high-voltage system, cable runs can be long, and series inductances and resistances can be significant. Therefore, a transient with a fast rate of rise of current (or rate of decay) or a high magnitude of current may be clamped to an acceptable level at a suppression device and still be intolerably large at a remote location. This problem has been discussed above.

While it is important to place suppression devices at the terminals of vulnerable devices on the high-voltage system, it is far less critical on the low-voltage utilization system. The low-voltage system is generally quite compact, and the series inductance or resistance of portable low-voltage cables is generally low owing to the short lengths involved. Therefore, suppression devices placed in a power center offer a reasonable degree of protection anywhere on the low-voltage system.

In the transient network analyzer tests, it was noticed that the presence of large energized motors has a beneficial effect by limiting the magnitude of slowly rising transients. This effect results from the fact that the motor basically acts like an ac source in series with an RL (resistance, inductance) circuit connected between line and ground. If the transient does not contain significant high frequency components, the motor will be effective in shunting the transient's energy to ground despite the fact that high-frequency transients place a severe stress on the insulation of both rotating machines and transformers. This phenomenon is due to the dynamic response of the winding that leads to a nonuniform distribution of electrical stress across the windings. This type of transient can cause turn-to-turn failures in windings.

PREVENTIVE MEASURES

It is probably apparent that certain network configurations are more prone to high per-unit transient overvoltages. In addition, the use of certain apparatus and certain operations can lead to more severe transients. In this section the following items will be discussed:

1. Sources of abnormal transients.

2. Influence of network parameters on transients (cable length, etc.).

Sources of Abnormal Transients

Since a power system must be able to withstand the effects of abnormal transients, it is very important that the mine electrical engineer be aware of their sources. In addition, the mine engineer who is aware of the sources of abnormal transients can sometimes reduce the number of abnormal transients by modifying design or operation. Sources of abnormal transients are as follows (2):

1. Current chopping (primarily in vacuum circuit breakers).

2. Circuit-breaker restriking.

3. Magnetizing inrush currents in transformers.

4. Ferroresonance.

5. Arcing ground faults.

6. Rectifier transients.

7. Voltage coupling via transformer interwinding capacitance.

8. Electromagnetic induction.

9. Electrostatic induction.

All of the items listed occur in mine power systems to a certain extent. Perhaps the least frequent to occur is an arcing ground fault because this phenomenon is primarily restricted to ungrounded systems, and most mine power systems are resistance grounded. Current chopping is largely a phenomenon associated with vacuum interruption. Even if vacuum interrupters are used, it is possible to limit current chopping by selecting interrupters with contacts made of copper-chromium alloy, which has proved less prone to current chopping in tests than copper-bismuth alloy (4).

Circuit-breaker restriking occurs most often when switching off capacitive loads (cable charging current or power factor correction capacitors). Limiting the amount of capacitive switching is a simple way of reducing the repetition rate of this type of transient. It is also possible to purchase circuit breakers that are relatively restrike-free.

Magnetizing inrush currents result when transformers are energized while they have significant residual flux. This transient is largely a current type of transient and does not lead to sufficient heating to damage apparatus. On the other hand, it may lead to current of sufficient magnitude and duration to trip overcurrent relays and hence cause operational problems. Relays with second harmonic restraint have the ability to "ride out" magnetizing inrush currents.

Ferroresonance is a phenomenon whereby the power system goes into series resonance due to the incremental value of inductance of a saturated transformer and the inherent system capacitance. Ferroresonance can happen when a fault occurs and the fault is only partially cleared by the operation of a protective device. This phenomenon appears less likely to occur in a resistance-grounded system than on a surface system.

Rectifiers are in a perpetual transient state. They can act as a source of harmonics on both the ac and dc systems. The order of harmonics available is largely a function of the number of phases available for rectification. On the ac side, the order of harmonics on an n-phase system will be $kn \pm 1$, where k is a positive integer. On the dc side, the order of harmonics will be kn. These harmonics can become a problem when the ac system represents a resonant system at the frequency of one of the harmonics. The rectifier will act as a current generator of the harmonic frequency. When the ac system is parallel resonant, large harmonic voltages may appear. This complex subject has been frequently addressed in the literature.

Voltage coupling via interwinding capacitance can be a problem only under the following conditions:

1. The turns ratio of the transformer is large.

2. The transformer has no electrostatic shield.

3. There is a source of steep front waves on the high voltage side.

Voltage coupling can be alleviated by artificially increasing the secondary winding capacitance of the transformer, because

$$V_2 = \frac{C_3}{C_2 + C_3} V_1 ,$$

where C_2 = secondary winding to ground capacitance,

C_3 = interwinding capacitance,

V_1 = incoming surge,

and V_2 = secondary surge.

The problem of electromagnetic induction is basically one of unwanted inductance between parallel circuits. In most cases, the problem arises when a high-current power circuit runs parallel to a low-voltage control or communications circuit for a substantial distance. Several things can be done to alleviate electromagnetic induction, including--

1. Separating the parallel circuits by a greater distance.
2. Using a twisted pair for the low-voltage circuit.
3. Enclosing the low-voltage circuit in a ferromagnetic conduit.
4. Transposing the phase conductors of the power circuit.

Electrostatic induction is analogous to electromagnetic induction, but it involves electric fields and mutual capacitance instead of magnetic fields and mutual inductance. The classic problem involves an unshielded, high-voltage cable in a poorly grounded or ungrounded cable tray. If the cable happens to be energized by unbalanced voltages (a breaker with one pole stuck closed), it is possible to get very high voltages on the cable tray with respect to earth. These voltages may be high, but they seldom represent significant energy because the source impedance is also quite high. The problem can be alleviated by using shielded cable with the shields properly grounded. When this is done, only a double contingency failure can cause an electrostatically induced voltage on the tray--a stuck breaker pole while the shield ground is disconnected.

Influence of Network Parameters on Transients

It is apparent that such factors as cable length, transformer ratings, and transformer leakage inductances influence resonant or natural frequencies in the system. The computer models developed to study transients are well-suited for determining the influence of network parameters on the peak magnitude, rise times, and duration of transients. The design of a system should not influence the repetition rate of transients, which is mainly a function of system operation procedures.

The computer-model study on the influence of system parameters on transient characteristics has not been completed, so firm conclusions have not been drawn.

TRANSIENT SPECIFICATIONS FOR DESIGN PURPOSES

To determine if a piece of equipment requires transient protection in a mine power system, specifications for the worst-case transient that can be expected are required. If the equipment can withstand the worst transient at the expected repetition rate, application of suppression devices is not necessary. If the equipment cannot withstand uncontrolled transients, one must determine if the device can withstand transients clamped at the voltage level determined by the suppression device. If so, the vulnerable device can be protected by the proper application of surge suppressors.

To specify the worst case transient, one must know several parameters. The most obvious parameter is the peak voltage reached by the transient. This parameter is not sufficient to specify the stress imposed on the insulation.

A long-duration transient has more energy than a short-duration transient and, therefore, imposes more stress on the insulation. In addition, a fast-rising transient will often impose a more severe stress on insulation than a slowly rising transient. At least two reasons exist for this phenomenon. In the case of suppressed or unsuppressed transients on transformer or machine windings, the fast-rising transient voltage will appear mostly across the first few turns of the winding and can cause turn-to-turn insulation breakdown. In the case of suppressed transients, a fast-rising transient may reach a value far in excess of the suppression device's clamping voltage before the suppression device can begin to conduct. Finally, a repetitive transient will create a greater stress on insulation than a single-shot transient.

From the above discussion, it is clear that four parameters are necessary to compute the worst case transient stress on insulation.

1. Peak voltage magnitude.
2. Rate of rise or rise time.
3. Duration.
4. Repetition rate.

These parameters will not be the same for the various types of power systems, such as high-voltage ac, low-voltage ac, and dc systems. Therefore, a total of 12 separate design parameters are required to cover the entire range of power systems normally encountered in a typical mine.

The two basic methods for determining the 12 parameters are field measurements and analytical means. The Pennsylvania State University has made various staged tests and field measurements to determine the parameters listed above for the three types of systems. In addition, West Virginia University has performed analytical calculations, and digital computer and analog simulations to determine the worst-case transient parameters. Based on these combined efforts, the worst-case transient parameters have been determined and are listed in table 4 (5).

TABLE 4. - Probable worst-case transients on various systems

	dc system	ac utilization system	ac distribution system
Peak transient voltage per unit.................	4	[1]5	[1]7
Fastest rise time...msec..	0.01	1	0.001
Longest duration....msec..	2	5	0.005
Repetition rate...........	10 pulses/hour	1-2 pulses/shift	1-2 pulses/shift

[1] Per unit of peak line-to-neutral ac system voltage.

RESULTS AND CONCLUSIONS

Based on field tests, laboratory tests, and computer simulations, several conclusions have been reached.

1. Surge suppression devices with adequate energy-handling capability and frequency response are commercially available. Comparisons of various devices are presented in tables 1, 2, and 3.

2. Guidelines for the placement of surge suppression devices have been presented.

3. Sources of abnormal transient voltages and currents are listed. The probability of these sources existing in a mine power system has also been discussed.

4. Worst-case transient voltages for the three types of systems normally encountered in a mine are listed in table 4. These data are based on field tests and computer simulations, and are useful in design of equipment.

Clearly, a few deficiencies exist in the knowledge of sources of transients, the effects of system parameters on transients, and the parameters of worst-case transients, but significant progress has been made toward the understanding of many complex phenomena.

ACKNOWLEDGMENT

The work reported in this paper was primarily supported by the U.S. Bureau of Mines through Grant No. G0144137 to West Virginia University.

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INNOVATIONS FOR EXPLOSIONPROOF ELECTRICAL ENCLOSURES

by

R. J. Gunderman[1]

ABSTRACT

This paper describes three innovative devices for explosionproof electrical enclosures being developed under U.S. Bureau of Mines Contract H0357107. These devices are a pressure vent, a innovative cable entry, and a quick access cover fastener. Concepts are explained, illustrations are provided for the devices, and potential applications are identified.

Work is continuing to develop design guidelines for pressure vents and for a range of cable entries, and to evaluate the devices while employed in a regular production section of an underground coal mine.

INTRODUCTION

Schedule 2G (now the Code of Federal Regulations, Title 30, Part 18) states requirements for permissible electrical enclosures. These are, to a large extent, design requirements, as opposed to performance requirements (2). This is indicative of a technology which has evolved over many years without a serious attempt to do much research and development aimed at the end objective.

The end objective is the ability to contain any explosion or fire that might result from ignition of a methane-air mixture within the enclosure. Such containment would prevent ignition propagated to the outside of the enclosure and insure the permissibility of the enclosure after such an internal ignition.

As a result of these requirements, permissible electrical enclosures are of very heavyweight construction for ruggedness and are difficult to enter. Frequent inspection is necessary to assure that these enclosures meet permissibility requirements.

The U.S. Bureau of Mines believed that improvements could be made in the design requirements of Schedule 2G. Consequently, in 1975 a request for proposal was released for a program for "Innovative Design of Explosion-Proof Electrical Enclosures."

The Jeffrey Mining Machinery Div., Dresser Industries, Inc., with its subcontractor, Design and Development, Inc., a unit of Booz-Allen & Hamilton, Inc., received the contract for this work. At the outset, a number of mining

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operations and suppliers were contacted and/or visited to gain an insight on desirable improvements. Work by other R&D operations and the academic community was also examined.

The Jeffrey Mining Machinery Div., as supplier of underground mining machinery, provides detailed design knowledge on electrical enclosures and motivation toward improved products. Its subcontractor, Design and Development (D&D), provides technical expertise needed to implement new concepts, reduce them to practice, and to evaluate them. This team approach gives fresh thinking, unbiased by previous practice, to apply to the problems.

ACKNOWLEDGMENT

This program is under the direction of Roger L. King, technical project officer, at the Bureau of Mines Pittsburgh Mining and Safety Research Center. Subcontract effort at (D&D) is led by Michael W. Riley, staff engineer. John Crabtree, also a staff engineer at D&D, provided significant contributions in the testing phases of the innovative enclosures.

OBJECTIVES

There is no question that existing explosionproof electrical enclosures are satisfactory for the purpose they serve (7), but some areas for improvement were repeatedly mentioned in the comments and suggestions received. These include maintenance, assurance of permissibility, and minimizing downtime.

Difficult maintenance adversely affects worker attitudes. For larger enclosures, more bolts are needed to hold the access cover, which results in a heavier cover. On large control cases, two employees are sometimes required to remove or replace the heavy cover. The flange surfaces and bolt holes must be clean to assure a permissible fit. Sometimes the cover must be replaced two or three times before the flange gap requirement is met. Location of the enclosures sometimes makes accessibility difficult, especially for some cable entries. Packing an entry in an awkward location is both difficult and time consuming.

The flame path gap requirements on cover flanges and shafts are very stringent. A surface may easily be scratched or nicked, or a cover warped to the point that the enclosure is no longer permissible. These clearance requirements are necessary because of the high pressures that result from an internal ignition. If the mating surfaces are worn or damaged, the permissibility is compromised and may go undetected for some time.

Lost production time is costly. If inspection discloses an out-of-compliance condition on an enclosure, the section is taken out of production until the problem is corrected and a satisfactory inspection is completed. Access to any malfunction within a permissible enclosure takes additional time because of the extra fasteners and the effort required to restore the enclosure and meet inspection requirements. Removing and reentering cables takes significant time and effort because of the asbestos packing.

The objectives for this program were established to bring about improvements in the above areas. Simply stated, these are (1) improved maintenance, (2) assurance of permissibility to increase safety and production, and (3) reduction of downtime.

CONCEPTS

Many different concepts were identified and considered. These were grouped into the following three categories:

1. Pressure venting to preclude internal pressure buildup beyond 12 psi due to any ignition. This would greatly reduce the forces through flange gaps, cable packing, and other flame paths. Consideration might then be given to possible relaxation of the flame path gap requirements in the regulations. Also, lighter weight enclosures would be possible, since the heavy structures presently needed to withstand high pressure would no longer be required.

2. Innovative cable entries (lead entrances) that eliminate the asbestos rope packing. These would greatly simplify and shorten the time required to enter or reenter a cable. A suitable new entry should maintain a permissible seal indefinitely, eliminating any potential problem of deterioration of the asbestos packing.

3. Quickly opening access covers. These would provide easy enclosure access without labor-intensive bolt removal. Properly designed, a quickly opening access cover should insure easier achievement of the gap requirements without a second person to assist.

Development of the most promising designs has progressed to the point where hardward has been successfully explosion tested and is now ready for underground evaluation pending MSHA approval. The concepts, the hardware, and the potential applications are described below.

PRESSURE VENT

Every permissible electrical enclosure vents pressure through small openings in the flange gap and control shaft gaps, as allowed by regulations. In some instances, additional pressure-venting devices have been added by manufacturers. However, the effective cross-sectional opening from the enclosure to the outside is so small that an internal methane-air ignition may build up 125 lb/in^2 pressure before it bleeds off to the outside. The buildup of pressure occurs in a fraction of a second and requires a number of seconds for dissipation (6).

Pressure-venting devices considered in the present research have a large effective area to dissipate the gas pressure buildup at a rapid rate. Figure 1 illustrates the pressure-venting concept (neglecting the presence of components inside the enclosure that act as baffles and reflectors to the pressure wave front). Figure 2 shows a typical pressure curve for a conventional enclosure and one for a pressure-vented enclosure. The guidelines established during the program allow a maximum of 12 lb/in^2, which is 1/10th the pressure

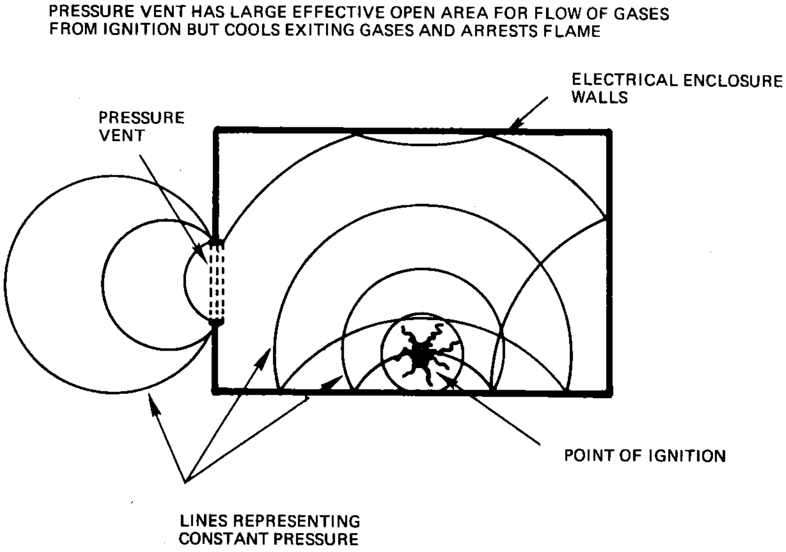


FIGURE 1. - Representation of pressure-venting concept for a methane-air ignition in an empty enclosure.

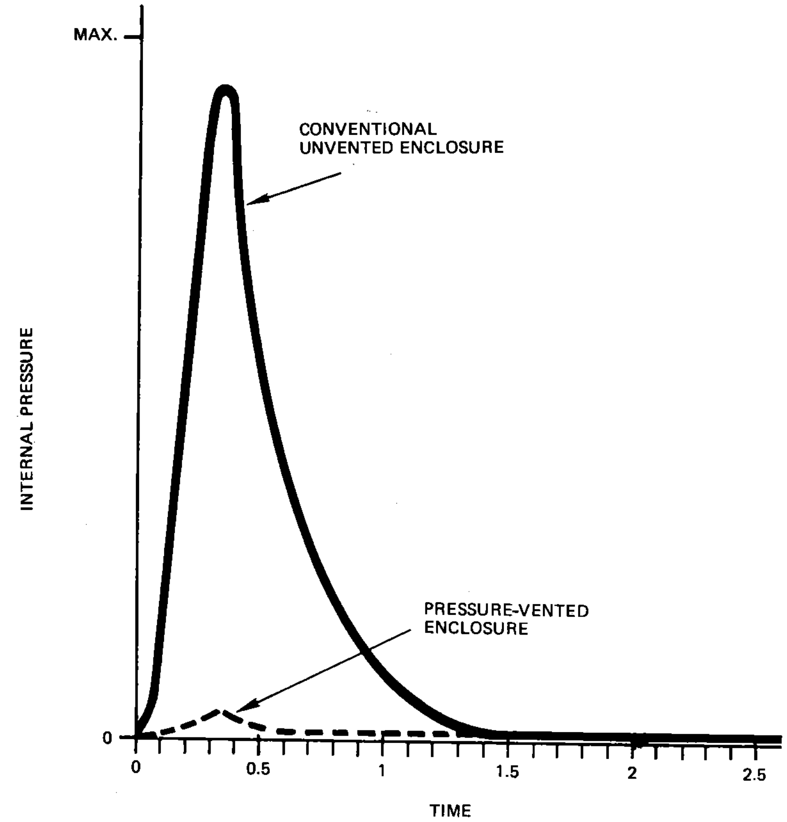


FIGURE 2. - Typical pressure buildup due to a methane-air ignition within an electrical enclosure.

allowance in existing regulations. Thus, the requirement for the pressure vent is to provide a large cross-section opening and yet prevent any flames or particles from reaching the outside on the enclosure.

Various vent devices have been considered in the past. Some of these are described in the references cited (1, 4-5, 8). Many were reviewed along with new ideas and materials. A material previously identified by Jeffrey Mining Machinery and used as a flame arrester in its diesel haulage vehicle intake has proved to be significantly better than any other identified arrester material or structure. This material is a stainless steel foam and is known by the trade name RETIMET.

The vent material, shown in figure 3, has a cellular structure similar to a sponge. The material can be made from various metals and allots with interconnecting cavities and has a very high void volume (approximately 95 pct). The size of the pore may be varied. A piece 13 mm thick will allow airflow equivalent to 25 pct for velocities such as experienced during a methane-air ignition. For example, a pressure vent of 100 in^2 will be an effective window of 25 in^2 during the pressure rise.

Size of the pressure vent was originally calculated on the basis of maintaining the ratio of actual

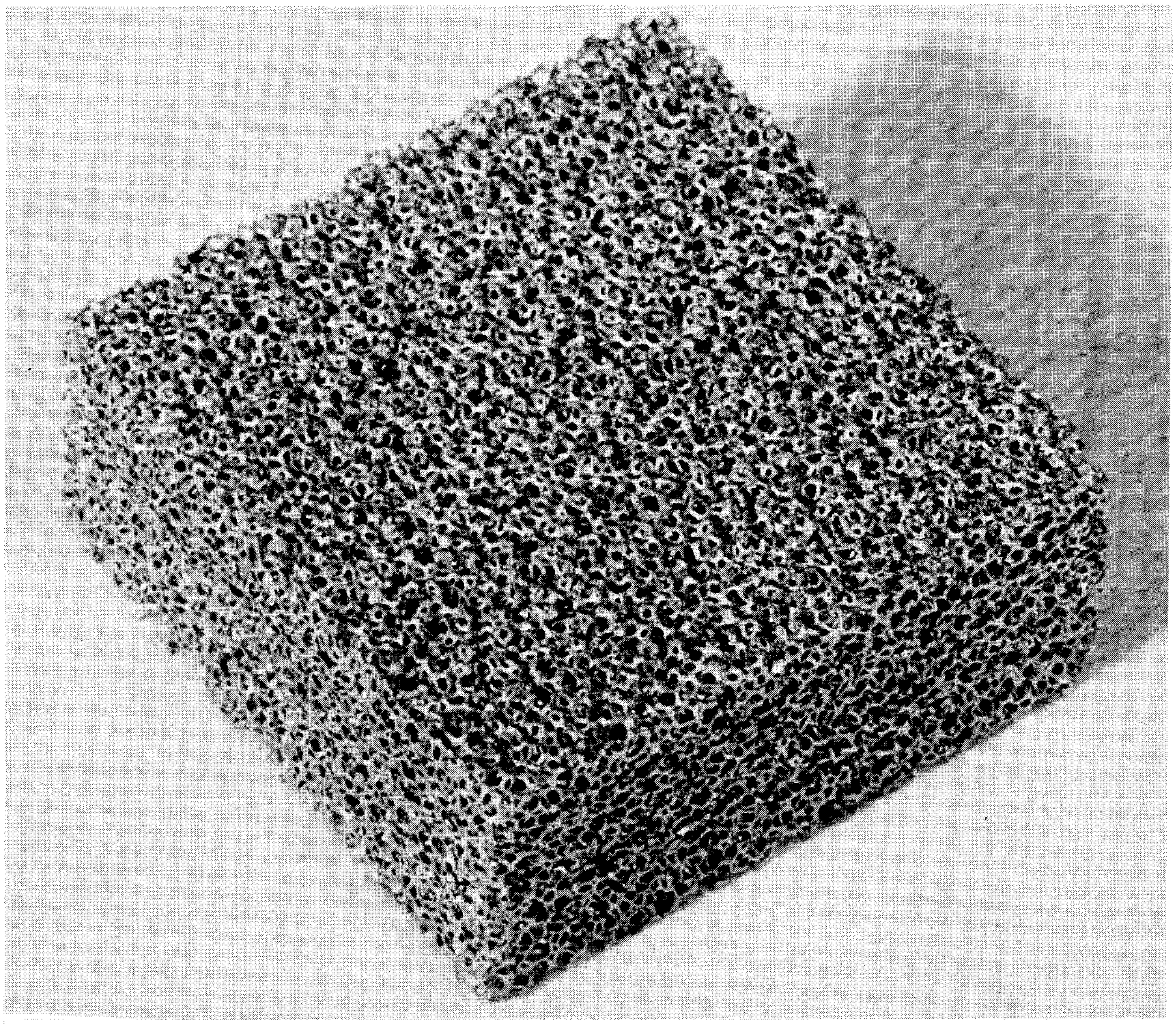


FIGURE 3. - Metal foam material for pressure vent.

vent area dimensions to enclosure volume high enough to meet the 12-lb/in^2 maximum. Although this vented the gases, the heat dissipation could damage the stainless steel vent material. Furthermore, it was found that the closer the point of ignition to the vent, the greater the thermal energy at the vent.

Survivability of the vent requires an even larger ratio of vent area to enclosure volume. The principle here is to distribute the energy over the area of the vent so that no one part is overheated. The ratio holds constant for different size enclosures because the energy in the ignition is a function of the gas volume. A minimum ratio of 12 to 16 in^2/ft^3 for the 1/2-inch-thick RETIMET appears, from empirical data, to be satisfactory.

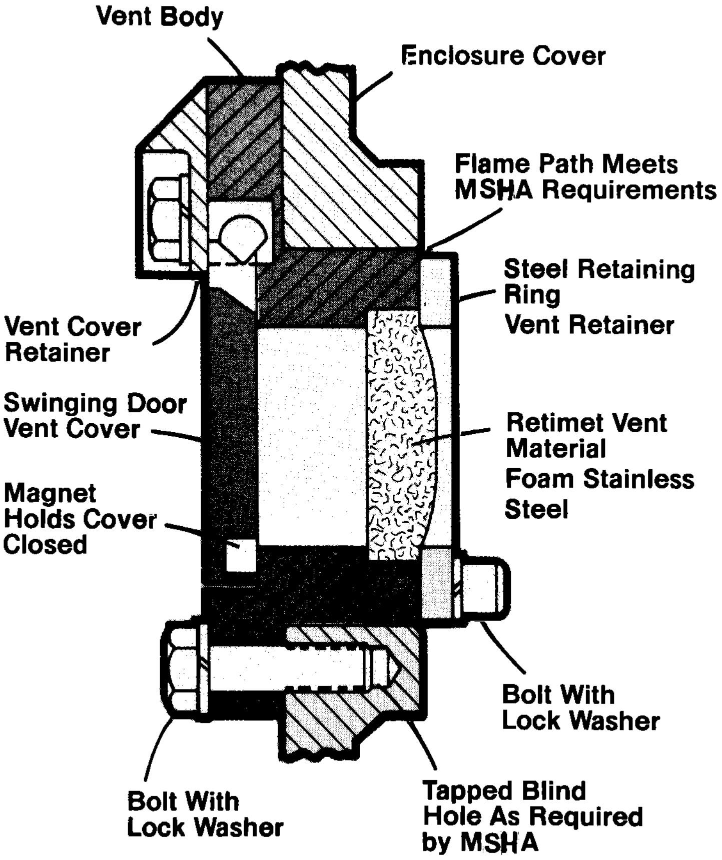


FIGURE 4. - Pressure-vent assembly.

Another consideration in the vent design is protection from impact damage and water entry. The stainless steel foam is sturdy, but it is not as rugged as metal plate. Also, water directed at the material will flow through due to gravitational forces.

The pressure vent design, as implemented, has a swinging door vent cover that protects against damage and entry of water from high-pressure spray. The prototype pressure-vent design is shown in figure 4. The protective door is hung on a knife edge hinge to minimize friction and possible binding. When an internal ignition occurs, the door opens (at approximately 2 lb/in^2) due to the pressure of exhaust gases. Peak internal pressure buildup during tests in an explosion test chamber with this vent and enclosure is typically 6 lb/in^2. The door is normally held closed by a small magnet. In all test observations to date, the door stays open for less than 1 sec.

As can be seen in figure 4, the pressure vent is contained in a vent body that mounts on a cover with a flametight joint. The metal foam vent is retained under compression in the body by a retaining ring. The vent material can be removed for inspection and cleaning.

Figures 5 and 6 show a pressure vent assembly on the cover for a trailing cable connection box. This assembly was tested by MSHA at the explosion test facility in Pittsburgh. The plan is to install the assembly on a continuous miner and evaluate it underground for 3 months.

For producibility, pressure-vent assemblies should be round or at least have rounded sides, instead of being square or rectangular. The assembly shown in figures 5 and 6 with square corners was originally designed for an enclosure where space was at a premium.

The pressure vent for initial underground evaluation is in an enclosure that conforms to the existing regulations (Schedule 2G) in all regards.

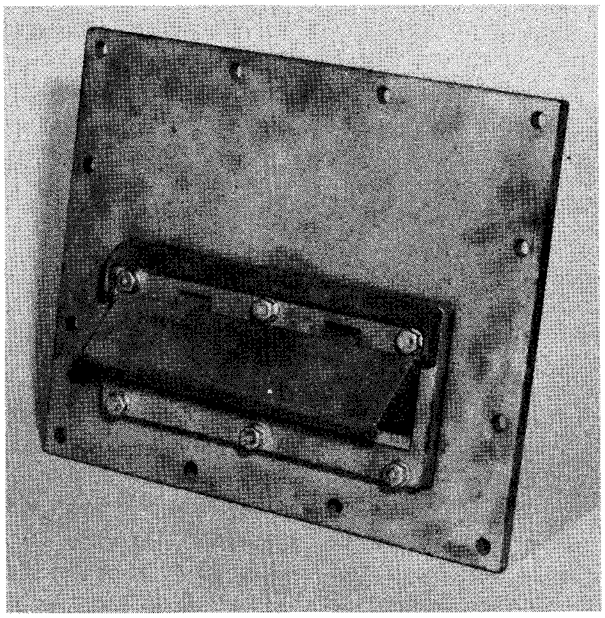


FIGURE 5. - Pressure-vent assembly with protective door open.

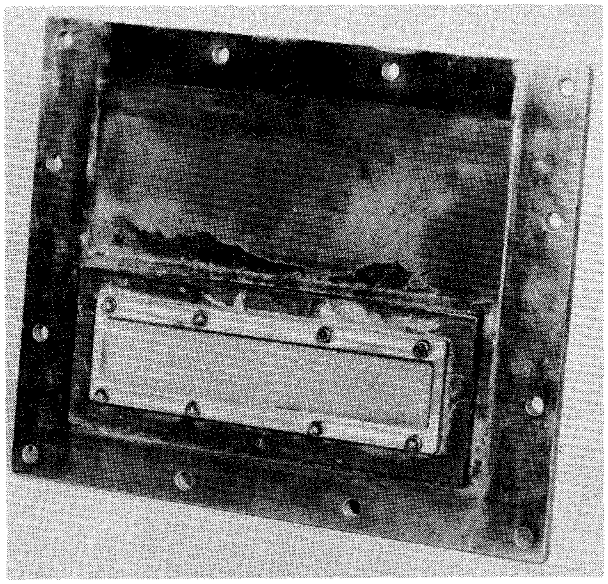


FIGURE 6. - View of pressure vent side internal to enclosure.

If MSHA approves these devices and regulations are changed, the devices have production application in--

a. Lightweight enclosures, since they need to withstand pressures no higher than 12 to 20 lb/in^2. For example, instrumentation such as an oscilloscope can be housed in a permissible enclosure light enough for one employee to carry.

b. Face equipment enclosures of reduced wall thickness, except where nonexplosion requirements dictate ruggedness. Lighter weight covers will be easier to handle.

Flametight joints on a pressure-vented enclosure are much easier to achieve, this fact should open the door for consideration of less stringent flame path design requirements. Gap allowances could be increased and/or path lengths decreased, which could increase productivity by reducing manufacturing costs and allowing easier maintenance.

INNOVATIVE CABLE ENTRIES

Most permissible cable entries (or lead entrances) use asbestos rope packing. Between 10 and 20 min is typically required in the factory environment to pack a single entry. Repacking an entry in the coal mine can sometimes require much more time, especially in awkward locations. Present regulations allow elastomeric grommets, but their use is infrequent because varying sizes of cable diameter and the fact that the radial clearance between the cable jacket and the nominal inside diameter of the packing material must not exceed one-thirty-second inch means that grommets would have to be in stock to match each basic cable size.

The specific requirement for a new cable entry was identified as a grommet-type device having compressibility such that a single size grommet can accommodate a range of cable sizes. In addition, the materials must comply with requirements for fire and toxicity.

Cable entries, in accordance with requirements of the National Electrical Manufacturers Association for explosionproof enclosures, were investigated for possible adaptation to the coal mine requirements. A configuration using a tapered grommet and plastic chuck looked promising. Brass slip-fit entries were designed and fabricated, and the entries with cables were subjected to extensive testing in an explosion test gallery. The results were favorable, but other testing showed two serious drawbacks. The tapered grommet wedged into the body so tightly that cable removal was very difficult after a few days. Also, the plastic chuck appeared too fragile.

Experience with the tapered neoprene grommet and chuck showed that a different type of material would be required to meet the objectives. Tapered neoprene grommets, even with different degrees of hardness, tend to lock up under compression and not release easily. Ultimately, a polyurethane material with a Shore A hardness of 85 was found that had a high degree of compressibility and good holding action when constrained on all sides, and which released easily when the packing nut was backed off.

A new cable entry design was made for a continuous miner trailing cable because the trailing cable is apt to be reentered frequently. Designing it to be interchangeable with a conventional asbestos packed entry greatly simplifies getting it on a machine underground for evaluation.

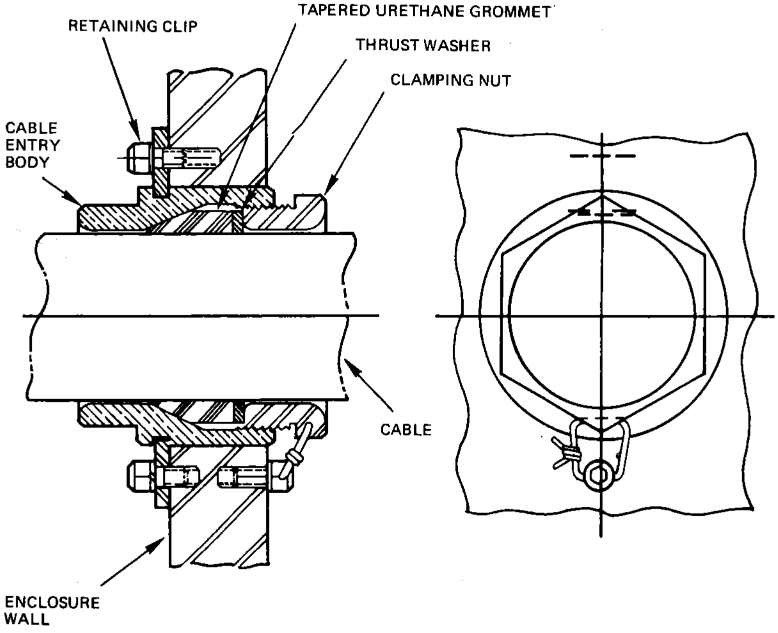


FIGURE 7. - Trailing cable entry assembly.

Figure 7 shows the innovative trailing cable entry design. The configuration is simple and straightforward. However, the right combination of dimensions is critical, especially for the included angle on the taper. Tolerances are not critical, and this entry uses typical values for cable entry manufacture.

As you can see in figure 8, the cable-packed entry looks similar on the outside to a conventional asbestos packed entry (figs. 8-9).

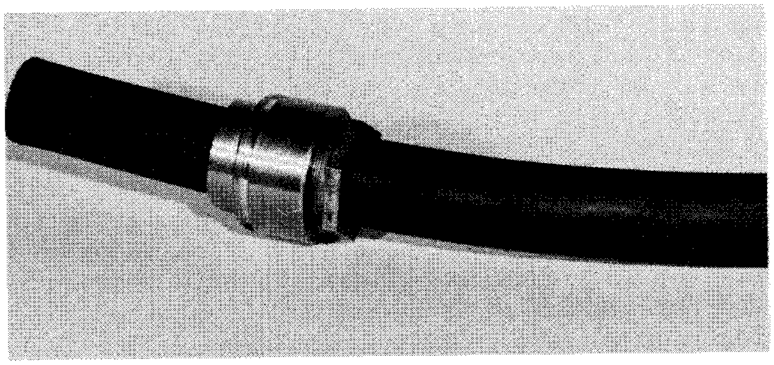


FIGURE 8. - Innovative trailing cable entry on short length of cable.

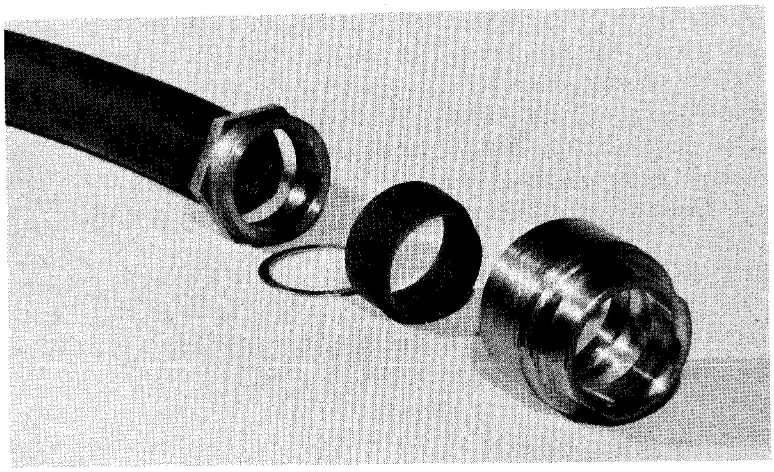


FIGURE 9. - Innovative trailing cable entry components.

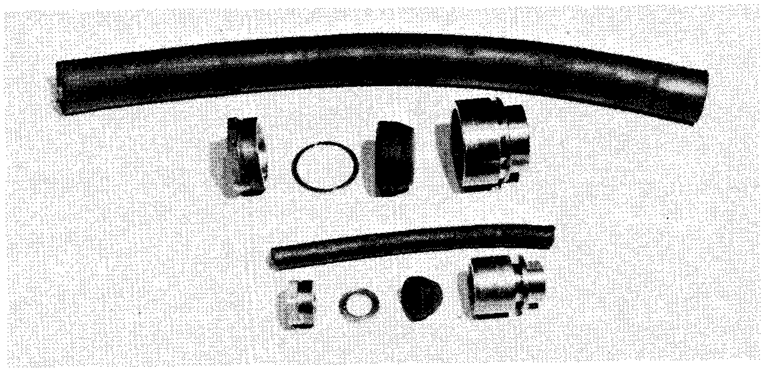


FIGURE 10. - Innovative cable entries for three-conductor 4/0 trailing cable and a single conductor 4/0 cable.

The cable can be removed from the innovative entry by loosening the packing nut and sliding the cable out of the assembly or by removing the clamping nut and pulling out the cable with the clamping nut and grommet still on the cable.

Two batch samples of this urethane material were subjected to flammability testing by D&D in accordance with Federal regulations, and found to be satisfactory.

Tests of the innovative trailing cable entry were conducted in an explosion test chamber at D&D's facility. No problems were noted, and the design and samples of urethane have been submitted to MSHA for approval.

Figure 10 shows a smaller entry (4/0 cable) and the trailing cable entry. Changes or difficulties with other cable sizes have not yet been investigated. Mechanical properties are tested and evaluated prior to testing in the explosion test chamber.

Inspection of the innovative entry may be performed by checking the gap between the body and packing nut, by attempting to insert a gage between the cable and grommet, and by pulling on the cable to verify that it is tight in the body.

QUICKLY OPENING ACCESS COVERS

Small access ports on permissible electrical enclosures have been used for some time. Typical of these is a single piece screw on a cover 6 to 12 inches in diameter. Previous Bureau of Mines research resulted in a screw-on cover design with multiple threads to engage every one-eighth of a turn and to fully close in less than one full turn (3).

The present research addressed the problem of opening the large, complete cover for maintenance access.

On a small enclosure with less than 12 cover bolts, the effort and time required to open and close are reasonable. Advantages of a quickly opening access cover are more significant on larger enclosures.

Brainstorming sessions identified many different concepts for a quickly opening cover, but most of them were not found satisfactory. Single-lever concepts are used on some European and Australian enclosures. However, these are cast rather than fabricated enclosures, and flange gap allowances are higher (for example, 0.019 inch compared with 0.005 inch). U.S. machines are not standardized to the same extent, and to accommodate a wide range of configurations, enclosures are fabricated.

The guidelines for the fasteners being investigated called for no holes in the mating flange surfaces and not more than a few turns of a screw. Some concepts appeared technically satisfactory but were discarded because of high manufacturing costs.

Two types of access-cover fasteners were developed and tested in an explosion test chamber. These are termed the flange dog and the internal rotary keeper, shown in figures 11 and 12. Both devices passed tests in the explosion test chamber, but the flange dog was less satisfactory. The mechanics of this device resulted in single-point contact rather than pressure distribution over an area such as on a bolt head. There was also a bending moment on the bolt, and the external protrusion was undesirable. Consequently, the flange dog was dropped from further consideration.

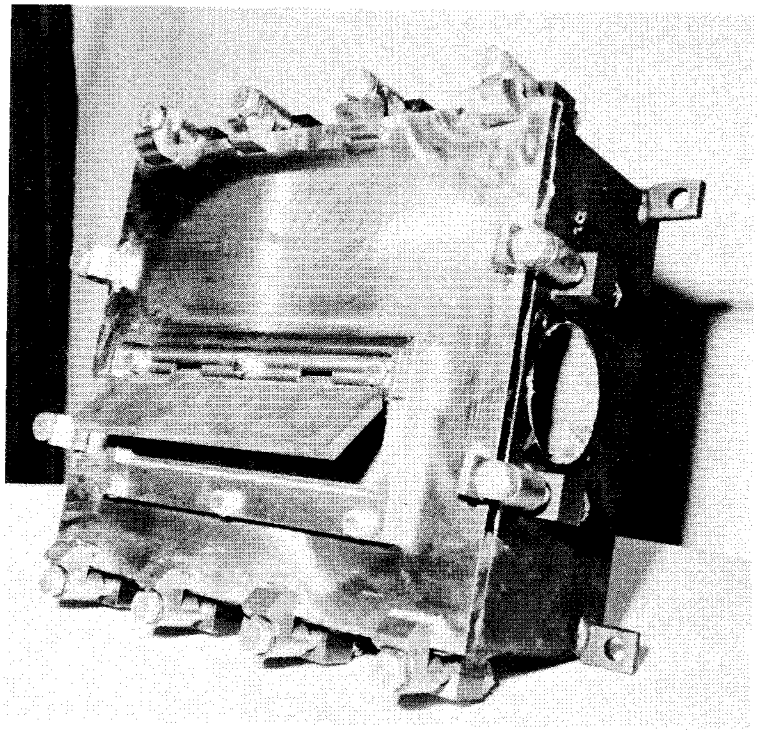


FIGURE 11. - The flange dog cover fasteners for quick access on a trailing cable connection box.

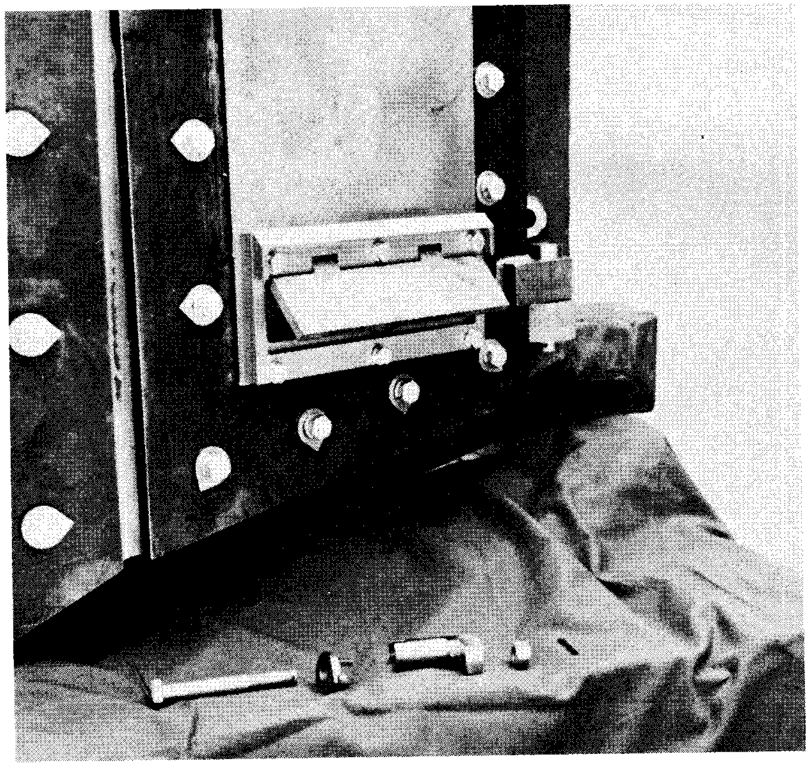


FIGURE 12. - The internal rotary keeper for quick access cover fastening.

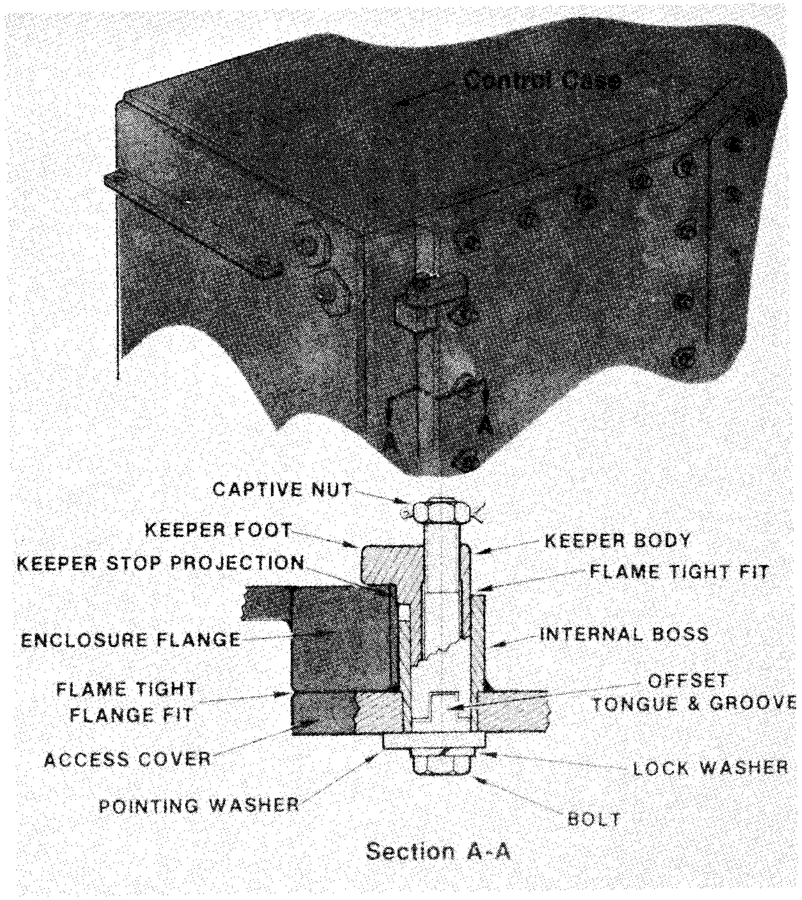


FIGURE 13. - Internal rotary keeper for explosionproof enclosure covers.

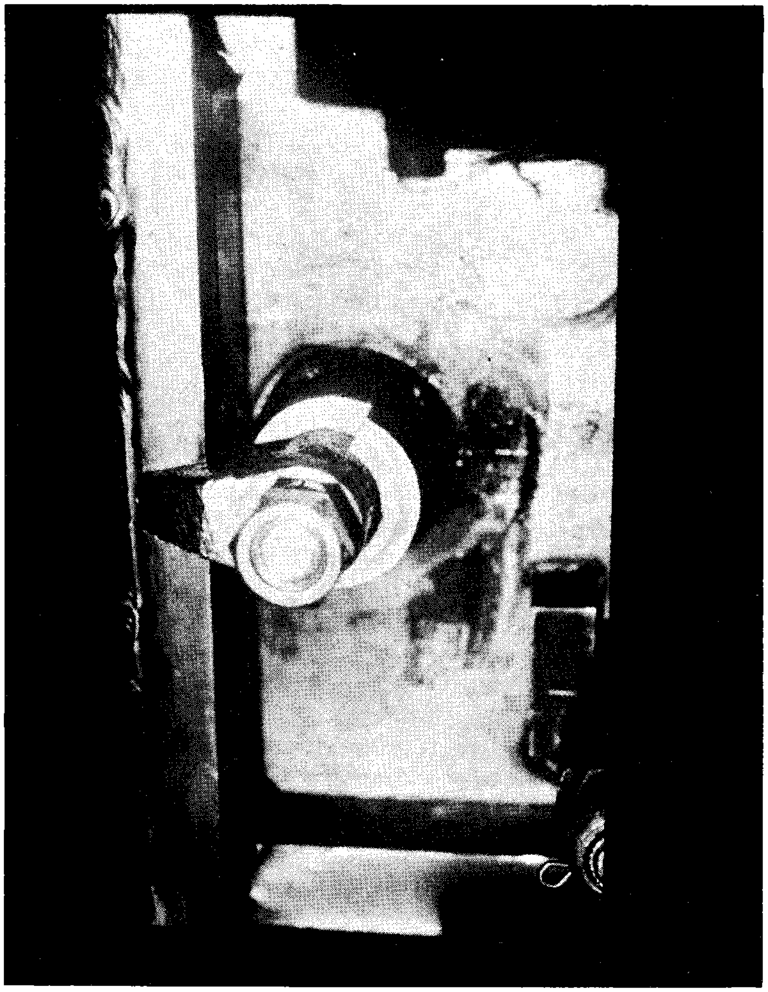
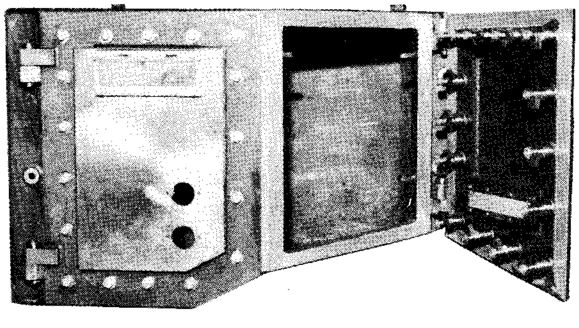


FIGURE 14. - Photo showing the keeper foot engaged under flange and the rotation stop.



ADVANTAGES:

- Eliminates large quantity of bolts that require multiple turns
- Flange surface free from bolt holes allowing easy cleaning and alignment
- Lift-off hinges provide cover support, alignment and keep cover off floor

FIGURE 15. - Quick access enclosure.

The internal rotary keeper (fig. 13) is rugged, has minimal external protrusion, and provides good clamping action. Because the fasteners are located inside the flange perimeter and have good area of contact, fewer rotary keepers are required compared with conventional bolts. The keeper foot is threaded and moves in and out as the bolt is turned, and the foot moves against a rotational stop (fig. 14). Approximately 1-1/2 turns of each bolt (13 threads per inch) are required to open or close. The pointing washer gives positive external indication of the keeper foot. All parts are captive.

Prototype hardware was machined from stock, but in production the keeper body pointing washer would probably be investment- or die-cast. The internal boss would be made from rod stock or possibly tubing, and the bolt and nut are standard (Grade 5). Figure 15 shows a "quick access" enclosure constructed utilizing the internal rotary keeper device rather than the conventional combination of screws and tapped holes in the flange. This enclosure will be used as a continuous miner control case.

UNDERGROUND COAL MINE EVALUATION

At this writing, a pressure-vent assembly and an innovative trailing cable entry assembly are ready for installation on a Jeffrey 120M continuous miner at a site in northern West Virginia (fig. 16). The vent is on a cover for the trailing cable connection box.

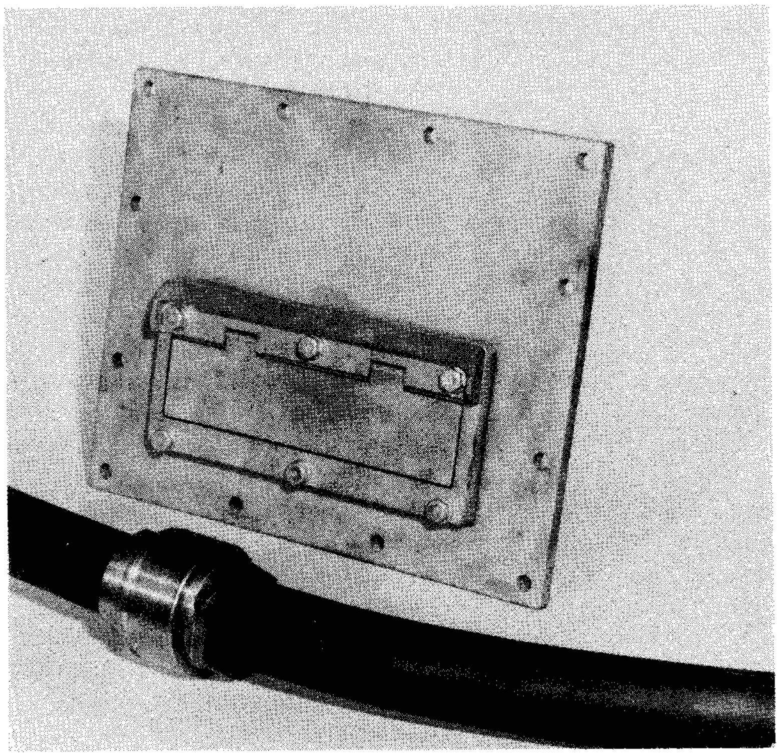


FIGURE 16. - Pressure vent and innovative cable entry for underground evaluation.

Both items are readily interchangeable with the conventional design. This hardware will be periodically evaluated over 3 months of regular production operations. The vent material will be replaced twice, and the removed vents will be tested in the laboratory for clogging and other potential deterioration. Early in the program, the metal foam was subjected to test after deliberate attempts to clog it with coal, rock dust, and oil. Results show it to be self-cleaning when subjected to a pressure differential. However, the evaluation underground should give further insight on need for inspection, cleaning, etc.

The continuous miner on which the innovative hardware will be evaluated is covered by an MSHA approval number. Data for the innovative hardware are being provided to the Bureau of Mines for use in obtaining a Bureau experimental permit.

FUTURE DEVELOPMENT

In addition to the underground evaluation, two tasks are underway. In the first, tests are being performed to establish design guidelines for application of pressure vents. The second task will establish innovative cable entry designs for a range of cable sizes. This work and the underground evaluation should be completed by year end 1979.

Patent disclosures have been filed through the Bureau of Mines for the pressure vent and for the internal rotary keeper.

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ARCING FAULTS IN COAL MINE ENCLOSURES

by

Frederick C. Trutt[1] and James W. Robinson[1]

ABSTRACT

Continuing research being performed by the U.S. Bureau of Mines and The Pennsylvania State University on arcing faults and their interactions with electrical insulating materials within coal mine power-system enclosures is described. Interim results are presented; additional research is planned to further integrate the simulations which have been constructed, as well as to continue application of developed experimental procedures to the evaluation of electrical insulating materials for use in coal mine enclosures.

The thrust of this research has been divided into several primary areas. These include the development of a theoretical procedure for computation of three-phase and line-to-line arcing fault currents as a function of time; formulation of an arc model based upon thermal-arc plasma properties so that arc voltages and energies may be computed; development of a simulation for pressure and temperature rises when an arc interacts with an electrical insulating material within an enclosure; experimental evaluation of electrical insulating materials in terms of their tendency to support an arc, as well as their potential contribution to enclosure pressure rises; and integration of the above research areas to form overall procedures for theoretical and experimental evaluation.

INTRODUCTION

Over the past several years, a number of incidents involving the bursting of flameproof coal mine enclosures have been reported in Canada, England, West Germany, and Poland (1-2).[2] Since it is known that a methane-air explosion alone cannot produce sufficient pressure to burst a standard flameproof enclosure, the cause of these incidents has been subject to speculation. The hypotheses advanced by the majority of researchers have indicated that gases generated by an arcing fault interacting with insulating materials within the enclosure may be responsible for the achievement of bursting pressures. This view has been supported by evidence of heavy currents and severe charring of insulating materials within all damaged enclosures. Further support for this viewpoint is also given by the work of Simon (9), which shows that the gases and heat evolved by application of an electric arc on an insulating material can burst a standard flameproof container. As a result, the Bureau of Mines decided to study the phenomenon further.

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

The selected approach consisted of complementary theoretical and experimental investigations aimed toward simulation of enclosure pressure rises when an arcing fault occurs, and toward the development of a means of evaluating insulating materials. Theoretical simulation has been divided into a number of related areas, as follows:

1. Developing a procedure for computing arcing fault currents in typical mine power systems as a function of time beginning with the instant of fault initiation. Three-phase and line-to-line arcing faults are considered of primary importance. It is assumed that faults involving ground will have arc currents limited by neutral grounding resistances. The contribution of induction machinery loads to the total fault energy is included.

2. Constructing an arc model for determining arc voltage as a function of arc current and enclosure pressure. In this way, the let-through energy to an enclosure during a fault may be determined if the instantaneous fault current is known.

3. Developing a model that will allow determination of pressure and temperature rises when an arcing fault interacts with a given insulating material. Let-through energy input from the arc model is required. This energy may cause pressure increases in the following ways:

   a. Initiation of an initial methane-air explosion or combustion.

   b. Heating of the enclosure atmosphere.

   c. Generation of additional gases within the enclosure due to decomposition of insulating materials.

It is also possible that the combustion of volatile gases, either initially present or generated, may cause additional arcing within an enclosure (2).

4. Integrating the previously described models to achieve an overall simulation of enclosure-pressure rises due to arc-material interactions in typical mine power systems.

Experimental investigations have been oriented toward the development of low-power tests for evaluating insulating materials that could be used in goal mine enclosures. Parameters considered to be of importance include material mass loss and pressure increase for a given arc exposure, the tendency to develop char and its resultant conductive path, the tendency to support an arc, ease of arc reignition, and flammability. To create the arcing situations necessary for a study of these variables, three experimental systems have been investigated. These include a capacitor discharge apparatus, a flywheel-generator system, and an arc welder. Using these devices, arcs may be created in a variety of ways on selected insulating materials, either with or without an enclosing pressure chamber, and the properties of interest for each material may be studied.

A brief summary of some of the procedures and results obtained in these areas of investigation is given herein. Additional information and results, as well as detailed discussions of theoretical and experimental approaches, are presented in the project's annual progress report (11).

THEORETICAL ANALYSIS

Fault Computations

A coal mine power system, such as that shown in figure 1, is a complex collection of electrical components, transmission cables, and mining machinery loads. To represent such a system for a given fault condition, a number of simplifying assumptions have been introduced. These include modeling circuit breakers as ideal switches, and representation of transformers, cables, and mining machinery motors by their electrical equivalent circuits. Typical impedance values are utilized for all components, and a typical set of prefault operating conditions for mining machinery loads (8) is assumed. Contributions to the fault energy from sections far removed from the fault are neglected because of the high impedance between these locations.

Using these assumptions as a base, and substituting and combining typical impedance and prefault loading values, Thevenin's theorem may be utilized to reduce a faulted power system to the representation shown in figure 2; $e_B(t)$ is the arc voltage and i is the arc (or fault) current, X_{in} and R_{in} represent the equivalent reactance and resistance, respectively, of the mine power system back to the utility connection, $E/\underline{\beta}$ represents the utility voltage source, X_m and R_m represent the combined equivalent reactance and resistance, respectively, of all pertinent system motors, τ is the combined equivalent time

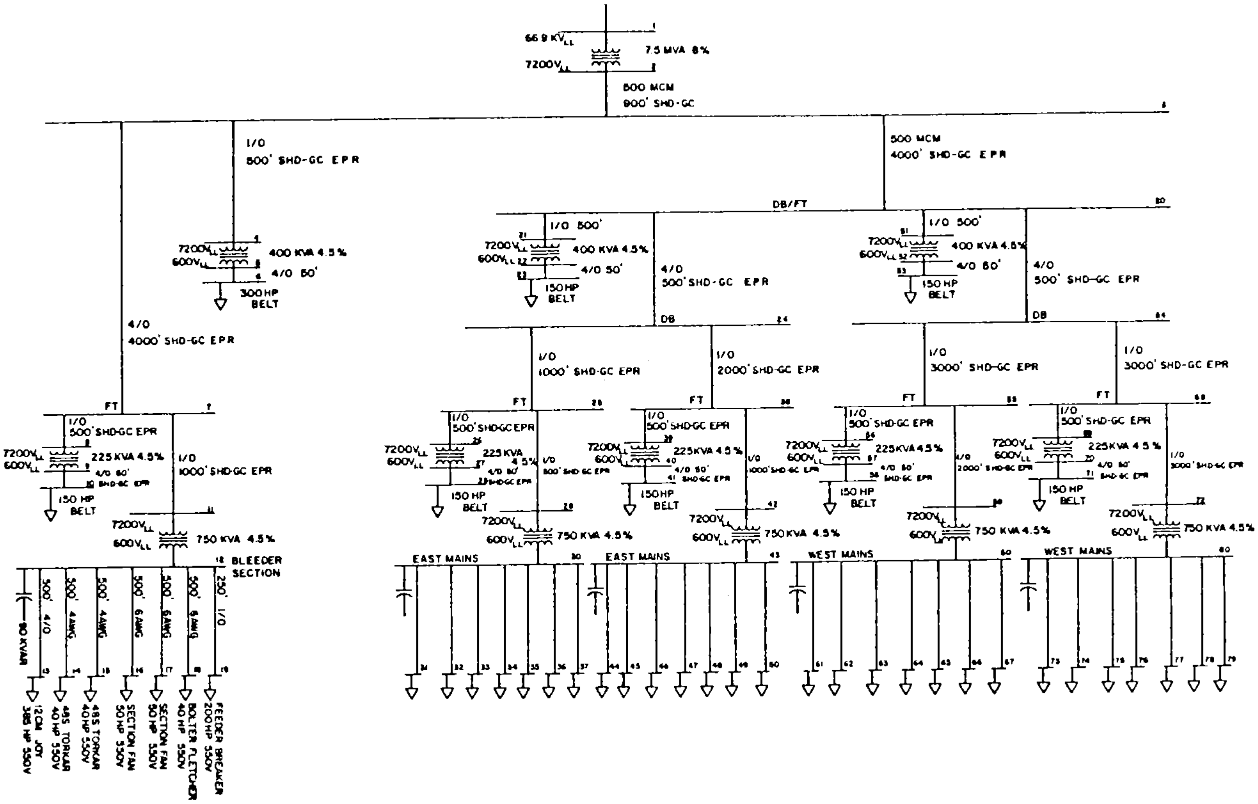

FIGURE 1. - A representative mine power system.

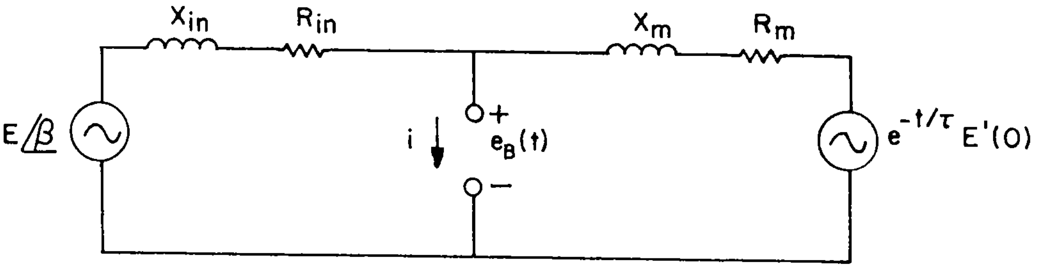

FIGURE 2. - Reduced mine power system equivalent circuit.

constant of the system motors, and E'(0) represents the combined equivalent initial motor voltage as determined from typical prefault operating conditions.

The problem of determining the fault current then reduces to a time domain solution of this circuit for a specified set of system parameters and the fault volt-ampere (e_B versus i) characteristic. During the course of this investigation, the following three methods for fault representation are being considered:

1. A simplified arc model which assumes a voltage, $e_B(t)$, of constant magnitude that changes in sign with the direction of the arc current.

2. An arc model based upon representation of the arc as a thermal plasma.

3. Representation of the fault by an impedance corresponding to resistive tracking through an insulating material.

Upon selection of a fault model, the fault current may be computed as a function of time. The energy delivered to the fault may then be determined as

$$W = \int_0^T e_B \; i \; dt, \qquad (1)$$

where W is the let-through energy and T is the assumed time duration of the fault. In this way, the energy available to interact with the enclosure environment and insulating materials for a given fault situation may be determined.

As an example of this type of computation, that a balanced, arcing fault has occurred on bus 12 of the power system shown in figure 1. The reduced mine power system equivalent circuit of figure 2 is then constructed from known component impedances and assumed prefault loading conditions. For this example, the simplified arc representation is utilized with an assumed arc voltage of ±30 volts depending upon fault current direction, and the system is solved with the aid of a Continuous System Modeling Program (CSMP) (10) on The Pennsylvania State University IBM 370/168 digital computer. Results showing the arc current and energy delivered to the fault are given in figures 3 and 4, respectively.

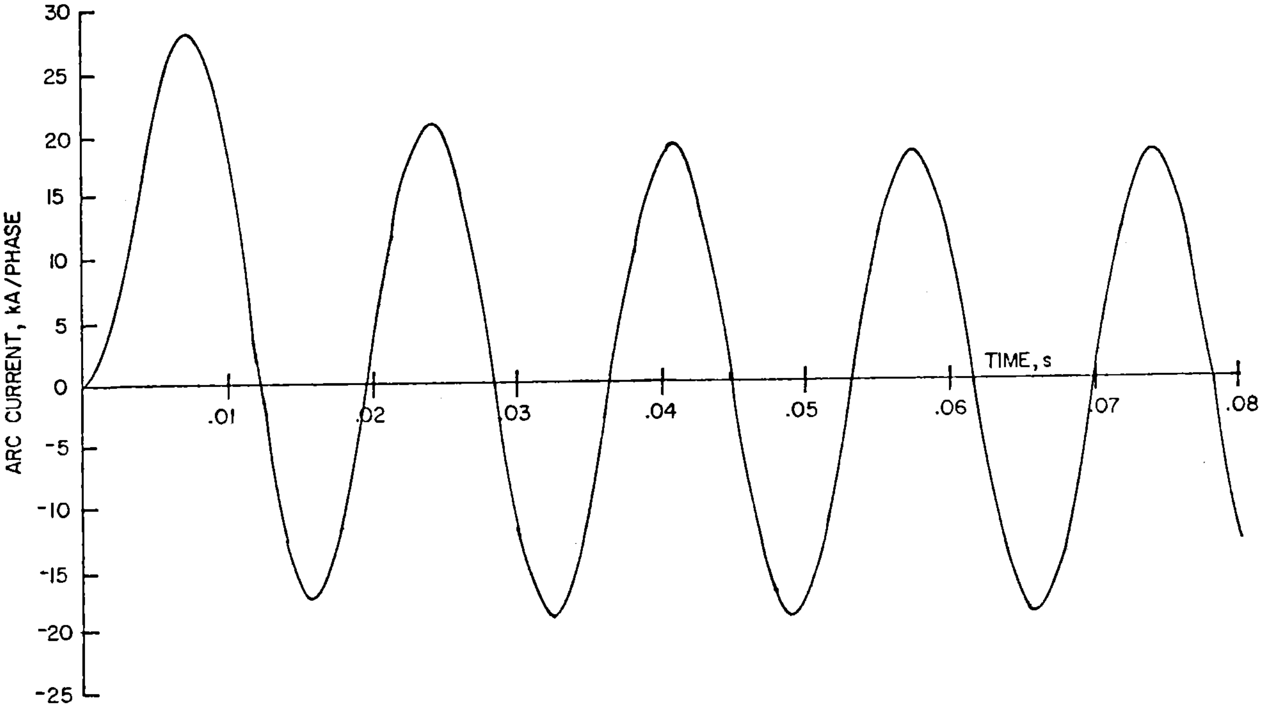

FIGURE 3. - Arc current for the specified fault condition.

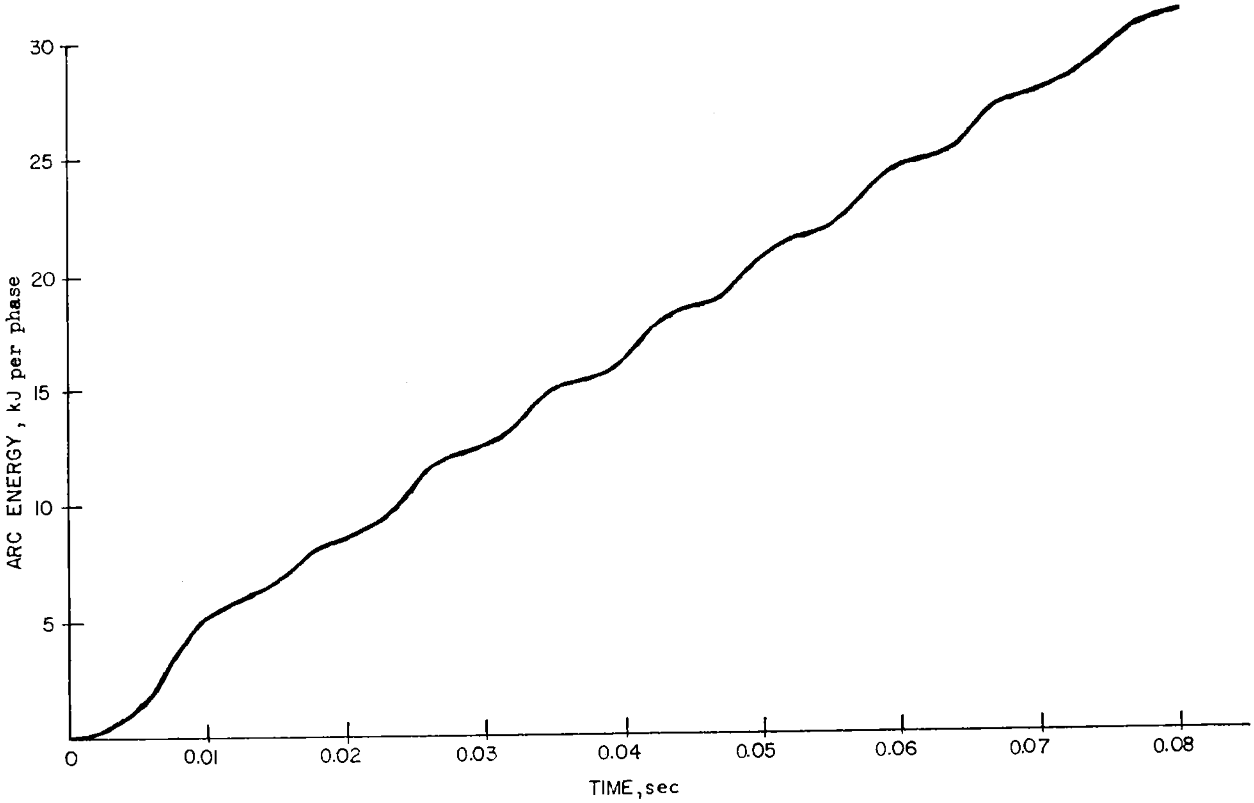

FIGURE 4. - Arc energy for the specified fault condition.

Similar computations may be performed for other fault locations as well as for different fault representations. Line-to-line faults may be modeled in a similar manner, except that positive and negative sequence impedances and the theory of symmetrical components are utilized in arriving at the simplified equivalent circuit (11).

Arc Representations

As discussed in the preceding section, an arcing fault in figure 2 may be represented by a simplified model consisting of a constant magnitude are voltage that alternates in sign as the arc current changes direction, or as a thermal plasma. The simplified model assumes an arc voltage that is independent of current magnitude as well as the pressure within an enclosure, but it is useful for comparative studies. However, the thermal plasma approach provides a means for incorporation of these dependencies.

The simplifying assumptions and theoretical approaches necessary for modeling the arc as a thermal plasma are given elsewhere (12) and will not be repeated here in detail. The procedures utilized involve confinement of the arc within an insulating material, and application of the Elenbaas-Heller energy balance equation (4-5) in a modified form to model a uniform thermal-arc plasma. Suitable boundary conditions are applied, and a pressure dependence is included by introducing nonlinear functions to represent variations in electrical path conductivity and arc energy radiation with increasing pressure. The resulting integral-differential equations are then solved for the arc voltage gradient as a function of current and pressure using iterative solution procedures on the digital computer. To achieve a solution, empirical data specifying electrical conductivity and energy radiation as a function of the arc heat flux and surrounding atmosphere are utilized. Since experimental data in this area is limited, the thermal-arc-plasma model is presently confined to fault currents of hundreds of amperes.

An example of arc volt-ampere characteristics determined in the manner outlined above is given in figure 5 for pressures of 1, 3, and 5 atm. In this case, the arc was considered to be constrained by a tube of insulating material having an inner radius of 0.25 cm, and it was assumed to occur in a nitrogen atmosphere. For purposes of comparison, measurements of a nitrogen-arc characteristic by Maecker (7) at 1 atm and by AVCO (1) at 3 atm are given.

Enclosure Pressure Rise

Once an arc model (or tracking model) has been selected to simulate a specific fault type at some location in the power system, the fault current and let-through energy to the fault as a function of time may be determined. The disposition of this energy, in terms of new particles generated within an enclosure by volatization of insulating materials, or by increasing the energy of existing particles, will then determine the resulting temperature and pressure rise within the enclosure. Internal combustion of volatile gases, as well as enclosure venting and heat-transfer characteristics, will also influence these parameters.

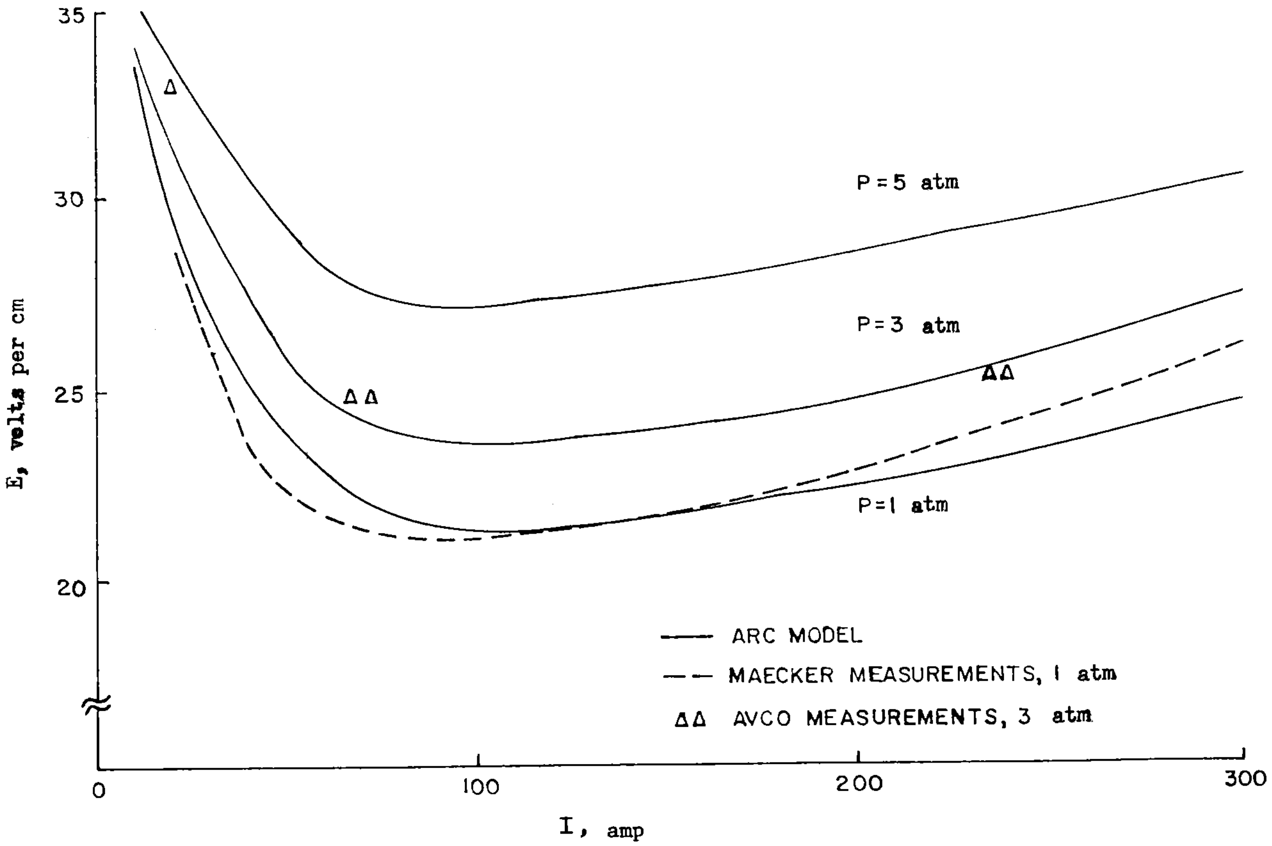

FIGURE 5. - Nitrogen-arc characteristics for different pressures; initial radius = 0.25 cm.

The theoretical determination of enclosure pressure rise requires simplifying assumptions as well as significant theoretical development (12) which cannot be detailed in this article. The basic procedure initially involves selection of an insulating material in which the fault will occur. Experimental data pertaining to the volatile products of this insulator produced at elevated temperatures, masses of these expelled particles, temperatures of decomposition, and heats of vaporization are then utilized in conjunction with the ideal gas equation of state and an energy balance equation to determine pressure and temperature rise within a specified volume enclosure during an incremental time period. This process is repeated over a number of time increments, during which an incremental amount of energy is supplied to the enclosure by the fault, so that temperature and pressure rise as a function of time may be determined.

Examples of such a computation for a polymethyl-methacrylate (plexiglass) insulator block are shown in figures 6 and 7. In each case, the thermal-plasma-arc model was utilized, and the fault current was assumed limited to 300 or 500 amp by an impedance in series with the fault. The initial arc radius was assumed equal to 0.25 cm in an enclosure of 0.001 m^3 free volume. The results of figure 7 reflect hydrocarbon dissociation of the volatile products of the polymethyl-methacrylate, while those of figure 6 do not allow for dissociation. Comparison of these results indicates that the particles created by dissociation do not increase the enclosure pressure as much as if the energy required to dissociate the molecules were utilized to increase the energy of existing particles.

Effects of an itial methane concentration with an enclosure may also be included in the analysis, as shown in figure 8. In this case, the fault current is limited to 300 amp and all other features remain as before. An initial 6-pct methane-air mixture is assumed such that an explosion may occur upon fault initiation. The explosion is assumed instantaneous with zero arc energy required for its initiation. Comparison with figure 6 indicates that the pressure increases at a greater rate in the case involving a methane

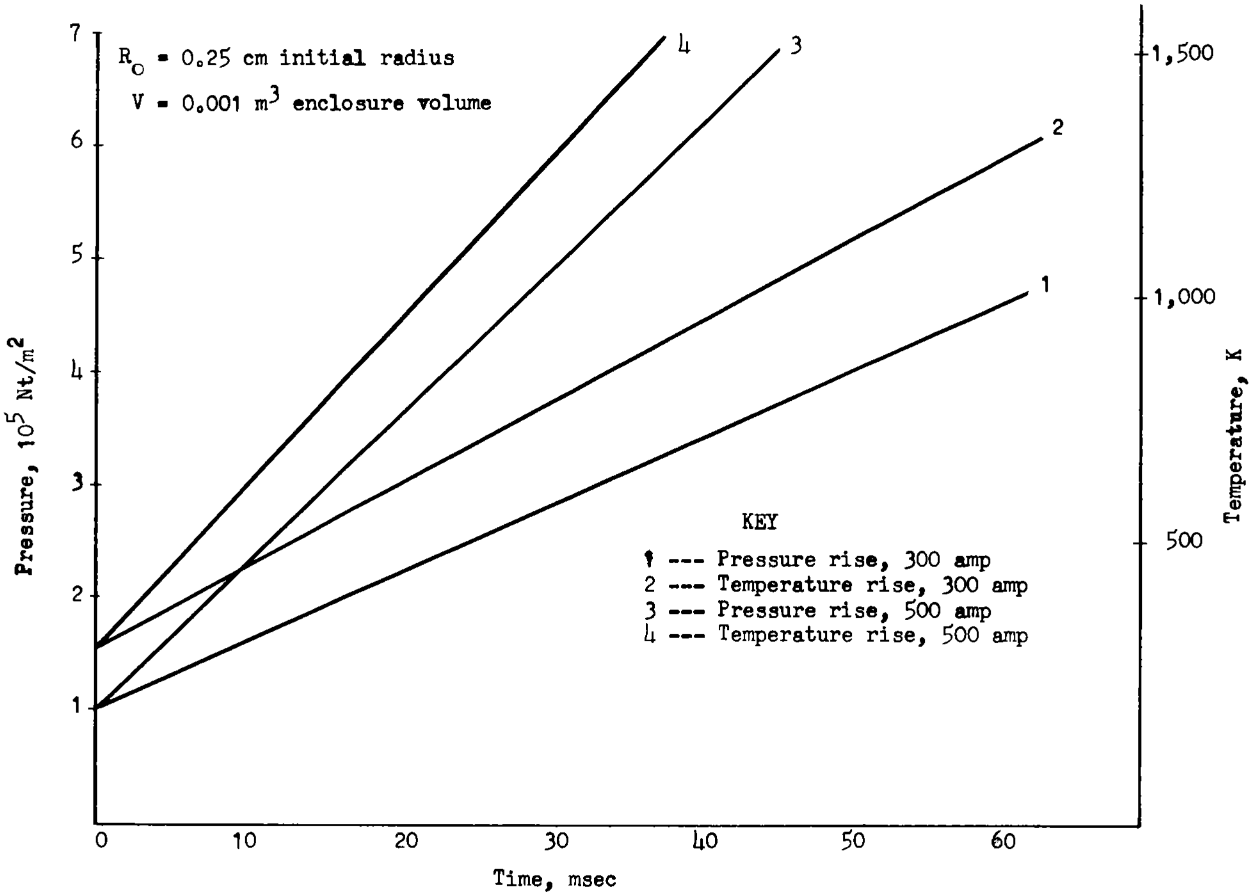

FIGURE 6. - Pressure and temperature rises due to electric arc within a polymethyl-methacrylate insulator block.

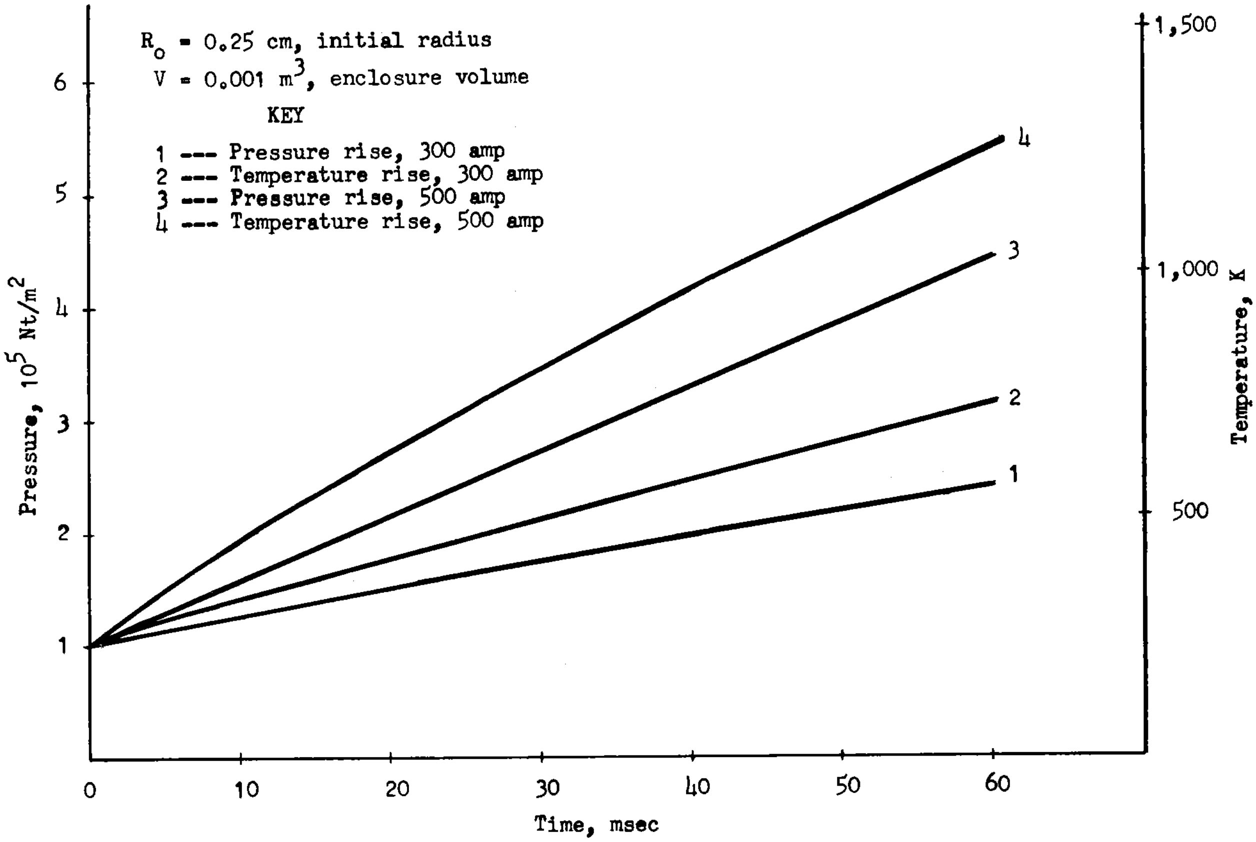

FIGURE 7. - Pressure and temperature rises due to arcing within the block of figure 6, with hydrocarbon disassociation.

explosion. This is due to high initial pressure increasing the electric field strength of the arc, thus increasing the energy dissipated by the arc. A relative pressure increase of approximately 20 pct over the case without the methane explosion is observed. Note that the methane explosion alone is not quite sufficient to challenge a 150-lb/in^2 rating of an enclosure, but the pressure increase due to the electric arc surpasses this rating after 20 msec.

The number of particles ablated from the insulator in the case of the methane explosion exceeds the number ablated in the original case by about 40 pct. This suggests that, although there is more energy dissipated by the arc, a greater portion of this energy goes into pyrolysis of the insulator rather than heating the enclosure atmosphere. Thus an equivalent relative temperature increase was not observed.

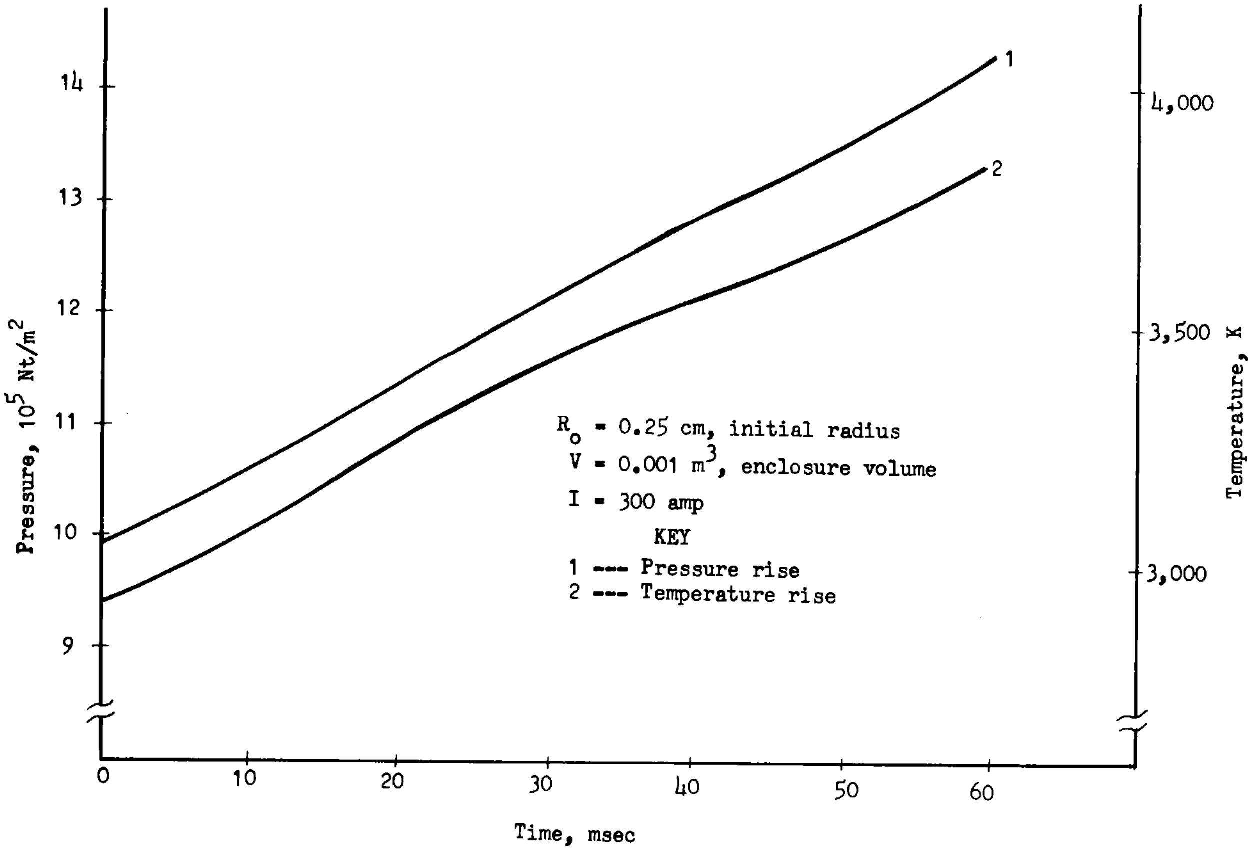

FIGURE 8. - Pressure and temperature rises within the block of figure 6, with an initial methane-air explosion and continued electric arcing.

EXPERIMENTAL PROGRAM

The experimental investigation of arcing and pressure rise in a closed container has been divided into two parts, which are distinguished by the magnitude of the arc current. Mechanisms that might case bursting of the container are significantly different in the two cases. Currents large enough to activate a breaker are considered to be in one category; currents that may persist for several seconds or even minutes are in the other.

High current arcs are presumed to be interrupted by a breaker; otherwise, designing a confinement system would be impractical. The action of the breaker limits the energy that may be deposited in a container and thus provides one guideline for design of an enclosure. Of course, the energy will depend upon the pressure inside the chamber at the time of arcing and the type of gas in the arc path. Some materials evolve hydrogen, which causes a relatively high arc voltage and, thus, a high energy. Nevertheless, an upper limit on energy is established by breaker action.

Arcs that do not activate a breaker will be of relatively low power but of unlimited energy. Consequently, the pressure produced by such an arc will build slowly as gas is evolved from dielectrics exposed to the arc. Chamber temperatures will be cooler because of ample time for heat conduction through the chamber walls, yet the pressure will increase as long as the arcing continues.

A summary of some of the experimental investigation that have been conducted are presented in this report. Detailed descriptions of experimental procedures and results are given by Trutt (11).

High Current Arcing

To achieve high current arcs, a bank of capacitors storing 5 kJ of energy was discharged across a 5-cm gap located within a sealed 0.82-liter pressure vessel. The oscillatory frequency of the discharge was 5,300 hertz, and the peak current was 22 ka. Although the discharge extinguished itself in approximately four cycles, the energy transferred to the chamber was, on the average, equal to about one-half of the stored energy. Power exceeded 1 Mw. A provision was made so that the arc path could be forced through a volume of water, and data were collected both with and without water present.

The principal results of these tests showed that adding water to the chamber increased the arc voltage and power such that total energy transfer also increased. Yet, even though greater energy was transferred with water present, the pressure rise was less. This result, perhaps surprising, is an indication of the fact that energy absorbed by dense materials is less effective at creating a pressure rise than energy which is expended in heating the existing gases in the chamber. The greatest pressure occurs when all of the energy is transferred to the existing gas.

One final caution is necessary. The energy transferred by a high current discharge will raise container pressure above its ambient level, and, if for some reason it is already high, then bursting of an otherwise safe container could occur. There are two possible ways of having a high ambient pressure. One would be that a detonation of methane could occur simultaneously or just prior to the arc, so that a high initial pressure would exist. Or, a low current arc might evolve a considerable amount of gas and raise the chamber pressure to a high level. The arc could then suddenly be transformed into a high current arc that could rupture the container.

The probability of occurrence of a stoichiometric mixture of methane and air is quite rare, and its coincidence with a high current fault even more so, yet this combination is a possible failure mechanism. The existence of gas evolved from a low current arc seems much more likely, and it is consistent with reported failures.

Low Current Arcing

In this category are placed those arcs that are current limited by a series impedance such that breakers do not trip. Arcing and decomposition of dielectrics can continue in a closed container over many seconds or minutes. Thus, the pressure gradually rises because of the accumulation of gases.

Temperature rises somewhat, but relatively little in comparison with the rise accompanying a high current arc. In this type of arcing situation, the arc characteristics and pressure rise depend strongly on the characteristics of the dielectric materials present.

Two test apparatus have been used to identify important material characteristics and to obtain representative data. One is a 15-hp generator that converts inertial, or flywheel, energy into an electrical pulse. This machine is capable of delivering up to 46 kw into an optimized load; typical usage has been in the range from 5 to 10 kw, with a total available energy of approximately 20 kJ. The other machine is a commercial arc welder rated at 200 amp. Each system has certain advantages. The 15-hp generator has the higher power capability and a larger open circuit voltage. Arcs 2 cm long can be maintained for several seconds in the presence of some materials. However, the power level and frequency drop rapidly as the rotor slows down. The welder has the advantage of providing constant power for a precisely controlled length of time such that measurements are more reproducible, and it provides an auxiliary high-frequency source to stabilize the arc. A further advantage is that similar welders would be readily available to others who wish to conduct tests. The main disadvantage is that its relatively low open circuit voltage requires that arcs be, at most, a few millimeters in length.

A test chamber and its associated instruments are used with either power supply. The chamber, having a volume of 6.5 liters, may be sealed or opened to the air for tests. By inserting inert fillers, one can reduce the volume to one-third of its normal value. Instrument transformers provide signals proportional to arc voltage and arc current, and a pressure gage provides a signal proportional to chamber pressure. The voltage and current signals are electronically multiplied and integrated so that a signal representing arc energy can be recorded along with the pressure signal on a strip-chart recorder. Oscilloscope traces show voltage and current waveforms.

Results of low current arc testing using these apparatus have indicated that the classification of dielectrics does not depend upon any single characteristic but upon many, including the tendency for tracking, the material's ability to support an arc once it has formed, the probability that a discharge will reform upon application of voltage after an arc has been interrupted, formation of a conductive char during the arcing process, gases evolved during decomposition, and the rate of evolution of these gases. Thus, a complete safety evaluation of a material should include consideration of these factors.

Many low power test procedures have been and are currently being conducted and evaluated as a means of classifying materials according to the properties specified above. Included are multiple fault initiations on a given specimen in a vented or closed chamber, measurements of mass loss per unit of delivered energy, evaluation of the ease of arc initiation and reignition, measurement of arc penetration, and so on. Upon completion of this experimentation, it is planned that low power testing procedures for the evaluation of insulating materials will be recommended.

CONCLUSIONS

During this investigation, methods and procedures have been developed for high and low power experimental investigations of arc-material interactions, theoretical determination of arc characteristic, simulation of pressure and temperature effects when an arc of specified current occurs in an insulating material within an air- or methane-air-filled enclosure, and computation of three-phase and line-to-line arcing fault currents as a function of time for typical mine-power-system configurations. These methods all appear well-suited to the research objectives and are providing useful information on enclosure safety.

Significant findings and conclusions thus far include the following:

1. Mine-power-system peak fault currents are typically 20 ka, though at these levels where breakers interrupt the current, the characteristics of the dielectric materials are of little significance. The worst possible case is one in which all of the arc energy is expended heating the existing gas.

2. When faults occur in high-impedance circuits such that currents are limited to hundreds of amperes, breakers may remain closed. Under this condition, gases evolved from dielectric materials may cause high pressures to develop.

3. Modeling requires numerous simplifying assumptions, among them the extent of homogeneity of gases in the chamber, the rate of heat loss to walls, the geometry of the arc, and the products of pyrolysis. Theoretical models are qualitative at best, and they are useful in parametric studies related to the early stages of the arc. Computer simulations of low current arcing and the pyrolysis of insulating materials have demonstrated the following useful concepts:

   a. For a given arc current, the greater the dissociation of pyrolysis products, the less is the pressure rise.

   b. Power and pyrolysis rate increase as pressure increases, though not drastically.

   c. Higher pressures are generated in smaller chambers.

4. Computer computations of arcing fault currents in a typical mine power system have indicated that--

   a. Energy stored in rotating machinery loads may contribute significantly to the arc energy.

   b. As expected, line-to-line arcs should contribute less energy to an enclosure than a fault involving all three phase conductors.

   c. The most severe fault location appears to be the load center bus because the line impedance limits fault current and thereby prolongs fault clearing time.

5. Certain materials, especially those that develop a conductive char, will support an arc for long periods of time while continually evolving gaseous byproducts. These should not be used where they might be exposed to arcs.

6. A desirable property of material is that its response to arc exposure will be the formation of nonconductive residues that act to extinguish the arc.

Planned research involves extension, refinement, and utilization of theoretical and experimental approaches, including refinement of low-power testing procedures for the safety ranking of insulating materials, and the performance of such testing upon materials found in coal mine enclosures. An additional area of consideration will be the uncertainties involved in projecting low power information to mine power levels, and the possible need for supplementary high power testing. Planned theoretical work includes the elimination of certain simplifying assumptions, the refinement of theoretical approaches, investigation of the effect of a hydrogen atmosphere upon arcing, integration of procedures, and further application to the real situations of interest.

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INT.-BU.OF MINES,PGH.,PA. 23934