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Thermal Characteristics of Energized Coal Mine Trailing Cables

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	in	inch
°C	degree Celsius	min	minute
°F	degree Fahrenheit	mm	millimeter
ft	foot	mV	millivolt
ft^2	square foot	pct	percent
ft/min	foot per minute	V	volt

THERMAL CHARACTERISTICS OF ENERGIZED COAL MINE TRAILING CABLES

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

ABSTRACT

The Bureau of Mines conducted research to determine the relationship between current load and temperature rises in coal mine trailing cables. Six low-voltage, unshielded, portable power cables were continuously and intermittently loaded with direct current of various magnitudes. Temperature rises within and on the cables were measured with thermocouples, and the data were recorded with a computer. Thermal time constants were calculated, which fixed the periods of the duty-cycle tests. Relationships between average temperature at the conductor-insulation interface and current load were established. The steady-state and intermittent currents that produce a 90° C average conductor-insulation temperature were then determined. Comparisons with Insulated Cable Engineers Association (ICEA) steady-state ratings revealed that 10 to 25 pct more current than recommended ICEA ampacities is required to reach rated insulation temperature. Examination of the maximum intermittent temperatures attained showed that autoignition of coal dust and burn injuries to personnel handling the cable would not be concerns if the temperature at the conductor-insulation interface averaged 90° C.

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INTRODUCTION

Mobile mining equipment has been a key element in underground coal production since the advent of mechanization in the early 1900's. Historically, this mobile equipment has been powered by electricity, tethered to the mine power system by portable trailing cables. These cables act as the machine's umbilical cord, the lifeline to the electrical distribution system, maintaining electrical system integrity within harsh surroundings. Although trailing cables are subject to severe service and mechanical abuse, they are expected to maintain system continuity without question. Personnel constantly handle cables during a normal workday with little thought of any potential danger (fig. 1). Coal dust accumulations may be ignited by heat or sparking, if the cable insulation should fail. In these surroundings, the proper selection and rating of trailing cables is critical, and an optimum balance of mechanical strength and electrical performance is required in any selected cable.

The foremost criterion used in the selection of cable size for any application is the current-carrying capacity (ampacity) of the cable's electrical conductors. The continuous ampacity ratings that are specified for underground coal mines are periodically revised to reflect the impact of technological improvements (such as increases in the temperature rating of insulation). The basic objection to the present standards stems from the belief of many in the mining industry that the selection of cable sizes should be based upon the level and duration of currents or duty cycles that are impressed upon them, rather than on continuous ratings. Further differences of opinion center around the nebulous origin of the existing ampacity tables, the applicability of derating factors to reeled cables, and nuisance tripping of short-circuit protection based on cable size.

These problems were brought to the attention of the Bureau of Mines by the American Mining Congress (AMC) at a meeting also attended by representatives of the U.S. Mine Safety and Health Administration (MSHA). The AMC contended that present trailing cable ampacities, as defined by MSHA, are somewhat restrictive in that they do not consider the cyclic nature of current consumption in mining. In the past, as machine horsepower increased, cable size increased to accommodate larger currents. Practical size limits have been reached today and are dictated by reel capacity and by the weight that miners can easily handle underground. Given greater horsepower demand, what is needed is a firm basis upon which the machine designer can justify increased intermittent loading of existing trailing cable sizes.

These concerns prompted the Bureau to propose a long-term in-house research program with the overall purpose of facilitating the selection of trailing cable size, given a particular level of loading at a specific duty cycle. Ultimately, the results of this comprehensive study are to be presented graphically for reference by both MSHA and mining machine designers in determining the appropriate cable size for new equipment.

This report documents preliminary research performed by the Bureau, correlating steady-state and cyclical loading with resulting temperature rise in six low-voltage unshielded trailing cables representative of industry usage. The investigation of other concerns associated with higher current loading is beyond the scope of this report.

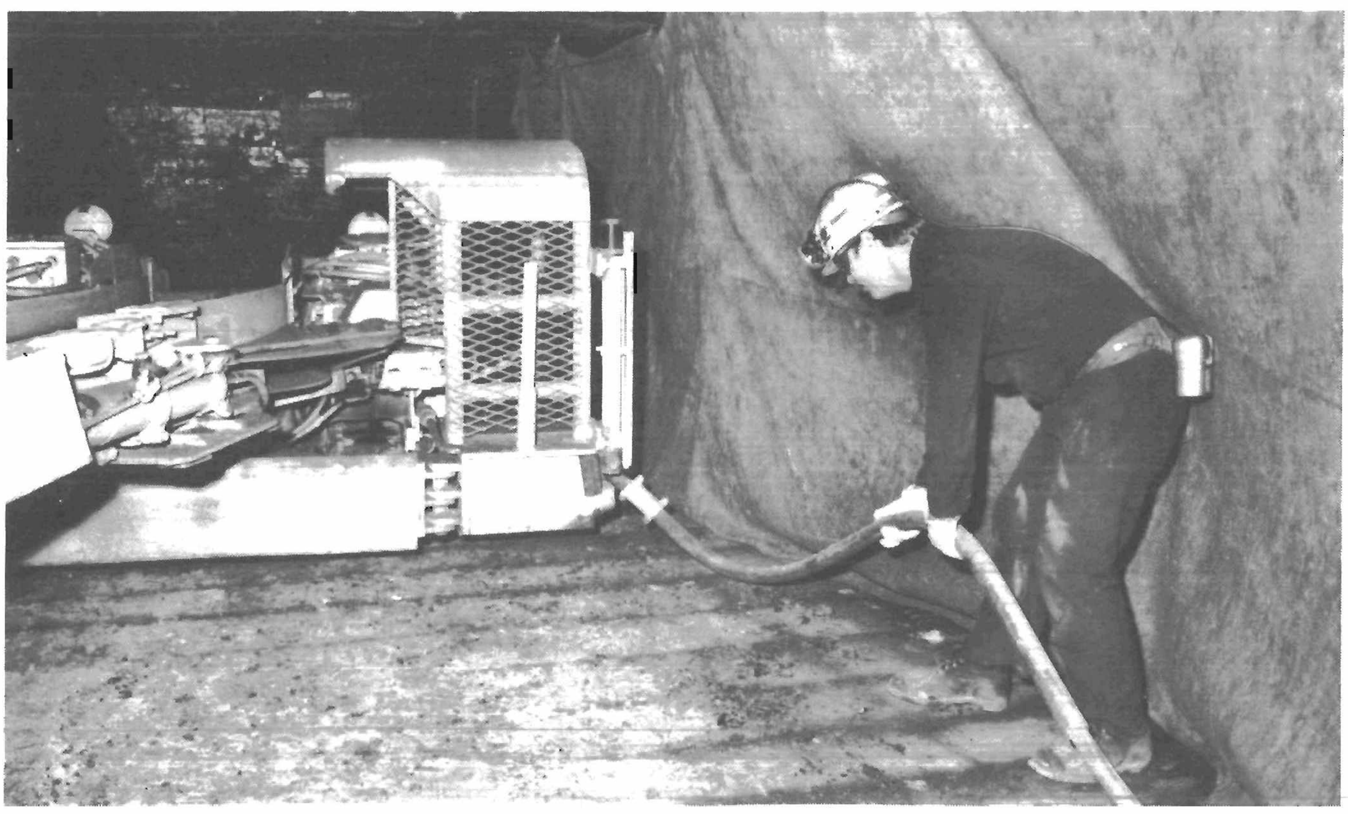


Figure 1.—Miner handling trailing cable underground.

ACKNOWLEDGMENTS

The authors acknowledge with thanks the contributions of other individuals at the Bureau of Mines, Pittsburgh Research Center, who were instrumental in assuring the success of this project: Wymar Cooper, computer programmer, devised the program to display and store the cable temperatures in real time. From these data, Anne Oyler, computer programmer, plotted numerous temperature-versus-time graphs. Richard Roth, engineering technician, assisted in the preparation of cable samples, monitored the cable loading tests, and photographed the test setup. Ray Vereneck, electronics technician, Boeing Services International, prepared the cable samples, monitored loading tests, installed and programmed the time controller, and repaired the datalogger.

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 an outer jacket. The conductors in trailing cables are composed of annealed copper wire, which has been coated with a layer of tin to protect the copper from corrosion and has been stranded in a rope-lay configuration, with bunch-stranded members for maximum flexibility. The ohmic resistance of these conductors is directly proportional to their length and inversely proportional to their cross-sectional area.

The insulating material that covers each of the individual conductors has as its primary function the prevention of leakage current between the conductors. Consequently, the insulation must remain electrically stable in the range of applied voltages and must also resist thermal degradation that 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. The insulating materials most commonly used in mine trailing cables are ethylene-propylene-rubber (EPR) and polychloroprene (neoprene), although there are some applications of styrene-butadiene-rubber (SBR) and polyethylene. These thermosetting and thermoplastic insulations, rated for 90° C operation, are an improvement over the 60° C natural rubber and rubberlike compounds common 30 years ago. They possess not only more favorable electrical properties but excellent physical properties such as tensile strength, workable elongation, and resistance to cutting, heat aging, and deformation.

To fulfill its function of physical protection of the internal components, the outer jacket material of mine-duty cables must have adequate tensile strength as well as resistance to moisture, heating, chemical attack, cutting, abrading, tearing, and impact damage. In addition, it must have adequate flexibility over a broad temperature range to resist cracking and creep. Commonly used compounds include chlorosulfonated polyethylene (CSP), nitrile-butadiene-rubber and polyvinyl chloride (NBR-PVC), and neoprene.

The amount of current that a cable can safely conduct, i.e., the ampacity of the cable, is a function of the rate at which heat generated by ohmic losses in the conductors can be dissipated without damage to conductor insulation or outer jacket materials. Mining cables are rated for continuous operation at certain ampacities depending on their size and the type of insulating materials used.

Thus, the ampacity is equivalent to a temperature rating because the power loss (the source of the heating) is equal to the product of the current squared and the electrical resistance of the metallic conductors (I^2R). Cables transfer the heat generated in the conductors to the environment by means of conduction, convection, and radiation. The rate of heat transfer depends on the difference between the conductor and ambient temperatures, the thermal resistance of the insulation, air density, and the velocity and direction of the ventilating air, as well as the amount of contact with, and the temperature of, any conducting medium with which the cable may be in contact *(1)*.[2]

Federal regulations *(2)* require that "portable cables and cords used to conduct electrical energy to face equipment shall . . . have each conductor of a current-carrying capacity consistent with the Insulated Power Cable Engineers Association (IPCEA) standards" [since 1979, the Insulated Cable Engineers Association (ICEA)]. For 90° C cable, the ampacities listed in ICEA standard S-68-516 *(3)* are applicable based on a constant load (table 1). These ICEA ampacities which apply to a cable suspended in still air, have been calculated using the Neher-McGrath method *(4)*. They are used in conjunction with correction factors or multipliers to adjust ampacities from the standard 40° C ambient temperature (table 2) *(3)*.

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

Table 1.—ICEA ampacities for 90° C portable power cables at 40° C ambient, amperes

Conductor size	2-conductor[1]	3-conductor[1]
AWG:		
8	72	59
6	95	79
4	127	104
3	145	120
2	167	138
1	191	161
1/0	217	186
2/0	250	215
3/0	286	249
4/0	328	287
MCM:		
250	363	320
300	400	357
350	436	394
400	470	430
500	524	487

AWG American wire gauge.
MCM Thousand circular mils.
[1]Round or flat, 0 to 2,000 V.

Table 2.—Factors that convert ampacity given at 40° C to ampacity at other ambient temperatures

Ambient temperature, °C	*Correction factor for 90° C insulation*
10	1.26
20	1.18
30	1.10
40	1.00
50	.90

Previous Bureau-sponsored research *(5)* has shown that conductors in a trailing cable do not reach their rated temperature when subjected to the ICEA ampacities. According to Luxbacher *(6)*, this difference may be the result of several assumptions. First, the calculations upon which the ratings are based assume that the jacket and insulation thermal resistivities are approximately the same; this is not valid for some cable constructions, such as EPR and neoprene. In addition, the formulas do not take into account the presence of ground and ground-check conductors common in mine trailing cables. Further, to simplify the calculation of heat transfer to the surrounding air, ICEA assumed a cable surface temperature of 60° C, irrespective of the conductor temperature. All of these factors may be related to the discrepancies in temperature rises when mine trailing cables are loaded according to ICEA steady-state ratings. An experimental approach can clarify this confusion by providing firm data on which recommendations may be formulated.

Transient heating and cooling of underground trailing cables must be considered when relating the loading conditions found in mining to the steady-state rating based on attainment of a specific insulation temperature. It must be remembered, however, that although current demand by a given piece of equipment is cyclic in nature as dictated by modern mining, the infinite variability of conditions makes it difficult to define current levels within a duty cycle with precision. Nevertheless, British *(7)* and Australian *(8)* mining laws both permit intermittent-duty ratings for mine trailing cables, based upon a standard duty cycle irrespective of cable size (table 3).

Numerous field investigations have been conducted to quantify the period and "on" time for equipment common in U.S. mines. McNiff and Shephard *(9)* evaluated and averaged the operating cycles of several shuttle cars. Stefanko, Morley, and Sinha *(10)* measured the performance characteristics of 34 different face machines in 4 different coal seams. Although they were able to draw general conclusions relating power consumption to machine type, examination of the strip chart recordings reveals a great variability in duty-cycle length and degree of loading. Follow-up work by Stefanko and Morley *(11)* substantiated this variance.

Moreover, these general conclusions represent a compromise of actual machine loading. Mining machines never operate in a manner where current load is a step function as shown in figure 2*A*. Instead, the more usual behavior is as shown in figure 2*B*, with many peaks and troughs. Even the choice of an "on" time is not simple, as headlights and idling motors may be energized throughout the cycle. Although these small currents contribute almost insignificantly to the heating of the trailing cable, their presence complicates the operating cycle definition. Conroy and Hill *(12)* recommend that a single root-mean-square (RMS) current be selected for the "on" time, with "on" time defined as that period when average current exceeds 25 pct of the continuous-duty rating of the machine trailing cable; they present a formula to calculate an intermittent-duty rating given machine period and duty cycle.

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 a function of coal hardness and seam impurities. Other operational variables include cutting height, cutting direction and rate of advancement. Finally, cycle period constantly changes as the distance from the working face to the shuttle car dump point. Consequently, intermittent ratings based on average or typical duty cycles measured in field investigations may not represent worst case situations. Confidence in intermittent ratings applicable to U.S. mines can only be instilled by incorporating appropriate safety factors in analyses of conservative laboratory tests.

Table 3.—Intermittent-duty ratings for trailing cables

Cable diam. mm	Approx. U.S. equivalent, AWG	Intermittent-current rating, A
	BRITISH PRACTICE[1]	
16	5	90
25	3	120
35	2	145
50	1/0	190
70	2/0	235
95	4/0	290
	AUSTRALIAN PRACTICE[2]	
21	4	95
33	2	125

AWG American wire gauge.
[1]Based on full-load current for 40 min, no-load current for 10 to 15 min, one-half full-load current for 40 min, no-load current for 10 to 15 min, in ambient of 25° C *(7)*.
[2]Based on full-load current for 30 min, no-load current for 30 min *(8)*.

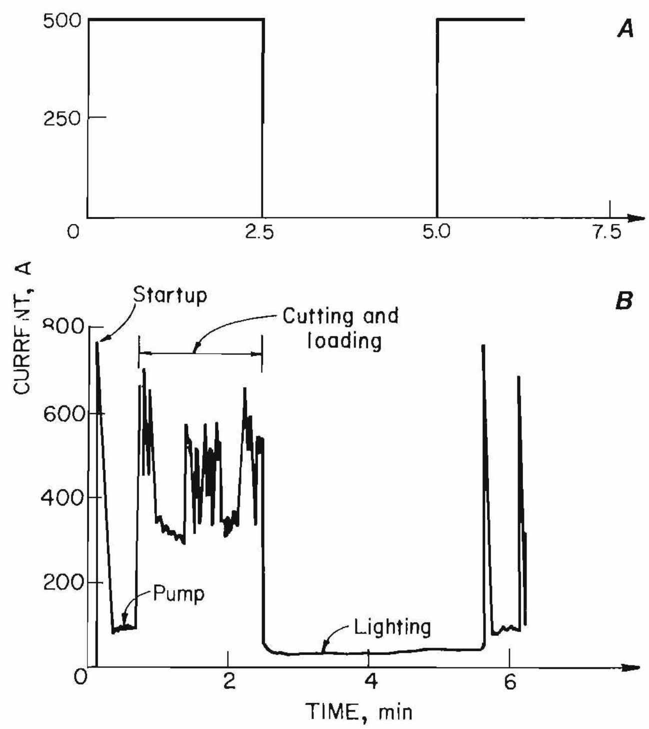


Figure 2.—Step function *(A)* and continuous miner current traces *(B)*.

RESEARCH OBJECTIVE

The specific purpose of the in-house research documented in this report was to measure temperature rises in the conductor, insulation, and jacket of various mine trailing cables, under steady-state and cyclical loading. Through data analyses, the relationship of temperature rise to current could be defined for each cable.

TECHNICAL APPROACH

Ampacity ratings are generally given for conditions similar to those in which the cable will be applied, for instance in air or in a conduit. In the mining environment, machine trailing cables are either left in contact with the bottom material (often a rock dust, coal dust, clay, and water mixture), loosely piled out of the way, hung along the roof or rib, or stored on a machine-mounted reel. The two situations in which the highest temperatures may be expected are when the cable is hung in air and when the cable is stored on a reel, because of the reduction of heat dissipation. The laboratory tests documented in this report focus on cables suspended in air.

Cables in underground mines are usually subjected to air movement as the air used for mine ventilation is circulated to the face area. An air velocity of 30 ft/min can decrease conductor temperature in a No. 4 AWG cable by 5 pct through enhanced convective heat transfer *(4)*. In addition, cables suspended vertically rather than horizontally experience a 22-pct increase in heat dissipation *(4)*. Finally, preliminary load tests showed that for flat cables, slightly higher temperature rises occur when the major axis is parallel to the floor. Consequently, in this investigation cables were suspended horizontally by rope 3 ft above and parallel to the laboratory floor in still air.

To minimize changes in ambient temperature as a result of cable loading, tests were run in an 800-ft^2 room with a 22-ft ceiling. To minimize errors in the translation of the results from the laboratory to the mine environment, the test site ambient temperature was maintained in the range of 18° to 23° C.

All tests were conducted with direct current from the field and armature supplies of a motor test station in the Mine Electrical Laboratory at the Bureau's Pittsburgh Research Center (fig. 3). It should be noted that alternating and direct currents of identical RMS or effective values exhibit virtually the same heating effects *(9)*. To ensure equivalent loading, the power conductors were configured in series with currents measured using a 750-A, 100-mV shunt. Test durations were set with a programmable timer-controller.

To minimize heat transfer, yet maintain mechanical integrity, No. 24 AWG, type T copper-constantan (copper-nickel) thermocouples, insulated with Teflon[3] fluorcarbon polymer, with accuracies of ±0.5° C or ±0.4 pct of reading, whichever is greater, were inserted within the cable. Tests were conducted to determine the optimum means of placement. To access the metallic conductor, the cable jacket and insulation could be pierced by a drill or an incision could be made. Although a small bore minimizes the disruption to the cable assembly, the better method of entry proved to be the incision, which ensured exact junction placement within the cable. Cuts were made perpendicular to the conductors, and the cable interior was accessed by twisting the cable (fig. 4). Power conductor location within round cables could be predicted knowing the repetitive spiraling pattern or conductor lay. The beaded junction of the thermocouples provided an anchoring means within the cable. Following insertion, the insulation and jacket were rebonded with an alpha-cyanoacrylate adhesive. A tie wrap was used to relieve any mechanical strain on the thermocouple lead. To assure proper readings on the jacket surface *(13)*, the thermocouples were embedded within a high-temperature, high-thermal-conductivity paste.

[3]Reference to specific products does not imply endorsement by the Bureau of Mines.

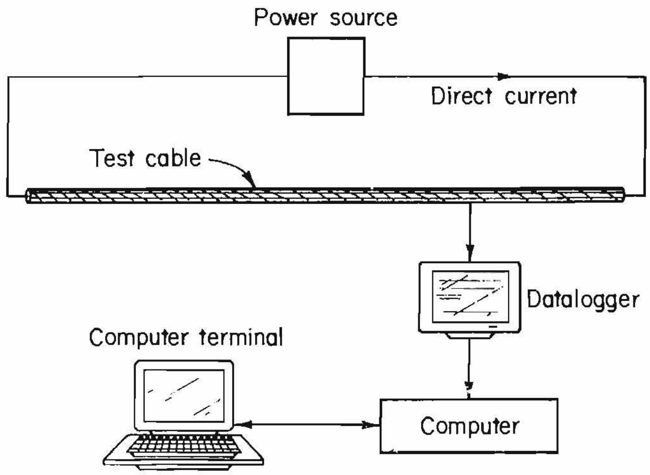


Figure 3.—Load test setup.

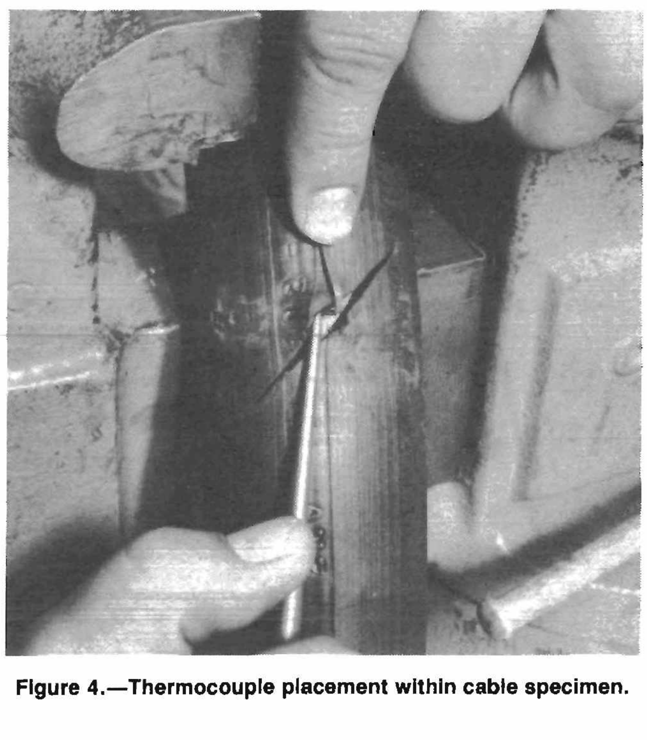


Figure 4.—Thermocouple placement within cable specimen.

The thermocouples were in turn connected to a datalogger (figs. 3, 5). One channel was dedicated to ambient monitoring and another to current measurement. This instrument provided a continuous display of all channel readings. In addition, it was programmed to read and transmit data, via an RS-232 interface, to the Mine Electrical Laboratory's LSI 11/73 computer. From the 11/73 computer, the data were transferred for analysis to a VAX 780 computer.

The influence of the cable terminations on the conductor temperature was determined during loading with electrical current. Thermocouples were inserted at 1-ft intervals in an end conductor of the test specimen, a No. 4 AWG three-conductor, flat, type G-GC, cable, 27 ft long. With a current of 125 A, the conductor temperature rise stabilized at 53° C above ambient. A plot of conductor temperature versus distance along the cable revealed opposing thermal phenomena at both ends of the cable (fig. 6). The absence of insulation and jacket within 4 in of the ends facilitated heat dissipation, cooling the conductor quite noticeably up to 12 in away. However, the resistance of the conductor bolt connectors resulted in slightly elevated temperatures extending 36 in toward the cable center. Conductor temperatures along the remainder of the cable were within 2° C of each other. Consequently, in subsequent experiments no thermocouples were placed within 42 in of cable terminations.

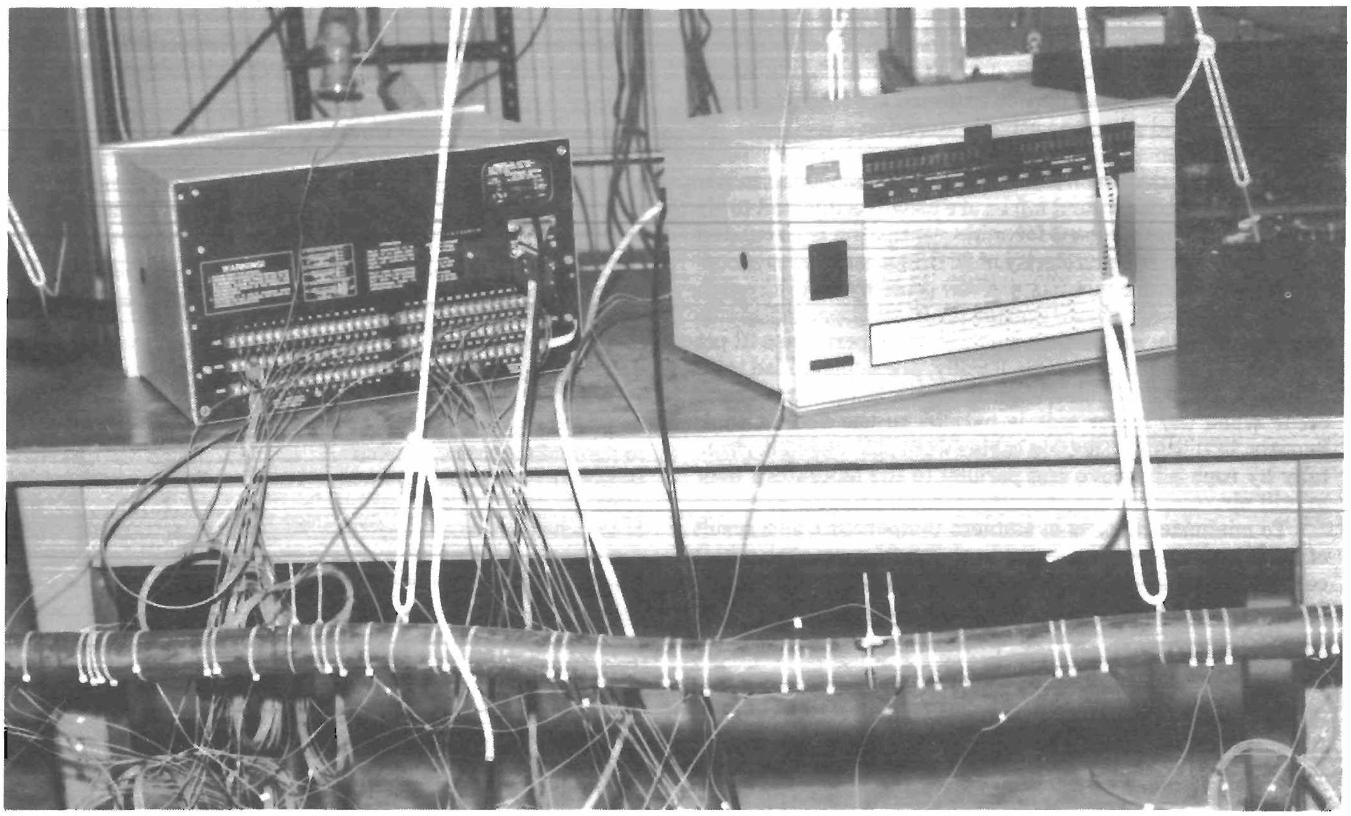


Figure 5.—Thermocouple connections to datalogger.

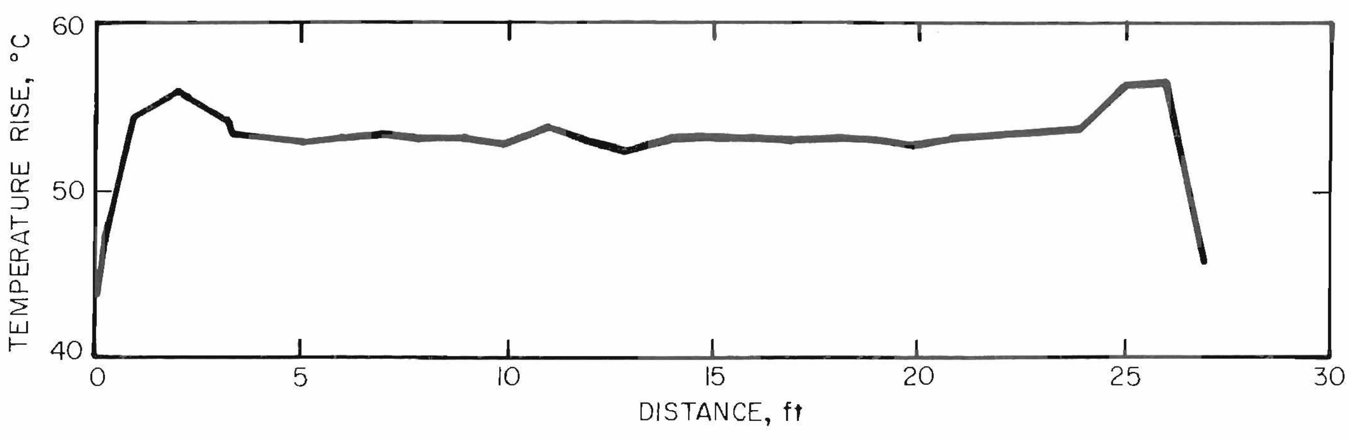


Figure 6.—End effects of cable in still air.

TEST PLAN

The cable specimens tested were intended to be representative of industry usage. Ideally, it was also desirable to investigate how size, cable type, and insulation and jacket material could affect temperature rise. However, steady-state and cyclical loading to stabilization requires 3 to 8 h per test. Since it was envisioned that up to 30 tests would be necessary for each cable and since only 2 tests could be run simultaneously in the Mine Electrical Laboratory, the evaluations were limited to 6 low-voltage unshielded cables (table 4).

To monitor temperature within and on the 14-ft cable length, 30 thermocouples were distributed along the center cable segment, approximately 7 ft long. Figure 7 shows the thermocouple placement within the power conductors, between the power conductors and insulation, between the insulation and jacket and ground-check conductor, and on the jacket surface for a round, type G-GC, cable cross section. Redundant locations assured data in the event of thermocouple malfunctions.

For each cable, five steady-state tests were conducted using fractional and overload multiples of the recommended ICEA ampacities (*3*). A constant direct current was applied and manually maintained within ±1 pct until cable temperatures stabilized. Power was then deenergized and the cable allowed to cool to ambient. Cable and ambient temperatures along with current magnitude were recorded at 1-min intervals for the test duration.

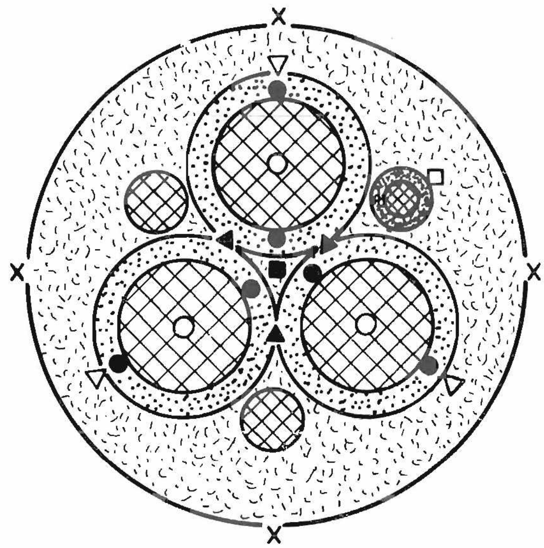
A literature search (*14*) revealed that, neglecting radiation and changes in conductor resistance, cable temperatures should rise and fall exponentially. Response can be predicted knowing the thermal time constants of heating and cooling. These constants represent a ratio of system heat capacity to the rate of heat transfer from the system. For heating, the constant can be defined as the time required to reach 63 pct of the final temperature rise. Therefore, in one constant, 63 pct of the final temperature is attained; in two, 86 pct; in three, 95 pct; in four, 98 pct; and in five, 99 pct.

In formulating a conservative test plan for intermittent loading, reference was made to Institute of Electrical and Electronics Engineers (IEEE) guidelines for the rating of electrical equipment of varying duty. Standard 96 (*15*) suggests that continuous-duty equipment can be rated intermittently if the period upon which the rating is based exceeds actual load cycle time and is on the order of 1 thermal time constant. Consequently, thermal time constants determined graphically from the steady-state tests could fix the period for the planned duty-cycle tests. For each of five current levels above and below the ICEA rating, loading was applied with "on" times of 25, 40, 50, 60, and 75 pct. Loading continued until maximum temperatures between cycles remained constant.

Table 4.—Cable specimens tested

Size, AWG	Conductors	Shape	Type	Voltage	Insulation[1]	Jacket
6	3	Round	G-GC	2,000	EPR	Neoprene.
4	3	Flat	G-GC	600	Neoprene	Do.
2	2	do	G	600–2,000	EPR	Do.
1/0	2	do	W	600	EPR	Do.
2/0	3	Round	G-GC	600–2,000	EPR	Do.
4/0	3	do	G-GC	2,000	EPR	CSP.

[1]Rated for 90° C.



KEY

- ■ In the center of the cable (3)
- ○ In the power conductor (3)
- ● On the power conductor (9)
- ▲ Between the power conductors (6)
- □ On the ground-check insulation (2)
- △ Between the jacket and insulation (3)
- × On the surface of the cable (4)

Figure 7.—G-GC cross section with thermocouple locations.

TEST RESULTS

Once a load test was completed and the data file transferred to the VAX 780 computer, the temperature data were examined to determine the rises of greatest magnitude at the conductor-insulation interface, at the insulation-jacket interface, and on the surface of the cable. Generally, within the cable, the highest interfacial temperatures were recorded on a line between the centers of the power conductors. The highest surface temperatures were measured where a power conductor lay directly beneath; the lowest surface temperatures were above filler material. The selected channel signals along with the ambient were then plotted versus time using RS-1, a commercial data analysis software package. Typical steady-state plots are shown in figure 8. It can be observed that the temperature rise at the insulation-jacket interface is approximately 25 pct less than at the conductor surface; the cable surface temperature is about midway between the conductor-insulation interface and ambient.

Thermal time constants of heating, calculated from the steady-state data, were independent of current, as expected. The average values shown in table 5 fixed the period for the subsequent duty-cycle tests. Generally, the larger the cable, the longer the time constant. In addition, cables with two conductors heated more rapidly than those with three. Typical duty-cycle plots are shown in figure 9.

From the load test results, relationships between average temperature rise at the conductor-insulation interface and current load were established for each cable for the steady-state or 100 pct duty cycle, and for duty cycles of 25, 40, 50, 60, and 75 pct (figs. 10–15). Examination of these curves shows that they may be approximated by the expression

$$\Theta = R_T(I)^b,$$

where Θ is temperature rise, °C,
I is current load, A,
R_T is net thermal resistance between conductors and ambient, ohms,
and b is a variable dependent on the duty cycle.

Table 5.—Thermal time constants of heating

Cable size, AWG, and type	*Time constant, min*
6, 3/c, round G-GC	20.3
4, 3/c, flat G-GC	27.7
2, 2/c, flat G	20.0
1/0, 2/c, flat W	25.6
2/0, 3/c, round G-GC	45.1
4/0, 3/c, round G-GC	50.4

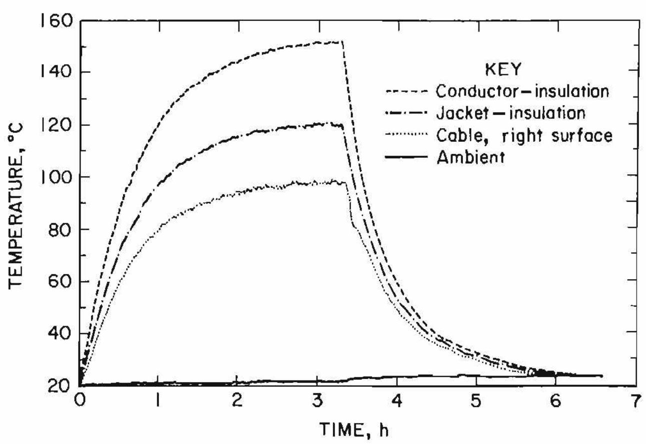


Figure 8.—Steady-state load test results for No. 2/0 AWG, 3/c, round G-GC cable loaded at 400 A.

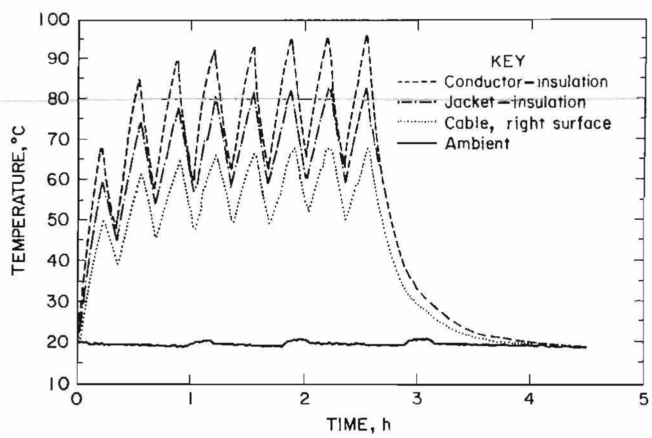


Figure 9.—Intermittent test of No. 2 AWG, 2/c, flat G cable loaded at 300 A for 60 pct of time.

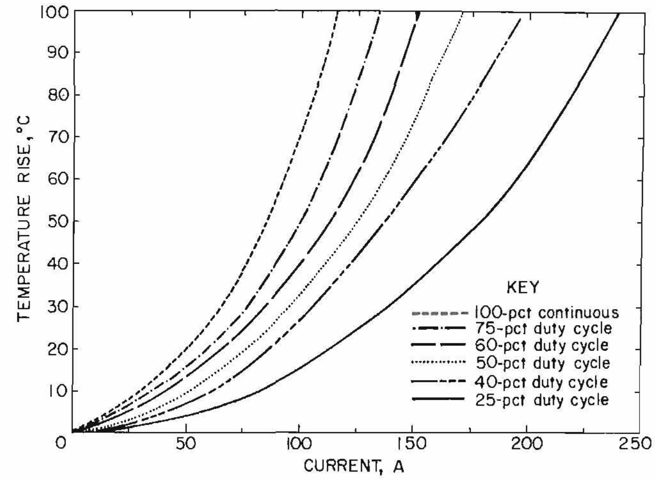


Figure 10.—Average rise above ambient of conductor-insulation interface in No. 6 AWG, 3/c, round G-GC cable.

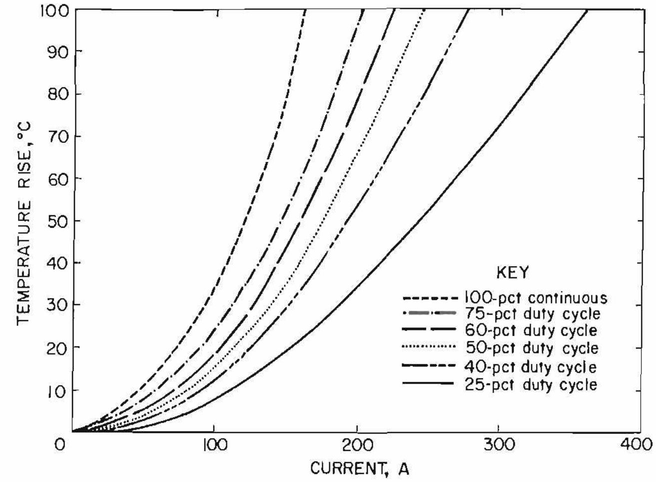


Figure 11.—Average rise above ambient of conductor-insulation interface in No. 4 AWG 3/c, flat G-GC cable.

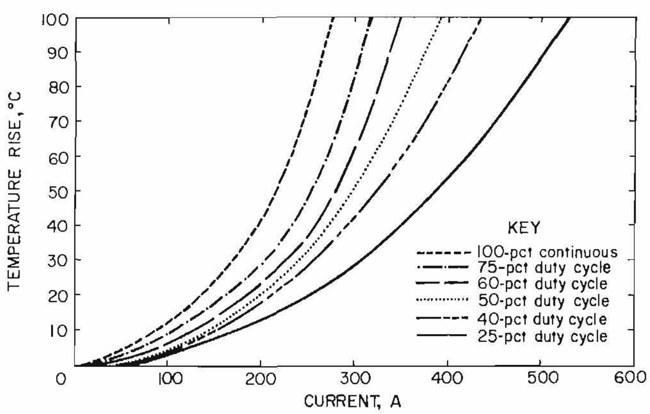


Figure 12.—Average rise above ambient of conductor-insulation interface in No. 2 AWG, 2/c, flat G cable.

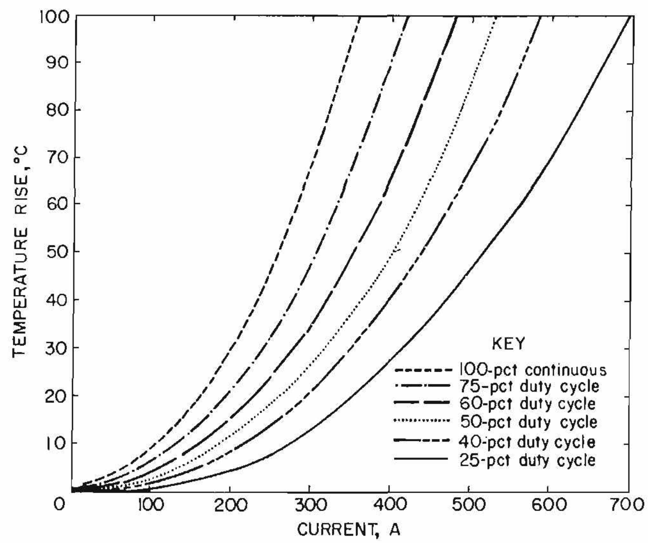


Figure 13.—Average rise above ambient of conductor-insulation interface in No. 1/0 AWG, 2/c, flat W cable.

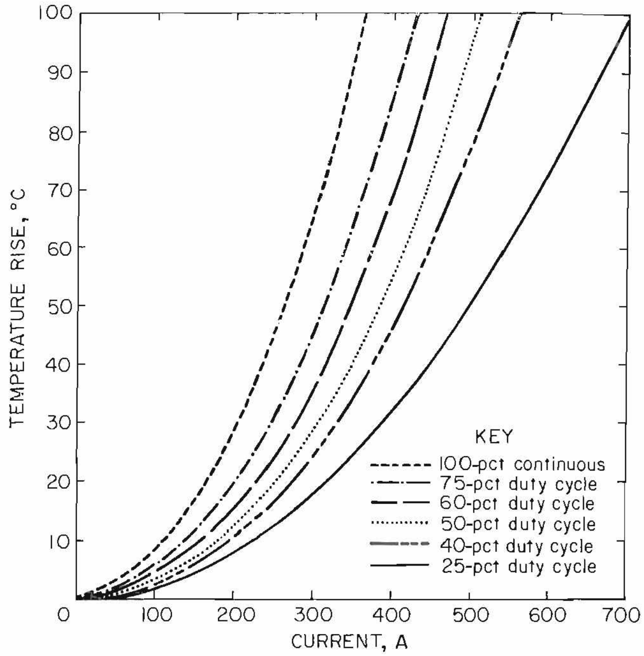


Figure 14.—Average rise above ambient of conductor-insulation interface in No. 2/0 AWG, 3/c, round G-GC cable.

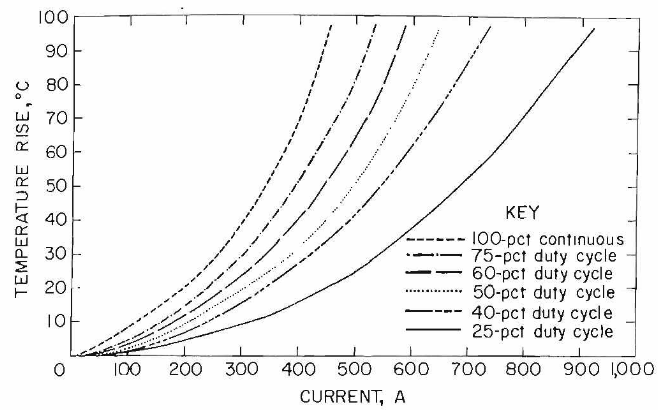


Figure 15.—Average rise above ambient of conductor-insulation interface in No. 4/0 AWG, 3/c, round G-GC cable.

Table 6.—Current required to induce an average 70° C rise at conductor-insulation interface, amperes

Cable size, AWG, and type	Duty cycle, pct					
	25	40	50	60	75	100
6, 3/c, round G-GC	216	157	140	131	117	102
4, 3/c, flat G-GC	276	226	202	191	171	142
2, 2/c, flat G	455	357	334	323	284	247
1/0, 2/c, flat W	622	470	425	416	341	295
2/0, 3/c, round G-GC	568	471	439	402	363	310
4/0, 3/c, round G-GC	794	647	579	518	452	391

All the cables tested featured insulations rated at 90° C continuously. Assuming a mine ambient of 20° C, the steady-state and intermittent currents necessary to produce an average temperature rise (above ambient), upon stabilization, of 70° C at the conductor-insulation interface are plotted in figure 16. This information is reproduced in tabular form in table 6. A comparison of the steady-state experimental results in table 6 with ICEA ampacities, corrected to a 20° C ambient (tables 1-2), is shown in table 7.

Table 7.—Comparison of steady-state experimental results for 70° C rise at 20° C ambient with ICEA ampacities

Cable size, AWG, and type	Steady-state test results, A	ICEA ampacity, A	Difference, pct
6, 3/c, round G-GC	102	93	+10
4, 3/c, flat G-GC	142	123	+15
2, 2/c, flat G	247	197	+25
1/0, 2/c, flat W	295	256	+15
2/0, 3/c, round G-GC	310	254	+22
4/0, 3/c, round G-GC	391	339	+15

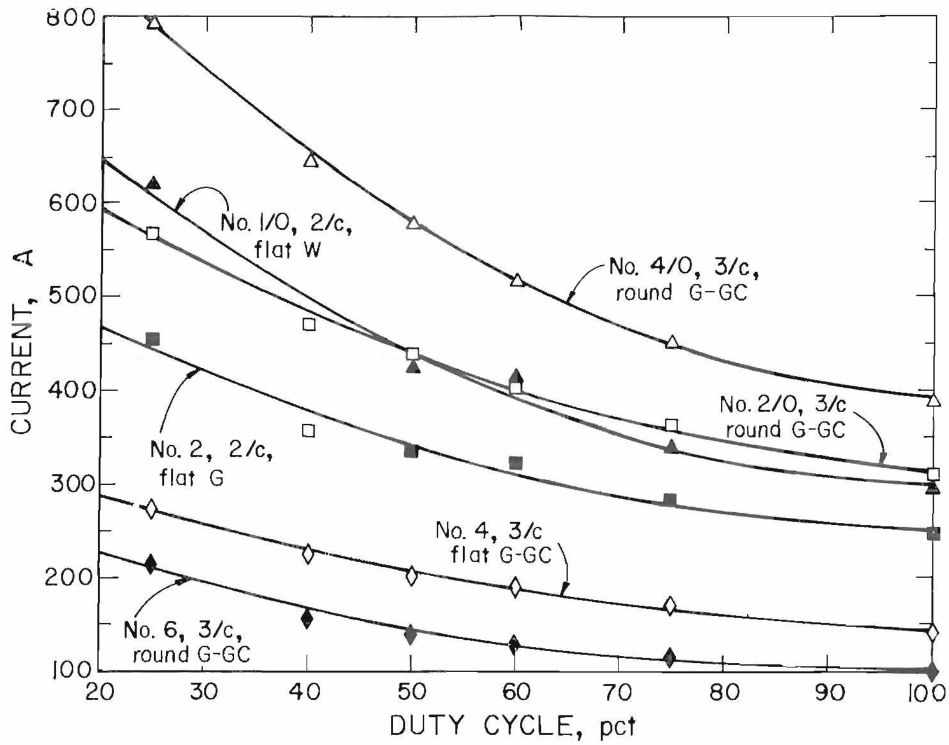


Figure 16.—Load required to effect a 70° C rise.

CONCLUSIONS

The comparisons of test results with ICEA steady-state ratings (table 7) confirm previous research (*5*), which concluded that trailing cables will not reach rated temperature when continuously loaded at ICEA ampacities. The discrepancies, ranging from 10 to 25 pct, may be considered as safety factors.

The cyclical results of table 6 show that, compared with foreign practice (table 3), U.S. cables may be loaded intermittently with much higher currents while still maintaining an average rated temperature at the conductor-insulation interface. However, there are additional factors to consider when applying trailing cables in underground coal mines.

The autoignition temperature of coal dust, mainly dependent on its volatility, has an established lower limit of 150° C (*16*). This provides a basis for 30 CFR 18.23, which states, in part, that "the temperature of the external surfaces of mechanical or electrical components shall not exceed 150° C (302° F) under normal operating conditions."

In addition, portable power cables, like giant extension cords, must be moved about extensively in underground mining. If protective gloves are not worn by personnel handling energized cables, burn injuries may result. Considering reaction time, thermal contact resistance, and injury extent, Luxbacher (*6*) placed a limit on outer jacket temperature of 100° C.

During intermittent loading (fig. 10) the temperatures of the cable components fluctuate considerably. However, an examination of the data reveal that, when subjected to the loading specified in table 6, the surfaces of the outer jackets would never attain even momentary rises (above ambient) of 80° C. Consequently, the autoignition of coal dust and burn injuries would not be concerns if the temperature at the conductor-insulation interface averaged 90° C.

RECOMMENDATIONS FOR FUTURE RESEARCH

The tests documented in this report were limited to six trailing cables, ranging in size from No. 6 to 4/0 AWG and including types G, G-GC, and W. Additional load tests are needed before interpolations can be made among sizes of similar types.

All cables tested were unshielded and rated 600 and/or 2,000 V with 90° C insulation. Mining equipment rated above 1,000 V is becoming increasingly common and requires cables employing metallic shields around each power conductor; research is needed to measure temperature rises in higher voltage shielded cables.

All documented tests were conducted with cables suspended in still air, the worst case for drag applications. However, it has been long established *(17)* that cables on reeled equipment attain very high temperatures while tightly wrapped on reels. These rises may exceed those for drag cables. This phenomenon should be simulated in the laboratory with a shuttle car reel, and the temperatures of each lap monitored.

Abnormal temperature rises are attained during overload and short circuits. These rises can easily exceed the dust ignition and burn thresholds of 150° and 100° C, respectively, for the outer surface. Tests should be conducted to determine the combination of current and time necessary to reach but not exceed these limits.

As stated at the outset, underground portable power cables are subject to extreme mechanical abuse. They are abraded against the coal rib, run over by mobile equipment, and pulled apart at splice points. The net result is that trailing cables rarely last a year in the coal mining environment *(18)*. This can be contrasted to most other industrial and commercial applications where the useful life of a cable may exceed 20 years and is based for the most part on thermal degradation. If material life is approximately halved for every 10° C *(19)*, then it would seem that a small increase above the 90° C standard operating temperature would have little impact on the useful life of coal mine trailing cables. Such an increase, if justifiable from a safety standpoint, may help ease the problems of cable sizing resulting from increased horsepower demands.

As long as a single chemical reaction predominates over a range of operating temperatures, material life will follow a straight line when plotted logarithmically versus temperature. Such a graph is termed an "Arrhenius model" *(20)* and is used to predict useful life at operating temperatures based upon experimental results at relatively high temperatures. Currently the Bureau is developing such a model for coal mine trailing cables. Insulation and jacket specimens are being aged thermally in air ovens. Followup mechanical and electrical tests will determine how various cable qualities deteriorate over time and identify the critical factor that precipitates cable failure due to thermal degradation. The relationship between trailing cable useful life and temperature will be established.

Ultimately this will be correlated with the temperature-versus-current plots of this report to calculate useful life, given any electrical load. Further revisions in ampacity ratings may then be possible, conceding a reduction in cable life by thermal degradation, with an appropriate safety factor. Consideration might then be given to a scheme designed to preclude cable operation underground beyond safe limits.

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