Information Circular 9278

# Impact of Current Load on Mine Trailing Cable Thermal Life

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BUREAU OF MINES
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**Library of Congress Cataloging in Publication Data:**

**Yenchek, M. R. (Michael R.)**
Impact of current load on mine trailing cable thermal life / by M. R. Yenchek and P. G. Kovalchik.

p. cm. -- (Information circular; 9278)

Includes bibliographical references.

Supt. of Docs. no.: I 28.27:9278.

1. Coal mining machinery--Electric equipment--Testing. 2. Electric cables--Thermal properties. 3. Electric currents--Heating effects. I. Kovalchik, Peter G. II. Title. III. Series: Information circular (United States. Bureau of Mines); 9278.

TN295.U4 [TN813] 622 s--dc20 [622'.48] 90-49809 CIP

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| A | ampere | hp | horsepower |
| °C | degree Celsius | K | kelvin |
| °F | degree Fahrenheit | min | minute |
| h | hour | pct | percent |

# IMPACT OF CURRENT LOAD ON MINE TRAILING CABLE THERMAL LIFE

By M. R. Yenchek[1] and P. G. Kovalchik[1]

## ABSTRACT

The U.S. Bureau of Mines has determined a method for calculating coal mine portable power cable thermal life for a specified temperature loading. This work was the culmination of a multifaceted research project involving (1) accelerated life tests of insulation and jacket materials and (2) steady-state and cyclical loading of cables. Composite Arrhenius curves were derived for common insulation and jacket materials to identify the key cable quality that precipitates thermal failure. Plots of temperature rise versus current for popular cable sizes were then referenced to develop a correspondence between cable life, based upon thermal degradation, and current loading. Predictions of cable thermal life were made through integration over variable load cycles and, consequently, variable operating temperatures. This procedure may have utility for both the U.S. Mine Safety and Health Administration and mining machine designers in determining the appropriate cable size for new equipment.

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## INTRODUCTION

Underground coal mine trailing cables are presently sized according to electrical ratings (*1*)[2] established for constant-current applications, despite the fact that mining equipment power requirements are intermittent. Equipment manufacturers maintain that the universal ampacity ratings constrain the machine designer unnecessarily, since these ratings do not account for the cyclic nature of face operations. In cooperation with the U.S. Mine Safety and Health Administration (MSHA), the American Mining Congress, and the Insulated Cable Engineers Association (ICEA), the U.S. Bureau of Mines proposed a research program with the overall purpose of facilitating the selection of a trailing cable size, given a particular level of loading at a specific duty cycle.

One facet of this project focused on relating current load to temperature rise in low-voltage cables operated in open air. The results (*2-3*) showed that these cables may be loaded on periodic bases with up to twice the continuous duty current without (1) exceeding average, rated, insulation temperature, (2) igniting coal dust accumulations, or (3) causing burns to personnel handling the cable. However, it was not known what effect increased amperages, hence increased operating temperatures, might have on useful trailing cable life.

Extreme mechanical abuse of cables is a characteristic of mobile equipment operation in underground coal mines, so much so that trailing cables rarely last a year in the coal-mining environment (*4*). This can be contrasted to most other industrial and commercial applications where useful cable life may exceed 20 years and is based essentially on thermal degradation. Ironically, the unfavorable mine circumstances may provide justification for increased cable operating temperatures. Since mine trailing cable failure occurs so quickly and is almost exclusively the result of mechanical abuse, small increases in operating temperature might have no significant impact on useful cable life underground. If safety is not compromised, such increases may allow larger horsepower machinery or, alternatively, smaller, more easily handled cables.

Given these potential benefits, the long-term effects of elevated temperatures on cable insulation and jacket performance were investigated. Accelerated-life testing of polymer samples confirmed that indeed, in underground coal-mining service, cables fail physically long before they deteriorate thermally (*5*).

An enormous amount of experimental data was analyzed by the Bureau to relate both current load to temperature rise, and thermal life to operating temperature. This material is available for reference at Bureau libraries (*2-3, 5*). In light of the success of these concurrent efforts, attention then focused on linking the results, i.e., establishing a correspondence between current load and useful thermal life. The degree of thermal deterioration in a cable and a safety factor might then be quantified, given the loading cycle and an acceptable service life. Such a methodology would be the realization of the overall program objective and have utility for both MSHA and mining machine designers in determining the appropriate cable size for new equipment.

In support of the Bureau's efforts to improve the general electrical safety in mines, this report presents a method that correlates cable thermal life with current loading based on the results of research performed at the Pittsburgh Research Center. The authors recognize that there are other concerns associated with mine trailing cable operation that are beyond the scope of this document. They are noted in the "Recommendations for Further Research" section.

## ACKNOWLEDGMENTS

The authors acknowledge with thanks the contributions of Anne Oyler, computer programmer, and Wayne Denlinger and Richard Roth, engineering technicians, Pittsburgh Research Center, who assisted in the analysis of the accelerated-life test results for cable jackets.

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

## TECHNICAL APPROACH

Cable insulation and jacket materials become elevated in temperature by the heat transfer that accompanies the flow of electric current. This exposure to higher temperatures leads to internal chemical changes, degradation, and eventually failure. The degree of thermal deterioration can be gauged through observation of mechanical and electrical properties. Cable life can be related to material temperature by the relationship (*6*)

$$L = \exp [(B/T) + A], \quad (1)$$

where $L$ = material life (time to reach minimum acceptable performance criterion),

$B, A$ = constants determined by activation energy of chemical reaction,

and $T$ = material temperature (constant over life).

Plots of accelerated-life test data, called Arrhenius models, are a graphical representation of the above relationship. They are used to predict useful life at specific operating temperatures based upon experimental results at relatively higher temperatures.

However, these models are not directly applicable to mine trailing cables in that such cables do not operate at a continuous, constant temperature throughout their service lives. Instead, these portable power cables are subjected to varying duty that is dependent, not only upon machine design, but also on geological and logistical factors underground. Under these circumstances, duty can be approximated by a series of operating intervals, each at a specific temperature and duration. From the Arrhenius relationship, Allen and Tustin (*7*) demonstrated that thermal loss of life at variable temperatures may be expressed as a summation of fractional loss-of-life increments,

$$L_T = \sum_{i=1}^{n} (t_i/L_i), \quad (2)$$

where $L_T$ = thermal loss of life,

$n$ = number of operating increments,

$t_i$ = time of operation at temperature $T_i$,

and $L_i$ = total available material life at temperature $T_i$,

obtained from Arrhenius model $L_i = \exp [(B/T_i) + A]$. The sum of these fractional increments equals unity when the material reaches the end of its thermal life, regardless of the sequence in which the various operating temperatures occur.

This relationship (equation 2) provides the key for correlating trailing-cable thermal life to variable load cycles. It has previously been used to predict useful life in analyses of electric-locomotive cable insulation (*8*). Thermal loss-of-life may be determined for any mine trailing cable when the loading is known. The calculated degree of thermal degradation can then be compared with actual service life to assist the mining machine designer in choosing the most efficient, yet safe, cable size.

## THERMAL FAILURE IN MINE TRAILING CABLES

Application of the incremental loss-of-life method (equation 2) to mine trailing cables requires knowledge, not only of a cable's thermal loading, but also of its accelerated-life characteristics, i.e., constants A and B. This information was obtained in previous Bureau research (*5*) for six low-voltage cables.

To determine the effects of elevated temperatures on the mechanical and electrical performance of mine trailing cables, insulation and jacket samples from four cable manufacturers were thermally aged in forced convection air ovens. At regular intervals over the test terms, samples were extracted and subjected to tests specified in ICEA Standard S-68-516 and Title 30 of the U.S. Code of Federal Regulations. For the ethylene-propylene-rubber (EPR) insulation samples, these tests included tensile strength, elongation at rupture, hot-creep elongation and set, insulation resistance, ac and dc dielectric breakdown, and ac and dc voltage. The following tests were applied to the chloroprene-rubber (CR), chlorosulfonated-polyethylene (CSPE), and chlorinated-polyethylene (CPE) jackets: flame resistance, tensile strength, elongation at rupture, set, tensile stress at 200 pct elongation, tear, tensile strength and elongation at rupture following oil immersion, and hardness. Characteristic variations over time were plotted for each aging temperature.

Arrhenius plots showed that 80 pct retention of tensile strength, 50 pct retention of elongation, and 50 pct retention of ac dielectric strength were determinants of thermal failure in the EPR insulation (*5*). With jackets, the factor first precipitating failure due to thermal degradation was dependent upon the material. For example, with CPE jackets, 80 pct retention of oil-immersion tensile strength was critical. With CR materials, the retention of 80 pct oil-immersion tensile strength and 50 pct tear properties was equally important. For CSPE jackets, retention of 50 pct of elongation at rupture and 80 pct of oil-immersion tensile strength was significant. Typical plots for insulation and jacket are shown in figures 1 and 2.

The accelerated life characteristics for insulation and jacket were then compared to determine the property having the greatest impact on trailing cable thermal life. This comparison is facilitated by plotting jacket and insulation aging data on one graph of life versus temperature. Conservatively, it was assumed that insulation temperature was equal to the temperature at the conductor-insulation interface. The jacket Arrhenius data were then converted to an equivalent conductor-insulation temperature by recognizing that the temperature rise above ambient at the conductor-insulation interface is approximately 1.33 times the insulation-jacket interface temperature rise above ambient. For example, if a jacket temperature of 110° C (230° F) is assumed, the conductor-insulation temperature is (110 - 20) × 1.33 + 20 = 140° C (284° F), at a standard mine ambient temperature of 20° C (68° F). A typical Arrhenius plot with both insulation and jacket data is shown in figure 3. Since the jacket temperature data were adjusted on figure 3, it is not appropriate to fit a straight line to these transposed points.

The composite Arrhenius analyses showed that, with the exception of the CPE-jacketed cable, jackets tend to degrade thermally before the EPR insulation. Consequently, for the cables with CR and CSPE jackets, oil-immersion tensile strength, elongation at rupture, and tear were the most critical properties. For the cable with the CPE jacket, oil-immersion tensile strength had the same significance as insulation tensile strength, elongation at rupture, and ac dielectric strength.

Equation 1 was then fitted to the jacket data by the least-squares method to determine the material constants A and B. These values are listed in table 1 and will be used to calculate consumed thermal life. Cables from four manufacturers are represented in table 1, with the No. 2 and both the 2/0 AWG sizes from the same manufacturer.

An attempt was made to determine the degree of thermal degradation in trailing cables actually used underground. Mine operators were solicited for donations of cables no longer considered usable in portable applications. Odd-length samples were subjected to the same end-of-life tests as conducted on thermally aged specimens. Two of these spent cables coincidentally featured insulation and jackets of the same chemical makeup as two of the specimens subjected to the accelerated life tests. The oil-immersion tensile strength and tear resistance of the CR-jacketed used cables were found to be comparable with that of the unaged jackets. This was also true of the elongation of the EPR insulation. Only the tensile strength of the used cable insulation exhibited appreciable degradation. No conclusions could be drawn from the conflicting results of these limited tests. The actual service life and the electrical load history of these samples were not known.

**Table 1.—Thermal aging characteristics of cable jackets**

| Cable size, AWG, and type | Jacket | Property | Material constants | |
|---|---|---|---|---|
| | | | A[1] | B |
| 6, 3-conductor, round, G-GC .... | CR | Tear ..... | -16.99 | 8,813 |
| 4, 4-conductor, round, W ..... | CPE | Oil-immersion tensile strength .. | -24.91 | 11,843 |
| 2, 2-conductor, flat, G ..... | CR | .. do..... | -11.17 | 6,763 |
| 2/0, 3-conductor, flat, G-GC .... | CR | .. do..... | -14.72 | 8,102 |
| 2/0, 3-conductor, round, G-GC .. | CR | .. do..... | -13.84 | 7,825 |
| 4/0, 3-conductor, round, G-GC .. | CSPE | .. do..... | -15.57 | 8,503 |

| | | | |
|---|---|---|---|
| AWG | American wire gauge. | G | Ground conductor. |
| CPE | Chlorinated polyethylene. | G-GC | Ground and ground-check conductors. |
| CR | Chloroprene rubber. | W | Without ground conductor. |
| CSPE | Chlorosulfonated polyethylene. | | |

[1]Value based upon life units of days.

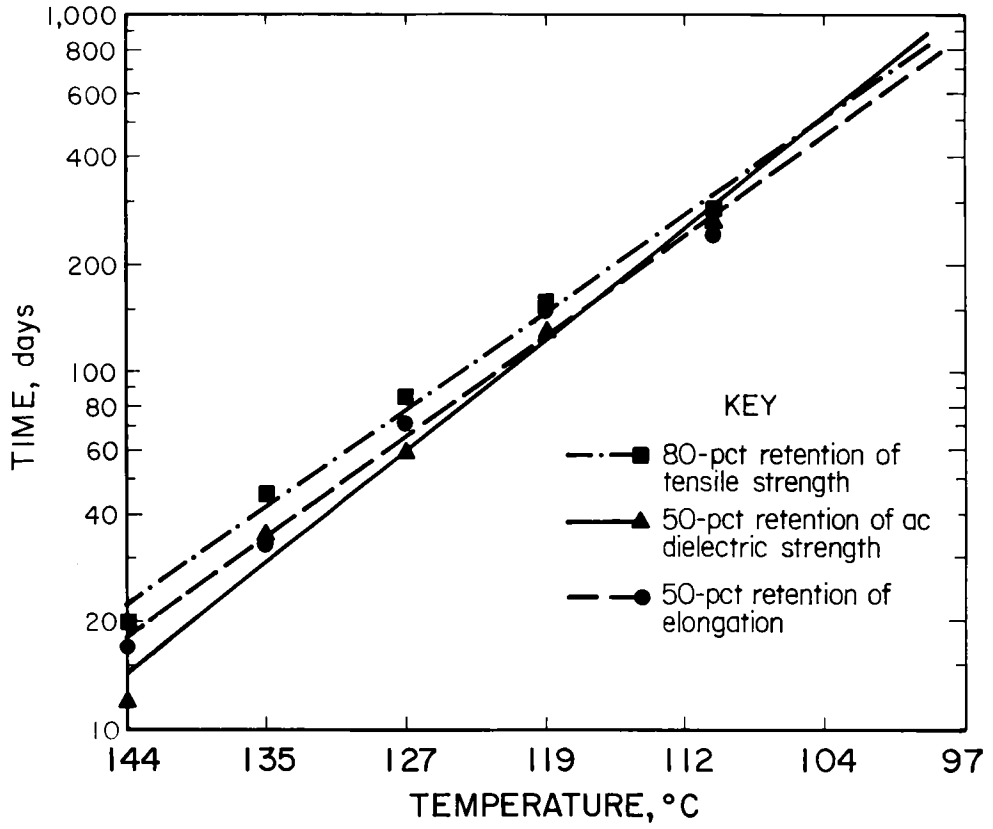



**Figure 1.—Arrhenius model for EPR insulation in 2/0 AWG, round, three-conductor, type G-GC cable.**

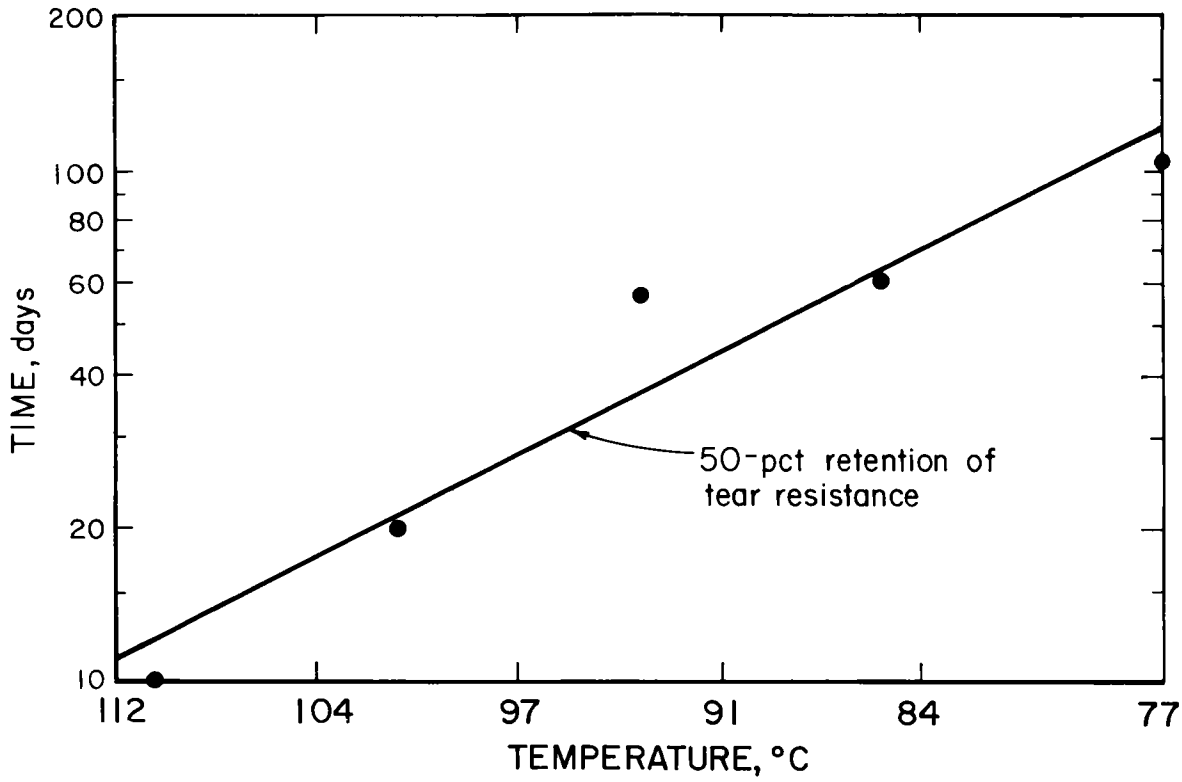



**Figure 2.—Arrhenius model for CR jacket in 2/0 AWG, round, three-conductor, type G-GC cable.**

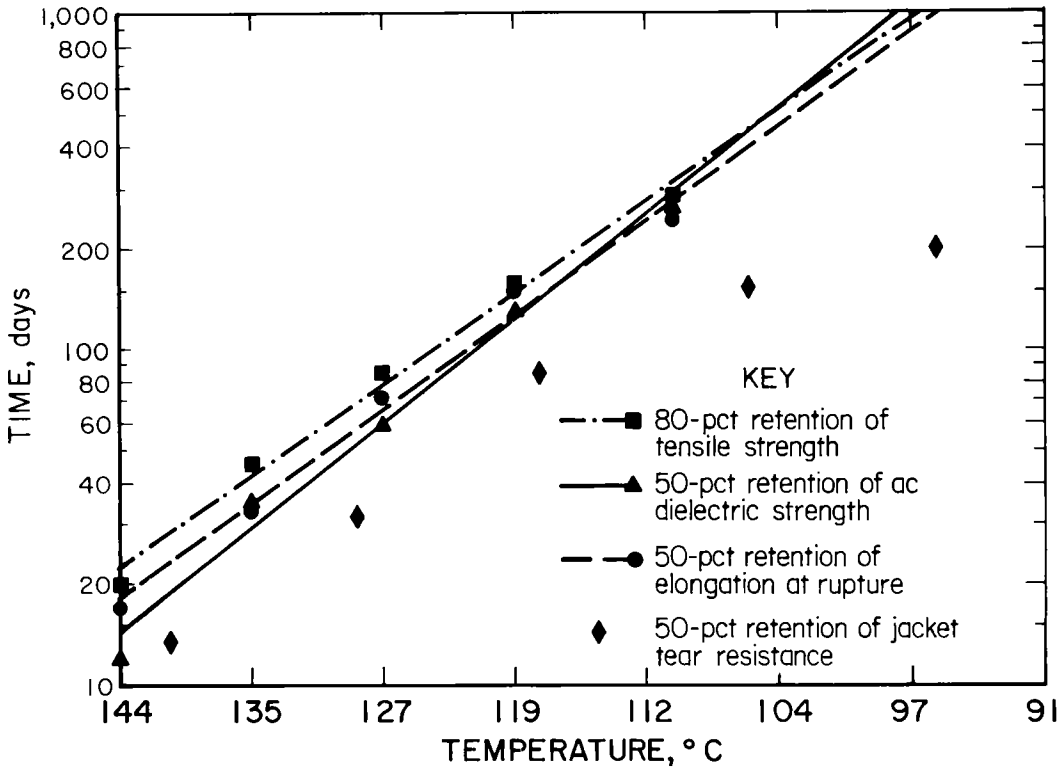



**Figure 3.—Composite Arrhenius plot for 2/0 AWG, round, three-conductor, type G-GC cable (tear data for jackets have been adjusted).**

## ELECTRICAL LOADING OF TRAILING CABLES

The Bureau has conducted research to determine the relationship between current load and temperature rises in coal mine trailing cables (*2-3*). Both shielded and unshielded portable power cables were continuously and periodically loaded with dc of various magnitudes. Temperature rises within and on the cables were measured with thermocouples, and the data recorded on a computer. A typical steady-state test result is shown in figure 4. Neglecting radiation and change in conductor resistance, cable temperature should rise and fall exponentially (*9*). Response can be predicted knowing the thermal time constants of heating and cooling. These constants represent a ratio of system heat capacity to the rate of heat transfer from the system. The thermal time constant, assumed to be independent of current magnitude, is defined here as the time to reach 63 pct of the final temperature rise. Cable time constants fixed the period for the subsequent duty cycle tests, conducted with "on" times of 25, 40, 50, 60, and 75 pct. A typical test plot is shown in figure 5. From these results, relationships between average temperature rise at the conductor-insulation interface and current load were established for each cable (fig. 6). These steady-state and duty-cycle tests represent operational extremes; equipment loading more closely resembles that shown in figure 7.

Numerous field investigations have been conducted to measure the actual loading applied to cables by portable equipment in underground coal mines. McNiff and Shepherd (*10*) evaluated and averaged the operating cycles of several shuttle cars. Stefanko, Sinha, and Morley (*11*) monitored the performance of 34 different face machines in four different coal seams. Their records show that

although mining machines work through a repetitive sequence of tasks, they are realistically subject to varying duty considering that current demand by a continuous miner is, in part, a function of coal hardness and seam impurities. Other operational variables include cutting height, cutting direction, and rate of advancement. Finally, the cycle period constantly changes as the distance from the working face to the shuttle car dumping point. Nevertheless, if machine loading can be represented as a series of short-term current steps, it is possible to predict cable temperature rise above ambient. By knowing the temperature at the beginning of each step and referencing the Bureau's load test results, the temperature at the end of the step may be calculated from a mathematical model of the cable's heat transfer behavior. Such a procedure is well suited for computer application as demonstrated by Mesina (*12*).

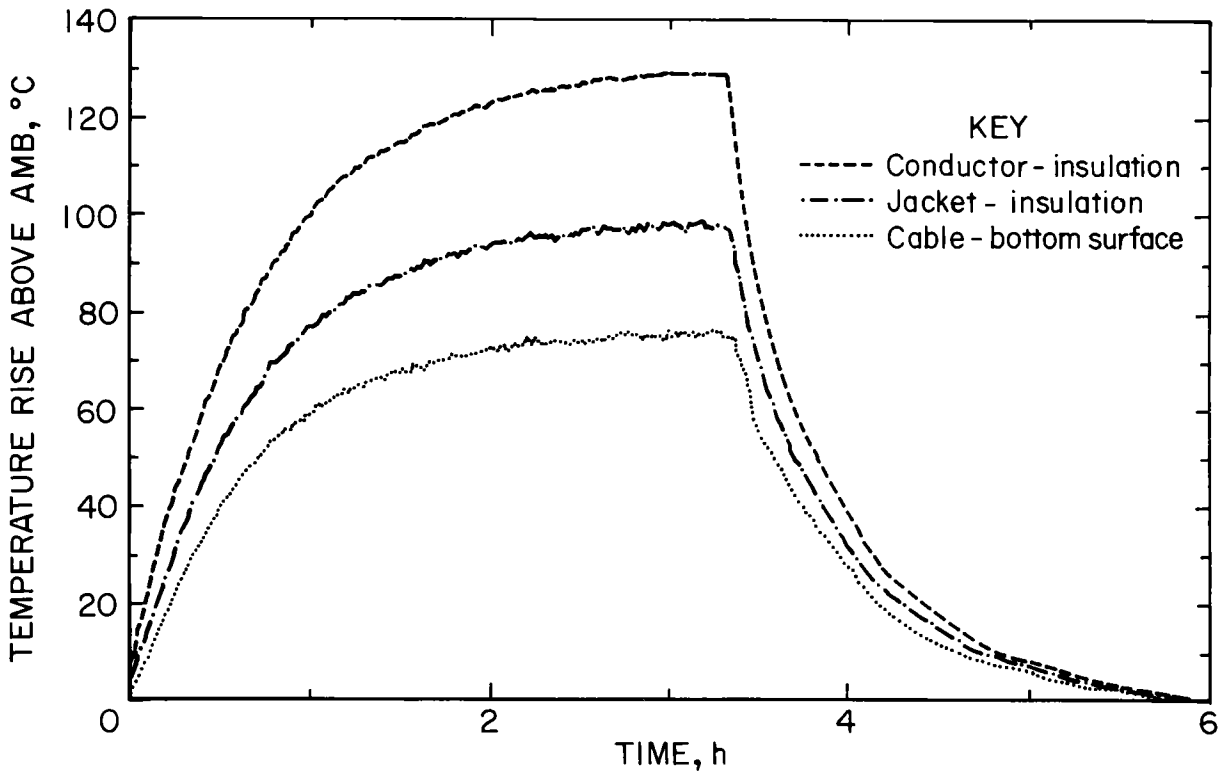



**Figure 4.—Temperature rise in 2/0 AWG, round, three-conductor, type G-GC cable loaded at 400 A.**

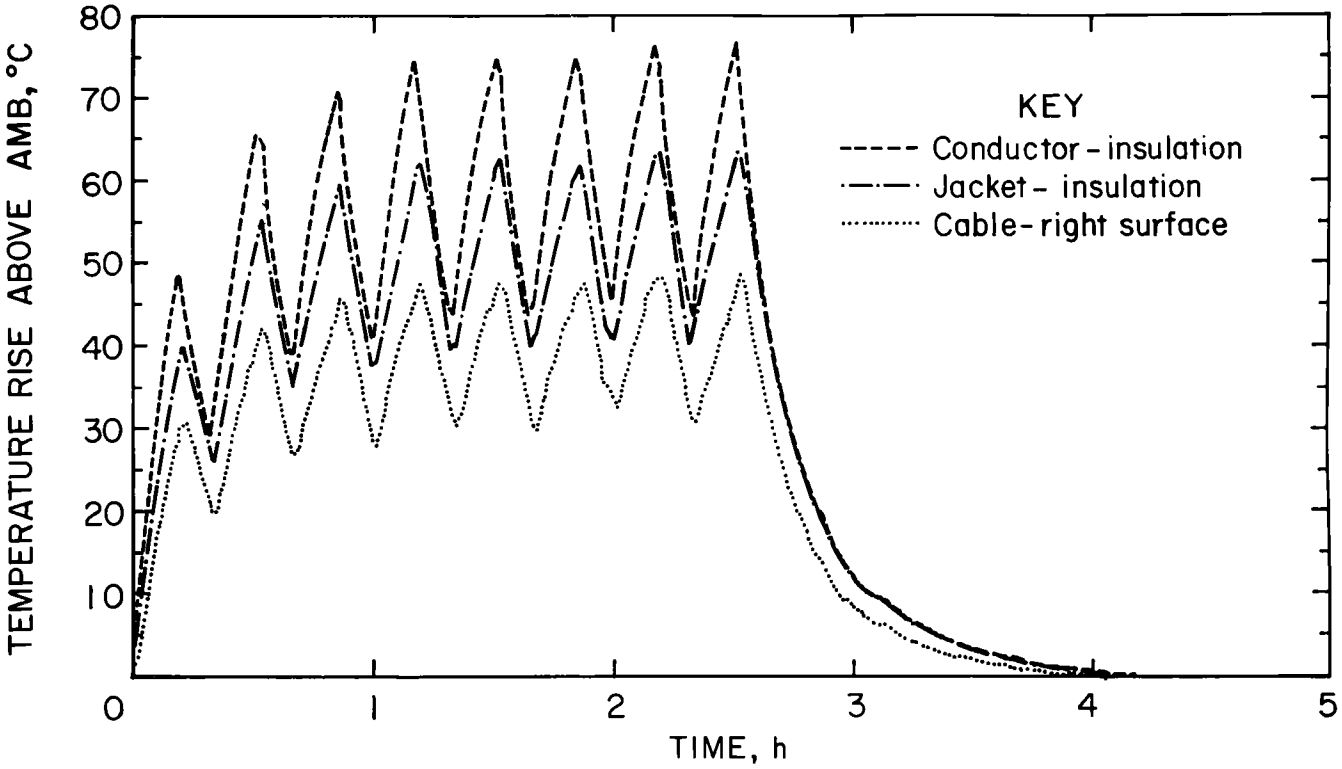



**Figure 5.—Temperature rise in 2 AWG, flat, two-conductor, type G cable loaded at 300 A for 60 pct of the time.**

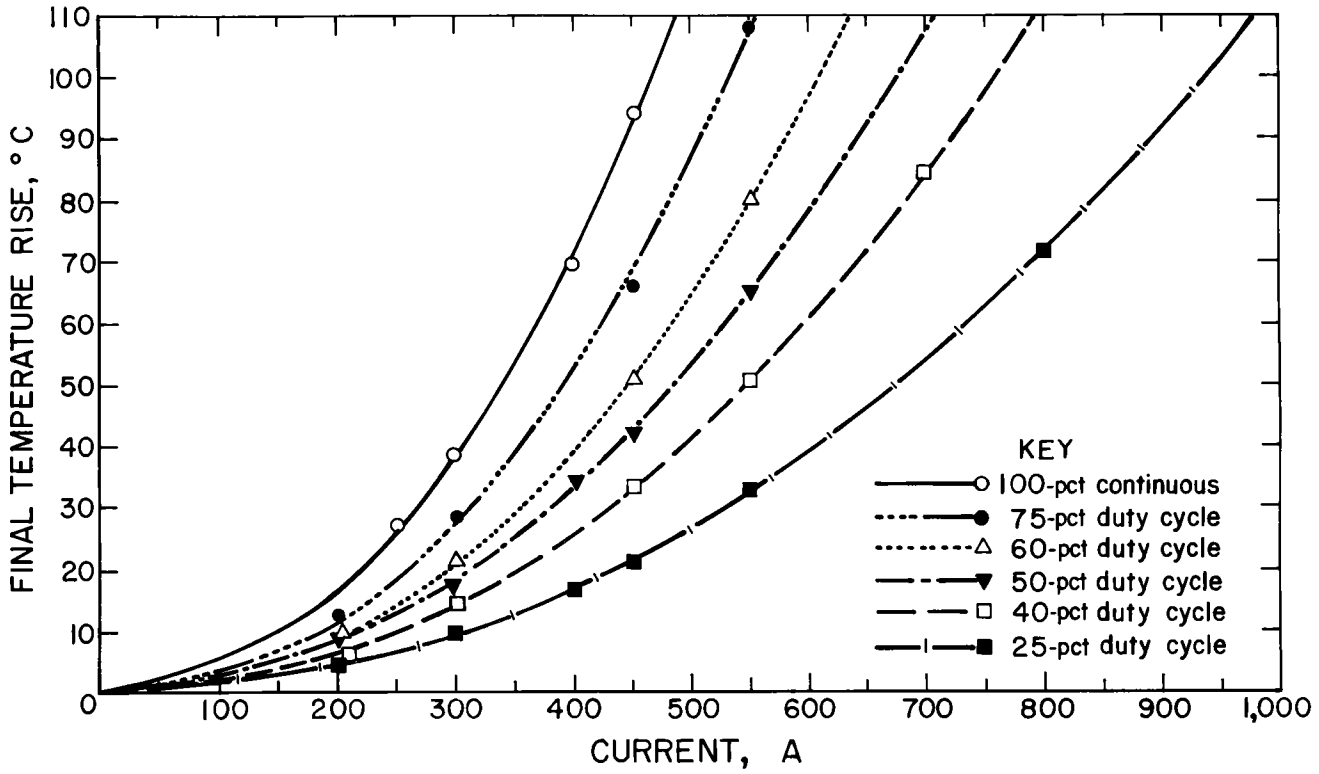



**Figure 6.—Average temperature rise above ambient of conductor-insulation interface in 4/0 AWG, round, three-conductor, type G-GC cable.**

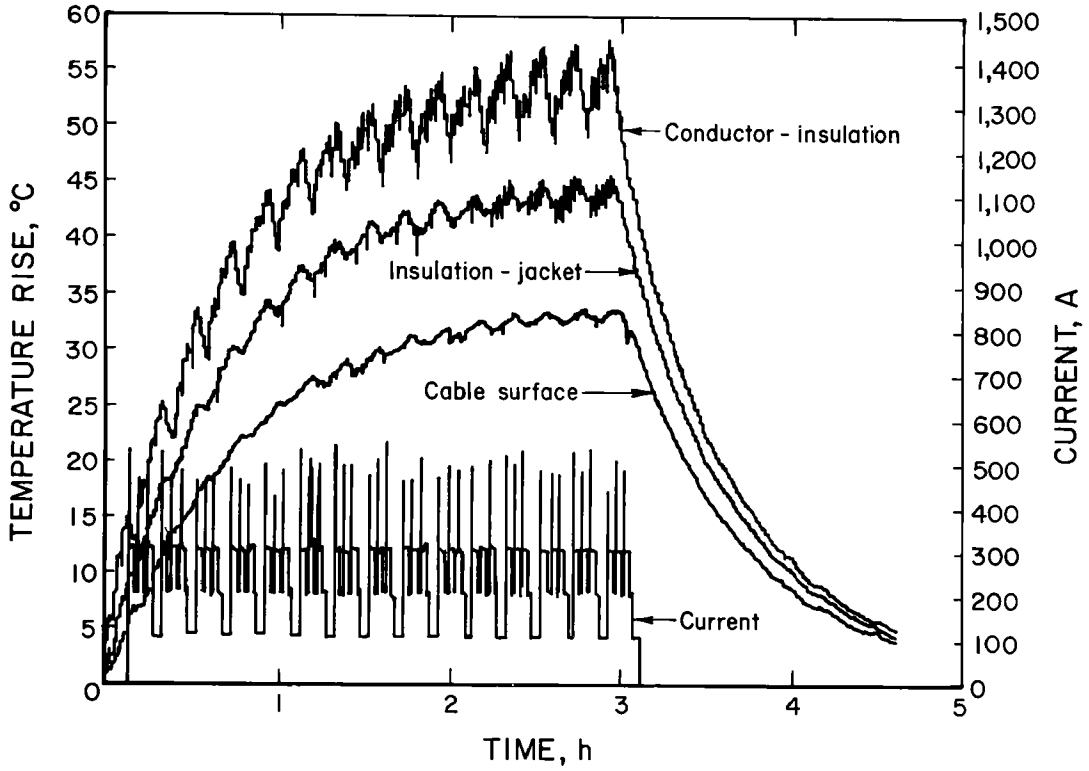



**Figure 7.—Simulated continuous miner load for 2/0 AWG, round, three-conductor, type G-GC cable.**

## CABLE THERMAL LIFE PREDICTIONS

The use of the incremental loss-of-life method to calculate consumed thermal life in trailing cables will be demonstrated for the case of a continuous mining machine. Stefanko and Morley (*13*) analyzed the idle and operating times of ac continuous miners in various coal seams. Averaging the data from nine machines with total motor ratings ranging from 150 to 400 hp, they found that 64 pct of the time the equipment was idle. Of the operational time, 54 pct was spent cutting and loading while the remainder was spent tramming. In addition, average currents during cutting and tramming were determined to be 373 and 90 A, respectively. Given this composite duty, several assumptions will be made, for demonstration purposes. First, it is assumed that during each of the machine functions, cable temperatures remain constant. A mathematical analysis of the accuracy of this supposition may be found in the literature (*14*). The resultant stabilized temperature at the insulation-jacket interface is obtained by referencing previous Bureau load test results (*2*) and assuming ambient temperature underground to be 20° C.

Percent consumed thermal life is then calculated using equation 3 for two sizes of a round, three-conductor, type G-GC (ground-check conductor) cable, each assumed to have the same jacket aging characteristics (A = -13.84, B = 7,825):

$$L_{CT} = \frac{t_i \times 100}{\exp\left[\left(\frac{7{,}825}{273 + T_j}\right) - 13.84\right]}, \qquad (3)$$

where $L_{CT}$ = consumed thermal life per shift at jacket temperature $T_j$, pct,

$t_i$ = portion of shift time spent at jacket temperature $T_j$, h,

and $T_j$ = jacket temperature, °C.

**Table 2.—Consumed thermal life per shift in round, three-conductor, type G-GC continuous miner trailing cables**

| Machine function | Time, h | Load, A | Insulation-jacket temperature, °C | | Consumed life per shift, pct | |
|---|---|---|---|---|---|---|
| | | | 2/0 AWG | 4/0 AWG | 2/0 AWG | 4/0 AWG |
| Idle, 64 pct of shift ..... | 5.12 | 0 | 20 | 20 | 0.0013 | 0.0013 |
| Cutting, 19 pct of shift .... | 1.56 | 373 | 108 | 65 | .1926 | .0141 |
| Tramming, 17 pct of shift .. | 1.32 | 90 | 27 | 26 | .0006 | .0006 |
| Total ..... | 8.00 | NAp | NAp | NAp | [1].1946 | [2].0160 |

AWG American wire gauge. NAp Not applicable.
[1]Total thermal life available, 513 shifts.
[2]Total thermal life available, 6,237 shifts.

As shown in table 2, with no load (machine idle), both insulation-jacket interface temperatures are at ambient (20° C), while with a light electrical load (machine tramming), jacket temperature rises in the two cables are approximately equal. However, during the cutting function, insulation-jacket temperatures increase dramatically, especially in the 2/0 American wire gauge (AWG) cable. The calculations demonstrate that this duty phase has the greatest impact upon thermal life. It should be noted that since the tramming function produces a temperature rise of 6° to 7° C, the jackets degrade at roughly twice the rate of an idle machine (*6*). Yet, consumed thermal life during idle time is about twice that while tramming, because time of exposure is quadrupled. Further, this example shows that the relative effects of cable size are dramatic; thermal life in the 2/0 AWG size is consumed at a rate 12 times that of the larger cable.

## CONCLUSIONS

A method was presented to quantify the impact of current load on the thermal life of portable power cables. This incremental loss-of-life technique may facilitate the selection of an appropriate trailing cable for a particular mining machine.

However, equipment designers should exercise care in using the technique. For example, referring to table 1, it is clear that cable jacket materials exhibit a range of aging characteristics (constants A and B). This is true not only among the various materials utilized for jackets, but also for the same generic material. The variability of A and B is probably reflective of the fact that cable polymers are custom blended by manufacturers to achieve particular cable qualities. Consequently, consumed thermal life as calculated for table 2 can be significantly different for cables of even the same gauge. The consumed thermal life calculations were based upon the conservative assumption that jacket material temperatures are equal to the temperature at the insulation-jacket interface.

Also, it is important to note that the calculated cable thermal life should be compared with the actual service life underground. For instance, the performance history at a mine may indicate that cables last only 300 shifts before damage from accumulated mechanical abuse makes them unusable. This may justify the choice of a smaller cable with a suitable thermal-life safety factor.

## RECOMMENDATIONS FOR FURTHER RESEARCH

The hypothetical example used to demonstrate the incremental loss-of-life method was based upon simplistic premises. Aside from normal machine functions, there are other factors to consider that may impact the thermal life of trailing cables. These include transient events such as motor starts, overloads, and short circuits that result in large conductor temperature excursions over short time periods. Such occurrences shorten the thermal life of cable insulation and jacket; in the extreme, they can cause immediate cable failure. Consequently, the Bureau plans to investigate the thermal characteristics of short-circuited and overloaded cables and define the current time envelope for safe operation.

As stated previously, the prediction of instantaneous cable temperatures for complex duty cycles is readily accomplished by computer from a mathematical model of the cable. MSHA and the Bureau have proposed a scope of work to support the development of a computerized model for portable power cables; a tentative model has been described (*12*). Such a tool would assist the equipment designer and also MSHA in approving cables for new mining equipment. However, there exists no means

to guarantee that the cables, once underground, will not be operated beyond safe limits.

To ensure that cables are not misapplied requires a protection system that accounts for all aspects of operation. A microprocessor-based sensor is envisioned with programmable response for flexibility in use. The protective device should act to interrupt power instantaneously if cable jacket temperatures exceed coal dust or methane ignition thresholds. In addition, the device should have the ability to integrate temperature rise over time to protect against cable failure due to thermal degradation of the insulation and jacket.

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