Investigation of Ampacity Derating Factors for Shuttle Cars Using Fiber Optics Technology

Peter G. Kovalchik
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236-0070 USA
Phone (412) 892-6098 Fax (412) 892-4384 E-Mail: pdk0@cdc.gov WWW: http://www.usbm.gov

Lawrence W. Scott
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236-0070 USA
Phone (412) 892-6607 Fax (412) 892-4384 E-Mail: lns5@cdc.gov WWW: http://www.usbm.gov

Frank T. Duda
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236-0070 USA
Phone (412) 892-4624 Fax (412) 892-4384 E-Mail: fbd2@cdc.gov WWW: http://www.usbm.gov

Thomas H. Dubaniewicz
National Institute for Occupational Safety and Health
Pittsburgh, PA 15236-0070 USA
Phone (412) 892-6596 Fax (412) 892-6764 E-Mail: tcd5@cdc.gov WWW: http://www.usbm.gov

***Abstract* - 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; it 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.**

This paper discusses a research project conducted by the National Institute for Occupational Safety and Health, Pittsburgh Research Center to determine dynamically the conductor temperature of reeled shuttle car cables using fiber optics technology. The research portrays typical shuttle car loading cycles (both current and time cycles). Root-mean-square current loading is calculated based on the results. The thrust of this effort is to provide the scientific basis for ampacity derating factors specifically for mine machinery using reeled cables. This information will reduce the probability of electrical hazards from reeled cables.

I. 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 [1]. These Federal regulations require trailing cables to be rated according to the standards set by the Insulated Cable Engineers Association (ICEA) [2].

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; it 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 supported ICEA efforts to established appropriate derating factors for reeled 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 the 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 1 of the current study involves round trailing cables. Flat cables will be studied at a later date.

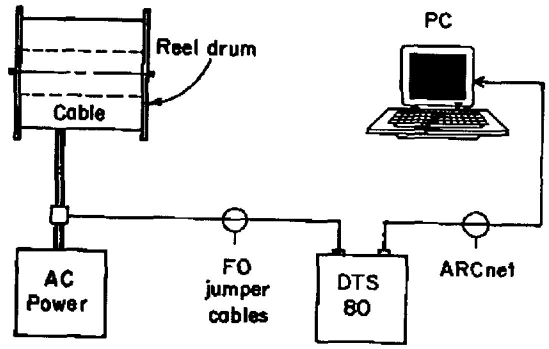

Figure 1. Test setup.

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. 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 ARCnet 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 required for scattered light to reach a photo detector. 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. TEST PLAN

Four separate dynamic tests were conducted. For each test, the shuttle car was driven back and forth over a 27.69 m test track for a period of 8 hours or until temperature stabilization. The shuttle car was loaded with 6.25 tons of material. A 139 m length of No. 4 AWG round 3 conductor G-GC trailing cable instrumented with fiber optics embedded in the center of each conductor was used to conduct power to the shuttle car, as well as provide a temperature profile. A 74 m length of this cable spanning the distance from the load center to the area in the vicinity of the tie-off point always remained in contact with the ground. For the first test, one layer was manually wrapped onto the cable reel and a second layer was spooled on and off the reel as the shuttle car was driven over the test track. As the car was driven from the tie point, the cable was spooled off to the ground and as the car was driven back to the tie point the cable was spooled back onto the reel. For the second test, two layers were manually wrapped onto the cable reel and a third layer was spooled off and on as the car was driven. The third and fourth tests were conducted with four and five layers permanently on the reel and the fifth and sixth layers respectively spooled off and on. Each layer consisted of 15 wraps of cable with layer 1 having 12.9 m of cable, layer 2 having 14.8 m of cable, layer 3 having 17.3 m of cable, and layer 4 having 20 m of cable.

The DTS-80 fiber-optic instrumentation provided the capability to monitor the conductor temperature as a function of time over the test period and as a function of distance over the entire 139 m length of cable. A data logger in conjunction with a shunt provided the capability to monitor the shuttle car load currents as a function of time. A typical DTS 80 display shows temperature readings as a function of distance from the instrument (figure 2). 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 2 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.

To characterize the changing currents obtained by the data logger over an eight-hour test due to the dynamic operation of the shuttle car, a generalized ampacity equation based on an n-segment duty cycle developed by John Mesina of MSHA's Approval and Certification Center was used to calculate an RMS current. The data logger sampled current values at a rate of one sample every two seconds. Therefore, the test cycle of one 8 hours was divided up into approximately 14,400

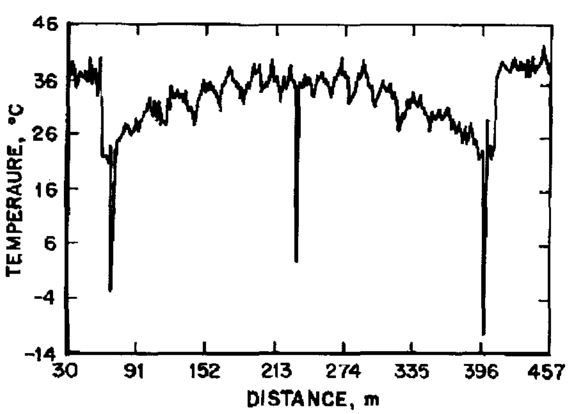

Figure 2. DTS 80 display.

segments. The following equation for an n-segment duty cycle was used to obtain an RMS value:

$$\text{Ampacity of n segment duty cycle} \quad \left[\frac{\sum_{s1}^{sn} (ts2 \quad ts1) \dfrac{Is2^2 \quad Is1^2 \quad Is1Is2}{3}}{tn2 \quad t11} \right]^{1/2} \tag{1}$$

where s = segment number - general notation,
n = total number of segments in one duty cycle,
1 = designates values at the start of segment s,
2 = designates values at the end of segment s,
tn2 = time at the end of segment n,
t11 = time at the start of segment 1 (usually zero)

An RMS value was obtained for each of the four tests.

A second series of four static tests was conducted to determine if the RMS characterizations of the currents were suitable. The same 139 m length of cable was used for these static tests. For the first test, two layers were manually wrapped on the spool and the cable was energized with a d.c. current equivalent to the calculated RMS value obtained from the first dynamic test. Again the conductor temperature was monitored with the DTS 80/fiber optic instrumentation as a function of distance and time. The test was considered complete when the hottest temperature was reached and stabilized for 1 hour. The other three tests were conducted in a similar manner using the RMS values obtained from the dynamic test. Table I lists the calculated RMS values from all four dynamic tests.

IV. TEST RESULTS

Static tests were compared to the dynamic tests with the results shown in Table II. Results show the static and dynamic tests within 1 or 2 degrees C of each other. Each layer tests had similar temperature profiles with the maximum temperature occurring in the center wrap of each layer. The hottest overall layer was found to be a function of the number of layers on the reel and independent of the shuttle car speed, duty cycle, and current. These initial tests indicate that the calculated RMS currents are viable solutions for determining ampacity ratings for reeled cables. However, these are only a handful of test results and further testing must be conducted not only for round cable, but also flat cables.

V. SUMMARY

The conductor temperatures of reeled shuttle car cables were determined dynamically using fiber optics technology. The sensor was a 50 micrometer core silica optical fiber embedded in the conductors at the time of manufacture. Temperature

TABLE I

CALCULATED RMS CURRENTS

Test Number	Maximum layers on, during test	Calculated RMS current
1	2	34.4 amps
2	3	31.5 amps
3	4	33.0 amps
4	5	32.5 amps

TABLE II

TEST RESULTS

Test Number	Maximum layers on, during test	Dynamic Tests Hottest temperature	Static Tests Hottest temperature
1	2	49 °C	48 °C
2	3	60 °C	61 °C
3	4	78 °C	80 °C
4	5	86 °C	84 °C

measurements were made using a DTS 80 Distributed Temperature Measuring System. Static tests were compared to dynamic tests. Results showed the static and dynamic tests were within 1 or 2 °C of each other. Each test had similar temperature profiles, with the maximum temperature occurring in the center wrap of each layer. The hottest layer was found to be a function of the number of layers and independent of the shuttle car's speed, duty cycle, and current. Results indicated that a calculated RMS current value is a viable solution for determining ampacity ratings for reeled shuttle car cables and maintaining operating temperatures at safe thermal limits. This method of determining the ampacity rating for mine machinery using reeled cables will provide a complete picture of realistic trailing cable usage.

VI. 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; pp. 501-625; 1994.

[2] Insulated Cable Engineers Association. Ethylene-propylene-rubber-insulated wire and cable for the transmission and distribution of electrical energy. ICEA Publ. S-68-516, 1985. Available from Natl. Electr. manuf. Assoc. [WC8-1976(RI 1982)]. Part 8, p. 7.

[3] P.G. Kovalchik, G.P. Cole, and F.T. Duda. "Thermal characteristics of reeled trailing cables for shuttle cars," USBM IC 9414, 1994, 14 pp.