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

IEEE Power and Energy Society

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USA

IEEE Std 738™-2012
(Revision of
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Approved 19 October 2012

IEEE-SA Standards Board

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 nor does it recommend appropriately conservative weather conditions for the rating of overhead power lines. It does, however, provide a standard method for doing such calculations for both constant and variable conductor current and weather conditions.

Keywords: bare overhead lines, current-temperature relationship, IEEE 738™

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IEEE Std 738-2012

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Introduction

This introduction is not part of IEEE Std 738-2012, IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.

In 1986, IEEE Std 738, 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.

In the 2006 revision, SI units were added throughout, the solar heating calculation was extensively revised, and many editorial changes were made. This standard includes a computer program listing in “pseudo-code.” The working group has made every effort to ensure that the numerical algorithms included in the listing are accurate, but the user is cautioned that there may be values of rating parameters for which the method is not appropriate. The listing does not include input or output commands but is included to allow the user to develop their own computer program of spreadsheet application using proven algorithms.

Richard E. Kennon, James Larkey, Jerry Reding, and Dale Douglass (Task Force Chairman) did much of the revisions in the 1993 and 2006 versions of the standard.

Many persons have contributed to the preparation of this most recent standard. The primary contributors were Dale Douglass, Glenn Davidson, Zsolt Peter, Dean Stoddart, Jerry Reding, and Bill Black. Mark Lancaster, Tapani Seppa, Mark Ryan, Mohammad Pasha, Cody Davis, Francesco Zanellato, Gord Baker, Kathy Beaman, and Doug Harms provided both editorial and technical support. Many other members of IEEE W.G. 15.11.02/06 “T&D Overhead Conductors & Accessories,” chaired by Craig Pon, contributed their time and thought.

We would also 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.

Incorporated corrections were made to Clause 4 as required by IEEE Std 738-2012/Cor 1-2013.

Contents

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

1. Overview

1.1 Scope

The standard describes a numerical method by which the core and surface temperatures of a bare stranded overhead conductor are related to the steady or time-varying electrical current and weather conditions. The method may also be used to determine the conductor current that corresponds to conductor temperature limits. The standard does not recommend suitable weather conditions or conductor parameters for use in line rating calculations.

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 Working Group on Calculation of Bare Overhead Conductor Temperatures of the Towers, Poles and Conductors Subcommittee has made every effort to ensure that the computer 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 *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. [1]

conductor temperature: The temperature of a conductor, T_{avg}, is normally assumed to be isothermal (i.e., no axial or radial temperature variation). In those cases where the current density exceeds 0.5 A/mm^2 (1 A/kcmil), especially for those conductors with more than two layers of aluminum strands, the difference between the core and surface may be significant. Also, the axial variation along the line may be important. Finally, for transient calculations where the time period of interest is less than 1 min with non-homogeneous aluminum conductor steel reinforced (ACSR) conductors, the aluminum strands may reach a high temperature before the relatively non-conducting steel core.

effective (radial) thermal conductivity: Effective radial thermal conductivity characterizes the bare stranded conductor's heterogeneous structure (including aluminum strands, air gaps, oxide layers) as if it were a single, homogeneous conducting medium. The use of effective thermal conductivity in the thermal model simplifies the calculation process and avoids complex calculations on a microscopic level including the assessment of contact thermal resistances between strands, heat radiation and convection in air gaps locked between strands.

heat capacity (material): When the average temperature of a conductor material is increased by dT as a result of adding a quantity of heat dQ, the ratio, dQ/dT, is the heat capacity of the conductor.

maximum allowable conductor temperature: The maximum conductor temperature limit that is selected in order to minimize loss of conductor strength, and which limits sag in order to maintain adequate electrical clearances along the lines.

Reynolds number: A dimensionless number equal to air velocity time the air density times conductor diameter divided by the kinematic viscosity of air, all expressed in consistent units. The Reynolds number, in this case, is equal to the ratio of inertia forces to the viscous force on the conductor. It is typically used to differentiate between laminar and turbulent flow.

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

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

thermal time constant: In response to a sudden change in current (or weather conditions), the conductor temperature will change in an approximately exponential manner, eventually reaching a new steady-state temperature if there is no further change. The thermal time constant is the time required for the conductor temperature to accomplish 63.2% of this change. The exact change in temperature is not exponential so the thermal time constant is not used in the calculation described in this standard. It is, however, a useful concept in understanding line ratings.

time-varying weather and current: Neither weather conditions nor the electrical current carried by an overhead transmission line is typically constant over time. Yet both are assumed constant in conventional steady-state rating calculations. Even in the transient rating calculation where the current undergoes a step-change, the weather conditions are typically assumed constant. Only real-time rating methods consider the time-variation of line current and weather.

transient thermal rating: The line current can change suddenly. The conductor temperature cannot. For short-time emergency line currents, the delay in heating the conductor may allow relatively high currents to be applied for short times (e.g., less than 3 thermal time constants) without exceeding the maximum

[1]*IEEE Standards Dictionary Online* subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

allowable conductor temperature. The transient thermal rating is that emergency current (I_f) that yields the maximum allowable conductor surface or core temperature in a specified short time (typically less than 30 min) after a step change in electrical current from its initial current, I_i

wind direction: Wind direction is relative to the conductor axis (where both 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." In general, winds are neither parallel nor perpendicular to the line. At low wind speeds, where the wind is turbulent, it may have no persistent direction.

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 "US" units. This standard includes both SI and US units with SI units preferred.[2]

Table 1—Units and identification of letter symbols

Symbol	Description	SI units	US units
A'	Projected area of conductor	m^2/linear m	ft^2/linear ft
C	Solar azimuth constant	deg	deg
C_{pi}	Specific heat of i^{th} conductor material	J/kg-°C	J/lb-°C
D_0	Outside diameter of conductor	m	ft
D_{core}	Conductor core diameter	m	ft
H_c	Altitude of sun (0 to 90)	deg	deg
H_e	Elevation of conductor above sea level	m	ft
I	Conductor current	A	A
I_i	Initial current before step change	A	A
I_f	Final current after step change	A	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)	W/(ft-°C)
k_{th}	Effective radial thermal conductivity of conductor	W/m-°C	W/(ft-°C)
Lat	Degrees of latitude	deg	deg
mC_p	Total heat capacity of conductor	J/(m-°C)	J/(ft-°C)
m_i	Mass per unit length of i^{th} conductor material	kg/m	lb/ft
N	Day of the year (January 21 = 21, Solstices on 172 and 355)	–	–
N_{Re}	Dimensionless Reynolds number	–	–
q_{cn}, q_{c1}, q_{c2}, q_c	Convection heat loss rate per unit length	W/m	W/ft

[2] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Symbol	Description	SI units	US units
q_r	Radiated heat loss rate per unit length	W/m	W/ft
q_s	Heat gain rate from sun	W/m	W/ft
Q_s	Total solar and sky radiated heat intensity	W/m^2	W/ft^2
Q_{se}	Total solar and sky radiated heat intensity corrected for elevation	W/m^2	W/ft^2
$R(T_{avg})$	AC resistance of conductor at temperature, T_{avg}	Ω/m	Ω/ft
T_a	Ambient air temperature	°C	°C
T_{avg}	Average temperature of aluminum strand layers	°C	°C
T_s	Conductor surface temperature	°C	°C
T_{core}	Conductor core temperature	°C	°C
T_f	Conductor temperature many time constants after step increase	°C	°C
T_i	Conductor temperature prior to step increase	°C	°C
T_{film}	Average temperature of the boundary layer $(T_s + T_a)/2$	°C	°C
T_{low}	Low average conductor temperature for which ac resistance is specified	°C	°C
T_{high}	High average conductor temperature for which ac resistance is specified	°C	°C
V_w	Speed of air stream at conductor	m/s	ft/s
Y	Year	–	–
Z_c	Azimuth of sun	deg	deg
Z_l	Azimuth of line	deg	deg
Δt	Time step used in transient calculation	s	s
ΔT_c	Conductor temperature increment corresponding to time step	°C	°C
α	Solar absorptivity (.23 to .91)	–	–
δ	Solar declination (–23.45 to +23.45)	deg	deg
ε	Emissivity (.23 to .91)	–	–
τ	Thermal time constant of the conductor	min	min
ϕ	Angle between wind and axis of conductor	deg	deg
β	Angle between wind and perpendicular to conduct axis	deg	deg
ρ_f	Density of air	kg/m^3	lb/ft^3
θ	Effective angle of incidence of the sun's rays	deg	deg
μ_f	Absolute (dynamic) viscosity of air	kg/m-s	lb/ft-hr
ω	Hour angle relative to noon, 15*(Time-12), at 11AM, Time = 11 and the Hour angle= –15 deg	deg	deg
χ	Solar azimuth variable	–	–

4. Temperature calculation methods

The Working Group on the Calculation of Bare Overhead Conductor Temperatures and preceding working groups have conducted studies of the various methods used in calculating heat transfer and heat balance of bare overhead transmission line conductors. Methods that were studied included the following:

a) House and Tuttle [B24][3]
b) House and Tuttle, as modified by East Central Area Reliability (ECAR) [B34]
c) Mussen, G. A. [B28]
d) Pennsylvania-New Jersey-Maryland Interconnection (Davidson et al. [B10] and PJM Task Force [B15])
e) Schurig and Frick [B30]
f) Davis [B11]
g) Morgan [B26]
h) Black, Bush, Rehberg, and Byrd ([B3], [B4], and [B5])
i) Foss, Lin, and Fernandez [B20]
j) CIGRE Technical Brochure 207 [B9]

The mathematical models of this standard are based upon the House and Tuttle method as modified by ECAR [B34]. The House and Tuttle formulas consider all of the essential factors without the simplifications that are made in some of the other formulas.

To differentiate between laminar and turbulent air flow, the House and Tuttle method [B24] 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 [B24], ECAR [B34] elected to make the change from laminar to turbulent air flow at the point where the curves developed from the two formulas [Equations (3a) and (3b)] cross. The formulas for forced convection heat loss have an upper limit of application validity of a Reynolds number of 50 000 [B25], which is an order of magnitude higher than overhead transmission line conductor's experience. For additional information on convection heat loss, see 4.4.3 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 [B11], the heat balance equation is expressed as a bi-quadratic equation that can be solved to give the conductor temperature directly. In Black and Rehberg [B5] and Wong, et al. [B35], the radiation term is linearized and the resulting approximate linearized heat balance equation is solved using standard methods of linear differential equations. In Foss [B20], 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] Numbers in brackets correspond to those of the bibliography in Annex I.

Conductor temperatures are a function of:

a) Conductor material properties (primarily electrical conductivity)
b) Conductor diameter
c) Conductor surface condition (primarily emissivity and absorptivity)
d) Weather conditions (air temperature, solar heating, wind speed and direction)
e) Conductor electrical current

The first two of these properties are specific physical properties that usually remain constant over the life of the line. The conductor surface condition will change over time as the outermost layer of strands darkens due to particulate precipitation in an energized line. Weather conditions vary greatly with the hour and season. The fifth, conductor electrical current, varies with power system loading, generation dispatch, and other factors.

This standard acknowledges that bare stranded overhead conductors may not be isothermal under very high current densities even in the steady-state. A method of calculating radial temperature differences is included and axial temperature variation is discussed.

The equations relating electrical current to conductor temperature may be used to:

— Calculate the conductor temperature when the electrical current is known.
— Calculate the current (thermal rating) that yields a given maximum allowable conductor temperature.

The numerical thermal model presented in this standard is very general. It may be applied as follows:

a) The "Steady-State Case" where the electrical current, conductor temperature, and weather conditions are assumed constant for all time.
b) The "Transient Case" where the weather conditions are held constant but the electrical current undergoes a step change from an initial to a final value and the conductor temperature increases or decreases in a "nearly" exponential fashion from an initial temperature until it eventually reaches a new final temperature.
c) The "Dynamic Case" where the conductor temperature is calculated for an electrical current and weather conditions which vary over time in any fashion.

This standard includes a complete description of the generally applicable numerical mathematical method and indicates sources of the values to be used in the calculation of "steady-state" and "transient" 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, this 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. *CIGRE Technical Brochure 299*, "Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings" [B8], provides excellent guidance in selecting weather data for use in line rating calculations.

4.1 Steady-state case

4.1.1 Steady-state thermal rating

For a bare stranded conductor, if the conductor's surface temperature (T_S) 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 $R(T_{avg})$ can be calculated by the formulas of 4.4. 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 4.4.1]. While this calculation can be done for any conductor temperature and any weather conditions for which the heat transfer models are adequate, a maximum allowable conductor temperature (e.g., 95 °C) and "conservative" weather conditions (e.g., 0.6 m/s perpendicular wind speed, full sun, and 40 °C summer air temperature) are often used to calculate a steady-state thermal rating for the conductor.

[B8] suggests both default values for weather parameters and a procedure that can be followed in order to derive suitably conservative values for wind speed, air temperature, and solar heating.

4.1.2 Steady-state conductor temperature for a given current and ambient temperature

Heat transfer terms and conductor resistance are a function of conductor temperature while solar heat input to the conductor is not. If the conductor temperature is to be calculated rather than specified (as in 4.1.1), then the heat balance equation [Equation (1b) of 4.4.1] must be solved for conductor temperature in terms of the current and weather variables by a process of numerical iteration (i.e., estimating a conductor temperature and solving for the current), even if the conductor is assumed to be in steady-state.

The use of a numerical solution method, as described in this standard, avoids the need to make complex and time consuming approximations necessary to linearize the radiation and convection heat loss rates. Using suitable steady-state weather conditions, the calculation process is straightforward:

a) The solar heat input to the conductor is calculated (it is independent of conductor temperature).
b) A trial conductor temperature is assumed.
c) The conductor resistance is calculated for the trial temperature.
d) In combination with the assumed weather conditions, the convection and radiation heat loss terms are calculated.
e) The conductor current is calculated by means of the heat balance in Equation (1b) of 4.4.1.
f) The calculated current is compared to the trial conductor current.
g) The trial conductor temperature is then increased or decreased until the calculated current equals the trial current within a user-specified tolerance.

The numerical method listed in Annex A to this standard utilizes a very powerful numerical tool (the "RTMI MUELLER-S ITERATION METHOD") which consistently produces numerical convergence.

4.2 Transient calculations

4.2.1 Transient conductor temperature

The temperature of a bare overhead transmission line conductor is constantly changing in response to changes in electrical current and weather conditions (T_a, Q_s, V_w, ϕ). In the transient calculations described in this section, however, weather parameters 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, at a time designated "t = 0" as illustrated in Figure 1.

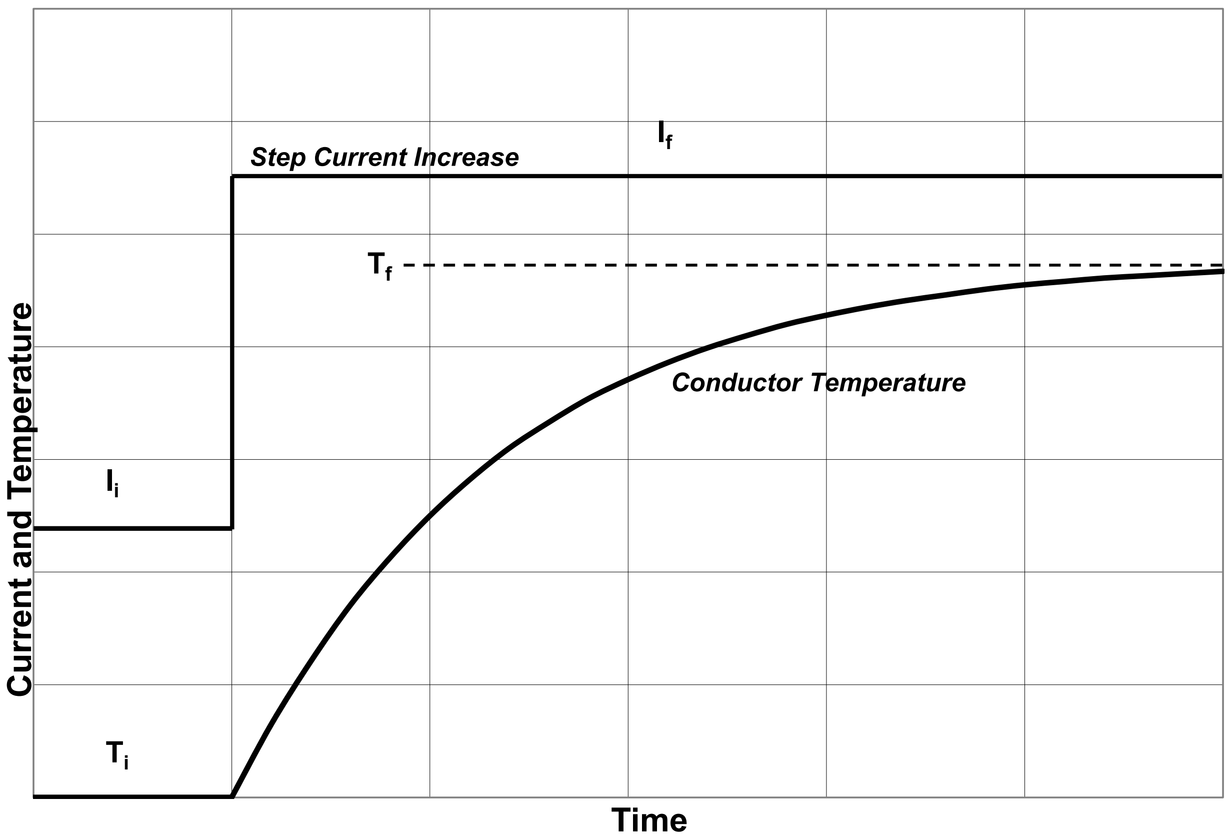


Figure 1— "Step" change in conductor current and corresponding change in conductor temperature

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 Joule heating, $I_f^2R\ (T_{avg})$, 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 Joule heating, now $I_f^2R\ (T_{avg})$, has increased. As a result of this thermal unbalance at time t = 0+, the heat, which cannot be immediately convected or radiated away, goes into conductor heat storage and the conductor temperature begins to increase at a rate given by the non-steady-state heat balance Equation (2b) in 4.4.2.

After a period of time, Δt, the conductor temperature has increased by a temperature change of ΔT_{avg}. The increased conductor temperature yields higher heat losses due to convection and radiation and somewhat higher Joule 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, Δt, the corresponding increase in conductor temperature may be calculated using the formulas given in 4.4. The computer program included in Annex A calculates the conductor temperature as a function of time after the step change in current.

As described in Annex F, the rate of change in bare overhead conductor temperature is approximately exponential, with a thermal time constant that is on the order of 5 min to 20 min for typical transmission conductors where the longest time constant corresponds to the largest conductors. With reference to Figure 1, this implies that the conductor temperature increases to its final value in a time period of 15 min to 60 min. Transient ratings are therefore typically calculated for emergency currents persisting for 5 min and 30 min.

Accuracy in the iterative transient calculation requires that the time interval chosen be sufficiently small with respect to the thermal time constant. It is always prudent to rerun the calculation with a smaller time interval to check whether the calculated values change. For most calculations with typical bare overhead stranded conductors, a calculation interval of 10 seconds or less is sufficient.

4.2.2 Transient thermal rating

The transient thermal rating is normally calculated by repeating the preceding calculations of T_{avg}(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.

4.2.3 Fault current calculations

Conductor temperature changes in response to “fault” currents are calculated in the same manner as in 4.2.1, 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. These calculations are essentially adiabatic because the heat loss by convection and radiation during such short times is negligible in comparison to the heat stored in the conductor.

With non-homogeneous 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 seconds from any step change in current. This is discussed further in 4.4.8.

4.3 Time-varying weather and current calculations

The temperature of an overhead power conductor is constantly changing in response to changes in electrical current and weather. The thermal model described in this standard may be applied to this case. To do this the user must perform a series of calculations, each applying to a short period of time (as was done for the transient case) during which the current and weather parameters (wind speed and direction, ambient temperature, etc.) are assumed to remain constant and equal to their values at the beginning of the interval.

The change in conductor temperature, ΔT_{avg}, during the time interval, Δt, is calculated using the non-steady-state heat balance equation [see Equation (2a) and Equation (2b) in 4.4]. The conductor temperature at the end of the time interval is simply the initial temperature plus the change in temperature. Through a series of such time steps, the conductor temperature is calculated at the end of each interval, thus producing an approximation to the conductor temperature as it varies over time with the line current and weather conditions.

As for the "transient" calculation, the accuracy of the resulting dynamic temperature calculation requires that the time step chosen be sufficiently small with respect to the thermal time constant.

4.4 Formulas

4.4.1 Steady-state heat balance

$$q_c + q_r = q_s + I^2 \cdot R\left(T_{avg}\right) \tag{1a}$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{R\left(T_{avg}\right)}} \tag{1b}$$

4.4.2 Non-steady-state heat balance

$$q_c + q_r + m \cdot C_p \cdot \frac{dT_{avg}}{dt} = q_s + I^2 \cdot R(T_{avg}) \tag{2a}$$

$$\frac{dT_{avg}}{dt} = \frac{1}{m \cdot C_p}\left[R(T_{avg}) \cdot I^2 + q_s - q_c - q_r\right] \tag{2b}$$

4.4.3 Convective heat loss

Convective heat loss is customarily divided into two types: Natural Convection and Forced Convection. Many researchers have measured the heat loss by convection and the results are well documented in the heat transfer literature. This standard uses the formulae for convection from cylinders recommended by McAdams [B25]. Natural Convection, or Free Convection, occurs during still air conditions, where, in a continuous process, cool air surrounding the hot conductor is heated and rises, and is replaced by cool surrounding air. Forced Convection occurs when blowing air moving past the conductor carries the heated air away. Natural Convection has low cooling power compared to Forced Convection, being equivalent to Forced Convection at a wind speed of less than 0.2 m/s (0.6 ft/s).

The magnitude of convective heat loss generally is a function of a dimensionless number known as Reynolds number. Reynolds number is given Equation (2c):

$$N_{\mathrm{Re}} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f} \tag{2c}$$

This equation shows that the Reynolds number is directly proportional to the conductor diameter, D_0, and the wind velocity, V_w. Air density, ρ_f, and the dynamic viscosity of air, μ_f, are calculated at the mean film temperature of the conductor boundary layer. For low wind velocities, McAdams [B25] recommends calculating both the Natural Convection heat loss and the Forced Convection Heat loss and using the greater of the two values. That is the convention adopted by this standard.

The Forced and Natural Convection heat loss equations described in this section of the standard are based upon extensive wind tunnel measurements reported by McAdams. McAdams based his recommended curve on the reported work of many researchers. He plotted their results, which were in very close agreement, and developed coordinates for a recommended cooling curve. His equations, Equation (3a) and Equation (3b) below, are curve fits to his recommended coordinates. Because of the huge range of Reynolds numbers in his curve, he fit the curve in the two sections described by the two following equations.

4.4.3.1 Forced convection

Equation (3a) is a fit to the low Reynolds number end of the curve and Equation (3b) is fit to the high Reynolds number end of the curve (note that K_{angle} is defined below). Equation (3a) is correct at low winds but underestimates forced convection at high wind speeds. Equation (3b) is correct at high wind speeds but underestimates forced convection at low wind speeds. At any wind speed, this standard recommends calculating convective heat loss with both equations, and using the larger of the two calculated convection heat loss rates.

$$q_{c1} = K_{angle} \cdot \left[1.01 + 1.35 \cdot N_{\text{Re}}{}^{0.52}\right] \cdot k_f \cdot \left(T_s - T_a\right) \quad \text{[watts/ft or watts/m]} \tag{3a}$$

$$q_{c2} = K_{angle} \cdot 0.754 \cdot N_{\text{Re}}{}^{0.6} \cdot k_f \cdot \left(T_s - T_a\right) \quad \text{[watts/m or watts/ft]} \tag{3b}$$

The forced convection heat loss equations are valid over a large range of variables: [B31]

Variable	SI units	US units
Diameter	0.01 – 150 mm	3E^{-05} – 0.49 ft
Air velocity	0 – 18.9 m/s	0 – 62 ft/s
Air temperature	15.6 – 260 ˚C (60 – 500˚F)	
Wire temperature	21 – 1004 ˚C (70 – 1840˚F)	
Air pressure	40.5 – 405 kPa	0.4 – 4.0 Atm.

This wide range of applicability is far greater than the range of rating parameters used in line design.

The convective heat loss rate, calculated with Equation (3a) and Equation (3b), must be multiplied by the wind direction factor, K_{angle}, where ϕ is the angle between the wind direction and the conductor axis [see Equation (4a)].

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

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

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

This is the form of the wind direction factor as originally suggested in [B11] and is used in the computer programs listed in the Annexes of this standard.

4.4.3.2 Natural convection

With zero wind speed ("still air"), natural convection occurs, where the rate of heat loss is:

$$q_{cn} = 3.645 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25} \qquad W/m \tag{5a}$$

$$q_{cn} = 1.825 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25} \qquad W/ft \tag{5b}$$

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 [B26]. 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 A 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 calculated with the equations of 4.5 at the temperature of the boundary layer, T_{film}, where:

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

4.4.4 Radiated heat loss rate

When a bare overhead conductor is heated above the temperature of its surroundings, energy is transmitted by radiation to the surroundings. The rate at which the energy is radiated is dependent primarily on the difference in temperature between the conductor and its surroundings, which are assumed to be at ambient temperature. The surface condition of the conductor, its emissivity, also affects the radiative heat transfer. Radiation is described by the Stefan-Boltzmann law, relating the radiative energy transmission to the difference between the conductor surface temperature and the surrounding temperature, expressed in absolute (Kelvin) degrees to the fourth power. The constants in Equations (7) include the Stefan – Boltzmann constant and conversion factors to produce a result in the desired units.

$$q_r = 17.8 \cdot D_0 \cdot \varepsilon \cdot \left[\left(\frac{T_s + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \qquad W/m \tag{7a}$$

$$q_r = 1.656 \cdot D_0 \cdot \varepsilon \cdot \left[\left(\frac{T_s + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \qquad W/ft \tag{7b}$$

4.4.5 Rate of solar heat gain

The sun provides heat energy to the conductor. The amount of solar heat energy delivered to the conductor depends on the sun's position in the sky, the Solar Constant [the amount of energy per m^2 (ft^2) outside of the earth's atmosphere], the amount of that energy that is transmitted through the earth's atmosphere to the conductor, the orientation of the conductor, and the conductor's surface condition (its absorptivity). Bright, shiny conductors reflect most of the sun's energy and black weathered conductors absorb most of the sun's energy. The equations given in 4.5.4, 4.5.5, 4.5.6, and 4.5.7 are used to calculate the values of the variables in the following equations to determine the solar heat input to the conductor.

$$q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A' \qquad [W/m \;\; or \;\; W/ft] \tag{8}$$

where:

$$\theta = \arccos\left[\cos(H_c) \cdot \cos(Z_c - Z_1)\right] \tag{9}$$

4.4.6 Conductor electrical resistance ([B7] and [B17])

The electrical resistance of bare overhead stranded conductor varies with the conductor cross-section areas, power frequency, current, and temperature. At a frequency of 60 Hz, at temperatures of 25 °C to 75 °C, the *Aluminum Electrical Conductor Handbook* [B1] and the *Overhead Conductor Manual* [B29]list tabulated values of 60 Hz electrical resistance for most sizes and types of bare stranded overhead power conductors. Conductor manufacturers typically provide such resistance values for their conductors. The 60 Hz conductor resistances at any conductor temperature should include skin effect, and for one and three layer ACSR, magnetic core effects. Adjustment of resistance for radial temperature gradients is discussed within this section.

In this version of the standard, electrical resistance is adjusted linearly for conductor surface temperature. It is assumed that the tabular resistance values account for skin effect and current magnitude. For example, the conductor resistance at a high temperature, T_{high}, and a low temperature, T_{low}, may be taken from the tabulated values in one of the above references or may be provided by the manufacturer. The conductor resistance at any other temperature, T_{avg}, is found by linear interpolation according to Equation (10).

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right] \cdot (T_{avg} - T_{low}) + R(T_{low}) \tag{10}$$

This method of resistance calculation allows the use widely accepted high and low temperature resistance values, which include magnetic effects, skin effect, and lay ratios. As discussed in the next section, the high-temperature, T_{high}, should be greater than or equal to the conductor temperature assumed for rating calculations. That is, if the thermal rating of a bare overhead conductor is to be calculated for 180 °C, the high temperature resistance value to be used in Equation (10) should be 200 °C.

4.4.6.1 Limitations of linear interpolation of AC resistance

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.

Normally, Equation (10) should not be used to calculate resistance at temperatures more than 25 °C above T_{high}, however, given the approximate nature of fault current calculations, this simple linear equation is often used to estimate resistance for conductor temperatures much higher than T_{high}.

4.4.6.2 Skin effect component of AC resistance

The resistance values in the referenced handbooks ([B1] and [B29]) include the frequency-dependent "skin effect" for all types of stranded conductors. The flow of AC current within a metal conductor tends to migrate toward the surface of the conductor due to internal flux within the stranded layers comprising the conductor, hence skin effect. At 60 Hz, the increase in resistance due to skin effect in an aluminum conductor of overall diameter 30 mm is on the order of 1% to 2%. For larger conductors such as 1090 mm^2 (2156 kcmil) Bluebird ACSR, which has an outside diameter of 46.5 mm (1.831 in), the increase in resistance due to skin effect is on the order of 8%.

When calculating the resistance for a DC conductor application, the skin effect is not appropriate and the corresponding DC resistance should be substituted for the T_{low} and T_{high} values. Also included in the referenced handbooks ([B1] and [B29]) is the conductor DC resistance at 20 °C, which can be utilized as a reference value to scale the DC resistance up to other values of interest using the simple equations in the reference handbooks.

4.4.6.3 Magnetic core effect on AC resistance

Within steel-core conductors such as ACSR and ACSS, the flow of AC current is primarily through the aluminum strands. Since the helically-wound aluminum strands surround the steel core in an alternating left-hand and right-hand lay direction, magnetic flux is generated in the steel core, much like a solenoid, increasing with the magnitude of current. The core's impact on conductor resistance depends on the construction of the bare stranded conductor:

For ACSR/ACSS conductors (Drake, Ibis, Bluebird) the magnetic core flux produced by the current in each layer essentially cancels, and level of magnetic flux in the core is quite low.

For single-layer ACSR/ACSS conductors, the magnetic flux in the steel core is quite high and the resulting magnetic hysteresis and eddy current losses in the core can increase the effective resistance by as much as 20% at high current levels.

For three-layer ACSR/ACSS, there is partial magnetic field cancelation in the steel core so that the losses in the core are much smaller, but the solenoid effect couples the layer currents, making the current densities unequal and increasing the overall AC resistance of the conductor by as much as 5% at high current levels.

The resistance values for single-layer ACSR and ACSS in the referenced handbooks ([B1] and [B29]) include the effects of magnetic core losses at each temperature but only for certain assumed weather conditions. The resistance values for three-layer ACSR/ACSS conductors must be supplemented by "correction curves" to obtain a resistance multiplier as a function of current density. Of the two recommended correction schemes, [B29] is the easiest to model and is slightly more conservative. Engineering judgment is required in thermal calculations involving these steel-core conductors.

4.4.6.4 Radial thermal gradient component of AC/DC resistance

Since this standard was first published in 1986, the maximum conductor temperatures used to determine line ratings with conventional bare stranded conductors has gradually increased from the range of 50 °C to 75 °C, to the range of 95 °C to 150 °C. In addition, high-temperature, low-sag conductors rated at from 150 °C to 250 °C have come into widespread use. As a result, the internal temperature difference between core and surface of conductors can no longer be neglected in all cases. This phenomenon is discussed in more detail in 4.4.7.

In terms of conductor resistance, if the core of the stranded conductor is more than a few degrees hotter than the surface, the resistance of the conductor should be calculated for the average conducting wire temperature and not the surface temperature. Numerous references have reported measured radial temperature differences as large as 10 °C to 25 °C. For aluminum conductors, if the average temperature is 10 °C hotter than the surface, the conductor resistance is approximately 4% higher.

4.4.7 Radial temperature gradient within the conductor ([B16] and [B27])

Bare stranded transmission conductors are typically 12 mm to 50 mm in diameter, having one to four layers of helically stranded aluminum wires. High temperature conductors are designed to handle current densities as high as 5 A/mm^2 (2.5 A/kcmil) attaining surface temperatures as high as 250 °C. Heat generated in the inner layers of aluminum strands must be conducted to the surface layer in order to be dissipated and, since heat only flows from high to low temperature, it is reasonable to suspect that the core of the conductor may be somewhat hotter than the surface. Weather parameters have a direct effect on the surface temperature (as described in this standard) but only an indirect effect on the radial temperature gradient within the conductor. A reduction in the tension in the aluminum layers may be expected to reduce the contact pressure between the layers and increase any radial temperature gradient.

The magnitude of the radial temperature difference depends on a number of conductor parameters, including:

a) Conductor strand shape (round or trapezoidal or “Z” shaped).
b) Magnitude of the electrical current in aluminum layers.
c) Electrical resistance of the aluminum strand layers.
d) The number of layers of aluminum wires.
e) The condition of aged conductor (i.e., corrosion and bird-caging).
f) The contact area and pressure between aluminum layers.

Regardless of the conductor construction, the radial temperature difference is typically less than 5 °C when the current density is less than 1 A/mm^2 (1/2 amp/kcmil) and the radial temperature difference may be neglected. This typically corresponds to ratings with a maximum conductor surface temperature of less than 100 °C.

At higher current densities, especially for large conductors with three or four layers of aluminum strands, radial temperature differences as large as 10 °C to 25 °C have been measured in laboratory tests.

Significant radial temperature differences are possible in any multi-layer aluminum conductor, whether having a steel core or not. Heat generation in the steel core of ACSR is normally less than 2% of the total Joule heat generated.

Because of the greater contact area between aluminum layers, the use of trapezoidal aluminum wires may reduce the radial temperature difference as long as the wires are under tension. However, once the aluminum wires have bird-caged, whether plastic elongation due to high ice loads or thermal elongation due to high temperature, the lack of contact pressure between aluminum layers is likely to lead to a significant radial temperature difference between the conductor core and surface.

CIGRE Technical Brochure 207, “Thermal Behaviour of Overhead Conductors” [B9], includes an equation that allows the calculation of temperature difference if the “effective radial thermal conductivity” of the conductor is specified. The equation is:

$$T_{core} - T_s = \frac{I^2 \cdot R(T_{avg})}{2\pi \cdot k_{th}} \cdot \left[\frac{1}{2} - \frac{D_{core}^2}{D_0^2 - D_{core}^2} \cdot \left(\ln \frac{D_0}{D_{core}} \right) \right] \tag{11a}$$

For all aluminum conductors, the equation for radial temperature difference is simpler as shown in the Equation (11b):

$$T_{core} - T_s = \frac{I^2 \cdot R\left(T_{avg}\right)}{4\pi \cdot k_{th}} \tag{11b}$$

In these equations, the resistance per unit length and the effective radial thermal conductivity should be in consistent units. In SI units, resistance is in Ω/m and thermal conductivity is in W/m-°C. In mixed US units, the resistance is in Ω/ft, and the effective radial thermal conductivity is in W/ft-°C.

There is extensive technical literature that supports the existence of such radial temperature gradients at high current densities, but there is considerable variation in the recommended value for effective radial thermal conductivity, k_{th}. The literature (and CIGRE 207) demonstrate that a reasonable range of values is between 4 and 0.5 W/m-s. CIGRE 207 recommends a value equal to 2, but the experimental data upon which this value is based concerned only conventional ACSR conductors at moderate current densities where the tension in the aluminum layers is not zero.

For ACSR conductors below their "knee-point temperature" [B6] with tension in the aluminum strand layers, an effective thermal conductivity (k_{th}) of 2 W/m-°C appears to be reasonable. For ACSR conductors above their knee-point temperature and for other conductors where there is little or no tension in the aluminum strand layers, the use of an effective thermal conductivity equal to 1 watt/m-°C also appears to be reasonable.

In those calculations where the core of the conductor is significantly hotter than the surface, the sags of the line will be higher, the core material may experience greater deterioration, and the resistance of the conductor may be greater than anticipated if all of these calculations are based upon the conductor surface temperature.

For thermal rating calculations, if the temperature gradient is found to exceed 10 °C, then the maximum allowed conductor surface temperature should be reduced if the higher core temperature results in conductor deterioration or inadequate sag clearance.

4.4.8 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 conductor heat capacity is equal to the sum of the heat capacities of the core and the outer strands, each defined in this way.

For a non-homogeneous stranded conductor such as ACSR, most of the heat (98% to 99%) is generated in the aluminum strands and transferred to the steel core with an internal time constant of less than 1 min. For steady-state and transient thermal rating calculations with durations of 5 min to 30 min, the temperature of the conductor components (aluminum and steel) may be assumed equal and the heat capacity of the conductor can be calculated as the sum of the component heat capacities as shown in Equation (12):

$$mC_p = \sum m_i \cdot C_{pi} \tag{12}$$

Values for the specific heat of common metals used in stranded overhead conductors are listed in [B5] and in 5.6 of this standard.

With a non-homogeneous conductor such as ACSR, for faults with durations of less than 60 s, the internal temperature difference between the core and the outer strands cannot be neglected and the heat capacity of the relatively non-conducting steel core should be neglected. For calculations of conductor temperature and rating, whose duration is greater than 60 seconds, the heat capacity of the core should be included as shown in Equation (11). For step current durations less than 60 seconds, the calculated conductor temperatures will be somewhat conservative.

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

In the following section, equations are defined for: air properties (dynamic viscosity, density, and thermal conductivity); solar heating angles relative to the conductor (solar altitude and solar azimuth); and solar heat intensity or flux including an adjustment for altitude.

In addition, tables of air properties, the relationships of solar angles to latitude and time-of-day, solar flux intensity, and adjustment of solar flux for altitude (Table H.1, Table H.2, Table H.3, and Table H.4) are included in Annex H. The tabular values can be useful for common-sense checking of values calculated with the equations presented in 4.5.

4.5.1 Dynamic viscosity of air (see also Table H.1)

The dynamic viscosity of air is determined by Equation (13):

$$\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4} \qquad [kg/m-s\ or\ N-s/m^2] \tag{13a}$$

$$\mu_f = \frac{0.00353 \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4} \qquad [lb/ft-hr] \tag{13b}$$

Note that 1 N-s/m^2 = 1 kg/m-s in SI units.

4.5.2 Air density (see also Table H.1)

Air density is a function of elevation and air temperature in the conductor boundary layer:

$$\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}} \qquad [kg/m^3] \tag{14a}$$

$$\rho_f = \frac{0.080695 - 2.901 \cdot 10^{-6} \cdot H_e + 3.7 \cdot 10^{-11} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}} \qquad [lb/ft^3] \tag{14b}$$

4.5.3 Thermal conductivity of air (see also Table H.1)

The thermal conductivity of the air depends on air temperature in the boundary layer:

$$k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2 \qquad [W/m \cdot °C] \tag{15a}$$

$$k_f = 7.388 \cdot 10^{-3} + 2.279 \cdot 10^{-5} \cdot T_{film} - 1.343 \cdot 10^{-9} \cdot T_{film}^2 \qquad [W/ft \cdot °C] \tag{15b}$$

4.5.4 Altitude of the sun (see also Table H.2)

The solar altitude of the sun, H_c, in degrees (or radians) is given by the Equation (16a), where inverse trigonometric function arguments are in degrees (or radians):

$$H_c = \arcsin\left[\cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta)\right] \tag{16a}$$

The hour angle, ω, is the number of hours from noon times 15 degrees (11AM is –15°, 2PM is +30°).

The solar declination, δ, in degrees, is:

$$\delta = 23.46 \cdot \sin\left[\frac{284 + N}{365} \cdot 360\right] \tag{16b}$$

where the argument of the sin is in degrees. The equation is valid for all latitudes whether positive (northern hemisphere) or negative (southern hemisphere). Solar declination ranges between –23.45 and +23.45 degrees. A solar declination of +23.45 degrees occurs at the summer solstice for the northern hemisphere.

4.5.5 Azimuth of the sun (see also Table H.2)

The solar azimuth, Z_c, (in degrees) is:

$$Z_c = C + \arctan(\chi) \tag{17a}$$

where:

$$\chi = \frac{\sin(\omega)}{\sin(Lat) \cdot \cos(\omega) - \cos(Lat) \cdot \tan(\delta)} \tag{17b}$$

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 2:

Table 2—Solar azimuth constant, C, as a function of "Hour angle," ω, and Solar Azimuth variable, χ

"Hour angle", ω, degrees	C if χ ≥ 0 degrees	C if χ < 0 degrees
–180 ≤ ω < 0	0	180
0 ≤ ω < 180	180	360

4.5.6 Total heat flux density (heat intensity) at sea level versus H_c (see also Table H.3)

The heat flux density received by a surface at sea level may be calculated with Equation (18) using the coefficients for either clear or industrial air quality shown in Table 3.

$$Q_S = A + B H_C + C H_C^2 + D H_C^3 + E H_C^4 + F H_C^5 + G H_C^6 \tag{18}$$

where:

Q_S = total heat flux density (W/m^2 or W/ft^2)

H_C = solar altitude (degrees)

Table 3—Polynomial coefficients for solar heat intensity as a function of solar altitude

	SI	**US**
Clear atmosphere		
A	–42.2391	–3.9241
B	63.8044	5.9276
C	–1.9220	-1.7856×10^{-1}
D	3.46921×10^{-2}	3.223×10^{-3}
E	-3.61118×10^{-4}	-3.3549×10^{-5}
F	1.94318×10^{-6}	1.8053×10^{-7}
G	-4.07608×10^{-9}	-3.7868×10^{-10}
Industrial atmosphere		
A	53.1821	4.9408
B	14.2110	1.3202
C	6.6138×10^{-1}	6.1444×10^{-2}
D	-3.1658×10^{-2}	-2.9411×10^{-3}
E	$+5.4654\times10^{-4}$	5.07752×10^{-5}
F	-4.3446×10^{-6}	-4.03627×10^{-7}
G	$+1.3236\times10^{-8}$	1.22967×10^{-9}

The reader may also refer to the heat flux density values in Table H.3 of Annex H to verify the calculated values.

4.5.7 Elevation correction factor (see also Table H.4)

The solar heat intensity at the earth's surface may be corrected for altitude by Equation (19):

$$Q_{se} = K_{solar}\, Q_s \tag{19}$$

where:

$$K_{solar} = A + B \cdot H_e + C \cdot H_e^2 \tag{20}$$

Table 4—Coefficients for solar flux altitude correction in Equation (20)

	SI	US
A	1	1
B	$1.148 \cdot 10^{-4}$	$3.500 \cdot 10^{-5}$
C	$^{-}1.108 \cdot 10^{-8}$	$-1.000 \cdot 10^{-9}$

The reader may also refer to Table H.4 in Annex H.

4.6 Sample calculations

4.6.1 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 use of a computer program such as that included in Annex A. Calculation results are also included in Annex B, Annex C, Annex D, and Annex E. The computer program listed in Annex A is included with the standard as a matter of convenience and is not part of the standard.

A calculation of steady-state thermal rating is included in Annex B. The assumptions regarding weather conditions, conductor parameters are similar but not identical to the sample calculations in this section of the standard. In the following sample calculation, iterative calculations are not required since the conductor temperature is specified. It is intended to demonstrate the use of the formulas discussed in this standard and, hopefully, 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.

Please also note that the choice of weather conditions used in the following sample problem do not constitute a recommendation of suitably conservative "worst-case" weather conditions for line thermal rating calculations.

4.6.1.1 Problem statement

Find the steady-state thermal rating (ampacity) for a 795 kcmil 26/7 Drake ACSR conductor, under the following conditions:

a) Wind speed (V_w) is 0.61 m/s (2 ft/s) perpendicular to the conductor.

b) Emissivity ($\in$) is 0.8.

c) Solar absorptivity (α) is 0.8.

d) Ambient air temperature is 40 °C.

e) Maximum allowable conductor temperature is 100 °C.

f) Conductor outside diameter (D_0) is 28.14 mm (1.108 in).

g) Conductor AC resistance [$R(T_{avg})$] is:

R(25 °C) = 7.283 10-5 Ω/m (2.220 10-5 Ω/ft)
R(75 °C) = 8.688 10-5 Ω/m (2.633 10-5 Ω/ft)

h) The line runs in an east to 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 am on June 10 (Day 161).

l) Line elevation, H_e, is 0 m (0 ft).

4.6.1.2 Air and conductor properties

D_0 =28.1 mm = 0.281 m

D_c = 10.4 mm = 0.0104 m

T_s = 100 °C

T_a = 40 °C

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

ρ_f = 1.029 kg/m^3

μ_f = 2.043 10^{-5} kg/m-s or N-s/m^2

k_f = 0.02945 W/m-°C

D_0 = 1.108 in = 0.0923 ft

D_c = 0.408 in = 0.0340 ft

T_s = 100 °C

T_a = 40 °C

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

ρ_f = 0.0643 lb/ft^3

μ_f = 4.946 10^{-2} lb/ft-hr

k_f = 0.008977 W/ft-°C

The natural convection heat loss is calculated by means of Equation (5a) or Equation (5b):

q_{cn}= 3.635· (1.029)$^{0.5}$ · (0.02814)$^{0.75}$· (100– 40)$^{1.25}$
= 42.4 W/m

q_{cn}= 1.825· (0.0643)$^{0.5}$ · (0.0923)$^{0.75}$· (100– 40)$^{1.25}$
=12.86 W/ft

Since the wind speed is greater than zero, the forced convection heat loss for perpendicular wind is calculated according to both Equation (3a) and Equation (3b) with K_{angle} = 1, 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.

The Reynolds number is dimensionless and therefore the same in either set of units:

$$N_{\mathrm{Re}} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f} = \frac{0.0281 \cdot 1.029 \cdot 0.61}{2.043 \cdot 10^{-5}} = 865$$

q_{c1}=[1.01 + 1.347 · (865)$^{0.52}$] · 0.02945 · (60)
= 81.93 W/m

q_{c1}=[1.01 + 1.347 · (865)$^{0.52}$] · 0.009877 · (60)
= 24.97 W/ft

q_{c2}= 0.754 · (865)$^{0.6}$ · 0.02945 · (60)
= 77.06 W/m

q_{c2} = 0.754 · (865)$^{0.6}$] · 0.009877 · (60)
= 23.49 W/ft

As instructed in 4.4.3, select the larger of the two calculated convection heat losses, which is:

$q_c = 81.93$ W/m $\qquad$ $q_c = 24.97$ 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.

4.6.1.3 Radiated heat loss (q_r)

$$q_r = 17.8 \cdot 0.02814 \cdot 0.8 \cdot \left[\left(\frac{373}{100}\right)^4 - \left(\frac{313}{100}\right)^4\right] \qquad q_r = 1.656 \cdot 0.09233 \cdot 0.8 \cdot \left[\left(\frac{373}{100}\right)^4 - \left(\frac{313}{100}\right)^4\right]$$

$q_r = 39.1$ W/m $\qquad$ $q_r = 11.9$ W/ft

4.6.1.4 Solar heat gain (q_s)

The conductor is at 30° North latitude and the line is oriented east to west. While the interpolation of tabular values is a perfectly valid method of determining the solar azimuth and altitude, the use of the Equations (16) and Equations (17) for solar heat input to the conductor will yield values that are more precise. Also, the use of the algebraic equations is appropriate:

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

b) For times of the day before 10AM and after 2PM

c) For latitudes less than 20 degrees or greater than 70 degrees

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 (16b):

$$\delta = 23.46 \cdot \sin\left[\frac{284+161}{365} \cdot 360\right]$$

$$\delta = 23.46 \cdot 0.981 = 23.0 \text{ deg}$$

The solar altitude, H_c, is found from the latitude (30 degrees), the solar declination (23.0 degrees) and the hour angle, ω, (–15 degrees) with the use of Equation (16a):

$$H_C = \arcsin\left[\cos(30) \cdot \cos(23.0) \cdot \cos(-15) + \sin(30) \cdot \sin(23.0)\right]$$
$$H_C = \arcsin[0.866 \cdot 0.920 \cdot 0.966 + 0.500 \cdot 0.391 = 74.8 \text{ deg}$$

The solar heat flux (heat intensity), Q_s, for clear air at sea level is given by Equation (18):

$$Q_s = -42.2391 + 63.8044 \cdot 74.8 - 1.922 \cdot 74.8^2 + 3.46921 \cdot 10^{-2} \cdot 74.8^3 - 3.61118 \cdot 10^{-4} \cdot 74.8^4 + $$
$$+1.94318 \cdot 10^{-6} \cdot 74.8^5 - 4.07608 \cdot 10^{-9} \cdot 74.8^6 = 1027 w/m^2$$

A similar calculation with Equation (18) using the US unit coefficients yields 95.5 W/ft^2.

In order to calculate the solar azimuth, referring to Equation (17), one must first calculate the solar azimuth variable, χ. The solar azimuth variable, χ, for this example problem is:

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

From Table 2, since the solar azimuth variable, χ, is less than 0, and the "hour angle," ω, at 11AM is –15 degrees, then the solar azimuth constant, C, is equal to 180 degrees.

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

$Z_c = 18 + \arctan(-2.24) = 180 - 65.9 = 114$ degrees

The effective angle of incidence of the solar rays with the conductor is:

$\theta = \arccos[\cos(74.8)\cdot\cos(114-90)] = 76.1$ degrees

$q_S = 0.8 \cdot 1027 \cdot \sin(76.1) \cdot 0.02814 = 22.44$ W/m $\quad q_S = 0.8 \cdot 95.5 \cdot \sin(76.1) \cdot 0.0923 = 6.84$ W/ft

4.6.1.5 Resistance at 100 °C

$$R(100) = R(25) + \left(\frac{R(75)-R(25)}{72-25}\right)\cdot(100-25)$$

$$= 7.283\cdot10^{-5} + \left[\frac{8.688-7.283}{50}\right]\cdot10^{-5}\cdot75\ \Omega/m \qquad = 2.220\cdot10^{-5} + \left[\frac{2.648-2.220}{50}\right]\cdot10^{-5}\cdot75\ \Omega/ft$$

$= 9.390.10^{-5}\ \Omega/m$ $\qquad$ $=2.862^{-5}\ \Omega/$ ft

4.6.1.6 Steady-state thermal rating

Summary of results from preceding calculations:

q_c	=	81.93 W/m	q_c	=	24.97 W/ft
q_r	=	39.1 W/m	q_r	=	11.9 W/ft
q_S	=	22.44 W/m	q_S	=	6.84 W/ft
$R(100^\circ C)$	=	$9.390\cdot10^{-5}$ Ω/m	$R(100^\circ C)$	=	$2.862\cdot10^{-5}$ Ω/ft

Calculation of steady-state thermal rating using Equation (1b):

$$\sqrt{\frac{81.93+39.1-22.44}{9.390\cdot10^{-5}}} = 1025\,A \qquad \sqrt{\frac{24.97+11.9-6.84}{2.862\cdot10^{-5}}} = 1024\,A$$

4.6.1.7 Check radial temperature steady-state thermal rating

Having determined the current in the conductor and the resistance, the radial temperature gradient can be calculated using Equation (11). In choosing the appropriate value of effective radial thermal resistivity, it should be noted that the conductor is at a temperature above its final knee-point temperature. Unless experimental data indicates otherwise, a k_{th} value of 1 W/m-°C (0.305 W/ft-°C) can be used as a conservative estimate.

$T_C - T_S = \frac{I^2 \cdot R(Tavg)}{2\pi \cdot k_{th}} \left[\frac{1}{2} - \frac{D_C^2}{D_S^2 - D_C^2} \cdot \left(\ln \frac{D_S}{D_C} \right) \right]$	$T_C - T_S = \frac{I^2 \cdot R(Tavg)}{2\pi \cdot k_{th}} \left[\frac{1}{2} - \frac{D_C^2}{D_S^2 - D_C^2} \cdot \left(\ln \frac{D_S}{D_C} \right) \right]$
$\frac{1025^2 \cdot 9.39 \cdot 10^{-5}}{2\pi \cdot 1.0} \cdot \left[\frac{1}{2} - \frac{10.4^2}{28.0^2 - 10.4^2} \cdot \left(\ln \frac{28.0}{10.4} \right) \right]$	$\frac{1024^2 \cdot 2.862 \cdot 10^{-5}}{2\pi \cdot 0.305} \cdot \left[\frac{1}{2} - \frac{0.408^2}{1.108^2 - 0.408^2} \cdot \left(\ln \frac{1.108}{0.408} \right) \right]$
5.1 °C	5.1 °C

Clearly, under these conditions, the radial temperature difference is negligible and the rating does not need to be adjusted. A value in excess of 10 °C should be noted and, depending on the type of conductor and the electrical line clearances available, the rating might have to be reduced.

For example, repeating the example problem for a surface temperature of 200 °C yields a radial temperature difference of 17 °C, which is not negligible in terms of sag clearance.

4.6.2 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 A. A sample calculation is included in Annex C. 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.

4.6.3 Transient conductor temperature

The heat balance formula, Equation (2b), is a first order differential equation. It can be rewritten as a difference equation in the following form:

$$\Delta T_{avg} = \frac{\mathrm{R(T_{avg}) \cdot I^2 + q_S - q_C - q_R}}{\mathrm{mC_p}} \cdot \Delta \mathrm{t}$$

Assuming that the conductor begins in the steady-state condition described in the example problem, this equation can be used to calculate the initial change in conductor temperature that occurs as a result of a sudden change in line current from 991 A to 1200 A while the weather conditions remain constant:

a) Choose a time interval of one minute.

b) Since the time is relatively short, assume that the heat loss terms are unchanged and all of the heat goes into storage in the conductor, raising its temperature.

Substituting the heat flow and resistance values from the example problem where the conductor is at a surface temperature of 100 °C and the current is 991 A:

$$\Delta T_{avg} = \frac{9.390 \cdot 10^{-5} \cdot 1200^2 + 14.18 - 81.93 - 24.43}{1310} \cdot 60 = 1.97^o C$$

At the end of this first minute after the step change from 991 A to 1200 A, the conductor temperature has increased from 100 °C to 101.97 °C. To continue the conductor temperature calculation, the conductor resistance, convection, and radiation heat loss terms must be recalculated for a temperature of 101.97 °C. The solar heat input is unchanged. During the next 60 seconds, the change in conductor temperature is slightly less as shown in the following equation with the revised resistance and heat loss values:

$$\Delta T_{avg} = \frac{9.450 \cdot 10^{-5} \cdot 1200^2 + 14.18 - 84.27 - 25.52}{1310} \cdot 60 = 1.85^o C$$

As long as the weather conditions and higher line current (i.e., 1200 A) remain the same, the conductor temperature can be “tracked” by this method.

It is important to notice that the method works equally well in calculating the conductor temperature response to a sudden change in weather conditions (e.g., a drop in the wind speed). It also works if the weather conditions and line current are different in every calculation interval but, of course, the conductor temperature will not approach a new steady-state value unless both the weather conditions and line current stabilize.

These calculations are more easily accomplished by numerical computation. A numerical implementation of the calculation method is included in Annex A. The computer program listed there can be adapted to perform conductor temperature calculations under steady-state or transient conditions. It can also be used to calculate thermal ratings of almost any sort, including real-time thermal ratings.

For example, one may calculate the transient conductor temperature for the same Drake ACSR conductor and weather parameters as used in the previous steady-state sample calculation of 4.6.1, 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.

With reference to Annex D, 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 runs of Annex D, conductor temperature is calculated for every 2 min after the step change in current. Plots of conductor temperature versus time are shown in Figure 2 for the first 60 min after the increase in current.

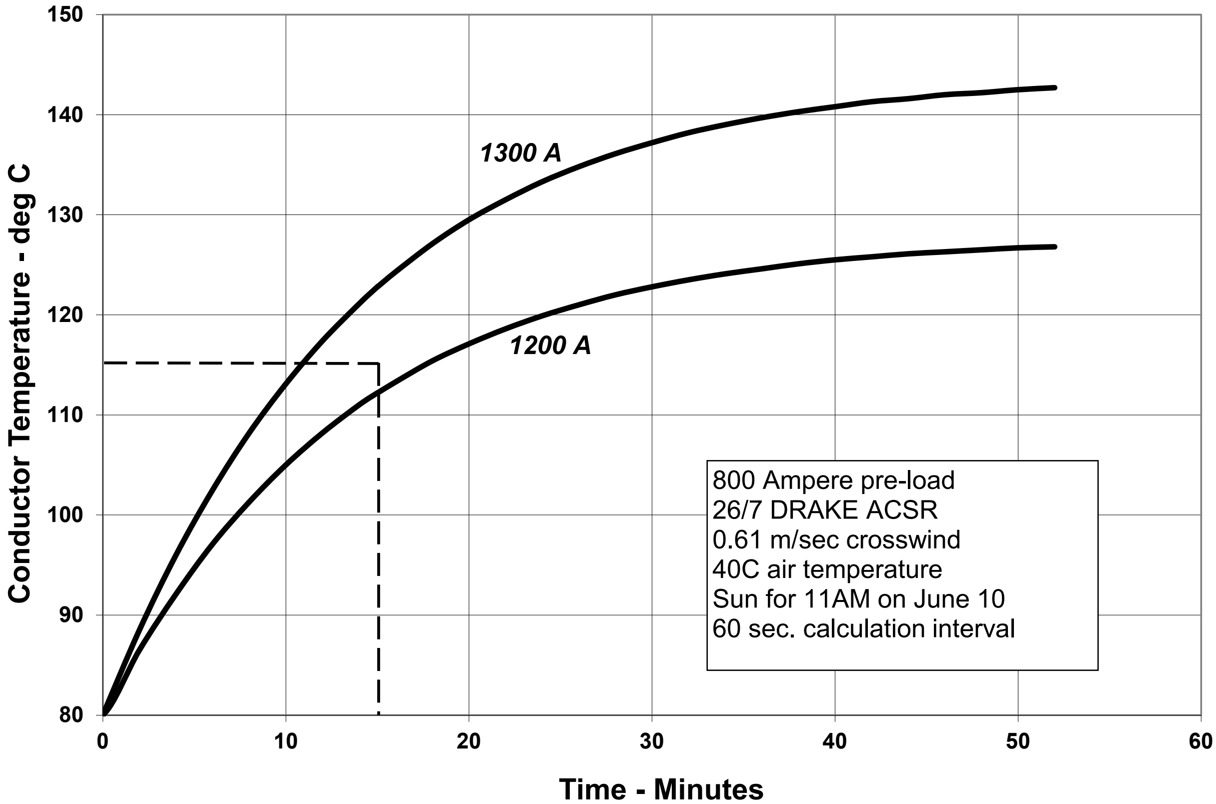


Figure 2—Transient temperature response to a step increase in current

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.

4.6.4 Transient thermal ratings

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

The initial electrical current in a Drake ACSR 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.

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. Therefore, the 15 min transient thermal rating is between 1200 A and 1300 A for the given ambient conditions.

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. As shown in Annex E, an emergency current of 1642 A causes the conductor temperature to reach 150 °C in 15 min. The 15 min transient thermal rating of the Drake ACSR conductor is therefore 1642 A under the assumed ambient conditions.

Fault current ratings can also be calculated with this program.

4.6.5 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 ACSR conductor exposed to a step increase in current from 800 A 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 12.5 min. See Annex F for a more detailed discussion of time constant.

4.6.6 Time-varying conductor current and weather conditions.

In the most general case thermal calculation, the line current and weather conditions vary over time as in the following example recorded for a transmission line with Drake ACSR conductor.

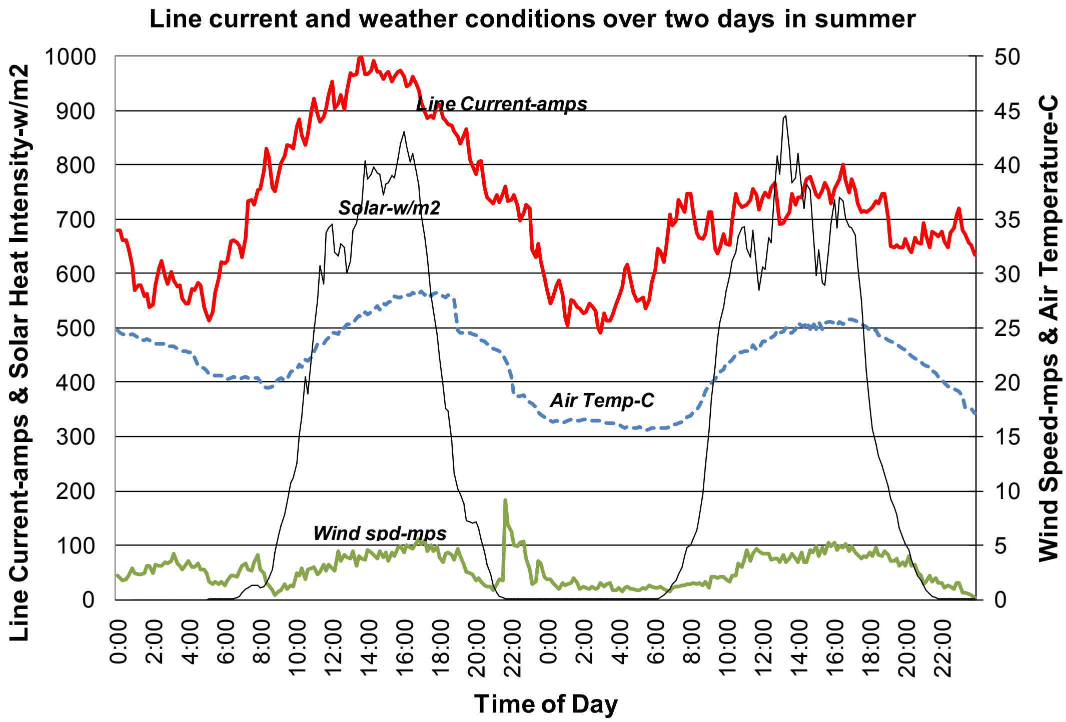


Figure 3—Line current and weather conditions over a two-day period

Thus, for example, consider the first 10-min time interval between midnight (00:00) and 10 min after midnight (00:10). In this particular case, the weather conditions and the line current are averaged over each 10-min time interval. During this time interval, the line current and weather conditions are assumed constant:

a) Line current = 678 A

b) Air temp = 25 °C

c) Solar heat = 0.0 W/m^2

d) Wind speed = 2.1 m/s

e) Wind direction = 208^o clockwise from North (62^o from parallel to the conductor)

To begin the process of tracking the conductor temperature over the two days for which the field data is available, assume that, at the beginning of the 10-min interval, the Drake ACSR conductor is at 50 °C. Of course, it may be hotter or cooler than this depending on what the line current and weather conditions were previous to the field data test period, but the conductor temperature will converge to its true value after a number of 10-min time intervals.

In doing these numerical calculations we will follow a simple procedure: for each 10-min time interval, the change in conductor temperature will be based on the conductor temperature at the beginning of the interval and the line current and weather conditions during it.

Therefore, for this first time interval, the terms in the heat balance will be calculated for the conductor temperature at 00:00 (i.e., 50 °C), a line current of 678 A, and the weather conditions listed in the preceding for the first 10-min time interval.

From the discussion in Annex F, we know that the thermal time constant of Drake ACSR is approximately 10 min, depending on the wind speed and direction. Therefore, in order to make the numerical calculation reasonably accurate, we will keep the calculation interval to less than 10% of the conductor thermal time constant. For simplicity, we will use a calculation interval of 1 min in this case. When we are done, we can evaluate the accuracy by repeating the calculation with a shorter calculation interval to see if the answers change significantly.

For the first 1 minute calculation interval, the change in temperature is determined by Equation (2b) with the following heat balance terms:

a) $R(50\ °\text{C})*I^2 = 0.0796*678^2 = 36.6$ W/m

b) $Q_s = 0.0$ W/m

c) $q_r = 7.52$ W/m

d) $q_c = 64.19$ W/m

e) $m*C_P$ = (1066+244) J/(m-°C) = 1310 W-sec/(m-°C) (see 4.6 for derivation)

$$T_{avg} = \frac{36.6+0.0-64.19-7.52}{1310} = 0.0268\,°\text{C}/\text{sec}\cdot 60\,\text{sec/min} = -1.61\,°\text{C}$$

The average conductor temperature therefore drops from 50 °C to 48.39 °C.

During the next 1-min calculation interval, the weather conditions and line current remain the same, but the conductor temperature used to calculate the heat balance terms drops to 48.39 °C.

After 10 such calculation intervals, the weather conditions and line current are adjusted to their next 10-min average values and the process repeated. Going through all of the available 10-min intervals indicated in Figure 3, the conductor temperature can be plotted as a function of time as shown in the following Figure 4.

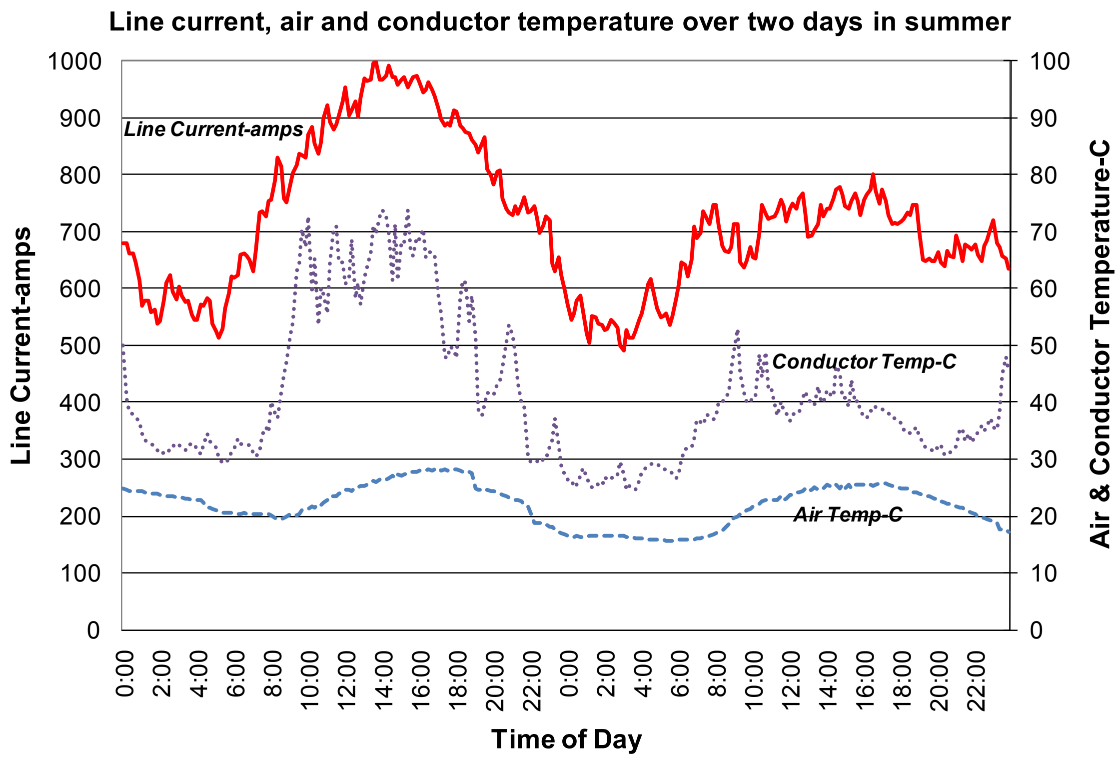


Figure 4—Conductor temperature calculated by the IEEE 738 numerical method, given time-varying line current and weather conditions.

In summary, the numerical heat balance method described in this standard works equally well when performing steady-state, transient, and temperature tracking calculations.

5. Input data

5.1 General

This standard primarily concerns mathematical methods by which the temperature of a bare overhead conductor can be accurately calculated given the electrical current through it and the weather conditions immediately around it. Obviously, even the most sophisticated calculation method can give inaccurate answers if the conductor parameters (resistance, emissivity and absorptivity), the solar heat intensity and solar angles, and the weather parameters (wind speed, wind direction, and air temperature) are inaccurate. In particular, the accurate specification of wind speed and direction, for both steady-state thermal ("book" ratings) and for real-time thermal rating calculations, requires considerable engineering judgment.

The selection of these conductor and weather parameters are discussed in this section, though the selection of suitably conservative air temperature, wind speed and wind direction for steady-state "book" rating calculations, is largely deferred to [B8]. Similarly, the attainment of proper weather data necessary for accurate real-time rating calculations is also deferred to ([B4], [B8], [B14], and [B20]).

5.2 Selection of air temperature and wind conditions for line ratings

Weather conditions have a considerable effect on the thermal loading of bare overhead conductors. Heat is lost from the bare conductor, primarily by means of heat radiation, q_r, and 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.

Historically, weather information for rating overhead lines has been obtained from local weather bureaus and, occasionally, from other local weather stations, but recorded wind speeds of less than 1.5 m/s (4.92 f/s) from weather bureau records are often inaccurate [B32]. 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. In addition, most recorded wind speeds are not direct measurements but rather the observer's estimate from a minute or so out of each hour.

The effect of wind direction relative to the conductor is included in this standard as Equation (4) in the form suggested by Davis [B11]. The difference between the wind correction factors suggested by Morgan [B26] and Davis [B11] 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. Morgan suggests that true parallel wind flow along lines does not occur due to natural turbulence (i.e., variable direction) at low wind speeds.

The effects of conductor stranding appears 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 higher wind speeds and wind shielding. Higher voltage lines (where the conductor ground clearance is greater) may be expected to experience higher wind speeds due both to boundary layer effects and to reduced wind shielding by trees and terrain.

The process of selecting conservative weather conditions for conventional steady-state "book" line ratings, based upon the methods described in CIGRE [B8]are summarized in Annex G of this standard. This reference provides guidance for four separate types of rating calculations. A summary of the process of selection is as follows:

a) In the absence of data from field rating studies, the use of certain worst-case weather conditions including a 2 ft/s (0.61 m/s) perpendicular wind speed and an air temperature near the seasonal maximum should be used.
b) If field rating studies are undertaken, the transmission line owner/operator may base the rating weather assumptions of selected lines or transmission regions upon such studies, provided that they are conducted in the actual transmission line environment, using the instrumentation methods recommended in [B8].
c) Ratings can be adjusted based on measured or forecasted ambient temperatures in the vicinity of the line. These are termed continually ambient-adjusted ratings, and [B8] suggests that the choice of worst-case wind speeds should depend on the assumed air temperature.
d) The transmission line owner/operator may elect to use real-time monitoring equipment for determining the line rating, provided that the monitoring equipment meets certain sensitivity, accuracy, and calibration requirements specified in [B8].

5.3 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 the equations in 4.5. These air parameters are a function of the air temperature and the conductor surface temperature. Air density is also a function of elevation above sea level. 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.

5.4 Conductor emissivity and absorptivity

Reports, such as Taylor and House [B33] and House, et al. [B23], indicate both that ε and α increase with age and line voltage starting at values in the range of 0.2 to 0.3 for new conductors, and reaching values in excess of 0.7 within several years. Emissivity and absorptivity are generally correlated, with both increasing over time and atmospheric pollution.

Recent laboratory measurements of conductor samples by EPRI support the use of an initial value of between 0.2 and 0.4 and an eventual increase to 0.5 to 0.9. The exact rate of increase depends on the density of atmospheric particulates and the line's operating voltage.

Historically, in North America, values for thermal rating calculations have been either that both parameters are 0.5 or (more recently) that both are in the range of 0.7 to 0.9. CIGRE [B8] suggests that, if field measurements are not made, an absorptivity value of no less than 0.8 should be used with an "…emissivity of no more than 0.1 below absorptivity." In the sample problem described in 4.6, the absorptivity and emissivity are each taken equal to 0.8.

For thermal rating calculations, at modest conductor temperatures (less than 100 °C), with sun, the values selected by the engineer do not have a large impact on the rating. At high conductor temperatures (greater than 150 °C), the value of emissivity has a larger impact on thermal rating because of increased radiation heat loss. At low conductor temperatures (less than 75 °C), the value of absorptivity has a larger impact on rating because of the importance of solar temperature rise.

When interpreting real-time monitor measurements made at normal line loadings, an incorrect absorptivity value can lead to large dynamic rating calculation errors.

In those cases, where there is doubt as to what value of emissivity is to be assumed, measurements can be performed on conductor samples taken from the field. The absorptivity can be taken as equal or slightly higher (0.0 to 0.2).

5.5 Solar heat gain

The exact calculation of conductor solar heat gain per unit length can be quite complex (e.g., [B11]). There are three sources of solar heating: direct solar heating; diffuse solar heating; and reflection from the ground under the line. This standard considers only direct solar heating, which is the largest of the three sources, but allows for all times of day, all days of year, and all latitudes. The calculation method is described in 4.4.

Utility steady-state thermal line ratings are often calculated for summer and winter. The solar heating is usually taken as being at noon during the highest solar flux day for the season. For real-time rating calculations, the direct-beamed and sky or diffuse radiation may be input directly from data obtained from weather stations ([B12] and [B14]).

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.

Although not included in the direct solar heat gain calculations of this standard, it should be noted that [B9] allows the inclusion of both diffuse and reflected solar heating. This calculation requires the specification of reflectance (albedo) for the ground under the line. For most applications, the method in this standard is conservative, though solar reflectance may have some impact on thermal rating calculations for low conductor design temperatures (i.e., 60 °C or lower).

5.6 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 [B1]. The specific heats of usual conductor materials are listed below as taken from this reference.

For 795 kcmil 26/7 Drake ACSR, the weights of the steel core and the outer aluminum are 1.116 kg/m (0.344 lb/ft) and 0.5119 kg/m (0.750 lb/ft), respectively, so that the total conductor heat capacity at 25 °C is:

$$mC_p(Al) = 1.116\, kg/m \cdot 955\, J/kg \cdot {}^oC \qquad mC_p(Al) = .750 \cdot 433\, J/lb \cdot {}^oC$$

$$= 1066\, J/m \cdot {}^oC \qquad = 325\, J/ft \cdot {}^oC$$

$$mC_p(St) = .5119\, kg/m \cdot 476\, J/kg \cdot {}^oC \qquad mC_p(St) = 0.344\, lb/ft \cdot 216\, J/lb \cdot {}^oC$$

$$= 243.7\, J/m \cdot {}^oC \qquad = 74.3\, J/ft \cdot {}^oC$$

As listed in [B4], the specific heats of conductor materials are shown in Table 5:

Table 5—Specific heat of typical conductor metal wires

Material	C_p(J/lb· °C)	C_p(J/kg· °C)
Aluminum	433	955
Copper	192	423
Steel	216	476
Aluminum-clad steel[a]	242*	534*
[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.		

5.7 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 slowly 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.

a) 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.

b) 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.

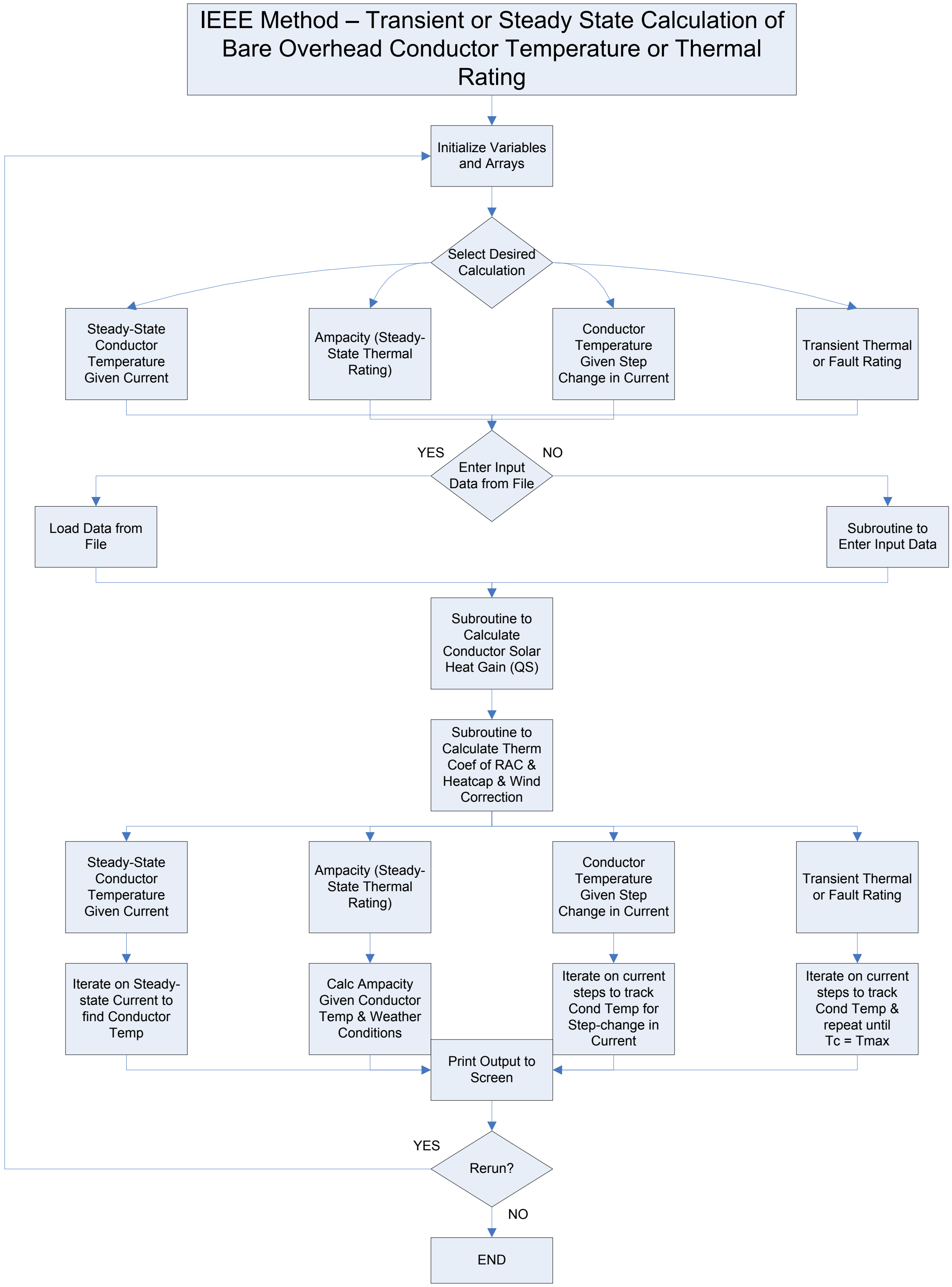
5.8 Time step

For calculation of conductor temperature and thermal ratings where the line current and/or weather conditions vary over time, the calculation time step must be chosen sufficiently small so as to result in an accurate calculation. A time step less than or equal to 1% of the conductor thermal time constant is usually sufficient. For a typical bare overhead conductor, this corresponds to a time step of about 10 seconds or less. Given the speed of modern computers, there seems to be little advantage in using a time step greater than 1 second. The accuracy of calculations can be tested by varying the time step.

Annex A

(informative)

(“RATEIEEE” numerical method listing – SI units) flowchart of numerical method


IEEE Method – Transient or Steady State Calculation of Bare Overhead Conductor Temperature or Thermal Rating
Initialize Variables and Arrays
Select Desired Calculation
Steady-State Conductor Temperature Given Current
Ampacity (Steady-State Thermal Rating)
Conductor Temperature Given Step Change in Current
Transient Thermal or Fault Rating
YES
Enter Input Data from File
NO
Load Data from File
Subroutine to Enter Input Data
Subroutine to Calculate Conductor Solar Heat Gain (QS)
Subroutine to Calculate Therm Coef of RAC & Heatcap & Wind Correction
Steady-State Conductor Temperature Given Current
Ampacity (Steady-State Thermal Rating)
Conductor Temperature Given Step Change in Current
Transient Thermal or Fault Rating
Iterate on Steady-state Current to find Conductor Temp
Calc Ampacity Given Conductor Temp & Weather Conditions
Iterate on current steps to track Cond Temp for Step-change in Current
Iterate on current steps to track Cond Temp & repeat until Tc = Tmax
Print Output to Screen
YES
Rerun?
NO
END

Program listing

```
10 REM ****************************************************************
20 REM *   IEEE METHOD - TRANSIENT OR STEADY STATE CALCULATION
30 REM *  OF BARE OVERHEAD CONDUCTOR TEMPERATURE OR THERMAL RATING
40 REM *
50 REM *
60 REM *
70 REM *    ASSUMES SI UNITS FOR INPUT
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 FOLLOWING 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 738-2012
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$(56, 45)
590 REM ******************************
600 REM * START REPEAT CALCULATION HERE
610 REM ******************************
620 FOR KI = 1 TO 1000
630 ATCDR(KI) = 0
640 TIME(KI) = 0
650 NEXT KI
660 NFLAG = 0
670 PI = 3.141593
672 PIANG = PI / 180!
680 IF FLAG1 = 99 GOTO 1120
690 REM ********************************************
700 REM * SPECIFY DATA INPUT ASCII FILE NAME
710 REM ********************************************
720 CLS
730 INPUT "ENTER INPUT FILE NAME ", F$: OPEN F$ FOR INPUT AS #1
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 REM ***************************
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
1570 REM * CURRENT (XIPRELOAD)
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 FURTHER 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
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"
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
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)
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)
5542 IF QS < 0 THEN QS=0.0
5545
5550 GOTO 5570
5560 QS = 0!
5570 RETURN
8000 REM ////////////////////////////////
```

```
8010 REM / SUBROUTINE TO ENTER INPUT DATA
8020 REM ///////////////////////////////
8030 REM NSELECT IS TYPE OF CALCULATION
8040 REM 1 = STEADY-STATE TEMP, 2 = STEADY-STATE RATING
8045 REM 3 = TRANSIENT TEMP, 4 TRANSIENT RATING
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
8560 REM *********************
8570 REM * SOLAR HEATING DATA
8580 REM *********************
8585 REM SPECIFY LATITUDE AND SUN TIME
8590 INPUT #1, CDR.LAT.DEG, 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 AND B1 IN OHM/M
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
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 ***********************************************
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 ******************************************************
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)
15125 REM * NOTE CONVECTION EQUATIONS FORM IS DIFFERENT THAN IN BODY OF 738
15128 REM * BUT THE RESULTS OF CALCULATION ARE THE SAME
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
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/M
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
20000 REM /////////////////////
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
```

Annex B

(informative)

Numerical example: steady-state conductor temperature calculation (SI units)

```
Input File - Steady State Conductor Temperature Calculation - SI Units

1               "NSELECT VALUE"
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 738-2012 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
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 45 DEG FROM NORTH AND THE ATMOSPHERE IS CLEAR


STEADY STATE THERMAL CALCULATIONS
QS IS  13.738 WATTS PER METER OF CONDUCTOR
R 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
```

Annex C

(informative)

Numerical example: Steady-state thermal rating calculation (SI units)

```
Input File - Steady State Conductor Thermal Rating Calculation - SI Units

2               "NSELECT"
101.1             "STEADY STATE CURRENT "
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, 161           "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 738-2012 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
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 45 DEG FROM NORTH 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
```

Annex D

(informative)

Numerical calculation of transient conductor temperature

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

3               "NSELECT"
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 METERS"
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 738-2012 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
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 45 DEG FROM NORTH 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
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
-------------------------------------------------------
```

Annex E

(informative)

Numerical Calculation of Transient Thermal Rating

Input File - Transient Conductor Thermal Rating Calculation - SI Units

```
4               "NSELECT"
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 METERS"
45         "CDR DIRECTION IN DEG CW FROM NORTH"
43               "CDR LATITUDE IN DEGREES"
12, 161          "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 738-2012 METHOD FOR CALCULATION OF
BARE OVERHEAD CONDUCTOR TEMPERATURES & THERMAL RATINGS
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 45 DEG FROM NORTH 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
```

Annex F

(informative)

Conductor thermal time constant

The non-steady-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 Joule 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.

Several references [B5], [B20], and [B26] describe methods 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:

$$\frac{d}{dt}(T_c - T_a) = K_1(T_c - T_a) + K_2 I^2 \tag{F1}$$

For a step change in electrical current, the solution of the linearized non-steady-state heat balance equation is:

$$T_c(t) = T_i + (T_f - T_i) \cdot (1 - e^{-t/\tau}) \tag{F2}$$

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 the formula:

$$\tau = \frac{(T_f - T_i) \cdot mC_p}{R(T_c) \cdot (I_f^2 - I_i^2)} \tag{F3}$$

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 F.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 A to 1200 A. If the average conductor temperature is taken as 100 °C, the resistance of the Drake ACSR conductor is 2.86×10^{-5} Ω/ft. From 5.6 of this standard, the heat capacity of the conductor is 399 W-s/ft-°C. The time constant is:

$$\tau = \frac{(128 - 80) \cdot 399}{2.86 \cdot 10^{-5} (1200^2 - 800^2)} = 837\ s$$

$$= 14 \min$$

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

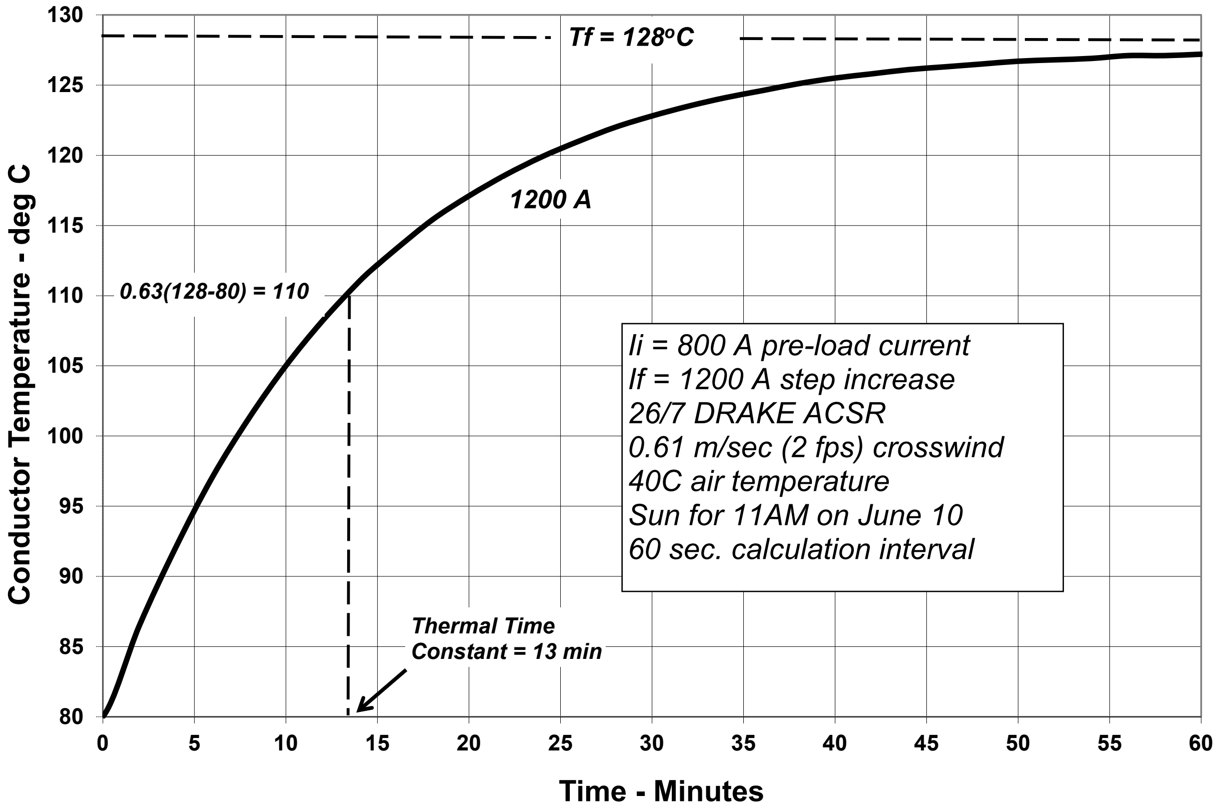


Figure F.1 – Conductor temperature vs. time curve

Annex G

(informative)

Selection of weather conditions

In a recently published *CIGRE Technical Brochure 299*, "Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings" [B8], the issue of selecting weather conditions for line ratings is discussed at some length based on an exhaustive review of the technical literature. The recommendations provided in [B8] represent a practical guide for developing conservative thermal rating estimates for overhead lines, assuming that the engineer recognizes the need for normal clearance and safety margins employed in the design and operation of overhead transmission lines. There were also a series of qualifying objectives set forth by the brochure for the determination of the weather parameters.

The default recommendations for base ratings in [B8] are based on the likelihood of coincident worst rating conditions. For example, while effective wind speeds are sometimes lower than 0.6 m/s, it is extremely unlikely that they are lower than that value if the ambient temperature and solar radiation are high. Nevertheless, if, for example, ambient temperature and solar radiation are lower, wind speeds lower than 0.6 m/s are more likely. Similarly, values of total solar radiation (the sum of direct, indirect, and reflected radiation) can be higher or lower than 1000 W/m^2 varying with time-of-day and season and reflected radiation, caused by ground albedo, can be negligible or as large as 15% to 25% of direct radiation in the visual and 25% to 35% in the near-infrared range. In [B8] it was decided to simply use a solar heat intensity of 1000 W/m^2 direct radiation as a part of most severe coincident conditions (In IEEE Std 738-2012, indirect and reflected solar radiation are ignored but the direct solar heat intensity can be calculated as a function of date, time-of-day, and latitude).

In short summary, selection of ratings can be chosen using four different levels: base ratings; study-based ratings; ambient-adjusted ratings; or real time ratings.

G.1 Base ratings

Base ratings may be applied for any transmission line and should be used unless the utility adopts alternative practices as described below.

a) For sag-limited lines, [B8] recommends that base ratings be calculated for an effective wind speed of 0.6 m/s (2 ft/s), an ambient temperature close to the annual maximum of ambient temperature along the line route and a solar radiation of 1000 W/m^2 (92.9 W/ft^2). When combined with an assumed conductor absorptivity of no less than 0.8 and emissivity of no more than 0.1 below absorptivity, this combination can be considered safe for thermal rating calculations without field measurements.

b) For those lines where annealing of conductors is the primary concern, having narrow, sheltered corridors, with energized conductors either below tree canopy height or between buildings, the base rating should be estimated based on either a 0.4 m/s (1.3 ft/s) effective wind speed or by reducing the maximum conductor design temperature by 10 °C. Although the average conductor temperature, which determines the line sag, is not likely to be higher than that based on 0.6 m/s (2 ft/s) wind speed, the local effective wind speed in sheltered locations may be significantly lower.

c) Seasonal ratings should be based on an ambient temperature close to the maximum value of the season along the line and other criteria above, although the precautions discussed in Section 4 of [B8] should be exercised.

G.2 Study-based ratings

The transmission line owner/operator may base the rating assumptions of selected lines or regions on actual weather or rating studies, provided that:

a) Rating weather studies are conducted in the actual transmission line environment, using the methods recommended in Section 5 of [B8]. If seasonal ratings are applied, such studies must include the respective seasons.

b) Alternatively, rating studies can be conducted with devices that monitor line tension, sag, clearance, or conductor temperature. The methods are specified in Section 5 of [B8].

G.3 Ambient-adjusted ratings

Ratings can be adjusted based on varying ambient temperatures measures at the time. These are termed continually ambient-adjusted ratings. In this case, unless real time rating systems are used, the wind speed should be based on the assumption of a more conservative effective wind speed than base ratings. The extensive literature review by the [B8] task force clearly indicates that ambient temperature and wind speed are not independent parameters, higher wind speeds being associated with high ambient temperatures.

If the base rating is to be adjusted for daytime conditions, [B8] recommends the following: if the ambient temperature adjustment is less than 8 °C compared to the temperature selected for base rating conditions (for example, if the base ambient temperature is 35 °C and the actual ambient temperature is between 35 °C and 27 °C), the effective wind speed should be selected as no higher than 0.5 m/s (1.64 ft/s). If the temperature adjustment is more than 8 °C, the effective wind speed should be selected as no more than 0.4 m/s (1.3 ft/s). For nighttime ambient-adjusted ratings (between sunset and sunrise when solar radiation is zero), wind speed should be selected as zero (natural convection only), and solar radiation can also be considered nil. Continually ambient-adjusted ratings can provide technically justified ampacity increases for lines that are designed for low maximum conductor temperatures (e.g., below 60 °C to 70 °C). On the other hand, they will generally not provide technically justified benefits for lines designed for 100 °C or higher temperatures and their use is not recommended.

If a study-based line rating is to be adjusted for ambient temperature, the engineer must be careful to reduce the assumed wind speed to account for correlation with ambient temperature. As with ambient adjustment of base ratings, the wind speed at night should be much lower.

G.4 Real-time ratings

Rather than using “worst-case” weather assumptions, the transmission line owner/operator may elect to use real time monitoring equipment for determining the line rating, provided:

a) Monitoring equipment meets the sensitivity, accuracy, and calibration requirements specified in Section 5 of [B8].

b) It has been verified that the lines that are to be monitored meet the design clearance requirements.

c) Monitors are installed in sufficient quantity to provide statistically valid information of the sag or temperature over the entire length of the monitored circuit. See Section 4.5 and Section 5.6 of [B8] for additional guidance.

d) The operator has the capability of adjusting the line current to the level of standard or enhanced ratings in emergency conditions.

Annex H

(informative)

Tables for solar heating and air properties

Algebraic equations are presented for air properties, solar angles, and heat flux in 4.5 of this standard. These equations are appropriate as part of the numerical calculation process that the standard recommends. Nonetheless, tables of some of these properties can provide valuable insight into the relationships of these properties.

Table H.1 – Viscosity, density, and thermal conductivity of air (SI)

Temperature T_{film}		Absolute or dynamic viscosity [B15] μ_f (kg/m-s)	Air density [B17] ρ_f (kg/m^3)				Thermal conductivity of air [B18] k_f (W/m– °C)
°F	°C		0 m	1000 m	2000 m	4000 m	
32	0	1.72e-05	1.293	1.147	1.014	0.785	0.0242
41	5	1.74e-05	1.270	1.126	0.995	0.771	0.0246
50	10	1.76e-05	1.247	1.106	0.978	0.757	0.0250
59	15	1.79e-05	1.226	1.087	0.961	0.744	0.0254
68	20	1.81e-05	1.205	1.068	0.944	0.731	0.0257
77	25	1.84e-05	1.184	1.051	0.928	0.719	0.0261
86	30	1.86e-05	1.165	1.033	0.913	0.707	0.0265
95	35	1.88e-05	1.146	1.016	0.898	0.696	0.0269
104	40	1.91e-05	1.127	1.000	0.884	0.685	0.0272
113	45	1.93e-05	1.110	0.984	0.870	0.674	0.0276
122	50	1.95e-05	1.093	0.969	0.856	0.663	0.0280
131	55	1.98e-05	1.076	0.954	0.843	0.653	0.0283
140	60	2.00e-05	1.060	0.940	0.831	0.643	0.0287
149	65	2.02e-05	1.044	0.926	0.818	0.634	0.0291
158	70	2.04e-05	1.029	0.912	0.806	0.625	0.0295
167	75	2.07e-05	1.014	0.899	0.795	0.616	0.0298
176	80	2.09e-05	1.000	0.887	0.783	0.607	0.0302
185	85	2.11e-05	0.986	0.874	0.773	0.598	0.0306
194	90	2.13e-05	0.972	0.862	0.762	0.590	0.0309
203	95	2.15e-05	0.959	0.850	0.752	0.582	0.0313
212	100	2.17e-05	0.946	0.839	0.741	0.574	0.0317

Table H.2 – Viscosity, density, and thermal conductivity of air (US)

Temperature T_{film}		Absolute or dynamic viscosity [B22] μ_f (lb/ft·hr)	Air density [B17] ρ_f (lb/ft^3)				Thermal conductivity of air [B25] k_f (W/ft-°C)
°F	°C		Sea level	5000 ft	10000 ft	15000 ft	
32	0	0.0415	0.0807	0.0671	0.0554	0.0455	0.00739
41	5	0.0421	0.0793	0.0660	0.0545	0.0447	0.00750
50	10	0.0427	0.0779	0.0648	0.0535	0.0439	0.00762
59	15	0.0433	0.0765	0.0636	0.0526	0.0431	0.00773
68	20	0.0439	0.0752	0.0626	0.0517	0.0424	0.00784
77	25	0.0444	0.0740	0.0616	0.0508	0.0417	0.00795
86	30	0.0450	0.0728	0.0606	0.0500	0.0411	0.00807
95	35	0.0456	0.0716	0.0596	0.0492	0.0404	0.00818
104	40	0.0461	0.0704	0.0586	0.0484	0.0397	0.00830
113	45	0.0467	0.0693	0.0577	0.0476	0.0391	0.00841
122	50	0.0473	0.0683	0.0568	0.0469	0.0385	0.00852
131	55	0.0478	0.0672	0.0559	0.0462	0.0379	0.00864
140	60	0.0484	0.0661	0.0550	0.0454	0.0373	0.00875
149	65	0.0489	0.0652	0.0542	0.0448	0.0367	0.00886
158	70	0.0494	0.0643	0.0535	0.0442	0.0363	0.00898
167	75	0.0500	0.0634	0.0527	0.0436	0.0358	0.00909
176	80	0.0505	0.0627	0.0522	0.0431	0.0354	0.00921
185	85	0.0510	0.0616	0.0513	0.0423	0.0347	0.00932
194	90	0.0515	0.0608	0.0506	0.0418	0.0343	0.00943
203	95	0.0521	0.0599	0.0498	0.0412	0.0338	0.00952
212	100	0.0526	0.0591	0.0492	0.0406	0.0333	0.00966

Table H.3 is provided for the user's convenience. It lists values of solar attitude and azimuth as a function of latitude for the day of the year that yields peak solar heating.

Table H.3 – Altitude, H_c, and Azimuth, Z_c, in degrees of the sun at various latitudes for an annual peak solar heat input

Degrees north latitude	Local sun time						
Lat	10:00AM		Noon		2:00PM		
	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

Table H.4 lists values of total heat flux received by a surface at sea level (heat intensity), as a function of the solar altitude, H_c, for two levels of atmospheric clarity. It is included for the user's convenience.

Table H.4 – Total heat flux received by a surface at sea level normal to the sun's rays as a function of solar altitude

Degrees solar altitude, H_c	Clear atmosphere		Industrial atmosphere	
	Q_S (W/m^2)	Q_S (W/ft^2)	Q_S (W/m^2)	Q_S (W/ft^2)
5	234	21.7	136	12.6
10	433	40.2	240	22.3
15	583	54.2	328	30.5
20	693	64.4	422	39.2
25	770	71.5	502	46.6
30	829	77.0	571	53.0
35	877	81.5	619	57.5
40	913	84.8	662	61.5
45	941	87.4	694	64.5
50	969	90.0	727	67.5
60	1000	92.9	771	71.6
70	1020	95.0	809	75.2
80	1030	95.8	833	77.4
90	1040	96.4	849	78.9

Table H.5— Solar heat multiplying factors, K_{solar} for high altitudes [B16]

Elevation above sea level H_e - m	Multiplier for values in Table H.4	Elevation above sea level H_e - ft	Multiplier for values in Table H.4
0	1.00	0	1.00
1 000	1.10	5 000	1.15
2 000	1.19	10 000	1.25
4 000	1.28	15 000	1.30

Annex I

(informative)

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Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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