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Operational Characteristics of Trailing Cable Splices

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By Michael R. Yenchek, Kevin C. Schuster,
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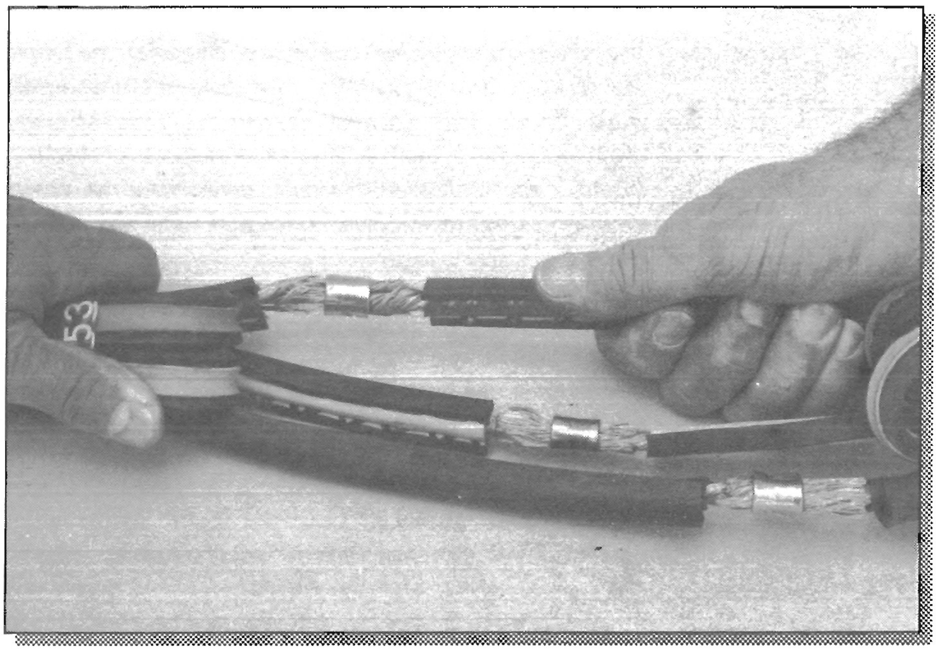

UNITED STATES DEPARTMENT OF THE INTERIOR

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Cover: Spliced cable joints are sources of heat. Better splicing materials and techniques could reduce the chances of fire and extend the service life of mine trailing cables.

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	V	volt
cm	centimeter	W	watt
kN	kilonewton	$\mu\Omega$	microhm
kV	kilovolt	°C	degree Celsius
m	meter		

OPERATIONAL CHARACTERISTICS OF TRAILING CABLE SPLICES

By Michael R. Yenchek,[1] Kevin C. Schuster,[2] and Arthur J. Hudson[3]

ABSTRACT

The U.S. Bureau of Mines investigated the operational characteristics of spliced portable power cables. This research had a dual purpose: (1) to determine the thermal and mechanical performance of repaired trailing cables and compare them with undamaged cables and (2) to gauge the impact of long-term, localized heating on the insulating and jacketing materials contained in cable splice kits accepted or approved by the Mine Safety and Health Administration. The ranges of splice joint resistance and tensile breaking strength were determined from laboratory measurements. The choice of crimping tools affected the strength of the splice under tension. Thermal profiles of energized spliced cables were constructed, which showed that spliced conductor joints operated 5 to 20 °C hotter than the intact cable at rated currents. Accelerated life tests of thermally aged samples of splice kit insulation and jacket materials confirmed a deficiency in the thermal rating of the insulating tape. The recommendations in this report may be utilized to revise splice kit design, splice kit approval criteria, and trailing cable loading guidelines. Characterizing the thermal operating limits of spliced trailing cables may help to minimize the associated risks from explosions, fires, personnel burns, and shock.

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INTRODUCTION

Abuse of trailing cables is characteristic of mobile equipment operation in underground coal mines. Accordingly, cables rarely last a year in this environment. During the course of a cable's brief service life, broken or weakened metallic stranding, short circuits, or exposed conductors are repaired in situ. Restoration typically involves excising the defective cable portion, rejoining the conductors, insulating, and sealing the splice from moisture.

These so-called "permanent splices," a misnomer, are only temporarily effective. Repeated flexure of the repaired section results in conductor fatigue and increased electrical resistance at the joint. Initially, this added resistance does not affect power delivery to the machine, but it does result in localized heat generation that accelerates the rate of splice deterioration. When heavy currents are drawn for several minutes, the splice may catch fire or rupture, jeopardizing underground safety and disrupting production. In fact, the largest criminal penalty ever assessed for mine safety violations ($1 million) involved a defective splice that resulted in a fatality (*1-2*).[4] If the current-induced temperature rises of damaged or spliced cable sections could be confined to appropriate limits, trailing cable service life would be lengthened. In addition, splice kit materials that are appropriately rated for the application would minimize the risk that such weakened sections pose from explosion, fire, or personnel burns.

This report documents the accomplishments of a research project supporting the U.S. Bureau of Mines (USBM) goal of enhancing the safety of the Nation's underground miners. The specific objectives of this project were (1) to evaluate damaged and spliced trailing cable samples and determine their thermal and physical performance relative to undamaged cables and (2) to gauge the impact of long-term, localized heating on the insulating and jacketing materials contained in cable splice kits approved by the U.S. Mine Safety and Health Administration (MSHA). The results of this work may be useful in revising splice kit design, splice kit approval criteria, and trailing cable loading guidelines.

BACKGROUND

Trailing cable splice kits are utilized to repair damaged cables in underground coal mines. These kits, consisting of conductor connectors and substitute insulation and jacket materials, are accepted or approved for use by MSHA solely on the basis of flame resistance (*3*). Other key qualities, such as dielectric and mechanical strength, may only be evaluated after the splice is in service (*4*). Further, it is not known how these desired characteristics are affected by long-term elevated temperatures.

There has been limited work to define splice characteristics and performance. In the 1970's, the USBM sponsored research to determine the effectiveness of splice kits to exclude moisture following mechanical aging.[5] Unfortunately, many of the kits evaluated are no longer commercially available. Other sponsored work demonstrated how cable surface temperatures are related to splice resistance (*5*). But these laboratory evaluations were confined to a single cable in confirming a theoretical analysis. To fully understand the thermal aspects of splices requires a more comprehensive effort using various cable sizes and splice kits that are currently manufactured.

In more recent in-house research, operating limits were defined for undamaged coal mine trailing cables under a variety of loading circumstances (*6-9*). However, investigations into the thermal characteristics of damaged or spliced cables were beyond the scope of these undertakings.

CABLE SPLICE SAMPLE PREPARATION

Initially, a listing of accepted or approved trailing cable splice kits was obtained from the MSHA Approval and Certification Center in Triadelphia, WV. Active kit manufacturers were then contacted to determine the prevalent kit types in use today. Preliminary conversations indicated that kits featuring an outer covering applied to the surface by external heat make up only a small share of the mining market. They are mainly used in small mines or to splice single-phase cables. Consequently, this kit type was not evaluated in this research project. In addition, it was learned that kit materials have varying shelf lives. For example, one manufacturer uses a linerless rubber tape with a shelf life of 5 years while another includes a neoprene wrap good for only 1 year. This seems to indicate that cable splice materials can be expected to degrade

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

[5]Electrical Materials Analysis—Mine Cable Splices, by J. N. Tomlinson, R. H. King, and L. A. Morley, Oct. 30, 1977. Work done by Pennsylvania State University under USBM grant G0155197.

with age much more rapidly than the original cable insulation and jacket.

Three brands of MSHA-accepted splice kits were ordered for the investigation. All the kits utilized copper sleeves to rejoin the metallic conductors, and vinyl plastic electrical tape was typically used to reinsulate the joined conductors. The kits differed mainly in the way the outer covering was applied to the spliced area. One kit brand featured a force-fit jacket that is glued over the cable (figure 1). Another brand contained an adhesive wrap (figure 2). The third utilized a prestretched tube for 2-kV cables (figure 3) and cast resin for 5-kV cables.

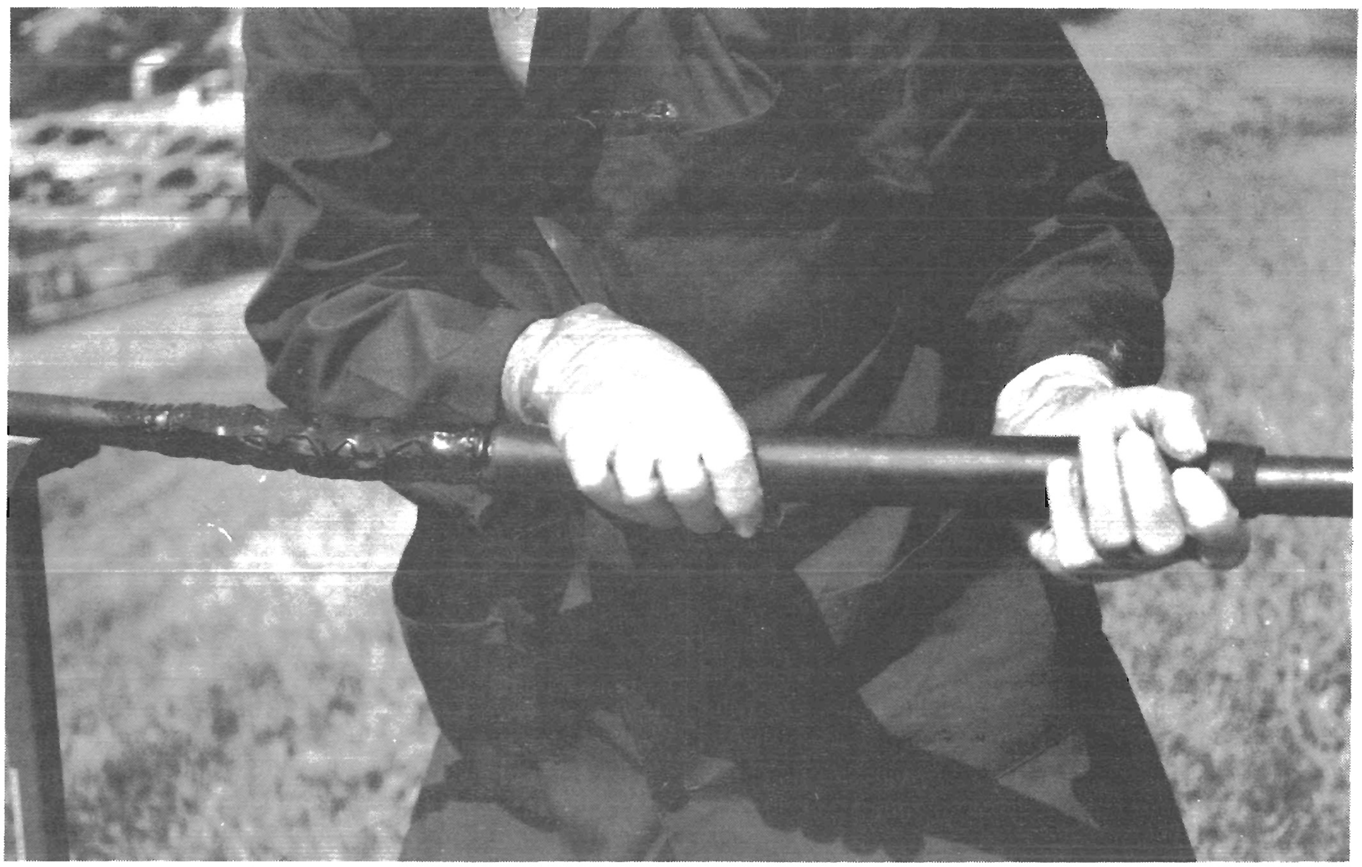
It was desirable to compare the thermal characteristics of damaged and spliced cables with results achieved previously for undamaged specimens. Consequently, 152 m of the same cable sizes and types evaluated in prior research (*6-9*) were procured:

#6 AWG,	3-conductor, 2-kV, round G-GC
#4 AWG,	3-conductor, 2-kV, flat G-GC
#2/0 AWG,	3-conductor, 2-kV, round G-GC
#4/0 AWG,	3-conductor, 2-kV, round G-GC
#1/0 AWG,	3-conductor, 5-kV, round SHD-GC
#4/0 AWG,	3-conductor, 2-kV, round SHD-GC

Spliced cable samples were prepared for a number of purposes: (1) for tensile strength tests that gauge the mechanical strength of crimped connectors, (2) for electrical load tests that measure temperature rises in the splice vicinity, and (3) for accelerated life tests that determine the effects of long-term elevated temperatures on kit materials. Kit manufacturers' representatives were consulted regarding appropriate splice techniques. The kit instructions and published guidelines from past USBM research (*10*) were also referenced.

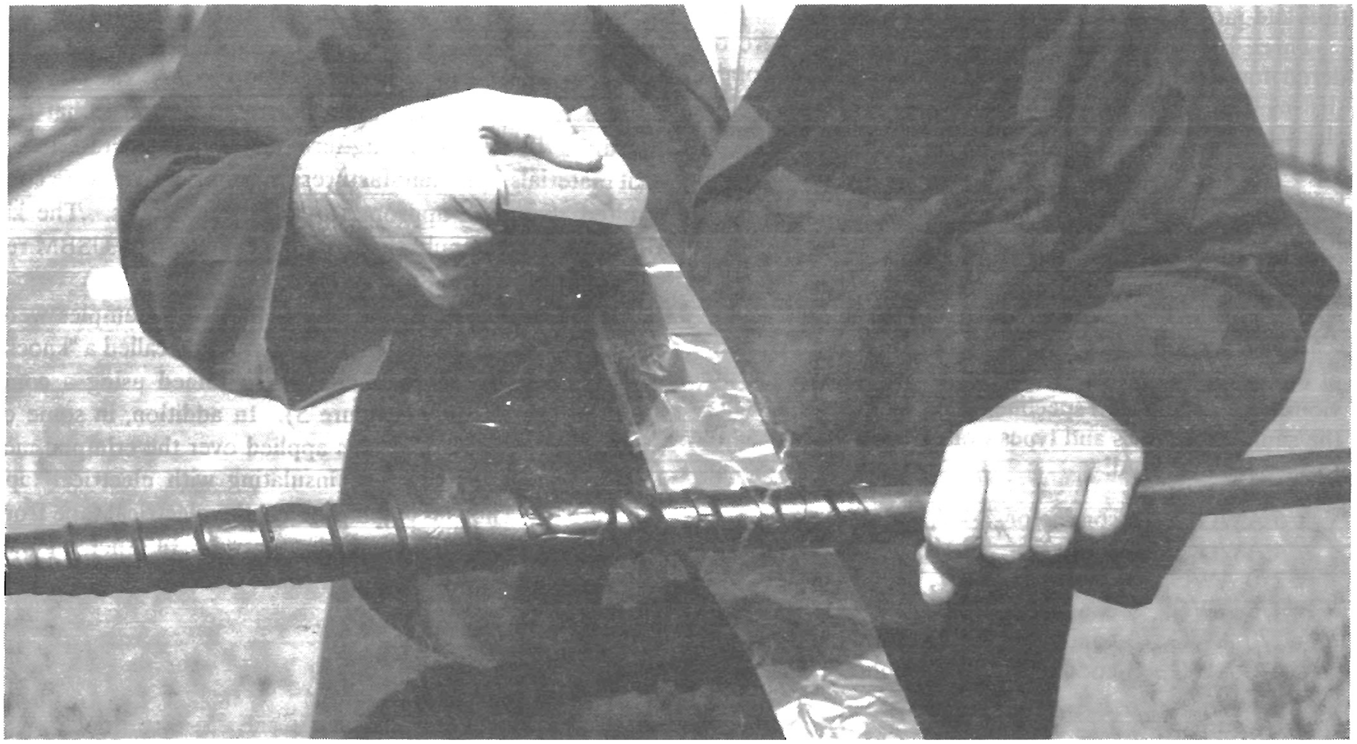
Reflecting mining practice, some of the samples were spliced using an anvil-type tool, commonly called a "knocker" (figure 4); the remainder were joined using a commercial wire crimper (figure 5). In addition, in some of the samples, glass tape was applied over the crimped metallic connectors prior to insulating with electrical tape (figure 6). The glass tape protects the electrical tape from being pierced by the conductor strands. In other samples it was omitted, as is done at times underground.

Figure 1



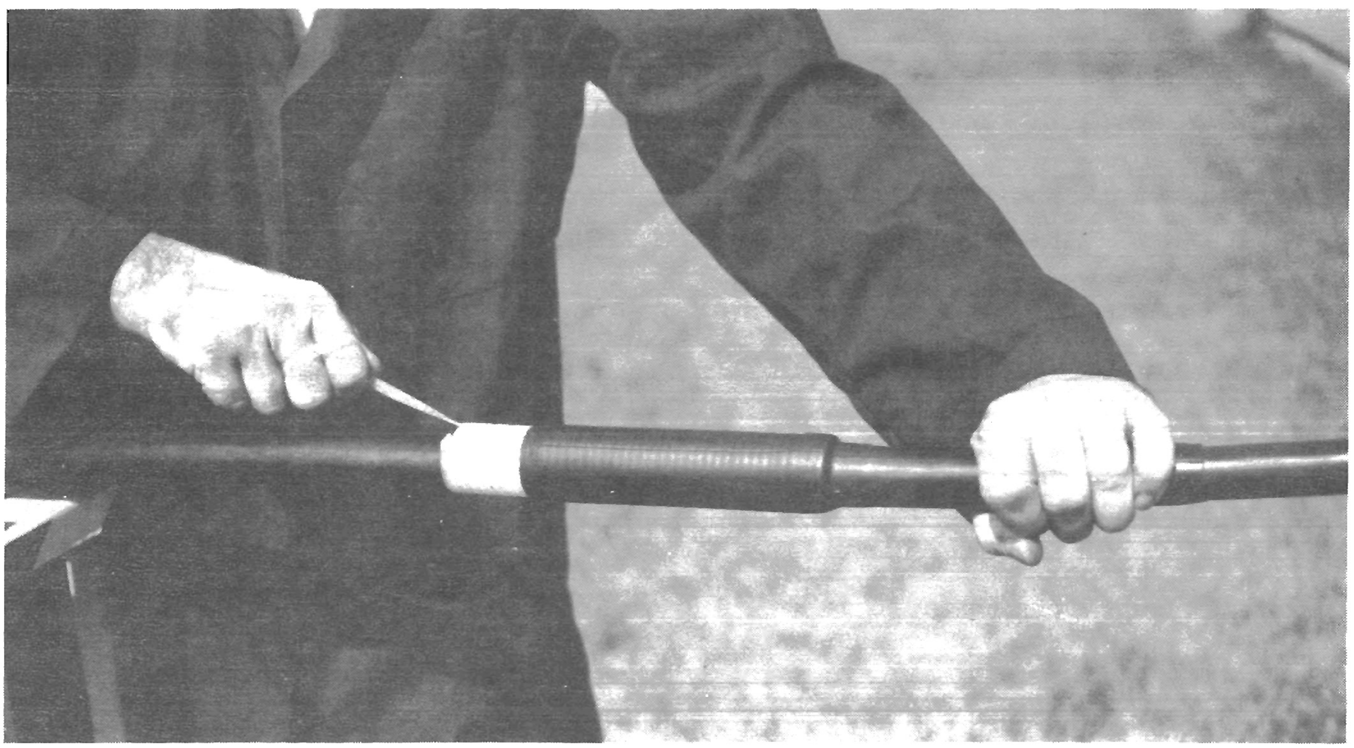
Force-fit jacket glued over splice.

Figure 2



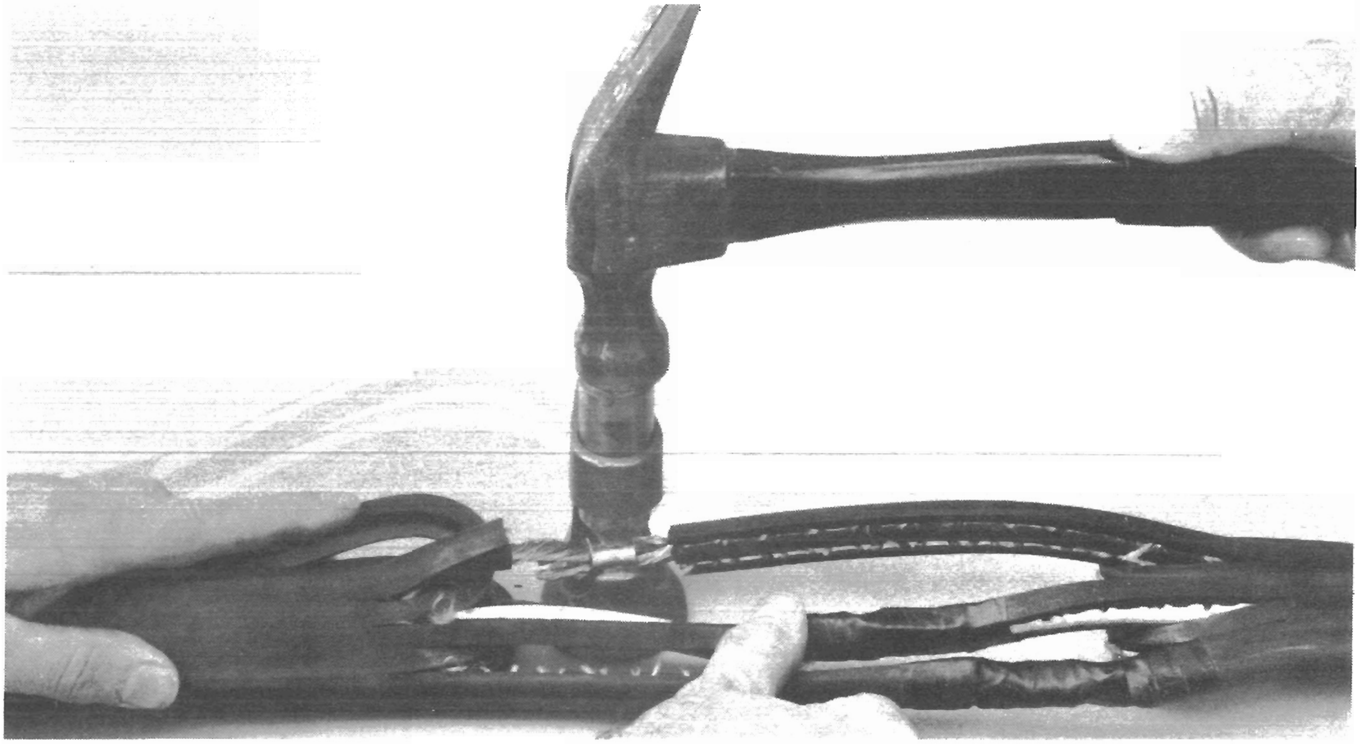
Adhesive wrap as outer splice covering.

Figure 3



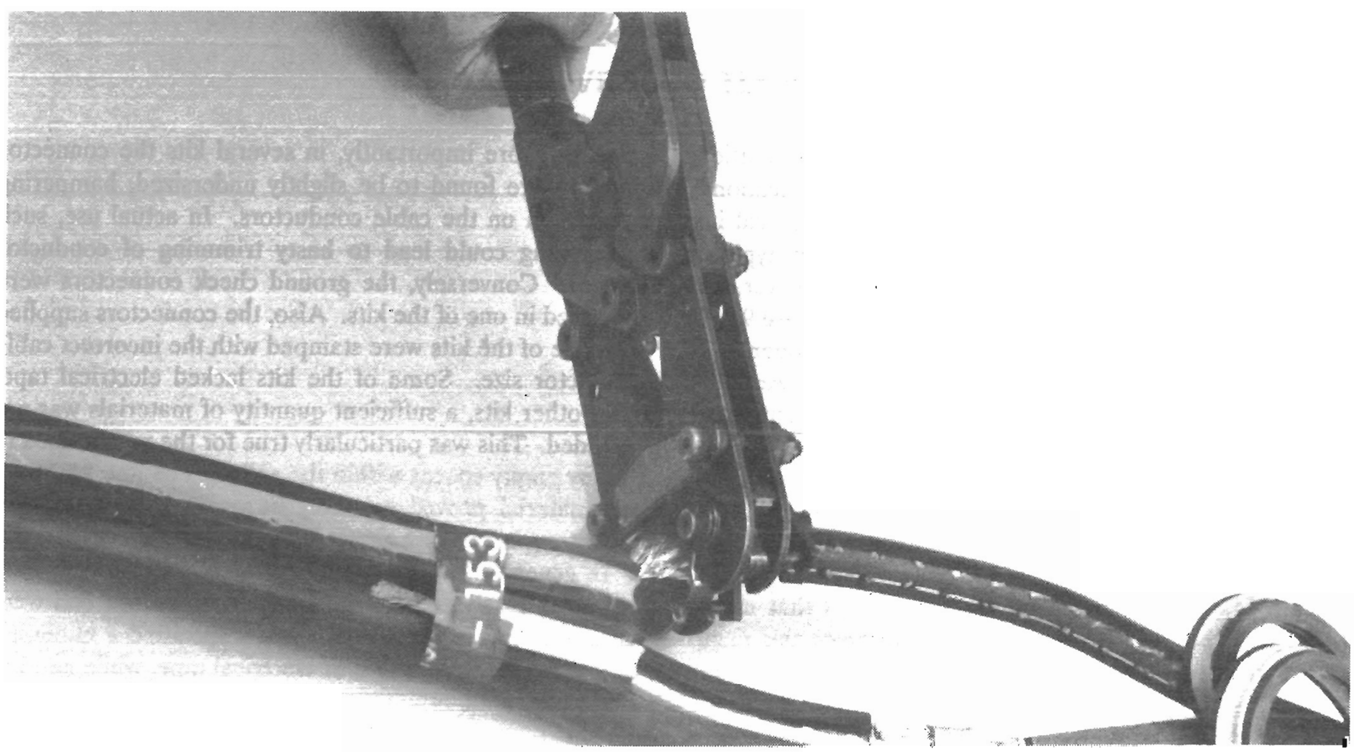
Prestretched tube.

Figure 4



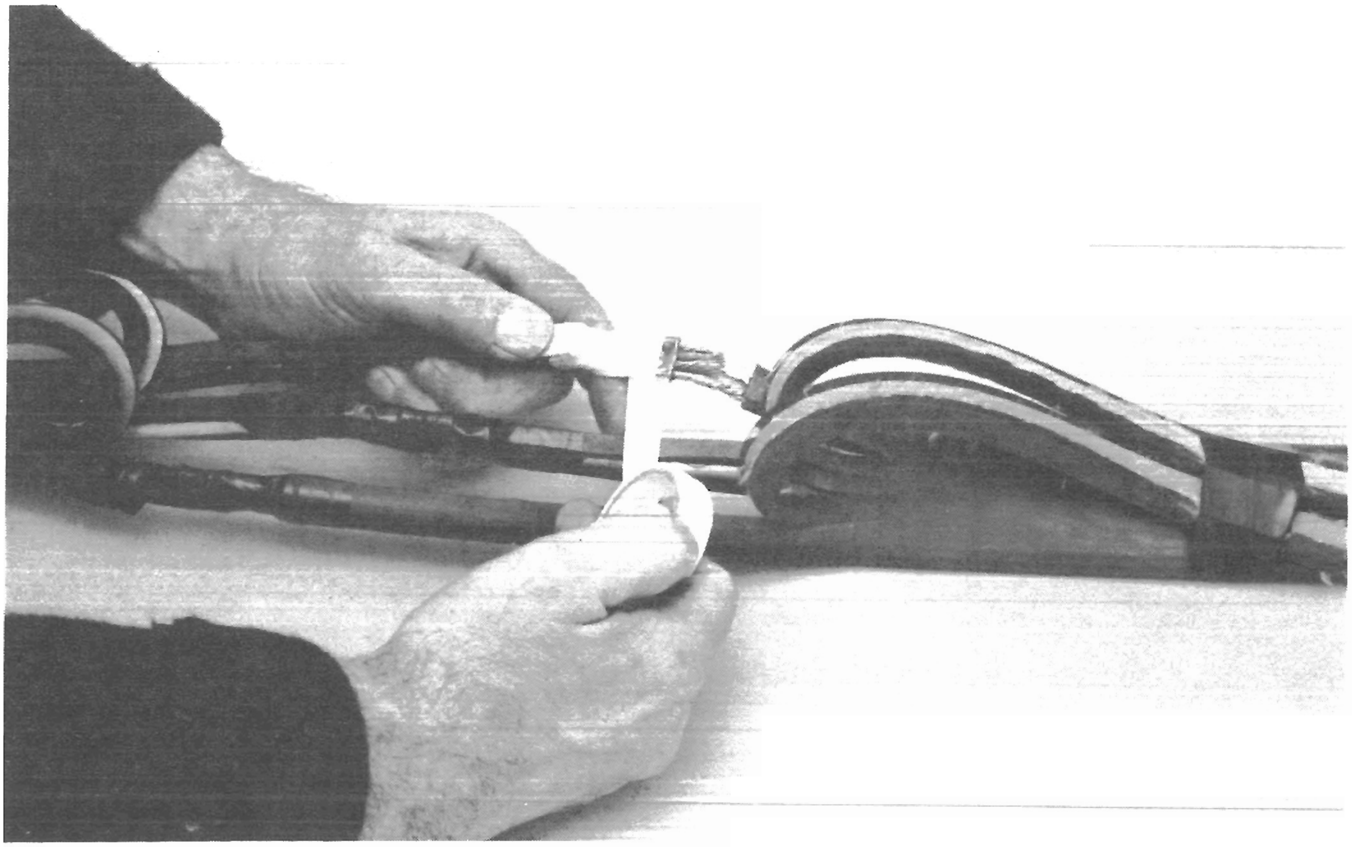
Anvil-type crimping tool.

Figure 5



Commercial wire crimper.

Figure 6



Glass tape applied over splice conductor.

SPLICE KIT OBSERVATIONS

In the course of sample preparation, a key observation was made concerning splice kit material specifications. The temperature and voltage ratings of the electrical insulating tape supplied by the kit manufacturers are typically 80 °C and 600 V, respectively (figure 7). However, the equivalent ratings of the original cable insulation are 90 °C and 2,000 V, leading to speculation that the underrated tape may contribute to short-lived cable splices. Accelerated life tests of splice kit materials were planned to investigate this.

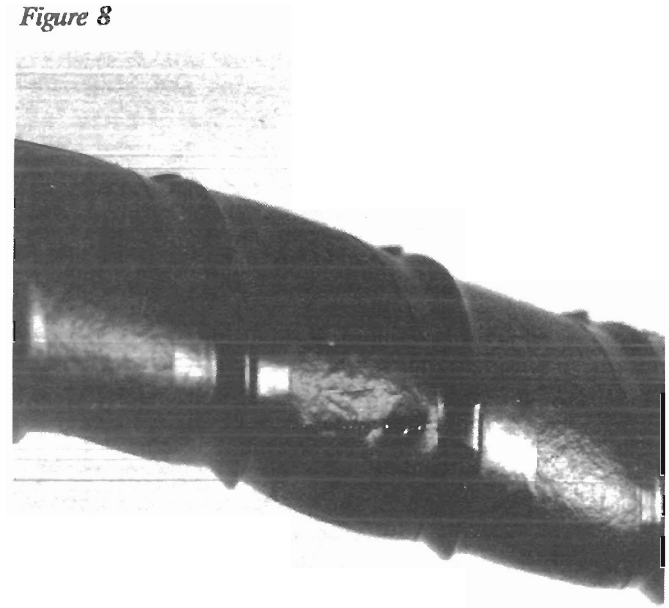
Many kit deficiencies were documented that could be addressed through improved quality control. For example, apparent defects were seen in some of the wrapping material used as an outer covering in one of the kit brands. These defects take the form of perforations that nearly penetrate the wrap thickness (figure 8). Since this material is overlapped when applied, this defect is not deemed critical. More importantly, in several kits the connector sleeves were found to be slightly undersized, hampering installation on the cable conductors. In actual use, such undersizing could lead to hasty trimming of conductor strands. Conversely, the ground check connectors were oversized in one of the kits. Also, the connectors supplied with one of the kits were stamped with the incorrect cable conductor size. Some of the kits lacked electrical tape. With other kits, a sufficient quantity of materials was not provided. This was particularly true for the mastic used to fill any empty spaces within the splice. For one kit brand this material proved unwieldy in application, tending to stick, tear, and bunch.

In general, the instructions supplied with the kits were not clear on all aspects of the splice procedure and were somewhat inconsistent. One brand specified a minimum of <u>four</u> half-lapped layers of electrical tape, while another

Figure 7

Splice kit insulating tape.

Figure 8



Apparent defects in kit outer wrap.

stated that <u>two</u> layers should be utilized. The third brand instructed that the spliced conductors be wrapped "with a generous amount of black electrical tape." In addition, a materials list was not provided with the kits. This would be helpful since some brands specify the use of materials that must be purchased separately. Also, the instructions sometimes presume a certain degree of proficiency. For instance, one brand's instructions did not specify how far back to strip the insulation and jacket and how to stagger conductor joints. Finally, since the kits contain potentially toxic adhesives and cleaners, Material Safety Data Sheets should be supplied.

SPLICE TENSILE STRENGTH AND RESISTANCE

As mentioned previously, the severed metallic conductors within a splice are joined by a crimped metallic sleeve. This connection has inherent electrical resistance that varies according to the crimp workmanship and other factors. This resistance causes the conductors at the splice to attain higher temperatures than the remainder of the cable. These connections also exhibit reduced tensile strength compared with the intact cable, which is likely related to the electrical resistance.

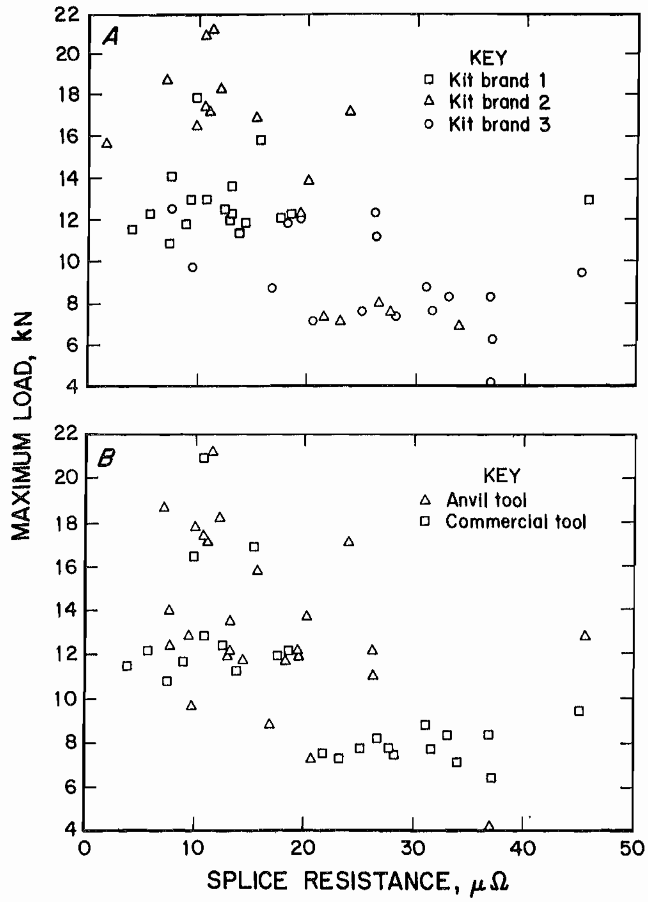
The instrumentation necessary to calculate the low electrical contact resistance of cable splices consisted of a precision current source and a nanovoltmeter. The resistance of 7.6-m lengths of new, unspliced cables was first determined for each of the six cable types by the Kelvin four-wire technique. With a 0.100-A test current, voltage drops across each of the three metallic conductors were measured and then averaged to obtain resistance values per unit length. Next, the resistance of 1.2-m spliced cable samples was evaluated. The added resistance of the splice joint was calculated by subtracting the resistance of an unspliced sample of the same length. As an example, joint resistance ranged from 2.2 to 46.2 $\mu\Omega$ for the #4/0 SHD-GC cable.

Following measurement of electrical resistance, the samples were subjected to tensile strength tests in accordance with American Society for Testing and Materials (ASTM) Standard E 8M-90a, "Standard Test Methods for Tension Testing of Metallic Materials." Samples were tensioned at a uniform displacement rate to yield, and the maximum load was recorded. Typical plots of maximum load versus splice resistance are shown in figure 9 for the #4/0 SHD-GC cable. A cursory observation reveals significant variance among the data to the extent that it seemed inappropriate to fit lines to the points. This variance was attributed to crimping tool wear over the course of sample preparation and to the fact that several individuals were making the splices.

On closer examination, a number of trends became apparent. Overall, as expected, splice resistance increased as breaking strength decreased. In figure 9*A*, the results are categorized by kit brand. The data obtained with one of the kit brands (kit brand 1, which had adhesive wrap as the outer covering) were tightly clustered; this brand also had the lowest average resistance of the three brands for the #4/0 SHD-GC cable. Similar analyses of the other cable sizes showed that no one brand exhibited consistently superior results. Crimping tool performance is compared in figure 9*B* for the #4/0 SHD-GC cable. It can be seen that the splices made with the anvil-type crimping tool exhibited higher tensile strengths on average than those made with the commercial wire crimper. This was true for four of the six cable sizes evaluated. These results suggested that anvil-type crimping tools have the capability of making stronger joints than commercial crimpers. However, it must be noted that this aspect of the investigation was limited in scope. There are other commercial crimpers that were not evaluated during the sample preparation. Also, the ratio of splice connector inner diameter to cable conductor outer diameter varies not only among splice kit brands but also among cable sizes.

Comparisons were then made with intact undamaged cables. The electrical resistance that a spliced joint adds to a cable is manifested in additional heat losses. At rated currents such losses ranged from 2 to 20 W per conductor, depending on cable size. Subsequent electrical load tests quantified these losses in terms of conductor temperature rise. Overall, the tensile strengths obtained for the spliced samples averaged only 30% of the original cable tensile strength as tested by the same procedure. Obviously this would have a critical impact on spliced cable service life, especially for reeled applications.

Figure 9



Splice tensile strength and electrical resistance.

SPLICE THERMAL PROFILES

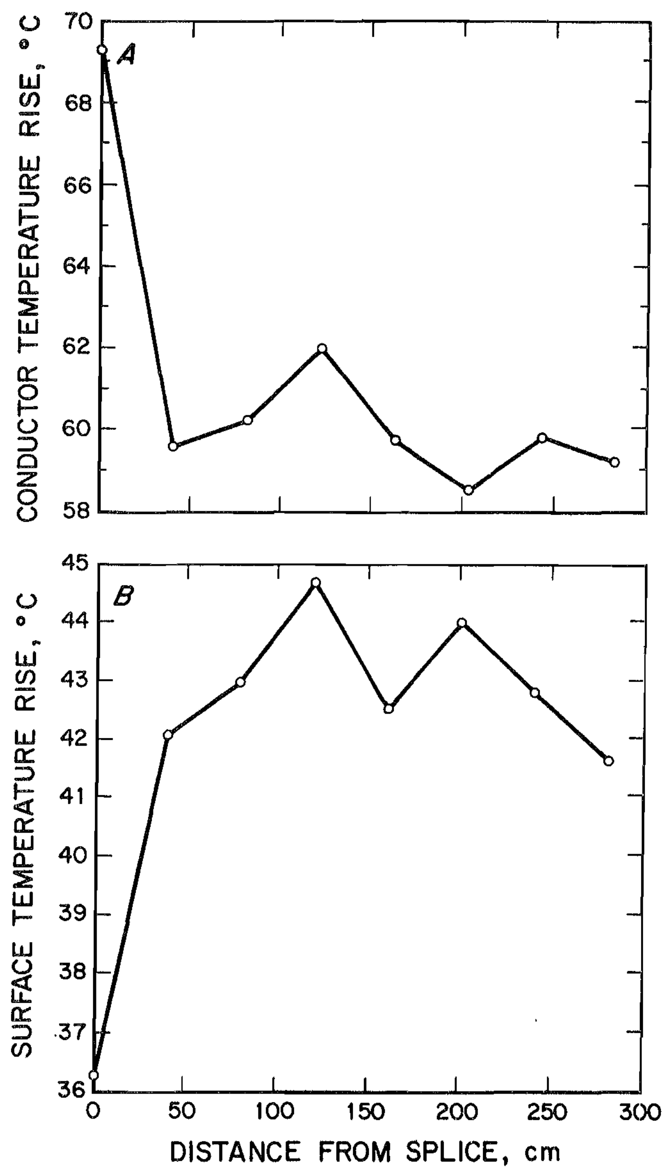
Tests were conducted to determine the thermal characteristics of spliced cables while carrying electrical current. Comparisons were made with the performance of undamaged, intact cable. Type T, #24 AWG thermocouples were inserted at key locations within and on the spliced samples to be subjected to electrical load tests.

The 5.2-m sections were suspended horizontally by rope 0.9 m above and parallel to the floor. The test site ambient was maintained free of drafts. All load tests were conducted with the dc series field supply of the motor test station in the Mine Electrical Laboratory at the USBM's Pittsburgh Research Center. Load current was applied to the samples until temperatures stabilized. The thermocouples were connected to a 32-channel datalogger that was programmed to read and transmit data to a personal computer. Commercial data acquisition software was used to collect the data, display them in real time, and store them on a disk.

Profiles of temperature in the splice vicinity were constructed. Not unexpectedly, the stabilized temperature rise of the spliced conductors near rated current ranged 5 to 20 °C higher than that of the undamaged conductors 1.8 m away. Figure 10*A* shows a typical result for a #4 flat G-GC cable loaded at 130 A. The spliced conductor caused a temperature elevation as far as 0.3 m away. Conversely, the temperature of the outer splice boot was approximately 7 °C cooler than the cable jacket surface 1.8 m away (figure 10*B*). This surface temperature at the splice was dependent upon the splice kit brand. Splices made with the kits utilizing the prestretched tubing and adhesive wrap exhibited average surface temperatures 8 °C cooler than the remainder of the cable. The surface temperature of splices made with the kit using the force-fit jacket was about the same as the rest of the cable.

The load tests confirmed first, that spliced conductors attain higher temperatures than the intact cables for a given amount of current. Consequently, the insulating materials supplied with cable splice kits should have *higher* thermal ratings than the original cable insulation. Second, the temperature rise at the outer splice surface depends upon kit materials. The thickness of the outer splice covering and how well it adheres to the repaired area affects thermal conduction relative to the undamaged cable.

Figure 10



Splice temperature profile.

ACCELERATED LIFE TESTS OF KIT MATERIALS

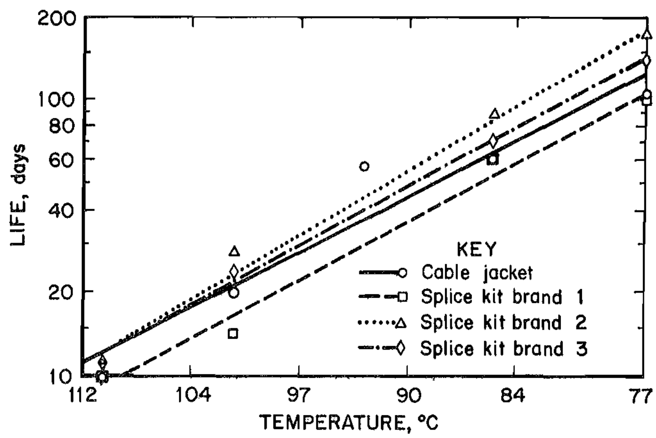
Accelerated life tests of thermally aged splice kit materials were then conducted to determine the impact of long-term elevated temperatures. It had already been shown that such materials are exposed to higher temperatures relative to the intact cable portions and, consequently, may contribute to shorter splice life. The two critical components of the kits are the vinyl tape, typically used to electrically reinsulate the power conductor connections, and the outer covering that provides mechanical protection for the splice. Since these materials substitute for the cable insulation and jacket, it was deemed appropriate to submit them to the same tests that are applied to the original cable polymers by the cable industry. Such requirements are contained in the standards of the Insulated Cable Engineers Association (ICEA) (*11-12*). For the insulating tape the characteristics tested include dielectric breakdown, tensile strength, elongation at rupture, hot creep elongation, and hot creep set. For the outer splice coverings the applicable characteristics tested are tensile strength, elongation at rupture, tensile stress, set, oil immersion, tear, and hardness. Over 2,800 samples were prepared, representing the three repair kit brands.

The kit material samples were aged by the USBM in air ovens at various temperatures for varying terms. Thermally aged insulating and jacketing material samples were periodically extracted from the ovens and subjected to end-of-life mechanical and electrical tests by an outside laboratory. This test plan followed that used previously for new cable materials (*7*).

Analysis of the mechanical tests that followed aging showed that 50% retention of elongation was the key determinant of thermal failure for the splice outer coverings. Arrhenius models, relating thermal life and temperature, were constructed and compared with those previously developed for original cable jackets (*9*). The results of the accelerated life tests show a consistency among kit brands despite the variety of application methods used for the outer coverings. The plots (figure 11) further reveal that the thermal life of outer splice coverings approximate that of the original cable jacket materials. For the three kit brands evaluated this does not appear to be inappropriate considering the lower surface temperatures of energized splices measured in the laboratory.

The mechanical results obtained with the aged insulating tape were far different. As samples of the tape were removed from the air ovens, it was obvious from their fragility and embrittlement (figure 12) that many were exhibiting premature thermal failure. In many instances, the samples had deteriorated to the extent that end-of-life tests were impractical. For two of the three brands this occurred within 40 days at 110 °C. By comparison, in previous tests the thermal life of ethylene-propylene-rubber cable insulation was 250 days at 110 °C (*7*). Compounding the problem is the fact that the splice kit tape is exposed to a higher operating temperature than the intact cable insulation because of the added resistance of the conductor joint. From an electrical standpoint, the ac dielectric breakdown tests conducted following aging showed no significant deterioration in insulating properties up to the point of mechanical failure.

Figure 11



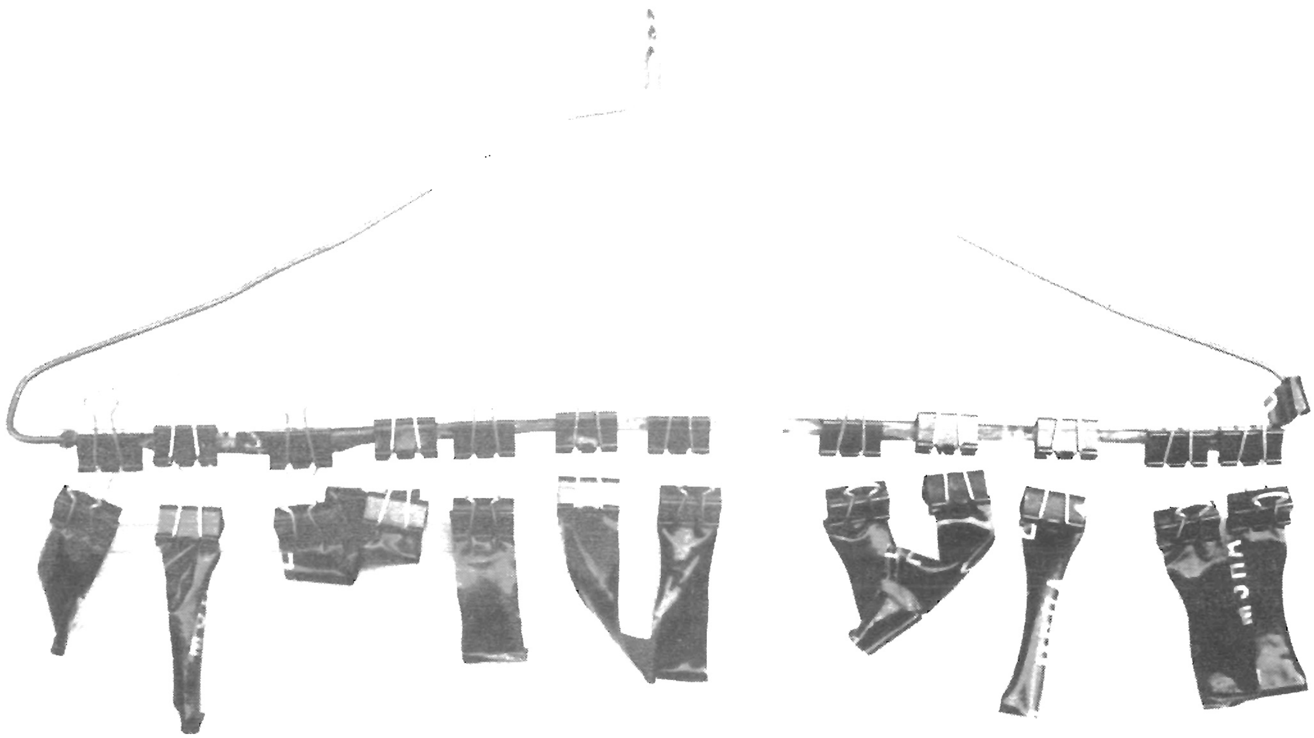
Arrhenius models for cable jacket and splice kit outer coverings.

The accelerated life tests confirmed the suspicion that splice kit insulating tape is deficient in thermal rating. This deficiency in all likelihood is a major cause of splice failures underground. To preclude premature thermal failure of tape from existing kits would require a significant reduction in spliced cable ampacity. Such a solution is deemed impractical. It is not unreasonable to expect that the materials being substituted for the original cable insulation and jacket be appropriately rated for field service. Accordingly, splice kit manufacturers should upgrade the thermal rating of the tape used in their products.

CONCLUSIONS AND RECOMMENDATIONS

The USBM has conducted an in-depth laboratory examination of the operating characteristics of portable cable splices. This investigation focused upon splice kit quality control, kit instructions, splice tensile strength, electrical resistance, thermal profiles, and accelerated life tests of materials. The findings of this project are based upon tests of three kit brands selected for the variety of ways in which their outer coverings are applied. The deficiencies uncovered are not an indictment of these particular brands, but are believed to be symptomatic of trailing cable splice kits. To rectify this, the following recommendations are made to all splice kit manufacturers:

Figure 12



Brittle insulating tape samples following thermal aging.

1. Splice kit instructions should be explicitly written, with step-by-step procedures augmented with illustrations.
2. For training purposes, a videotape showing proper splicing procedures could be made available by the kit manufacturer to improve the skills of those using the kits.
3. Kit instructions should contain a materials list to ensure that all components are compatible physically.
4. All materials listed should be supplied with the approved kits.
5. Anvil-type crimping tools should be recommended to maximize tensile strength.
6. Application of glass tape should be a prerequisite to prevent conductor strands from piercing the insulating tape.
7. Ratings of the insulating tape used in splice kits should be upgraded from 80 °C and 600 V to 110 °C and 2,000 V to reflect actual service conditions.
8. Application of insulating tape should be consistent among kits since it provides protection against internal faults and electrical shock. Four half-lapped layers are recommended over each spliced joint for 2-kV cable.
9. Material Safety Data Sheets should be supplied for all kits using potentially toxic adhesives and cleaners.
10. The dielectric and mechanical strength of assembled splices should be evaluated as part of the splice kit approval process. Appropriate quality control measures will ensure that splice kits are sold as originally evaluated.

The characterization of the thermal aspects of trailing cable splice performance can have a positive impact, on both underground mine safety and efficiency. Due consideration of splices as the cable's "weak links" further outlines the safety boundaries for using coal mine trailing cables underground. An awareness of how heat affects the performance and safety of splices is important when considering the ampacity or current-carrying capacity of a spliced cable. The data in this report augment prior data that defined the ampacity for unspliced cables.

In addition, accelerated life tests of splice kit materials yield recommendations for improvement in kit design that ultimately can prolong the service life of cables underground. The definition of the thermal operating limits of spliced cables facilitates refinements in splice kit design, splice kit approval criteria, and trailing cable loading guidelines.

ACKNOWLEDGMENTS

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