# Mechanical Performance of Thermally Aged Trailing-Cable Insulation

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*Abstract*— As part of an overall effort relating cable life and current load, the Bureau of Mines conducted research to determine the effects of elevated temperatures on the mechanical performance of coal mine trailing cable insulation. Insulation samples from six low-voltage unshielded portable power cables were thermally aged in air ovens. The specimens were exposed to constant temperatures ranging from 230 to 290° F for periods up to 10 months. At regular intervals over the test terms, samples were extracted and subjected to mechanical tests in accordance with Insulated Cable Engineers Association Standard S-68-516. These tests included tensile strength, elongation at rupture, hot creep elongation, and set. Characteristic variations over time were plotted for each aging temperature. Arrhenius (useful life) graphs showed that 80 percent retention of tensile strength and 50 percent retention of elongation were equally critical determinants of thermal degradation. Extrapolation to 90° C yielded useful lives ranging from 4.4 to 7.5 years for the cables evaluated. The findings support the tentative contention that, in service underground, cables fail mechanically long before they deteriorate thermally.

## INTRODUCTION

THE Bureau of Mines was approached by the American Mining Congress (AMC) concerning current federal electrical ratings of trailing cables. Equipment manufacturers, many of whom are members of the AMC, maintained that the current regulations are unnecessarily restrictive since they do not account for the cyclic nature of current consumption in mining. At a meeting at the Bureau's Pittsburgh Research Center (PRC), representatives of the AMC, the Mine Safety and Health Administration (MSHA), and the Bureau agreed to investigate the relationship between current loads and resultant temperature rises in coal mine trailing cables. Initial research results [1] indicated that, indeed, the cable current-carrying capacities, or ampacities, specified in the *Code of Federal Regulations* [2] could be increased without exceeding rated cable insulation temperature. However, it was not known what effect increased ampacities might have on useful trailing cable life.

Extreme mechanical abuse of cables is inherent with mobile equipment operation in underground coal mines. Cables are abraded against the coal rib, run over, and pulled apart at splice points. The net result is that trailing cables rarely last a year in the coal mining environment [3]. This can be con-trasted to most industrial and commercial applications where useful life may exceed 20 years and is based for the most part on thermal degradation.

Ironically, these unfavorable circumstances may provide justification for increased cable operating temperatures. Since trailing cable deterioration is almost exclusively the result of mechanical degradation, small increases in operating temperature (hence thermal degradation of the polymers comprising cable jacket and insulation) might have no impact on useful cable life underground. If safety is not compromised, such increases may allow larger horsepower machinery or, alternatively, smaller cables. In turn, lighter cables are more easily handled whether reeled by equipment or dragged by miners. Given these potential benefits, the Bureau proposed to determine the long-term effects of elevated temperatures on cable performance.

This report documents preliminary research, performed at the Pittsburgh Research Center, correlating mechanical performance of trailing cable insulation with exposure to long-term elevated temperatures. The authors recognize that there are other concerns associated with higher temperature operation that are beyond the scope of this report. They are summarized in the "Ongoing Research" section.

## BACKGROUND

The basic components of a portable power cable are the electrical conductors, insulating material around each conductor, filler material that may be needed to maintain a stable geometric configuration, and outer jacket. The insulating material that covers each of the individual conductors has as its primary function the prevention of electrical contact between the conductors. Consequently, the insulation, typically ethylene–propylene–rubber (EPR), must remain electrically stable in the range of applied voltages. It must also resist thermal degradation, which could possibly occur as a result of conductor heating at excessive current levels. These two requirements form the basis for the selection of the polymeric composition of conductor insulation.

Since the insulation is in intimate contact with the metallic conductors, it becomes elevated in temperature by the heat transfer that accompanies the flow of electrical current. Designers of electrical apparatus have long recognized that this has an impact on the apparatus life. Efforts relating exposure temperature to life date back at least 75 years. For example, in 1913 Steinmetz and Lamme [4] demonstrated that insulation deteriorates over a period of time at a fixed temperature. In 1930 Montsinger [5] advanced the concept of mechanical fail-

ure as an end-of-life criterion for insulation. In 1945, Moses [6] coined the empirical "10 degree rule." This rule of thumb stated that thermal life of insulation is halved for each increase of 10° C (subsequently this was refined to the range of 7 to 10° C).

Modern theory was fathered in 1948 by Dakin's classic paper [7] on thermal deterioration. His work was based upon the chemical rate equation devised by Svante Arrhenius, a Swedish physical chemist. This was a logical approach since the observed physical changes are a reflection of internal chemical change. Thus it not only provided a satisfactory expression but resulted in a more exact measure of deterioration than the 10° C rule. This relationship takes the form

$$L = A \exp [B/T] \tag{1}$$

where

$L$       life
$A$ and $B$   constants determined by the activation energy of the particular reaction

and

$T$      temperature in K

Taking the logarithm of both sides

$$L = \ln A + B/T. \tag{2}$$

Thus if the log of life of the insulation is plotted against the reciprocal of the absolute temperature, a straight line should result. This relationship was generally confirmed except where second- and higher-order chemical reactions entered into the aging phenomena.

With accelerated life testing, the rate of degradation of an item leading to "old age" or "wear-out" is increased. This is accomplished by increasing the stress exposure or the rate of stress exposure. The survival time or degradation rate at the elevated exposure level is equated to normal exposure levels through a mathematical expression (2). For example, exposing a cable to an elevated temperature will increase the rate of the molecular processes that cause degradation of the material constituents. For the insulation, such degradation includes embrittlement, which can lead to fracturing or, ultimately, disintegration. This can occur at normal operating temperatures but over a much greater time span. The resultant plot of (2) is termed an Arrhenius model and is used to predict useful life at operating temperatures based upon experimental results at relatively higher temperatures.

Arrhenius models for EPR insulation have been developed for many cable applications ranging from electric locomotives [8] to submarines [9]. Also, cables intended for use in nuclear power plants must be subjected to accelerated life tests as specified in IEEE Standard 383 [10]. These results are well documented in the available literature.

Such models, however, are not translatable to the mining environment. The portable power cables used in underground coal mines, as opposed to most other industrial and commercial applications, are constantly moved about. Consequently, they are designed for maximum flexibility using a custom blend of ingredients, typically ethylene and propylene with plasticizers added for flexibility. This mix alters insulation characteristics such that models for other applications cannot be used. In addition, most accelerated life tests of EPR insulation have traditionally employed elongation as the sole end-of-life criterion. However, the environment of the working face is unique with contaminants such as water and hydraulic fluid and hazards from coal dust and methane accumulations. Consequently, the time to thermal failure in the laboratory may be shortened by focusing on additional cable insulation qualities. Accordingly, an experimental approach is necessary to relate trailing cable life to steady-state temperature.

## TECHNICAL APPROACH

To develop an Arrhenius model, several concerns must be addressed, among them how to induce thermal aging. Portable power cables could experience thermal deterioration when loaded with electrical current. This simulates actual service conditions and provides an opportunity to correlate steady-state current with conductor, insulation, and jacket temperatures. Further, it tests the compatibility of adjacent materials such as EPR and neoprene that may comprise the insulation and jacket. However, if the power conductors are the source of heat, radial and circumferential temperature gradients within the insulation and jacket would cause nonuniform degradation and an increased scatter in the test results. This would hinder extrapolation of life at high temperatures to that of actual mining duty.

IEEE Standard 99 [11] recommends that aging of insulation be conducted in an oven to provide consistent control and recording of temperature exposure. This method regulates chemical degradation quite well by maintaining a constant temperature throughout the specimen. Also, it appears to be a universally accepted method as documented by recent research on aging. Therefore it was employed in this project.

Recommended performance specifications for electrically heated forced-convection ovens used for the laboratory evaluation of electrical insulation are contained in American Society for Testing and Materials (ASTM) Standard D-2436 [12]. Two identical air ovens (Fig. 1) were procured and comply with the temperature regulation recommendations of this standard. These units are fully adjustable from near ambient to 300° C and are equipped with a digital temperature display and an adjustable high-limit control. They also have an adjustable filtered fresh air intake, forced interior circulation, and forced exhaust capable of between 100 and 200 air changes per hour. This ventilation rate is necessary to facilitate thermal degradation; oxygen within the chamber must be replenished to ensure that the chemical reactions associated with aging proceed unhindered. Steffens [13] warns that lower rates extend insulation life unrealistically.

Since the results of this research will be scrutinized by the trailing cable industry, the end-of-life tests selected must facilitate interpretation of the findings. The choice of subjective custom tests, no matter how well conceived and justified, will not foster acceptance of the results. Consequently, only those tests that are customarily performed by the portable power cable industry were considered. Tests meeting this criterion
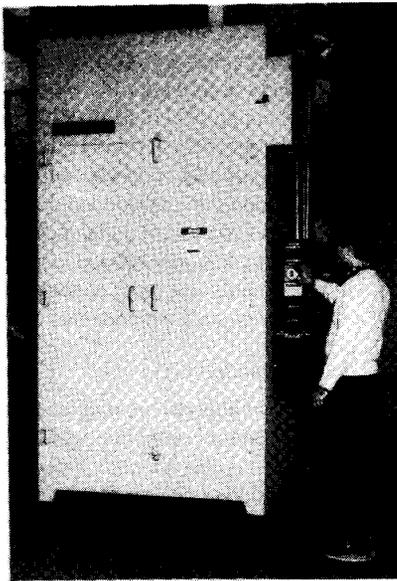
Fig. 1.   Air oven with forced exhaust.

are contained in the standards of the Insulated Cable Engineers Association (ICEA), whose members include trailing cable manufacturers. Detailed test procedures for newly manufactured EPR-insulated cable are contained in ICEA Publication No. S-68-516, "Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy" [14]. They include tensile strength, elongation at rupture, hot creep elongation, and hot creep set.

Tensile strength and elongation, conducted simultaneously [15], serve as indices of flexibility, a critical property in underground service. They relate to the ability of the insulation to withstand bending without physical cracking, which can allow moisture entry and ultimate electrical failure. The hot creep tests measure the degree of crosslinking or heat resistance of a polymer [16].

## Test Plan

According to Occhini et al. [17], more reliable results are obtained from end-of-life tests on full-scale extruded cables or on samples thereof. This is preferable to using raw materials obtained from polymer suppliers. Cable processing results in molecular reorientation, residual stresses, shrinkage after extrusion, and microvoids, all of which can have an important influence on the cable behavior. Accordingly, six low-voltage unshielded trailing cables of size and type representative of industry usage were procured for evaluation:

1) round, type G-GC, 3/C, 6 AWG, 2000 V
2) round, type W, 4/C, 4 AWG, 2000 V
3) flat, type G, 2/C, 2 AWG, 600/2000 V
4) round, type G-GC, 3/C, 2/0 AWG, 600/2000 V
5) flat, type G-GC, 3/C, 2/0 AWG, 600/2000 V
6) round, type G-GC, 3/C, 4/0 AWG, 2000 V.

Type G-GC cables feature both ground and ground-check conductors, while type G cables have only ground conductors. Type W cables have neither ground nor ground-check conductors; one of the power conductors is used as a ground conductor.

Four manufacturers and two types of EPR insulation are represented [14]. Type I is softer and more flexible with lower tensile strength and higher elongation. Type II is a newer design with higher tensile strength and lower elongation requirements.

These cables could have been aged in ovens as received, or insulation test specimens could have been prepared prior to aging. The latter option was exercised by many researchers [8], [9], [18], [19]. Since thermally aged material can exhibit a degree of embrittlement that impedes insulation sample preparation, it was deemed prudent to prepare end-of-life specimens prior to oven insertion.

Aging duration was carefully selected to minimize errors in extrapolating thermal endurance data, while adhering to a reasonable project schedule. IEEE Standard 98 [20] cautions that significant errors may result if the end of useful life is reached in less than 100 h. It recommends maximum terms of more than 5000 hours. Brancato [21] states that to obtain a life-temperature characteristic curve, a year of experimental time is required. With two ovens available to expedite the work, a maximum aging term of 10 months was chosen.

Next, the range of aging temperatures was selected. As noted, Arrhenius plots yield straight lines only if a single chemical reaction predominates over the range of temperatures utilized. Arrhenius plots of EPR insulation in medium- and high-voltage cables display a knee at about 165° C, implying differing reaction rates above this point [17]. Tests were conducted to determine this threshold for the EPR insulation used in coal mine trailing cables. Insulation samples were suspended in the oven chambers with the temperature set initially at 125° C. Following exposure for 4 h, the samples were removed and examined. Four-hour heating tests continued with oven temperature increasing in 5° increments. At 170° C, gross changes were manifested through softening and deformation. Consequently, high temperature test terms exceeding 100 h were conducted well below this limit.

Alternately, IEEE Standard 99 [11] recommends that the lowest aging temperature should not exceed by more than 20° C the temperature to which the results will be extrapolated. Since EPR-insulated trailing cables are rated for 90° C operation, the lowest test temperature was chosen to be 110° C (230° F). In accordance with recognized standards [11], [20], a total of five test temperatures were employed, each separated by 8.3° C (15° F). This assured an accurate extrapolation to lower temperatures and provided a check on the basic assumption that a linear relationship exists between the logarithm of time and the reciprocal absolute temperature. Applying the "10 degree rule," as the temperature was increased, the test term was approximately halved. Since it was not known when the end of useful life would be reached at a certain temperature, 20 percent of the samples were removed from the oven at regular intervals and subjected to the mechanical tests. This test program is depicted in Table I. Thus oven A was employed for 10 months exclusively for aging at 230° F, while oven B was used simultaneously for shorter term tests at higher temperatures. For example, following removal of the final fifth

TABLE I
THERMAL-AGING SCHEDULE

| Oven/ | | | | | Time, months | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| °F | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| A/230 | | | X | | X | | X | | X | | X |
| B/245 | | X | X | X | X | X | | | | | |
| B/260 | | | | | | | X X X X X | | | | |
| B/275 | | | | | | | | | | X X X X X | |
| B/290 | | | | | | | | | | | XXXXX |

Note: X denotes when samples were extracted from ovens.

batch aged at 245° F, oven B was reloaded with unaged samples and the temperature was increased to 260° F.

Since standardized test equipment was not available at PRC to conduct the mechanical end-of-life tests, the services of a commercial laboratory were obtained via a service contract. The test specimens were prepared from cables supplied by the Bureau prior to insertion in the air ovens. As a control, mechanical tests were then conducted on an unaged sample batch. The samples were identified by a three-digit code denoting cable type, aging temperature, and order of batch pull. Oven temperature was recorded hourly by a 32-channel datalogger. To preclude mechanical and thermal damage during shipment, aged samples were transported from the Bureau to the commercial lab by van.

## TEST RESULTS

Each batch, aged at a specific temperature for a specific term, contained a sufficient number of samples to perform each mechanical test three times on each individual conductor's insulation. The results, for all the conductor insulations within a specific cable, were then averaged as recommended by IEC Standard 216-1 [22]. Since the cables evaluated consisted of 2, 3, or 4 conductors, each datum is the average of 6 to 12 tests. The mechanical results were plotted versus time, and typical data are shown in Figs. 2–5 for the flat #2 cable. Polynomial curves were then fitted to the tensile strength and elongation data of each aging temperature.

Both tensile strength and elongation followed a repeatable pattern over time as aging temperature increased. Tensile strength typically declined slightly, then increased, and finally decreased precipitously for all the cable insulations. A similar phenomenon was observed with cables on submarines [9] and was attributed to additional curing of the polymer. In general, elongation at rupture declined slightly, then more steeply after leveling.

Characteristic curves were not discernible from the hot creep set data. Most of the results at 230° F oscillated near zero, while those at 260° F generally increased positively. The majority of the data at the higher temperatures was zero. There was similar nonconformity in the hot creep elongation data. Consultations with engineers at several cable companies did not reveal a suitable explanation. Perhaps aging terms were too short or, more likely, hot creep tests simply are not a good gauge of thermal deterioration as evidenced by their absence in past aging research.

Consequently, only the tensile strength and elongation data were analyzed further to develop Arrhenius plots. Examina-
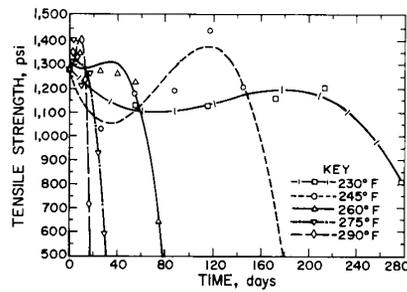


Fig. 2.   Tensile strength variation over time at constant temperatures for #2 flat cable.
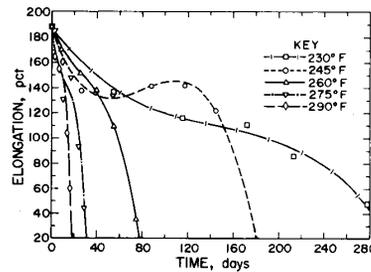


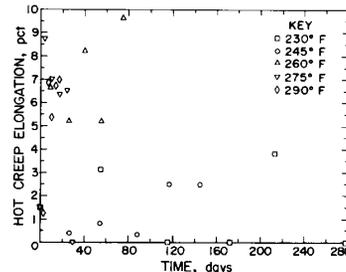Fig. 3.   Elongation variation over time at constant temperatures for #2 flat cable.



Fig. 4.   Hot creep elongation variation over time at constant temperatures for #2 flat cable.
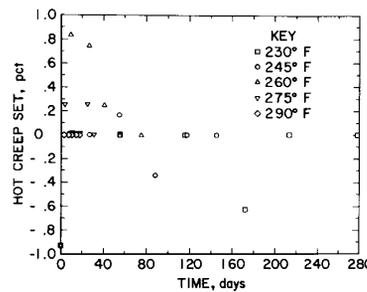


Fig. 5.   Hot creep set variation over time at constant temperature for #2 flat cable.

tion of the curves of Figs. 2 and 3 shows that failure is imminent once tensile strength or elongation begins to rapidly decrease, irrespective of its magnitude. Thus end-of-life can be more appropriately expressed as a fixed percentage of the unaged value rather than an absolute value. In previous research [9] this point was placed below the knee of the curves. Examining Figs. 2 and 3 resulted in the selection of 80 and 50 percent for tensile strength and elongation, respectively,
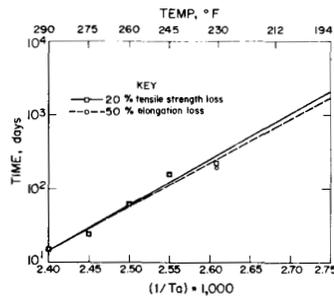
Fig. 6.   Arrhenius plot of #2 flat cable.

both of these levels having precedence. The 80-percent retention level of tensile strength was employed in previous aging research [19], while 50-percent retention of elongation has been judged [23] a conservative level where insulation cracking should not occur during flexing.

The intersection of the 50 and 80 percent levels with the constant aging temperatures curves of Figs. 2 and 3 yielded five time-temperature data points for both tensile strength and elongation. Transfer of those data to graphs where the log of life is plotted against the reciprocal of the absolute temperature resulted in Arrhenius plots (Fig. 6 for the #2 flat) for each cable. The straight lines fitted to the tensile strength and elongation data are nearly coincident, indicating that the selected end points have mutual criticality. Upon extrapolation to 90° C ($1/T \times 1000 = 2.75$), the plots yielded insulation lives ranging from 4.4–7.5 years for all the cables evaluated.

## CONCLUSION

The Arrhenius graphs showed that 80-percent retention of tensile strength and 50-percent retention of elongation were equally critical indications of thermal degradation. Previous research on aging [18], [23] concluded that Arrhenius evaluations result in conservative estimates of cable life at actual operating temperatures. However, the presence of contaminants such as acidic water and hydraulic fluid underground may well have an opposing effect. Consequently, the projected lives derived from the Arrhenius extrapolations are considered realistic.

The range in useful lives of 4.4–7.5 years at rated 90° C operation may stem from the fact that all trailing cable insulations are custom-blended proprietary mixes. In some cases, manufacturers may intentionally sacrifice thermal life in favor of superior performance in another aspect of operation, e.g., dielectric strength. Nevertheless, the overall findings support a broad tentative conclusion that mining trailing cables fail physically long before they have deteriorated thermally. Accordingly, based upon the mechanical performance of thermally aged insulation, it appears that portable power cables may be loaded above rated temperature. For example, referring to Fig. 6, if the #2 flat cable is operated at 100° C continuously, it will have a useful life of 2.7 years before deteriorating thermally. This is twice the actual life of mechanically abused cables underground. Considering that mine cables are not loaded continuously, the levels of allowable cyclic loading may be increased even further to the extent that smaller cables or greater horsepower machinery are possible. However, such

conclusions must remain preliminary until investigations into other aspects are completed.

## ONGOING RESEARCH

The end-of-life criteria used in this report for thermally aged cables were restricted to mechanical performance evaluations of the insulation. This is important as the insulation must remain flexible throughout its service life underground. Nevertheless, the primary function of the insulation is to prevent current flow among conductors and so it must have high dielectric strength. Several tests are specified by the ICEA [14] to measure this quality. They include water absorption, insulation resistance, and ac and dc voltage tests. Space limitations within the ovens precluded the simultaneous aging of samples for all these electrical tests. Consequently, electrical sample aging was initiated following the aging of specimens for mechanical tests.

Aside from insulation, another key polymeric cable component is the outer jacket that physically protects the internal structure. Cable jackets must have adequate tensile strength as well as resistance to moisture, heating, chemical attack, cutting, abrading, tearing, and impact damage. Applicable tests include tensile strength, elongation, tensile stress, set, tear, oil immersion, and flame resistance. Currently, thermally aged jacket samples from the same cables evaluated in this report are undergoing these end-of-life tests.

Arrhenius plots will be derived from these additional evaluations and compared to the plots of this report. This will ensure identification of the criterion that first precipitates thermal failure. Only then can definitive recommendations be made regarding maximum cable operating temperature.

In addition, mine operators were solicited for donations of trailing cable that were considered unusable. Odd length samples are being subjected to the same end-of-life tests as conducted on thermally aged specimens to determine the degree of thermal degradation.

Once the relationship of useful life and temperature has been confirmed, it will be coupled to concurrent work involving current load and temperature rise to derive a correspondence between current load and useful life. Ultimately, deterioration can be integrated over a variable load cycle to predict useful life, given the load characteristics of a particular machine. The mathematics of this technique were developed for general use by Whitman and Whitman [24] and have been applied successfully to electric locomotive cables [8], medium-voltage power cables [23], and metalized paper capacitors [25].

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