DYNAMIC TEMPERATURE MEASUREMENT OF OVERHEATED SHUTTLE CAR TRAILING CABLES IN UNDERGROUND COAL MINES

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ABSTRACT

Recent research conducted by NIOSH, Pittsburgh Research Laboratory showed that electrical current levels permitted under present regulations may not limit cable temperatures to less than 90 °C in reeled trailing cables. Reeled cables, tightly wrapped with many turns, all carrying current in an enclosed space, can become overheated due to poor heat transfer. This overheating can cause the cable insulation to soften and become easily damaged. The damaged insulation reduces the life of the cable and can lead to shock, electrocution, and mine fires.

This paper describes a method of measuring the conductor temperature of mine trailing cables during normal operation. The temperature is measured using a 50/125 micrometer Graded Index Multimode Optical Fiber located in the center of the metallic conductors. Distributed temperature measurements are made using an Optical Time Domain Reflectometer (OTDR). This system is capable of measuring temperature with an accuracy of plus or minus one degree centigrade over a length of 4 km at 1-m intervals. With this unique way of measuring temperature, tests can be conducted simulating actual mine conditions and provide important data to allow MSHA's Approval and Certification Center to develop approval criteria for cyclically rated reeled machines.

INTRODUCTION

The safe electrical operation of shuttle cars depends upon maintaining temperatures at or below 90 °C for the trailing cable. Present electrical requirements for trailing cables used in underground coal mining are contained in 30 CFR Parts 18 and 75 (U.S. Code of Federal Regulations, 1994). These Federal regulations require trailing cables to be rated according to the standards set by the Insulated Cable Engineers Association (ICEA) (Insulated Cable Engineers Association, 1985).

Overheating of electric cables on shuttle cars has long been recognized as a cause of premature insulation failure leading to shock and electrocution. Use of cable reels on shuttle cars can cause excessive heat build up which, in turn, causes the cable insulation to soften and become easily damaged. This heat-softened insulation reduces the life of the cable. Repeated cycling of a cable in this manner can cause premature aging of the insulation. The insulation becomes brittle, cracks, and allows electrical leakage paths to form. These leakage paths provide the opportunity for shock and electrocution to occur if miners come in contact with the damaged section of cable. It is imperative that cable operating temperatures be maintained at safe thermal limits.

A previous study by the former U.S. Bureau of Mines (USBM) supported ICEA efforts to establish appropriate derating factors for reeled mine trailing cables (Kovalchik et al., 1994). Empirical and theoretical models were established to simulate a variety of test conditions, including those that cannot be conducted in the laboratory. Results showed, under static test conditions, excessive heating can occur for round trailing cables operated using presently accepted derating factors. Results for the flat cables showed the derating factors to be on the conservative side. The success of this effort prompted the ICEA to request the study of flat and round cables be extended to include dynamic loads to provide a complete picture of realistic trailing cable usage. Phase 1 of the current study involves round trailing cables. Flat cables will be studied at a later date.

TECHNICAL APPROACH

Monitoring cable temperatures under dynamic conditions requires a different approach than previously used. Under static test conditions, researchers could place thermocouples under conductor insulation at many locations simultaneously along the reeled cable. This approach becomes unworkable when the cable is constantly reeled in and payed out, as is done in practice. One example is a shuttle car operated in a room-and-pillar scenario. Constant movement of the trailing cable would entangle the thermocouple leads and increase the risk of electrocution by the energized conductor. A new approach, using a distributed fiber-optic sensor embedded within conductors along the entire length of the trailing cable, can overcome these obstacles.

The test setup is shown in Figure 1. A trailing cable with an embedded optical fiber is reeled onto a shuttle car drum and connected to a 550-V, three-phase, ac power source. The shuttle car drum diameter is 25 cm. Connections to the optical fibers are made near the ac power source with fiber-optic jumper cables. The exposed conductors at the sensor breakout locations are reinsulated. The reinsulation procedure and the electrical isolation provided by the fiber-optic cables minimize risk of electrocution. The optical signal is processed by a York DTS 80 distributed temperature measuring system. Temperature and distance data are then downloaded via an ARC Net link to a personal computer for logging and visual display. With this setup, the shuttle car can move freely without interfering with the data acquisition process.

The DTS 80 is capable of measuring temperatures at 1-m intervals along the entire length of the optical fiber. The sensing technique is based on temperature-dependent Raman scatter of light pulses launched into the optical fiber. The standard DTS 80 is configured for communication grade 50-μm core silica optical fiber, although other fiber options are available. Distance measurements to localized hot spots along the fiber are calculated after tracking the time required for scattered light to reach a photo detector. Although temperature measurements can be made from

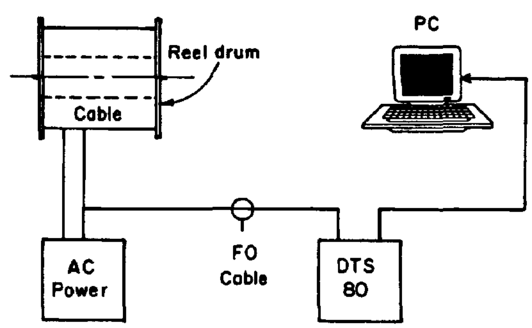


Figure 1. Test setup.

a single end connection, maximum performance requires connection of both ends to the instrument. For the shuttle car test setup, the "loop" was completed by installing a short fiber-optic jumper cable inside the drum. One of three separate loops embedded in the trailing cable is typically monitored during shuttle car tests. With this loop configuration, temperature resolution at each 1-m interval is 1 °C.

<u>Optical Fiber Installation</u>

The fiber-optic sensors must be protected in accordance with the intended application. In this case, the fiber-optic sensors were embedded within a Tiger Brand #4 AWG, 3-conductor, G-GC trailing cable during the manufacturing process. A fiber-optic cable containing two optical fibers replaced the center copper element of the #4 AWG conductors as shown in Figure 2. Outer copper elements were wrapped around the fiber-optic cable as it was pulled through the cabling machine. The cross-sectional areas of the copper elements were adjusted to maintain the equivalent cross-sectional area of a #4 AWG conductor. Insulation was extruded over the fiber-optic embedded #4 AWG conductor. The insulated conductor was then cut into thirds and extruded again to complete the final product. These manufacturing processes dictate that the sensor jacket must be abrasion resistant, able to tolerate high extrusion temperatures, and withstand stresses associated with pulling of the cable. To minimize special setup procedures, the overall diameter of the fiber sensor jacket should be compatible with standard cable manufacturing dimensions. Operating conditions such as the drum diameter, temperature, and number of test cycles the cable is expected to endure over a 6-month test period, must also be considered. Some of these fiber jacket design parameters are:

Initial extrusion temperature	220 °C
Final 2-day cure temperature	150 °C
Operating temperature	90 °C
Bend radius	10 cm
Approximate flex cycles	10,000

Optical fiber protection options were proposed by various vendors. One proposal consisted of two polyimide-coated, 50-μm core optical fibers contained within a polyvinylidene fluoride (PVDF) loose tube buffer. A sample of this cable was incorporated into a production run of a #4 AWG conductor. An optical time domain reflectometer (OTDR) monitored the attenuation characteristics of one of the optical fibers as the sensor cable was pulled through the machine. The OTDR display showed intensity of back-scattered light as a function of fiber length (Figure 3). As the test run started, it soon became apparent the fiber was undergoing excessive stress as indicated by the signal attenuation between markers "A" and "B". The problem was caused by excessive pulling tension between the main capstan and a gear driven take-up reel. Although a clutch adjustment to the take-up reel eliminated further problems, this experience suggested more substantial protection was needed. An alternative design including stress-bearing kevlar strands was subsequently chosen. In this configuration, an inner tefzel loose tube isolates two polyimide-coated, 50-μm core optical fibers from the kevlar. An outer tefzel tube protects the kevlar strands from abrasion.

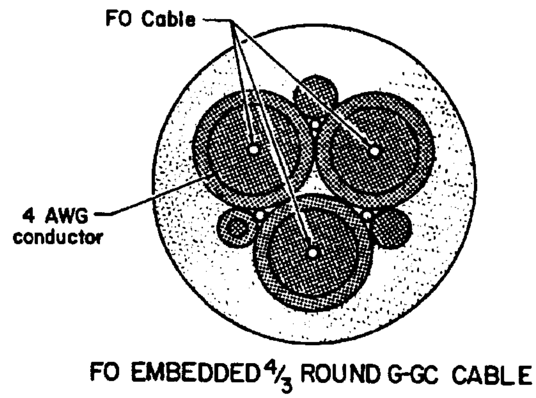


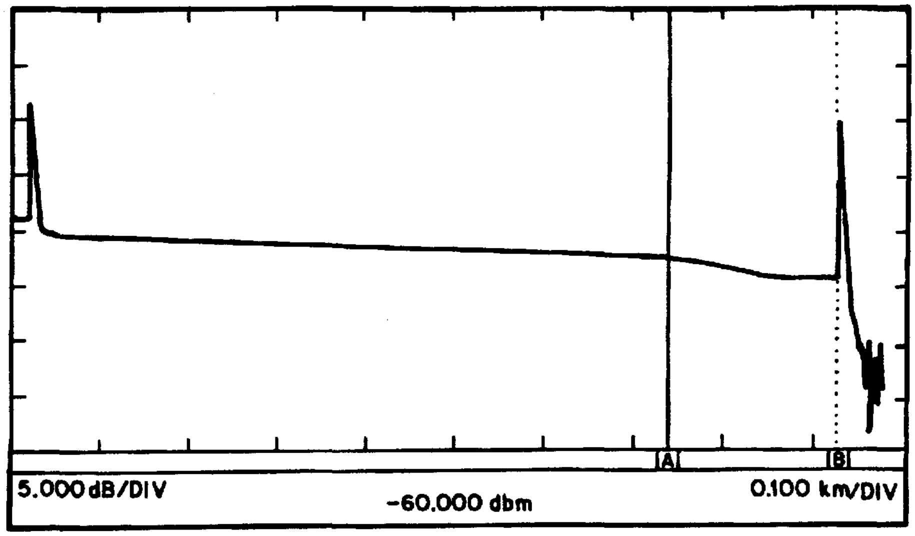
Figure 2. Cross section of fiber-optic embedded test cable.

RESULTS

Researchers compared DTS 80 measurements with thermocouple measurements using a simple laboratory setup. First, an 8-m length of standard 3-conductor #4 AWG G-GC trailing cable was suspended in the air. A length of fiber-optic cable was tie wrapped to the trailing cable and connected to the DTS 80. Eight thermocouples were then attached to the fiber-optic cable at locations roughly corresponding to the midpoint of the 1-m intervals defined by the DTS 80. The trailing cable was then energized until thermocouple readings indicated the cable had reached thermal equilibrium. DTS 80 measurements at thermal equilibrium were within ± 1 °C of the thermocouple measurements, verifying the specified accuracy of the DTS 80 over the expected temperature range of the shuttle car tests.

Researchers also conducted preliminary shuttle car tests with the fiber-optic-embedded trailing cable. The shuttle car was loaded with coal and operated in a manner similar to a room-and-pillar scenario. A typical DTS 80 display shows temperature readings as a function of distance from the instrument (Figure 4). The drum-terminated end of the trailing cable corresponds with the sharp downward peak in the center of the figure. This downward peak is caused by jumper cable connector reflections in the center of the drum and should not be misinterpreted as actual temperature. Reflections effectively blind the DTS 80 over short distances, commonly referred to as dead zones. Dead zones can be eliminated by replacing connector interfaces with splices. However, space limitations inside the drum make reliable splice installation difficult. Dead zones are an example of concepts that need to be understood when interpreting DTS 80 generated data.

The symmetrical side lobes around the central dead zone in Figure 4 represent temperature readings from two fiber-optic sensors. These jumper-connected fiber-optic sensors form one sensor loop. The periodic downward peaks indicating lower temperature are consistent with sections of cable closest to the outside of the reel. These sections of cable are most susceptible to convective cooling effects from the surrounding atmosphere. Further testing is required to make quantitative assessments of



Marker Information:

A	0.768 km
B	0.950 km
Distance	0.187 km
2 Pt Loss	2.147 dB

Figure 3. OTDR display.

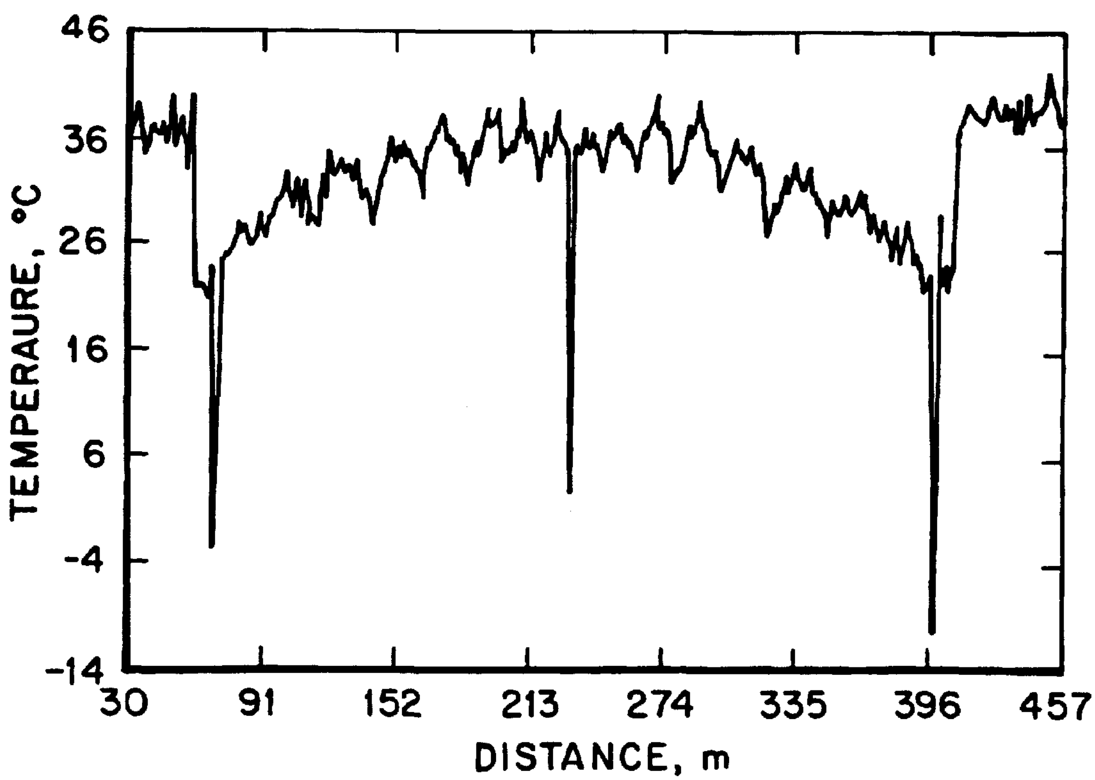


Figure 4. DTS 80 display which shows 7 layers of cable.

thermal characteristics of the trailing cable under dynamic test conditions.

DISCUSSION

A distributed temperature measuring system based on fiber-optic technology allows researchers to safely monitor temperatures along an energized mine trailing cable under dynamic test conditions. A fiber-optic-embedded test cable requires only one access point to measure temperatures to within ± 1 °C at 1-m intervals along the entire cable. As with most sophisticated instruments, a basic understanding of the underlying technology is necessary to correctly interpret generated data. Special precautions are necessary to protect the fiber-optic sensor embedded in the trailing cable. An OTDR proved to be a valuable quality assurance tool during the test cable manufacturing process. Initial shuttle car tests indicate the fiber-optic approach is viable. Subsequent research will allow quantitative assessment of thermal characteristics of reeled trailing cables under dynamic conditions.

REFERENCES

Insulated Cable Engineers Association, 1985, "Ethylene-propylene-rubber-insulated wire and cable for the transmission and distribution of electrical energy," ICEA Publ. S-68-516. Available from Natl. Electr. Manuf. Assoc. [WC8-1976(R1982)]. Part 8, p. 7.

Kovalchik, P. G., Cole, G. P., and Duda, F. T., 1994, "Thermal characteristics of reeled trailing cables for shuttle cars," Bureau of Mines Information Circular (IC 9414), 14 pp.

U.S. Code of Federal Regulations, 1994, Title 30-Mineral Resources; Chapter I-Mine Safety and Health Administration, Department of Labor, Subchapter B-Testing Evaluation, and Approval of Mine Products; Part 18-Electric Motor-Driven Mine Equipment and Accessories; pp. 115-150; Part 75-Mandatory Safety Standards-Underground Coal Mines; pp. 501-625.