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COAL MINE ELECTRICAL SYSTEM EVALUATION, VOLUME III - SHIELDED CABLES

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by

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CERTIFICATION OF THE ABSENCE OF PATENTS AND INVENTIONS

This statement certifies that at the grant report date, no inventions have been developed from Grant G0155003. Consequently, no patents are pending.

Lloyd A. Morley, Project Director

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16. Abstract

Proposed advantages and disadvantages of low-voltage shielded trailing cables are formulated utilizing the literature and industry sources. A partial analysis of these proposed advantages and disadvantages is completed through a review of the literature. Cable costs are assembled from mine operators, cable and splice manufacturers, and actual cable purchases.

To confirm each advantage and disadvantage, an underground test site is established, and testing is performed here and in the laboratory. All testing procedures are completely described. The results of this investigation are reported and used to formulate recommendations attendant to low-voltage shielded cables. Suggestions for installation, handling, and maintenance are presented.

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This report is a summary of the work recently completed as part of this grant during the period 5 November, 1975 to 4 November, 1976. This report was submitted by the authors on 15 January, 1977.

This technical report has been reviewed and approved.

PREFACE

This document is also available as a thesis from the Department of Mineral Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802.

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Special thanks are in order for the many people in the underground coal mining industry for answering countless questions and permitting field trips and experimentation in their mines. An indebtedness exists also to the many sources within the electrical cable industry for their aid.

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To confirm each advantage and disadvantage, an underground test site is established, and testing is performed here and in the laboratory. All testing procedures are completely described. The results of this investigation are reported and used to formulate recommendations attendant to low-voltage shielded cables. Suggestions for installation, handling, and maintenance are presented.

CHAPTER I

INTRODUCTION

A number of accidents involving miners who were handling or repairing energized trailing cables have led Mining Enforcement and Safety Administration (MESA) personnel to propose shielding for low-voltage trailing cables, purely as personnel protection. However, several difficulties are anticipated with such a switch. Included among these problems are cost, maintenance, proper cable construction, and physical characteristics such as size and weight. The objective of this report is to evaluate the hypothesis that shielded low-voltage trailing cables is a practical solution to the safety problem resulting from miners handling energized cables.

Shielding is currently used in underground coal mines in the United States for high-voltage power feeder cable and, in isolated instances, for medium-voltage trailing cables. Power feeder cable supplies power from the mine's main substation to the load center of each working section. It is normally hung from the roof of the mine. The other type - trailing cable - is "flame resistant, flexible cable or cord, through which electrical energy is transmitted directly to a machine or accessory"(63). The Federal Coal Mine Health and Safety Act of 1969 requires that all underground high-voltage (more than 1000 V) cables used in resistance grounded systems be equipped with metallic shields around each power conductor (9, 64). The Act requires medium-voltage circuit cable (661 to 1000 V) to contain grounded metallic shields around each power conductor, or a grounded metallic shield over the assembly. However, on medium-voltage equipment employing cable reels, cables without shields may be used if the insulation is rated 2000 V or more. Shielding is not currently used (to a significant extent) on any reeled vehicles. No provision is made in the Act for the shielding of low-voltage cables (up to and including 660 V).

A study conducted by MESA personnel has shown that more than 96 percent of 1,404 recent injuries related to electricity in underground bituminous coal mines were caused by the following: (43)

1. arcs which result in burns,
2. electrically generated heat resulting in burns and scalds, plus
3. electrocution and shock.

For the years 1972 and 1973, approximately 80 percent of the 1,404 accidents resulted in electrical arcs and burns (43). As can be seen from Table 1, contact with energized cables was the leading cause of arcs and burns.

Attendantly, Mason (43) recommends an investigation of the use of cables with circuit conductor shields to prevent shocks, burns, and arcs. This research will evaluate the effects of requiring low-voltage cables to be shielded.

Prior to making a statement of the problem, a few definitions must be presented. The cable shielding configuration known as the SH-D cable is illustrated in Figure 1; note that a metallic shield surrounds each of the three phase conductors. The SH-C type cable with a common shield for all phases is illustrated in Figure 2. For low-voltage applications, either of the configurations can consist of metal tape, metal braid, or single wires. Several cable producers utilize a shield consisting of a fabric-copper braided combination. High-voltage cable applications dictate the use of a semi-conducting material in addition to the metallic shield.

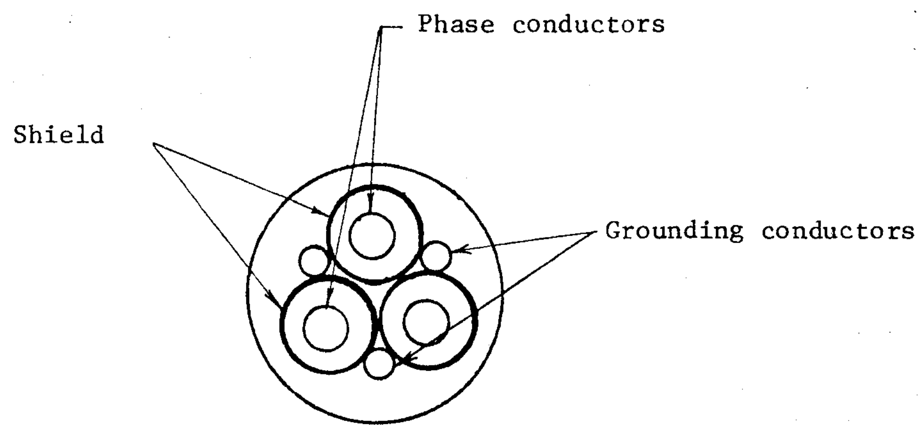

Figure 1. Three-conductor Round Type SH-D.

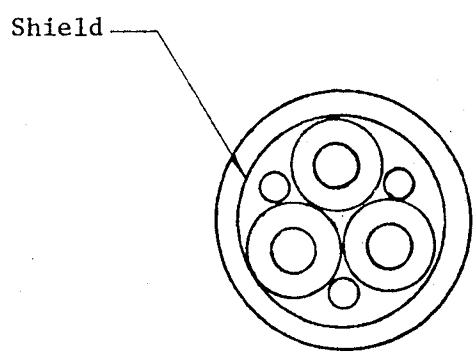

Figure 2. Three-conductor Round Type SH-C.

Table 1. Main Causes of Electrical Arcs and Burns in Mining Situations (Mason, Reference 43).

Cause	1972 Number	1972 Percent	1973 Number	1973 Percent
Cables	155	29.92	197	32.40
Trolleys	81	15.64	94	15.46
Switches	58	11.20	80	13.16
Haulage Equipment	35	6.76	60	9.87
Electrical Apparatus	25	4.83	31	5.10
Power and Lighting Circuits	18	3.47	21	3.45
Mining Machinery	15	2.90	31	5.10
All Others	131	25.28	94	15.46
	518	100.00	608	100.00

Statement of the Problem

Each year in the underground coal mining industry, a number of fatal and non-fatal injuries are caused by low-voltage trailing cables. According to common opinion, shielding will increase safety, especially in the area of shock protection. The introduction of low-voltage shielding, while providing additional safety, will also pose several new problems or intensify old ones for underground coal mine operators.

One problem associated with shielded cable is higher purchasing cost. For instance, shielded cables may cost as high as 68 percent more. Further, the general industry consensus is that shielded cables take longer to install, are more difficult to troubleshoot, and are harder to splice. Thus, the problem of higher initial cost could possibly be compounded by high maintenance costs brought about by more materials per splice and longer down time per splice. It is doubtful that workers would realize the additional cost factors and take better care of shielded cable. Another uncertainty for mine operators is how these cables last relative to their non-shielded counterparts. The determining factor here may be damage caused by flexing shielded trailing cable. Flexing damage would most likely occur on a machine employing a cable reel.

All of the above considerations lead to the question of whether the additional safety achieved by shielded low-voltage cable use can justify the added costs. It must be stressed that not just any shielded cable will work. Therefore, of vital interest is proper shielded cable design and construction as dictated by various safety and economic considerations. An area of prime concern here is finding out what percentage of coverage of the insulation by the shield is actually needed to prevent injury. The shield must also be constructed to be flexible, to present a resistance to crushing, and be able to transmit enough current to trip the outby circuit breakers. Both type SH-D and SH-C cable construction should be specified and analyzed.

Scope of Work

A change from non-shielded low-voltage cables has brought about several questions. The scope of work is devised to provide an efficient method of solving the perplexities. A review of literature concerned with shielded cable should be conducted. Proposed advantages and disadvantages should be extracted using this literature and other applicable sources. The ultimate goal should be to prove or disprove the advantages and disadvantages.

An accident analysis should be included to determine the safety gains possible with low-voltage shielding. Following this, a series of laboratory tests must be undertaken, including percent coverage experiments, a splicing time-study, plus flexing of cables and shielding components.

To obtain a clear demonstration of the preceding work results, an underground site for the in-mine testing of shielded cables must be established. Cable and splice kit purchases for this site will provide a good indication of additional direct costs that might face the mine operators. Added cost information relative to capital expenditures on the part of cable producers can be assembled. The underground test site will aid the gathering of data in a number of areas. Included here are fault locating, splicing, and problems associated with reeling and dragging cables.

This report will then be limited to a feasibility study of low-voltage shielded trailing cables. Such cables are examined for use in the United States for underground continuous mining of coal. Various types of shields will be analyzed. Included are cotton-copper (or nylon-copper) braid, full copper braid, and wire shielding in conjunction with semi-conducting material. The research will cover both reeled and drag cable applications.

Report Format

The following chapter commences with a presentation of the literature review which is pointed at shield theory, construction, and underground usage. Penetrating coverage is given to low-voltage shielded cable proposed advantages and disadvantages. The next chapter will then detail the underground and laboratory testing procedures necessary for evaluation of these advantages and disadvantages. Afterwards, the efficiency of shielding and percent coverage are discussed, along with a thorough description of proper shielded trailing cable splicing methods and suggestions for proper cable constructions. A discussion of the laboratory and underground testing results, along with recommendations, will be presented in the fourth chapter. The final chapter will cover conclusions and suggestions for future research. Appendices to the report are constructed to report field investigation findings, to give background on ampacity and tensile strength ratings for cables, plus other related areas.

CHAPTER II

LITERATURE REVIEW

Theory

The Simplex Manual (56) explains the practice of shielding an electric power cable as confining the electric field to the inside of the cable insulation by surrounding the insulation or assembly with a grounded conducting medium called a shield. In practice, two shield types are used: metallic shields which cover the insulation only, and nonmetallic or semi-conducting shields that may cover the conductor or the insulation (56, 62). The roles of the conductor shield are to eliminate voltage stresses in air spaces or voids between the conductor and insulation and to present a smooth electrode to the inner insulation surface (26, 56, 61, 62). The conductor shield is not utilized in the low-voltage applications covered herein (33), and therefore will not be discussed further.

Insulation shielding, the second type, performs three principal functions (26, 61).

1. It attempts to obtain a symmetrical radial stress distribution and to eliminate tangential and longitudinal stresses on the insulation or outer jacket surface.
2. It provides a continuous capacitance to ground for the conductor thus providing a uniform surge impedance and minimizing the reflection of voltage waves within the cable.
3. It decreases the hazards of shock, fire, and explosion.

Decreasing shock hazards is the most important shield function coupled with this research. However, the ability to reduce electrical stresses in insulation is first summarized in the following to provide adequate background coverage of the concept of shielding.

Stress Distribution. Radial stresses are always present in cable insulation when the cable is energized. If the electrical field is uniformly distributed about the conductor, within the envelope of the cable insulation, the most efficient insulation utilization arises. A nonuniform electric field increases the radial stress thereby reducing the effective dielectric constant. A shield, applied over individual conductor insulations, removes the cable fillers from the electric field. This creates a symmetrically distributed radial stress, utilizing the insulation to its greatest efficiency and in the direction of highest strength (26).

A basic law of electric fields states that when a voltage is applied across dielectrics in series, the voltage will divide in inverse proportion to the dielectric constant of the material (26, 61). Therefore, an air gap in series with the cable insulation will have a portion of the voltage appearing across it. The voltage can approach the full conductor potential if the air gap is sufficiently large, and it will be near ground potential when the surface is in contact with a grounded surface. Tangential and longitudinal (normal) stresses result at the interface of materials with different dielectric constants.

Tangential stresses are always associated with nonuniform radial stresses and occur in non-shielded multi-conductor cables. They also take place in all single-conductor non-shielded cables which have been installed so that non-symmetrical relations exist between conductor and adjacent grounded surfaces (26, 61).

Longitudinal stresses are not necessarily related to nonuniform radial stresses but are always connected with radial stresses of different magnitude along the cable length. Longitudinal stresses occur in non-shielded cables installed so there are intermittent contacts or variable spacings between the cable surface and grounded objects. Examples are metal conducting areas and wet spots in ducts (26, 56, 61).

A properly applied external shielding system will eliminate tangential and longitudinal stresses by bringing the entire surface to ground potential (26).

Cable Capacitance. Relative to providing a definite continuous capacitance to ground for the insulated conductor, the following should be considered. Cables which are laid in ducts or directly in the earth will often run through sections with varying electrical characteristics (for example, dry or wet soil). The results of both is fluctuating electrostatic capacity to ground, hence a change in the surge impedance of the cable (26, 61). In addition, cables entering metallic ducts or risers will have a change in impedance due to varying capacitance to ground.

In cables connected to overhead lines, traveling waves due to lightning strokes or induction from charged clouds or fog drifts will be partially reflected at surge impedance discontinuities, resulting in escalating the surge voltage in the cable (61). A breakdown of the insulation may result. In some cases where cables run through very dry ground, traveling waves may be induced by direct induction from the clouds (61). A metallic shield applied over the insulation of individual conductors or over the entire assembly of a multi-conductor cable reduces the cable surge impedance as well as the discontinuities. This is very important in minimizing the effect of power system transients (22).

Shock, Fire, and Explosion Hazards. As was previously discussed, when the outer insulation or covering surface of insulated cables is not in contact with a ground throughout the entire cable length, a large potential difference may exist between the outer surface and the ground. Touching an energized area may startle a victim, resulting in falls or other secondary accidents even if the electrical shock was not lethal. Obviously, contact with the covering under some conditions may be an electrical shock hazard if the charging current from a considerable cable length is carried by the covering to the contact point. As an example, this might occur on a heavily-contaminated, damp cable surface (26, 61). A final hazard condition could arise when the potential difference is sufficient to cause sparking, resulting in ignition of explosive gas mixtures.

A properly-grounded metallic shield will eliminate these hazards by confining the electric field to the insulation and providing a path to ground. However, the shield should be applied over the insulation of the individual conductors rather than the entire assembly to obtain best results. Shielding provides additional personnel protection when handling cables containing bad splices or faulty insulation. A certain amount of protection is also provided for workers who cut into an energized cable. Because of the paramount importance, these and other personnel protection advantages receive further coverage later in this chapter.

Shield Construction

The high-voltage insulation shield is generally comprised of two parts. The first is an extruded layer of wrapped electrically conducting material (actually a semi-conductor) which is applied directly over the insulation. The second portion is metallic and nonmagnetic and, as mentioned in the Introduction, it typically consists of metal tape, metal braid, spirally-wound metal wires, a cotton or nylon twine combined with metal wires, or a metallic sheath (26, 68).

The first part of an insulation shield, the semi-conductive material, is considered to have a shield area of coverage of 100 percent but has an associated high resistivity. The type of shield, composed entirely of copper braid, covers 85 percent of the area, while wire shielding or cotton-copper braid covers 65 percent (33). Wire shielding consists of uni-directional spirally-wound wires. Anticipated changes to Section 75, Title 30 would set the minimum coverage at 84 percent for metal braid shielding and 60 percent for wire shielding and cotton (or nylon)-copper braid (2).

The insulation shield must be in intimate contact with the insulation under all conditions in order to be effective. The metallic portion serves as a current carrying medium for charging and leakage currents (26).

Section 75.804(a) (underground high-voltage cables) of Title 30, Code of Federal Regulations requires the use of the SH-D shielding configuration for high-voltage (greater than 1000 V) applications and states: (64)

> Underground high-voltage cables used in resistance grounded systems shall be equipped with metallic shields around each power conductor with one or more

in the ground wires and reduces the possibility of heavy induced circulating currents. Therefore, through shielding, the problems of nuisance tripping and inter-machine arcing might be lessened (4).

3. Shields maintain the integrity of the cable grounding system (4).
4. Shielded cables may have a lower operating temperature.
5. Maintenance testing of shielded cables is more easily accomplished (38).

The items listed below are the possible disadvantages of low-voltage shielded cables.

1. Shielded cables have higher purchasing and operating costs (4, 23, 27, 39, 53).
2. Limited availability of a wide range of low-voltage shielded cables might create future problems (23, 39).
3. The possibility of reduced cable life from impaired flexibility might exist (4, 11, 23, 27, 29, 39, 52, 53).
4. Extra steps are involved in splicing and a limited splice life may result due to the inability to effectively replace the shield within a splice (23, 27, 37, 39).
5. Crushing the shield during equipment runovers, roof falls, and rib sloughing could decrease safety and increase downtime (4, 29, 52).
6. Shielded cables are slightly larger in diameter than non-shielded cables. This may cause a reduction in

> ground conductors having a total cross-sectional area of not less than one-half the power conductor, and with an insulated internal or external conductor not smaller than No. 8 (AWG) for the ground continuity check circuit.

Either the SH-D or the SH-C insulation configuration is permitted for medium-voltage cables (from 661 to 1000 V) under Section 75.907, "Design of trailing cables for medium-voltage circuits": (64)

> Trailing cables for medium-voltage circuits shall include grounding conductors, a ground check conductor, and grounded metallic shields around each power conductor or a ground metallic shield over the assembly, except that on equipment employing cable reels, cables without shields may be used if the insulation is rated 2,000 volts or more.

In summary, the SH-D type cable provides the following four functions (26, 61).

A. Creating a uniform capacitance from conductor to ground, resulting in a uniform surge impedance along the cable, thus preventing partial reflections and the consequent building up of the surge voltages within the cable.
B. Providing maximum capacitance from conductor to ground, thereby effecting the maximum reduction of the incoming surge potential.
C. Absorbing surge energy in the same manner as the conductor by reason of the current induced magnetically in the shield.
D. Reducing stress on insulation under many circuit arrangements because surge potential will momentarily exist on both conductors and shield.

The SH-C type cable has been found to be somewhat less effective with respect to items A and C above and also does not provide maximum capacitance (item B). However, it is an improvement over non-shielded, non-metallic-covered cables and is probably equal to type SH-D for function D (61).

The addition of a ground-check wire, which is used to verify the continuity of the cable grounding system, gives rise to several other cable configurations (68). When the ground-check wire replaces one of the ground wires in the cable, the G-GC, SHC-GC, or SHD-GC designations are used (68). Placing the ground-check wire at the center of the cable while retaining all three ground wires results in the G plus GC, SHC plus GC, or SHD plus GC cable types.

Underground Usage

At least one large western mine extensively uses low-voltage SH-D shielded cables on its equipment (4). Trona is produced at this underground mine with conventional and continuous mining sections which are very similar to their counterparts in underground coal. The company's original decision to employ these trailing cables was based on the inherent safety features, mainly the low shock hazard. A safety record compiled for more than 15 years of shielded cable usage has shown the decision to be sound.

This fine underground cable safety record is apparently no surprise to engineers who are familiar with surface mining applications (4). Most surface mines utilize shielded high-voltage trailing cables. As a result, extensive experience in shielded trailing cables has been attained. The additional safety in high, as well as low-voltage applications is largely the result of having shielded conductors in addition to the ground wires. This added safety is a consequence of the additional grounding ability obtained by surrounding each conductor with a grounded shield. Essentially all cable faults then have to be of a line-to-ground nature (48).

However, an apparent underground mining industry concern about introducing a low-voltage shielding requirement is that they may not be as good as non-shielded cables in withstanding the rigors of underground mining (especially in cable reeling applications). Using a flex test and a cable reel cycling test, experiments performed by one cable manufacturer on SH-D have revealed adequate flex life (4). In a flex test to "destruction" of a type SHD plus GC, all grounding conductors, all shield wires, and the phase conductors were broken. The ground-check conductor remained intact. In spite of all the damage, ground continuity was maintained because the interwoven (or braided) copper shield provided numerous parallel paths. This piece of literature makes no mention of whether a dielectric strength test (insulation test) was performed on the flexed cable. Quite possibly, the broken shield or phase wires could have damaged the insulation.

Shielded cables are currently being used at the Jenny mine, a joint project of FMC Corporation, Island Creek Coal, and the U.S. Bureau of Mines. The Jenny Mine personnel feel that shielded cables have greatly increased safety features, and a complete listing of their reasons can be found in Appendix I.

Proposed Advantages and Disadvantages

After reviewing the appropriate literature concerned with shielded cables and conferring with industry sources in the field, it becomes apparent that shielded cables could have several advantages as well as disadvantages. A listing of the possible advantages follows.

1. Shielded cables provide protection from electrical shock and are more sensitive in terms of circuit breaker settings (a shielded cable can cause an interrupter to trip in cases where a non-shielded cable would not necessarily do so) (4, 27, 53).
2. Shielding maintains the symmetry of cables. A cable which is symmetrical in cross-section eliminates induced voltages

the amount of cable which can be placed on a reel (37, 52, 68).

7. Shielded cables are stiffer, making drag cables slightly harder to handle (27, 52). Associated with this stiffness may be a difficulty in feeding a cable onto a reeling device, requiring additional tension.

8. Locating internal faults on shielded cables may be difficult (23, 39, 53).

9. Shielded cables weigh more than non-shielded cables (23, 27, 39).

10. Time required to install couplers is longer for shielded cables because of the extra connection for the shield (52).

In the following paragraphs, each of the proposed advantages and disadvantages will be discussed and proved or disproved from available material. The unanswered questions will then be attacked through additional research. However, in order to provide an understanding of why improved grounding is necessary, a brief discussion of electric current and the human body is presented next.

Effects of Electricity on the Human Body

The amount of electric current which is tolerable by the human body depends upon the frequency, magnitude, and duration of the current flowing through the vital areas of the body. The human body is most susceptible to alternating currents with frequencies of 50 to 60 Hz, and the body can tolerate as much as five times as much direct-current (17). Studies have shown, however, that for frequencies ranging from

10 to 300 Hz the response of the human body is practically uniform (15).

Let-go current can be defined as the maximum current that the body can tolerate and still be able to release or let-go its grasp of an energized conductor by using the muscles directly stimulated by that current (17). The 60 Hz let-go current is approximately 9.0 mA (milliamperes) and 6.0 mA for men and women, respectively. Reasonably safe let-go d-c currents are 62 ma for women and 81 ma for men.

At values of current greater than let-go current, breathing becomes difficult or impossible due to paralysis of the breathing muscles. Power systems should be designed so a man will not be subjected to more than 9.0 mA a-c or 60 mA d-c for a length of time which results in death from asphyxiation (17).

The condition in which the heart beats wildly and out of control is called ventricular fibrillation. It results when a small current passes through the heart and disturbs its normal, coordinated rythm. The human heart does not recover spontaneously from ventricular fibrillation and while the heart is in this condition, there is no circulation and death will ensue (46). Whether or not fibrillation occurs depends upon the magnitude of the current flow, current duration, and the body weight of the individual (17).

Based upon tests performed on animals, the relationship between current and time required to produce fibrillation in humans is an I^2t relationship. In other words, $I^2t = K$, which is a constant. The value of K selected is based upon a man weighing at least 100 pounds, and the K value will not cause fibrillation in 99.5 percent of humans subjected to that value of current. Additionally, the value of K is valid for a duration of current flow from 8.0 msec to 5.0 sec. Based upon all of this, K = 116, hence the following formula: (17)

$$I = \frac{116}{(t)^{1/2}} \qquad (1)$$

where

I = total circuit current in mA

t = time, in sec.

Using the above equation, for a contact time of 2.0 sec, the current is 82 mA. With this duration, the current is just below the value required to produce fibrillation.

Table 2 represents the effects on the human body of currents greater than those required to produce fibrillation (42). For grounding system designs, it is important to consider the 9.0 mA limit for let-go currents. Also very noteworthy is the I^2t relationship for protective devices (17). A testing procedure which simulates the amount of current that a worker would draw when cutting into an energized shielded cable is presented in Chapter III.

Advantages

Shock Hazards. The advantage of shock hazard reduction afforded by shielded cables is well-known (4, 27, 53, 56, 61). For low-voltage cables, the general industry consensus as shown from the literature is that confining the electric field to inside the cable jacket is not critical (26, 56). However, the shock reduction advantage is of great importance, and an analysis of accident statistics relative to cables could show if shielding can act as a preventive.

Accordingly, the Accident Analysis Group of MESA in Denver has supplied the non-fatal cable accident reports for the years 1972, 1973,

Table 2. Current Range and Effect on 150 Pound Man (Lee, Reference 42).

Current	Physiological phenomena	Effect on human
<1 mA	None	Imperceptible
1 mA	Perception threshold	
1-3 mA		Mild sensation
3-10 mA		Painful sensation
10 mA	Paralysis threshold of arms	Cannot release hand grip; if no grip, victim may be thrown clear; may progress to higher current and be fatal
30 mA	Respiratory paralysis	Stoppage of breathing; frequently fatal
75 mA	Fibrillation threshold	Heart action discoordinated; probably fatal
4 A	Heart paralysis threshold (no fibrillation)	Heart stops on current passage; normally restarts when current interrupted
>5 A	Tissue burning	Not fatal unless vital organs are burned

and 1974 (44). The Beckley, West Virginia office of MESA Technical Support has provided copies of fatal accident reports for the above years and 1975 (19). These reports have been analyzed, and Table 3 summarizes the results. In compilation, it has been assumed that d-c cables can be shielded, and those accidents, which could have been prevented by shielding d-c cables, are included. However, it is not present cable manufacturing practice to shield d-c cables. Only those accidents pertaining to shock have been included (neglecting injuries such as tripping over cables, straining the back while moving, and so forth.

It is interesting that a large number of these accidents (or injuries have been caused by:

1. failure to properly shut-off and tag a cable prior to making a splice,
2. handling cables with bad splices, and
3. handling cables with areas of defective insulation.

A shielded cable would have prevented injury in the first and last cases. If splices in shielded cables are made properly and the shield reinstalled, then shielding could prevent bad splice related accidents. However, if the shield is not replaced within a splice, the cable is no safer at the spliced region than a non-shielded cable. In fact, some workers may not treat spliced areas as cautiously if they are relying on the protection of shielded cables.

Table 3. Accident Analysis Summary.

Year	Total Number of (Non-Fatal) Disabling Injuries	Number Which Shielding Might Have Prevented	Total Number of Fatalities	Number Which Shielding Might Have Prevented
1972	81	71	0	-
1973	64	57	2	2
1974	27	26	3	1
1975	Not Yet Available		3	2

The accidents summarized on the following pages caused death by electrocution and might possibly have been prevented by shielding. The manner in which shielding may have intervened is discussed.

Accident One. An electrocution occurred while the victim was standing in a puddle of water next to a continuous miner trailing cable splice (19). The splice outer jacket was poorly bonded and did not provide proper insulating properties. The electrocution took place when the victim placed one foot into the operator's station on a shuttle car which provided a path to ground from the puddle through his body and into the machine frame.

In this situation, a shield could have presented a path for the current to flow into the cable ground system and trip the circuit breaker, providing the shield was replaced in the splice and the ground current activated circuit breaker was set and operating properly.

Accident Two. Here, the victim was handling an energized low-voltage trailing cable leading to a roof bolter (19). He was not wearing gloves, and his hands and leather shoes were wet. Electrocution occurred when the victim encountered an area of the cable with damaged insulation and jacket.

Shielding would have prevented this accident by providing a direct path to the cable ground system and, if the ground current activated circuit breaker was operating properly, the power to the cable would have been shut off until a proper repair had been made.

Accident Three. The victim was electrocuted when he contacted an energized shuttle car frame (19). The trailing cable insulation and jacket was damaged near the entrance to the cable reeling unit and a bare phase conductor contacted the shuttle car frame. The ground-wire did not remain continuous throughout the cable since it became severed in a spliced area. Because of this condition, the machine frame remained energized.

The cable was a four conductor Type W so the ground-wire was insulated. Consequently, the shield would not have necessarily provided ground-wire continuity within the broken area. However, the shield could have carried the current to the circuit breaker if, in fact, it had been replaced in the repair.

Accident Four. In this case, the victim was electrocuted while trying to reinsulate a defective shuttle car trailing cable splice (19). He had not de-energized the cable prior to starting the repair. The victim had apparently removed the jacket from the old permanent splice and contacted a bare place in the phase wire insulation while trying to retape the conductors.

A shield surrounding the phase conductor (if it was replaced in the splice) would have prevented the accident. The bad insulation would have allowed current to flow into the cable ground, and power would have been shut off before the man attempted to make a repair.

Accident Five. A repairman was electrocuted when he cut into an energized conductor in a shuttle car trailing cable while attempting to splice the cable (19). Prior to the accident, the victim opened the circuit breaker and removed and tagged out the cable connector for the wrong trailing cable. A shield again might have prevented this accident by providing a path to the ground system when the cable was cut.

Accident Six. Shielded cable will not always prevent electrocutions because, as is noted in the following, occurrence (19), human performance always plays an important role.

A de-energized, d-c power distribution box was being moved manually by the victim and five other employees. The victim was using a metal bar to assist in moving and sliding the box while the other five were pushing by hand. While in the process of moving the box, it was inadvertently pushed or dropped onto a spliced area in an energized 4160 V cable. A short-circuit resulted, and the box became energized. The victim was electrocuted and another man was slightly injured.

Shielding could have played an important part here in saving a life. Shielded high-voltage cables are presently required, but in this case someone had inadvertently omitted the metallic shielding from the splice.

Percent Coverage. In order for a shield to act as a shock preventive, several conditions must be met. First, to attain complete shock protection, adequate coverage of the conductor insulation by the shield is necessary. Also, the shield must be grounded both at the machine frame and the load center in order to carry off any fault current. The test devised to determine the adequacy of this coverage is discussed in Chapter III.

Circuit Breaker Tripping. Another condition associated with proper protection by shielded cables is that, as in any power system, the protective circuitry associated with the ground system must be completely operational. Protective relaying is applied to electrical equipment systems to minimize the exposure of the personnel as well as equipment to the electrical and mechanical hazards of abnormal or defective operation (14). Whenever electricity strays from its proper path, a fault occurs and, due to the presence of shielded cables and grounded switchgear, line-to-ground faults are the most prevalent in mining (12,18).

For purposes of this thesis, the protective circuitry associated with low and medium-voltage trailing cables will be discussed. Circuit breakers of different types are utilized to provide ground-current protection, and one of the most popular and effective methods utilizes a balanced-flux current transformer (CT). As Figure 3 shows, the phase conductors are passed through the transformer core, forming the primary of the CT (14). For a symmetrical phase set, the vector sum of the three currents in the primary circuit will be zero, and no current flows in the secondary. However, during a line-to-ground fault, an unbalance will result, producing current flow in the CT secondary, activating control circuitry that will trip a circuit breaker (66). The balanced-flux form of breaker is the most commonly used for ground overcurrent and has an instantaneous trip setting for face or trailing cable applications. Trip setting is important in terms of personnel protection because, as discussed earlier, the amount of current which is tolerable by the human body in part depends upon the duration of the flow.

Additional Federal safety requirements dictate the use of a grounding resistor to limit the voltage drop across ground conductors under ground-fault conditions to 40 V in low and medium-voltage systems (12, 64). A further requirement limits the ground-fault current to 25 A. It is the practice of some mines to further limit ground current to 15 A.

As shown by Figure 3, a current transformer can be placed on the ground-wire between the transformer neutral and the grounding resistor to backup the balanced flux CT protection. Any irregular flow of ground current indicates a malfunction, and the CT will detect this current and initiate the opening of a breaker. Some ground current flow is normal, due to either system unbalance, capacitive charging currents,

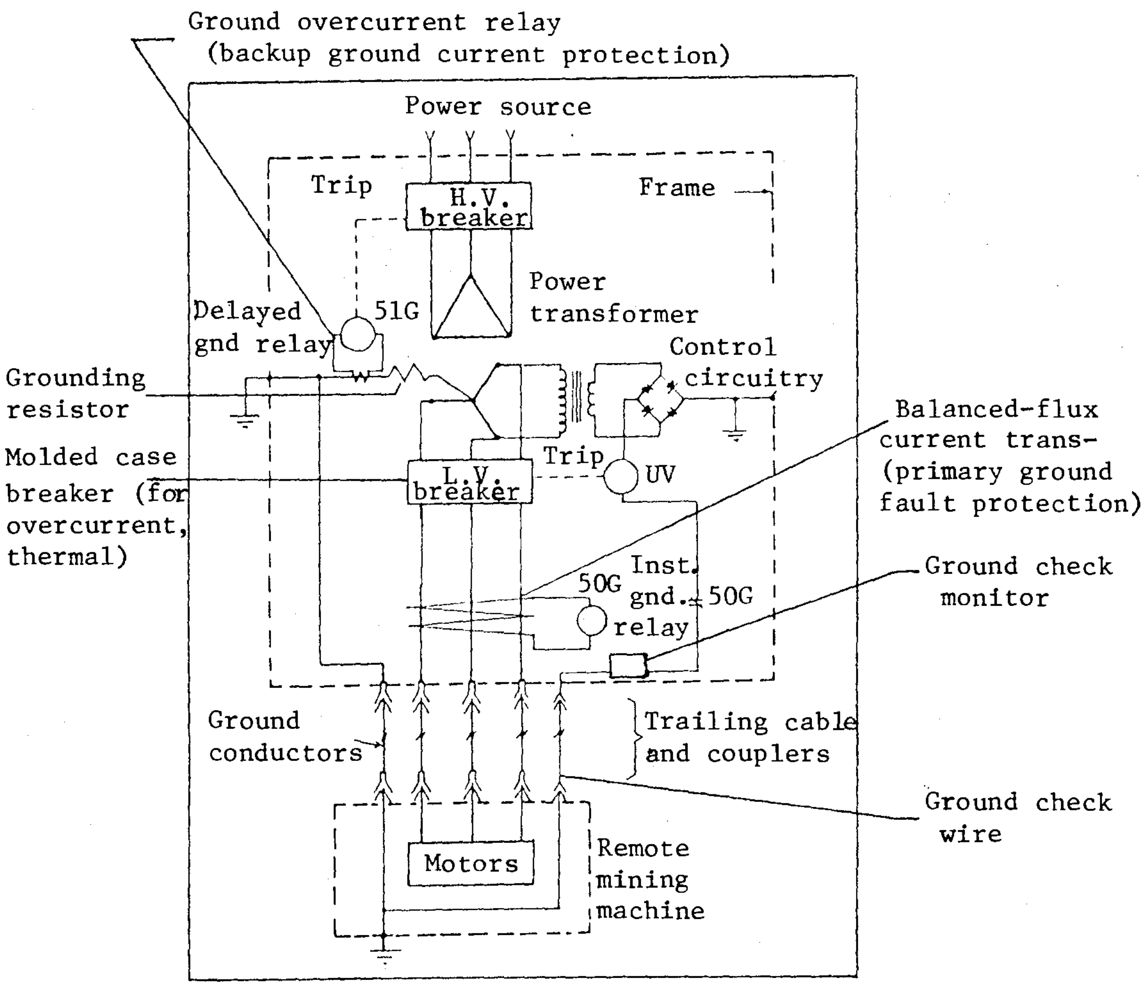

Figure 3. Typical Sectional Load Center (Cummins, Reference 14).

or inductive coupling effects, so the circuitry must be adjusted to act only when the normal level is exceeded (14, 66). However, trip levels must not be set too high so hazardous conditions can be detected.

The final form of protective circuitry normally found in the section load center is the molded case circuit breaker, also shown in Figure 3. This circuit breaker, which has adjustable time delays for the trip settings, provides overcurrent protection for the phase conductors and, in most cases, thermal over-load protection. In an undervoltage situation, the control circuitry can also activate this circuit breaker.

Designing protective circuitry for d-c power systems continues to be a problem. Because there is no natural current zero and the circuit breaker must force the current to zero, current interruption in a d-c circuit is more difficult than in an a-c circuit (54). Most d-c trailing cables have only two conductors, a carrier and a return. Any fault current, therefore, is difficult to detect.

It is not common practice to provide ground overcurrent protection for d-c systems because of the acceptability of other methods not using a solid grounding conductor, such as diode grounding. There are, however, a variety of ground trips which can be used with a three-wire trailing cable. The third wire of such a cable is the ground, and a shield can be used for this purpose. One such circuit consists basically of a center tapped resistor and three relays (34). If either the positive or the negative goes to ground, there will be a current flowing in the ground wire causing the potential across one of the voltage relays to increase, while the potential across the other decreases. Therefore, one of the voltage relays or the ground relay can be used to trip the circuit breaker during ground faults. Another type of circuit utilizes shunts or the hall effect in the ground wire (or shield) driving a relay. For this case, whenever a ground overcurrent is sensed, the d-c breaker is thrown.

With a non-shielded trailing cable, it is possible to cut or enter the cable without contacting a ground conductor. In other words, the ground-overcurrent relay would still be engaged, the cable remaining energized. In hypothesis, several hazardous situations obviously might result. A battery scoop tractor could cut a cable thus energizing its frame, a worker could energize a cable during a splicing operation, or a miner could handle a defective splice or insulation repair. A cut or nicked cable (which is not shielded) can cause injury if the damaged section is lying in a pool of water and leaking current (into the water). In this situation, it is likely that the leakage could not be detected by tripping devices. However, in all cases the result is the same: shock, burns, and possibly electrocution.

A shielded cable would have prevented injury from any of these problems. For example, a foreign object entering the cable would have contacted the shield and tripped the ground overcurrent relay. In this manner, mine power system protection is more sentient.

The extra awareness of a shielded cable can be further illustrated. Suppose that because of flexing, the wires of one conductor break and become separated. Arcing and sparking could then result, and it is entirely possible that the cable could "blow" as a result. If it blows opposite the ground and goes undetected, a fire or explosion could result. A shield over the conductor would prevent this from occurring as the "blowout" area would be confined by the shield, causing current to flow into the ground system and trip a breaker.

Induced Ground Voltages. Induced voltages in the ground-wire of multiple-conductor cables can be an extreme hazard. A fail-safe ground-check circuit in low- and medium-voltage a-c circuits is a requirement of the coal Mine Health and Safety Act of 1969 (25, 64). In those instances where a pilot-wire is to be used, the non-shielded Type G cable is changed to Type G-GC by replacing one of the uninsulated grounding-conductors with an insulated ground-check conductor. The size of the remaining two grounding conductors is then increased. An equivalent shielded configuration is the SHD-GC.

The result of this modification causes an electrical imbalance and results in an induced voltage on the grounding conductors. An investigation into this phenomenon by MESA personnel has shown that the electric arcing between the frames of mobile electric face equipment is of sufficient magnitude with non-shielded cables to ignite explosive methane-air mixtures (41).

Several methods have been devised for elimination of the induced voltages. For example, equal transposition for elimination of the phase conductors through the cable's length will result in total cancellation. This is regardless of ground conductor location with respect to the phase conductors (25, 41). A further approach involves installation of an energy absorbing diode bridge or saturable reactors in the circuit (4, 41).

However, these proposals are not the ultimate solutions. Even though conductor transposition is technically sound, it requires accurate measurement of the cable when first installed and also maintenance of the equal lengths between transposed splices. The resulting splices are bulky and costly and weak points in the cable. Transposition could be easily removed during a splice repair. Drawbacks to the use of diodes include precise measurement, maintenance, and monitoring (4). Saturable reactors require care in placement and often coupler modifications.

The best solution to the problem of induced voltages is through the use of cable which is symmetrical in cross-section. Such a geometrical configuration provides an electrical balance that eliminates the need for either diodes, saturable reactors, or transposition.

Popular knowledge incorrectly believes that induced ground voltages are eliminated in all shielded cables. It is extremely important to emphasize here that induced voltages can only be eliminated by a cable which is symmetrical in cross-section (57). Type SH-D falls in this class. The addition of a ground-check wire in the center of the configuration (in other words, Type SHD plus CG) does not affect the symmetry. However, replacing one ground wire with an insulated ground-check wire, as in Type SHD-GC, does alter the uniformity. Also noteworthy is the fact that symmetrical cables can only prevent induced voltages for a balanced, three-phase load.

Use of shielded type SH-D cable provides an infinite number of parallel paths between the grounding conductors as they are in contact with the braided shields encasing each phase conductor (4). This design also can be referred to as an integrated grounding system (25). The previous belief was that through these paths, shielding eliminates the large induced circulating currents found within G-GC cable. However, this is also incorrect but at present these circulating currents are not thought to be harmful (57).

Temperature Differentials. Electrical overload is a primary cause of elevating the temperature of the conductors, insulations, and jacket of a trailing cable (6). Both the resistance of the copper and voltage drop in the cable are increased, and a reduced voltage is supplied to the machine (6). These cause a need for more current which adds to cable heating. (Appendix II contains a discussion of cable selection based upon tensile strength required and ampere rating).

The insulation and jacket of trailing cables exhibit maximum resistance to abuse at mine temperatures, the temperature range they are designed to operate. However, the ability of these rubber components to withstand abuse decreases as the air temperature increases. At elevated temperatures, the tough outer jacket has lost much of its resistance to cutting, crushing, tearing and abrasion.

In low- and medium-voltage applications, numerous mining machines employ cable reels. When a cable is placed on a reel and is subjected to its normal current capacity or greater, a heating condition is possible. The heat developed cannot be dissipated fast enough to prevent initiating rapid insulation breakdown (30, 31, 36). A continued exposure to elevated temperatures will age the jacket, making it hard or brittle, and will cause crazing or cracking upon subsequent reeling.

It is thought (by the author) that shielding may reduce the operating temperature of cables. However, no literature can be found for this particular area because of the very limited use of low-voltage shielded cables.

Maintenance Testing. Shielded cables, regardless of construction or configuration, are very easily tested with standard d-c over-potential test equipment, and the test results readily interpreted (38). This assumes, of course, that the test equipment operator is qualified.

Individual conductor insulations are the object of the test. Faulty insulation is usually indicated by a leakage current to ground. With non-shielded multiple conductor cables, in order to achieve an effective test, the cable should be immersed in a grounded tank of water, and the potential applied separately across each phase. The other phases are solidly grounded together. By following this procedure, a leakage current can be detected between one phase and the others or one phase and the water (38). For non-shielded underground mining cables, the examination would have to be performed on the surface where a tank of water is readily accessable. The test can be accomplished without water, but a break or weakness in the insulation wall away from the other conductors will not be readily detected. However, because the conductors of shielded cables are completely surrounded by a grounding medium (which performs the same function as a water bath) they can be easily tested in-situ.

The superior method of performing in-mine testing utilizes a portable d-c over-potential tester. When implemented in a regular preventive maintenance program, the incidence of cable insulation failure due to testing is diminished. Non-destructive testing should be performed on a regular basis with the calculated resistance being plotted against the voltage. This is done simply by using Ohm's Law, $R = V/I$. For cable measurements, the relation is: (38)

$$\text{Thousands of Megohms} = \frac{\text{Kilovolts}}{\text{Microamperes}}.$$

When test plots are analyzed on a regular basis and a reduction in insulation resistance is found with increasing voltage, the cables should be changed-out and repaired (38).

Disadvantages

Costs and Availability. (Disadvantages 1 and 2). The most important cost factor associated with shielded cables are additional direct costs for their purchase. Most producers agree that shielded cables will ultimately cost 10 to 20 percent more than their non-shielded counterparts (23, 39). However, the experience of Penn State researchers purchasing cables for underground test sites has revealed much higher prices.

One such underground mine requires the use of three-conductor round and flat Type G-GC cables. In the round 4/0 AWG cable size (continuous miner cables), Type G cables cost $7780.00 per 1000 ft. The type SH-D cables cost $9564.00 per 1000 ft or 22.9 percent more than the non-shielded. The flat three-conductor number 2 AWG cables for use on shuttle cars and roof bolters increased in cost by 66.5 percent for the SH-D configuration. The corresponding prices for this increase are $3238.00 per 1000 ft for Type G and $5390.00 per ft for the SH-D. An apparent reason for this disparity is that the three-conductor flat number 2 cables are a special order for a short length requiring a special cable design and a semi-conducting saddle never before used.

The second purchase was for two, three-conductor round number 6 AWG cables for shuttle car use only. Three cable types, G-GC, SHD-GC, and SHC-GC were considered. The SHD-GC cables cost $3585.00 per 1000 ft and the SHC-GC cables cost $3192.00 per 1000 ft versus $1438.00 per 1000 ft for the type G-GC. This represents a price increase of 149 percent for the SHD-GC and 122 percent for the SHC-GC over the G-GC. However, this great increase in cost is due in part to the fact that only 1000 ft of each type cable was ordered. An example more representative of the long run is found in the 10,000 ft order estimated prices of the same cables. For example, the Type SHD-GC cables are 68 percent more expensive and the type SHC-GC cables are 40 percent more. In part, the high charge for those cables is due to a current lack of demand and initial design expenses. Special order cables will always be costlier.

Also associated with a cable evaluation are costs not as apparent as purchase price. Cable life is one such cost. To determine shielded cable life, laboratory, and underground tests were performed. These will be discussed in Chapter III.

Cable manufacturers were consulted for a preliminary analysis of their increased expenses resulting from a switch to low-voltage shielded cables; five of the manufacturers reported. As the following information was obtained in confidence, no references are furnished.

Company A anticipates a capital investment for additional braiding machines, but an exact figure could not be given for such a conversion. However, company officials estimate a time lag of one to two years before they would be in a position to handle their present share of the low-voltage shielded cable market. This company was also quick to point out that no moves toward purchasing additional braiding capacity would be made until such legislation became a reality.

An extensive review of Company B's braiding capacity showed that a switch to low-voltage shielding would have little effect. This company could accommodate the change with little or no need for new equipment or plant modification. Also, company personnel can foresee no manufacturing problems.

Company C is also in a good position to begin shielding low-voltage mining cables. Any additional braiding capacity and associated costs will largely be determined by the demand from the mining market. The company does not anticipate any time delay in a switch to producing these cables.

The most specific answer to the project's hypothetical question was provided by Company D. This firm estimates a capital investment of $350,000 to $500,000 to obtain additional braiding capacity. Furthermore, they estimate a cost increase for cables with braided shielding of 10 percent. Finally, a nine-month production delay would result after the order has been placed for additional equipment.

Company E estimates a capital investment for equipment and installation of $300,000. Required lead time for such a conversion is nine months for Company E.

The total market share (also compiled in confidence) held by the above manufacturers was compiled. They are, in fact, quite a representative sampling as they hold between 75 percent and 90 percent of the low-voltage cable market.

Flexibility. Sources in the literature cite the lack of flexibility of shielded cable as a major detriment to their use (4, 11, 29, 52). For coal mine applications greater than 125 V, the Canadian Electrical Code requires the use of shielded cables (10, 11). Therefore, the flexibility problem was posed to several Canadian sources.

One Canadian states it has been his experience that shielded cables are much less flexible than non-shielded (27). Furthermore, he relates that shielded cable is more susceptible to damage due to flexing. Another Canadian, an Inspector of Mines, Electrical, was able to provide historical information for an a-c shuttle car using shielded cable (11). Employed in a development coal mine, the operators claim that the individually shielded power-conductor cable (SH-D) did not stand up. However, the inspector stated: (11)

> I am not convinced, however, that their reports were not unbiased, since they particularly favor a cable design using conductive rubber shielding.

As a clarification, semi-conducting shields are also known as rubber shields (56).

Shielded cables are also required in The Republic of South Africa. The cable configuration used is a three-conductor round with only one ground wire, and either overall or individual shielding is permitted. One mine manager has stated that shielded cables are used on reeling applications without any particular problems (67). No underground splicing is permitted, and this necessitates cable change-outs. Again according to this source, the cables usually last three to four shifts before a change-out occurs.

Splicing. The fourth problem associated with shielded cables is the possible longer splice time and limited splice life. Title 30, Code of Federal Regulations, Section 75.906, "Trailing Cables for Mobile Equipment, Ground Wires, and Ground-Check Wires" states that "splices made in the cables shall provide continuity of all components" (64).

A number of sources were consulted to determine the proper procedure for low-voltage shielded cable splicing (3, 6, 9, 26, 50, 51, 64). The cable illustrated in Figure 4 (drawn two times normal diameter) will serve as a reference for the explanation which draws attention to the extra steps required (over non-shielded and high-voltage cables),

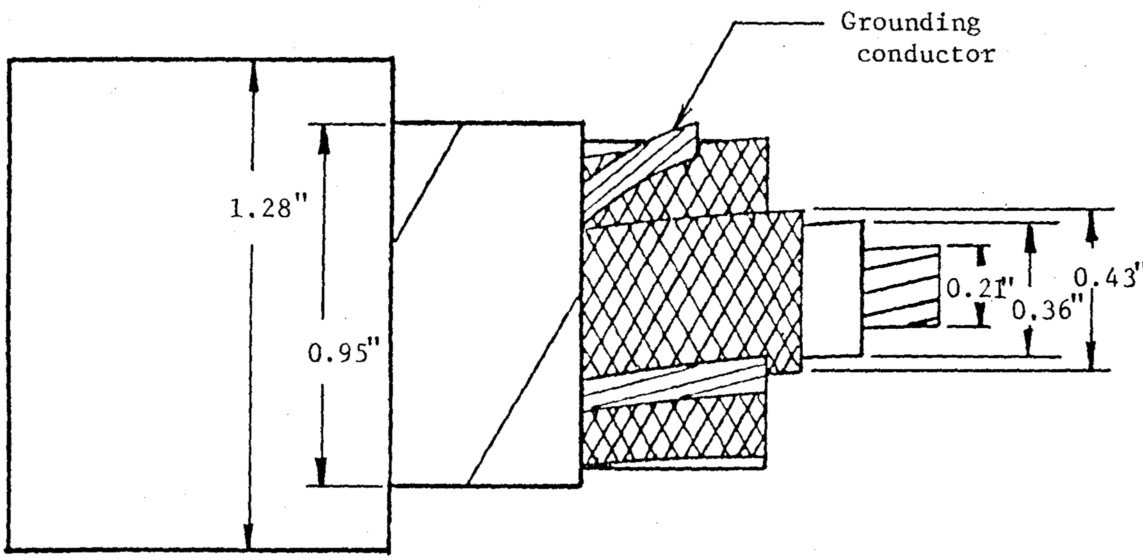

Figure 4. An Exposed Shielded Cable.

The cable illustrated has an hypalon outer jacket and ethylene propylene (EP) primary insulation (68).

To begin the splice, the conductors and the grounding system are measured then cut and sized as usual to afford a properly spaced, close fitting splice. In splicing a low-voltage shielded instead of non-shielded cable, there are actually only two extra steps. These are:

1. removing the shield and bedding tape from around the primary insulation and
2. replacing the shield after the conductor has been joined together and reinsulated.

Differing from high-voltage applications, no semi-conductive tape is used over the conductor (which eliminates the act of replacing). Also, voids, sharp points, and inclusions are not as injurious as they are in high-voltage; however, voids and sharp points should not be present in any splice and care should be taken to keep the splice clean.

The splicing process for each phase conductor (of a three-conductor cable) is as follows. Figure 5 gives the dimensions for one bared conductor and the amount of shielding which is stripped away, and Figure 6 illustrates an optional step, penciling the insulation. Each conductor is then connected as shown in Figure 7. After rejoining, the area is reinsulated (Figure 8), and shielding is replaced over the entire joint (extending over the original shielding). Figure 9 shows the shielding tape half-lapped beyond the splice area. However, another possibility for shielding replacement exists. By placing a single (shield) sheet, a tube of braid, or double-layered tape over the joint area, no separation of the shield will occur under flexure (possible with

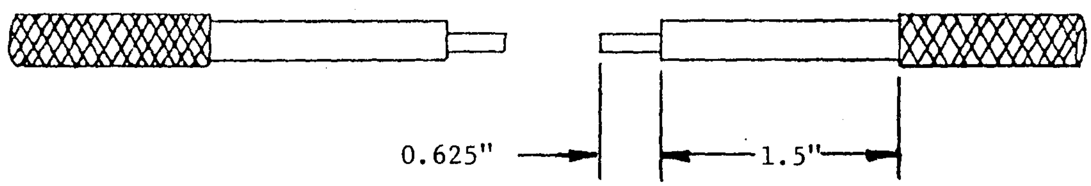

Figure 5. Shielding and Bared Conductor Dimensions for Splicing.

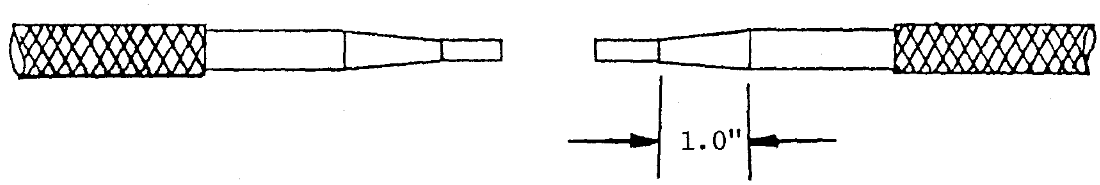

Figure 6. Penciling the Insulation for Splicing.

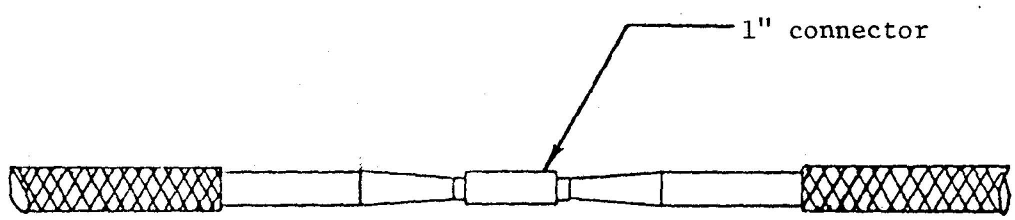

Figure 7. Joined Conductor Prior to Reinsulation.

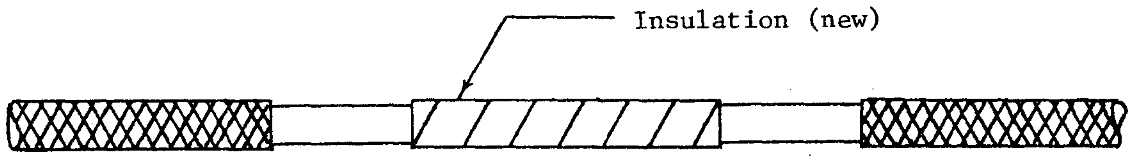

Figure 8. Reinsulating the Connector Area.

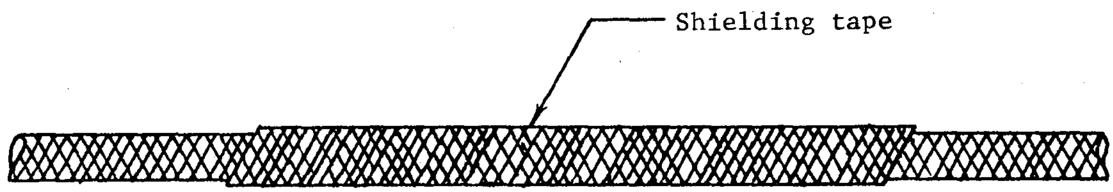

Figure 9. Half-lapped Shielding Tape Over Spliced Area.

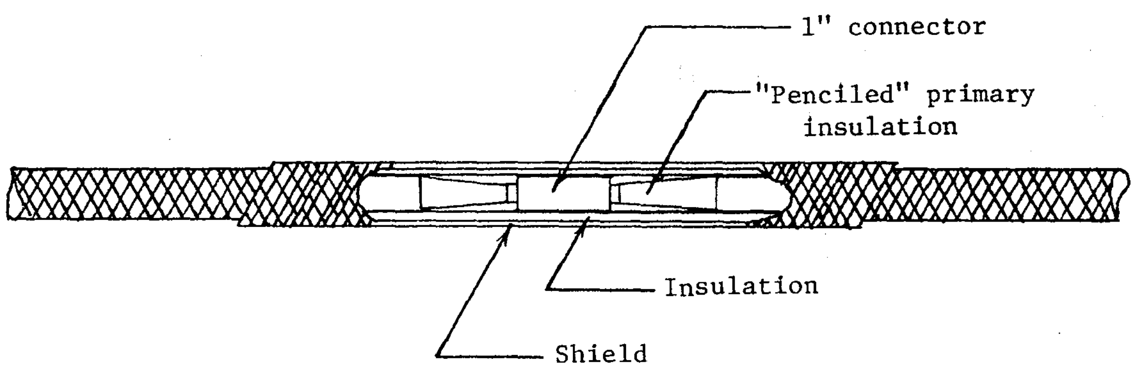

Figure 10. Splice Components; Cut-away View.

half-lapped tape). Figure 10 provides a cut-away view of all the components in the individual conductor splice.

The above process is then repeated for the two remaining phase conductors. The ground-wires and ground-check wire are joined in usual splicing techniques, and the entire splice assembly is covered with a new outer sleeve.

Crushing the Shield. Equipment runovers, roof falls, and rib sloughing may decrease safety and increase downtime (the fourth possible disadvantage). During a field trip (See Appendix III), a shielded continuous miner cable was observed. Between the load center and working section, a portion of the cable was covered by rock from a roof fall. The rock slabs were quite large (one was too large to be lifted by two persons). However, the cable was not crushed to the extent that it tripped the circuit breaker or interrupted power to the equipment.

Cable Diameter. In general, shielded cables are of slightly larger diameter than their non-shielded counterparts. For example, from an in-mine measurement (Appendix III), a shielded 4/0 three-conductor cable (SHD plus GC rated at 2000 V) has a 2.355 inch diameter, while the same dimension for a non-shielded 4/0 three conductor cable (Type G rated at 600 V) is 2.05 inches. (An in-mine measurement was necessary in this case because of a lack of manufacturer's specifications for low-voltage shielded cables.) It is interesting to note that in many new cables (of any configuration), a change in outer jacket and conductor insulation materials has raised the 600 V rating to 2000 V.

The slightly larger diameter shielded cable could cause a reeling application problem. Simply, as the cable diameter increases, the length that can be placed on the reel decreases, thus more frequent load center moves or more shuttle car back-spooling is required. The need to modify cable spooling devices and sheave wheels can also be encountered. Additional problems arise in selecting splice kits, packing glands, and couplers for the larger cables.

Stiffness. The apparent stiffness of shielded cables (as compared to non-shielded) can most probably result from the extra components necessary for the shield. In quoting directly from a mine's monthly test report (again, see Appendix III), "men on section said it was a stiffer cable and harder to handle."

It has been thought that shielded cable lack of flexibility may require extra tension on cable reeling devices. Many cable failures are the direct result of excessive tension (6). Cables, subjected to stretching, no longer have balanced construction, and failures are accelerated once the balance is lost. However, a spokesman for a Western U.S. mine, which uses shielded cables extensively, stated that he felt that no additional tension is required to handle shielded cables on a reeling device (see Appendix II).

Fault Locating. Because of construction, shielded cables can be crushed or otherwise injured (and cause a relay to trip) with little or no visible damage. Associated is a difficulty in locating the faulted area.

The pinched or metallic contact in cables (or splices) usually exist in "bolted faults" (13). Such short circuits has a very low resistance, unless current flow is sufficient to vaporize one of the conductors and cause an open-circuit. If an open-circuit does not result, the chances are that the cable outer insulation will be breached by expanding gases, so the location of the fault can often be visually spotted (13). The bolted fault, if not initially visible, could be made so by connecting the cable across a high energy power source (usually d-c), and blowing it out. (A mine employing shielded cables has reported the use of this method.) If flammable substances are present, as would be the case in an underground coal mine, a fire or explosion could result. Since very high currents are used, the rest of the cable is stressed, probably deteriorating it (13). There is a physical danger to nearby personnel and power source components are over-stressed.

One viable alternative to this method is the use of time domain reflectometry (TDR). This technique utilizes a voltage pulse with fairly steep rise time (13). The voltage pulse is sent down cable pairs, and the pulse reflection from any discontinuity is noted. The echo will act to either reinforce or reduce the originating pulse amplitude, depending upon whether the discontinuity is an open or a short. The arrival time of the echo is proportional to the location of the discontinuity along the length of the cable. A TDR rugged enough for underground usage is currently being developed for the U.S. Bureau of Mines (13). One problem encountered with the present model is that faults are only approximately located. Roughly 30 ft of cable must be searched with a probe supplied as part of the system. A newer model will give precise location of multiple faults in one test. The TDR is suitable for use on both shielded and non-shielded cables (13).

An infrared probe is an alternative to TDR usage. However, the probe is limited to only locating short circuits, which are believed to be the most common type of shielded cable fault. Current from a source connected to the cable terminals and flowing through the short circuit raises the temperature at the faulted area (13). This temperature rise is sensed by an infrared probe sensitive to about 1 to 2 °F. The infrared unit can be used with both shielded and non-shielded cables and is the only probe type of apparatus capable of consistently locating short circuits in shielded cable (13).

Weight. Shielded cables weigh more than non-shielded cables of the same size and design. The weight factor could be a problem in transporting, handling, and reeling shielded cables. Table 4 gives a comparison of cable weights, obtained from three manufacturers, for the most common cable sizes used in low-voltage applications (7, 28, 55).

Coupler Installation. The final disadvantage to shielded cables is the additional time required for installation. An extra connection is needed for the shield or shields, and there is seemingly no way to circumvent this problem. Also, increased cable outside diameter may necessitate the use of larger couplers. However, one consolation is that installation is not frequent.

Summary

This analysis of literature attendant to shielded cable has revealed a number of items important to this report. Specifically, shielded cables present a number of possible advantages and disadvantages. Paramount on the list of advantages is the additional safety which may be gained through the use of shielding. As was shown in the literature, shielding (especially the SH-D configuration) brings about an integrated grounding system. It is in this light, as an addition to the cable ground, that shielding should be viewed. In terms of personnel protection, shielding can only function properly if grounded at the cable ends and continued through spliced regions plus if the

Table 4. Weight Comparison of Shielded Versus Non-shielded 2000 V Cables (Pounds per 1000 ft).

Sizes-AWG	Company A (28)		Company B (55)		Company C (7)	
	Shielded	Non-shielded	Shielded	Non-shielded	Shielded	Non-shielded
6	1170	800	960	830	1220	760
4	1470	1090	1410	1170	1510	1088
3	1720	1280	--	--	--	--
2	1940	1500	1940	1620	1960	1462
1	2410	1900	2325	2050	2365	1910
1/0	2840	2300	2950	2450	2570	2280
2/0	3370	2700	3470	2930	3160	2650
3/0	3970	3340	3950	3420	--	--
4/0	4780	3910	4800	4250	4250	3910

Note: In all cases shielded indicates three-conductor round type SHD-GC and non-shielded indicates type G-GC.

protective circuitry is operational. As shown in the accident analysis summary, one fatality resulted from an improper splice of a high-voltage shielded cable.

Alternatively, shielding may present a number of problems to underground coal mine operators. Heading this list are cost and maintenance. Placing a dollar figure on a prevented accident or a human life is nearly an impossible task and will not be attempted in this thesis.

The following advantages have been adequately analyzed through the literature review, found to be true, and receive no further coverage.

1. Shielding (Type SH-D) maintains the symmetry of cables.
2. Maintenance testing of shielded cables is more readily accomplished.

In addition, the following disadvantages will not be discussed further.

1. Shielded cables have higher purchasing costs.
2. Availability of a wide range of low-voltage shielded cables may be a problem area.

The latter disadvantage is not necessarily true. Also, it was shown through the literature review that the disadvantage of fault locating is easily accomplished with the proper equipment and an operator qualified for its use.

Chapter III will now attempt to discuss the remaining advantages and disadvantages through laboratory testing and experiments at a field test site. As shown by the foregoing literature review, these areas deserving further research are:

1. temperature,
2. flexibility,
3. splicing,

4. shield crushing,
5. cable diameter,
6. weight, and
7. coupler installation.

CHAPTER III

LABORATORY AND UNDERGROUND TESTING AND RESULTS

General

From the review of literature just presented, the adequacy of the shield in personnel protection is a basic area requiring further investigation. If low-voltage shielding is not capable of providing protection from serious injury to mining personnel, then it is of questionable usefulness. The first areas of testing should examine what happens when a miner employs a foreign object to enter an energized cable.

The flex life of shielded cables has been presented as another problem area. This examination is necessary to show the adequacy of shielded cables used in a flexing or reeling application.

Splicing shielded cables is perhaps the area of greatest concern to mine operators. Laboratory and field work is needed here to determine not only a comparison of relative times for splicing, but also techniques, shielding components, and cost information for splice kit purchases. Operators have also expressed concern over nuisance tripping caused by a cable which has been run over or crushed, and tests are required in this area.

The literature has shown that shielded cables are physically larger, are stiffer, and weigh more than their non-shielded counterparts. These areas should be examined in the field and the laboratory. The increased size and stiffness could cause problems in reeling applications, and the added weight may also cause problems in reeling and dragging cables. Packing gland and coupler sizing should also be looked at in terms of the larger shielded cable size.

A description of these needed tests and their results follows the underground test site description. Several photographs were taken during the tests, and some of these will be presented in Chapter IV.

Description of the Underground Test Site

The cooperating mine for underground testing is relatively new, having just begun production in 1974; the operator's name is withheld attendant to the company's wishes. Metallurgical grade coal is mined from the Pittsburgh Seam which averages 6.0 ft in height at this location. At present, four continuous units are in operation, and 21 will be utilized at full production of four million tons annually. The mine has an estimated life of 25 to 30 years. Conveyor belt haulage is used for moving the coal from the sections to the surface, and the coal is then barged to another location for preparation.

The test site was established so that complete shielded and non-shielded sections could be monitored. Each section contains a continuous miner, two shuttle cars, and a roof bolter. At the time of cable installation, both sections were driving adjacent main entries, each with nearly identical mining conditions: good roof, dry, and 300 ft of cover.

Electrical power is delivered through a borehole from the mine surface substation at 7200 Vac. General Electric 1000 kVA section load centers transform the 7200 V to necessary face utilization voltages. Each section employ a Lee-Norse 486 continuous miner operating at 550 Vac. However, the two National Mine Service Company Torkar 48A 40 shuttle cars and the Fletcher dual boom roof bolter operate at 440 Vac.

Trailing cables for the miners are 4/0, three-conductor round, 2000 V, Type SHD-GC or G-GC. Each of the miner trailing cables is 850 ft long. The remainder of the sectional equipment utilizes 750 ft of number 2 AWG, three conductor flat, 2000 V, Type SHD-GC or G-GC. The shields are all full-copper braid.

Figure 11 provides the mining layout for the sections. The face cuts shown were completed in the shielded section at the time of installation. The pillars are cut on 95 ft by 75 ft centers, and the entry width is 16 ft. At least two sets of open crosscuts, not including the face crosscuts, are maintained at all times to allow for shuttle car haulage routes.

The gathering of information from the test site is facilitated by the use of weekly performance reports completed by mine maintenance personnel. On such reports the location of all cable incidents in the test sections, including pinches, splices, jacket repairs, and re-entries are recorded.

Percent Coverage

Measurements were performed in the laboratory to determine the percent coverage by the shield which is necessary for complete shock protection. The procedure involved repeatedly driving a sharp object (a six-penny coated nail with an average diameter of 0.0857 inches) into the cable. A portable Kelvin bridge (20) or an ohmmeter were used to monitor the contact resistance between the penetrating nail and the shield. Shielding types tested included copper braid, cotton-copper or nylon-copper braid, tape, and wire.

A six-penny nail was chosen as it represents one of the smallest objects in a coal mine that might be driven into a cable. Although an

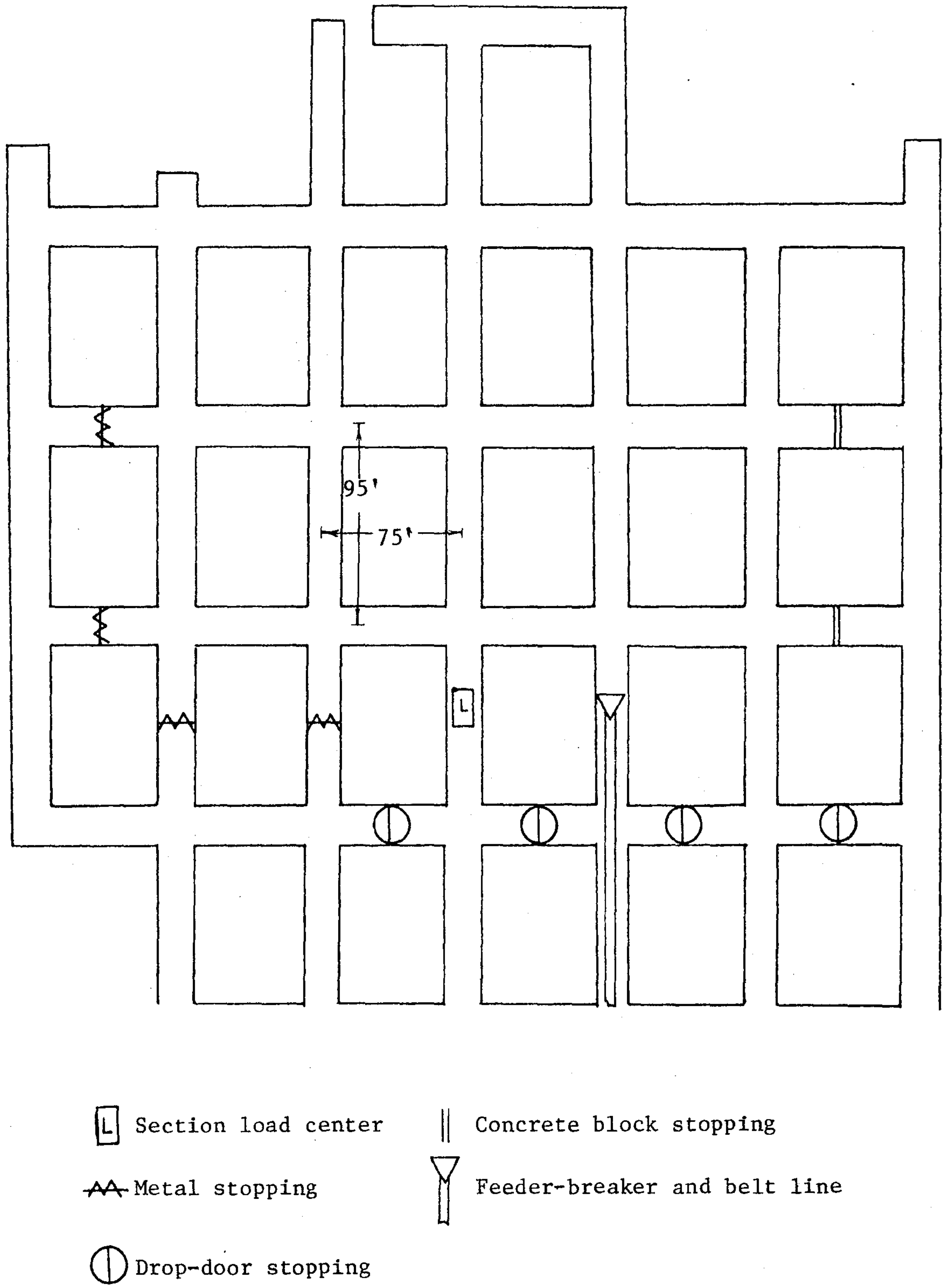

Figure 11. Shielded Mining Section at the Test Site.

extremely dangerous practice, some mine personnel drive nails into one of the phase conductors to obtain power for an auxiliary apparatus, and it is common to use brattice nails (which are readily available). As further justification of this testing procedure, the following accident report (received from MESA's Accident Analysis Center, Denver) is presented in Table 5 (44). A shielded cable with the proper percentage of coverage could have prevented this accident (providing the circuit breakers in the load center are operational, set to trip at the proper level, and the shield and ground wires are properly connected through splices, couplers, and machine entries).

Description of the Test. Prior to beginning the actual testing, the resistance of the grounding system through the entire cable length (10 ft) was measured. This was accomplished by soldering the test leads from the Kelvin bridge (Leeds and Northrup, Model 4288-2) to an exposed ground wire at either cable end. As the shield contacts the ground

Table 5. Trailing Cable Accident Report.

General Information	
Date of occurrence:	June 15, 1973
Cause of accident:	Checking cables and stuck ice pick in (into) cable causing him to burn his right hand and eyes.
Equipment:	Shuttle car.
Unsafe acts contributing to accident:	Checking cable with power on.
Regular job title:	Electrician.
Years of experience on regular job:	5 years.

wires throughout the cable, it is not of particular importance which ground wire was used. When the shield was not in intimate contact with the ground wire, another procedure is used and is described later. The single conductor cable test was an exception to this rule. Here, the Kelvin bridge leads were soldered to the ends of the wire shield (twisted together at both cable ends).

After the foregoing resistance was checked, the nail penetration tests were begun. A test lead was soldered to the ground wire, cut, and soldered to the nail. The nail was sanded to remove the surface coating and then was driven at random 25 times into each sample. The distance from the ground connection cable end to the nail was measured, as was the resistance, for each trial. Figure 12 shows the typical test arrangement. Note that the nail is always driven far enough into the cable to penetrate the shield.

For those cables employing a wire shield in conjunction with a semi-conductive tape or other material, it was necessary to use a Fluke ohmmeter, Model 8000-A in parallel with the Kelvin bridge. If the nail missed one of the shielded wires, the resistance was beyond the range of the Kelvin bridge, and the ohmmeter was used. Connections to the ohmmeter were also soldered. Lead wires for both instruments were number 16 AWG.

Figure 13 shows a flat SH-D cable which was designed for the underground test site. This particular design utilizes a braided copper shield over each of the phase conductors. A specially designed saddle of semi-conducting material has been extruded over each ground wire to provide a low resistance path from it to each shield. In addition, a semi-conducting tape is wrapped around each ground wire to keep the

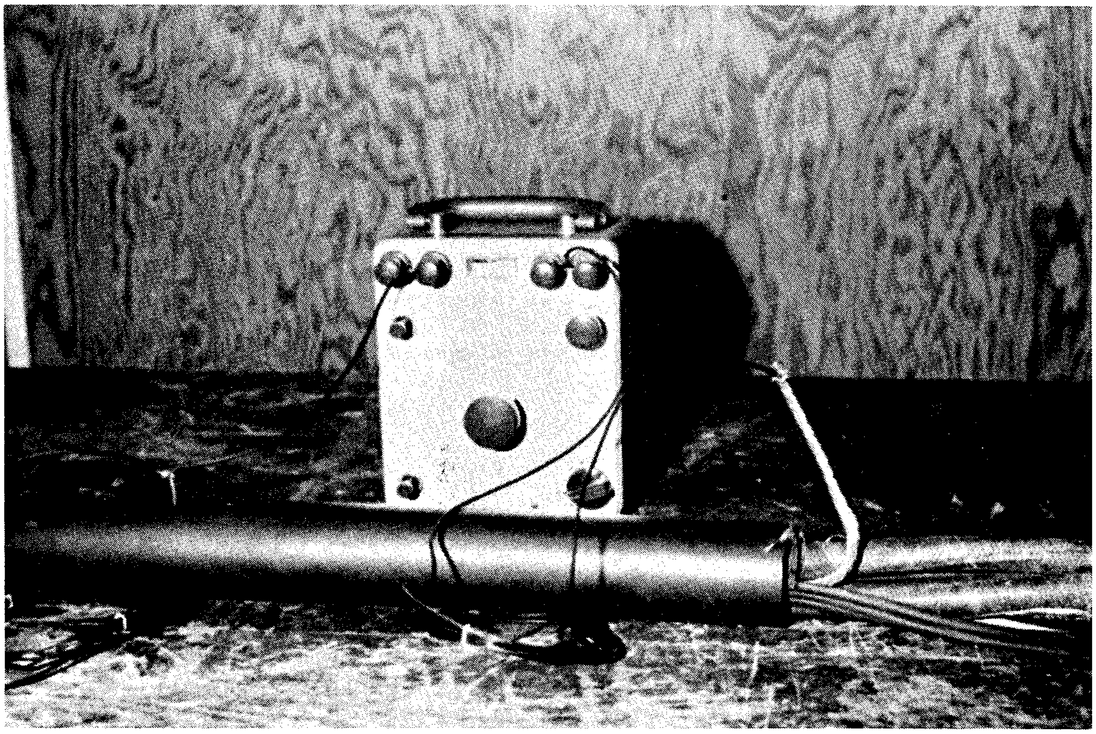

Figure 12. Shield Percent Coverage Test Apparatus.

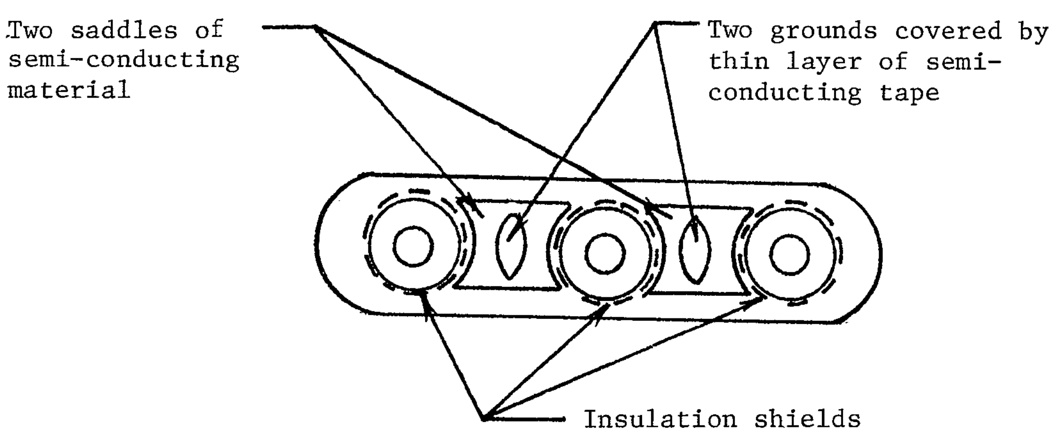

Figure 13. Triple Flat Shielded Cable Construction.

saddle material from being extruded into the ground wire strands during manufacture. The semi-conducting material was designed for a 50 Ω/cm resistance. As shown by the following calculation, a 40 mil saddle thickness between ground wires and shield indicates the maximum resistance from shield to ground wire should be 5 Ω:

$$(50\ \Omega/\text{cm})(2.54\ \text{cm/inch})(0.04\ \text{inch}) = 5\ \Omega.$$

However, according to the producer, the resistance of this semiconductor tends to decrease with increasing current (49).

In order to determine how closely the cables conformed to this design, the nail test was also performed on them. This case required the ground wires to be soldered together at both of the cable ends. An ohmmeter was used to measure resistance.

Another special test case involved a round three-conductor Type SH-C shuttle car cable. Here, the shield was separated from the ground wires (and the rest of the cable assembly) by a reinforcing cloth tape. This cloth was not semi-conducting and therefore of a very high resistance. This case again required the ground wires to be soldered at both ends of the cable and the use of an ohmmeter.

Figure 14 gives a diagram of the test circuit. As can be seen, the total circuit resistance can be defined by the following equation:

$$R_{Total} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 + R_8 + R_9 \qquad (2)$$

where

R_1 = soldered joint contact resistance for the first test lead to the Kelvin bridge,

R_2 = first test lead resistance,

R_3 = soldered joint contact resistance,

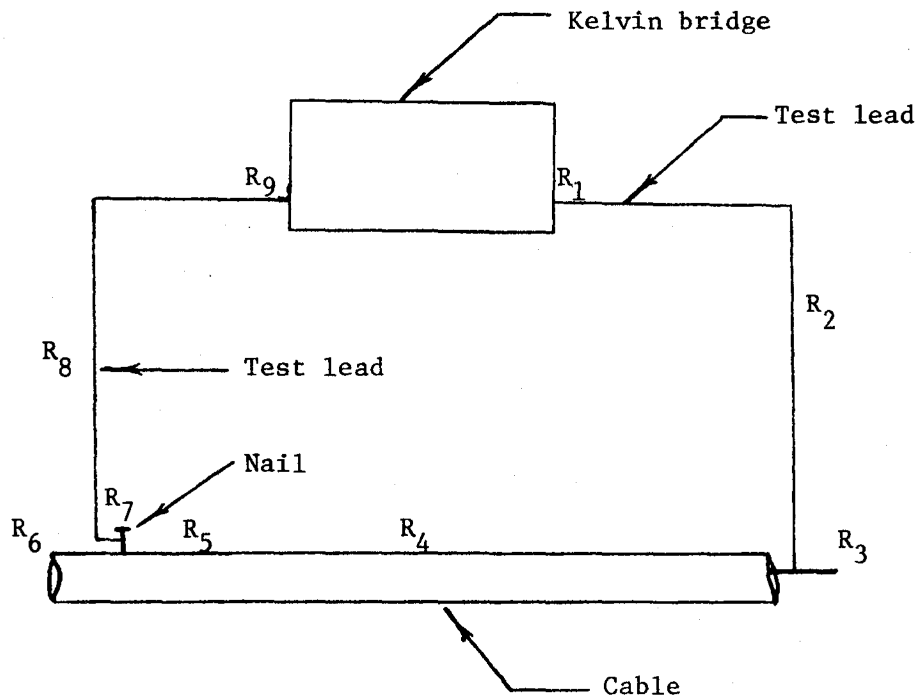

Figure 14. Diagram of Shield Percent Coverage Test Circuit.

R_4 = resistance through the cable grounding system,

R_5 = contact resistance of the nail to the shield,

R_6 = soldered joint contact resistance for the nail to the second test lead,

R_7 = resistance of the nail,

R_8 = resistance of the second test lead,

R_9 = soldered joint contact resistance for the second test lead to the Kelvin bridge, and

R_{Total} = the measured resistance for each trial.

It was assumed that all of the soldered joints and the nail have negligible resistance. The equation therefore reduces to:

$$R_{Total} = R_2 + R_4 + R_5 + R_8. \tag{3}$$

The test lead resistance was measured prior to beginning each measurement series. For the first three tests, the test lead resistance (R_2 and R_8) was 0.024 Ω. The value was between 0.064 Ω for the next five tests (the length of the leads was increased).

The nail contact resistance, R_5, and the cable resistance itself, R_4, are the remaining unknowns. R_4 for each trial can be found by subtracting the test lead resistance from the cable grounding system resistance (R_{cgs}) then multiplying by the ratio of the distance to the nail over total cable length:

$$R_4 = [R_{cgs} - (R_2 + R_8)] \left[\frac{\text{Distance to nail}}{\text{Cable length}}\right] \tag{4}$$

R_{cgs} was measured prior to each test.

Results. Detailed measurement results can be found in Appendix VI. The tests reveal that SH-D cables with a cotton-copper braid, full copper braid, or a metallic tape shield all yield resistance values of lower than 0.1 Ω. One exception to this was the three-conductor flat shielded cable (Figure 13). As can be seen in Appendix IV, when the nail was close enough to contact a phase conductor in the three-conductor flat shielded cable, the resistance readings were 10.1 Ω or less.

The test results reveal a different finding for the round SH-C cable. The test was again simulating an ungrounded or floating shield. This time, however, very high-resistance readings were observed. Readings of 2000 kΩ were not uncommon.

The case for wire shields used in conjunction with the semiconductive tape again produced high-resistance values. Observed resistance readings for these samples went as high as 1146 Ω.

Energized Cable Test

This test was devised to show the effects caused by a person using a metal object to cut into or otherwise enter an energized cable. To observe shield effectiveness under worst-case conditions, the ground current limiting resistor was eliminated from the circuit. In this manner, the current through the shield was enabled to rise above 25 A and damage, if any, to the shield could be noted.

A six-penny nail was again chosen as the penetrating medium. Figure 15 shows the general test arrangement. The 218 Vac source was used to power two series-connected 100 W electric lights. One wire of the circuit was routed through a sample of flat shielded Type SH-D cable from the test site. The nail was connected to a 1000 Ω resistor and then grounded to simulate a worker also under worst-case conditions. Under ideal conditions, such as a wet hand holding pliers, or touching with a wet palm, human body resistance has been found to be about 1000 Ω (32, 42).

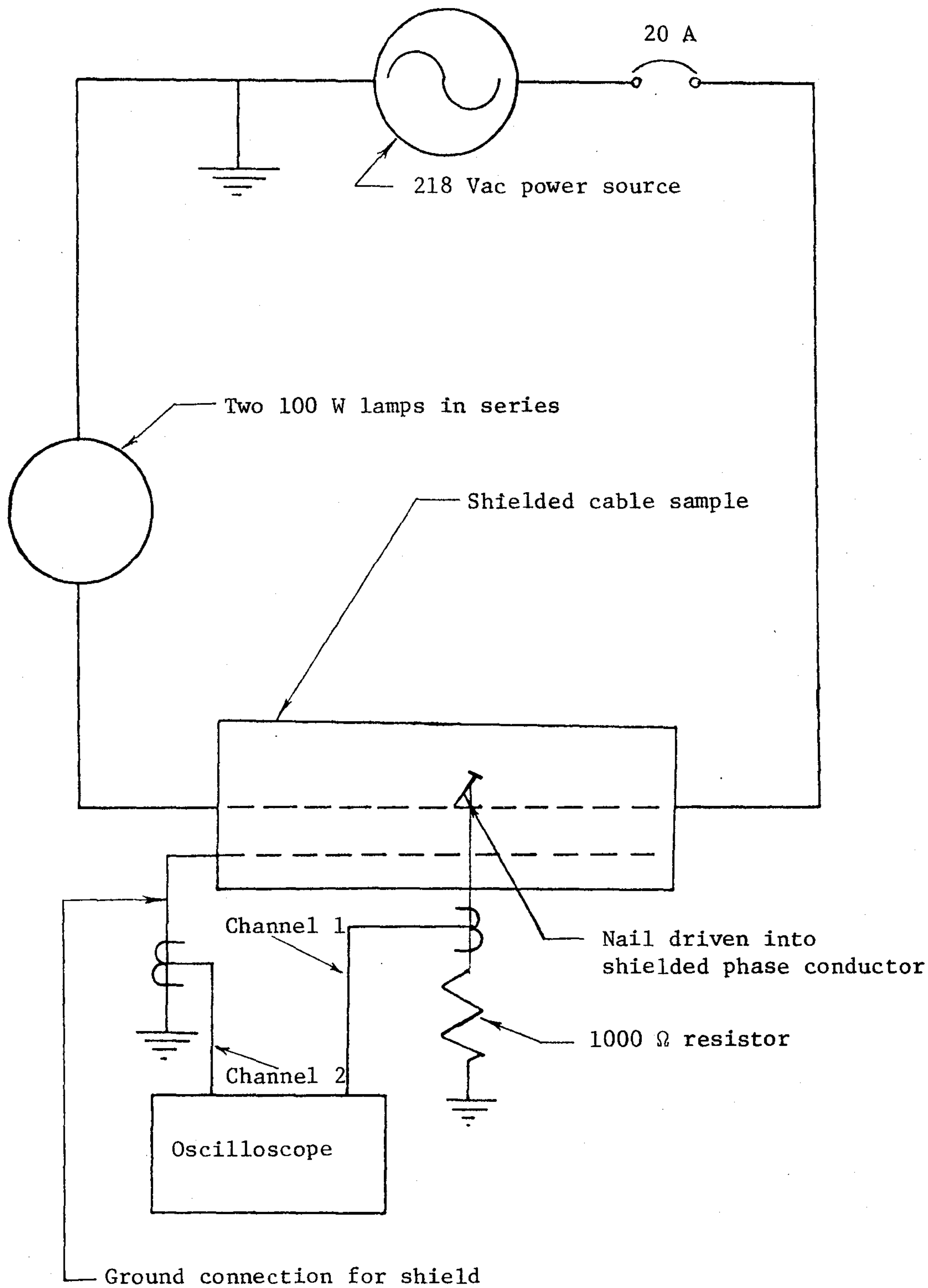

Figure 15. Circuit Diagram for Energized Cable Test.

After the cable was energized, a nail was driven into it by a remote apparatus which dropped a hammer onto the nail. As the nail entered the shield and phase conductor, a Hewlett-Packard Model 456-A current probe was used to monitor the current flowing through the 1000 Ω resistor, and a Fluke clamp-on Model AOI-600, ac current probe monitored the current flowing from the shield over the conductor. A Tektronix Model 7603 multiple-channel, single-trace oscilloscope connected to the current probes facilitated current measurement. The oscilloscope was triggered by the current flowing through the ground shield, and an oscilloscope camera recorded the trace on the screen.

Results. Ten trials of the test were performed. In nine of the 10, the current flowing through the shield was sufficient to trip the 20 A circuit breaker connected to the 218 Vac line. The test results were very repetitive for these nine trials as identical current levels were observed in each. During these nine trials, the shield sustained no noticeable damage. However, during one attempt, the breaker was not activated, and the shield around the nail penetration area was destroyed. Figure 16, which is typical of all results, shows the current levels recorded for the "man" and the grounded shield. The upper trace is the current flowing through the "man", approximately 2 mA peak-to-peak. Current flowing through the shield, the lower trace, is 1800 A peak-to-peak. It can also be seen from the illustrated current levels that the circuit breaker was tripped in 5 cycles or 83 msec.

Flex Testing

Description of the Test. Laboratory tests were performed at MESA's Approval and Certification Laboratory in Pittsburgh to compare the flex-life of shielded versus non-shielded cables (47). Similar non-shielded

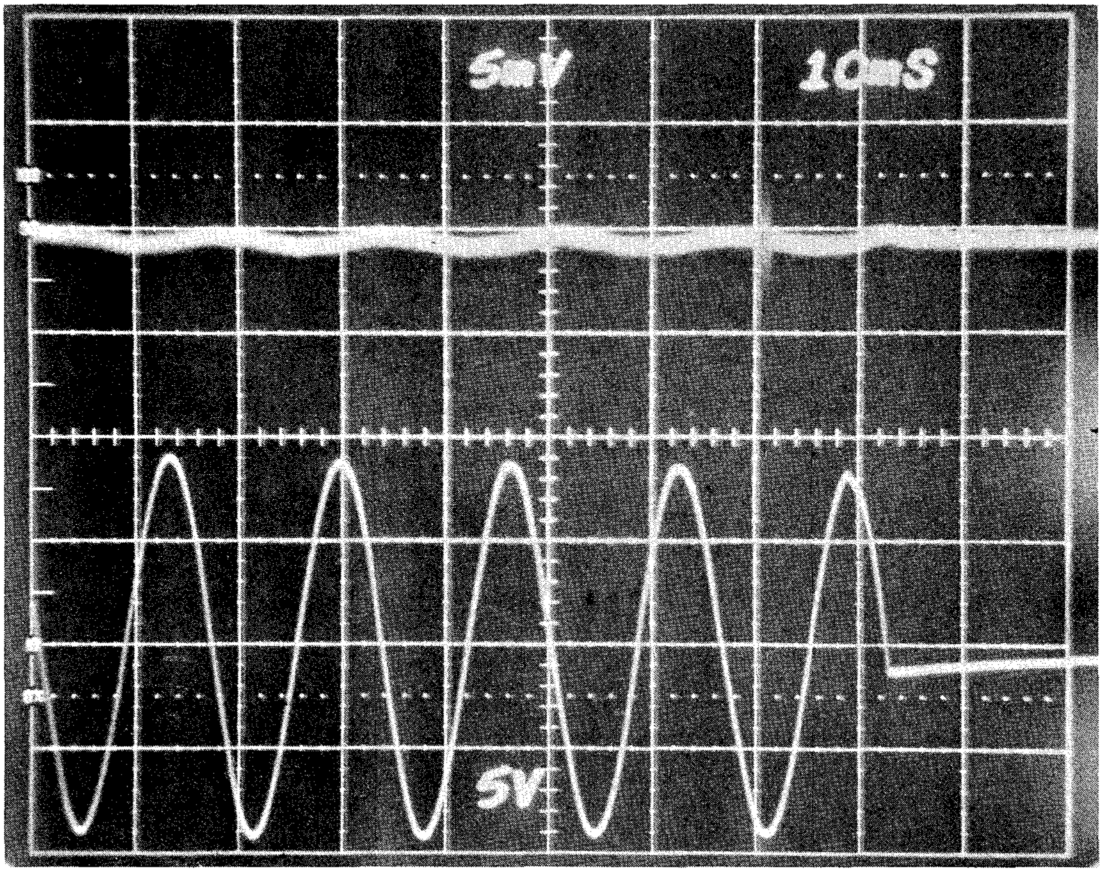

Figure 16. Recorded Current Levels for Energized Cable Test.

and shielded cables were placed on a flexing machine and flexed either to destruction or to approximately 10,000 cycles, whichever came first. The flexing action produced by the machine closely resembles shuttle car sheave wheel bending effects. A continuously monitoring Kelvin bridge was employed to determine when failure occurred in any of the cable components. The components monitored included:

1. the phase conductors,
2. the shield,
3. the ground conductors, and
4. the ground check wire

Results. The test results are given in Table 6. Further flex testing has been performed on shielded cable splice components. The test procedure and results are presented in the next section.

Table 6. Flex Test Results.

Sample Description	Results
1. 2/0, three-conductor Type SHD plus GC, 2000 V	10,400 cycles with no failures
2. 2/0, three-conductor Type G plus GC, 2000 V	10,386 cycles with no failures
3. Number 4 AWG, three-conductor Type SHD-GC, 5000 V	690 cycles - all three phases were broken, the same cable was flexed to 10,000 cycles with no failure to ground system.
4. Number 4 AWG, three-conductor Type G-GC, 2000 V	10,300 cycles with no failures

Splicing

Test Procedure. In order to determine the additional time necessary to splice a low-voltage shielded cable, a time-study was undertaken. The study was performed on an experienced splicer working above-ground in a shop. Accordingly, the durations recorded may be faster than for an "in-mine" operation. However, the total time percentage used to remove and replace the shield should give an idea of the additional time required. The cable was a 2/0 three-conductor, Type SHD plus GC, 2000 V.

Results. The study resulted in the elemental times presented in Appendix V. Total elapsed time for the splice was one hour, seven minutes, and 24 sec, and the time spent in removing and replacing the shield was ten minutes and 42 sec. Therefore, the precentage of total time spent on the shield is:

$$\frac{10{:}42}{1{:}07{:}24} = \frac{642 \text{ sec}}{4044 \text{ sec}} = 0.159 \text{ or } 15.9 \text{ percent.}$$

Shield Replacement Procedures. Figures 17 through 19 are photographs taken during the splice time-study. The first, presents a fast yet simple method for removing a cotton-copper braid shield. The shield should first be sanded to break-up the cotton strings, allowing the remaining copper wires to unravel in one direction.

Figure 18 shows the shield being replaced over one phase conductor. The shield tape (as recommended) is half-lapped over the splice area. It is necessary to hold the newly-repaired shield in place over the old shield at either conductor juncture end as illustrated in Figure 19. For this purpose, electrical tape is recommended.

Replacement Shield Flexing. To ascertain the best means of shield replacement within a splice, a second scheme of flex testing was

Figure 17. Sanding the Shield to Break Up Cotton Wires (Strings).

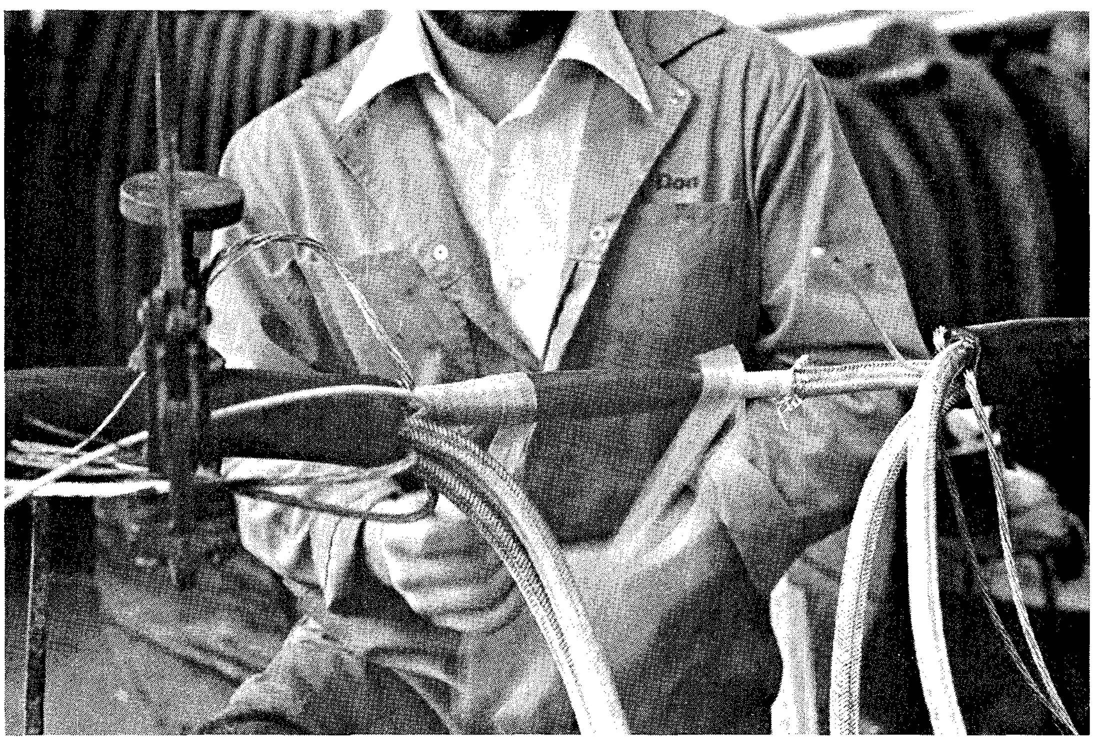

Figure 18. Replacing the Shield.

developed. This procedure utilized a continuous loop flexing machine (47). This particular machine can either be used in a "racetrack" or a "figure eight" configuration.

Three types of shielding components were flexed in conjunction with three different methods of attaching them within a splice. The shielding types were:

1. a tube of full copper braid,
2. a copper braid tape shield, and
3. a sheet of braid shield.

These shields were then attached using either electrical solder, liquid solder, or electrical tape.

Size 1/0 conductors with cotton-copper braid shields were used as test specimens. The first step in sample preparation was to remove an amount of shielding long enough to accommodate the insulator from the center of the length of conductor, as shown in Figure 20. Next, the insulation was removed and an insulator was placed over the bared conductor, Figure 21. Figure 22 shows the new shielding material in place over the insulator. The shield component is then attached by one of the means mentioned above.

The ends of the conductor were then joined to form a closed loop. To do so, the shielding and insulation were stripped back grom the conductor ends, and the shield was taped down. The shielding ends were taped to prevent fraying during flexure. The final preparation steps were crow's footing the cable ends (Figure 23) and joining the conductor ends with punch lock bands (Figure 24). Shield component types were first soldered in place as shielding was assumed to be the most

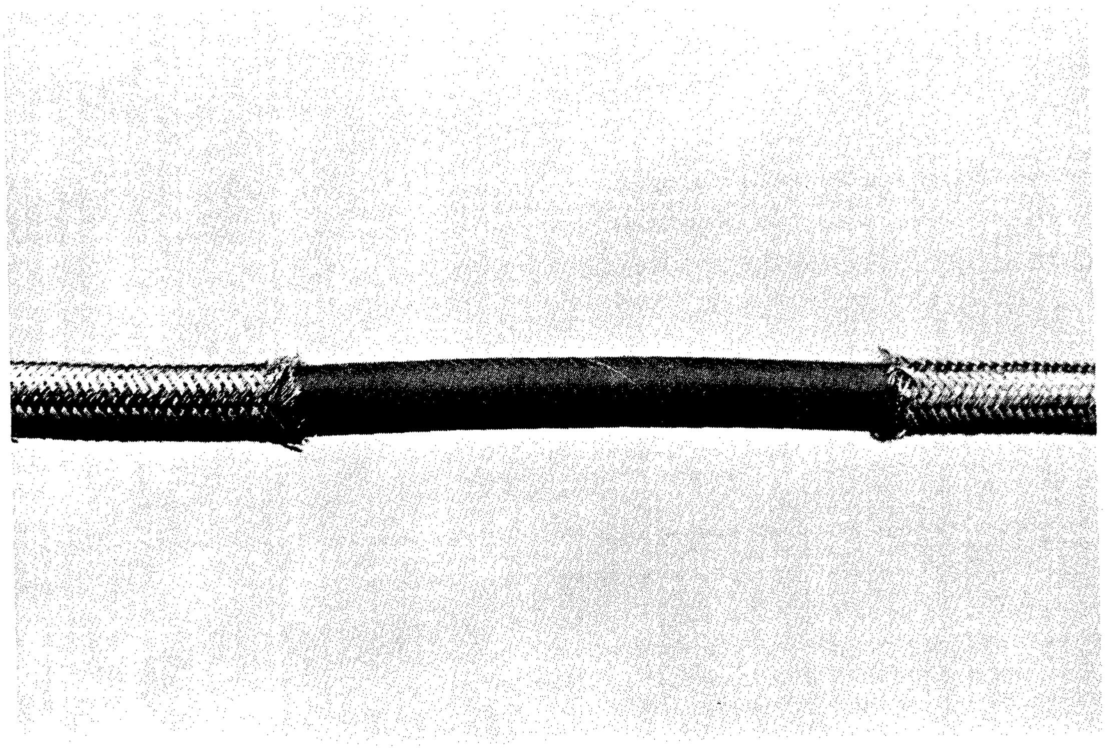

Figure 20. Shield is First Removed Prior to Testing.

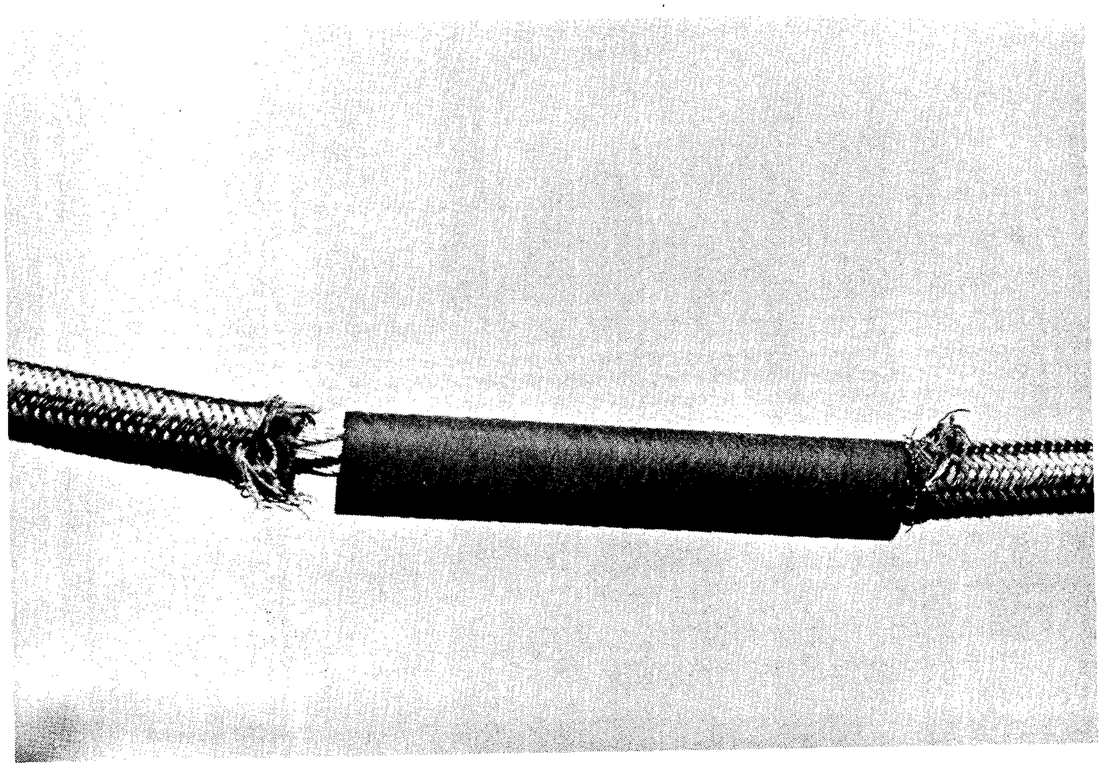

Figure 21. New Insulation in Place.

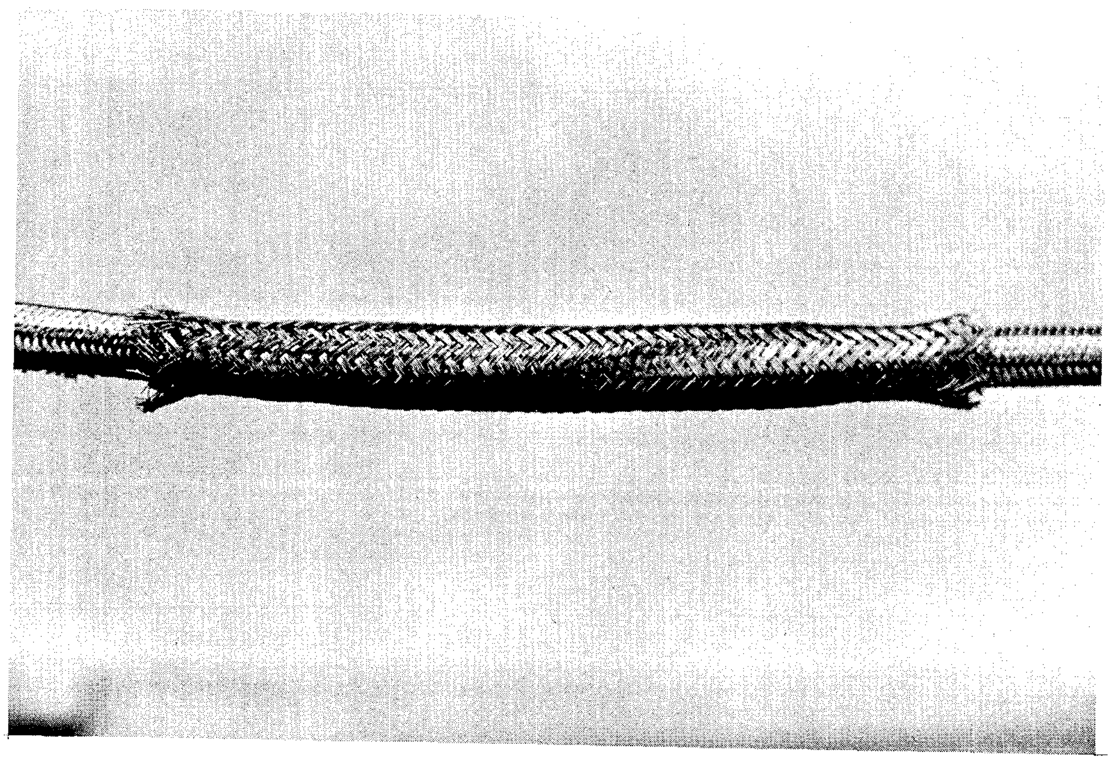

Figure 22. Shielding Material in Place.

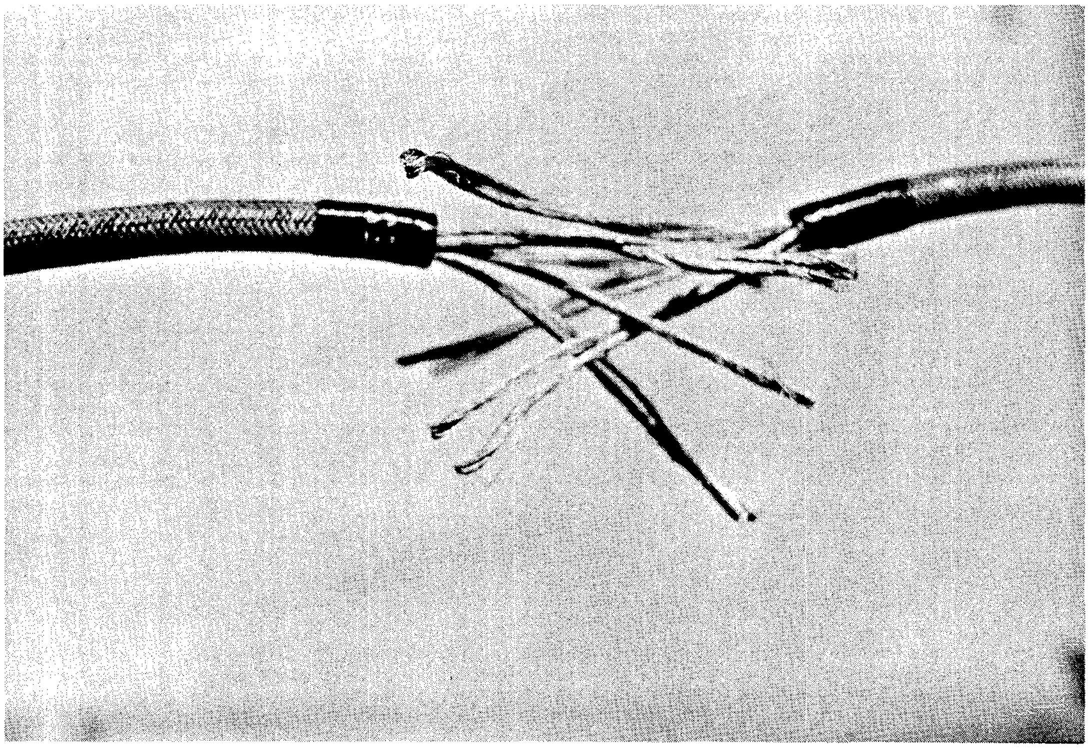

Figure 23. Crow's-footed Conductors Used to Join Sample Ends.

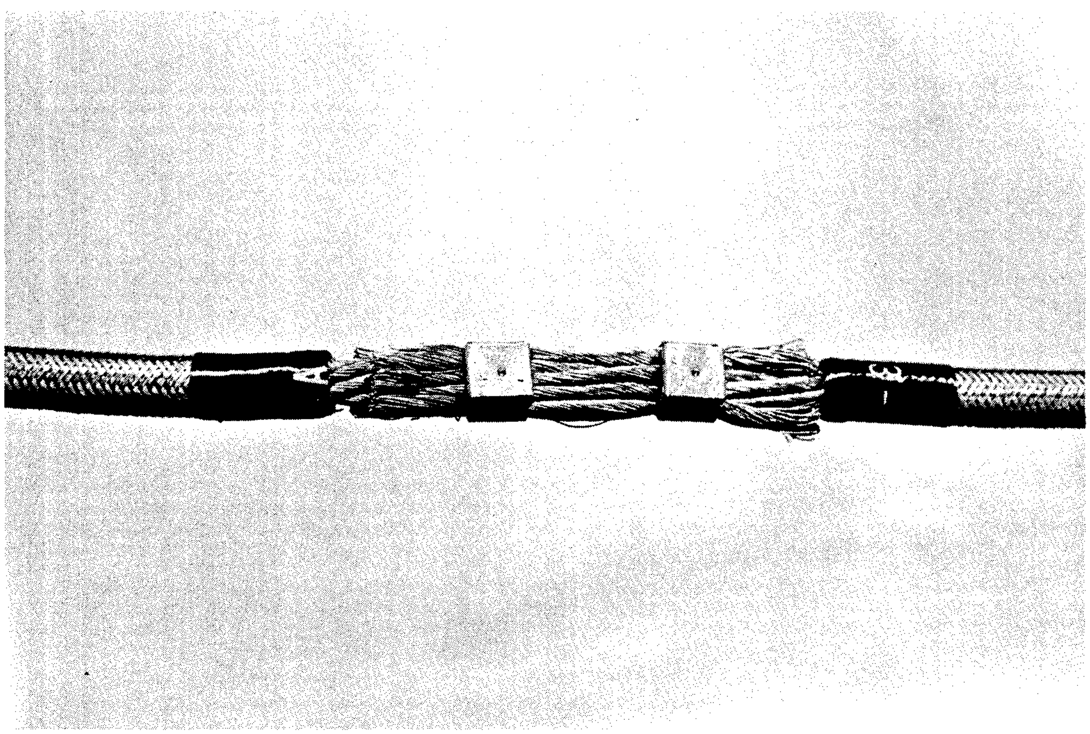

Figure 24. Punch-lock Bands Used for Mechanical
Strength of Sample.

durable method of attachment. In this manner, the best shielding material could be determined and, in turn, used to test the remaining methods of attachment.

The samples were then placed on the sheave wheels of the flexing machine in the racetrack configuration and run at 20 cycles per minute. A constant tension of 100 pounds was maintained in each side of the sample so as to not bias testing due to premature tensile failure.

Results. Table 7 gives the results of the testing.

Cable Reeling

Amount. The amount of cable which can be placed on a shuttle car or roof bolter reeling unit is of extreme importance. If a sufficient amount of cable cannot be placed on the reel, more frequent load center moves are needed, or backspooling must be practiced. When a shuttle car backspools, the tie-off point for its cable is moved further inby the dumping point than it would normally be. As the shuttle car passes the tie-off point when returning to the discharge (dumping) location, it must begin to play off cable from the reel. At this time, the reel

Table 7. Results of Replacement Shield Flexing.

	Type of Shield	Method of Attachment	Number of Cycles	Observed Failure
1.	Full Braid Tube	Solder	4427	Conductor
2.	Braid Tape	Solder	3889	Conductor
3.	Braid Sheet	Solder	4463	Conductor
4.	Full Braid Tube	Tape	4832	Conductor
5.	Full Braid Tube	Liquid Solder	4678	Conductor

is at the front of the car and, when the car reverses direction to return to the face, it frequently runs over the cable causing damage. Some backspooling is usually necessary in arriving at the discharge station, but the problem of decreased reel capacity serves to increase the backspooling distance and raise the probability of cable run-over.

A shuttle car manufacturer was contacted to find how much cable would be "lost" as a result of the increased diameter of shielded cables. The equation, which shows approximately how much cable of a given diameter can be placed on a cable reel, is as follows: (8)

$$X = \frac{(6.55 \times 10^{-2}) \, [L_2 \times (D_1 + D_2)(D_1 - D_2)]}{(L_1)(T)} \qquad (5)$$

where,

X = maximum cable length on the reel (in ft),

D_1 = outside diameter of the last cable layer (same as the reel flange diameter, in inches),

D_2 = drum diameter (in inches),

L_1 = spooling device lead (equal to the cable width if flat or the cable diameter if round plus 0.005 inches, in inches),

L_2 = spooling device travel (in inches),

T = cable thickness if flat or the cable diameter if round (in inches).

The above formula can be used to illustrate the importance of adequate reel capacity.

The test site utilizes two Torkar Type 48A 40 shuttle cars on each section. The variables for this car are as follows:

D_1 = 37.05 inches,

D_2 = 11.05 inches,

L_1 = Cable Width +0.005 inches,

L_2 = 15 inches, and

T = Cable Thickness.

The equation for this shuttle car then reduces to:

$$X = \frac{1228.7145}{(\text{Width} + 0.005)(\text{Thickness})} \quad (6)$$

The cross sections for the shuttle car/roof bolter cables used at the test site are shown in Figure 25. A Vernier caliper was used and the dimensions for the non-shielded cable were 2.162 inches by 0.900 inches. The shielded cable measured to 2.468 inches by 1.098 inches. The corresponding reel capacity calculations were as follows:

$$\frac{1228.7145}{(2.167)(0.900)} = 630 \text{ ft of non-shielded, and}$$

$$\frac{1228.7145}{(2.473)(1.098)} = 453 \text{ ft of shielded.}$$

More recent production runs have resulted in slightly smaller flat shielded cables, measuring 2.440 inches by 0.9804 inches. The reel capacity calculation for this newer cable is:

$$\frac{1228.7145}{(2.445)(0.9804)} = 513 \text{ ft.}$$

In order to more accurately define how much of each type cable could be placed on the reel and also to check the accuracy of the equation, actual measurements were made for each of the shielded and non-shielded cables.

Reeling Test. The amount of flat, shielded number 2 AWG cable that could be reeled by a Torkar 48A 40 was first reeled in an above-ground

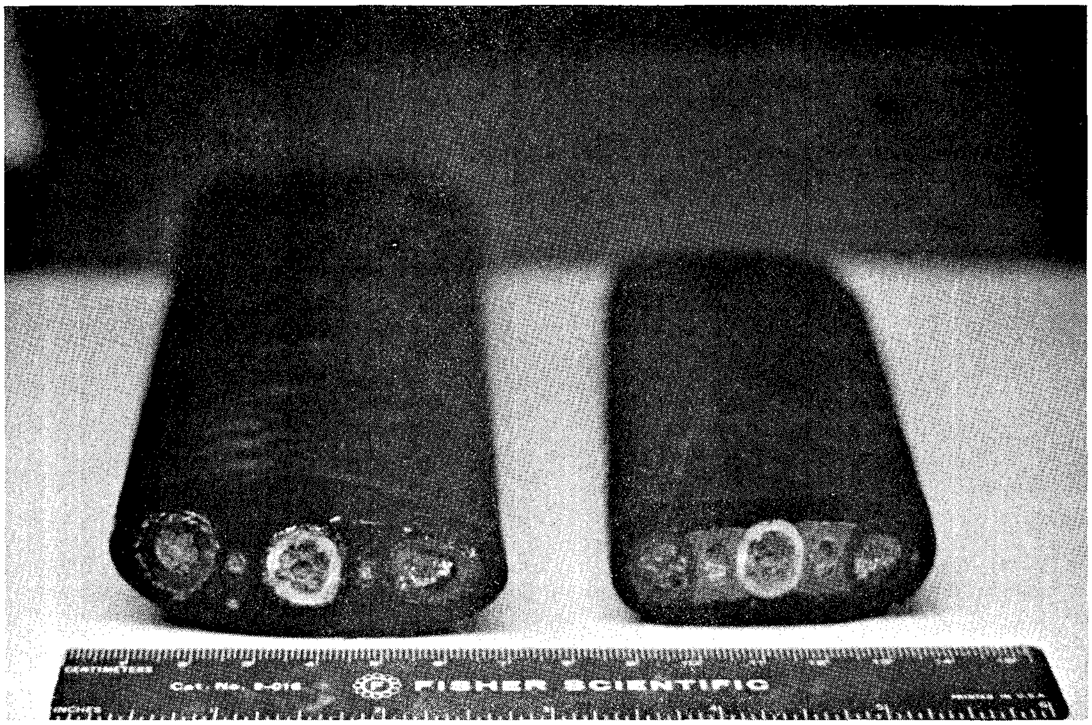

Figure 25. Cross Section of Flat Shielded, Non-shielded Cables.

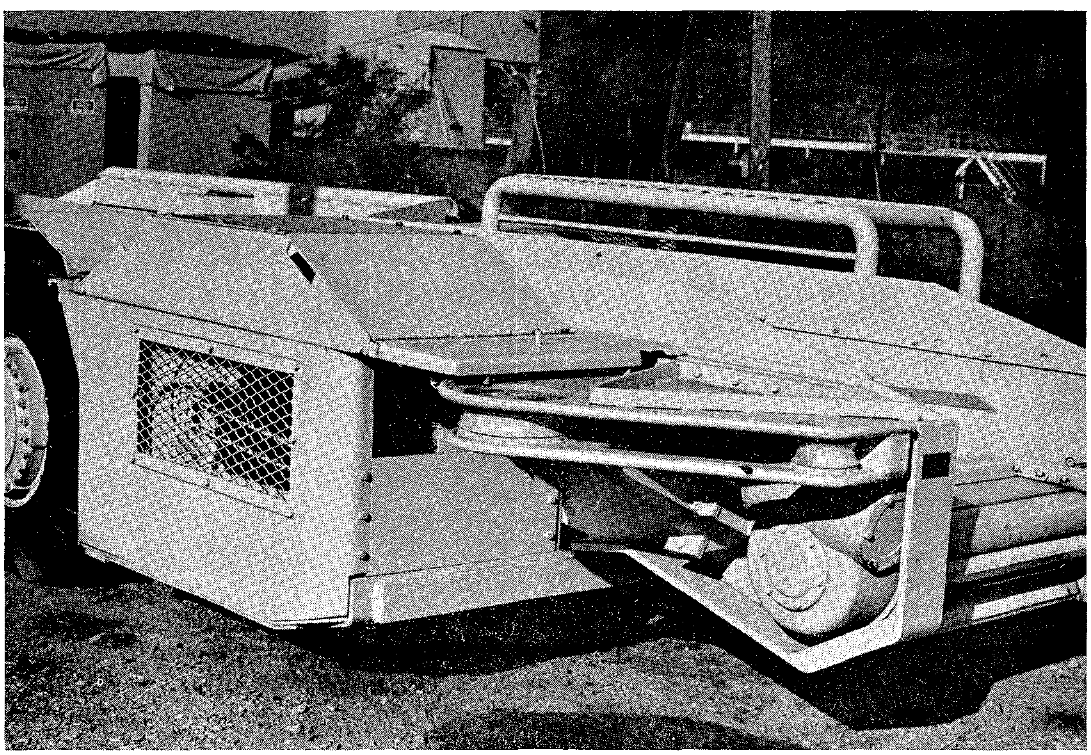

Figure 26. Torkar Cable Reeling Unit.

test. Next, a non-shielded cable, comparable to the ones used at the test site (but made by a different producer), was measured on a shuttle car reel underground.

Figure 26 shows the cable reeling unit of a Torkar Type 48A 40 shuttle car. The sheave wheels near the center of the illustration feed the cable to a spooler (or reel guide) and cable reel which are located in the protective enclosure just left of the larger sheave wheel. A better view of the reel guide, indicated by A, and the cable reel, indicated by B, is shown in Figure 27. The area in Figure 27 shown by C is the housing covering the spooling spindle. This spindle operates by a gear-driven chain and causes the reel guide to travel back-and-forth in front of the revolving cable reel, thus placing the cable neatly on the reel. Figure 28 shows a similar exposed spooling spindle from a Fletcher roof bolter.

Results. The amount of flat, shielded number 2 AWG cable that was reeled by the Torkar 48A 40 was 320 ft. The amount of non-shielded cable reeled was 590 ft.

Cable Weights

Underground tests were performed to further define the weight difference between shielded and non-shielded cables. The tests involved lifting and dragging continuous miner cables.

Because of their size (usually 4/0, three-conductor round) continuous miner cables cannot be reeled by a machine and are normally handled as drag cables. As such, miner cables must be hung from the ribs or roof to keep entries clear for other section machinery. The first test was developed to aid in determining how much a cable weighs

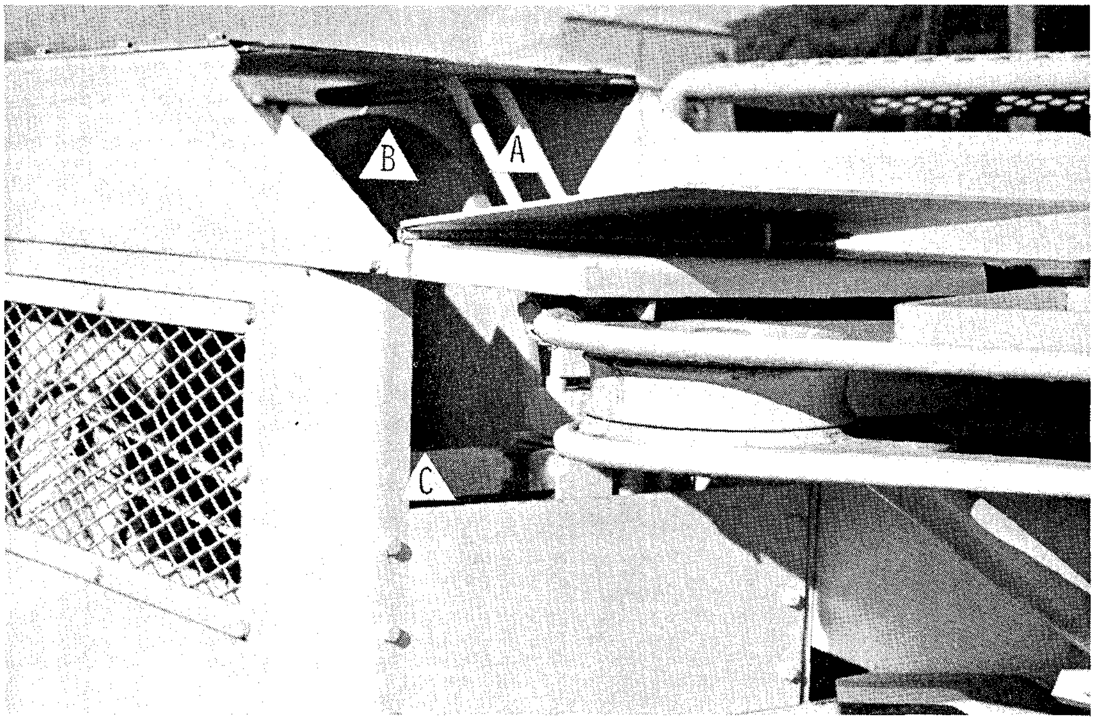

Figure 27. Close-up of Torkar Reeling Unit.

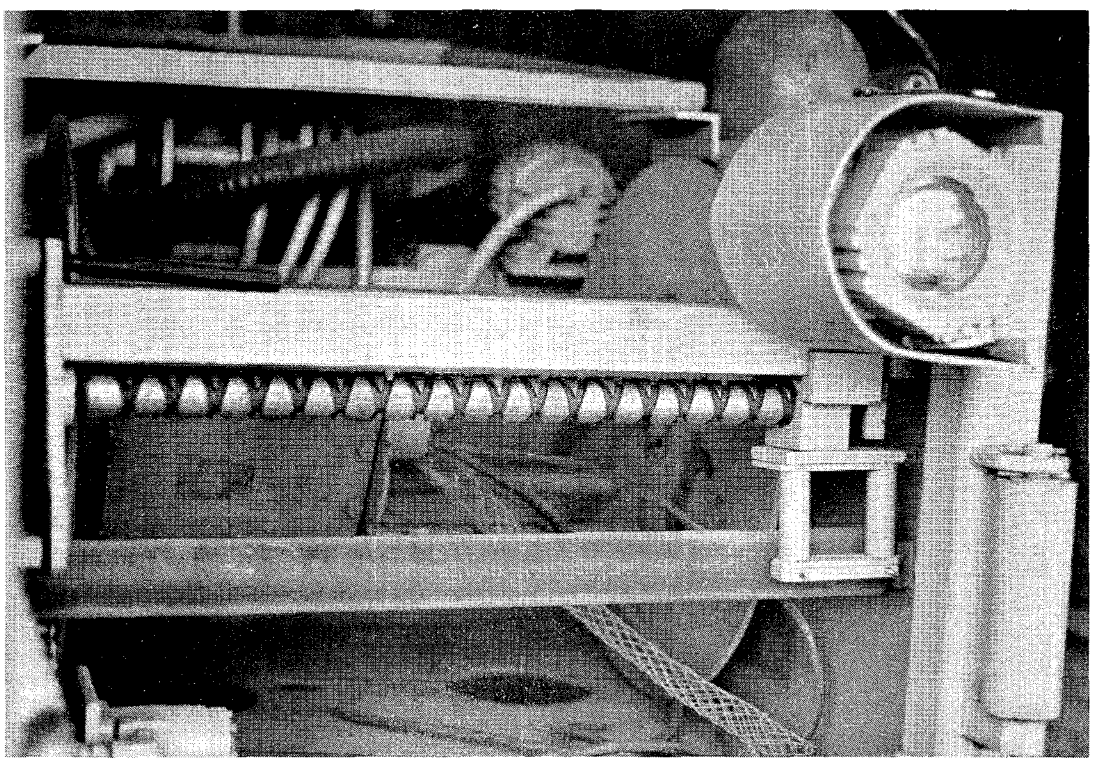

Figure 28. Spooling Spindle for a Fletcher Roof Bolter.

as it is hung from a hook or how much weight must be lifted to hang a cable on a hook.

Lifting Test. To set up the experiment, a scale with an adequate range (0 to 500 pounds) was hung from a roof bolt plate, and a cable hook was attached to the scale bottom. By use of a chain between the scale and roof bolt, the setup was arranged so that the bottom of the hook was 54 inches from the mine floor. Next, the miner cable was arranged so as it was lifted to the hook it would have no tension at either end, thus insuring that only the weight of the cable for that particular span was being measured.

Results. Using this arrangement, the span of shielded miner cable was found to weigh 90 pounds. The non-shielded miner cable weighed significantly less at 75 pounds.

Drag Test. The second test involved dragging the cables along the mine floor. The cables were first arranged as shown in Figure 29. The scale was attached to the cable by a rope, and the cable was dragged by pulling the scale (and thus the cable) in the direction shown. The highest recorded reading on the scale was used for each test. The test was considered completed when all slack was taken from the cables in the looped area. In both cases the cables were lying on dry, level floor covered with rock dust and a small amount of fine coal.

Results. An average of 95 pounds was needed to drag the shielded cable, while the non-shielded required 80 pounds of drag.

Coupler Installation

Coupler installation as well as the cable entries into machines require more time for shielded cables. Coupler installation time for the

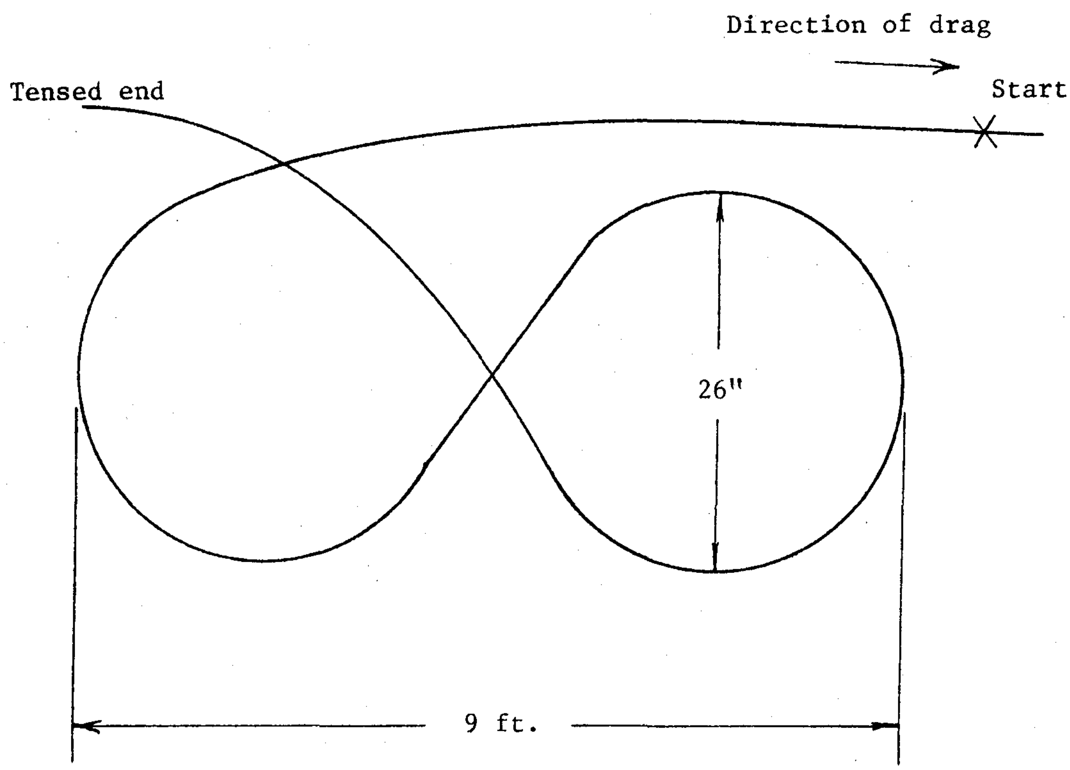

Figure 29. Setup for Cable Drag.

shielded 4/0 miner cable at the test site was one hour, 25 minutes, or roughly twice the normal installation time.

Summary

The test procedures and results just completed will provide an excellent foundation for the evaluation of proposed advantages and disadvantages and subsequent formulation of recommendations. The next chapter puts forth this evaluation of results and the recommendations drawn from them.

CHAPTER IV

DISCUSSION OF RESULTS AND RECOMMENDATIONS

General

A preliminary analysis of several of the proposed advantages and disadvantages was performed in Chapter II. To help answer the balance of questions remaining from that effort, a series of laboratory and field tests have been performed and were set forth in Chapter III. An analysis of the research results in light of each proposed advantage and disadvantage will now be discussed and subsequent recommendations will be presented.

Advantages

Advantage One. Shielded cables provide protection from electric shock and are more sensitive in terms of circuit breaker settings.

The literature review has made reference to a number of authors who point to the shock prevention advantage of shielded cables. The accident analysis also pointed to the hazard reduction potential afforded by low-voltage shielded cables. Before shielded cables can intervene in an accident situation, however, several conditions must be met. The shield must be low enough in resistance and of the proper percent coverage to act in saving lives or preventing injuries.

Percent Coverage. As the percent coverage tests demonstrated, not all shielded cables have a low-resistance from the ungrounded shield to cable ground wires. This is especially true of those cables which require a construction support for the ground wires or for those SH-C designs which separate the shield from the balance of the cabled assembly with a reinforcing cloth. Other cables with high-resistance from shield to ground wires are those utilizing wire shields in conjunction with extruded or tape semi-conductors.

The human body resistance of 1000 Ω under ideal conditions is a critical value in the analysis of shield percent coverage. This value can approach 10,000 Ω or higher under less severe conditions. Obviously, by using the 1000 Ω value in comparison with a resistance of 0.1 Ω or less, the human body would be fairly safe from shock (most of the current would follow the least resistive path through the shield and ground wires). However, not all cables tested exhibit such a low-resistance from shield to ground.

The flat shielded cable showed resistance readings always less than 10.1 Ω, even if the shield were not directly grounded at both ends. Again, the human body would be fairly safe. This is especially true if the resistance of the semi-conducting material decreases under increasing current flow.

High-resistance values (2000 kΩ) for the round SH-C cable can be attributed mainly to the non-conducting cloth which separates the shield from the balance of the cable components, including the grounding wires. This test also simulated a floating shield which would result between two splices if the shield had been omitted or if the shield failed at more than one location during flexure. Low-resistance values near the end of this test were caused by a shield wire which was driven through the cloth and remained attached to a ground wire.

Observed resistance readings for the wire shields used in conjunction with the semi-conductive tape went as high as 1146 Ω. Using the resistance value of 1000 Ω, the human body in contact with the nail now becomes the lowest resistance path to ground. Obviously, high-resistance readings can be improved by placing the shield wires more closely together. The current would then have to travel through less of the high-resistance semi-conductive material.

In order to insure shielding effectiveness in preventing electrical shock, a performance test could be employed. The percent coverage testing procedure and a safety factor of two (500 Ω) for human body resistance is suggested as the criteria.

Current IPCEA standards call for a 60 percent coverage for a cotton-copper shield (33). Utilizing the following formula, one cable manufacturer was able to determine which percent wire shield coverage would allow the six-penny nail to fit through a cotton-copper shield, just touching on either side (24).

$$\text{Percent Coverage} = \frac{Nd}{W} \times 100, \qquad (7)$$

where

N = number of parallel wires,

d = diameter of individual wires (in inches),

W = $\pi D \cos (a)$

D = diameter under shield (in inches),

a = angle between serving wires and axis of cable,

Tan a = $\pi D/C$, and

C = pitch of serving in inches.

A 51 percent coverage is necessary to allow for an 0.085 inch gap (equal to the nail diameter), using an 84 wire shield construction. For a 60 wire shield construction, a 42 percent coverage would allow for the same gap. These figures are for a cotton-copper shield only. When a cotton-copper shield is constructed to yield a 60 percent coverage, the gap between shield strands ranges from 0.059 inches for 84 wires to 0.042 inches for 60 wires. (24) This indicates that for a cotton-copper shield the percent coverage requirement of 60 percent allows for a margin of safety. However, dropping below the required 60 percent level might seriously impair the current-carrying capacity of this type shield.

Energized Cable. The importance of a low-resistance shield capable of withstanding high currents was shown by this series of tests. Test results indicated that the full copper braided shield was capable of handling currents of 1800 A peak-to-peak for the 83 msec necessary to trip the 20A breaker. However, as illustrated by Figure 30, when this current duration was longer (for one trial only) because the breaker failed to trip, the shield was completely destroyed. The simulated man received line voltage. Figure 30 also shows another nail hole which was not burned-out and caused the breaker to trip.

In low-voltage mine power distribution networks, grounding resistors are required to limit the fault current to ground to 25A. Assuming such a limit, the shield would probably not have been destroyed, and the man would not have been harmed. The test circuit employed did not include a grounding resistor to simulate the worst case in terms of possible shield destruction.

For the nine cases where the shield caused the breaker to trip, the man was receiving only 2 mA (peak-to-peak) of current, which is below the human perception threshold. Utilizing the relation $I = 116/(t)^{1/2}$ from Chapter II, the threshold level fibrillation current can be calculated. For a time of 83 msec, the allowable current is

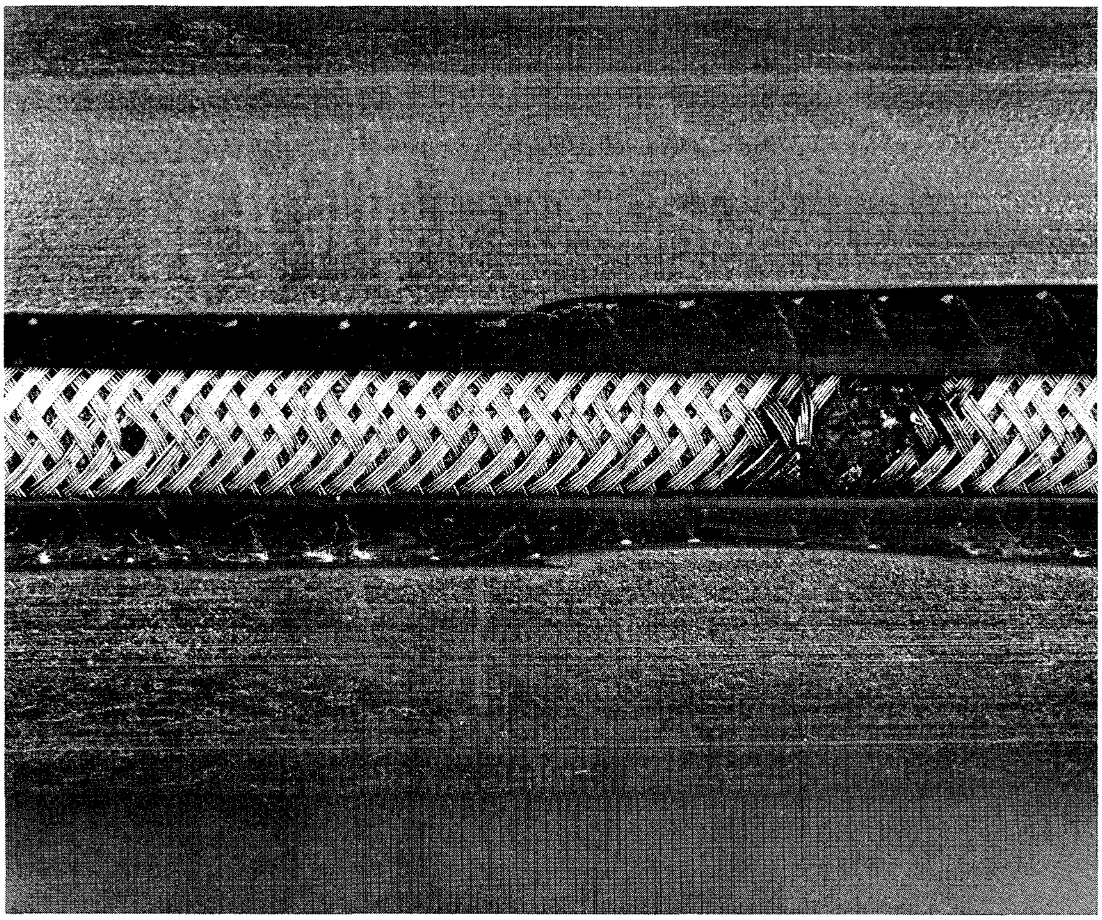

Figure 30. Shield Damage Caused by High-current.

calculated at 402.6 mA (rms). The observed current of 2 mA (peak-to-peak) or 0.7 mA (rms) is far below the fibrillation threshold.

The reason for the breaker not tripping for one of the trials was probably because of poor initial contact from shield to nail. The nail did not enter the cable properly and bent at the first drop of the hammer. When it was removed and reinserted into the same hole for the second hammer drop, the shield may have been spread-apart. Thus, as the nail passed through again and contacted the phase-conductor, a high contact resistance from nail to shield resulted, causing the shield to burn (Figure 30). Therefore, assuming a low contact resistance, the shield can be effective in accident protection. As a backup system, the grounding resistor, in limiting current flow to 25A can prevent the shield from being destroyed, thus grounding the fault current.

Inherent in the shield functioning as a shock preventive is a properly-operating ground-overcurrent circuit breaker. If the breaker is set at too high a current trip level or is too slow in responding to this current flow, then the shield is of questionable usefulness, especially in high contact-resistance situations.

Advantage Two. Shielding maintains the symmetry of cables.

When ground wires are placed in intimate contact with shields, the symmetry of a cable can be maintained. In the event of an undetected break in a ground wire, the SH-D or SHD plus GC cable acts as a type of "patch" at the break area. It does so by allowing current to flow from the ground wire into the shield and then back to the ground wire.

Symmetrical cables have the ability to prevent induced voltages. By acting to maintain symmetry, the SH-D cable has a positive influence in preventing induced voltages.

Advantage Three. Shields maintain the integrity of the cable grounding system.

This area is related to Advantage Two in that shielding acts to maintain broken ground wires. Shields must be in intimate contact with ground wires to accomplish this advantage.

Advantage Four. Shielded cables may have a lower operating temperature.

The metallic shield may be capable of dissipating heat faster. However, this advantage was the only one for which there are no concrete findings. Temperature studies were planned for the underground test site, but installation delays have prevented them. Cable design changes, which are detailed in the Cable Reeling section of Disadvantage Six, for the shuttle car and roof bolter shielded cables were the cause for delay. In the Literature Review the temperature problem was shown to be critical only for cables on reels. If the temperature advantage is found to be sound, then a further possibility of using smaller conductor sized cables on reels exists. As will be noted in the next chapter, this area should receive future consideration.

Advantage Five. Maintenance testing of shielded cables is more easily accomplished.

As was defined in the Literature Review, individual conductor insulations are the object of this type test. Faulty insulation is usually indicated by a leakage current to ground and, with non-shielded cables, a water immersion tank is necessary to most effectively perform the test. Therefore, because shields can provide a ground plane to surround each conductor, successful maintenance testing can easily be accomplished in-situ. If implemented in a regular preventive maintenance program, the incidence of cable insulation failure due to testing is diminished.

Disadvantages

Disadvantage One. Shielded cables have higher purchasing and operating costs.

Purchases of cables for in-mine testing have provided insight into this area of low-voltage shielded cable costs. Increases over non-shielded types ranging from 22.9 percent to 68 percent were encountered. Most cable producers initially felt that ultimate cost increases would be from 10 percent to 20 percent. Cables purchased by this researcher certainly do not reflect this early estimation made by producers.

Other costs associated with shielded cables are cost of down-time, or the expense caused by a possible limited cable life. As will be discussed under the splicing area, shielded cables do take more time to repair. In terms of lost production, this can only be determined on an individual company basis. On a per-kit basis, added splicing components will typically cost about $1.50. This cost, when compared to the total kit price of $29.30 represents a five percent increase in cost. Additional expense caused by a limited cable life was just mentioned as an associated cost for shielded cables. Flex testing in the laboratory has shown the flex life of the shield to be adequate.

Disadvantage Two. Availability of a wide range of low-voltage shielded cables might create future problems.

Research in this area has shown that five cable producers hold between 75 and 90 percent of the low-voltage cable market. A survey of these companies showed that two of the five could immediately begin producing their share of shielded low-voltage cables. The other three would require extensive capital modifications and an associated nine month to two year lead time. This important input factor must be considered before any action is taken on a switch to shielded cables. The two companies with adequate braiding capacity for their current share of the market may not be able to cope with a large increase in demand while the other two are adding capacity.

Disadvantage Three. The possibility of reduced cable life from impaired flexibility might exist. Laboratory flex testing has shown an adequate life for shielded cables. The testing results indicated the grounding systems for the cables tested are at least as strong (or flexible) as their respective phase conductors. Because of the many parallel paths to ground, it is important to note that it is possible to completely destroy a ground conductor in an SH-D cable without detection by the Kelvin bridge. For this reason, each of the SH-D cables tested has been cut open for a closer look. Figures 31 and 32 show the internal damage to a cable after flexing.

The cable illustrated in Figure 31 (a SHD plus GC) suffered no noticeable damage to any ground wires throughout the entire cable length. However, the cotton portion of the cotton-copper braid was completely destroyed due to a rubbing action against the cable outer jacket, hence the unidirectional appearance of the shield wires. Further, the spacing between shield wires was changed. The small broken wires in the lower portion of picture were from the shield. The shield wires were examined at areas of breakage, and none were found to have entered the phase conductor insulation. An experienced source stated that the phase conductor normally breaks through to the shield and not vice versa (53).

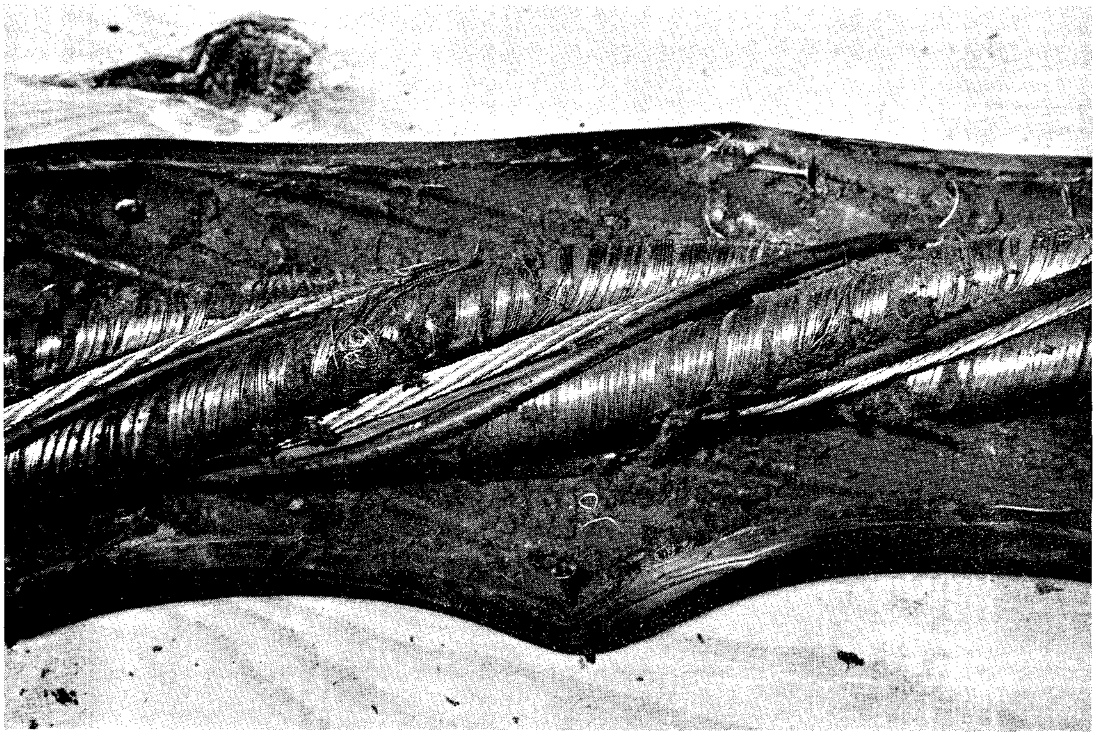

Figure 31. A 2/0, Three-conductor, SHD Plus GC, 2000 V Cable After Flexing.

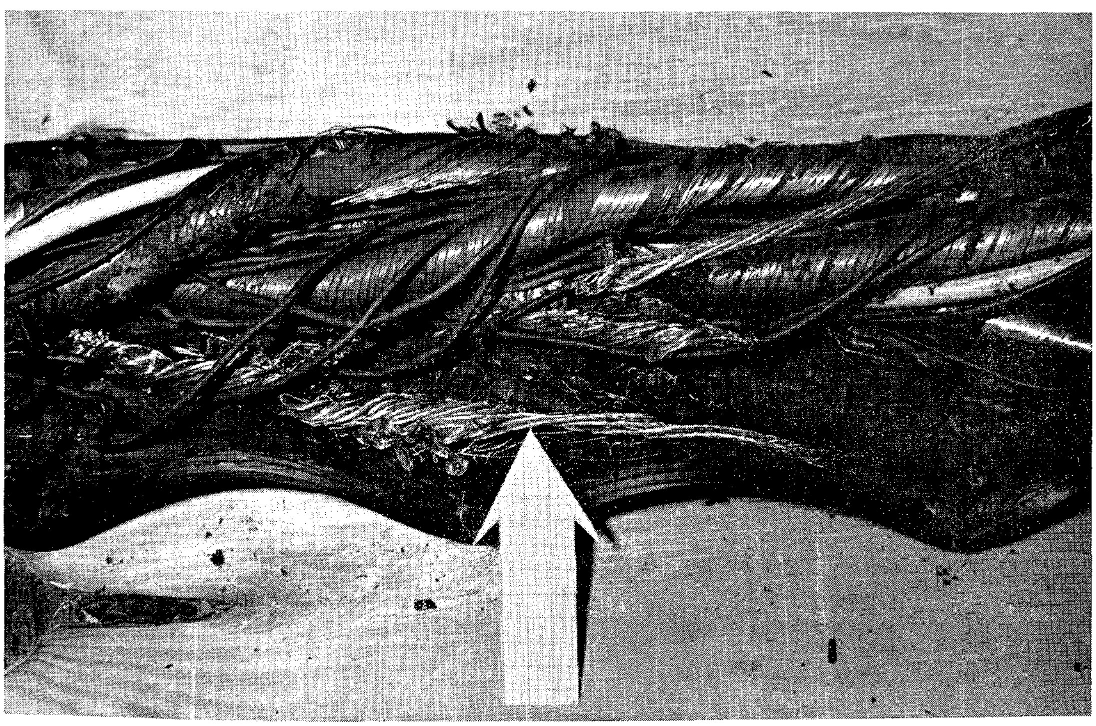

Figure 32. A Number 4 AWG, Three-conductor, SHD-GC, 5000 V Cable After Flexing.

Additional information about the breakage phenomenon has been included in Appendix III.

The cable shown in Figure 32 also experienced a frayed cotton portion of the cotton-copper braid (in fact, it was completely worn away). As had been suspected, the ground wires were completely broken in several locations (note the arrow) even though the Kelvin bridge indicated an intact grounding system. Separation of the copper wires in the shield again occurred. Again, broken shield wires did not enter the phase conductor.

Disadvantage Four. Extra steps are involved in splicing and a limited splice life may result due to the inability to effectively replace the shield within a splice.

Time Study. With regards to the first portion of this disadvantage, it is true that extra steps are involved in a shielded cable splice. The time-study of a shielded splice revealed that 15.9 percent of total splice time was spent in removing and replacing the shield. The importance of this area comes in terms of the cost of downtime in completing a cable repair. It must be noted that this timed splice was done on a cable utilizing a cotton-copper braid, which can be removed more easily and faster than a full copper braid. This removal is shown in the splicing section of Chapter III.

Because the splice is one of the most vunerable cable areas, the shield must always be replaced. From a safety standpoint, eliminating the shield from a splice (to effect a more durable splice) is not desirable. From a legal standpoint, Section 75.906 of Title 30, Code of Federal Regulations, maintains that all mobile equipment trailing cables shall provide continuity of all components (64). Furthermore, proposed revisions to Section 75, under 75.603 (revisions), suggest that each power conductor, grounding conductor, and metallic shield in a splice shall be welded, soldered, or joined together with mechanical connectors so as to assure adequate mechanical strength, electrical conductivity, and flexibility (2). Based upon the safety and legal considerations, shield continuation throughout the splice area is essential.

Replacement Shield Flexibility. The second portion of disadvantage four, the possibility of the spliced shield having a short life, was resolved in the replacement shield flexing experiments. This problem first became apparent during a field trip to a western mine (described in Appendix III). At the mine, the shield was supposedly being installed over each phase conductor during splicing. However, a discussion with a maintenance worker revealed that the practice had been discontinued. Apparently, the shield would tend to "bunch up" in a splice after it was put into operation.

The results of this test pointed to a tube of braided shield, shown in Figure 33, as the superior method of attachment. Electrical tape was found to be an acceptable medium for shield attachment. In lieu of a tube of braided shield, braid tape was found to be a more readily available, although a slightly less effective means of shield replacement. This testing has shown that properly installed shielded splices can last as long as similar non-shielded splices. Some of the cotton portion of the cotton/copper shield (right side of Figure 33) was destroyed by the torch during soldering. The ability of the shield (copper braid tube) to move freely greatly contributes to the flex life of the joined area.

Figure 34 shows a tape shield; at 196 cycles, the tape shield began to separate on the sheave wheel side. As can be seen, at failure the shield was more noticeably damaged. Separation and tearing of the shield occurred at the edge of the insulator, but the shield was essentially intact.

A sheet of shielding, wrapped over the insulator, was the final type of shielding to be soldered in place. Figure 35 shows how flimsy this type of shielding can be. At 103 cycles, the wheel side of the shielding started to wear through and separate. The lack of percentage of insulation coverage provided by the braid sheet is apparent.

In all three cases, the conductor failed at the connector area prior to the shield junction. The full braid tube was obviously the best shield type. Because of this, it was used in conjunction with taping and liquid soldering to determine the best of these two methods. The tape specimen frayed slightly during flexing (Figure 36) but otherwise provided a good bond. It also provided for the easiest installation. The liquid solder joint specimen showed no noticeable damage throughout flexing, and this joint again outlasted the conductor itself.

Because soldering, taping, and liquid solder all outlasted the conductor samples, the easiest method should be the one selected. Liquid solder requires a long setting-up time, and soldering requires a heat source. The obvious (and cheapest) choice is then electrical tape. As a recommendation, electrical tape should be used in conjunction with a full braid tube of shielding. However, availability may dictate the use of the braid tape shield and electrical tape. The test site has utilized the braid tape shield and electrical tape method for splicing.

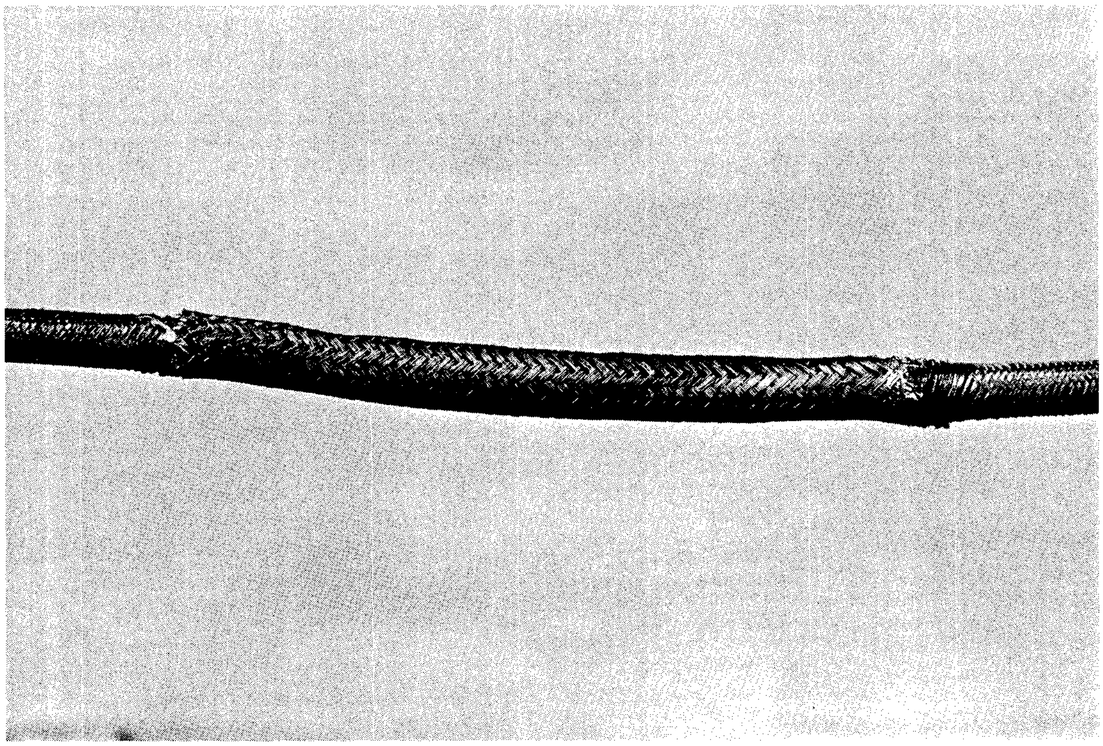

Figure 33. Full Braid Tube of Shielding Test Specimen.

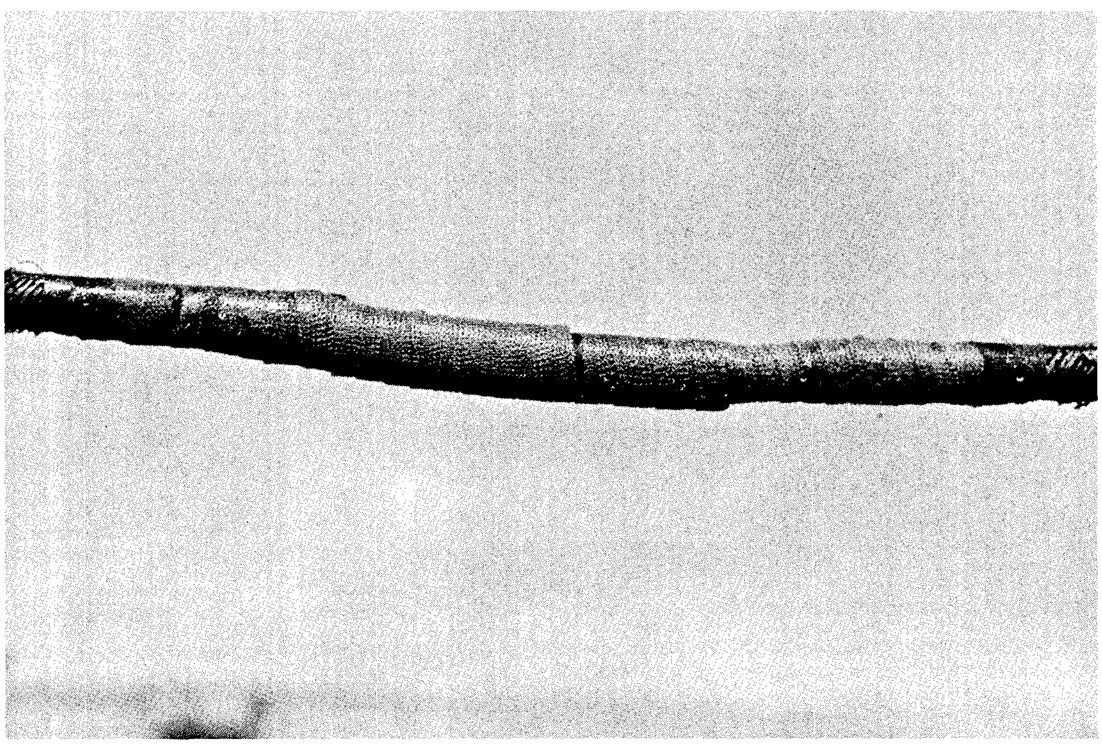

Figure 34. Copper Braid Tape Shield Test Specimen.

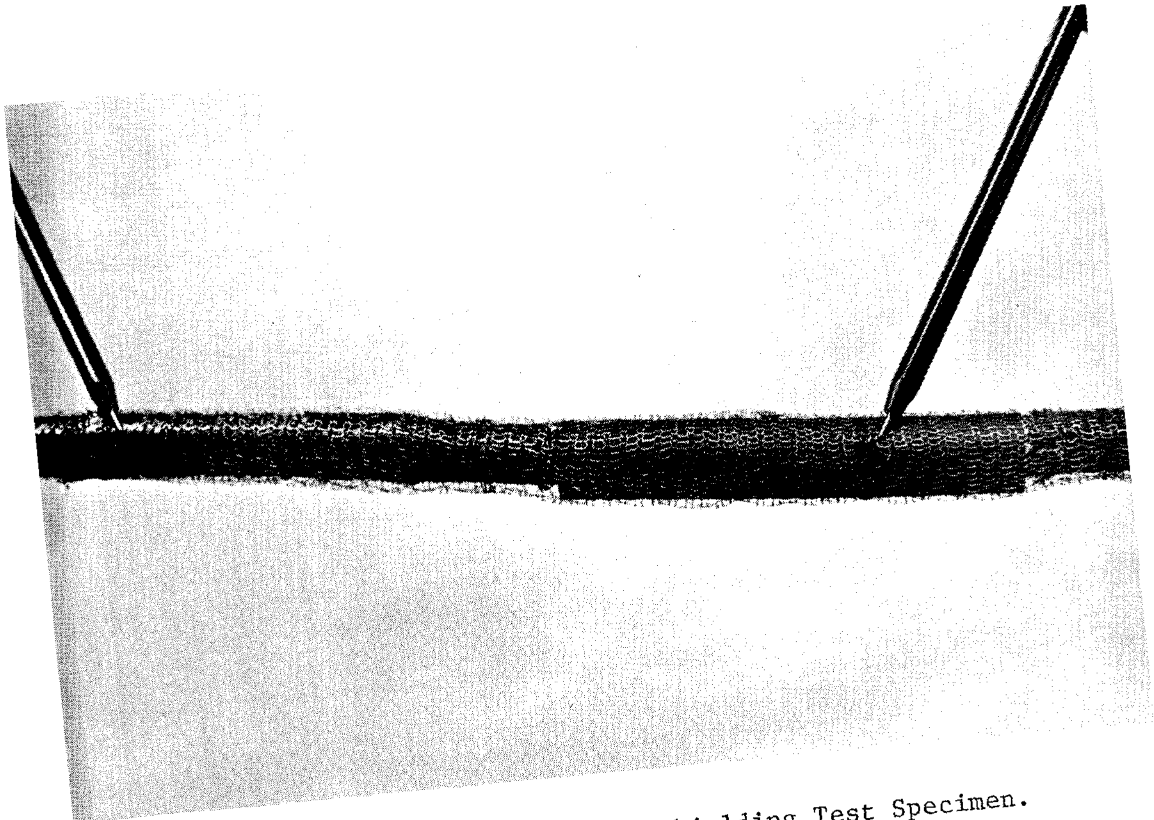

Figure 35. Sheet of Braid Shielding Test Specimen.

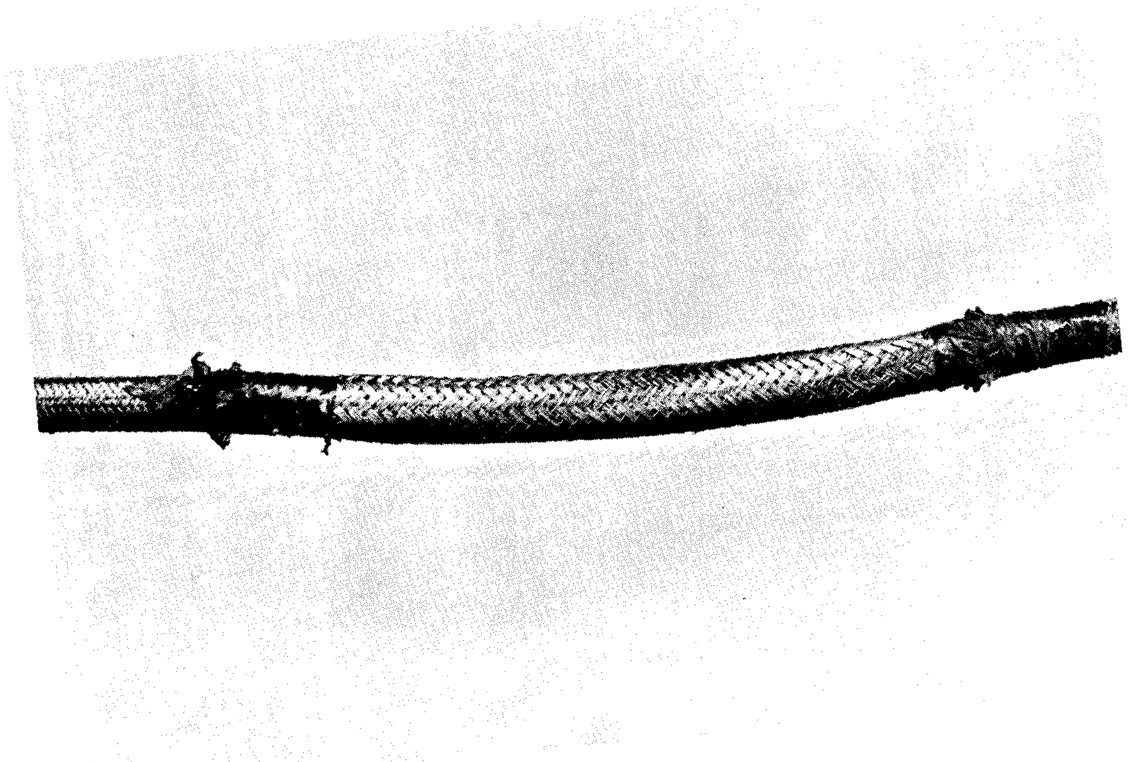

Figure 36. Shield Attached with Vinyl Tape.

Splicing at the Test Site. Splice kits were required for three-conductor round 4/0 continuous miner cable and number 2 AWG, flat, three-conductor shuttle car and roof bolter cable at the test site. Prior to the cable installations, splicing demonstrations were given. Both shielded and non-shielded 4/0 miner cables utilize a shrink-type outer jacket splice kit. During splicing, the only major problem encountered was a tendancy for the shielding to adhere to the bedding tape over each phase conductor. This adhesion problem makes shield removal more difficult.

Figure 37 shows the number 2 AWG, flat, three-conductor cables originally designed for use at the test site. The shielded cable (top of picture) is much larger than its non-shielded counterpart. Because of this size difference, a great deal of difficulty was encountered in selecting an adequate splice kit. Two types of kits were considered, the slide-on, fixed jacket type, and the shrink jacket type. Use of a fixed jacket type required use of a number 1 AWG jacket for the shielded cable and a number 2 AWG jacket for the non-shielded cable. A shrink type splice kit of the same type used on the continuous miner cables was also considered. However, to arrive at a size large enough for the flat shielded cable, a 4/0 jacket was needed. Neither of these solutions was feasible, especially since the splice jackets were too large to pass through the cable spooler on the reeling device. This area of cable size receives greater coverage in the Cable Reeling section later in this chapter.

Relative to costs, little variation is found between the shielded and non-shielded kits. Any non-shielded kit can be transformed into a shielded kit by adding the shielding material, providing, of course,

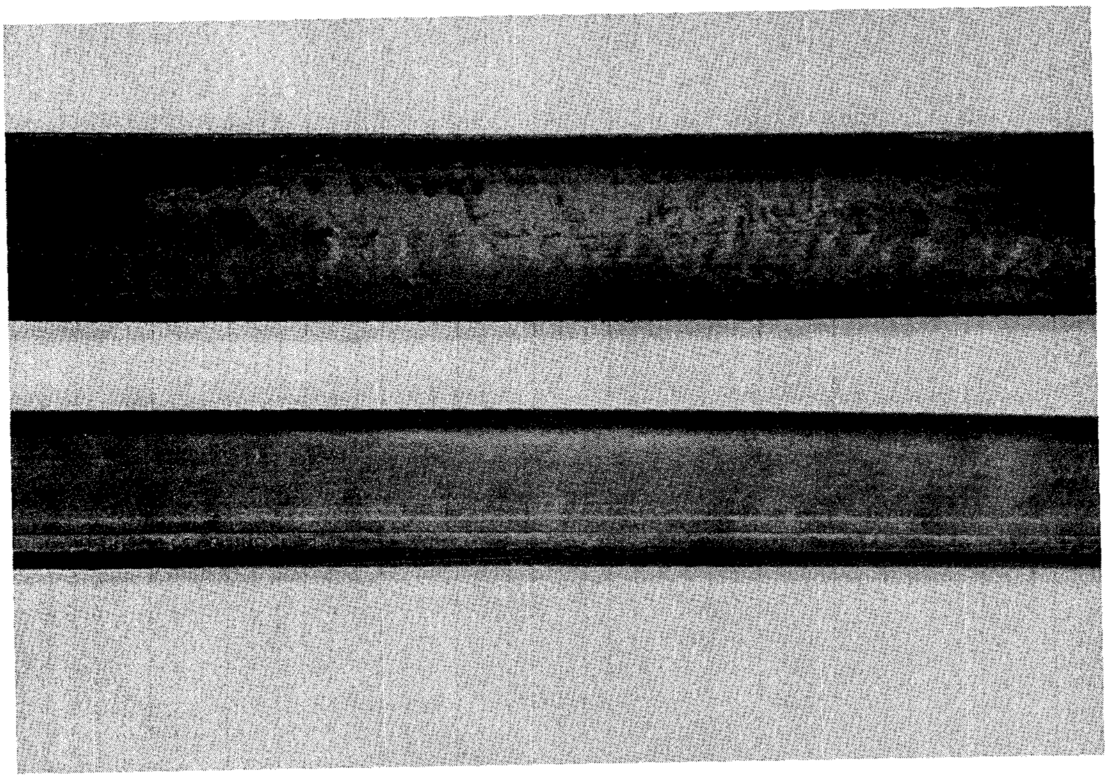

Figure 37. Flat, Number 2 AWG, Three-conductor Shielded (top) and Non-shielded Cables.

that the outer jacket is adequately sized. As mentioned earlier in this chapter, the additional cost of a shielded miner splice kit is five percent.

Disadvantage Five. Crushing the shield during equipment runovers, roof falls, and rib sloughing could decrease safety and increase downtime.

This anticipated difficulty was observed during field trips and during mining operations at the underground test site. The findings were that shielded cables are not any more susceptible to damage then are non-shielded cables. Both types of cables were runover and crushed during various phases of mining and both were damaged to the extent that repair was required to the outer jacket and primary insulation. It is true that shielded cables do cause circuit breakers to throw when they are crushed or pinched even with no visible damage. These pinched areas should be noted for future reference in locating a troublesome fault.

Twice,the shielded miner cable at the underground test site was damaged sufficiently to trip the circuit breaker without any visible damage. The first incident occurred as the cable was being dragged by placing it over the cutting head of the machine. The cable was pulled tight over an empty bit-block as it neared the working face, and the breaker tripped. The area was marked for reference. The second incident took place when the cable was pinched between the rear bumper on the miner and the mine floor. Again, the outer jacket was not damaged. In the first case, had the breaker not tripped and the cable split open, sparking could have resulted. A hazardous situation may have resulted if an accumulation of gas had been present.

Disadvantage Six. Shielded cables are slightly larger in diameter than non-shielded cables. This may cause a reduction in the amount of cable which can be placed on a reel.

Cable Reeling. Cable reel calculations and reeling experiments at the test site have shown this to be only too true. The reduction in the amount of cable being placed on a reel could alter mining plans. At the very least, tie-off points must be moved further inby thus necessitating more shuttle car backspooling. More serious changes involve more frequent load center moves or otherwise reducing the length of haul for shuttle cars. The effect of less cable on the reel is not as critical for roof bolters.

The calculated amounts of cable which could be placed on the Torkar shuttle car were 630 ft of non-shielded and 453 ft of shielded. However, the actual amounts of non-shielded and shielded cable resulting from the reeling tests were 590 ft and 320 ft, respectively. The measured divided by the calculated amount for the first-run shielded cable is a percentage equal to 71 percent. The large discrepancy here is probably due to the inability of the cable reeling device to function properly, as will be discussed next. The percentage of the measured to the calculated is equal to 84 percent for the non-shielded cable. Part of both these discrepancies is due to the fact that the equation was developed for a Joy shuttle car. However National Mine Service Company does not have available an equation for exact cable reel calculations for cables of this size.

More of flat shielded cables from the later production run could have been placed on the reel during testing, as evidenced by the calculation in Chapter III. However, even the calculated change of 60 ft (from 453 ft to 513 ft) is of little consequence as this amount is still too small for the test site mining plan.

As will be shown by the following series of illustrations, cable reeling was not easily accomplished with the large flat shielded cable. For simplicity, the test was set-up above ground with the Torkar shuttle car reeling directly from a new reel of shielded cable. As is shown by Figures 38 and 39 the reeling of this particular cable was haphazard from the start. There was a tendency for the reel guide to lay cable on top of the previous turn because it was designed to move slower for a narrower number two AWG cable. Also, because of the tendency for the cable to lay partially on top of previous wraps, there was a build up of cable first at the right side of the reel (Figure 40) and then at the left side of the reel (Figure 41). An illustration of the cable lying directly over the previous turn is shown by Figure 42.

The stiffness of the cable was difficult for the spooler to overcome in order to provide a more orderly lay of cable. Also, the need for more force in reeling the cable was demonstrated as the reel was stopped near the end of the reeling cycle. At this time, the reel would not start again. The cable had to be fed by hand past the sheave wheels in order to facilitate takeup. The overall size of the cable caused problems for individual components also. Please refer to Figure 43, and note how tightly the cable fits through the reel guide. Most of the time, the cable had to go through at an angle, as shown by Figure 44. Additionally, the cable is too large for the "elephant ear" enclosed sheave wheels shown in Figure 45. It is doubtful that a splice could properly fit through either the spooler or the sheave wheel assembly.

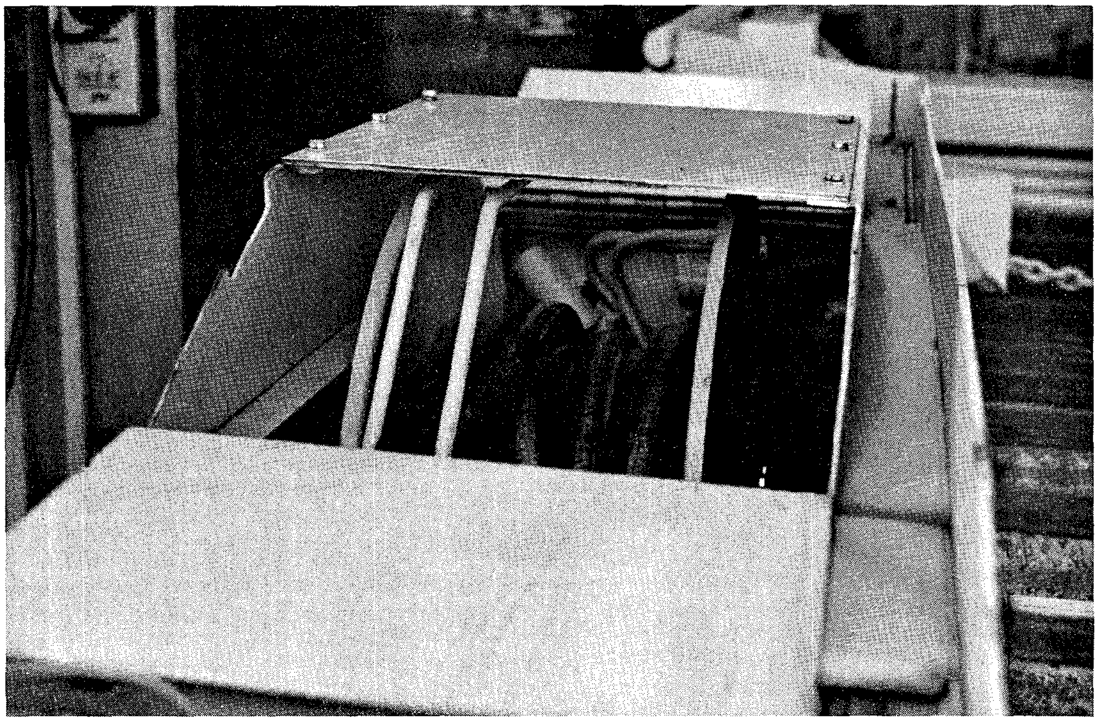

Figure 38. Exposed Reel for Above-ground Reeling Test.

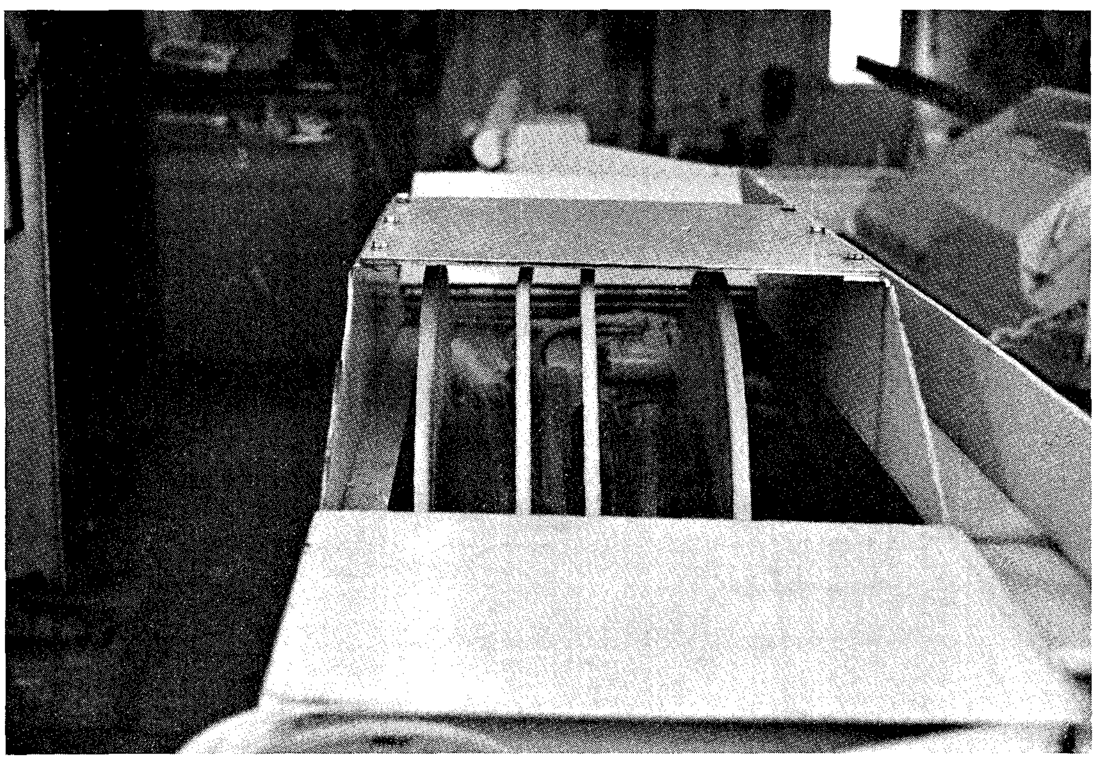

Figure 39. Haphazard Placement of Cable on Reel.

The overall result of this reeling experiment was to evaluate steps necessary to modify the cable reeling unit, Modifications would certainly be needed to the sheave wheel assembly, the reel guide, and the speed control for the spooling assembly. Also, more pressure was needed from the hydraulic valve which drives the reeling unit. However, these modifications would be in vain as the unit would still be limited by the amount of cable which could be placed on the reel. The largest amount to be hoped for would be 380.5 ft (453 ft as calculated x 84 percent). This has prompted work in the area of a smaller shielded cable design.

A more compact design is thought to best solution to the cable reeling problem. By keeping the non-shielded and shielded cable sizes relatively similar, modifications to the cable reeling unit are not necessary. Also, more of the shielded cable can be placed on the machine reel.

Cable Entry Points. Additional problems caused by the larger diameter could come in the form of coupler size modifications and the sizing of cable entry points on machines. Cable entry points include packing glands, packing grommets, and holding devices for reeled cables.

The increased size of shielded cables could necessitate the use of larger packing glands and grommets to surround cable entry locations on mining machinery and also the use of larger couplers. This was not found to be the case at the underground test site. The shielded continuous miner cable had an outside diameter of 2.31 inches, while the non-shielded cable outside diameter was 2.07 inches. However, both were

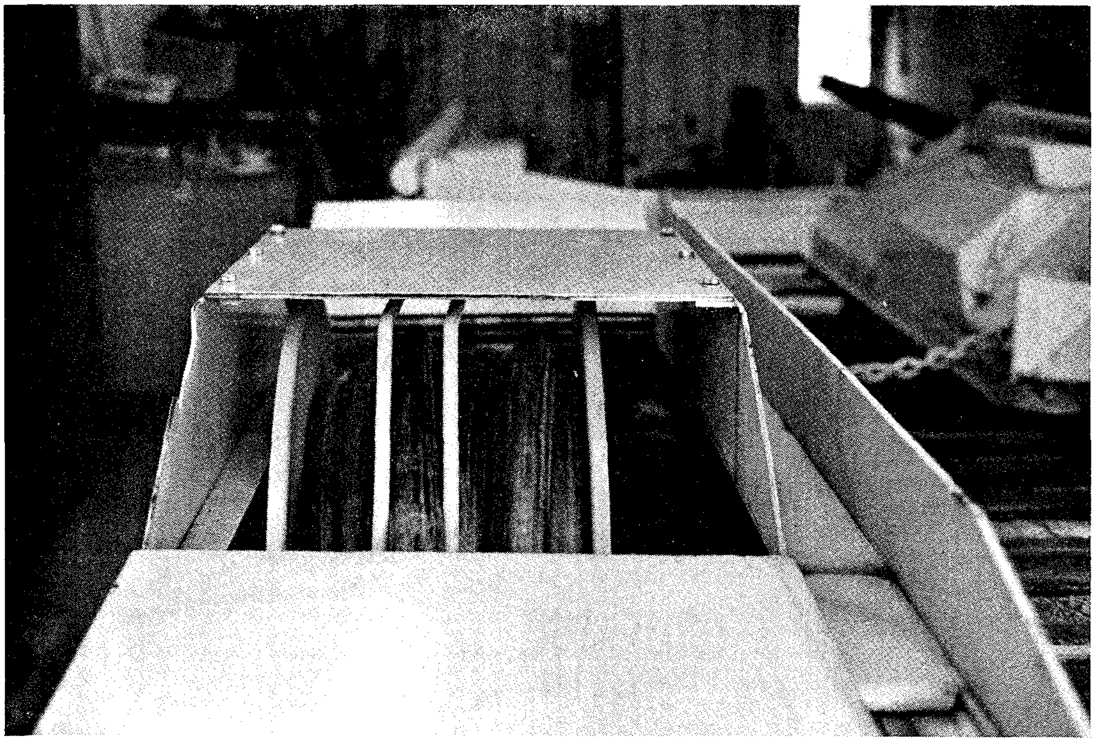

Figure 40. Cable Piles up at Right of Reel.

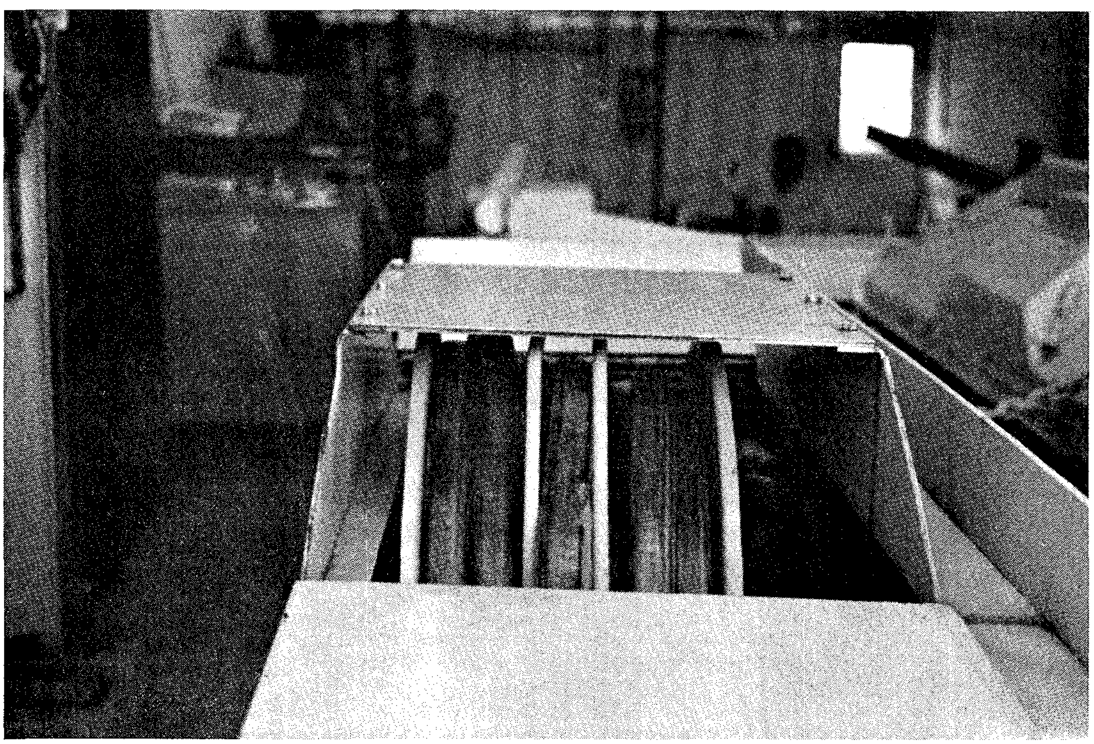

Figure 41. Cable Piles up at Left of Reel.

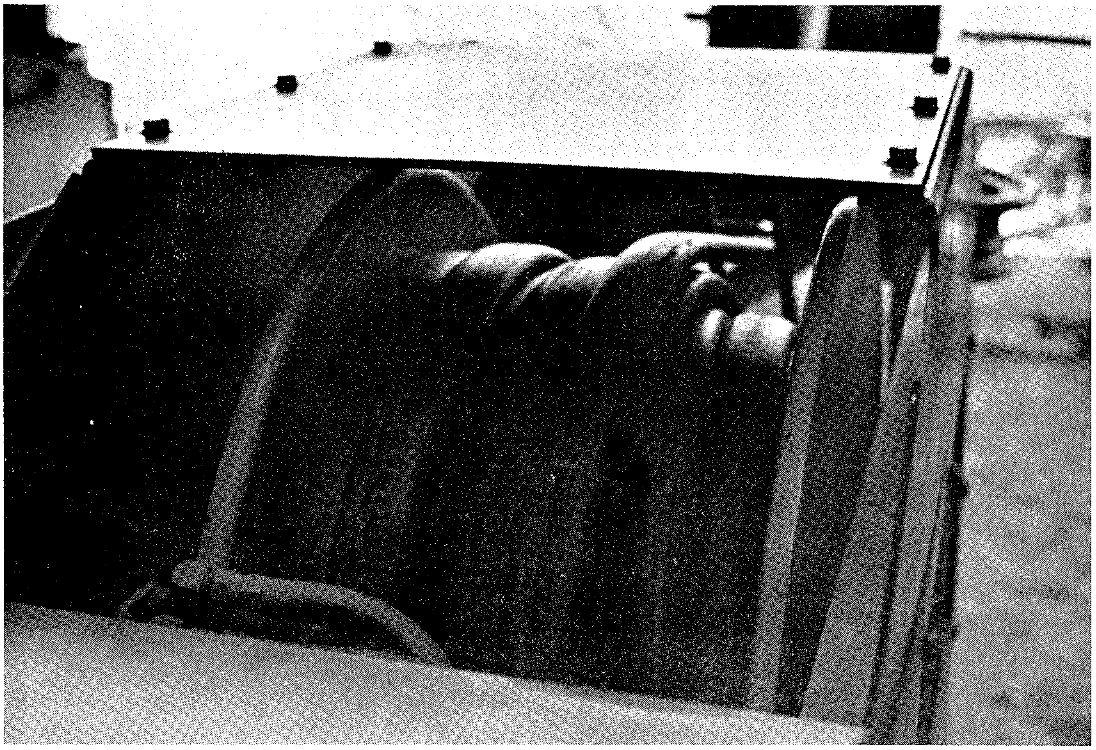

Figure 42. Previous Turn of Cable is Covered During Reeling.

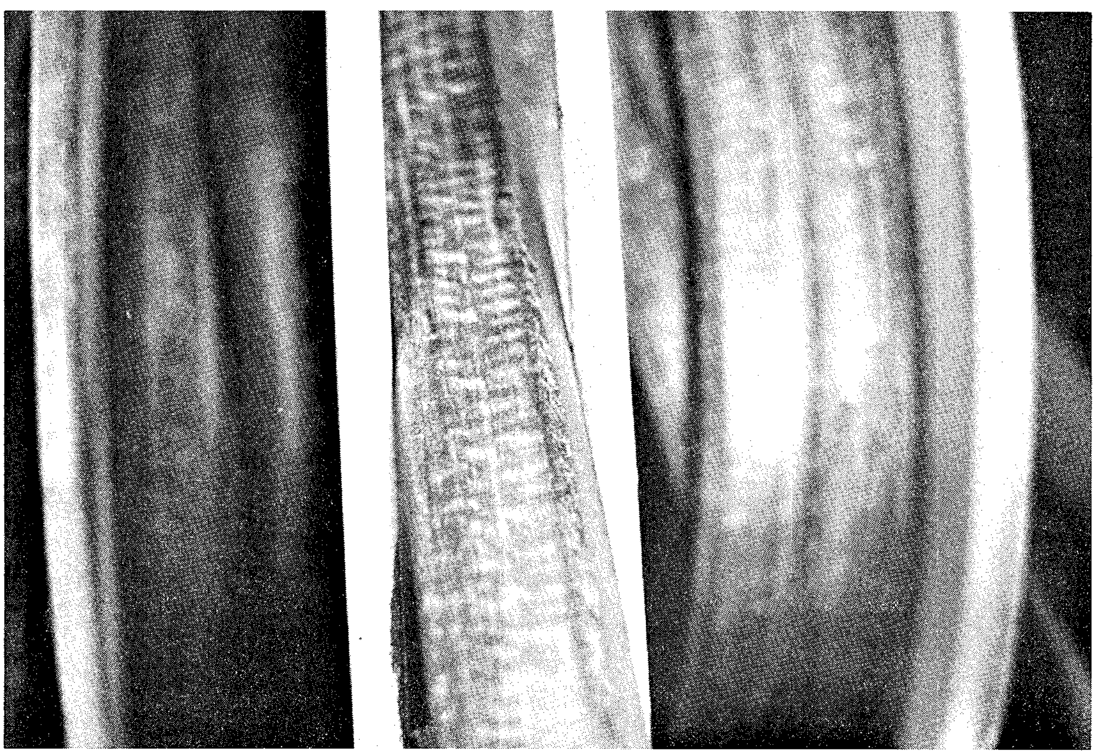

Figure 43. Cable Fits Tightly Through Reel Guide.

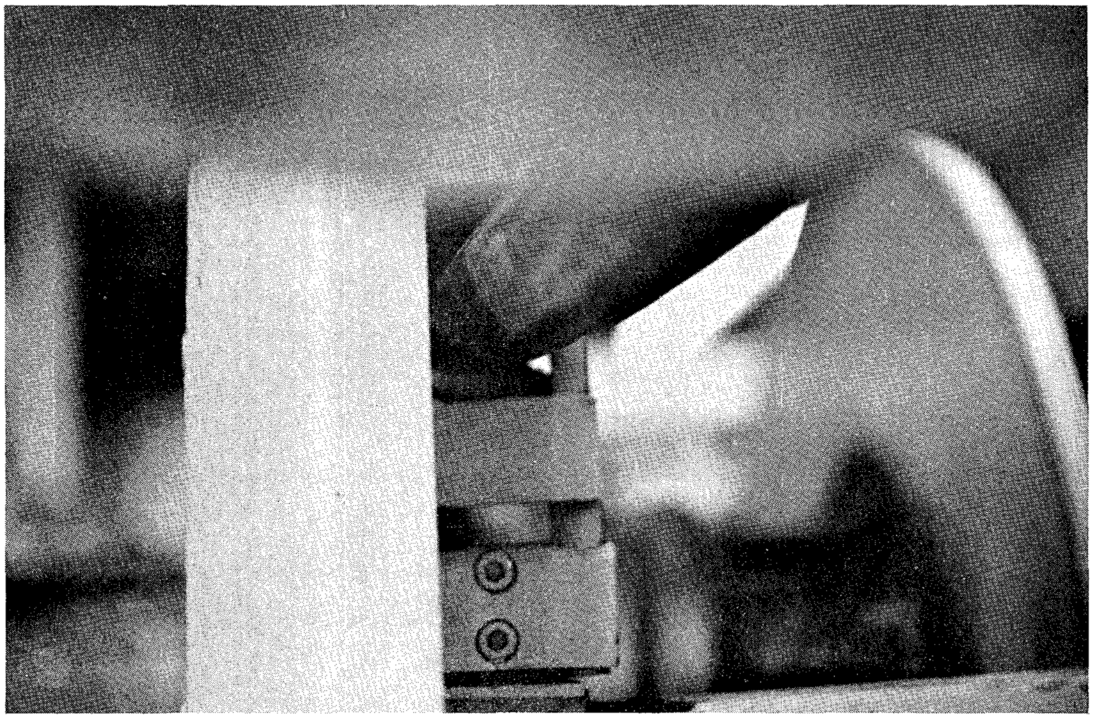

Figure 44. Cable Enters Reel Guide on an Angle.

Figure 45. Tight Fit at Sheave Wheel.

accommodated by the same size couplers. Further, both cables required the same size packing glands on the Lee Norse 486 continuous miners.

Disadvantage Seven. Shielded cables are stiffer, making drag cables slightly harder to handle. Associated with this stiffness may be a difficulty in feeding a cable onto a reeling device, requiring additional tension.

In-mine observations have shown shielded drag cables to be more unwieldy than non-shielded ones. This can be attributed, in part, to the added stiffness of the cable and also to their added weight (Disadvantage Nine). The cable reeling experiment showed the stiffer, larger shielded cable to provide problems in getting proper lay on the reel and in take-up difficulties for the reel drive mechanism. Increasing tension on the reel can solve part of the stiffness problem but it may be largely inherent in shielded cable constructions.

Disadvantage Eight. Locating internal faults on shielded cables may be difficult.

Analysis of various methods of cable fault location has shown two methods of fault location to be adequate for shielded cables. These are, time domain reflectometry (TDR) and infrared probing. TDR units are capable of locating both short- and open-circuits while infrared units can only locate shorts, the most common type fault in shielded cables. Therefore, assuming proper detection instruments and personnel trained in their use, locating faults in shielded cables should not be a problem.

Disadvantage Nine. Shielded cables weigh more than non-shielded cables.

Cable data from manufacturers has shown this to be true. Experiments at the underground site have also verified that shielded cables are significantly heavier to lift and hang and require more effort in dragging. The underground lifting experiment showed a span of shielded cable to be 20 percent heavier. The extra copper required for the shield, as well as a larger outer jacket to accommodate the shield cause the increase in weight. Design changes in shielded cables may lessen this weight difference, but it will never be completely eliminated.

Disadvantage Ten. Time required to install couplers is longer for shielded cables because of the extra connection for the shield.

Test site results have shown that shielded coupler installation can take up to twice as long. In part, this longer installation time can be attributed to the method used for this particular installation. The braided shields over each of the three phase wires were first unbraided, twisted together, and then joined to the three grounds using a lap connector. This assembly of grounds and shields was then trimmed as necessary and entered into the ground terminal on the coupler. Approximately the same procedure was used for entry into the continuous miner power box.

It was determined that the use of punch lock bands could greatly reduce the time for coupler installation and machine entry. Each shield can be joined to a nearby ground wire by use of the encircling band, and the need for unbraiding and re-braiding is thereby eliminated.

Recommendations

Based upon the foregoing analysis, a number of recommendations concerning shielded cables can be made. These are now set forth.

The percent coverage test should be used as a performance test criterion in determining the acceptability of the percent coverage of conductor insulation by various shielding designs.

Work is necessary in the area of shielded cable design and construction techniques to effectively reduce their weight, stiffness, and outside diameter. Additional input is especially needed into the design of flat shielded cables. Achieving direct shield-to-ground contact in flat and other cable configurations should be another area of concern.

A possible solution to the weight, stiffness, and outside diameter problem is the use of the SH-C configuration. SH-C cables can provide adequate shock protection if properly constructed, grounded, and maintained. In any event, shielded cables, whether Type SH-C or SH-D, should be designed to provide an adequate percent coverage and to have a very low-resistance from the shield to ground wires. The suggested 500 Ω shield-to-ground-wire resistance from the shield percent coverage test should never be exceeded, but 5.0 Ω or less will provide a much higher level of safety. Nevertheless, as stated above, the ideal situation involves having the shield in intimate contact with the ground wires.

Shielding can act as a preventive only if the other components of the safety grounded system are operational. The ground overcurrent protective circuitry must be set at proper trip levels with instantaneous trip times and adequately maintained. Also, the resistance of the cable grounding system must be considered when selecting the grounding resistor. A 40 percent of ground-fault current limit for protective circuitry pick-up (as set forth in the proposed changes of Title 30, Part 75, Code of Federal Regulations) will provide an ample margin of safety for tripping (2).

In terms of maintaining shielded cables, when splicing, a tube of braided shield should be employed and attached with electrical tape for shield replacement. If this component is not available, then braid tape shield and electrical tape should be used. Regular maintenance testing of cables (shielded or not) is advisable in avoiding unnecessary downtime.

Cable producers should be given adequate time to install additional capital equipment as needed before any switch to low-voltage shielded cable takes place. A lead time of nine months to two years should be adequate.

Summary

The results of the analysis of the proposed advantages and disadvantages have led to several suggestions. Conclusions can now be drawn from the research information and are furnished next.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Now presented is a listing of how the Scope of Work objectives were accomplished.

1. Proposed advantages and disadvantages should be extracted from the literature and other sources. These proposed advantages and disadvantages are put forth in Chapter II.
2. An accident analysis should be included to determine the safety gains possible with low-voltage shielding. Chapter II provides the data compiled for the accident analysis.
3. A series of laboratory tests must be undertaken, including percent coverage experiments, a splicing time-study, plus flexing of cables and shielding components. These tests have all been completed and their procedures and results are provided in Chapter III. A discussion of these test results ensues in Chapter IV. During this phase of the research, a need was also determined for shield effectiveness testing for energized cables. This test is similarly reported in Chapters III and IV.
4. An underground test site for the in-mine testing of shielded cables must be established. This test site, as described in Chapter III, has helped to achieve a more clear demonstration of the preceding test results, and has provided a location for further field testing in areas such as cable reeling, cable weights, and splicing, the results of which appear in Chapter III, followed by a discussion in Chapter IV.

Additionally, the underground test site has provided solid cost information for cable and splice kit purchases.

5. Other cost information relative to capital expenditures on the part of cable producers has been assembled. These cost figures are delineated and explained in Chapter II.

Suggestions for Future Research

Shielded cables have been shown to be costlier, somewhat harder to splice, and to be physically larger and heavier than non-shielded cables. Conversely, if properly constructed, installed and grounded, maintained, and used in conjunction with adequate protective circuitry (likewise cared-for), they can be much safer cables. However, as implied by the last statement, increased safety does not just happen when a shielded cable is introduced to the working section.

A more thorough look at the flex-life, temperature, and other operating characteristics of shielded cables is needed. In part, this can be accomplished by the continuation of research at the underground test site. Further work into the areas of cable design and construction will also provide input into this appraisal. The suggested areas for future research, listed below, delinate areas which will facilitate a future yes or no answer to the question at hand. Should low-voltage shielded cables be required in underground bituminous coal mines?

1. Temperature studies should be conducted on shielded and non-shielded cables to measure temperature variations between the two when used in reeled applications.

2. The life span of shielded cables used underground must be determined, a shield which becomes separated and broken

during flexing may not be capable of carrying a ground-fault current.

3. Work on cable design and construction is needed. Areas of prime concern include lowering shield-to-ground-wire resistance, lessening cable outside diameter and weight, and insuring the adequacy of a shield under high current flow. Also, the size of shield wires, the angle at which they are braided (angle of lay), the wire diameter, and bedding materials should be examined in terms of shield cost and life.
4. The use of shielded cables in conjunction with various wireless ground-check monitoring units should be examined.
5. Further laboratory flex testing of SH-D and SH-C cables is an important area and should be continued. This is especially true of the flat SH-D design for the underground test site and an SH-C design being contemplated for further underground testing.
6. Effort should be directed towards the improvement of protective circuitry systems for mining. Included here should be work in dependability, in maintenance, and in providing a practical means for spot-checking the interruption capability of an operating circuit breaker.
7. Finally, shuttle car reeling mechanisms should be re-designed to accommodate shielded cables.

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APPENDIX I
THE USE OF SHIELDED CABLE AT THE JENNY MINE

The Jenny Mine is an underground U.S. coal mine which has limited experience in the use of shielded cables on reels. The following is a memorandum (dated May 13, 1975) from Frank E. McCall, Supervisory Engineer, Jenny Mine. Subject of the memorandum is underground shielded cable usage.

At out particular mine a 12,500 V shielded cable carries the mine power from the primary transformer outside to the underground transformer module which converts the power to 1,040 V for the distribution module. The 950 V shielded trailing cables service the automated roof bolter, cutting machine, coal drill, and loading machine, all of which have cable reels capable of holding 500 ft of shielded cable except the loading machine which is designed to hold 50 ft.

Effectiveness-Shielded cables are as effective in all aspects as unshielded cables.

Increased safety - The shield surrounding the conductor greatly increases safety due to the following reasons:

A. Short circuits are of low magnitude because the shield rather than the conductor trips the circuit breaker and, consequently, less cable damage occurs.

B. If the breaker fails to trip, less heat is generated at the fault, hence, the insulation does not smoke. The danger of fire is therefore minimized.

C. Usually a circuit breaker can be reset after adjusting the trip unit. This will allow the heat sensing fault finder to locate the damaged spot in the cable. This cannot be done with conventional cable.

D. Danger from electrical shock is virtually eliminated because the conductor is protected from direct contact by the shield. At the present state of the art life expectancy advantage lies with the shielded cable. In the event of cable damage the unshielded is usually more costly to repair, takes longer, and often times long sections must be cut out. This is not the case with shielded cable, however.

The splicing of shielded cable is no problem.

Shielded cable is substantially more expensive than unshielded. This extra cost is offset by the low maintenance, longer life expectancy, and more available productive time.

Note: Paragraph D. above presents several apparent inconsistencies. The author of this memo feels that faults occurring in shielded cables are not as damaging to the cable as are faults in non-shielded cables. Therefore, splicing the less serious faults in shielded cables is less costly. The author of the memo further reasons that larger cable life is expected of shielded cables because of these less serious faults.

APPENDIX II
CABLE SIZE FOR REELING APPLICATIONS

General

The following is a preliminary analysis of recommending a minimum cable size for use in a reeling application. Tensile strength and ampacity are the main parameters to be considered. The most significant source of excessive tension on shuttle car cables results from cable whip. Shuttle car trailing cable whip occurs when the car stops suddenly or reverses direction. Probable causes for the whip include: (21)

1. poor quality hydraulic components in the reel mechanism,
2. improper adjustment of the hydraulic system, and
3. the hydraulic circuit design not appropriate for the components selected.

Tension. The 1300 pound tension value during cable whip measured by FMC personnel (21) will be considered the minimum required tensile strength. The tests utilized a Joy Manufacturing Company shuttle car reel test unit. The unit employed a shuttle valve, model number A26566, which could not be properly adjusted to eliminate whip. Further testing by FMC revealed that the best results were obtained with a Joy constant-pressure system incorporating a variable-displacement pressure pump. With this unit, cable whip was essentially zero (21).

A more common system, utilizing the Joy Manufacturing Company 3026566-2 shuttle valve, can be adjusted to closely approach the whipless performance of the constant-pressure system. A simple adjustment of an existing cable reel unit may therefore eliminate whip problems. The new valve, 3026566-2, is being installed in all new shuttle cars (35).

However, a significant amount of old valves (A26566) are still in service. Therefore, the tensile strength requirement may vary for different shuttle car models.

Table 8 gives the breaking strengths and tensile strengths required of typical sized conductors.

Table 8. Soft Annealed Copper Wire Breaking Strength and Required Tensile Strength for Spliced Conductor.

Conductor Size-AWG	Breaking Strength (pounds/conductor)	Conductor Size-AWG	Tensile Strength Required Per Spliced Conductor (pounds)
8	480		
6	763	8	250
4	1213	7	325
3	1530	6	400
2	1929	5	525
1	2432	4	650
1/0	2984	3	800
2/0	3762	2	950
3/0	4745	1	1300
4/0	5983	1/0	2500
		2/0	3200
		3/0	4100
		4/0	5100

The breaking strengths above are for conductors in perfect condition and free of splices or defects. Trailing cables used underground are prone to breakage and are likely to contain one or more splices. For this reason, a standard of comparison for various sized trailing cables should assume a spliced conductor. Therefore, Table 8 also provides the tensile strength required of a spliced conductor. This data was compiled under USBM Grant Number G0133077 and provides a suggested guideline for determining the adequacy of a splice (59).

The probability of a temporary splice being placed in a cable should also be considered. In this situation, generally less time and care are put into making the splice, and it does not have the same quality as a permanent splice. Naturally, its tensile strength will be lower. However, as a basis for establishing a selection criteria for cable size, the tensile strength required under Table 8 will be used.

The potential danger at a splice includes more than just complete and immediate failure of the splice under tension. Addtionally, a partially separated connection can lead to cable deterioration and resultant I^2R heating. An improperly spliced cable can fail at less than its computed tensile strength. Probable causes for this include unequal length conductors within the splice or one conductor which is not properly joined.

Currently, neither Schedule 2G nor Title 30, Code of Federal Regulations, Part 75 specifies the smallest conductor size allowed for a reeling application (63, 64). However, Section 75.701-4, Title 30 does specify the required ground wire size. When the power conductor is number six AWG or larger, the cross-sectional area of the grounding wire must be at least one-half the cross-sectional area of the power conductor according to 75.701-4(a). This section further provides that the ground size should equal that of the power conductor for sizes smaller than number six AWG (64).

Table 9 gives typical ground wire sizes as obtained from manufacturer's specifications.

The following is a sample tensile strength calculation. The cable is a flat two-conductor number eight AWG, Type G. Each power conductor has a 250 pound tensile strength as does the ground. Therefore, 2 x 250 pound (power conductor) + 250 pound (for the ground) = 750 pound tensile strength.

A 1300 pound tensile strength requirement means this cable is not acceptable. Table 10 summarizes the tensile strengths of various size cables based on spliced conductor strength requirements.

Table 9. Ground Wire Sizes for Selected Cables.

	Ground Wire Size		
Conductor AWG	Flat Two-Conductor Type G	Flat Three-Conductor Type G (a-c)	Round Three-Conductor Type G (a-c)
10	10	10	10
8	8	8	8
6	8	8	8
4	7	8	8
3	6	7	8
2	5	6	8

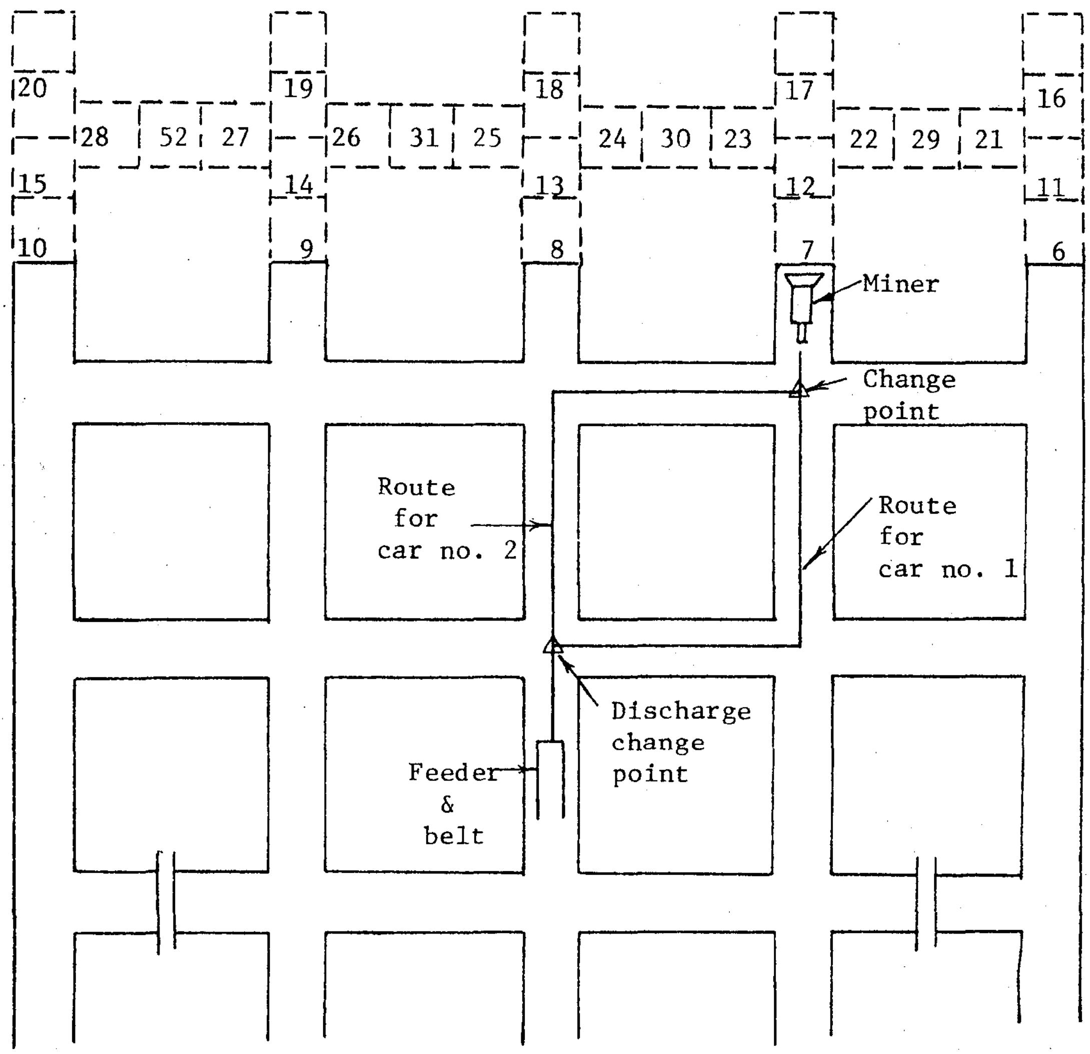
Table 10. Computed Cable Tensile Strengths.

		Tensile Strengths in Pounds			
Conductor Size-AWG	Spliced Tensile Strength	Flat Two-Conductor Type W	Flat Two-Conductor Type G	Flat Three-Conductor Type G (a-c)	Round Three-Conductor Type G (a-c)
8	250	500	750	1250	*
6	400	800	1050	*	1500
4	650	*	*	1700	
3	800	1600	1625		
2	950				
1	1300				
1/0	2500				
2/0	3200				
3/0	4100				
4/0	5100				

In Table 10, asterisks have been placed in each of the columns to signify that values below the astericks have acceptable tensile strength ratings.

Ampacity. Another factor which effectively limits reeled cable size is the current rating. To find the amount of current used by a shuttle car, the final report from USBM Grant Number G0101729 was consulted (58). Tables 11 and 12 use data extracted from this report.

The duty cycle for shuttle car motor operation plays an important role in this analysis. In order to explain the duty cycle, a typical underground coal mine section is diagrammed in Figure 46. In Figure 46,



Note: Pillars are located on 80 ft centers and entries are 20 ft wide.

Figure 46. Typical Coal Mining Section (Suboleski, Reference 60).

Table 11. Currents for an a-c Shuttle Car.

Machine	Job Type	Current Measured - in A		
		Average	Maximum	Minimum
Type 48 S Tokar	Loading	34	>150	27
60 hp	Starting Tramming Motor	--	>150	--
	Tramming, Loaded	60	>150	25
	Unloading	54	86	25
	Starting Tramming Motor	96	>150	18
	Tramming, Empty	41	53	27

Table 12. Recorded Currents for a d-c Shuttle Car

Machine	Job Type	Current Measured - in A		
		Average	Maximum	Minimum
Joy 18 SC	Loading	10	39.6	4.8
250 V dc	Tramming Loaded	24	62.5	3.0
	Unloading	11	16.8	5.0
10 hp Conveyor Motor 15 hp Hydraulic Pump Motor 2x15 hp Traction Motors	Tramming Empty	14	38	2.8

the miner and both shuttle cars are operating in cut number 7. The distance traveled by both cars is approximately 200 ft. Typical cycle times for shuttle car loading and unloading are 1.0 min and

1.5 min, respectively. Based upon a speed of 250 for tramming loaded, the elemental time is 0.8 min. In a similar fashion, a tramming empty speed of 300 ft per min yields 0.66 min elemental time. Corner speeds and change out times have not been considered in this approximation.

A continuous mining section can produce up to 1600 tons in an eight hour shift. If two eight ton shuttle cars were used, each car would be required to make 100 trips. Assuming a total cycle time of 3.16 min, each car would be in operation 396 min.

However, at the present average 350 tons per shift, only 22 cycles need be made by each shuttle car. This would represent a total of 87.12 operating min for each shuttle car. Using a shuttle car at the average production rate would certainly result in less of a heating problem. The current derating equations do not, however, consider time of operation.

Now, using the average current measured for the shuttle cars from Tables 11 and 12 and the duty cycle, a weighted average of current consumed can be calculated. Weighted average amperage for a-c car = 48 A. Weighed average amperage for d-c car - 13.9 A.

Table 13 shows the current carrying capacity of various cables as furnished by a cable manufacturer. It is important to realize that in most cases these ratings are much lower than the actual capacity of the cable. However, they reflect the minimum standards as provided for by IPCEA and NEMA (16). Specifications from another manufacturer showed that ampacities for cables rated at 90°C were much higher.

When trailing cables are used with one or more layers wound on a gathering reel, the current-carrying capacities should be corrected or derated. Before a cable is spooled onto a reel, it generally lies on

Table 13. Ampacities and Thicknesses for Various Sized Cables.

Type Cable	Size	Ampacities*	Thickness in Inches (Diameter if Round)
Two-conductor Flat, Type W	6	68	0.56
	4	95	0.61
	3	108	0.68
	2	123	0.73
	1	148	0.81
Two-conductor Flat, Type G	6	68	0.56
	4	95	0.61
	3	108	0.68
	2	123	0.73
	1	148	0.81
Three-conductor Flat, Type G	6	68	0.68
	4	89	0.75
	3	103	0.77
	2	118	0.81
	1	138	0.97
Three-conductor Round, Type G	8	50	0.91
	6	68	1.01
	4	89	1.17
	3	103	1.24
	2	118	1.34
	1	138	1.51

*These ampacities are based on 75°C conductor temperatures, 40°C ambient.

the mine floor surrounded by air on three sides. Once on the reel, it is tightly packed with many turns, all carrying current and in an enclosed space with little air circulation between layers. A direct result of the restriction of heat flow is that a cable will operate at increased temperatures in a reel. Therefore, the amount of current it may carry without exceeding safe conductor temperatures decreases. Since more layers contribute to the heat source, this further decreases the allowable current (45).

Table 14 gives the derating factors to be applied to cables placed on a reel. For this calculation, a cable reel with a drum diameter of 10 inches and a flange diameter of 25 inches is being considered. The width inside the flanges is 18 inches, see Figure 47. From the diagram, it is apparent that 7.5 inches of space is available for the layers of cable to be stacked on top of each other.

Referring back to Table 13 for cable diameters or thicknesses, it is noted that the largest shuttle car cable to be considered, the number 1 AWG, three-conductor, round has a diameter of 1.51 inches. This cable

Table 14. Derating Factors Assuming 60°C

Conductor Temperature (Reference 40).

Number of Layers	Percent of Specified Value
1	85
2	65
3	45
4	35

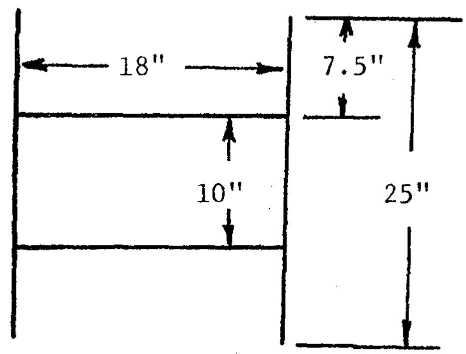


Figure 47. Cable Reel Dimensions for Shuttle Car.

could easily have four layers on the reel at the dump point. Since other cables are smaller in diameter, they also could have at least four layers on the reel while dumping. It is assumed that 600 ft of cable can be placed on the reel; however, this varies with cable size. The shuttle car must unspool 200 ft to reach the miner. A cable with a 0.69 inches thickness can have approximately 11 layers on the reel. And referring to reel capacity calculations, 607 ft of 0.69 inches thick cable can be wound on the reel.

Since the shuttle car reel "looses" 200 ft of cable in reaching the miner, one-third (200/600) less wraps will be on the reel. However, more layers than the four necessary for a maximum cable deration remain on the reel. However, the 1.51 inch diameter cable may have only two or three wraps on the reel at the miner, but this size cable is seldom used on shuttle cars. Additionally, shuttle cars for use in higher coal have larger reels which increases cable capacity and more layers are wound on the reel. Consequently, the maximum derating factor for four or more layers will be used.

Since the 48S Torkar from Table 11 is an a-c shuttle car, three conductor round or flat cables can be used on this machine. The weighted average amperage for this car was 48 A. When three-conductor cables were derated, the results shown in Table 15 were obtained.

The Joy 18 SC tested is a d-c machine with a weighted 13.9 A average current consumption. Cables used on this machine are two-conductor flat in either Type G or W. Derating d-c cables produced the results in Table 16.

Table 15. Acceptability of Various a-c Shuttle Car Cables.

Type Cable	Size	Acceptable
Three-conductor Flat, Type G	6	no
	4	no
	3	no
	2	no
	1	yes
Three-conductor Round, Type G	8	no
	6	no
	4	no
	3	no
	2	no
	1	yes

Table 16. Acceptability of Various d-c Shuttle Car Cables.

Type of Cable	Size	Acceptable
Two-conductor Flat, Type W	6	yes
	4	yes
	3	yes
	2	yes
	1	yes
Two-conductor Flat, Type G	6	yes
	4	yes
	3	yes
	2	yes
	1	yes

The above analysis, especially the a-c section, may be seriously questioned. Surely the usefulness of a cable larger than a number 1 AWG on a reel is doubtful. The analysis shows either an extreme need for changing a-c cable designs or an error in derating. A portion of the problem is due to the 65 hp motor which is in continuous operation on the Torkar. The d-c machine has much smaller motors (three 15 hp and one 10 hp) which do not all operate in unison.

However, the cause for this apparent discrepancy may not be due to the above reasons alone. The derating factors used were developed at a time when cable ampacity ratings were based upon a 60°C conductor temperature. Currently cables in the 600 V range are rated for 75°C and the 2000 V cables are rated at 90°C conductor temperatures. The increase in temperature rating increases the ampacity rating. Basically, new derating factors should be derived to keep pace with the higher temperature rated cables.

The Code of Federal Regulations relies heavily upon IPCEA and NEMA Standards for determining the adequacy of cables for use underground (33). Ampacity calculations for 2000 V cables are presently based upon continuous duty at 90°C (conductor temperature, 40°C ambient, with the cable in free air). The adequacy of ampacity ratings for underground cables based upon these conditions is doubtful, at best. The underground trailing cable is seldom hung so it is in free air -- more often it is lying on the mine floor. Worse yet, it is wound around a reel where the ambient temperature may be greater than 40°C. Even if the cables were suspended in free air, the ambient mine temperature would be closer to 20 or 25°C and not the suggested 40°C. Also, continuous amperage is uncommon to trailing cables.

As was previously mentioned, different size shuttle cars have different reel and motor sizes. As a result, the preliminary analysis indicates that cables should be rated as acceptable on a machine-by-machine basis and not for all reeled equipment.

In conclusion, Table 17 is presented for purposes of summarizing the adequacy of cables considered in the previous preliminary analysis.

Table 17. Adequacy of Cables Based Upon Tension and Current Capacity.

Type of Cable	Size	Adequate for: Tension	Adequate for: Ampacity
a-c Cables			
Three-conductor Flat, Type G	8	no	no
	6	yes	no
	4	yes	no
	3	yes	no
	2	yes	no
	1	yes	yes
Three-conductor Round, Type G	8	yes	no
	6	yes	no
	4	yes	no
	3	yes	no
	2	yes	no
	1	yes	yes
d-c Cables			
Two-conductor Flat, Type W	8	no	*
	6	no	yes
	4	yes	yes
	3	yes	yes
	2	yes	yes
	1	yes	yes
Two-conductor Flat, Type G	8	no	*
	6	no	yes
	4	yes	yes

Table 17. (Continued) Adequacy of Cables Based Upon Tension and Current Capacity.

Type of Cable	Size	Adequate for: Tension	Ampacity
	3	yes	yes
	2	yes	yes
	1	yes	yes

*Ampacity information not readily available as this is not a stock item.

APPENDIX III
FIELD TRIPS TO UNDERGROUND MINES

Mine One

Location: Southern West Virginia

Date: November 3, 1974

Purpose of Visit: The field trip was undertaken to observe a 4/0 plus GC 2000 V cable in actual operation.

Cable Location: The cable was installed on a Joy 9CM continuous miner. The seam being mined was the Number 2 Gas Seam, and the cover was approximately 700 ft at this point.

Remarks: The cable was installed September 9, 1974. Its length was 523 ft consisting of a 190 ft and a 333 ft length cable, the two being spliced together.

The cable was larger in diameter than the one it replaced, and the packing gland had to be changed. The men on the section said that the cable was stiffer and harder to handle.

During the first month of operation, the cable was "mashed" a little with no damage occurring. This section of the cable was cut out and spliced. As of the last correspondence with this mine, there had been two additional splices placed in the cable. A spokesman for the mine said that the splices were necessitated when the cable was pinched between the miner and a shuttle car. The maintenance people had no trouble splicing the cable, and they felt that the cable should "work out real well." Also, as of this date, the cable has not "loosened up" any although the men on the section are used to the stiffness.

Mine Two

Location: Wyoming

Date: June 16, 1975

Purpose of Visit: This trip was undertaken to observe a mine which uses shielded a-c cables almost exclusively.

Location of Cables: Both conventional and continuous mining are practiced in the mining of trona. In the continuous sections, shielded cables are used on National Mine Service Marietta Miners and on Jeffrey Heliminers. Face haulage is via d-c shuttle cars, but these cables are not shielded. Both the continuous and the conventional sections use shielded cables on the roof bolters. Conventional sections also employ shielded cables with cable reels on the cutters, drills, and loaders.

Remarks: Shielded cable was selected for use at this mine because of its inherent safety features. Over 20 years ago, a man was electrocuted when he picked up a cable while standing in a puddle of water, and this prompted the company to switch to shielded cables. Since the change, mine personnel do not know of any injuries or electrocutions caused by a shield cable. This would include injuries caused by picking up a splice, electrical discharge into the atmosphere, or by a cable lying in a puddle. However, injuries have resulted when people have attempted to hook up or disconnect cables without cutting the power to the cable.

Induced voltages are not a problem at this mine even though many of the cables have only one grounding conductor.

Mining conditions are very similar to coal, except that trona is harder and more abrasive. Therefore, rib corners could potentially cause greater wear than their underground coal mine counterparts.

Cable life is quite variable, depending to a large extent on how the cables are treated. Cables have lasted from three weeks to a year. It is interesting to note that a braid (shield) seldom breaks up and enters the phase conductor. However, the phase conductor often enters the braid, causing a line-to-neutral fault. Because of the shield, then, more faults appear to result. This is especially true when the cables are used in a reeling application, according to mine personnel.

APPENDIX IV
SHIELD PERCENT COVERAGE TESTS

Test Number 1

Type Cable: 2/0, Three-conductor Type SH-D plus GC, 2000 V

Type Shield: Cotton-copper Braid

Total Resistance: 0.037 Ω

Cable Total Length = 120 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	72	0.01
2	73	0.01
3	44.5	0.01
4	13.5	0.01
5	22	0.01
6	29	0.01
7	25	0.01
8	33	0.01
9	47	0.01
10	44.5	0.01
11	92	0
12	86.5	0.01
13	79.5	0
14	93	0.01
15	66	0.01
16	61.5	0.01
17	70	0

Test Number 1 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
18	53	0.01
19	52	0.01
20	30	0.01
21	19	0.01
22	88	0.01
23	69	0.01
24	40	0.01
25	48	0.01

Test Number 2

Type Cable: Number 2 AWG, Three-conductor, SHD-GC, 5000 V

Type Shield: Cotton-copper Braid

Total Resistance: 0.0354 Ω

Cable Total Length: 120 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	12	0.01
2	15	0.01
3	20.5	0.01
4	24	0.01
5	28	0.01
6	33.5	0.01
7	38	0.01
8	47.5	0.01
9	48.5	0.01
10	54	0.01
11	50	0.01
12	60.5	0
13	57	0.01
14	65.5*	0.01
15	65.5*	0.01
16	70	0.01
17	74	0
18	75	Too large to be measured**

Test Number 2 (Continued)

Trial Number	Inches of Cable From End of Nail	Contact Resistance of Nail to Shield in Ohms.
19	74.5	0
20	80	0
21	81	0
22	88	0
23	92	0
24	107	0
25	111.5	0

* The same hole was used. The nail was removed and driven in again.
** The nail was driven in on an angle so that it stayed in outer jacket.

Test Number 3

Type Cable: Number 2 AWG, Three-conductor, SHD-GC, 8000 V

Type Shield: Full Copper Braid

Total Resistance: 0.0315 Ω

Cable Total Length: 120 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	8.5	0.01
2	11.5	0.01
3	15	0.01
4	13.5	0.01
5	20.5*	0.01
6	20.5*	0.01
7	19	0.01
8	24	0.01
9	27	0.01
10	32.5	0.01
11	39	0
12	49	0
13	51	0
14	59	0
15	64.5	0
16	67	0
17	69	0
18	76	0

Test Number 3 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
19	86.5	0
20	83	0
21	102	0
22	103.5	0
23	105	0
24	112.5	0
25	115	0

*Same hole was used, the nail was removed and driven in again.

Test Number 4

Type Cable: Single-conductor, Power Feeder Cable, Type RHH or RHW, 5000 V

Type Shield: Wire and Semiconductive Material

Total Resistance: 0.094 Ω

Cable Total Length: 112 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	13.5	0.02
2	16	1083.0
3	18.5	0.01
4	20	0.01
5	20.5	1132.0
6	20.5*	1127.0
7	25.5	1146.0
8	33	0.03
9	36	1141.0
10	39.5	0.03
11	41	1075.0
12	45	1106.0
13	50.5	0.03
14	56.5	0.075
15	58	0.0
16	71	1107.0
17	72	1124.0
18	75	0.02

Test Number 4 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
19	80.5	0.02
20	81.5	0.02
21	83.5	1098.0
22	91	1136.0
23	95.5	0.02
24	103.5	1117.0
25	109	1124.0

*The nail was driven further into same hole.

Note: This cable required the use of the Kelvin bridge and an ohmmeter.

Test Number 5

Type Cable: 300 MCM, Three-conductor, Mine Power Cable, Type 2, 8000 V

Type Shield: Wire Shield and Semiconductive Material

Total Resistance: 0.0754 Ω

Cable Total Length: 120 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	6	0.01
2	8	0.03
3	11.5	505.0
4	13	0.01
5	19	368.0
6	23	492.0
7	30	456.0
8	40.5	0.01
9	43.5	713.0
10	47.5	0.01
11	51.5	0.01
12	55	595.0
13	56	399.0
14	57	406.0
15	61.5	0
16	66.5	821.0
17	73.5	0.01
18	75	556.0

Test Number 6

Type Cable: Number 2 AWG, Three-conductor, Mine Power-GC, 8000 V

Type Shield: Tinned Copper Tape

Total Resistance: 0.0784 Ω

Cable Total Length: 119 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
1	8	0.01
2	10	0.01
3	13	0.01
4	16.5	0.01
5	21.5	0.01
6	25.5	0.01
7	30.5	0
8	34	0
9	40.5	0
10	47	0
11	54.5	0
12	60	0
13	64.5	0
14	74.5*	0
15	74.5*	0
16	77	0
17	78	0
18	85	0

Test Number 5 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
19	76.5	760.0
20	81	0.01
21	90	329.0
22	94	0
23	100	665.0
24	105.5	0
25	114	490.0

Note: This cable required the use of the Kelvin bridge and an ohmmeter.

Test Number 6 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms.
19	86	0
20	89	0
21	95	0
22	96	0
23	101	0
24	106	0
25	112	0

*Different holes were used.

Test Number 7

Type Cable: 2/0, Three-conductor, Mine Power-GC, 5000 V

Type Shield: Copper Tape Shield

Total Resistance: 0.0692 Ω

Cable Total Length: 117 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohm
1	5.5	0.01
2	8.5	0.01
3	8.5	0.01
4	11.5	0.01
5	19	0
6	20	0
7	27.5	0
8	32.5	0
9	37.5	0
10	45	0
11	46	0
12	49	0
13	55.5	0.01
14	60	0
15	66.5	0
16	69	0.01
17	73.5	0
18	77	0

Test Number 7 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms
19	82.5	0
20	87	0
21	90.5	0
22	95.5	0
23	97	0
24	102.5	0
25	110.5	0

Test Number 8

Type Cable: 1/0, Three-conductor, Type SHD-GC, 8000 V

Type Shield: Full Copper Braid

Total Resistance: 0.0694 Ω

Cable Total Length: 119.5 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms
1	9	0
2	13	0.02
3	17	0.01
4	20	0
5	23.5	0.01
6	27	0
7	28	0.01
8	35	0.01
9	44	0
10	47.5	0.01
11	50	0.01
12	51.5	0.01
13	55	0
14	60	0
15	66.5	0
16	71.5	0.02
17	72.5	0.01
18	77	0.01

Test Number 8 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield in Ohms
19	81	0
20	88	0
21	93.5	0
22	96.5	0.01
23	100	0
24	108	0.01
25	111.5	0

Test Number 9

Type Cable: Number 6 AWG, Three-conductor, Type SHC-GC, 2000 V

Type Shield: Overall, combination Nylon-copper Braid

Total Ground Wire Resistance: less than 0.1 Ω

Cable Total Length: 125 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield to Ground in Ohms
1	72	0.01
2	97	2000K
3	60	2000K
4	108	2000K
5	67	2000K
6	124	2000K
7	72	0.1
8	36	2000K
9	16	0.2
10	28	2000K
11	6	2000K
12	102	2000K
13	117	2000K
14	20	2000K
15	2	2000K
16	48	2000K
17	104	0.1
18	75	0.2

Test Number 9 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield to Ground in Ohms
19	28	0.3
20	65	0.2
21	47	0.2
22	76	0.2
23	95	0.2
24	25	0.1
25	93	0.1

Test Number 10

Type Cable: Number 2 AWG, Three-conductor flat, Type SHD-GC, 2000 V

Type Shield: Full Copper Braid

Total Ground Wire Resistance: less than 0.1 Ω

Cable Total Length: 119 inches

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield to Ground in Ohms
1	96	3.0
2	72	9.1
3	60	6.3
4	112	640.0*
5	24	0.3
6	48	0.3
7	82	0.1
8	103	6.2
9	115	9.1
10	24	9.4
11	57	600.0*
12	71	3.0
13	56	3.0
14	91	3.0
15	36	0.1
16	16	3.0
17	6	8.9
18	47	6.2

Test Number 10 (Continued)

Trial Number	Inches of Cable From End to Nail	Contact Resistance of Nail to Shield to Ground in Ohms
19	60	0.1
20	40	3.0
21	100	9.2
22	91	1007.0*
23	82	9.5
24	108	10.1
25	80	0.1

*Nail would have been driven in too shallow to contact phase wire.

TIME STUDY OF SHIELDED CABLE SPLICE

General

The following elemental time study was done on a splice of a 2/0, three-conductor Type SHD plus GC, 2000 V. The splice kit used was a heat-shrink type and tools used for this time splice included:

1. crimper,
2. knife,
3. vice grips,
4. pruning shears,
5. tin snips,
6. tape measure,
7. sandpaper,
8. gas torch, and
9. striker.

Activity	Elapsed Time
Remove jacket and fillers	1:56 (one minute, 56 seconds)
Preparation time	2:42
Remove jacket and fillers from other end of cable	4:18
Preparation time	5:16
Adjust jig	6:08
Sandpaper shield to break cotton braid	--
Remove shield	6:45
Match conductors (colors)	--
Cut conductor for stagger (black)	--
Remove insulation (cut and pencil)	7:23
Apply connector	--

Time Study of Shielded Cable Splice (Continued)

Activity	Elapsed Time
Crimp connector	7:47
Cut connector (other end of black)	8:32
Sandpaper shield	8:46
Remove shield	9:07
Remove insulation	9:49
Slip insulation sleeve on	9:58
Insert conductor into connector	10:13
Crimp connector	10:29
Preparation time (relax tension on jig, etc.)	11:09
Heat shrink inner sleeve	12:28
Replace shield with shield tape and tape ends	14:37
Preparation time (relax tension)	16:22
Cut white conductor for stagger	16:38
Sandpaper shield	16:58
Remove shield	17:35
Remove insulation (cut and pencil)	18:28
Apply connector	--
Crimp connector	18:48
Cut other conductor end (white)	19:15
Sandpaper shield	19:32
Remove shield	19:54
Remove insulation (cut and pencil)	20:26
Slip on inner sleeve	20:45
Insert conductor into connector	--

Time Study of Shielded Cable Splice (Continued)

Activity	Elapsed Time
Crimp connector	21:09
Apply heat and shrink inner sleeve	23:00
Replace shield with shield tape	25:39
Cut ground-check conductor to length	27:13
Strip insulation	27:38
Apply connector	28:08
Crimp connector	28:32
Cut other end to size and strip	29:01
Slip ground-check conductor into connector	29:27
Crimp connector	29:50
Heat shrink insulation	30:13
Cut red connector (stagger)	31:06
Sandpaper shield	--
Remove shield	31:46
Remove insulation	32:21
Apply connector	--
Crimp connector	32:43
Cut other end of conductor	33:08
Sandpaper shield	33:21
Remove shield	33:43
Remove insulation	34:18
Slip on inner sleeve	34:30
Slip conductor into connector	--
Crimp connector	34:58

Time Study of Shielded Cable Splice (Continued)

Activity	Elapsed Time
Apply heat and shrink inner sleeve	36:37
Apply shield and tape	39:07
Preparation time	--
Cut ground wire	39:43
Apply connector	40:02
Crimp connector (to one end)	40:13
Cut other end of ground wire	40:51
Slip into connector	41:08
Crimp connector	41:16
Preparation time	--
Cut second ground wire	42:45
Apply connector	42:59
Crimp connector	43:07
Cut other end of ground wire	43:26
Apply connector	44:11
Crimp connector	44:18
Cut third ground wire	44:32
Apply connector	44:44
Crimp connector	45:27
Cut other end	45:37
Preparation time (one end too long)	--
Slip into connector	47:19
Crimp connector	47:34
Clean cable jacket	49:12

Time Study of Shielded Cable Splice (Continued)

Activity	Elapsed Time
Twist cable	49:39
Apply putty (used as a filler for roundness)	52:44
Preheat cable and rebuff with sandpaper	54:27
Slide jacket over splice	54:48
Prepration time (align jacket)	55:02
Heat shrink outer jacket	1:06:45 (one hour, six minutes, 45 seconds)
Wipe jacket edges	1:07:24

The total elapsed time for the splice was one hour, seven minutes, and 24 seconds.