IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors

IEEE Power Engineering Society

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Approved 16 November 2006

IEEE-SA Standards Board

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Abstract: A method of calculating the current-temperature relationship of bare overhead lines, given the weather conditions, is presented. Along with a mathematical method, sources of the values to be used in the calculation are indicated. This standard does not undertake to list actual temperature-ampacity relationships for a large number of conductors, but rather provides a standard method of doing such calculations.
Keywords: bare overhead lines, current-temperature relationship

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Introduction

This introduction is not part of IEEE Std 738-2006, IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors.

In 1986, IEEE Std 738-1993, IEEE Standard for Calculation of Bare Overhead Conductor Temperature and Ampacity Under Steady-State Conditions, was first published. The standard was developed "so that a practical sound, and uniform method (of calculation) might be utilized and referenced." As part of the revision in 1993, the Working Group on the Calculation of Bare Overhead Conductor Temperatures, which was responsible for the revision of this standard, decided to address fault current and transient ratings and include their calculation in this standard.

In the present revision, SI units were added throughout, the solar heating calculation was extensively revised, and many editorial changes were made.

Consistent with IEEE guidelines for standards such as this, SI units are used exclusively in the main body. "English" units are used in Annex A since they are widely utilized by power transmission line design engineers in North America.

This standard includes a computer program listing to serve as a basis for program development. The working group has made every effort to ensure that the program yields accurate results. The user is cautioned that there may be values of rating parameters for which the method is not appropriate.

Many persons have contributed to the preparation, analysis, and review of this standard. We would like to recognize the contribution of the late B.S. Howington, who served as chair of the working group for many years and was responsible for developing the original standard. Richard E. Kennon, James Larkey, Jerry Reding, and Dale Douglass (Task Force Chairman) did most of the revisions in the latest version of the standard. Many of the other Working Group members contributed their time and thought. Catherine Berger, an IEEE staff editor, was immensely helpful in getting the standard completed in an acceptable format.

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IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors

1. Overview

1.1 Scope

The purpose of this standard is to present a method of calculating the current-temperature relationship of bare overhead conductors.

Conductor surface temperatures are a function of the following:

a) Conductor material properties

b) Conductor diameter

c) Conductor surface conditions

d) Ambient weather conditions

e) Conductor electrical current

The first two of these properties are specific chemical and physical properties. The third may vary with time and be dependent upon ambient atmospheric conditions other than weather. The fourth, weather, varies greatly with the hour and season. The fifth, conductor electrical current, may be constant or may vary with power system loading, generation dispatch, and other factors.

The equations relating electrical current to conductor temperature may be used in either of the following two ways:

— To calculate the conductor temperature when the electrical current is known

— To calculate the current that yields a given maximum allowable conductor temperature

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For the purposes of this standard, either the electrical current is assumed constant for all time or it is assumed to undergo a step change from an initial current to a final current. The ambient weather conditions are assumed to be constant with time in both the steady-state and transient calculation methods described in this standard.

This standard includes mathematical methods and indicates sources of the values to be used in the calculation of conductor temperatures and conductor thermal ratings. However, because there is a great diversity of weather conditions and operating circumstances for which conductor temperatures and/or thermal ratings must be calculated, the standard does not undertake to list actual temperature-current relationships for specific conductors or weather conditions. Each user must make their own assessment of which weather data and conductor characteristics best pertain to their area or particular transmission line.

The calculation methods in this standard are also valid for the calculation of conductor temperature under fault conditions.

1.2 Disclaimer

A computer program is included in this standard as a convenience to the user. Other numerical methods may well be more appropriate in certain situations.

The IEEE Conductors Working Group of the Towers, Poles, and Conductors Subcommittee has made every effort to ensure that the program yields accurate calculations under anticipated conditions; however, there may well be certain calculations for which the method is not appropriate. It is the responsibility of the user to check calculations against either test data or other existing calculation methods.

2 Definitions

For the purposes of this document, the following terms and definitions apply. The Authoritative Dictionary of IEEE Standard Terms [B21][1] should be referenced for terms not defined in this clause.

2.1 conductor temperature: The temperature of a conductor is assumed to be isothermal (i.e., no axial or radial temperature variation) for all steady-state calculations and for all transient calculations where the time period of interest exceeds 1 min or the conductor consists of a single material. With transient calculations for times less than 1 min with non-homogeneous aluminum conductor steel reinforced (ACSR) conductors, the aluminum strands are isothermal, but the heat capacity of the steel core is assumed to be zero.

2.2 heat capacity (material): When the conductor temperature is increased by dT_c as a result of adding a quantity of heat dQ_c, the ratio, dQ_c/dT_c, is the heat capacity of the conductor.

2.3 maximum allowable conductor temperature: The maximum temperature limit that is selected in order to minimize loss of strength, sag, line losses, or a combination of the above.

2.4 Reynolds number: A non-dimensional number equal to air velocity (V_w) times conductor diameter (D) divided by kinematic viscosity (μ_f/ρ_f).

2.5 specific heat: The specific heat of a conductor material is its heat capacity divided by its mass.

2.6 steady-state thermal rating: The constant electrical current that would yield the maximum allowable conductor temperature for specified weather conditions and conductor characteristics under the assumption that the conductor is in thermal equilibrium (steady state).

[1] The numbers in brackets correspond to those of the bibliography in Annex H

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2.7 thermal time constant: The time required for the conductor temperature to accomplish 63.2% of a change in initial temperature to the final temperature when the electrical current going through a conductor undergoes a step change.

2.8 transient thermal rating: The transient thermal rating is that final current (I_f) that yields the maximum allowable conductor temperature (T_c) in a specified time after a step change in electrical current from some initial current, I_i.

2.9 wind direction: The direction of the movement of air relative to the conductor axis. The wind direction and the conductor axis are assumed to be in a plane parallel to the earth. When the wind is blowing parallel to the conductor axis it is termed "parallel wind." When the wind is blowing perpendicularly to the conductor axis, it is termed "perpendicular wind."

3. Temperature calculation methods

The Working Group on the Calculation of Bare Overhead Conductor Temperatures has conducted a study on the various methods used in calculating heat transfer and ampacities of transmission line conductors. Methods that were studied include the methods contained in the following publications:

a) House and Tuttle [B20]

b) ECAR, House and Tuttle method as modified by East Central Area Reliability [B29]

c) Mussen [B24]

d) Pennsylvania-New Jersey-Maryland Interconnection [B11]

e) Schurig and Frick [B25]

f) Hilpert [B17]

g) Davis [B9]

h) Morgan [B22]

i) Black and Bush [B3]

j) Black and Byrd [B4]

k) Foss, Lin, and Fernandez [B15]

The mathematical models of this standard are based upon the House and Tuttle method as modified by ECAR [B29]. The House and Tuttle formulas consider all of the essential factors without the simplifications that were made in some of the other formulas.

To differentiate between laminar and turbulent air flow, the House and Tuttle method [B20] uses two different formulas for forced convection; the transition from one to the other is made at a Reynolds number of 1000. Because turbulence begins at some wind velocity and reaches its peak at some higher velocity, the transition from one curve to another is a curved line, not a discontinuity. The single transition value was selected as a convenience in calculating conductor ampacities.

The single transition value results in a discontinuity in current magnitude when this value is reached. Therefore, to avoid this discontinuity that occurs using the House and Tuttle method [B20], ECAR [B29] elected to make the change from laminar to turbulent air flow at the point where the curves developed from

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the two formulas [Equation (3a) and Equation (3b)] cross. The formulas for forced convection heat loss have an upper limit of application validity at a Reynolds number of 50 000 (see McAdams [B22]). For additional information on convection heat loss, see 4.2 of this standard.

The primary application of this standard is anticipated to be the calculation of steady-state and transient thermal ratings and conductor temperatures under constant weather conditions. Given the widespread availability of desktop personal computers, the calculation method specified avoids certain simplifications that might be advisable where the speed or complexity of calculations is important.

In Davis [B9], the heat balance equation is expressed as a biquadratic equation that can be solved to give the conductor temperature directly. In Black and Rehberg [B5] and Wong, et al. [B30], the radiation term is linearized and the resulting approximate linearized heat balance equation is solved using standard methods of linear differential equations. In Foss [B14], a somewhat more precise linearized radiation term is used to reduce the number of iterations required. These methods are computationally faster than the iterative method described in this standard; however, the algebraic expressions are more complex.

3.1 Steady-state calculations

3.1.1 Steady-state thermal rating

For a bare stranded conductor, if the conductor temperature (T_c) and the steady-state weather parameters (V_w, T_a, etc.) are known, the heat losses due to convection and radiation (q_c and q_r), the solar heat gain (q_s), and the conductor resistance $R(T_c)$ can be calculated by the formulas of 3.4. The corresponding conductor current (I) that produced this conductor temperature under these weather conditions can be found from the steady-state heat balance [Equation (1b) of 3.4.1]. While this calculation can be done for any conductor temperature and any weather conditions, a maximum allowable conductor temperature (e.g., 75 °C to 150 °C) and "conservative" weather conditions (e.g., 0.6 m/s to 1.2 m/s wind speed, 30 °C to 45 °C summer ambient) [2] are often used to calculate a steady-state thermal rating for the conductor.

3.1.2 Steady-state conductor temperature

Since the radiation and convection heat loss rates are not linearly dependent on the conductor temperature, the heat balance equation [Equation (1b) of 3.4.1] is solved for conductor temperature in terms of the current and weather variables by a process of iteration—that is, given a conductor current,

a) A conductor temperature is assumed.

b) The corresponding heat losses are calculated.

c) The conductor current that yields this conductor temperature is calculated by means of Equation (1b).

d) The calculated current is compared to the given conductor current.

e) The conductor temperature is then increased or decreased until the calculated current equals the given current.

[2] This wind speed in English units would be 2 ft/s to 4 ft/s.

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3.2 Transient calculations

3.2.1 Transient conductor temperature

The temperature of an overhead power conductor is constantly changing in response to changes in electrical current and weather. In this standard, however, weather parameters (wind speed and direction, ambient temperature, etc.) are assumed to remain constant; and any change in electrical current is limited to a step change from an initial current, I_i, to a final current, I_f, as illustrated in Figure 1.

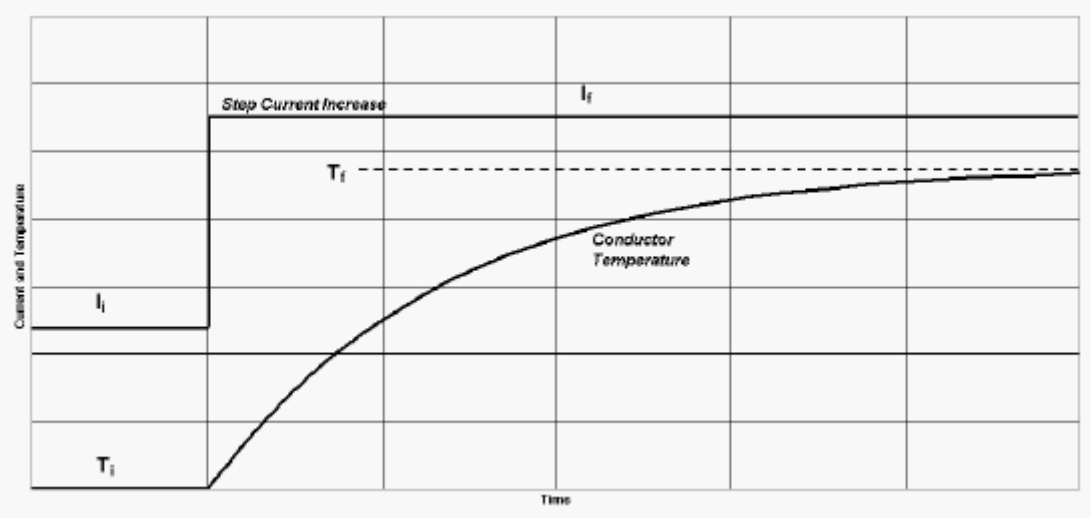

Figure 1— "Step" change in current

Immediately prior to the current step change ($t = 0^-$), the conductor is assumed to be in thermal equilibrium. That is, the sum of heat generation by Ohmic losses and solar heating equals the heat loss by convection and radiation.

Immediately after the current step change ($t = 0^+$), the conductor temperature is unchanged (as are the conductor resistance and the heat loss rate due to convection and radiation), but the rate of heat generation due to Ohmic losses has increased. Therefore, at time $t = 0^+$, the temperature of the conductor begins to increase at a rate given by the non-steady-state heat balance Equation (2b) in 3.4.2.

After a period of time, Δt, the conductor temperature has increased by a temperature change of ΔT_c. The increased conductor temperature yields higher heat losses due to convection and radiation and somewhat higher Ohmic heat generation due to the increased conductor resistance. From Δt to $2\Delta t$, the conductor temperature continues to increase, but does so at a lower rate. After a large number of such time intervals, the conductor temperature approaches its final steady-state temperature (T_f).

During each interval of time, the corresponding increase in conductor temperature may be calculated using the formulas given in 3.4. The computer program included in Annex B calculates the conductor temperature as a function of time after the step change in current.

Accuracy in the iterative transient calculation requires that the time step chosen be sufficiently small with respect to the thermal time constant. It is always prudent to rerun the calculation with a smaller time step to check whether the calculated values change.

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3.2.2 Transient thermal rating

The transient thermal rating is normally calculated by repeating the preceding calculations of $T_c(t)$ over a range of I_f values, then selecting the I_f value that causes the conductor temperature to reach its maximum allowable value in the allotted time.

3.2.3 Fault current calculations

Conductor temperature changes in response to "fault" currents are calculated in the same manner as in 3.2.1, except that the step increase in current is usually quite large (>10 000 A), the corresponding time to reach maximum allowable temperature is typically short (<1 s), and the maximum temperatures attained may approach the melting point of aluminum or copper.

With nonhomogeneous conductors, such as aluminum conductor steel reinforced (ACSR), the heat generation in the lower conductivity steel core is much lower than in the surrounding aluminum strand layers. The resulting temperature difference between the core and the surrounding aluminum strands abates after no more than 60 s from any step change in current. This is discussed further in 3.4.8.

3.3 Units and identification of letter symbols

NOTE—SI units are the preferred unit of measure. However, in the United States the calculations described in this standard have frequently been performed using a combination of units that will be referred to throughout this document as "English" units. See Annex A for an analysis using these units.[3]

Table 1—Units and identification of letter symbols

Symbol	Description	SI units
A'	Projected area of conductor per unit length	m^2/m
C	Solar azimuth constant	degrees
C_{pi}	Specific heat of i^{th} conductor material	J/(kg-°C)
D	Conductor diameter	mm
H_c	Altitude of sun	degrees
H_e	Elevation of conductor above sea level	m
I	Conductor current	A
I_i	Initial current before step change	A
I_f	Final current after step change	A
K_{angle}	Wind direction factor	—
K_{solar}	Solar altitude correction factor	—
k_f	Thermal conductivity of air at temperature T_{film}	W/(m-°C)
Lat	Degrees of latitude	degrees
mC_p	Total heat capacity of conductor	J/(m-°C)
m_i	Mass per unit length of i^{th} conductor material	kg/m
N	Day of the year (January 21 = 21, February 12 = 43, etc.)	—
q_{cn}, q_{c1}, q_{c2}, q_c	Convected heat loss rate per unit length	W/m
q_r	Radiated heat loss rate per unit length	W/m

[3] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

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Table 1—Units and identification of letter symbols *(continued)*

Symbol	Description	SI units
q_s	Heat gain rate from sun	W/m
Q_s	Total solar and sky radiated heat flux rate	W/m^2
Q_{se}	Total solar and sky radiated heat flux rate elevation corrected	W/m^2
$R(T_c)$	AC resistance of conductor at temperature, T_c	Ω/m
T_a	Ambient air temperature	°C
T_c	Conductor temperature	°C
T_f	Conductor temperature many time constants after step increase	°C
T_i	Conductor temperature prior to step increase	°C
T_{film}	$(T_c + T_a)/2$	°C
T_{low}	Minimum conductor temperature for which ac resistance is specified	°C
T_{high}	Maximum conductor temperature for which ac resistance is specified	°C
V_w	Speed of air stream at conductor	m/s
Z_c	Azimuth of sun	degrees
Z_l	Azimuth of line	degrees
Δt	Time step used in transient calculation	s
ΔT_c	Conductor temperature increment corresponding to time step	°C
α	Solar absorptivity (0.23 to 0.91)	—
δ	Solar declination (0 to 90)	degrees
ε	Emissivity (0.23 to 0.91)	—
τ	Thermal time constant of the conductor	s
ϕ	Angle between wind and axis of conductor	degrees
β	Angle between wind and perpendicular to conductor axis	degrees
ρ_f	Density of air	kg/m^3
θ	Effective angle of incidence of the sun's rays	degrees
μ_f	Dynamic viscosity of air	Pa-s
ω	Hours from local sun noon times 15	degrees
χ	Solar azimuth variable	—

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3.4 Formulas

3.4.1 Steady-state heat balance

$$q_c + q_r = q_s + I^2 R(T_c) \tag{1a}$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \tag{1b}$$

3.4.2 Non-steady-state heat balance

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c) \tag{2a}$$

$$\frac{dT_c}{dt} = \frac{1}{mC_p}\left[R(T_c)I^2 + q_s - q_c - q_r\right] \tag{2b}$$

3.4.3 Forced convection heat loss rate

NOTE—The English unit equivalents of these equations can be found in A.2.1.

$$q_{c1} = \left[1.01 + 0.0372\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.52}\right] k_f K_{angle}\left(T_c - T_a\right) \tag{3a}$$

$$q_{c2} = \left[0.0119\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.6} k_f K_{angle}\left(T_c - T_a\right)\right] \tag{3b}$$

Equation (3a) applies at low winds but is incorrect at high wind speeds. Equation (3b) applies at high wind speeds, being incorrect at low wind speeds. At any wind speed, the larger of the two calculated convection heat loss rates is used.

The convective heat loss rate is multiplied by the wind direction factor, K_{angle}, where ϕ is the angle between the wind direction and the conductor axis [see Equation (4a)].

$$K_{angle} = 1.194 - \cos(\phi) + 0.194\cos(2\phi) + 0.368\sin(2\phi) \tag{4a}$$

Alternatively, the wind direction factor may be expressed as a function of the angle, ß, between the wind direction and a perpendicular to the conductor axis. This angle is the complement of ϕ, and the wind direction factor becomes as shown in Equation (4b).

$$K_{angle} = 1.194 - \sin(\beta) - 0.194\cos(2\beta) + 0.368\sin(2\beta) \tag{4b}$$

This is the form of the wind direction factor as originally suggested in Davis [B9] and is used in the computer program listed in Annex B.

3.4.4 Natural convection

With zero wind speed, natural convection occurs, where the rate of heat loss is as shown in Equation (5).

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$$q_{cn} = 0.0205\rho_f^{0.5} D^{0.75} \left(T_c - T_a\right)^{1.25} \tag{5}$$

NOTE—The English unit equivalent of this equation can be found in A.2.2.

It has been argued that at low wind speeds, the convection cooling rate should be calculated by using a vector sum of the wind speed and a "natural" wind speed, see Morgan [B23]. However, it is recommended that only the larger of the forced and natural convection heat loss rates be used at low wind speeds instead of their vector sum as this is conservative. The computer program listed in Annex B takes this approach.

For both forced and natural convection, air density (ρ_f), air viscosity (μ_f), and coefficient of thermal conductivity of air (k_f) are taken from Table 1 or calculated with the equations of 3.5 at T_{film} where:

$$T_{film} = \frac{T_c + T_a}{2} \tag{6}$$

3.4.5 Radiated heat loss rate

$$q_r = 0.0178 D \varepsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \tag{7}$$

NOTE—The English unit equivalent of this equation can be found in A.2.3.

3.4.6 Rate of solar heat gain (see Table 4, Table 5, and Table 6)

$$q_s = \alpha Q_{se} \sin(\theta) A' \tag{8}$$

where

$$\theta = \arccos\left[\cos(H_c)\cos(Z_c - Z_l)\right] \tag{9}$$

NOTE—The English unit equivalent of this equation can be found in A.2.4.

3.4.7 Conductor electrical resistance

The electrical resistance of bare stranded conductor varies with frequency, average current density, and temperature. For 60 Hz ac, at temperatures of 25 °C to 75 °C, the *Aluminum Electrical Conductor Handbook* [B1] gives calculated values of electrical resistance for most standard aluminum power conductors.

These calculated values include the frequency-dependent "skin effect" for all types of stranded conductor, but, for other than single-layer ACSR, do not include a correction for current density dependent magnetic core effects, which is significant for ACSR conductors having odd numbers of layers of aluminum strands. The resistance of single-layer ACSR conductors (6/1, 7/1, 12/7) is shown to be increased as much as 20% in the *Aluminum Electrical Conductor Handbook* [B1]. The resistance of three-layer ACSR (45/7, 54/7, etc.) may be as much as 3% higher than the tabulated values. Engineering judgment is required in thermal calculations involving these ACSR conductors.

Resistance at temperatures above 75 °C may be calculated according to the methods described in the *Aluminum Electrical Conductor Handbook* [B1], Black and Bush [B3], and Douglass, et al. [B12].

In this standard, electrical resistance is calculated solely as a function of conductor temperature; however, the resistance values entered may be a function of frequency and current density. For example, the values of conductor resistance at high temperature, T_{high}, and low temperature, T_{low}, may be taken from the

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tabulated values in the *Aluminum Electrical Conductor Handbook* [B1]. The conductor resistance at any other temperature, T_c, is found by linear interpolation according to Equation (10).

$$R(T_c) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}} \right] (T_c - T_{low}) + R(T_{low}) \quad (10)$$

This method of resistance calculation allows the user to calculate the high and low temperature resistance values by whatever means is appropriate.

Since the resistivity of most common metals used in stranded conductors increases somewhat faster than linearly with temperature, the resistance calculated by Equation (10) will be somewhat high (and thus conservative for rating calculations) so long as conductor temperature is between T_{low} and T_{high}. If the conductor temperature exceeds T_{high}, however, the calculated resistance will be somewhat low (and thus non-conservative for rating calculations). For example, based upon measurements of individual 1350 H19 aluminum strand resistance for a temperature range of 20 °C to 500 °C, entry of resistance values at temperatures of 25 °C and 75 °C will yield estimates of conductor resistance that are approximately 1% and 5% lower than measured values at temperatures of 175 °C and 500 °C, respectively. Between 25 °C and 75 °C, the error is negligible. Similarly, entry of resistance values at temperatures of 25 °C and 175 °C, will yield estimates that are approximately 3% too low at 500 °C but 0.5% too high at 75 °C.

It is concluded that the use of resistance data for temperatures of 25 °C and 75 °C from the *Aluminum Electrical Conductor Handbook* [B1] is adequate for rough calculations of steady-state and transient thermal ratings for conductor temperatures up to 175 °C, and may be used for approximate fault calculations up to the melting point of typical conductor materials.

3.4.8 Conductor heat capacity

Conductor heat capacity is defined as the product of specific heat and mass per unit length. If the conductor consists of more than one material (e.g., ACSR), then the heat capacities of the core and the outer strands are each defined in this way.

For transient thermal rating calculations with durations of 5 min to 30 min, the temperature of the conductor components remains approximately equal after the step increase in current. The heat capacity of the conductor can be calculated as the sum of the component heat capacities as shown in Equation (11).

$$mC_p = \sum m_i C_{pi} \quad (11)$$

Values for the specific heat of common metals used in stranded overhead conductors are listed in Black and Rehberg [B5] and in 4.6 of this standard.

With a nonhomogeneous conductor, for faults with durations of less than 60 s, the internal temperature difference between the core and the outer strands can be neglected. In particular, for ACSR conductor, the heat capacity of the relatively nonconducting steel core should be neglected for step currents whose duration is less than 60 s. For step currents whose duration is greater than 60 s, the heat capacity of the core is included. For step current durations of 10 s to 60 s, the calculated conductor temperatures are somewhat conservative because any temperature difference between the core and outer strands decreases to zero with an internal thermal time constant of the order of 10 s to 20 s.

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3.5 Equations for air properties, solar angles, and solar heat flux

In the following section, least square polynomial regressions were performed on tabular data for thermal conductivity (3.5.3), total heat flux (3.5.6), and solar heat correction for elevation (3.5.7) to fit an equation of the following form:

$$Y = A + BX + CX^2 + DX^3 + EX^4 + FX^5 + GX^6$$

Algebraic equations are given for viscosity (3.5.1), density (3.5.2), solar altitude (3.5.4), azimuth (3.5.5).

Tables of typical values are provided for convenience.

3.5.1 Dynamic viscosity of air

The dynamic viscosity of air is determined by the algebraic equation listed in Equation (12).

$$\mu_f = \frac{1.458 \times 10^{-6} (T_{film} + 273)^{1.5}}{T_{film} + 383.4} \quad (12)$$

NOTE—The English unit equivalent of this equation can be found in A.3.1.

3.5.2 Air density (Table 2)

$$\rho_f = \frac{1.293 - 1.525 \times 10^{-4} H_e + 6.379 \times 10^{-9} H_e^2}{1 + 0.00367 T_{film}} \quad (13)$$

NOTE—The English unit equivalent of this equation can be found in A.3.2.

3.5.3 Thermal conductivity of air (Table 2)

$$k_f = 2.424 \times 10^{-2} + 7.477 \times 10^{-5} T_{film} - 4.407 \times 10^{-9} T_{film}^2 \quad (14)$$

NOTE—The English unit equivalent of this equation can be found in A.3.3.

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Table 2—Viscosity, density, and thermal conductivity of air

Temperature T_{film}	Dynamic discosity μ_f	Air density ρ_f (kg/m^3)				Thermal conductivity of air k_f
°C	(Pa·s)	0 m	1000 m	2000 m	4000 m	W/(m·°C)
0	0.0000172	1.293	1.147	1.014	0.785	0.0242
5	0.0000174	1.270	1.126	0.995	0.771	0.0246
10	0.0000176	1.247	1.106	0.978	0.757	0.0250
15	0.0000179	1.226	1.087	0.961	0.744	0.0254
20	0.0000181	1.205	1.068	0.944	0.731	0.0257
25	0.0000184	1.184	1.051	0.928	0.719	0.0261
30	0.0000186	1.165	1.033	0.913	0.707	0.0265
35	0.0000188	1.146	1.016	0.898	0.696	0.0269
40	0.0000191	1.127	1.000	0.884	0.685	0.0272
45	0.0000193	1.110	0.984	0.870	0.674	0.0276
50	0.0000195	1.093	0.969	0.856	0.663	0.0280
55	0.0000198	1.076	0.954	0.843	0.653	0.0283
60	0.0000200	1.060	0.940	0.831	0.643	0.0287
65	0.0000202	1.044	0.926	0.818	0.634	0.0291
70	0.0000204	1.029	0.912	0.806	0.625	0.0295
75	0.0000207	1.014	0.899	0.795	0.616	0.0298
80	0.0000209	1.000	0.887	0.783	0.607	0.0302
85	0.0000211	0.986	0.874	0.773	0.598	0.0306
90	0.0000213	0.972	0.862	0.762	0.590	0.0309
95	0.0000215	0.959	0.850	0.752	0.582	0.0313
100	0.0000217	0.946	0.839	0.741	0.574	0.0317

3.5.4 Altitude of the sun (Table 4)

The solar altitude of the sun, H_c, in degrees (or radians) is given by Equation (15a) where inverse trigonometric function arguments are in degrees (or radians).

$$H_c = \arcsin\left[\cos(Lat)\cos(\delta)\cos(\omega) + \sin(Lat)\sin(\delta)\right] \quad (15a)$$

The hour angle, ω, is the number of hours from noon times 15° (for example, 11 a.m. is –15°, 2 p.m. is +30°).

The solar declination, δ, is shown in Equation (15b).

$$\delta = 23.4583\sin\left[\frac{284+N}{365}360\right] \quad (15b)$$

where the argument of the sin is in degrees.

The equation is valid for all latitudes whether positive (northern hemisphere) or negative (southern hemisphere).

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3.5.5 Azimuth of the sun (Table 4)

The solar azimuth, Z_c, (in degrees) is shown in Equation (16a):

$$Z_c = C + \arctan(\chi) \tag{16a}$$

where

$$\chi = \frac{\sin(\omega)}{\sin(Lat)\cos(\omega) - \cos(Lat)\tan(\delta)} \tag{16b}$$

The solar azimuth constant, C, (in degrees), is a function of the "hour angle", ω, and the solar azimuth variable, χ, as shown in the Table 3.

Table 3—Solar azimuth constant, C, as a function of "hour angle", ω, and solar azimuth variable, χ

"Hour Angle," ω (degrees)	C if $\chi \geq 0$ (degrees)	C if $\chi < 0$ (degrees)
$-180 \leq \omega < 0$	0	180
$0 \leq \omega \leq 180$	180	360

Table 4—Solar altitude, H_c, and azimuth, Z_c, at various latitudes for an annual peak solar heat input

	Local sun time						
Latitude	10:00 a.m.		Noon		2:00 p.m.		
(Degrees North)	H_c	Z_c	H_c	Z_c	H_c	Z_c	N
–80	32	33	33	180	32	327	350
–70	40	37	43	180	40	323	350
–60	48	43	53	180	48	317	350
–50	55	52	63	180	55	308	350
–40	60	66	73	180	60	294	350
–30	62	83	83	180	62	277	350
–20	62	96	90	180	62	264	20
–10	61	97	88	180	61	263	50
0	60	91	90	180	60	269	80
10	61	85	89	180	61	275	110
20	62	85	90	180	62	275	140
30	62	97	83	180	62	263	170
40	60	114	73	180	60	245	170
50	55	128	63	180	55	232	170
60	48	137	53	180	48	223	170
70	40	143	43	180	40	217	170
80	32	147	33	180	32	213	170

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3.5.6 Total heat flux received by a surface at sea level (Table 5 and Table 6)

The total solar heat flux density at sea level is dependent on both the solar altitude and atmospheric clarity (see the Heating, Ventilating and Air Conditioning Guide [B16]).

The heat flux density received by a surface at sea level as shown in Table 5 may be represented by the following regression equation [Equation (17)].

Y = total heat flux, Q_S (w/m^2)

X = solar altitude, H_C (degrees)

$$Q_s = A + BH_c + CH_c^2 + DH_c^3 + EH_c^4 + FH_c^5 + GH_c^6 \quad (17)$$

Table 5—Coefficients for Equation (17)

Clear atmosphere	
A	–42.2391
B	63.8044
C	–1.9220
D	3.46921×10^{-2}
E	-3.61118×10^{-4}
F	1.94318×10^{-6}
G	-4.07608×10^{-9}
Industrial atmosphere	
A	53.1821
B	14.2110
C	6.6138×10^{-1}
D	-3.1658×10^{-2}
E	5.4654×10^{-4}
F	-4.3446×10^{-6}
G	1.3236×10^{-8}

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Table 6—Total heat flux received by a surface at sea level normal to the sun's rays

Degrees solar altitude	Clear atmosphere	Industrial atmosphere
H_c (deg)	Q_s (W/m^2)	Q_s (W/m^2)
5	234	136
10	433	240
15	583	328
20	693	422
25	770	502
30	829	571
35	877	619
40	913	662
45	941	694
50	969	727
60	1000	771
70	1020	809
80	1030	833
90	1040	849

3.5.7 Total heat flux elevation correction factor (Table 7)

$$Q_{se} = K_{solar}\, Q_s \tag{18}$$

where

$$K_{solar} = A + BH_e + CH_e^2 \tag{19}$$

$A = 1$

$B = 1.148 \times 10^{-4}$

$C = -1.108 \times 10^{-8}$

Table 7—Solar heat multiplying factors, K_{solar} for high altitudes (Yellot [B31])

Elevation above sea level H_e (m)	Multipliers for values in Table 5
0	1.00
1 000	1.10
2 000	1.19
4 000	1.28

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3.6 Sample calculations

3.6.1 Steady-state thermal rating

The calculation of steady-state thermal rating given a maximum allowable conductor temperature, weather conditions, and conductor characteristics may be performed by the computer program in Annex B. The following sample calculation is done with that program and is included in Annex C. However, since the process does not require iterative calculations, it can also be done by hand. Doing so demonstrates the use of the formulas and yields some insight into the calculation process.

Note that in the following, the number of significant digits does not indicate the accuracy of the formula.

3.6.1.1 Problem statement

Find the steady-state thermal rating (ampacity) for a "Drake" 26/7 ACSR conductor, under the following conditions:

a) Wind speed (V_w) is 0.61 m/s perpendicular to the conductor.

b) Emissivity (ε) is 0.5.

c) Solar absorptivity (α) is 0.5.

d) Ambient air temperature is 40 °C.

e) Maximum allowable conductor temperature is 100 °C.

f) Conductor outside diameter (D) is 28.1 mm.

g) Conductor ac resistance [$R(T_c)$] is:

$$R(25\ °C) = 7.283 \times 10^{-5}\ (\Omega/m)$$

$$R(75\ °C) = 8.688 \times 10^{-5}\ (\Omega/m)$$

h) The line runs in an East-West direction so azimuth of line, $Z_l = 90°$.

i) Latitude is 30° North.

j) The atmosphere is clear.

k) Solar altitude (H_c) for 11:00 a.m. on June 10.

l) Average conductor elevation 100 m.

3.6.1.2 Convection heat loss (q_c)

The natural convection heat loss is calculated by means of Equation (5). See 3.4.4.

where

$D = 28.1$ mm

$T_c = 100$ °C

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$T_a = 40\ °C$

$T_{film} = \frac{100+40}{2} = 70\ °C$

$\rho_f = 1.029\ \text{kg/m}^3\ (\text{Table 2})$

$q_{cn} = 0.02050 \times (1.029)^{0.5} \times (28.1)^{0.75} \times (100-40)^{1.25} = 42.4\ \text{W/m}$

Since the wind speed is greater than zero, the forced convection heat loss for perpendicular wind is calculated according to Equation (3a) and Equation (3b), corrected for wind direction and compared to the natural convection heat loss. The largest of the heat losses due to both natural and forced heat convection is used to calculate the thermal rating.

where

$D = 28.1\ \text{mm}$

$V_w = 0.61\ \text{m/s}$

$T_c = 100\ °C$

$T_a = 40\ °C$

$T_{film} = \frac{100+40}{2} = 70\ °C$

$\mu_f = 2.04 \times 10^{-5}\ Pa-s\ (\text{Table 2})$

$\rho_f = 1.029\ \text{kg/m}^3\ (\text{Table 2})$

$k_f = 0.0295\ \text{W/(m}-°\text{C)}\ (\text{Table 2})$

$$q_{cl} = \left[1.01 + 0.0372\left(\frac{28.1 \times 1.029 \times 0.61}{2.04 \times 10^{-5}}\right)^{0.52}\right] \times 0.0295 \times (100-40) = 82.3\ \text{W/m}$$

$$q_{c2} = 0.0119\left(\frac{28.1 \times 1.029 \times 0.61}{2.04 \times 10^{-5}}\right)^{0.6} \times 0.0295 \times (100-40) = 76.9\ \text{W/m}$$

As instructed in 3.4.3, select the larger of the two calculated convection heat losses.

$q_c = 82.3\ \text{W/m}$

Since the wind is perpendicular to the axis of the conductor, the wind direction multiplier, K_{angle}, is 1.0, and the forced convection heat loss is greater than the natural convection heat loss. Therefore, the forced convection heat loss will be used in the calculation of thermal rating.

3.6.1.3 Radiated heat loss (q_r)

The radiated heat loss is calculated with Equation (7).

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where

$D = 28.1$ mm

$\varepsilon = 0.5$

$T_c = 100$ °C

$T_a = 40$ °C

$$q_r = 0.0178 \times 28.14 \times 0.5 \times \left[\left(\frac{373}{100} \right)^4 - \left(\frac{313}{100} \right)^4 \right]$$

$q_r = 24.44$ W/m

3.6.1.4 Solar heat gain (q_s)

The conductor is at 30° North latitude: Approximate values of H_c and Z_c can be obtained by interpolating from Table 4 and Table 5. From Table 4, the solar altitude, H_c, and the solar azimuth, Z_c, can be determined as follows:

H_c at 10 : 00 a.m. = 62°

H_c at 12 : 00 noon = 83°

$$H_c \text{ at } 11:00 \text{ a.m.} = \frac{83 + 62}{2} = 72.5°$$

Z_c at 10 : 00 a.m. = 98°

Z_c at 12 : 00 noon = 180°

$$Z_c \text{ at } 11:00 \text{ a.m.} = \frac{98 + 180}{2} = 139°$$

From Table 6 for H_c = 72.5° with clear atmosphere:

$Q_s = 1023$ W/m^2 (By interpolation)

$Z_l = 90°$ or 270°

$$\theta = \arccos\left[\cos(72.5°)\cos(139° - 90°)\right] = 78.62°$$

where

$\alpha = 0.5$

$A' = D/1000 = 28.1/1000 = 0.02814$ m^2/m

$K_{solar} = 1.0$

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$$q_s = 0.5 \times 1023 \times \sin\left(78.62^\circ\right) \times 0.02814$$

$$q_s = 14.1 \text{ W/m}$$

In determining solar azimuth and altitude, Equation (15) and Equation (16) should be used:

— For times of the year other than June 10 and July 3

— For times of the day before 10 a.m. and after 2 p.m.

— For latitudes less than 20°or greater than 70°

In this example, the equations will be used to allow a comparison to the approximate angles obtained from the tables in this standard.

In order to calculate the solar altitude, the day of the year, *N*, must first be found. For June 10, the day of the year is:

$$N = 31 + 28 + 31 + 30 + 31 + 10 = 161$$

The solar declination for June 10 is given by Equation (15b):

$$\delta = 23.4583 \times \sin\left[\frac{284 + 161}{365} \times 360\right]$$

$$\delta = 23.4583 \times 0.981 = 23.02^\circ$$

The solar altitude, H_c, is found by use of Equation (15a) where Lat = 30°:

$$H_c = \arcsin\left[\cos(30) \times \cos(23.0) \times \cos(-15) + \sin(30) \times \sin(23.0)\right]$$

$$H_c = \arcsin\left[0.866 \times 0.920 \times 0.966 + 0.500 \times 0.391\right] = 74.8^\circ$$

In order to calculate the solar azimuth, referring to Equation (16), one must first calculate the solar azimuth variable, χ. The solar azimuth variable, χ, for this example problem is as follows:

$$\chi = \frac{\sin(-15)}{\sin(30) \times \cos(-15) - \cos(30) \times \tan(23.0)} = \frac{-0.259}{(0.500)(0.966) - (0.866)(0.425)} = -2.24$$

From Table 3, since the solar azimuth variable, χ, is less than 0, and since the "hour angle", ω, is –15°, the solar azimuth constant, C, is equal to 180°.

Having determined both the solar azimuth variable, χ, and the constant C, the solar azimuth angle in degrees is as follows:

$$Z_c = 180 + \arctan(-2.24) = 180 - 65.9 = 114^\circ$$

Repeating the earlier calculation of solar heat gain with the new solar azimuth and altitude, the solar heat gain is as follows:

$$\theta = \arccos\left[\cos(75) \times \cos(114 - 90)\right] = 76.3^\circ$$

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$$q_s = 0.5 \times 1023 \times \sin(76.3°) \times 0.02814 = 14.0 \text{ W/m}$$

3.6.1.5 Resistance at 100 °C

$$R(100) = R(25) + \left(\frac{R(75) - R(25)}{75 - 25} \right) \times (100 - 25)$$

$$R(100) = 7.283 \times 10^{-5} + \left[\frac{8.688 \times 10^{-5} - 7.283 \times 10^{-5}}{50} \right] \times 75$$

$$R(100) = 9.390 \times 10^{-5} \ \Omega/\text{m}$$

3.6.1.6 Steady-state thermal rating

Using Equation (1), the steady-state thermal rating can be found where:

$q_c = 82.3$ W/m

$q_r = 24.44$ W/m

$q_s = 14.0$ W/m (from equations)

$R(100) = 9.390 \times 10^{-5}$ Ω/m

$$I = \sqrt{\frac{82.3 + 24.4 - 14.0}{9.390 \times 10^{-5}}}$$

$I = 994$ A

The program listed in Annex B can also be used to calculate the steady-state thermal rating. The results of such a run are presented in Annex C.

3.6.2 Steady-state conductor temperature

The steady-state conductor temperature for a given electrical current, weather conditions, and conductor characteristics can be calculated by means of the computer program in Annex B. A sample calculation is included in Annex D. This calculation cannot easily be done by hand since it requires repeated calculations of current, given trial values of conductor temperature, to converge to a solution.

3.6.3 Transient conductor temperature

The calculation of conductor temperature versus time in response to a step change in electrical current can be accomplished by means of the program in Annex B. The program is capable of calculating conductor temperature changes in response to a step change in electrical current where either the initial current or the initial conductor temperature is known.

For example, one may calculate the transient conductor temperature for the same “Drake” conductor and weather parameters as used in the previous steady-state sample calculation of 3.6.1, but where there is a step change in current from an initial current of 800 A to final currents of 1200 A and 1300 A. The weather conditions and conductor parameters are assumed constant for all time before and after the step change in current.

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With reference to Annex G and Figure 2, it can be seen that the steady-state conductor temperature corresponding to an initial current of 800 A is 81 °C. The steady-state conductor temperatures corresponding to the final current of 1200 A and 1300 A are 128 °C and 144 °C, respectively. In the computer-generated plots found in Annex G (Figure G.1), conductor temperature is calculated for every 2 min after the step change in current. Plots of conductor temperature vs. time are shown in Figure 2 for the first 60 min after the increase in current.

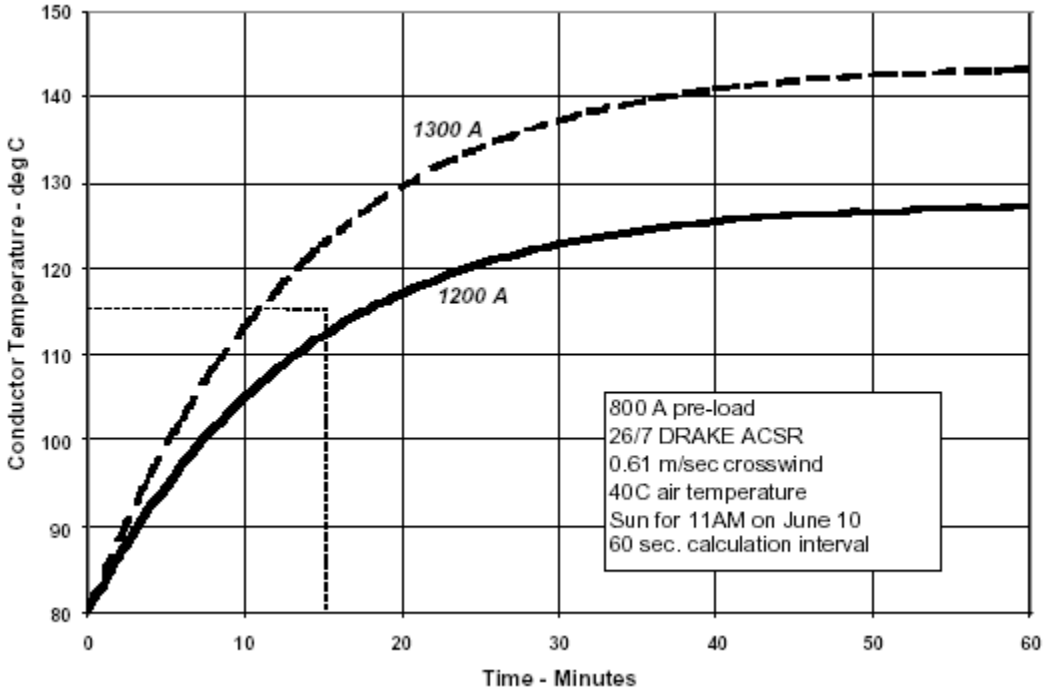

Figure 2—Transient temperature response to a "step" change in current

From Figure 2, it may be seen that the rate of increase in conductor temperature after the current step and the final steady-state conductor temperature both increase as the final current increases. The variation in conductor temperature with time is approximately exponential.

Transient conductor temperature calculations for relatively high fault currents for short times can also be performed with the same program. For example, using the program on Drake conductor carrying a step fault current of 80 000 A will predict a rapid increase in conductor temperature to over 300 °C in 0.5 s.

3.6.4 Transient thermal ratings

Transient thermal ratings may also be calculated with the computer program included in Annex B. The program determines transient thermal ratings by calculating a number of conductor temperature vs. time curves (such as those shown in Figure 2). This is illustrated in the following sample problem.

The initial electrical current in a Drake conductor is 800 A. The final current level that will yield a maximum allowable conductor temperature of 115 °C in 15 min, i.e., the 15 min transient thermal rating, is to be found. The weather conditions and conductor parameters remain the same as in the preceding examples.

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Referring to Figure 2, it can be seen that a final current of 1200 A causes the conductor temperature to increase from 81 °C to 115 °C in about 17 min. From the same figure, one can also see that a final current of 1300 A causes the conductor temperature to reach 115 °C in about 10 min. The 15 min transient thermal rating is therefore between 1200 A and 1300 A.

The computer program performs a series of such calculations, adjusting the assumed final current until the conductor temperature just reaches 115 °C, 15 min after the step increase in current. An emergency current of 1231 A causes the conductor temperature to reach 115 °C in 15 min. The 15 min transient thermal rating of the Drake conductor is therefore 1231 A.

3.6.5 Thermal time constant

The thermal time constant is a useful concept in thermal ratings in that it allows convenient comparison of thermal response time for overhead conductors and other potentially thermally limited equipment such as transformers or circuit breakers. As an example, consider the Drake conductor exposed to a step increase in current from 800 to 1200 A as shown in Figure 2. Reading from the figure directly, the conductor temperature increases from 81 °C to 111 °C, [81 °C + 0.63 (128 °C – 81 °C)], in 13.5 min. See Annex G for a more detailed discussion of time constant.

4. Input data

4.1 Introduction

Careful selection of input data for current-temperature relationships is as important as the method of calculation itself, and requires considerable engineering judgment in the selection of values for each of the variables. These variables are discussed separately under separate headings, with suggestions given on how to select values to suit particular circumstances. Some suggestions are given as to what factors should be considered when it is necessary to make decisions.

4.2 Wind and ambient temperature

Weather conditions have a considerable effect on the thermal loading of bare overhead conductors. The weather provides cooling, principally by means of convective heat loss, q_c, to the surrounding air. The degree of cooling depends on air temperature and the wind velocity component perpendicular to the conductor.

Weather information can be obtained from local weather bureaus and, possibly, from other local weather stations. Recorded wind speeds of less than 1.5 m/s from weather bureau records are often inaccurate (see *Surface Observatories, Federal Meteorological Handbook* [B27]). Most wind speeds have been obtained by the weather bureau standard cup-type anemometer, which has significant starting inertia; therefore, readings at low wind speeds are in doubt.

The effect of wind direction relative to the conductor is included in this standard as Equation (4) in the form suggested by Davis [B9]. The difference between the wind correction factors suggested by Morgan [B23] and Davis [B9] are considered to be minor. For a given wind speed, winds blowing parallel result in a 60% lower convective heat loss than winds blowing perpendicular to the conductor.

Effects of wind turbulence and conductor stranding appear to be of minor importance in thermal rating or conductor temperature calculations. Evaporative cooling is a major factor, but it occurs sporadically along transmission lines. Both are neglected in this standard.

Height of conductors above ground is significant in terms of wind shielding. Higher voltage lines (where the conductor ground clearance is greater) may be expected to be less shielded by trees and terrain than low-voltage lines.

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Several cautions are included in this standard with regard to the proper choice of weather conditions for thermal line rating calculations with bare overhead conductors. Since the wind is normally assumed to be perpendicular to the conductor axis for rating calculations, a primary concern or caution must involve the choice of wind speed and direction.

1) There is considerable evidence from field measurement that still air conditions can exist over limited lengths of line for periods of up to several hours particularly near sunset and sunrise. This is particularly true in areas of heavy foliage where the conductor catenaries are below tree tops. During periods of still air, convective cooling of the conductor is limited to natural convection, which is equivalent to forced convection at a wind speed of 0.2 m/s.

2) Measurements of wind speeds at a single location will always indicate higher average and minimum wind speeds than simultaneous measurements of wind speed at multiple locations along a transmission line. Thus indications of wind speed from measurements at a single location are usually a poor basis for line ratings since it is likely that wind conditions are less favorable at another location along the line.

3) Convective cooling of a bare overhead conductor is dependent on both the wind speed and wind direction. As shown in Table 8, a perpendicular wind speed of 0.6 m/s yields the same convective cooling as a wind of 1.3 m/s at an angle of 22.5°. Thus, when choosing an appropriately conservative wind speed for thermal rating calculations, both the angle and the wind speed should be considered. The conventional assumption of perpendicular wind flow is not conservative.

Table 8—Equivalent combinations of wind speed and direction for equal convective cooling

Wind speed [m/s]	Wind direction relative to conductor axis [degrees]
0.6	90
0.8	45
1.3	22.5
2.2	0

4.3 Air density, viscosity, and conductivity

The density, viscosity, and thermal conductivity of air are used in the calculation of convection losses and can be obtained from Table 2. The equations provided in 3.5 may be more useful for computer applications, as they can reduce the amount of data stored and save on computer time.

Regardless of whether the tables or equations are used, it is recommended that the highest altitude that is applicable at the location of the line be selected, because this will tend to give the most conservative results.

4.4 Emissivity and absorptivity

Reports, such as Taylor and House [B28] and House, et al. [B19], indicate that ε and α increase from about 0.2 to about 0.9 with age. The exact rate of increase depends on the level of atmospheric pollution and the line's operating voltage. α is generally higher than ε over the life of the conductor. Both values increase with age and atmospheric pollution. Values of 0.5 for both absorptivity and emissivity, or 0.9 for absorptivity and 0.7 for emissivity, have been used when the actual conductor surface condition is unknown.

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4.5 Solar heat gain

A simple method for the calculation of solar heat gain is provided by Equation (8) and Equation (9). The most conservative results are obtained by assuming an angle of incidence of 90°, which will give the lowest value of ampacity and will be appropriate for many purposes.

It may be desired to establish summer and winter values, in which case it is suggested that House, et al. [B19] and *Site Reduction Tables for Air Navigators* [B26] be consulted for values appropriate to the location, time of year, and time of day.

Weather simulation models (see Davis [B10]) may also be used. For real-time rating systems, the direct-beamed and sky or diffuse radiation may be input directly from data obtained from weather stations, see Davis [B7] and Davis [B8].

Solar heat input to a bare overhead conductor can cause a conductor temperature rise above air temperature of up to 15 °C in still air. However, more typically, periods of maximum solar heat input are associated with significant wind activity and the actual temperature rise measured for bare conductors in overhead transmission lines seldom exceeds 5 °C to 10 °C.

4.6 Conductor heat capacity

The conductor heat capacity is the sum of the products of specific heat and mass per unit length of its components. The mass per unit length of conductor and conductor components for all common aluminum and aluminum composite conductors is given in the *Aluminum Electrical Conductor Handbook* [B1]. The specific heats of usual conductor materials are listed below as taken from this reference.

For 26/7 Drake ACSR, the weights of the steel core and the outer aluminum are 1.116 kg/m and .5119 kg/m, respectively, so that the total conductor heat capacity at 25 °C is as follows:

$$mC_p(Al) = 1.116 \text{ kg/m} \times 955 \text{ J/(kg} - \text{°C)}$$

$$mC_p(Al) = 1066 \text{ J/(m} - \text{°C)}$$

$$mC_p(St) = 0.5519 \text{ kg/m} \times 476 \text{ J/(kg} - \text{°C)}$$

$$mC_p(St) = 243.7 \text{ J/(m} - \text{°C)}$$

As listed in Black and Byrd [B4], the specific heats of conductor materials are as follows in Table 9.

Table 9—Specific heat of conductor wire materials

Material	C_p J/(kg - °C)
Aluminum	955
Copper	423
Steel	476
Aluminum Clad Steel	534[a]

[a]The specific heat of Aluminum Clad Steel depends on the aluminum-to-steel ratio. This is a typical value for Aluminum Clad Steel wire with a conductivity of 20.3% I.A.C.S.

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4.7 Maximum allowable conductor temperature

Since the thermal rating of any conductor is dependent upon its maximum allowable temperature, and since this temperature varies widely according to engineering practice and judgment (temperatures of 50 °C to 180 °C are in use for ACSR), the thermal rating of any conductor also varies widely. Therefore, one of the most important aspects of thermal rating calculations is the proper selection of a maximum allowable conductor temperature.

The maximum allowable conductor temperature is normally selected so as to limit either conductor loss of strength due to the annealing of aluminum or to maintain adequate ground clearance. Loss of conductor strength and/or permanent sag increase due to creep elongation of the conductor accumulates over time. When these effects are considered, it is common to use a higher maximum allowable conductor temperature for transient thermal rating calculations than for steady-state thermal rating calculations. For fault calculations, the maximum allowable temperature is normally close to the melting point of the conductor material.

Overhead line thermal ratings are normally selected either to avoid annealing copper or aluminum strands or to avoid excessive sag of the conductor leading to violation of minimum electrical clearances to ground and other conductors.

1) In selecting weather conditions for line ratings whose purpose it is to limit loss of conductor tensile strength through annealing, it may be appropriate to consider the most sheltered location along the line. Local hot spots can yield local high temperatures and must be of concern in determining whether mechanical failure may occur under heavy ice and wind loads at a future time.

2) In selecting weather conditions for line ratings whose purpose it is to limit sag at high temperature, it may be appropriate to consider the most sheltered line section (a series of suspension spans mechanically isolated by strain structures at each end) since local hot spots within such a line section are less important in determining the sag in any span than the average conditions in all the suspension spans.

4.8 Time step

For calculation of transient ampacity and temperature, the time step must be made sufficiently small so as to result in an accurate calculation. A time step equal to 1% of the conductor thermal time constant is usually sufficient.

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Annex A

(informative)

English unit equivalents for SI units used in this standard

A.1 Units and identification of letter symbols

NOTE—SI units are the preferred unit of measure. However, in the United States the calculations described in this standard have frequently been performed using a combination of units that will be referred to throughout this document as "English" units. This annex provides an analysis using these units.

Table A.1—Units and identification of letter symbols

Symbol	Description	SI units
A'	Projected area of conductor per unit length	ft^2/ft
C	Solar azimuth constant	degrees
C_{pi}	Specific heat of i^{th} conductor material	J/(lb-°C)
D	Conductor diameter	in
H_c	Altitude of sun	degrees
H_e	Elevation of conductor above sea level	ft
I	Conductor current	A
I_i	Initial current before step change	A
I_f	Final current after step change	A
K_{angle}	Wind direction factor	—
K_{solar}	Solar altitude correction factor	—
k_f	Thermal conductivity of air at temperature T_{film}	W/ft-°C)
Lat	Degrees of latitude	degrees
mC_p	Total heat capacity of conductor	J/(ft-°C)
m_i	Weight per unit length of i^{th} conductor material	lb/ft
N	Day of the year (January 21 = 21, February 12 = 43, etc.)	—
q_{cn}, q_{c1}, q_{c2}, q_c	Convected heat loss rate per unit length	W/ft
q_r	Radiated heat loss rate per unit length	W/ft
q_s	Heat gain rate from sun	W/ft
Q_s	Total solar and sky radiated heat flux rate	W/ft^2
Q_{se}	Total solar and sky radiated heat flux rate elevation corrected	W/ft^2
$R(T_c)$	AC resistance of conductor at temperature, T_c	Ω/ft
T_a	Ambient air temperature	°C

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Table A.1—Units and identification of letter symbols *(continued)*

Symbol	Description	SI units
T_c	Conductor temperature	°C
T_f	Conductor temperature many time constants after step increase	°C
T_i	Conductor temperature prior to step increase	°C
T_{film}	$(T_c + T_a)/2$	°C
T_{low}	Minimum conductor temperature for which ac resistance is specified	°C
T_{high}	Maximum conductor temperature for which ac resistance is specified	°C
V_w	Speed of air stream at conductor	ft/hr
Z_c	Azimuth of sun	degrees
Z_l	Azimuth of line	degrees
Δt	Time step used in transient calculation	s
ΔT_c	Conductor temperature increment corresponding to time step	°C
α	Solar absorptivity (0.23 to 0.91)	—
δ	Solar declination (0 to 90)	degrees
ε	Emissivity (0.23 to 0.91)	—
τ	Thermal time constant of the conductor	s
ϕ	Angle between wind and axis of conductor	degrees
β	Angle between wind and perpendicular to conductor axis	degrees
ρ_f	Density of air	lb/ft^3
θ	Effective angle of incidence of the Sun's rays	degrees
μ_f	Dynamic viscosity of air	lb/ft-hr
ω	Hours from local sun noon time 15	degrees
χ	Solar azimuth variable	—

A.2 Formulas

A.2.1 Forced convection heat loss rate

$$q_{cl} = \left[1.01 + 0.371\left(\frac{D\rho_f V_w}{\mu_f}\right)^{0.52}\right] k_f K_{angle}\left(T_c - T_a\right) \text{ W/ft} \qquad \text{(A.1a)}$$

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$$q_{c2} = \left[0.1695 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.6} k_f K_{angle} (T_c - T_a) \right] \text{ W/ft} \quad \text{(A.1b)}$$

Equation (A.1a) applies at low winds but is too low at high speeds. Equation (A.1b) applies at high wind speeds, being too low at low wind speeds. At any wind speed, the larger of the two calculated convection heat loss rates is used.

The convective heat loss rate is multiplied by the wind direction factor, K_{angle}, where ϕ is the angle between the wind direction and the conductor axis:

$$K_{angle} = 1.194 - \cos(\phi) + 0.194 \cos(2\phi) + 0.368 \sin(2\phi) \quad \text{(A.2a)}$$

Alternatively, the wind direction factor may be expressed as a function of the angle, ß, between the wind direction and a perpendicular to the conductor axis. This angle is the complement of ϕ, and the wind direction factor becomes:

$$K_{angle} = 1.194 - \sin(\beta) - 0.194 \cos(2\beta) + 0.368 \sin(2\beta) \quad \text{(A.2b)}$$

This is the form of the wind direction factor as originally suggested in Davis [B9] and is used in the computer program listed in Annex B.

A.2.2 Natural convection

With zero wind speed, natural convection occurs, where the rate of heat loss is shown in Equation (A.3).

$$q_{cn} = 0.283 \rho_f^{0.5} D^{0.75} (T_c - T_a)^{1.25} \text{ W/ft} \quad \text{(A.3)}$$

It has been argued that at low wind speeds, the convection cooling rate should be calculated by using a vector sum of the wind speed and a "natural" wind speed, see Morgan [B23]. However, it is recommended that only the larger of the forced and natural convection heat loss rates be used at low wind speeds because this is conservative. The computer program listed in Annex B takes this approach.

For both forced and natural convection, air density (ρ_f), air viscosity (μ_f), and coefficient of thermal conductivity of air (k_f) are taken from Table A.2 at T_{film}, where

$$T_{film} = \frac{T_c + T_a}{2} \quad \text{(A.4)}$$

A.2.3 Radiated heat loss rate

$$q_r = 0.138 D \varepsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \text{ W/ft} \quad \text{(A.5)}$$

A.2.4 Rate of solar heat gain (see Table A.3 and Table A.4)

$$q_s = \alpha Q_{se} \sin(\theta) A' \quad \text{(A.6)}$$

where

$$\theta = \arccos[\cos(H_c) \cos(Z_c - Z_l)] \quad \text{(A.7)}$$

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A.3 Equations for air properties, solar angles, and solar heat flux

In the following subclauses, least square polynomial regressions were performed on tabular data for thermal conductivity (A.3.3), total heat flux (A.3.4), and solar heat correction for elevation (A.3.5) to fit an equation of the following form:

$$Y = A + BX + CX^2 + DX^3 + EX^4 + FX^5 + GX^6$$

Algebraic equations are given for air viscosity (A.3.1), and air density (A.3.2).

Tables of typical values are provided for convenience.

A.3.1 Dynamic viscosity of air

The viscosity of air is determined by the algebraic equation listed in Equation (A.8):

$$\mu_f = \frac{0.00353(T_{film} + 273)^{1.5}}{T_{film} + 383.4} \quad \text{(A.8)}$$

A.3.2 Air density (Table A.2)

$$\rho_f = \frac{0.080695 - 2.901\times10^{-6} H_e + 3.7\times10^{-11} H_e^2}{1 + 0.00367 T_{film}} \quad \text{lb/ft}^3 \quad \text{(A.9)}$$

A.3.3 Thermal conductivity of air (Table A.2)

$$k_f = 7.388\times10^{-3} + 2.279\times10^{-5} T_{film} - 1.343\times10^{-9} T_{film}^2 \quad \text{W/(ft-°C)} \quad \text{(A.10)}$$

Table A.2—Viscosity, density, and thermal conductivity of air

Temperature T_{film}	Dynamic viscosity [B18] μ_f	Air density [B13] ρ_f (lb/ft^3)				Thermal conductivity of air [B22] k_f
°C	(lb/ft-hr)	Sea level	5 000 ft	10 000 ft	15 000 ft	W/(ft·°C)
0	0.0415	0.0807	0.0671	0.0554	0.0455	0.00739
5	0.0421	0.0793	0.0660	0.0545	0.0447	0.00750
10	0.0427	0.0779	0.0648	0.0535	0.0439	0.00762
15	0.0433	0.0765	0.0636	0.0526	0.0431	0.00773
20	0.0439	0.0752	0.0626	0.0517	0.0424	0.00784
25	0.0444	0.0740	0.0616	0.0508	0.0417	0.00795
30	0.0450	0.0728	0.0606	0.0500	0.0411	0.00807
35	0.0456	0.0716	0.0596	0.0492	0.0404	0.00818
40	0.0461	0.0704	0.0586	0.0484	0.0397	0.00830
45	0.0467	0.0693	0.0577	0.0476	0.0391	0.00841

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Table A.2 – Viscosity, density, and thermal conductivity of air *(continued)*

Temperature T_{film}	Dynamic viscosity [B18] μ_f	Air density [B13] ρ_f (lb/ft^3)				Thermal conductivity of air [B22] k_f
°C	(lb/ft-hr)	Sea Level	5 000 ft	10 000 ft	15 000 ft	W/(ft·°C)
50	0.0473	0.0683	0.0568	0.0469	0.0385	0.00852
55	0.0478	0.0672	0.0559	0.0462	0.0379	0.00864
60	0.0484	0.0661	0.0550	0.0454	0.0373	0.00875
65	0.0489	0.0652	0.0542	0.0448	0.0367	0.00886
70	0.0494	0.0643	0.0535	0.0442	0.0363	0.00898
75	0.0500	0.0634	0.0527	0.0436	0.0358	0.00909
80	0.0505	0.0627	0.0522	0.0431	0.0354	0.00921
85	0.0510	0.0616	0.0513	0.0423	0.0347	0.00932
90	0.0515	0.0608	0.0506	0.0418	0.0343	0.00943
95	0.0521	0.0599	0.0498	0.0412	0.0338	0.00952
100	0.0526	0.0591	0.0492	0.0406	0.0333	0.00966

A.3.4 Total heat flux received by a surface at sea level (Table A.3 and Table A.4)

The total solar heat flux density at sea level is dependent on both the solar altitude and atmospheric clarity.

The heat flux density received by a surface at sea level as shown in Table A.3 may be represented by the following regression equation [Equation (A.11)].

Y = total heat flux, Q_S (w/ft^2)

X = solar altitude, H_C (degrees)

$$Q_s = A + BH_c + CH_c^2 + DH_c^3 + EH_c^4 + FH_c^5 + GH_c^6 \quad \text{(A.11)}$$

Table A.3—Coefficients for Equation (A.11)

Clear atmosphere	
A	–3.9241
B	5.9276
C	-1.7856×10^{-1}
D	3.223×10^{-3}
E	-3.3549×10^{-5}
F	1.8053×10^{-7}
G	-3.7868×10^{-10}

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Table A.3—Coefficients for Equation (A.11) *(continued)*

Industrial atmosphere	
A	4.9408
B	1.3202
C	6.1444×10^{-2}
D	-2.9411×10^{-3}
E	5.07752×10^{-5}
F	-4.03627×10^{-7}
G	1.22967×10^{-9}

Table A.4—Total heat flux received by a surface at sea level normal to the sun's rays

Degrees solar altitude	Clear atmosphere	Industrial atmosphere
H_c (deg)	Q_s (W/ft^2)	Q_s (W/ft^2)
5	21.7	12.6
10	40.2	22.3
15	54.2	30.5
20	64.4	39.2
25	71.5	46.6
30	77.0	53.0
35	81.5	57.5
40	84.8	61.5
45	87.4	64.5
50	90.0	67.5
60	92.9	71.6
70	95.0	75.2
80	95.8	77.4
90	96.4	78.9

A.3.5 Total heat flux elevation correction factor (Table A.5)

$$Q_{se} = K_{\text{solar}}\, Q_s \tag{A.12}$$

where

$$K_{\text{solar}} = A + BH_e + CH_e^2 \tag{A.13}$$

$A = 1$

$B = 3.500 \times 10^{-5}$

$C = -1.000 \times 10^{-9}$

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Table A.5—Solar heat multiplying factors, K_{solar} for high altitudes (Yellot [B31])

Elevation above sea level H_e (ft)	Multipliers for values in Table 5
0	1.00
5 000	1.15
10 000	1.25
15 000	1.30

A.4 Sample calculations

A.4.1 Steady-state thermal rating

The calculation of steady-state thermal rating given a maximum allowable conductor temperature, weather conditions, and conductor characteristics may be performed by the computer program in Annex B. The following sample calculation is done with that program and is included in Annex C. However, since the process does not require iterative calculations, it can also be done by hand. Doing so demonstrates the use of the formulas and yields some insight into the calculation process.

Note that in the following, the number of significant digits does not indicate the accuracy of the formula.

A.4.1.1 Problem statement

Find the steady-state thermal rating (ampacity) for a "Drake" 26/7 ACSR conductor, under the following conditions:

a) Wind speed (V_w) is 2 ft/s perpendicular to the conductor.

b) Emissivity (ε) is 0.5.

c) Solar absorptivity (α) is 0.5.

d) Ambient air temperature is 40 °C.

e) Maximum allowable conductor temperature is 100 °C.

f) Conductor outside diameter (D) is 1.108 in.

g) Conductor ac resistance [$R(T_c)$] is:

$R(25\ °C) = 2.220 \times 10^{-5}$ (Ω/ft)

$R(75\ °C) = 2.648 \times 10^{-5}$ (Ω/ft)

h) The line runs in an East-West direction so azimuth of line, $Z_l = 90°$.

i) Latitude is 30° North.

j) The atmosphere is clear.

k) Solar altitude (H_c) for 11:00 a.m. on June 10.

l) Average conductor elevation 328 ft.

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A.4.1.2 Convection heat loss (q_c)

The natural convection heat loss is calculated by means of Equation (A.4):

where

$D = 1.108$ in

$T_c = 100$ °C

$T_a = 40$ °C

$T_{film} = \frac{100 + 40}{2} = 70$ °C

$\rho_f = 0.0643$ lb/ft^3 (Table A.2)

$q_{cn} = 0.283 \times (0.0643)^{0.5} \times (1.108)^{0.75} \times (100 - 40)^{1.25} = 12.9$ W/ft

Since the wind speed is greater than zero, the forced convection heat loss for perpendicular wind is calculated according to both Equation (A.1a) and Equation (A.1b), corrected for wind direction and compared to the natural convection heat loss. The largest of the heat losses due to both natural and forced heat convection is used to calculate the thermal rating.

where

$D = 1.108$ in

$V_w = 2$ ft/s $\times$ 3600 s/h

$T_c = 100$ °C

$T_a = 40$ °C

$T_{film} = \frac{100 + 40}{2} = 70$ °C

$\mu_f = 0.0494$ lb/h – ft (Table A.2)

$\rho_f = 0.0643$ lb/ft^3 (Table A.2)

$k_f = 0.00898$ W/ft (Table A.2)

$$q_{cl} = \left[1.01 + 0.371\left(\frac{1.108 \times 0.0643 \times 7200}{0.0494}\right)^{0.52}\right] \times 0.00898 \times (100 - 40) = 25.1 \text{ W/ft}$$

$$q_{c2} = 0.1695 \times \left(\frac{1.108 \times 0.0643 \times 7200}{0.0494}\right)^{0.6} \times 0.00898 \times (100 - 40) = 23.5 \text{ W/ft}$$

As instructed in A.2.1, select the larger of the two calculated convection heat losses.

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$q_c = 25.1$ W/ft

Since the wind is perpendicular to the axis of the conductor, the wind direction multiplier, K_{angle}, is 1.0, and the forced convection heat loss is greater than the natural convection heat loss. Therefore, the forced convection heat loss will be used in the calculation of thermal rating.

A.4.1.3 Radiated heat loss (q_r)

The radiated heat loss is calculated with Equation (A.5).

$D = 1.108$ in

$\varepsilon = 0.5$

$T_c = 100\ °C$

$T_a = 40\ °C$

$$q_r = 0.138 \times 1.108 \times 0.5 \times \left[\left(\frac{373}{100} \right)^4 - \left(\frac{313}{100} \right)^4 \right]$$

$q_r = 7.5$ W/ft

A.4.1.4 Solar heat gain (q_s)

The conductor is at 30° North latitude: Approximate values of H_c and Z_c can be obtained by interpolating from Table 4 and Table 5. From Table 4, the solar altitude, H_c, and the solar azimuth, Z_c, can be determined as follows:

H_c at $10:00$ a.m. $= 62°$

H_c at $12:00$ noon $= 83°$

$$H_c \text{ at } 11:00 \text{ a.m.} = \frac{83 + 62}{2} = 72.5°$$

Z_c at $10:00$ a.m. $= 98°$

Z_c at $12:00$ noon $= 180°$

$$Z_c \text{ at } 11:00 \text{ a.m.} = \frac{98 + 180}{2} = 139°$$

From Table A.3 for $H_c = 72.5°$ with clear atmosphere:

$Q_s = 95.2$ W/ft^2 (By interpolation)

$Z_l = 90°$ *or* $270°$

$$\theta = \arccos\left[\cos(72.5°)\cos(139° - 90°)\right] = 78.62°$$

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where

$\alpha = 0.5$

$K_{\text{solar}} = 1.0$

$A' = D/12 = 1.108/12 = 0.0923 \text{ ft}^2/\text{ft}$

$q_s = 0.5 \times 95.2 \times \sin(78.62°) \times 0.0923$

$q_s = 4.3 \text{ W/ft}$

In determining solar azimuth and altitude, Equation (15) and Equation (16) should be used:

— For times of the year other than June 10 and July 3

— For times of the day before 10 a.m. and after 2 p.m.

— For latitudes less than 20°or greater than 70°

In this example, the equations will be used to allow a comparison to the approximate angles obtained from the tables in this standard.

In order to calculate the solar altitude, the day of the year, *N*, must first be found. For June 10, the day of the year is as follows:

$N = 31 + 28 + 31 + 30 + 31 + 10 = 161$

The solar declination for June 10 is given by Equation (15b):

$$\delta = 23.4583 \times \sin\left[\frac{284 + 161}{365} \times 360\right]$$

$\delta = 23.4583 \times 0.981 = 23.02°$

The solar altitude, H_c, is found by use of Equation (15a) where Lat = 30°:

$H_c = \arcsin[\cos(30) \times \cos(23.0) \times \cos(-15) + \sin(30) \times \sin(23.0)]$

$H_c = \arcsin[0.866 \times 0.920 \times 0.966 + 0.500 \times 0.391] = 74.8°$

In order to calculate the solar azimuth, referring to Equation (16), one must first calculate the solar azimuth variable, χ. The solar azimuth variable, χ, for this example problem is as follows:

$$\chi = \frac{\sin(-15)}{\sin(30) \times \cos(-15) - \cos(30) \times \tan(23.0)} = \frac{-0.259}{(0.500)(0.966) - (0.866)(0.425)} = -2.24$$

From Table 3, since the solar azimuth variable, χ, is less than 0, and since the "hour angle", ω, is –15°, the solar azimuth constant, C, is equal to 180°.

Having determined both the solar azimuth variable, χ, and the constant C, the solar azimuth angle in degrees is as follows:

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$$Z_c = 180 + \arctan(-2.24) = 180 - 65.9 = 114°$$

Repeating the earlier calculation of solar heat gain with the new solar azimuth and altitude, the solar heat gain is as follows:

$$\theta = \arccos[\cos(75) \times \cos(114 - 90)] = 76.3°$$

$$q_s = 0.5 \times 95.2 \times \sin(76.3) \times 0.0923 = 4.26 \text{ W/ft}$$

A.4.1.5 Resistance at 100 °C

$$R(100) = R(25) + \left(\frac{R(75) - R(25)}{75 - 25} \right) \times (100 - 25)$$

$$R(100) = 2.220 \times 10^{-5} + \left[\frac{2.648 \times 10^{-5} - 2.220 \times 10^{-5}}{50} \right] \times 75$$

$$R(100) = 2.862 \times 10^{-5} \ \Omega/\text{ft}$$

A.4.1.6 Steady-state thermal rating

Using Equation (1) the steady-state thermal rating can be found where:

$q_c = 25.1$ W/ft

$q_r = 7.461$ W/ft

$q_s = 4.26$ W/ft (from equations)

$R(100) = 2.862 \times 10^{-5}$ Ω/ft

$$I = \sqrt{\frac{25.1 + 7.46 - 4.26}{2.862 \times 10^{-5}}}$$

$I = 994$ A

The program listed in Annex B can also be used to calculate the steady-state thermal rating. The results of such a run are presented in Annex C.

A.5 Wind and ambient temperature

Weather conditions have a considerable effect on the thermal loading of bare overhead conductors. The weather provides cooling, principally by means of convective heat loss, q_c, to the surrounding air. The degree of cooling depends on air temperature and the wind velocity component perpendicular to the conductor.

Weather information can be obtained from local weather bureaus and, possibly, from other local weather stations. Recorded wind speeds of less than 5 ft/s from weather bureau records are often inaccurate (see *Surface Observatories, Federal Meteorological Handbook* [B27]). Most wind speeds have been obtained by the weather bureau standard cup-type anemometer, which has significant starting inertia; therefore, readings at low wind speeds are in doubt.

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The effect of wind direction relative to the conductor is included in this standard as Equation (4) in the form suggested by Davis [B9]. The difference between the wind correction factors suggested by Morgan [B22] and Davis are considered to be minor. For a given wind speed, winds blowing parallel result in a 60% lower convective heat loss than winds blowing perpendicular to the conductor.

Effects of wind turbulence and conductor stranding appear to be of minor importance in thermal rating or conductor temperature calculations. Evaporative cooling is a major factor, but it occurs sporadically along transmission lines. Both are neglected in this standard.

Height of conductors above ground is significant in terms of wind shielding. Higher voltage lines (where the conductor ground clearance is greater) may be expected to be less shielded by trees and terrain than low-voltage lines.

Several cautions are included in this standard with regard to the proper choice of weather conditions for thermal line rating calculations with bare overhead conductors. Since the wind is normally assumed to be perpendicular to the conductor axis for rating calculations, the primary concern is with the choice of wind speed.

1) There is considerable evidence from field measurement that still air conditions can exist over limited lengths of line for periods of up to several hours particularly near sunset and sunrise. This is particularly true in areas of heavy foliage where the conductor catenaries are below tree tops. During periods of still air, convective cooling of the conductor is limited to natural convection, which is equivalent to forced convection at a wind speed of 2 ft/s.

2) Measurements of wind speeds at a single location will always indicate higher average and minimum wind speeds than simultaneous measurements of wind speed at multiple locations along a transmission line. Thus indications of wind speed from measurements at a single location are usually a poor basis for line ratings since it is likely that wind conditions are less favorable at another location along the line.

3) Convective cooling of a bare overhead conductor is dependent on both the wind speed and wind direction. As shown in Table A.6, a perpendicular wind speed of 2 ft/s yields the same convective cooling as a wind of 4.4 ft/s at an angle of 22.5°. Thus, when choosing an appropriately conservative wind speed for thermal rating calculations, both the angle and the wind speed should be considered. The conventional assumption of perpendicular wind flow is not conservative.

Table A.6—Equivalent combinations of wind speed and direction for equal convective cooling

Wind speed [ft/s]	Wind direction relative to conductor axis [degrees]
2.0	90
2.7	45
4.4	22.5
10.2	0

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A.6 Conductor heat capacity

The conductor heat capacity is the sum of the products of specific heat and mass per unit length of its components. The mass per unit length of conductor and conductor components for all common aluminum and aluminum composite conductors is given in the *Aluminum Electrical Conductor Handbook* [B1]. The specific heats of usual conductor materials are listed below as taken from this reference.

For 26/7 Drake ACSR, the weights of the steel core and the outer aluminum are 0.344 lb/ft and 0.750 lb/ft, respectively, so that the total conductor heat capacity at 25 °C is as follows:

$$mC_p(Al) = 0.750 \text{ lb/ft} \times 433 \text{ J/(lb} - \text{°C)}$$

$$mC_p(Al) = 325 \text{ J/(ft} - \text{°C)}$$

$$mC_p(St) = 0.344 \text{ lb/ft} \times 216 \text{ J/(lb} - \text{°C)}$$

$$mC_p(St) = 74.3 \text{ J/(ft} - \text{°C)}$$

As listed in Black and Byrd [B4], the specific heats of conductor materials are as follows in Table A.7.

Table A.7 – Specific heat of conductor wire materials

Material	C_p J/(lb – °C)
Aluminum	433
Copper	192
Steel	216
Aluminum Clad Steel	242[a]

[a]The specific heat of Aluminum Clad Steel depends on the aluminum-to-steel ratio. This is a typical value for Aluminum Clad Steel wire with a conductivity of 20.3% I.A.C.S.

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Annex B

(informative)

Listing of the “RATEIEEE” program for steady-state and transient calculations of temperature and thermal rating for bare overhead conductors

```
10  REM ************************************************************
20  REM *     IEEE METHOD - TRANSIENT OR STEADY STATE CALCULATION
30  REM *   OF BARE OVERHEAD CONDUCTOR TEMPERATURE OR THERMAL RATING
40  REM *                LAST MODIFIED 11/7/97 BY DAD
50  REM *               PROGRAM NAME IS "IEEE738SI.BAS"
60  REM *                 LANGUAGE IS "QUICK BASIC"
70  REM *        ASSUMES SI UNITS FOR INPUT FILE
80  REM *
90  REM *
240 REM *  IN COMPARISON WITH THE 1986 VERSION OF THIS PROGRAM, PROVIDED
250 REM *  BY THE IEEE, THE 1993 VERSION ADDED THE FOLLLOWING FEATURES:
260 REM *
290 REM *    - INITIAL CONDUCTOR TEMP OR CURRENT CAN BE USED IN
300 REM *        TRANSIENT CALCULATIONS
330 REM *    - VERY SHORT DURATION "FAULT" CURRENTS AS LARGE AS 1E6
340 REM *        AMPERES FOR TIMES AS SHORT AS 0.01 SEC CAN BE USED
350 REM *    - THE ORIGINAL NUMERICAL ITERATION METHOD HAS BEEN
360 REM *        REPLACED WITH A MUCH MORE EFFICIENT METHOD
370 REM *    - FOR ACSR CONDUCTOR, THE HEAT CAPACITY OF THE STEEL CORE
380 REM *        AND THE OUTER ALUM STRANDS ARE ENTERED SEPARATELY.
390 REM *
392 REM *  THIS VERSION IS CONSISTENT WITH IEEE STD 738-2006
394 REM *    - THE SOLAR MODEL ALLOWS ANY HOUR AND LATITUDE
396 REM *    - THE AIR PROPERTIES ARE CALCULATED WITH CLOSED FORM EQUATIONS
398 REM *    - THIS PROGRAM AND EQUATIONS USE SI UNITS
400 REM ************************************************************
410 REM **********************************
420 REM * INITIALIZE VARIABLES AND ARRAYS *
430 REM **********************************
440 DIM ATCDR(1000)
450 DIM TIME(1000)
460 FLAG1 = 0
470 XIDUMMY = 0
480 XIPRELOAD = 0
490 XISTEP = 0
500 TCDR = 0
510 TCDRPRELOAD = 0
520 TCDRMAX = 0
530 IORTPRELOAD = 0
540 DELTIME = 0
550 FS1 = 0
560 FS2 = 0
570 FS3 = 0
580 X$ = STRING$(56, 45)
590 REM ******************************
600 REM * START REPEAT CALCULATION HERE
610 REM ******************************
620 FOR KI = 1 TO 1000
630 ATCDR(KI) = 0
640 TIME(KI) = 0
650 NEXT KI
660 NFLAG = 0
670 PI = 3.141593
672 PIANG = PI / 180!
```


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```
680 IF FLAG1 = 99 GOTO 1120
690 REM ***********************************************
700 REM * SPECIFY DATA INPUT ASCII FILE NAME
710 REM ***********************************************
720 CLS
730 INPUT "ENTER INPUT FILE NAME ", F$: OPEN F$ FOR INPUT AS #1
780 REM *********************************
790 REM *  SPECIFY HOW DATA IS TO BE OUTPUT
800 REM *********************************
810 PRINT "DO YOU WANT THE OUTPUT TO GO TO SCREEN ONLY(0), FILE ONLY(1),"
820 INPUT "       OR TO BOTH SCREEN AND FILE(2)? ", SORF
830 IF SORF <> 0 AND SORF <> 1 AND SORF <> 2 THEN GOTO 810
840 IF SORF <> 0 THEN INPUT "ENTER OUTPUT FILE NAME  ", FOUT$: OPEN FOUT$ FOR
OUTPUT AS #2
845 INPUT "DO YOU WANT DEBUG CHECKS? YES (0), NO(1) ", DEBUG
850 REM ************************************************************
860 REM * ENTER DATA FROM INPUT FILE
870 REM ************************************************************
880 GOSUB 8000
1120 REM ***************************************
1130 REM * CALCULATE SOLAR HEAT INPUT TO CONDUCTOR
1140 REM ***************************************
1150 GOSUB 5000
1160 REM ************************************************************
1170 REM * CALCULATE THERMAL COEF OF RESISTANCE & WIND ANGLE CORRECTION
1180 REM ************************************************************
1190 GOSUB 9000
1200 REM *********************************
1210 REM * SELECT THE CALCULATION DESIRED
1220 REM *********************************
1230 ON NSELECT GOTO 1500, 1240, 1460, 1460
1240 REM ************************************************************************
1250 REM *                    FOR NSELECT = 2
1260 REM * GO TO AMPACITY SUBROUTINE TO CALCULATE THE STEADY STATE
1270 REM * CURRENT (TR) GIVEN THE STEADY STATE CONDUCTOR TEMPERATURE (TCDR)
1280 REM * THE CONDUCTOR TEMPERATURE IS GIVEN SO ONLY ONE PASS THROUGH
1290 REM * THE SUBROUTINE IS REQUIRED.
1300 REM ************************************************************************
1310 TCDR = TCDRPRELOAD
1320 GOSUB 15000
1330 GOTO 1730
1340 REM ************************************************************************
1350 REM
1360 REM ************************************************************************
1370 REM *                    FOR NSELECT = 1,3,OR 4
1380 REM * GO TO AMPACITY SUBROUTINE REPEATEDLY IN ORDER TO CALCULATE
1390 REM * THE STEADY STATE CURRENT (TR) CORRESPONDING TO TRIAL VALUES OF
1400 REM * CONDUCTOR TEMPERATURE (TCDR).  IF T=1 THEN THE OUTPUT OF THE
1410 REM * SUBROUTINE, TR, IS THE STEADY STATE CURRENT FOR
1420 REM * WHICH A STEADY STATE TEMPERATURE WAS TO BE FOUND.
1430 REM * IF T=3 OR 4 AND IORTPRELOAD=1, THEN TR IS THE INITIAL PRE-STEP
1440 REM * CHANGE CURRENT FOR WHICH AN INITIAL TEMPERATURE WAS TO BE CALCULATED.
1450 REM ************************************************************************
1460 ON IORTPRELOAD GOTO 1500, 1650
1470 REM *****************************************
1480 REM * CALCULATE TCDR GIVEN XIDUMMY = XIPRELOAD *
1490 REM *****************************************
1500 XIDUMMY = XIPRELOAD
1510 NFLAG = 0
1520 GOSUB 13000
1530 TCDRPRELOAD = TCDR
1540 REM ************************************************************
1550 REM * FOR NSELECT = 1  THE PROGRAM HAS FOUND THE STEADY STATE CONDUCTOR
1560 REM * TEMPERATURE (TCDRPRELOAD) CORRESPONDING TO THE GIVEN STEADY STATE
```


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```
1570 REM * CURRENT (XIPRELOAD) AND CONTROL IS PASSED TO THE PRINTOUT SECTION
1580 REM ************************************************************
1590 IF NSELECT = 1 THEN 1730
1600 REM ************************************************************
1610 REM * FOR NSELECT = 3 OR 4, THE PROGRAM HAS DETERMINED (IORTPRELOAD=1) OR
BEEN
1620 REM * GIVEN (IORTPRELOAD=2) THE INITIAL STEADY STATE CONDUCTOR TEMPERATURE
1630 REM * AND CONTROL PASSES TO FURTHUR TRANSIENT  CALCULATIONS
1640 REM ************************************************************
1650 IF NSELECT = 4 THEN GOSUB 10000
1660 REM ************************************************************
1670 REM * BEGIN CALCULATION OF CONDUCTOR TEMP AS A FUNCTION OF TIME
1680 REM * FOR A STEP INCREASE IN ELECTRICAL CURRENT,  NSELECT = 3
1690 REM ************************************************************
1700 ET = 3600!
1710 XISTEP = XISTEP
1720 GOSUB 11000
1730 REM *************************
1740 REM * PRINT RESULTS TO SCREEN
1750 REM *************************
1760 IF SORF = 0 OR SORF = 2 THEN GOSUB 6000
1770 REM ************************
1780 REM * WRITE RESULTS TO FILE
1790 REM ************************
1800 IF SORF = 1 OR SORF = 2 THEN GOSUB 16000
1810 REM IF FS = 1 GOTO 1880
1820 IF NS < NSETS THEN GOTO 880 ELSE CLOSE #1
1830 IF SORF = 1 OR SORF = 2 THEN CLOSE #2
1840 GOTO 1930
1850 REM ****************************************
1860 REM * SETUP TO REPEAT PROGRAM CALCULATIONS WITH NEW DATA
1870 REM ****************************************
1880 REM INPUT "DO YOU WANT TO RUN THE PROGRAM AGAIN (YES = 1, NO = 2)", YN
1890 REM IF YN <> 1 AND YN <> 2 THEN GOTO 1880
1900 REM IF YN = 2 GOTO 1920
1910 REM IF YN = 1 THEN FLAG1 = 99: RESTORE: GOTO 620
1920 REM IF SORF = 1 OR SORF = 2 THEN CLOSE #2
1930 END
5000 REM ////////////////////////////////////////////////////
5010 REM / SUBROUTINE TO CALCULATE CONDUCTOR SOLAR HEAT GAIN (QS)
5020 REM ////////////////////////////////////////////////////
5030 IF SUN.TIME >= 24 THEN 5560
5040 DEG.TO.RAD = PI / 180!
5050 CDR.LAT.RAD = CDR.LAT.DEG * DEG.TO.RAD
5060 REM * SOLAR DECLINATION
5070 DECL.DEG = 23.4583 * SIN(((284 + NDAY) / 365) * 2 * PI)
5080 DECL.RAD = DECL.DEG * DEG.TO.RAD
5090 REM * SOLAR ANGLE RELATIVE TO NOON
5100 HOUR.ANG.DEG = (SUN.TIME - 12) * 15
5110 HOUR.ANG.RAD = HOUR.ANG.DEG * DEG.TO.RAD
5120 REM * FIND SOLAR ALTITUDE - H3
5130 H3ARG = COS(CDR.LAT.RAD) * COS(DECL.RAD) * COS(HOUR.ANG.RAD) +
SIN(CDR.LAT.RAD) * SIN(DECL.RAD)
5140 H3.RAD = ATN(H3ARG / SQR(1 - H3ARG ^ 2))
5150 H3.DEG = H3.RAD / DEG.TO.RAD
5160
5170 IF A3 = 1 THEN 5290
5180 REM ************************************************************
5190 REM * SOLAR HEATING (Q3) AT EARTH SURFACE (W/M2) IN CLEAR AIR (P6)
5200 REM ************************************************************
5210 Q3 = -42.2391 + 63.8044 * H3.DEG - 1.922 * H3.DEG ^ 2
5220 Q3 = Q3 + .034692 * H3.DEG ^ 3 - 3.6112E-04 * H3.DEG ^ 4
5230 Q3 = Q3 + 1.9432E-06 * H3.DEG ^ 5 - 4.0761E-09 * H3.DEG ^ 6
5240 B$ = "CLEAR"
```


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```
5250 GOTO 5330
5260 REM ************************************************************
5270 REM * SOLAR HEAT (Q3) AT EARTH SURFACE (W/M2) IN INDUSTRIAL AIR (P6)
5280 REM ************************************************************
5290 Q3 = 53.1821 + 14.211 * H3.DEG + .66138 * H3.DEG ^ 2
5300 Q3 = Q3 - .031658 * H3.DEG ^ 3 + 5.4654E-04 * H3.DEG ^ 4
5310 Q3 = Q3 - 4.3446E-06 * H3.DEG ^ 5 + 1.3236E-08 * H3.DEG ^ 6
5320 B$ = "INDUSTRIAL"
5330 REM * CALCULATE SOLAR AZIMUTH VARIABLE, CHI
5335 IF DEBUG = 0 THEN PRINT #2, " Q3 = "; Q3
5340 CHI.DENOM = SIN(CDR.LAT.RAD) * COS(HOUR.ANG.RAD) - COS(CDR.LAT.RAD) *
TAN(DECL.RAD)
5350 CHI = SIN(HOUR.ANG.RAD) / CHI.DENOM
5360 REM * CALCULATE SOLAR AZIMUTH CONSTANT, CAZ
5370 IF HOUR.ANG.DEG < 0 AND CHI >= 0 THEN
        CAZ = 0
5380 ELSEIF HOUR.ANG.DEG >= 0 AND CHI < 0 THEN
        CAZ = 360
5390 ELSE
        CAZ = 180
5495 END IF
5400 REM * CALCULATE SOLAR AZIMUTH IN DEGREES, Z4.DEG
5410 Z4.DEG = CAZ + ATN(CHI)/DEG.TO.RAD
5420 Z4.RAD = Z4.DEG * DEG.TO.RAD
5510 Z1.RAD = Z1.DEG * DEG.TO.RAD
5520 E1 = COS(H3.RAD) * COS(Z4.RAD - Z1.RAD)
5530 E2.RAD = ATN(SQR(1 / E1 ^ 2 - 1))
5540 QS = ABSORP * Q3 * SIN(E2.RAD) * D / 1000 * (1 + .0001148 * CDR.ELEV -
1.108E-08 * CDR.ELEV ^ 2)
5545 IF DEBUG = 0 THEN PRINT #2, " QS = "; QS
5550 GOTO 5570
5560 QS = 0!
5570 RETURN
6000 REM ////////////////////////////////////////////
6010 REM / SUBROUTINE TO PRINT OUTPUT TO MONITOR SCREEN
6020 REM ////////////////////////////////////////////
6030 REM *****************
6040 REM * PRINT TO SCREEN
6050 REM *****************
6060 CLS
6070 PRINT
6080 PRINT X$
6090 PRINT " IEEE STD 738-2006 METHOD OF CALCULATION"
6100 PRINT
6110 PRINT "AIR TEMPERATURE = "; TAMB; " DEG C  &";
6130 PRINT "WIND SPEED IS "; VWIND; " M / SEC"
6140 PRINT USING "THE ANGLE BETWEEN WIND AND CONDUCTOR IS ### DEG"; WINDANG.DEG
6150 PRINT USING "THE CONDUCTOR IS #####. M ABOVE SEA LEVEL;"; CDR.ELEV
6160 PRINT USING "AND ###.# DEG FROM NORTH;  AT A LATITUDE OF ###.# DEG";
Z1.DEG; CDR.LAT
6170 PRINT "THE SUN TIME IS "; SUN.TIME; "HOURS &"; " THE ATMOSPHERE IS "; B$
6180 PRINT
6240 PRINT "CONDUCTOR DIAMETER IS "; D; " MM"
6250 PRINT USING "CONDUCTOR RESISTANCE IS ##.#### OHMS/KM AT #### DEG C"; RLO *
1000; TLO
6260 PRINT USING "                    AND ##.#### OHMS/KM AT #### DEG C"; RHI *
1000; THI
6270 PRINT "COEF OF EMISSIVITY = "; EMISS; " & COEF OF ABSORPTIVITY = "; ABSORP
6280 IF NSELECT = 3 OR NSELECT = 4 GOTO 6490
6290 PRINT
6350 PRINT USING "SOLAR HEAT INPUT IS   ####.### WATTS PER CONDUCTOR METER"; QS
6360 PRINT USING "RADIATION COOLING IS  ####.### WATTS PER CONDUCTOR METER"; QR
6370 PRINT USING "CONVECTIVE COOLING IS ####.### WATTS PER CONDUCTOR METER"; QC
6380 PRINT
```


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```
6390 IF NSELECT = 1 THEN GOTO 6440
6400 PRINT USING "GIVEN A MAXIMUM CONDUCTOR TEMPERATURE OF #####.# DEG C,";
TCDRPRELOAD
6410 PRINT USING "THE STEADY STATE THERMAL RATING IS ######.# AMPERES"; TR
6420 GOSUB 7000
6430 RETURN
6440 IF XIPRELOAD = 1.111 THEN XIPRELOAD = 0
6450 PRINT USING "GIVEN A CONSTANT CURRENT OF #####.# AMPERES,"; XIPRELOAD
6460 PRINT USING "THE CONDUCTOR TEMPERATURE IS ####.# DEG C"; TCDRPRELOAD
6470 GOSUB 7000
6480 RETURN
6490 REM PRINT
6500 PRINT "    ******* TRANSIENT THERMAL CALCULATIONS *******"
6510 PRINT USING "INITIAL STEADY STATE CONDUCTOR TEMP =   ###.# DEG C";
TCDRPRELOAD
6520 IF IORTPRELOAD = 1 THEN PRINT USING "FOR A PRE-STEP STEADY STATE CURRENT =
#####.# AMPERES"; XIPRELOAD
6530 IF HNH = 2 THEN GOTO 6610
6550 PRINT USING "                      HEAT CAPACITY =  ####.# WATTS-SEC/M-C";
HEATCAP
6560 GOTO 6630
6610 PRINT USING "                  CORE HEAT CAPACITY = ####.# WATTS-SEC/M-C";
HEATCORE
6620 PRINT USING "   OUTER STRAND LAYERS HEAT CAPACITY = ####.# WATTS-SEC/M-C";
HEATOUT
6630 IF NSELECT = 4 THEN 6670
6640 PRINT "THE TOTAL TIME OF INTEREST AFTER THE CURRENT"
6650 IF SORM = 0 THEN PRINT USING "INCREASES TO #######.# AMPS =
####.#### SECONDS"; XISTEP; TT
6660 IF SORM = 1 THEN PRINT USING "INCREASES TO #######.# AMPS =
####.#### MINUTES"; XISTEP; TT / 60
6670 PRINT USING "CALCULATION TIME INTERVAL =           ###.#### SECONDS";
DELTIME
6680 IF ((ATCDR(2) - TAMB) / (ATCDR(KTIMEMAX) - TAMB)) < .05 THEN GOTO 6710
6690 PRINT " CALCULATION ACCURACY WOULD IMPROVE IF THIS TIME INTERVAL WERE
REDUCED "
6700 REM PRINT
6710 IF FLAG = 0 OR HEATCORE = 0 THEN 6730
6720 PRINT "CORE HEAT CAPACITY IS IGNORED SINCE STEP DURATION LESS THAN 60 SEC"
6730 IF NSELECT = 4 GOTO 6870
6740 IF ATCDR(KTIMEMAX) < TCDRMAX THEN GOTO 6780
6750 PRINT USING "IT TAKES ####.#### SEC (####.#### MIN) "; TIME(KTIMEMAX);
TIME(KTIMEMAX) / 60!
6760 PRINT "TO REACH THE MAXIMUM ALLOWABLE CONDUCTOR TEMPERATURE "
6770 PRINT USING "OF ####.# DEGREES C"; TCDRMAX
6780 GOSUB 7000
6790 FOR K = 1 TO KTIMEMAX
6800 IF SORM = 0 THEN PRINT USING "TIME=#####.#### SEC   CDRTEMP= ####.# DEG C";
TIME(K); ATCDR(K)
6810 IF SORM = 1 THEN PRINT USING "TIME=#####.#### MIN   CDRTEMP= ####.# DEG C";
TIME(K) / 60; ATCDR(K)
6820 IF K <> 20 AND K <> 40 AND K <> 60 AND K <> 80 THEN GOTO 6840
6830 GOSUB 7000
6840 NEXT K
6850 IF KTIMEMAX < 20 THEN GOSUB 7000
6860 RETURN
6870 PRINT USING "THE TRANSIENT THERMAL RATING =      ########.# AMPERES";
XISTEP
6880 PRINT "THAT IS, WITH THIS CURRENT, THE CDR TEMPERATURE JUST REACHES "
6890 IF TT > 60 THEN PRINT USING "THE MAXIMUM OF ####.# DEG C IN ##.####
MINUTES"; TCDRMAX; TT / 60!
6900 IF TT <= 60 THEN PRINT USING "THE MAXIMUM OF ####.# DEG C IN ###.####
SECONDS"; TCDRMAX; TT
6910 GOSUB 7000
```


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```
6920 RETURN
7000 REM ////////////////////////////////////
7010 REM /  SUBROUTINE TO FREEZE MONITOR SCREEN
7020 REM ////////////////////////////////////
7030 PRINT X$
7040 PRINT "PRESS PRTSC TO PRINT OR ANY KEY TO CONTINUE"
7050 FOR P = 1 TO 1000000!
7060 D$ = INKEY$: IF LEN(D$) <> 0 THEN 7090
7070 NEXT P
7080 CLS
7090 RETURN
8000 REM ////////////////////////////////////////////
8010 REM / SUBROUTINE TO ENTER INPUT DATA FROM ASCII FILE
8020 REM ////////////////////////////////////////////
8030 IF NS = 0 THEN INPUT #1, FILENAM$, Z$: INPUT #1, NSETS, Z$
8040 NS = NS + 1
8050 INPUT #1, COMMENT$, Z$
8060 REM INPUT #1, MOREIN, Z$
8070 REM INPUT #1, MOREOUT, Z$
8080 INPUT #1, NSELECT, Z$
8090 IF NSELECT = 1 THEN 8130
8100 IF NSELECT = 3 OR NSELECT = 4 THEN 8180
8110 INPUT #1, TCDRPRELOAD, Z$
8120 GOTO 8300
8130 INPUT #1, XIPRELOAD, Z$
8140 GOTO 8300
8150 REM *****************
8160 REM *  TRANSIENT DATA
8170 REM *****************
8180 INPUT #1, IORTPRELOAD, Z$
8190 IF IORTPRELOAD = 1 THEN INPUT #1, XIPRELOAD, Z$
8200 IF IORTPRELOAD = 2 THEN INPUT #1, TCDRPRELOAD, Z$
8210 IF NSELECT = 4 THEN INPUT #1, TCDRMAX, Z$ ELSE TCDRMAX = 1000
8220 IF NSELECT = 3 THEN INPUT #1, XISTEP, Z$
8230 INPUT #1, SORM, Z$
8240 INPUT #1, TT, Z$
8250 INPUT #1, DELTIME, Z$
8260 IF SORM = 1 THEN TT = TT * 60
8270 REM **************
8280 REM * WEATHER DATA
8290 REM **************
8300 INPUT #1, TAMB, Z$
8310 INPUT #1, VWIND, Z$
8320 INPUT #1, WINDANG.DEG, Z$
8340 REM *****************
8350 REM *  CONDUCTOR DATA
8360 REM *****************
8370 INPUT #1, C$, Z$
8380 INPUT #1, D, Z$
8390 INPUT #1, TLO, THI, Z$
8400 INPUT #1, RLO, RHI, Z$
8430 RLO = RLO / 1000
8440 RHI = RHI / 1000
8450 IF NSELECT = 1 OR NSELECT = 2 THEN 8510
8460 INPUT #1, HNH, Z$
8470 IF HNH = 1 THEN INPUT #1, HEATOUT, Z$: HEATCORE = 0
8480 IF HNH = 2 THEN INPUT #1, HEATOUT, HEATCORE, Z$
8490 REM
8500 REM
8510 HEATCAP = HEATOUT + HEATCORE
8520 INPUT #1, EMISS, ABSORP, Z$
8530 INPUT #1, CDR.ELEV, Z$
8540 INPUT #1, Z1.DEG, Z$
8550 REM
```


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```
8560 REM *********************
8570 REM *  SOLAR HEATING DATA
8580 REM *********************
8590 INPUT #1, CDR.LAT, Z$
8600 INPUT #1, SUN.TIME, NDAY, Z$
8610 INPUT #1, A3, B$, Z$
8620 RETURN
9000 REM ////////////////////////////////////////////////////////////////////
9010 REM / SUBROUTINE TO CALCULATE THERM COEF OF RAC & HEATCAP & WIND CORRECTION
9020 REM ////////////////////////////////////////////////////////////////////
9030 REM ************************************************************
9040 REM * SETUP LINEAR CONDUCTOR RESISTANCE EQ AS FUNCTION OF TEMP
9042 REM * B IN OHM/M-C OR OHM/FT-C AND B1 IN OHM/M OR OHM/FT
9050 REM ************************************************************
9060 B = (RHI - RLO) / (THI - TLO)
9070 B1 = RLO - B * TLO
9080 REM ***************************************************
9090 REM * SET UP LINEAR HEAT CAPACITY EQS AS FUNCTION OF TEMP
9100 REM ***************************************************
9110 REM ***************************************************
9120 REM * CORRECTION FACTOR (YC) FOR NON-PERPENDICULAR WIND
9130 REM ***************************************************
9140 WINDANG.RAD = 1.570796 - WINDANG.DEG * PIANG
9150 YC = 1.194 - SIN(WINDANG.RAD) - .194 * COS(2! * WINDANG.RAD) + .368 *
SIN(2! * WINDANG.RAD)
9160 RETURN
10000 REM ////////////////////////////////////////////////////////////
10010 REM /  SUBROUTINE TO CALCULATE STARTING VALUE FOR CURRENT ITERATION
10020 REM /  BY ASSUMING ADIABATIC HEATING DURING TIME TT
10030 REM ////////////////////////////////////////////////////////////
10040 TCDR = (TCDRMAX + TAMB) / 2
10050 IF TT < 60 THEN HEATCAP = HEATOUT ELSE HEATCAP = HEATOUT + HEATCORE
10060 GOSUB 15000
10070 AT = SQR(HEATCAP * (TCDRMAX - TAMB) / TT) / W4
10080 TCDR = TCDRPRELOAD
10090 NFLAG = 1
10100 GOSUB 13000
10110 RETURN
11000 REM ////////////////////////////////////////////////////////
11010 REM / SUBROUTINE CALCS CDR TEMP VS TIME FOR STEP CHANGE CURRENT
11020 REM ////////////////////////////////////////////////////////
11030 IF NSELECT = 4 THEN PRINT USING "TRYING A CURRENT OF #######.#### AMPS";
XISTEP
11040 FLAG = 0
11050 ATCDR(1) = TCDRPRELOAD
11060 TCDR = ATCDR(1)
11070 GOSUB 15000
11080 K = 1
11090 ATCDR(K + 1) = TCDR + (W4 ^ 2 * XISTEP ^ 2 + QS - QR - QC) * DELTIME /
HEATCAP
11100 TIME(K + 1) = TIME(K) + DELTIME
11110 TCDR = ATCDR(K + 1)
11115 IF NSELECT = 4 GOTO 11130
11120 PRINT "TIME = "; TIME(K + 1); " SECONDS / "; "CDR TEMP = "; TCDR; "DEG C"
11130 IF NSELECT = 3 AND TCDR > TCDRMAX THEN 11280
11140 REM ************************************************************************
11150 REM *
11160 REM ************************************************************************
11170 GOSUB 15000
11180 K = K + 1
11190 IF K = 3000 THEN PRINT "TIME INTERVAL TOO SMALL.  ARRAY OUT OF BOUNDS ":
GOTO 1880
11200 IF TIME(K) < TT THEN 11090
11210 IF XISTEP = 0 AND TCDR > TCDRMAX THEN 11220 ELSE 11250
```


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```
11220 PRINT "EVEN IF THE CURRENT IS REDUCED TO ZERO AMPS, THE CONDUCTOR"
11230 PRINT USING "TEMPERATURE WILL NOT DECREASE TO ####.# DEG C IN ####.#
MINUTES"; TCDRMAX; TT / 60
11240 GOTO 1880
11250 REM **********************************
11260 REM * CHECK FOR SHORT DURATION FAULTS
11270 REM **********************************
11280 IF TIME(K) >= 60 OR FLAG = 1 OR HEATCORE = 0 OR TT < 60 THEN GOTO 11320
11290 HEATCAP = HEATOUT
11300 FLAG = 1
11310 GOTO 11050
11320 KTIMEMAX = K
11330 RETURN
12000 REM ////////////////////////////////////////////////
12010 REM /  SUBROUTINE ITERATES TO FIND CONDUCTOR TEMPERATURE
12020 REM /  GIVEN THE CONDUCTOR CURRENT
12030 REM ////////////////////////////////////////////////
12040 IF NFLAG = 0 THEN TCDR = X: GOSUB 15000: TEMP = XIDUMMY - TR: RETURN
12050 IF NFLAG = 1 THEN XISTEP = X: GOSUB 11000
12060 IF TCDRPRELOAD <= TCDRMAX THEN TEMP = TCDRMAX - TCDR: RETURN
12070 IF TCDRPRELOAD > TCDRMAX THEN TEMP = TCDR - TCDRMAX: RETURN
13000 REM ////////////////////////////////////////////////////////////////
13010 REM / SUBROUTINE RTMI MUELLER-S ITERATION METHOD SELECTS A CURRENT
13020 REM / WHICH JUST RAISES TCDR TO TCDMAX IN THE TIME TT.  THIS CURRENT
13030 REM / IS THE TRANSIENT RATING OF THE CONDUCTOR.  IT DOES THIS BY
13040 REM / REPEATEDLY GUESSING A CURRENT - XISTEP - CALCULATING TCDR AT TT
13050 REM / AND COMPARING THE CALCULATED TCDR TO TCDRMAX.  ROUTINE SUPPLIED
13060 REM / COURTESY OF BILL HOWINGTON.
13070 REM ////////////////////////////////////////////////////////////////
13080 REM * START BY PREPARING TO ITERATE
13090 REM ******************************
13100 XLI = 0: XRI = 0: EPS = .049: IEND = 20: X = 0
13110 GOSUB 14000
13120 IER = 0: XL = XLI: XR = XRI: X = XL: TOL = X
13130 GOSUB 12000
13140 F = TEMP: IF XLI = XRI OR F = 0 THEN 13530
13150 FL = F: X = XR: TOL = X
13160 GOSUB 12000
13170 F = TEMP: IF F = 0 THEN 13530
13180 FR = F: IF (SGN(FL) + SGN(FR)) = 0 THEN 13200 ELSE 13760
13190 REM ************************************************
13200 REM BASIC ASSUMPTION FL*FR LESS THAN 0 IS SATISFIED.
13210 REM ************************************************
13220 I = 0
13230 REM ********************
13240 REM START ITERATION LOOP
13250 REM ********************
13260 I = I + 1
13270 REM ********************
13280 REM START BISECTION LOOP
13290 REM ********************
13300 FOR JK = 1 TO IEND
13310 X = .5 * (XL + XR): TOL = X: GOSUB 12000
13320 F = TEMP: IF F = 0 THEN 13530
13330 IF (SGN(F) + SGN(FR)) = 0 THEN 13370 ELSE 13380
13340 REM ************************************************************
13350 REM INTERCHANGE XL AND XR IN ORDER TO GET THE SAME SIGN IN F AND FR
13360 REM ************************************************************
13370 TOL = XL: XL = XR: XR = TOL: TOL = FL: FL = FR: FR = TOL
13380 TOL = F - FL: DA = F * TOL: DA = DA + DA
13390 IF (DA - FR * (FR - FL)) >= 0 THEN 13410
13400 IF (I - IEND) <= 0 THEN 13570
13410 XR = X: FR = F
13420 REM ********************************************
```


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```
13430 REM TEST ON SATISFACTORY ACCURACY IN BISECTION LOOP
13440 REM ***************************************************
13450 TOL = EPS
13460 IF (ABS(FR - FL) - TOL) <= 0 THEN 13530
13470 NEXT JK
13480 REM ************************************************************
13490 REM END OF BISECTION LOOP - NO CONVERGENCE AFTER IEND ITERATION STEPS
13500 REM FOLLOWED BY IEND SUCCESSIVE STEPS OF BISECTION
13510 REM ************************************************************
13520 IER = 1: GOTO 13780
13530 RETURN
13540 REM ************************************************************
13550 REM COMPUTATION OF ITERATED X-VALUE BY INVERSE PARABOLIC INTERPOLATION
13560 REM ************************************************************
13570 DA = FR - F: DX = (X - XL) * FL * (1 + F * (DA - TOL) / (DA * (FR - FL)))
/ TOL
13580 XM = X: FM = F: X = XL - DX: TOL = X
13590 GOSUB 12000
13600 F = TEMP: IF F = 0 THEN 13530
13610 REM ***************************************************
13620 REM TEST ON SATISFACTORY ACCURACY IN ITERATION LOOP
13630 REM ***************************************************
13640 TOL = EPS
13650 IF (ABS(F) - TOL) <= 0 THEN 13530
13660 REM **********************************
13670 REM PREPARATION OF NEXT BISECTION LOOP
13680 REM **********************************
13690 IF (SGN(F) + SGN(FL)) <> 0 THEN 13710
13700 XR = X: FR = F: GOTO 13260
13710 XL = X: FL = F: XR = XM: FR = FM: GOTO 13260
13720 REM ***************************************
13730 REM END OF ITERATION LOOP
13740 REM ERROR RETURN IN CASE OF WRONG INPUT DATA
13750 REM ***************************************
13760 IF XHI <> XLO THEN 13770 ELSE RETURN
13770 IER = 2: JK = 0
13780 BEEP: PRINT "NUMBER OF ITERATIONS= "; JK
13790 PRINT "ITERATION ROUTINE CONDITION CODE,IER= "; IER
13800 IF IER = 2 THEN PRINT "TCDR OUT OF TEMPERATURE RANGE"
13810 IF IER = 1 THEN PRINT "NO CONVERGENCE IN SUBROUTINE TRANS"
13820 STOP
14000 REM ////////////////////////////////////////////////////////
14010 REM / SUBROUTINE GUESS TO DETERMINE INITIAL BOUNDS FOR ITERATION
14020 REM ////////////////////////////////////////////////////////
14030 IF NFLAG = 0 THEN XLO = TAMB: XHI = 1000: DIV = 10
14040 IF NFLAG = 1 THEN XLO = 0: XHI = 10 * AT: DIV = 10
14050 CHA = (XHI - XLO) / DIV: NUM = INT(DIV): X = XLO
14060 GOSUB 12000
14070 FO = TEMP
14080 FOR JK = 1 TO NUM
14090 X = XLO + JK * CHA: GOSUB 12000
14100 FF = TEMP: IF (SGN(FF) + SGN(FO)) = 0 THEN 14140
14110 FO = FF
14120 NEXT JK
14130 XLI = XLO: XRI = XHI: RETURN
14140 XRI = X: XLI = X - CHA: RETURN
15000 REM ////////////////////////////////////////////////////////////////
15010 REM / SUBROUTINE T0 CALCULATE THERMAL RATING GIVEN A CDR TEMP (TCDR),
15020 REM / AND CONDUCTOR PARAMETERS AND WEATHER CONDITIONS
15030 REM ////////////////////////////////////////////////////////////////
15040 REM PRINT USING "TRYING A TCDR OF ####.### DEG C"; TCDR
15050 REM ******************************************************
15060 REM * CALC CONDUCTOR HEAT LOSS (QR) BY RADIATION (WATTS/M)
15070 REM ******************************************************
```


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```
15080 T3 = TCDR + 273
15090 T4 = TAMB + 273
15102 QR = .0178 * EMISS * D * ((T3 / 100) ^ 4 - (T4 / 100) ^ 4)
15110 REM ************************************************************
15120 REM * CALC CONDUCTOR HEAT LOSS BY CONVECTION (WATTS/M)
15130 REM ************************************************************
15140 T5 = (TCDR + TAMB) / 2
15160 U1 = 1.458E-06 * (T5 + 273) ^ 1.5 / (T5 + 383.4)
15172 P1 = (1.2932 - .0001525 * CDR.ELEV + 6.379E-09 * CDR.ELEV ^ 2) / (1 +
.00367 * T5)
15180 K1 = .02424 + 7.477E-05 * T5 - 4.407E-09 * T5 ^ 2
      IF DEBUG = 0 THEN PRINT #2, "U1,P1,K1 = "; U1, P1, K1
15182 REM ************************************************************
15184 REM * CALC CONDUCTOR HEAT LOSS (QC) BY NATURAL CONVECTION (WATTS/M)
15186 REM ************************************************************
15188 IF (TCDR - TAMB) < 0! THEN TCDR = TAMB + .1
15191 QC = .0205 * P1 ^ .5 * D ^ .75 * (TCDR - TAMB) ^ 1.25
15192 IF VWIND = 0 THEN 15450
15194 REM ************************************************************
15196 REM * CALC CONDUCTOR HEAT LOSS (QCF) BY FORCED CONVECTION (WATTS/M)
15198 REM ************************************************************
15202 Z = D * P1 * VWIND / U1
15212 Q1 = .0119 * Z ^ .6 * K1 * (TCDR - TAMB)
15222 Q2 = (1.01 + .0372 * Z ^ .52) * K1 * (TCDR - TAMB)
15230 IF Q1 - Q2 <= 0 THEN 15260
15240 QCF = Q1
15250 GOTO 15270
15260 QCF = Q2
15265 IF DEBUG = 0 THEN PRINT #2, "QCF = "; QCF
15270 QCF = QCF * YC
15370 REM ************************************************************
15380 REM * SELECT LARGER OF CONVECTIVE HEAT LOSSES (QC VERSUS QCF)
15390 REM ************************************************************
15400 IF QCF < QC THEN 15450
15410 QC = QCF
15420 REM ***************************************
15430 REM * CALC SUM OF STEADY STATE HEAT FLOWS
15440 REM ***************************************
15450 R5 = -QS + QC + QR
15460 REM ************************************************
15470 REM * CALC SQRT OF CONDUCTOR RESISTANCE IN OHMS/FT
15480 REM ************************************************
15492 W4 = SQR(B1 + B * TCDR)
15500 IF R5 <= 0 THEN TR = 0: GOTO 15560
15510 R4 = R5 ^ .5
15520 REM ************************************************
15530 REM * CALCULATE THERMAL RATING (AMPACITY) IN AMPERES
15540 REM ************************************************
15550 TR = R4 / W4
15560 RETURN
16000 REM ////////////////////////////////////////
16010 REM / SUBROUTINE TO WRITE OUTPUT DATA TO FILE
16020 REM ////////////////////////////////////////
16030 PRINT #2,
16040 PRINT #2,
16050 PRINT #2, X$
16060 PRINT #2, " IEEE STD 738-2006 METHOD FOR CALCULATION OF"
16070 PRINT #2, "BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS"
16080 PRINT #2, "INPUT DATA FILE NAME IS "; F$
16090 PRINT #2, COMMENT$
16100 PRINT #2, C$
16110 PRINT #2, "AIR TEMPERATURE IS "; TAMB; " DEG C"
16180 PRINT #2, "WIND SPEED IS "; VWIND; " M/SEC"
16190 PRINT #2, USING "ANGLE BETWEEN WIND AND CONDUCTOR IS ### DEG"; WINDANG.DEG
```


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```
16200 PRINT #2, "COEFFICIENT OF EMISSIVITY IS "; EMISS
16210 PRINT #2, "COEFFICIENT OF ABSORPTIVITY IS "; ABSORP
16220 PRINT #2, "LINE DIRECTION IS ### DEG FROM NORTH"; Z1.DEG; " AND THE
ATMOSPHERE IS "; B$
16230 IF NSELECT = 3 OR NSELECT = 4 THEN GOTO 16450
16240 PRINT #2,
16250 PRINT #2,
16260 PRINT #2, "STEADY STATE THERMAL CALCULATIONS"
16320 PRINT #2, USING "QS IS ####.### WATTS PER METER OF CONDUCTOR "; QS
16330 PRINT #2, USING "QR IS ####.### WATTS PER METER OF CONDUCTOR "; QR
16340 PRINT #2, USING "QC IS ####.### WATTS PER METER OF CONDUCTOR "; QC
16350 PRINT #2,
16360 IF NSELECT = 1 THEN GOTO 16400
16370 PRINT #2, USING "GIVEN A MAXIMUM CONDUCTOR TEMPERATURE OF ####.# DEG C,";
TCDRPRELOAD
16380 PRINT #2, USING "THE STEADY STATE THERMAL RATING IS ##### AMPERES"; TR
16390 GOTO 16430
16400 IF XIPRELOAD = 1.111 THEN XIPRELOAD = 0
16410 PRINT #2, USING "GIVEN A CONSTANT CURRENT OF ##### AMPERES"; XIPRELOAD
16420 PRINT #2, USING "THE CONDUCTOR TEMPERATURE IS ####.# DEG C"; TCDRPRELOAD
16430 REM
16440 GOTO 16740
16450 PRINT #2,
16460 PRINT #2,
16470 PRINT #2, "     TRANSIENT THERMAL CALCULATIONS "
16480 PRINT #2, USING "INITIAL STEADY STATE CDR TEMP IS ###.# DEG C";
TCDRPRELOAD
16490 IF IORTPRELOAD = 2 THEN PRINT #2,
16500 IF IORTPRELOAD = 1 THEN PRINT #2, USING "FOR A GIVEN INITIAL CURRENT OF
##### AMPERES,"; XIPRELOAD
16505 IF HNH = 2 THEN GOTO 16545
16515 PRINT #2, USING "                      HEAT CAPACITY =  ####.#WATTS-SEC/M-
C"; HEATCAP
16520 GOTO 16570
16545 PRINT #2, USING "                 CORE HEAT CAPACITY = ####.# WATTS-
SEC/M-C"; HEATCORE
16550 PRINT #2, USING "   OUTER STRAND LAYERS HEAT CAPACITY = ####.# WATTS-
SEC/M-C"; HEATOUT
16570 IF NSELECT = 4 THEN 16610
16580 PRINT #2, "THE MAXIMUM TIME OF INTEREST AFTER THE STEP CURRENT"
16590 IF SORM = 0 THEN PRINT #2, USING "INCREASES TO #######.# AMPS IS ####.####
SECONDS"; XISTEP; TT
16600 IF SORM = 1 THEN PRINT #2, USING "INCREASES TO #######.# AMPS IS ####.####
MINUTES"; XISTEP; TT / 60
16610 PRINT #2, USING "THE MAX ALLOWABLE CONDUCTOR TEMPERATURE IS ####.# DEG C";
TCDRMAX
16620 IF NSELECT = 4 GOTO 16680
16630 FOR I = 1 TO KTIMEMAX
16640 IF SORM = 0 THEN PRINT #2, USING "TIME=###.#### SEC   CDRTEMP= ###.# DEG
C"; TIME(I); ATCDR(I)
16650 IF SORM = 1 THEN PRINT #2, USING "TIME=###.### MIN   CDRTEMP= ###.# DEG
C"; TIME(I) / 60; ATCDR(I)
16660 NEXT I
16670 GOTO 16730
16680 PRINT #2, USING "THE TRANSIENT THERMAL RATING IS ########.# AMPERES";
XISTEP
16690 PRINT #2, "THAT IS, WITH THIS CURRENT, THE CONDUCTOR TEMPERATURE JUST
REACHES "
16700 PRINT #2, USING "THE MAXIMUM ALLOWABLE CDR TEMP OF ####.# DEG C"; TCDRMAX
16710 IF TT > 60 THEN PRINT #2, USING "IN ####.## MINUTES"; TT / 60
16720 IF TT < 60 THEN PRINT #2, USING "IN ###.#### SECONDS"; TT
16730 PRINT #2, X$
16740 RETURN
20000 REM ////////////////////
```


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```
20010 REM / COMMENTS ON PROGRAM
20020 REM ////////////////////
20030 REM *
20040 REM *  THE PROGRAM DOES NOT CALCULATE ANY INTERNAL RADIAL OR AXIAL
20050 REM *  TEMPERATURE GRADIENTS.  THIS IS NORMALLY NOT A SOURCE OF
20060 REM *  SIGNIFICANT ERROR EXCEPT FOR INTERNALLY COMPLEX CONDUCTORS
20070 REM *  SUCH AS FIBER-OPTIC SHIELD WIRE AND FOR NON-HOMOGENEOUS CONDUCTORS
20080 REM *  FOR FAULT CURRENTS OF LESS THAN 1 MINUTE.  THE PROGRAM DOES NOT
20090 REM *  APPLY TO INTERNALLY COMPLEX CONDUCTORS, IT DOES CALCULATE A WORST
20100 REM *  CASE ESTIMATE OF TEMPERATURE/RATING FOR ACSR OR ACSR/AW BY
NEGLECTING
20110 REM *  THE HEAT STORAGE CAPACITY OF THE RELATIVELY POORLY CONDUCTING CORE
20120 REM *  FOR STEP CURRENTS WHICH PERSIST FOR LESS THAN ONE MINUTE.
20130 REM *  THE VARIATION IN SPECIFIC HEAT WITH TEMPERATURE IS NEGLECTED.
20140 REM *  ADDED COMMENTS 7/97 DAD
20150 REM *  ADDED SI FORMULAS, SOLAR EQUATIONS, AND CHANGED AIR PARAMETERS
```


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Annex C

(informative)

Sample calculations of steady-state conductor temperature

```
Input File - Steady State Conductor Temperature Calculation - SI Units
"FILE SI_SSTMP.TXT"                     "FILE DESCRIPTION (SI UNITS)"
1                                       "NUMBER OF DATA SETS IS"
"STDY STATE CDR TEMP CALC"              "COMMENT ON FIRST DATA SET"
1                                       "SELECT CALCULATION"
1000                                    "STEADY STATE CURRENT IN AMPERES"
40                                      "AMBIENT TEMP IN DEG C IS"
0.61                                     "WIND SPEED (M/SEC)"
90                                       "ANGLE BETWEEN WIND & CDR AXIS IN DEG"
"400 MM2 DRAKE 26/7 ACSR"                "CONDUCTOR DESCRIPTION"
28.12                                    "CONDUCTOR DIAMETER (MM)"
25,75                                    "MIN & MAX CDR TEMP IN DEG C"
0.07284, 0.08689                         "MIN & MAX CDR RAC (OHMS/KM)"
0.5, 0.5                                 "COEF OF EMISS AND SOLAR ABSORP"
0.                                       "CDR ELEV ABOVE SEA LEVEL IN METERS"
45                                       "CDR DIRECTION CW RELATIVE TO NORTH"
43                                       "CDR LATITUDE IN DEGREES"
12, 161                    "SOLAR HOUR 14 = 2PM OR 99(NO SUN) & DAY OF THE YEAR"
0, "CLEAR"                               "AIR CLARITY - CLEAR(0), INDUST(1)"


Output File - Steady State Conductor Temperature Calculation - SI Units


--------------------------------------------------------------------------------
IEEE STD 738-2006 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
INPUT DATA FILE NAME IS SI_SSTMP.TXT
STDY STATE CDR TEMP CALC
400 MM2 DRAKE 26/7 ACSR
AIR TEMPERATURE IS 40 DEG C
WIND SPEED IS .61 M/SEC
ANGLE BETWEEN WIND AND CONDUCTOR IS 90 DEG
COEFFICIENT OF EMISSIVITY IS .5
COEFFICIENT OF ABSORPTIVITY IS .5
LINE DIRECTION IS ### DEG FROM NORTH 45 AND THE ATMOSPHERE IS CLEAR


STEADY STATE THERMAL CALCULATIONS
QS IS 13.738 WATTS PER METER OF CONDUCTOR
QR IS 24.791 WATTS PER METER OF CONDUCTOR
QC IS 83.061 WATTS PER METER OF CONDUCTOR


GIVEN A CONSTANT CURRENT OF 1000 AMPERES
THE CONDUCTOR TEMPERATURE IS 100.7 DEG C
```


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Annex D

(informative)

Sample calculation of steady-state thermal rating

```
(Input File - Steady State Conductor Thermal Rating Calculation - SI
Units
"FILE SI_SSAMP.TXT"            "FILE DESCRIPTION"
1                              "NUMBER OF DATA SETS IS"
"STDY STATE RATING CALC"       "COMMENT ON FIRST DATA SET"
2                              "SELECT CALCULATION"
101.1                          "STEADY STATE CONDUCTOR TEMPERATURE "
40                             "AMBIENT TEMP IN DEG C IS"
0.61                           "WIND SPEED (M/SEC)"
90                             "ANGLE BETWEEN WIND & CDR AXIS IN DEG"
"400 MM2 DRAKE 26/7 ACSR"      "CONDUCTOR DESCRIPTION"
28.12                          "CONDUCTOR DIAMETER (MM)"
25,75                          "MIN & MAX CDR TEMP IN DEG C"
0.07284, 0.08689               "MIN & MAX CDR RAC (OHMS/KM)"
0.5, 0.5                       "COEF OF EMISS AND SOLAR ABSORP"
0.                             "CDR ELEV ABOVE SEA LEVEL IN METERS"
45                             "CDR DIRECTION IN DEG CW FROM NORTH"
43                             "CDR LATITUDE IN DEGREES"
12                           "SOLAR HOUR 2PM=14 OR 99(NO SUN) & DAY OF THE YEAR"
0 , "CLEAR"                    "AIR CLARITY - CLEAR(0), INDUST(1)"


Output File - Steady State Conductor Thermal Rating Calculation - SI
Units


--------------------------------------------------------------------------------
IEEE STD 738-2006 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
INPUT DATA FILE NAME IS SI_SSAMP.TXT
STDY STATE RATING CALC
400 MM2 DRAKE 26/7 ACSR
AIR TEMPERATURE IS 40 DEG C
WIND SPEED IS .61 M/SEC
ANGLE BETWEEN WIND AND CONDUCTOR IS 90 DEG
COEFFICIENT OF EMISSIVITY IS .5
COEFFICIENT OF ABSORPTIVITY IS .5
LINE DIRECTION IS ### DEG FROM NORTH 45 AND THE ATMOSPHERE IS CLEAR


STEADY STATE THERMAL CALCULATIONS
QS IS 13.732 WATTS PER METER OF CONDUCTOR
QR IS 24.998 WATTS PER METER OF CONDUCTOR
QC IS 83.600 WATTS PER METER OF CONDUCTOR


GIVEN A MAXIMUM CONDUCTOR TEMPERATURE OF 101.1 DEG C,
THE STEADY STATE THERMAL RATING IS 1003 AMPERES
```


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Annex E

(informative)

Sample calculation of transient conductor temperature with a step increase in current

```
Input File - Transient Conductor Temperature Calculation - SI Units

"FILE SI_TRTMP.TXT"              "FILE DESCRIPTION"
1                                "NUMBER OF DATA SETS IS"
"CDR TEMP VS TIME CALC"          "COMMENT ON FIRST DATA SET"
3                                "SELECT CALCULATION"
1                                "PRE-STEP AMP(1) OR TEMP(2)"
400                              "PRE-STEP CURRENT"
1200                             "POST-STEP CURRENT"
1                                "UNITS OF STEP MIN(1) OR SEC(0)"
15                               "STEP DURATION IN ABOVE UNITS"
60                               "CALC TIME INTERVAL (SEC)"
40                               "AMBIENT TEMP IN DEG C IS"
0.61                             "WIND SPEED (M/SEC)"
90                               "ANGLE BETWEEN WIND & CDR AXIS IN DEG"
"400 MM2 DRAKE 26/7 ACSR"        "CONDUCTOR DESCRIPTION"
28.12                            "CONDUCTOR DIAMETER (MM)"
25,75                            "MIN & MAX CDR TEMP IN DEG C"
0.07284, 0.08689                 "MIN & MAX CDR RAC (OHMS/KM)"
2                                "CONDUCTOR HAS A STEEL CORE"
1066., 243                       "HEAT CAP OF OUTER & CORE STRANDS (W-SEC/M-C)"
0.5, 0.5                         "COEF OF EMISS AND SOLAR ABSORP"
0.                               "CDR ELEV ABOVE SEA LEVEL IN FEET"
45                               "CDR DIR IN DEG CW FROM NORTH"
43                               "CDR LATITUDE IN DEGREES"
12, 161                  "SOLAR HOUR (2PM=14) OR 99(NO SUN) & DAY OF THE YEAR"
0, "CLEAR"                       "AIR CLARITY - CLEAR(0), INDUST(1)"


Output File - Transient Conductor Temperature Calculation - SI Units


--------------------------------------------------------------------------------
IEEE STD 738-2006 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
INPUT DATA FILE NAME IS SI_TRTMP.TXT
CDR TEMP VS TIME CALC
400 MM2 DRAKE 26/7 ACSR
AIR TEMPERATURE IS 40 DEG C
WIND SPEED IS .61 M/SEC
ANGLE BETWEEN WIND AND CONDUCTOR IS 90 DEG
COEFFICIENT OF EMISSIVITY IS .5
COEFFICIENT OF ABSORPTIVITY IS .5
LINE DIRECTION IS ### DEG FROM NORTH 45 AND THE ATMOSPHERE IS CLEAR


TRANSIENT THERMAL CALCULATIONS
INITIAL STEADY STATE CDR TEMP IS 55.7 DEG C
FOR A GIVEN INITIAL CURRENT OF 400 AMPERES,
CORE HEAT CAPACITY = 243.0 WATTS-SEC/M-C
OUTER STRAND LAYERS HEAT CAPACITY = 1066.0 WATTS-SEC/M-C
THE MAXIMUM TIME OF INTEREST AFTER THE STEP CURRENT
INCREASES TO 1200.0 AMPS IS 15.0000 MINUTES
THE MAX ALLOWABLE CONDUCTOR TEMPERATURE IS 1000.0 DEG C
```


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```
TIME=    0.000 MIN    CDRTEMP=   55.7 DEG C
TIME=    1.000 MIN    CDRTEMP=   60.5 DEG C
TIME=    2.000 MIN    CDRTEMP=   65.0 DEG C
TIME=    3.000 MIN    CDRTEMP=   69.2 DEG C
TIME=    4.000 MIN    CDRTEMP=   73.2 DEG C
TIME=    5.000 MIN    CDRTEMP=   76.9 DEG C
TIME=    6.000 MIN    CDRTEMP=   80.3 DEG C
TIME=    7.000 MIN    CDRTEMP=   83.6 DEG C
TIME=    8.000 MIN    CDRTEMP=   86.6 DEG C
TIME=    9.000 MIN    CDRTEMP=   89.5 DEG C
TIME=   10.000 MIN    CDRTEMP=   92.1 DEG C
TIME=   11.000 MIN    CDRTEMP=   94.6 DEG C
TIME=   12.000 MIN    CDRTEMP=   96.9 DEG C
TIME=   13.000 MIN    CDRTEMP=   99.0 DEG C
TIME=   14.000 MIN    CDRTEMP=  101.1 DEG C
TIME=   15.000 MIN    CDRTEMP=  102.9 DEG C
```


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Annex F

(informative)

Sample calculation of transient thermal rating

Input File - Transient Conductor Thermal Rating Calculation - SI Units

```
"FILE SI_TRAMP.TXT"               "FILE DESCRIPTION (SI UNITS)"
1                                 "NUMBER OF DATA SETS IS"
"TRANSIENT RATING CALC"           "COMMENT ON FIRST DATA SET"
4                                 "SELECT CALCULATION"
2                                 "PRE-STEP AMP(1) OR TEMP(2)"
40                                "PRE-STEP CONDUCTOR TEMPERATURE"
150                               "MAX ALLOWED POST-STEP CDR TEMP"
1                                 "UNITS OF TIME STEP MIN(1) OR SEC(0)"
15                                "STEP DURATION TO REACH MAX CDR TEMP"
60                                "CALC TIME INTERVAL (SEC)"
40                                "AMBIENT TEMP IN DEG C IS"
0.61                              "WIND SPEED (M/SEC)"
90                                "ANGLE BETWEEN WIND & CDR AXIS IN DEG"
"400 MM2 DRAKE 26/7 ACSR"         "CONDUCTOR DESCRIPTION"
28.12                             "CONDUCTOR DIAMETER (MM)"
25,75                             "MIN & MAX CDR TEMP IN DEG C"
0.07284, 0.08689                  "MIN & MAX CDR RAC (OHMS/KM)"
2                                 "CONDUCTOR HAS A STEEL CORE"
1066., 243.0                      "HEAT CAP OF OUTER & CORE STRANDS (W-SEC/M-C)"
0.5, 0.5                          "COEF OF EMISS AND SOLAR ABSORP"
0.                                "CDR ELEV ABOVE SEA LEVEL IN FEET"
45                                "CDR DIRECTION IN DEG CW FROM NORTH"
43                                "CDR LATITUDE IN DEGREES"
12                              "SOLAR HR 14=2PM OR 99(NO SUN) & DAY OF THE YEAR"
0, "CLEAR"                        "AIR CLARITY - CLEAR(0), INDUST(1)"
```

Output File - Transient Conductor Thermal Rating Calculation - SI Units

```
--------------------------------------------------------------------------------
IEEE STD 738-2006 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
INPUT DATA FILE NAME IS SI_TRAMP.TXT
TRANSIENT RATING CALC
400 MM2 DRAKE 26/7 ACSR
AIR TEMPERATURE IS 40 DEG C
WIND SPEED IS .61 M/SEC
ANGLE BETWEEN WIND AND CONDUCTOR IS 90 DEG
COEFFICIENT OF EMISSIVITY IS .5
COEFFICIENT OF ABSORPTIVITY IS .5
LINE DIRECTION IS ### DEG FROM NORTH 45 AND THE ATMOSPHERE IS CLEAR


TRANSIENT THERMAL CALCULATIONS
INITIAL STEADY STATE CDR TEMP IS 40.0 DEG C

CORE HEAT CAPACITY = 243.0 WATTS-SEC/M-C
OUTER STRAND LAYERS HEAT CAPACITY = 1066.0 WATTS-SEC/M-C
THE MAX ALLOWABLE CONDUCTOR TEMPERATURE IS 150.0 DEG C

THE TRANSIENT THERMAL RATING IS 1642.0 AMPERES
THAT IS, WITH THIS CURRENT, THE CONDUCTOR TEMPERATURE JUST REACHES
THE MAXIMUM ALLOWABLE CDR TEMP OF 150.0 DEG C
IN 15.00 MINUTES.
```


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Annex G

(informative)

Thermal time constant

The non-steady-state heat balance Equation (2) cannot be solved analytically for conductor temperature as a function of time since certain of its terms are non-linear. Considering the equation term by term, it may be seen that the Ohmic heating term, and the forced convection equation term are linear in conductor temperature. The solar heating term is also linear since it is independent of conductor temperature. The radiation heat loss term and the natural convection (zero wind speed) term are both non-linear in conductor temperature.

Black and Rehberg [B5] describe a method of approximating the radiation cooling Equation (7) as a linear function of temperature. Doing so yields a linear non-steady-state heat balance equation of the form shown in Equation (G.1):

$$\frac{d}{dt}\left(T_c - T_a\right) = K_1\left(T_c - T_a\right) + K_2 I^2 \tag{G.1}$$

For a step change in electrical current, the solution of the linearized non-steady-state heat balance equation is shown in Equation (G.2).

$$T_c(t) = T_i + \left(T_f - T_i\right)\left(1 - e^{-t/\tau}\right) \tag{G.2}$$

The steady-state conductor temperature prior to the step increase in current is T_i. The steady-state conductor temperature which occurs long after the step increase in current is T_f. The thermal time constant, τ, may be calculated by use of Equation (G.3).

$$\tau = \frac{\left(T_f - T_i\right) mC_p}{R(T_c) \times \left(I_f^2 - I_i^2\right)} \tag{G.3}$$

where the conductor resistance is that corresponding to the average conductor temperature, $(T_i + T_f)/2$

Consider the exponential change in conductor temperature shown in Figure G.1. This is the "1200 amp" curve shown previously in Figure 2. The initial conductor temperature is 80 °C. The final conductor temperature is 128 °C. The current undergoes a step change from 800 to 1200 amperes. If the average conductor temperature is taken as 100 °C, the resistance of the Drake conductor is 2.86×10^{-5} ohms/ft. From A.6 of this standard, the heat capacity of the conductor is 300 W-s/ft -°C. The time constant is as follows:

$$\tau = \frac{(128 - 80) \times 399}{2.86 \times 10^{-5}\left(1200^2 - 800^2\right)}$$

$$\tau = 14 \text{ min}$$

Alternatively, the temperature change reaches 63% of its final value at a conductor temperature of 80 °C + (128 – 80) × 63 = 110 °C. From Figure G.1, this corresponds to a time of about 13 min.

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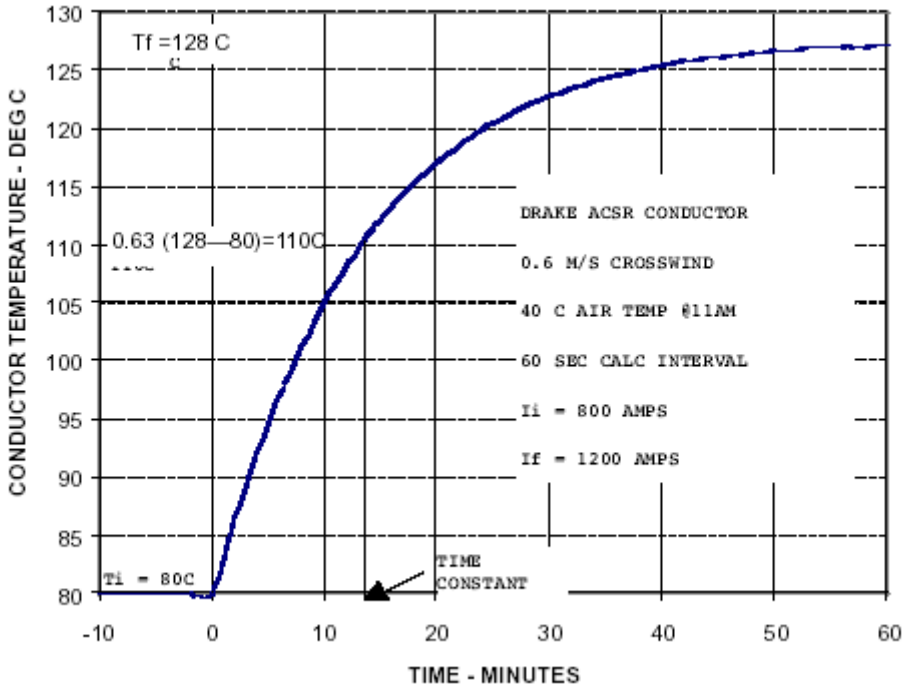

Figure G.1 – Conductor temperature vs. time curve

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Annex H

(informative)

Bibliography

[B1] *Aluminum Electrical Conductor Handbook*, 2nd ed. Washington, DC: The Aluminum Association, 1982.

[B2] *The American Nautical Almanac*. Washington, DC: U.S. Naval Observatory, 1957.

[B3] Black, W. Z. and Bush, R. A., "Conductor Temperature Research," EPRI Report EL 5707, May, 1988.

[B4] Black, W. Z. and Byrd, W. R., "Real-time ampacity model for overhead lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, No. 7, July 1983, pp. 2289-2293.

[B5] Black, W. Z. and Rehberg, R. L., "Simplified model for steady-state and real-time ampacity of overhead conductors," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, Oct. 1985, pp 29-42.

[B6] Davidson, G. A., et al., "Short-time thermal ratings for bare overhead conductors," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, No.3, Mar. 1969.

[B7] Davis, M. W.*, Development of Real Time Thermal Rating System*. St. Louis, MO: Edison Electrical Institute T&D, May 19, 1979.

[B8] Davis, M. W., "A new thermal rating approach: the real time thermal rating system for strategic overhead conductor transmission lines, Part III*." IEEE Transactions on Power Apparatus and Systems*, vol. PAS97, pp. 444-455, Mar./Apr. 1978.

[B9] Davis, M. W., "A new thermal rating approach: the real time thermal rating system for strategic overhead conductor transmission lines, Part II." *IEEE Transactions on Power Apparatus and Systems*, vol. PAS97, pp. 810-825, Mar./Apr. 1978.

[B10] Davis, M. W., "A new thermal rating approach: the real time thermal rating system for strategic overhead transmission lines, Part IV." *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-99, pp. 2184-2192, Nov./Dec. 1980.

[B11] "Determination of Bare Overhead Conductor Ratings." Conductor Rating Task Force, PA, NJ, and MD Interconnection, May 1973.

[B12] Douglass, D. A., Kirkpatrick, L. A. and Rathbun, L. S., "AC resistance of ACSR-Magnetic and temperature effects," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 6, pp. 1578-1584, June, 1985.

[B13] *Fan Engineering*, 5th ed., Richard D. Madison, Ed., Buffalo, New York: Forge Company, 1948.

[B14] Foss, S. D., "Dynamic Thermal Line Ratings Phases C,D, & E," Final Report No. EP81-6 to Empire State Electric Energy Research Corp., Dec. 1985.

[B15] Foss, S. D., Lin, S. H., and Fernandez, R. A., "Dynamic Thermal Line Ratings-Part 1-Dynamic ampacity rating algorithm." *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 6, pp. 1858-1864, June 1983.

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[B16] *Heating, Ventilating and Air-Conditioning Guide*. New York: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1956.

[B17] Hilpert, R., "Warmeabgabe von geheizten Drahten und Rohren im Luftstrom," *Forsch, Geb. Ingenieurw*, vol. 4, no. 5, Sep./Oct. 1933, pp. 215-224.

[B18] Hilsenrath and Toulokian, "The Viscosity, Thermal Conductivity and Prandtl Number for Air and Other Gases," *ASME Transactions*, vol. 76, pp. 967-981 1954.

[B19] House, H. E., Rigdon, W. S., Grosh, R. J., and Cottingham, W. B., "Emissivity of Weathered Conductors after Service in Rural and Industrial Environments*," AIEE Transactions*, pp. 891-896, Feb. 1963.

[B20] House, H. E. and Tuttle, P. D., "Current carrying capacity of ACSR," *IEEE Transactions on Power Apparatus and Systems*, pp. 1169-1178, Feb. 1958.

[B21] IEEE 100, *Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition, New York.

[B22] McAdams, W. H., *Heat Transmission*, 3rd ed. New York: McGraw-Hill, 1954.

[B23] Morgan, V. T., "The Current carrying capacities of overhead line conductors." Paper A75 575-3, IEEE/ PES Summer Meeting, Los Angeles, CA, 1978.

[B24] Mussen, G. A., "The Calculation of Current Carrying Capacity of Overhead Conductors." Alcan Research and Development Limited, Nov. 15, 1966.

[B25] Schurig, O. R. and Frick, C. U. "Heating and Current Carrying Capacity of Bare Conductor for Outdoor Service." *General Electric Review*, vol. 33, no. 3, pp. 141-157, Mar. 1930.

[B26] *Sight Reduction Tables for Air Navigators*. HO pub. no. 249, vols. II and III, U.S. Navy Hydrographic Office.

[B27] *Surface Observatories, Federal Meteorological Handbook No. 1*., PA-58, 2.20, Washington, DC, July 1, 1975.

[B28] Taylor, C. S., House, H. E., "Emissivity and its effects on the current carrying capacity of stranded aluminium conductors*," AIEE Transactions*, vol. 75, pt. III, pp. 970-976, Oct. 1956.

[B29] "Transmission Conductors Thermal Ratings," Paper 68-TAP-28, Report by Transmission Advisory Panel, East Central Area Reliability Coordination Agreement.

[B30] Wong, T. Y., Findlay, J. A., and McMurtie, A. N., "An On-Line Method for Transmission Ampacity Evaluation," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 2, Feb. 1982.

[B31] Yellot, J. I., "Power from Solar Energy," *ASME Transactions*, vol. 79, no. 6, pp. 1349-1357, Aug. 1956.

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