Distributed Measurement of Conductor Temperatures in Mine Trailing Cables Using Fiber-Optic Technology

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***Abstract*—Mine trailing cables operated above safe thermal limits can cause premature insulation failure, increasing electrocution and fire hazards. Previous U.S. Bureau of Mines Pittsburgh Research Center research showed that, under static test conditions, electrical current levels permitted under present regulations may not limit cable temperatures to less than the 90 °C rating of reeled trailing cable. Continuing research under the National Institute for Occupational Safety and Health (NIOSH) addresses thermal characteristics of reeled trailing cable under dynamic test conditions more representative of field conditions, where operators constantly reel in and pay out cable. This research is in support of efforts by industry associations and the Mine Safety and Health Administration to establish safety guidelines for cyclically rated reeled machines. This paper describes a unique approach to measuring temperatures within reeled cable under dynamic test conditions. Fiber-optic sensors embedded within the metallic conductors measure temperatures at 1-m intervals along the entire length of cable. Temperature measurements are reported to be accurate to within ±1 °C. The test setup requires access to only one end of the trailing cable, allowing researchers to freely reel in and pay out cable while temperature measurements are made, simulating field conditions. Manufacture of a fiber-optic-embedded trailing cable is described, along with initial test results that indicate the fiber-optic approach is viable.**

***Index Terms*—Fiber optics, mine trailing cable, temperature.**

I. INTRODUCTION

THE safe electrical operation of shuttle car trailing cables depends upon maintaining electrical conductor temperatures below 90 °C. Present electrical requirements for trailing cables used in underground coal mining are contained in Title 30 CFR, Parts 18 and 75 [1]. These Federal regulations require trailing cables to be rated according to the standards set by the Insulated Cable Engineers Association (ICEA) [2].

A previous study conducted by the U.S. Bureau of Mines (USBM) supported ICEA efforts to establish appropriate derating factors for reeled coal mine trailing cables [3]. Empirical and theoretical models were established to simulate a variety of test conditions, including those that cannot be conducted in the laboratory. Results showed that, under static test conditions, excessive heating can occur for round trailing cables operated using presently accepted derating factors. Results for flat cables showed the derating factors to be on the conservative side. The success of this effort prompted the ICEA to request that the study of flat and round cables be extended to include dynamic loads to provide a complete picture of realistic trailing cable usage. Phase one of the current study involves round trailing cables. Flat cables will be studied at a later date.

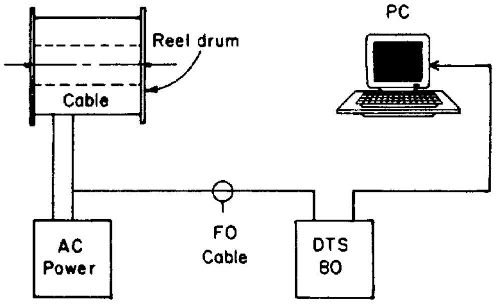

Fig. 1. Test setup.

II. 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, e.g., a shuttle car operated in a manner similar to 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 distributed fiber-optic sensors embedded within conductors along the entire length of the trailing cable, can overcome these obstacles.

The new test setup is shown in Fig. 1. A fiber-optic-embedded trailing cable is reeled onto a shuttle car drum and connected to a 550-V three-phase ac power source. The shuttle car drum diameter is about 22 cm. Connections to the fiber-optic sensors are made near the ac power source

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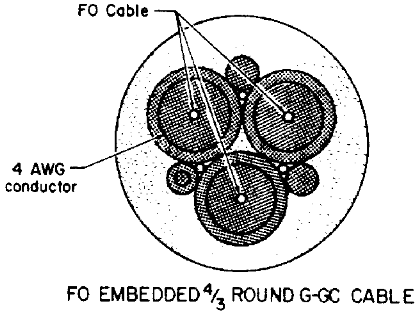

Fig. 2. Cross section of fiber-optic-embedded test cable.

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 minimizes risk of electrocution. The optical signal is processed by a York DTS 80 distributed temperature monitor. 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 a fiber-optic sensor. 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 it takes for scattered light to reach a photodetector. Although temperature measurements can be made from 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.

III. Optical Fiber Installation

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 three-conductor ground–ground check (G–GC) trailing cable during the trailing cable manufacturing process. A fiber-optic cable containing two optical fibers replaced the center copper element of the 4-AWG conductors, as shown in Fig. 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 capable of withstanding 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 six-month test period, must also be considered.

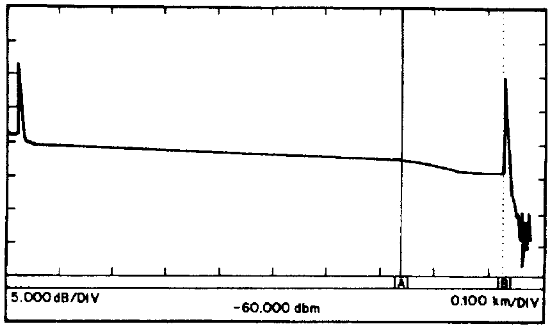

Fig. 3. OTDR display.

Some of these fiber jacket design parameters are as follows:

initial extrusion temperature	182 °C;
final 3-1/4 hour cure temperature	132 °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 in 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 (Fig. 3). As the test run started, it soon became apparent that 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 takeup reel. Although a clutch adjustment to the takeup 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.

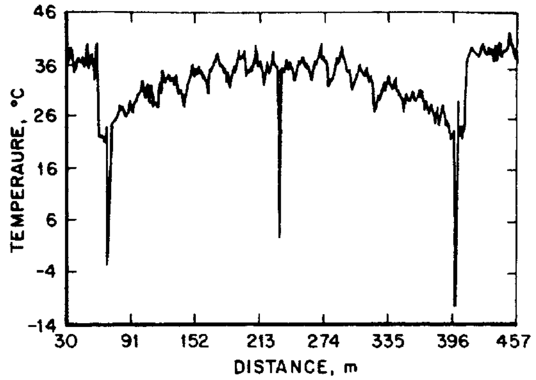

Fig. 4. DTS 80 display.

IV. RESULTS

Researchers compared DTS 80 measurements with thermocouple measurements using a simple laboratory setup. First, an 8-m length of standard three-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 (Fig. 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 Fig. 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 thermal characteristics of the trailing cable under dynamic test conditions.

V. 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

[1] U.S. Code of Federal Regulations, 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; 1994, pp. 501–625.

[2] "Ethylene-propylene-rubber-insulated wire and cable for the transmission and distribution of electrical energy," Insulated Cable Engineers Association, ICEA Pub. S-68-516, 1985, pt. 8, p. 7.

[3] P. G. Kovalchik , G. P. Cole, and F. T. Duda, "Thermal characteristics of reeled trailing cables for shuttle cars," U.S. Bureau of Mines, Washington, D.C., USBM IC 9414, 1994, p. 14.