THERMAL CHARACTERISICS OF SHUTTLE CAR CABLE REELS

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***Abstract*—The present method of calculating the ampacities of power cables that are wound on a cable reel involves the use of derating factors that are published in the Insulated Cable Engineers Association/National Electrical Manufacturers Association Standards (ICEA/NEMA) Publication WC8. These factors consider only one to four layers of cables and it is recommended that the derating values be multiplied by the ampacities of single cables suspended in air. No guidance is provided for installations that have greater than four layers of cables.**

This paper presents a mathematical model that is capable of calculating the ampacity of a wide variety of cable designs consisting of an arbitrary number of layers on a cable reel. The model considers round cables with copper conductors.

The validity and accuracy of the ampacity model were verified by comparing the predicted temperature distribution within the reel with measured temperatures collected during an extensive testing program conducted at the U.S. Bureau of Mines (USBM). The mathematical model predicted a temperature distribution within the cable layers that was very close to the measured variation in temperature.

The value of the program is illustrated by calculating ampacities for several copper conductor sizes. Those ampacities suggest that the ICEA/NEMA derating factors do not lead to conservative temperatures for modern designs when they are wound on reels. This conclusion can be very significant for those applications, such as trailing cables used in mobile mining equipment, in which the overheating of a cable reel can result in a hazardous situation.

I. INTRODUCTION

Cable ampacity ratings are generally determined by conditions similar to those in which the cable will be applied (such as environment and ambient temperatures), and by thermal resistance of the insulation. In a mining environment, the electrical requirements for trailing cables used to power mobile mining equipment are contained in Title 30 CFR, Parts 18 and 75 [1]. These federal regulations require that trailing cables be electrically rated according to the standards set by ICEA [2]. These ICEA ampacity ratings apply to cables suspended in still air and are used in conjunction with multipliers or derating factors that are used to correct for ambient temperatures different from the standard 40° C ambient temperature and for different number of layers of cables on the reels.

There are two main concerns about the present derating factors used for reeled trailing cables. The first concern is based upon the value of insulation thermal resistance. Present derating factors are based on rubber-insulated cables that consider a maximum operating temperature of 60° C. More recently, ethylene-propylene-rubber with a 90° C limiting temperature has been used to insulate mine trailing cables. The newer material possesses greater resistance to heat aging than the rubber-insulated materials that were commonly used 30 years ago. Consequently, the 90° C insulation will better resist thermal degradation that could occur as a result of conductor heating. Hence, an updated ampacity model should consider this newer insulation material when rating the cable.

The second concern involves the derating factors recommended by ICEA. The derating factors have been provided for only one to four layers. However, it is a common practice for cable reels to store up to ten layers. Therefore, a need exists for determining derating factors for reels which contain five to ten layers of cables.

These concerns prompted USBM to conduct an in-house research project to determine acceptable derating factors of reeled coal mine trailing cables. This work is part of an ongoing USBM project to expand the existing knowledge in the area of cable-reel ampacity [3-5]. In particular, the research focused on shuttle car reels and cable sizes as well as new cable designs that are representative of modern mining industry usage.

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This paper describes a computer program that is capable of calculating the ampacity of cables wound on shuttle car reels. The results of the program are compared with temperature data collected during the testing program carried out at USBM. The computer-generated ampacity values are then used to predict derating factors that can be used in conjunction with published ampacity values for single horizontal cables in still air. These newly generated derating factors indicate that the existing derating values can lead to serious overheating if they are applied to the rating of cables wound on reels. The program is used to generate ampacity values for typical cable and reel designs and a series of new derating factors are calculated to illustrate the utility of the program.

For your convenience, nomenclature, greek symbols and subscripts used in this paper are identified below.

Nomenclature

A	ampere
°C	degree Celsius
C_1	constant of integration given by equation 5 (°C)
C_2	constant of integration given by equation 6 (°C)
DF	derating factor defined in equation 16
D	outer diameter of cable (m)
g	acceleration of gravity(m/s^2)
h_1	thermal conductance at the inner surface of cable reel ($W/m^2 \cdot °C$)
h_2	thermal conductance at the outer surface of cable reel ($W/m^2 \cdot °C$)
h_{c_1}	convective heat transfer coefficient on inner surface of cable reel ($W/m^2 \cdot °C$)
h_{c_2}	convective heat transfer coefficient on outer surface of cable reel ($W/m^2 \cdot °C$)
h_{r_2}	radiative heat transfer coefficient on outer surface of cable reel ($W/m^2 \cdot °C$)
I	current through cable (amps)
$(I)_{reel}$	ampacity of cable on reel from model predictions (amps)
$(I)_{air}$	ampacity of cable suspended in air from ICEA reference (amps)
i	i th layer of cable on reel
in	inch
K	kelvin
k	thermal conductivity of cable mass ($W/m \cdot °C$)
k_a	thermal conductivity of air ($W/m \cdot °C$)
L	total length of cable on reel (m)
L_i	length of cable in i th layer on reel (m)
m	meter
N	total number of cable layers on reel
q_G'''	energy generated within the cables per unit volume of cable mass (W/m^3)
r	radius (m)
r_1	inner radius of the cable reel (m)
r_2	outer radius of the cable reel (m)
$r*$	radial location in the reel where the cable temperature is a maximum (m)
R	AC electrical resistance of the cable on the reel at the maximum cable temperature (ohms)
R'	AC resistance per unit length of cable on the reel (ohms/m)
T_{a_1}	average air temperature on inner surface of cable reel (°C)
T(r)	temperature within cable mass as a function of radius (°C)
T_∞	temperature of air surrounding the cable reel (°C)
V	total volume of cable mass on the reel (m^3)
w	width of cable reel (m)
W	watts

Greek Symbols

β_a	thermal expansion coefficient of air ($°C^{-1}$)
ε	emissivity of cable jacket
ν_a	kinematic viscosity of air (m^2/s)
σ	Stefan Boltzmann constant, 5.67 X 10^{-8} $W/m^2 K^4$

Subscript

a	property of air
i	i th layer of cable
1	a quantity evaluated at the inner surface of the cable reel
2	a quantity evaluated at the outer surface of the cable reel

II. MATHEMATICAL MODEL

The mathematical model is based on the geometry shown in Fig. 1. The resulting equations may be used to calculate the ampacity of the cable. The mathematical model is based on several assumptions that simplify the resulting analysis and allow the development of a PC-based computer program that can solve for the temperature distribution of the cables on the reel. The program provides a temperature distribution in the cable as a function of the radial thickness of the cable bundle wound on the reel. Therefore, it can be used to determine the ampacity in terms of the number of layers of cable on the reel. Some of the assumptions used in the program are intentionally selected to make the model conservative; i.e., the equations are formulated so that the resulting temperatures within the cable mass on the reel are maximized for the given current and operating conditions.

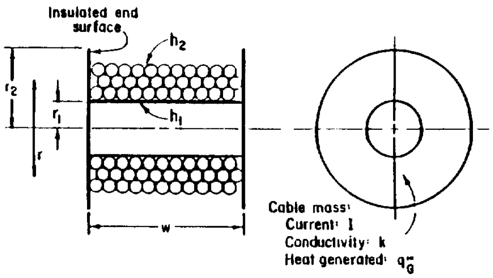

Fig. 1. **Cable and Reel Geometry**

The model assumes that steady-state conditions exist. The current, as well as environmental conditions, are independent of time. The heat generated within the cables is assumed to be distributed uniformly throughout the cable bundle. The cables are assumed to be round and they are arranged in a close-packed array with cables wound across the entire width of the reel (see Fig. 2). The ends of the reel are assumed to be insulated so that none of the heat generated within the cables is transferred off the end surface of the reel. This assumption leads to conservative results and it also simplifies the analysis, because it implies that the temperature is only a function of the radial position within the cable mass. The ambient air surrounding the reel is assumed to be stationary, which is another factor that produces conservative ampacity values. As a result of this assumption, the convection model used for the outer surface of the cables on the reel employs a free-convection correlation with the heat transferred to the stationary air at a known ambient temperature. The inner surface of the reel is enclosed so a free convection correlation is appropriate for that surface also. The thermal resistance of the reel is neglected in the model so that the temperature of the drum is assumed to be the same as the temperature of the cables that touch the reel. This assumption is fairly accurate for reels made from high-conductivity metallic materials, but its accuracy can decrease when the drum is an insulative reinforced composite material. The model does not consider a reel that is surrounded by any enclosure that will prevent a free circulation of air to the outer surface of the cables on the reel. If the air surrounding the reel is restricted from moving freely by some sort of enclosing structure, the program may not provide conservative ampacity values and should not be used.

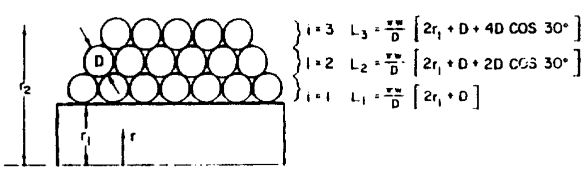

Fig. 2. Closely **Compacted** Cable Array

Applying these assumptions, the temperature distribution in the cables on the reel is governed by the differential equation:

$$\frac{k}{r}\frac{d}{dr}\left(r\frac{dT(r)}{dr}\right) + q_G''' = 0 \tag{1}$$

where the symbols are defined in the Nomenclature section. This differential equation requires two boundary conditions:

$$k\frac{dT(r)}{dr}\Big|_{r_1} = h_1\left[T(r_1) - T_\infty\right] \tag{2}$$

$$-k\frac{dT(r)}{dr}\Big|_{r_2} = h_2\left[T(r_2) - T_\infty\right] \tag{3}$$

which state that the heat generated by the cables is removed by a combination of convection and radiation from both the inner and outer surfaces of the reel.

The solution to equation 1 subject to the two boundary conditions (equations 2 and 3) is

$$T(r) = -\frac{q_G''' r^2}{4k} + C_1 \ln r + C_2 \tag{4}$$

where C_1 and C_2 are constants of integration equal to

$$C_1 = \frac{\dfrac{q_G''' r_2}{2h_2}\left\{1 + \dfrac{h_2}{h_1}\dfrac{r_1}{r_2} + \dfrac{h_2 r_2}{2k}\left[1 - \left(\dfrac{r_1}{r_2}\right)^2\right]\right\}}{\dfrac{k}{h_2 r_2} + \dfrac{k}{h_1 r_1} + \ln\left(\dfrac{r_2}{r_1}\right)} \tag{5}$$

$$C_2 = \frac{C_1}{h_1 r_1/k} + q_G''' \frac{r_1^2}{2k}\left[\frac{1}{2} - \frac{k}{h_1 r_1}\right] - C_1 \ln r_1 + T_\infty \tag{6}$$

The temperature distribution in the reel is therefore logarithmic with the radius r and the location of the maximum temperature in the cables is primarily a function of the current, thermal conductivity of the cable bundle, and the rate at which heat is transferred from the inside and outside surfaces of the reel.

Before the current-temperature relationship can be determined, expressions for h_1, h_2, and q_G''' must be determined in terms of known operating characteristics. The rate at which heat is generated within the cables can be expressed in terms of current, cable resistance, and geometry.

$$q_G''' = \frac{I^2 R}{\pi(r_2^2 - r_1^2)w} \quad (7)$$

where R is the ac electrical resistance of the total length of cable on the reel. In terms of the resistance of the conductor per unit length, R can be written as

$$R = R'\sum_{i=1}^{N} L_i = R'\frac{\pi w}{D}\sum_{i=1}^{N}\left[2r_1 + D + 2D(i-1)\cos 30^\circ\right] \quad (8)$$

when there are N full layers of cable with diameter D closely compacted on the reel as shown in Fig. 2.

The thermal conductances, h_1, h_2, at the two boundary surfaces of the cable reel are the sum of the convective and radiative heat transfer coefficients. For the outer surface at r_2 assuming surface temperatures less than 150° C [6],

$$h_2 = h_{c_2} + h_{r_2} = h_{c_2} + \varepsilon\sigma(T_2 + T_\infty)(T_2^2 + T_\infty^2) \quad (9)$$

and

$$h_{c_2} = 0.409\left[\frac{g}{r_2}\left(\frac{\beta k^4}{\nu^2}\right)_a (T_2 - T_\infty)\right]^{1/4} \quad (10)$$

The properties of air in equation 10 are determined at an average air temperature

$$T_{a_2} = \frac{T_2 + T_\infty}{2} \quad (11)$$

and values can be found in table G-1 of reference 7, for example.

The thermal conductance at the inner reel surface is assumed to consist only of a convective coefficient because the net radiative heat transfer from the enclosed inner surface will be negligible. This assumption adds to the conservative nature of the thermal model. Therefore, the thermal conductance at the inner reel surface is

$$h_1 = h_{c_1} \quad (12)$$

where the value for h_{c_1} can be approximated with equation 13.

$$h_{c_1} = 0.060\left[g\left(\frac{\beta k^3}{\nu^2}\right)_a (T_1 - T_\infty)\right]^{1/3} \quad (13)$$

The temperature dependent properties of air in equation 13 are evaluated at the average air temperature equal to

$$T_{a_1} = \frac{T_1 + T_\infty}{2} \quad (14)$$

The expression for the temperature distribution within the cables given by equation 4 plus the supporting equations 5-14 permit the calculation of the cable ampacity, because they relate the current in the cable to the maximum temperature in the cable mass. The maximum temperature occurs at the radial location

$$r* = \sqrt{\frac{2kC_1}{q_G'''}} \quad (15)$$

One final complicating factor must be considered before the ampacity can be calculated. The temperature in the cables, as well as their ampacity value, are dependent upon the rate at which heat is removed from the inner and outer surfaces of the reel. The surface heat transfer rates are a function of the two unknown surface temperatures (T_1, T_2) of the reel. Therefore, the solution becomes an iterative one in which the surface temperatures are assumed; the temperature distribution of the cables are then calculated using the assumed surface temperatures. The calculated surface temperatures are compared to the assumed values and adjustments are made until the two values converge, resulting in the correct temperature distribution in the cables and the correct ampacity of the cable.

III. EXPERIMENTAL VERIFICATION OF MODEL

Electrical loading tests were conducted on two popular cable-reel combinations to measure the temperature profile in each layer stored on the reel (table 1). The cables were continuously loaded with five different current magnitudes for each layer. All tests were conducted with direct current. To ensure equivalent loading in each of the three conductors, the three power conductors were connected in series. Copper-constantan thermocouples (Type T, 24 AWG) were used to measure temperature rise within each cable layer. Since it is known that the conductor is the hottest location within the cable cross-section, only the conductor temperatures were recorded. To determine axial temperature profiles across the reels, a thermocouple was secured within one conductor of every other wrap above the drum. The monitored locations

Table 1.—Cable-reel combinations

Cable size AWG and type	Reel dimensions
#6 and #4, 3-conductor, copper, round, G-GC	Drum diameter: .254 m (10 in)
	Flange diameter: .559 m (22 in)
	Distance between flanges: .406 m (16 in)

in succeeding layers were directly above those in the previous layer (Fig. 3).

The thermal performance of cumulative layering was evaluated with the remainder of the sample length configured conveniently nearby. The temperature of each incremental layer was examined at the five different current levels. The highest test current for each layer was empirically selected to ensure that the maximum recorded temperature would never exceed 170° C, which is the temperature that the cable insulation begins to melt.

Each load test for a given configuration was plotted showing the temperature rise as a function of current and the radial location inside the cables on the reel. From these data, the maximum temperature rise for each layer was determined by subtracting the ambient temperature from the temperature of the hottest wrap on that layer. The temperature rise for a given configuration was then plotted as a function of load current and the temperature rise data were then tabulated into a data base. A typical example of the temperature rise is shown in Fig. 4 which plots the result for #6 AWG round copper conductor G-GC cables. The specifics of the cable and reel design used during the experimental measurements are shown in table 1.

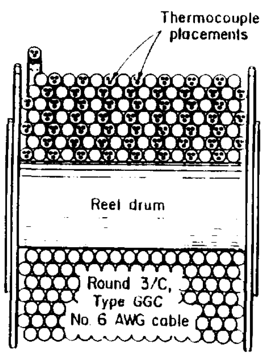

Fig. 3. Thermocouple placements

IV. RESULTS

A typical program-predicted temperature distribution is illustrated in Fig. 5 for a cable reel wound with a G-GC, #6 AWG 3-conductor copper cable. The figure shows the radial temperature variation for 2 through 6 layers of cable assuming a fixed current in all cases of 40 A. The radial position (r*) of the maximum cable temperature is shown on each curve; the curves illustrate the increase in temperature resulting from an increase in cable layers. The slope of the temperature curves show that most of the heat generated in the cables is removed from the outer surface of the cables and that the inner drum surface is relatively ineffective at transferring the heat to the air encapsulated inside the drum.

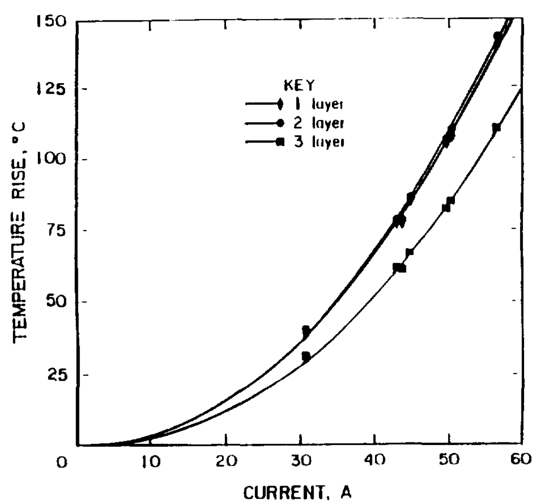

Fig. 4. Temperature rise as a function of current for #6 AWG GGC round with three layer

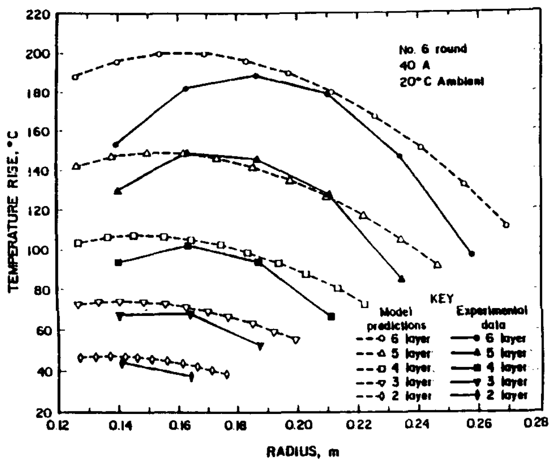

Fig. 5. Comparison of model and experimental data for temperature rise as a function of radius (6 AWG cable)

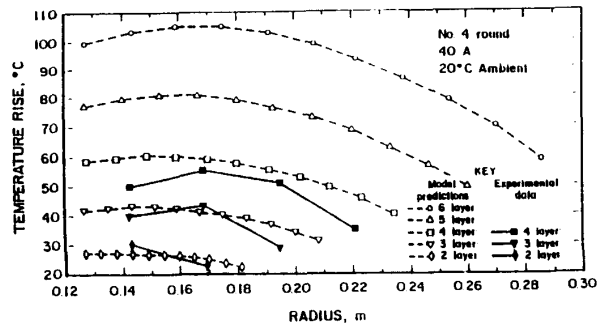

Fig. 6. Comparison of model and experimental data for temperature rise

Also included in Fig. 5 is the experimental data measured during laboratory testing using a reel with a design specified in table 1. The reel was wound with a #6 AWG 3-conductor copper cable and the ambient temperature was maintained at 20° C. The computer-predicted temperatures throughout the various layers of cable mass compare well with the measured temperatures, particularly for the maximum temperature within the cables. In general, the thermal model overpredicts the measured values, because the program was designed to provide conservative ampacity predictions. The measured surface temperatures are lower than the predicted values, indicating that the surface cooling that actually occurred in the laboratory was greater than calculated by the program. In part, this trend helps lead to the conservative nature of the thermal model.

The greatest difference between the model-predicted temperatures and the laboratory-measured values occurs at the surface of the drum. The model assumes that the air inside the drum is entirely encapsulated and can only circulate within the drum as a result of free convection effects. In reality, the drum has an access hole to permit passage of the cable onto the reel. Therefore, during the laboratory testing, air can leave and enter the interior portion of the drum and cool it more effectively than the model predicts. For this reason, the program overpredicts the temperature of the drum. The program also overpredicts the outer surface temperature of the cables, but to a lesser degree. This error is most likely due to the small, unavoidable air currents that existed in the laboratory that are not accounted for when a free-convection correlation is used in the model.

The data in Fig. 6 are similar to that shown in Fig. 5 except the conductor size has been changed to #4 AWG. Here again, the computer-generated temperatures are typically greater than the laboratory measurements. The maximum temperature within the layers is predicted fairly accurately with differences increasing at both the inner and outer surface of the cable bundle. Experimental tests were conducted for only three different layered configurations, while the computer-generated temperature distributions are provided for two to six layers of cables.

A final comparison of the computer-generated temperature data and the experimentally measured values is shown in Fig. 7. For this case, three layers of G-GC #6 AWG 3-conductor copper cable were wound on a reel and thermocouples were embedded in each layer. The dashed lines show the predicted temperature rise for the three layers as a function of current and the solid lines indicate the measured temperature rise for each of the three layers. For each set of experimental data, the program overpredicts the temperature rise of the cables on the reel.

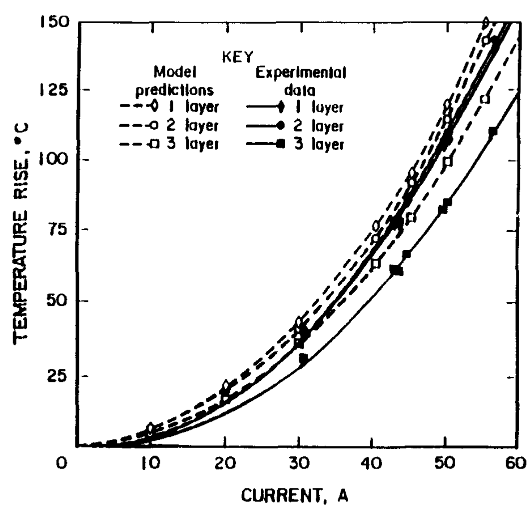

Fig. 7. Comparison of model and experimental data for temperature rise as a function of current

The program can be used to calculate ampacities of any type of round cable, wound on any type of reel, operating under any environmental temperature. As an example, the data in table 2 provide calculated cable ampacities for several typical copper-conductor sizes. The ampacity values in this table assume a 3-conductor, G-GC cable design with an ambient temperature of 40° C and a maximum conductor temperature of 90° C. The cable bundle was assumed to have an effective thermal conductivity of 1 W/m °C and a jacket surface emissivity of 0.9.

A convenient way to provide cable ampacities is to give so-called derating factors that can be used in conjunction with ampacities that have been calculated for a cable suspended in still air. The derating factor is defined as the ratio of the ampacity of the cable mass wound on the reel to the ampacity of the same sizecable suspended in air. Therefore, the ampacity of cables on a reel can be calculated from the relation

$$(I)_{reel} = (DF)(I)_{air} \qquad (16)$$

By using the ampacity values for cables on reels as given in table 2 and the ampacity values for cables suspended in air given in table J-1 of reference 2, derating factors can be determined for cables wound on reels. When derating factors are calculated in this way, the values do not vary significantly for different conductor sizes. Therefore, the derating factor within about 10 percent, is not a function of conductor size and it can be given only as a function of the number of cable layers on the reel. Calculated derating factors for one to ten layers of cable are shown in table 3. The derating factors for one to four cable layers recommended in reference 2 are also included in table 3 for comparison.

The calculated derating factors in table 3 are different from those provided in reference 2 and the difference is larger for a small number of cable layers. The difference disappears as the number of layers increases. Since the calculated derating factors in table 3 are less than the ones which are in reference 2, use of the NEMA ampacity values for cable reels can lead to overheating, particularly for those reels that have less than three layers of cables. Therefore, if the new derating factors are applied, cable reels should have their ampacity reduced in order to maintain a safe operating temperature level. These conditions were determined from static conditions only.

IV. CONCLUSIONS

The mathematical model presented in this paper is shown to be capable of calculating valid and accurate temperature distributions in a cable mass wound on a cable reel. The model predicts maximum temperature rises that are consistently within 10° C when compared to temperature rises measured during tests conducted on a cable reel system having from one to six layers of #6 and #4 AWG copper wire wound on a commonly used cable reel. In general, the mathematical model overpredicts temperature for a given ampacity, because the model is designed to provide conservative results.

The mathematical model is formulated into a PC-based computer program which is capable of predicting the ampacity of an arbitrary size aluminum or copper round cable wound on any type of reel operating under still air conditions. To demonstrate the value of the program, cable ampacities are calculated as a function of number of layers for two typical copper conductors. From these calculated ampacity values, derating factors are determined which can be used in

Table 2.—Model generated 90° C cable ampacities for G-GC, 3-conductor copper cables wound on reels ($k = 1 W/m\,°C$, $T_\infty = 40°\,C$, $D = 0.254$ m, $\varepsilon = 0.9$)

90° C ampacity (A)										
Conductor size	Number of layers on reel									
(AWG)	1	2	3	4	5	6	7	8	9	10
4/0	230	154	119	98	85	75	-	-	-	-
2/0	169	113	88	74	64	56	50	-	-	-
1/0	147	99	77	65	56	49	44	-	-	-
1	126	84	66	56	48	43	38	35	-	-
2	107	72	57	47	41	36	33	30	-	-
3	92	62	49	41	36	32	29	26	24	-
4	80	55	43	36	31	28	25	23	21	-
6	60	41	32	27	24	21	19	17	16	15
8	46	32	25	21	18	16	15	13	12	11

Table 3.—Derating factors for one to ten layers of cable wound on a reel

No. of layers	Derating factor from model	Derating factor from ref. [2]
1	0.78	0.85
2	0.53	0.65
3	0.41	0.45
4	0.34	0.35
5	0.30	-
6	0.27	-
7	0.24	-
8	0.22	-
9	0.20	-
10	0.19	-

conjunction with previously published ICEA/NEMA ampacities for cables suspended in air. The calculated derating factors are expanded to provide guidance on how heavily to load a cable reel wrapped with a large number of layers. The new derating factors are less than the previously published ICEA/NEMA values, particularly for those reels that have less than three layers of cable. Since the calculated ampacities are based on a conservative model, these ampacities suggest that the ICEA/NEMA derating factors do not lead to conservative temperatures for modern cable designs when they are wound on reels.

VI. REFERENCES

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VII. BIOGRAPHY

Peter G. Kovalchik was born in Johnstown, Pa., in 1952. He received the B.S. degree from University of Pittsburgh, Pa. in 1983. He joined the Bureau of Mines in March 1978 as an Electronic Technician in the Electrical and Electronic Systems Group. Currently he is with the Electrical and Electronic Systems Group of the Pittsburgh Research Center as an electronic engineer. He has been responsible for programs concerning trailing cables and hoisting.

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W. Z. Black received his B.S. and M.S. in Mechanical Engineering from the University of Illinois and his Ph.D. in M.E. from Purdue University. He is currently Regents Professor and Georgia Power Distinguished Professor of Mechanical Engineering at Georgia Institute of Technology in Atlanta. His research effort is concentrated in the area of heat transfer from electrical and electronic equipment. He has been Principal Investigator for several EPRI ampacity projects and he is active in IEEE committee work relating to the thermal ratings of overhead and underground conductors.