

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

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Abstract: A simplified 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-capacity relationships for a large number of conductors for a large number of conditions.

Keywords: bare overhead lines, current-temperature relationship.

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Introduction

(This introduction is not a part of IEEE Std 738-1993, IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.)

In 1986, IEEE Std 738-1993, IEEE Standard for Calculation of Bare Overhead Conductor Temperature and Ampacity Under Steady-State Conditions, was first published. The standard was developed “so that a practical, sound, and uniform method (of calculation) might be utilized and referenced.” As part of the revision cycle, 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. As a result of that decision, the name of this standard has been changed to reflect its broader application.

This standard includes a computer program on diskette. The working group has made every effort to ensure that the program yields accurate results. The user is cautioned that there may be values of rating parameters for which the method is not appropriate. A program listing, well documented with comment statements, is provided to allow the user to review the calculation method and assumptions to determine their validity for a particular case.

Many persons have contributed to the preparation, analysis, and review of this standard. We would like to recognize the contribution of the late B. S. Howington, who served as chair of the working group for many years and was responsible for developing the original standard and establishing the content of the revised standard.

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Contents

1. Overview	5
1.1 Introduction	5
1.2 Definition of terms	6
2. Temperature calculation methods	7
2.1 Steady-state calculations	8
2.2 Transient calculations	8
2.3 Identification of letter symbols	9
2.4 Formulas	10
2.5 Equations for tables 1, 2, 3, and 4	13
2.6 Sample calculations	17
3. Input data	22
3.1 Introduction	22
3.2 Wind and ambient temperature	22
3.3 Air density, viscosity, and conductivity	23
3.4 Emissivity and absorptivity	23
3.5 Solar heat gain	23
3.6 Conductor heat capacity	23
3.7 Maximum allowable conductor temperature	24
3.8 Time step	24
4. Bibliography	24
Annex A (informative) Listing of the “RATEIEEE program for steady-state and transient calculations of thermal temperature and thermal rating for bare overhead conductors	27
Annex B (informative) Sample calculation of steady-state thermal rating.	43
Annex C (informative) Sample calculation of steady-state conductor temperature	44
Annex D (informative) Sample calculation of transient conductor temperature for a step increase in current.	45
Annex E (informative) Sample calculation of transient thermal rating	49
Annex F (informative) Thermal time constant	50

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

1. Overview

1.1 Introduction

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

Conductor surface temperatures are a function of

- a) Conductor material properties
- b) Conductor diameter
- c) Conductor surface conditions
- d) Ambient weather conditions
- e) Conductor electrical current

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

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

- To calculate the conductor temperature when the electrical current is known
- To calculate the current that yields a given maximum allowable conductor temperature

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

This standard includes mathematical methods and indicates sources of the values to be used in the calculation of conductor temperatures and conductor thermal ratings. However, because there is a great diversity of

weather conditions and operating circumstances for which conductor temperatures and/or thermal ratings must be calculated, the standard does not undertake to list actual temperature-current relationships for specific conductors or weather conditions. Each user must make their own assessment of which weather data and conductor characteristics best pertain to their area or particular transmission line.

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

1.1.1 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 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.

1.2 Definition of terms

1.2.1 conductor temperature: The temperature of a conductor.

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

1.2.2 heat capacity: (A) *homogeneous conductors:* The specific heat of the conductor's material times the mass per unit length. (B) *nonhomogeneous conductors:* The sum of the heat capacities of the conductor's component materials.

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

1.2.4 Reynolds number: A nondimensional number equal to air velocity (V_w) times conductor diameter ($D/12$) divided by kinematic viscosity (μ_f/ρ_f).

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

1.2.6 transient thermal rating: The transient thermal rating is that final current (I_f) that yields the maximum allowable conductor temperature ($T_{\max}$) in a specified time after a step change in electrical current from some initial current, I_i .

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

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

2. Temperature calculation methods

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

- a) House and Tuttle [B19]¹
- b) House and Tuttle, as modified by East Central Area Reliability (ECAR) [B27]
- c) ALCAN [B23]
- d) Pennsylvania-New Jersey-Maryland Interconnection [B11], [B6]
- e) Schurig and Frick [B24]
- f) Hilpert [B17]
- g) Davis [B9]
- h) Morgan [B22]
- i) Black and Byrd [B3], [B5], [B3]
- j) Foss, Lin, and Fernandez [B14]

The mathematical models of this standard are based upon the House and Tuttle method as modified by ECAR [B27]. The House and Tuttle formulas consider all of the essential factors without the simplifications that made in some of the other formulas.

To differentiate between laminar and turbulent air flow, the House and Tuttle method [B19] 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 [B19], ECAR [B27] 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 [B21]. For additional information on convection heat loss, see 3.2 of this standard.

Since the primary purpose of this standard is the calculation of thermal ratings for constant weather conditions, the slower but simpler iterative approach is taken. Alternate noniterative methods may be used to calculate the conductor temperature given the current and weather conditions. In [B9], the heat balance equation is expressed as a biquadratic equation that can be solved to give the conductor temperature directly. In [B5] and [B29], the radiation term is linearized and the resulting approximate linearized heat balance equation is solved using standard methods of linear differential equations. In [B14], a somewhat more precise linearized radiation term is used to reduce the number of iterations required. These methods are computationally faster than the iterative method described in this standard; however, the algebraic expressions are more complex. While one expects to get the same answer from any valid calculation method, the noniterative methods are used normally in real-time thermal rating algorithms where calculation speed is essential.

2.1 Steady-state calculations

2.1.1 Steady-state thermal rating

For a bare stranded conductor, if the conductor temperature (T_c) and the steady state weather parameters (V_w , T_a , etc.) are known, the heat losses due to convection and radiation (q_c and q_r), the solar heat gain (q_s),

¹The numbers in brackets correspond to the bibliographic references in clause 4.

and the conductor resistance $R(T_c)$ can be calculated by the formulas of 2.4. 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 2.4.1]. While this calculation can be done for any conductor temperature and any weather conditions, a maximum allowable conductor temperature (e.g., 95 °C) and “conservative” weather conditions (e.g., 2 ft/s wind speed, 40 °C summer ambient) are often used to calculate a steady-state thermal rating for the conductor.

2.1.2 Steady-state conductor temperature

Since the radiation and convection heat loss rates are not linearly dependent on the conductor temperature, the heat balance equation [equation (1b) of 2.4.1] is solved for conductor temperature in terms of the current and weather variables by a process of iteration. That is, given a conductor current,

- a) A conductor temperature is assumed.
- b) The corresponding heat losses are calculated.
- c) The conductor current that yields this conductor temperature is calculated by means of equation (1b).
- d) The calculated current is compared to the given conductor current.
- e) The conductor temperature is then increased or decreased until the calculated current equals the given current.

2.2 Transient calculations

2.2.1 Transient conductor temperature

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

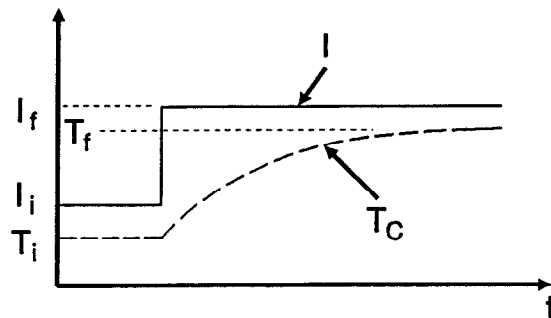


Figure 1 — Step change from initial current (I_i) to final current (I_f);

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

Immediately *after* the current step change ($t = 0^+$), the conductor temperature is unchanged (as are the conductor resistance and the heat loss rate due to convection and radiation), but the rate of heat generation due to Ohmic losses has increased. Therefore, at time $t = 0^+$, the temperature of the conductor begins to increase at a rate given by the non-steady-state heat balance equation (2b) in 2.4.2.

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

During each interval of time, the corresponding increase in conductor temperature may be calculated using the formulas given in 2.4. The computer program included in annex A calculates the conductor temperature as a function of time after the step change in current.

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

2.2.2 Transient thermal rating

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

2.2.3 Fault current calculations

Conductor temperature changes in response to “fault” currents are calculated in the same manner as in 2.2.1, except that the step increase in current is usually quite large ($>10\,000$ A), the corresponding time to reach maximum allowable temperature is typically short (<1 s), and the maximum temperatures attained may approach the melting point of aluminum or copper.

With nonhomogeneous conductors, such as ACSR (aluminum conductor steel reinforced), the heat generation in the lower conductivity steel core is much lower than in the surrounding aluminum strand layers. The resulting temperature difference between the core and the surrounding aluminum strands abates after no more than 60 s from any step change in current. This is discussed further in 2.4.8.

2.3 Identification of letter symbols

A'	projected area of conductor (square feet per lineal foot)
D	conductor diameter (in)
H_c	altitude of sun (degrees)
H_e	elevation of conductor above sea level (ft)
I	conductor current (A at 60 Hz)
I_i	initial current before step change (A at 60Hz)
I_f	final current after step change (A at 60Hz)
K_{angle}	wind direction factor
k_f	thermal conductivity of air at temperature T_{film} W/ft ($^{\circ}\text{C}$)
mC_p	total heat capacity of conductor (W·s/ft $^{\circ}\text{C}$)
m_i	weight per unit length of i^{th} conductor material (lb/ft)
q_c	convected heat loss (watts per lineal foot of conductor)
q_r	radiated heat loss (watts per lineal foot of conductor)
q_s	heat gain from the sun (watts per lineal foot of conductor)

Q_s =	total solar and sky radiated heat flux (W/ft ²)
$R(T_c)$ =	60 Hz ac resistance per lineal foot of conductor at T_c (Ω/ft)
T_a =	ambient temperature (°C)
T_c =	conductor temperature (°C)
T_f =	conductor temperature attained many time constants after step increase (°C)
T_i =	conductor temperature prior to step increase, (°C)
T_{film} =	$(T_c + T_a)/2$ = air film temperature (°C)
$T_{\text{Low}}, T_{\text{High}}$ =	minimum and maximum conductor temperatures for which the conductor's 60 Hz resistance is specified
V_w =	velocity of air stream (ft/h)
W =	watts
Z_c =	azimuth of sun (degrees)
Z_l =	azimuth of line (degrees)
C_{pi} =	specific heat of i^{th} conductor material (W·s/lb °C)
Δt =	time step used in transient calculation (s)
ΔT_c =	conductor temperature increment corresponding to time step Δt (°C)
α =	solar absorptivity (0.23 to 0.91)
ϵ =	emissivity (0.23 to 0.91)
τ =	thermal time constant of the conductor (min)
ϕ =	angle between wind and axis of conductor (degrees)
ρ_f =	density of air (lb/ft ³)
θ =	effective angle of incidence of the sun's rays (degrees)
μ_f =	absolute viscosity of air (lb/ft·hr)

2.4 Formulas

2.4.1 Steady-state heat balance

$$q_c + q_r = q_s + I^2 \cdot R(T_c) \quad (1a)$$

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

2.4.2 Non-steady-state heat balance

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

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

2.4.3 Forced convection heat loss

$$q_{c1} = \left[1.01 + 0.371 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.52} \right] \cdot k_f \cdot (T_c - T_a) \quad (3a)$$

$$q_{c2} = 0.1695 \left(\frac{D \rho_f V_w}{\mu_f} \right)^{0.6} \cdot k_f \cdot (T_c - T_a) \quad (3b)$$

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

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

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

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

$$K_{\text{angle}} = 1.194 - \sin(\omega) - 0.194 \cos(2\omega) + 0.368 \sin(2\omega) \quad (4b)$$

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

2.4.4 Natural convection

With zero wind speed, natural convection heat loss occurs, where

$$q_c = 0.283 \rho_f^{0.5} D^{0.75} (T_c - T_a)^{1.25} \quad (5)$$

It has been argued that at low wind speeds, the convection cooling should be calculated by using a vectorial sum of the wind speed and a “natural” wind speed, see [B22]. However, it is recommended that only the larger of the forced and natural convection heat losses 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 taken from table 1 at T_{film} , where

$$T_{\text{film}} = \frac{T_c + T_a}{2} \quad (6)$$

2.4.5 Radiated heat loss

$$q_r = 0.138 D \varepsilon \cdot \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right]$$

2.4.6 Solar heat gain (see tables 2 and 3)

$$q_s = \alpha Q_s \sin(\theta) A' \quad (8)$$

where

$$\theta = \cos^{-1}[\cos(H_c)\cos(Z_c - Z_l)] \quad (9)$$

2.4.7 Conductor electrical resistance

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

These calculated values include the frequency-dependent “skin effect” for all types of stranded conductor, but, for other than single-layer ACSR, do not include a correction for current density dependent magnetic core effects, which is significant for ACSR conductors having odd numbers of layers of aluminum strands. The resistance of single-layer ACSR conductors (6/1, 7/1, 8/1) is shown to be increased as much as 20% in [B1]. The resistance of three-layer ACSR (45/7, 54/7, etc.) may be as much as 3% higher than the tabulated values. Engineering judgment is required in thermal calculations involving these ACSR conductors.

Resistance at temperatures above 75 °C may be calculated according to the methods described in [B1], [B3], and [B12].

In this standard, electrical resistance is calculated solely as a function of conductor temperature; however, the resistance values entered may be a function of frequency and current density. For example, the values of conductor resistance at high temperature, T_{HIGH} , and low temperature, T_{LOW} , may be taken from the tabulated values in [B1]. The conductor resistance at any other temperature, T_c , is found by linear interpolation according to equation (10):

$$R(T_c) = \left[\frac{R(T_{\text{HIGH}}) - R(T_{\text{LOW}})}{T_{\text{HIGH}} - T_{\text{LOW}}} \right] \cdot (T_c - T_{\text{LOW}}) + R(T_{\text{LOW}}) \quad (10)$$

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

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

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

2.4.8 Conductor heat capacity

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

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

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

Values for the specific heat of common metals used in stranded overhead conductors are listed in [B5] and in 3.6 of this standard.

With a nonhomogeneous conductor, for faults with durations of less than 60 s, the internal temperature difference between the core and the outer strands cannot be neglected. In particular, for ACSR conductor, the heat capacity of the relatively nonconducting steel core should be neglected for step currents whose duration is less than 60 s. For step currents whose duration is greater than 60 s, the heat capacity of the core is included. For step current durations of 10 to 60 s, the calculated conductor temperatures are somewhat conservative because any temperature difference between the core and outer strands decreases to zero with an internal thermal time constant of the order of 10 to 20 s.

2.5 Equations for tables 1, 2, 3, and 4

Least square polynomial regressions were performed on tabular data in the included tables and coefficients determined to fit an equation of the form:

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

As suggested by Lutwen [B12], the equation for density takes a different form so as to evaluate the effects of both temperature and elevation. The coefficients for the polynomial expressions and the equation for density are as follows:

2.5.1 Viscosity (table 1)

$Y =$ absolute viscosity, μ_f (lb/ft·hr)

$X =$ temperature, T_{film} (°C)

$$A = 0.0415$$

$$B = 1.2034 \cdot 10^{-4}$$

$$C = -1.1442 \cdot 10^{-7}$$

$$D = 1.9416 \cdot 10^{-10}$$

$$E \text{ to } G = 0$$

2.5.2 Density (table 1)

$$\rho_f = \frac{0.080695 - 0.2901 \cdot 10^{-5}(H_c) + 0.37 \cdot 10^{-10}(H_c^2)}{1 + 0.00367(T_{film})}$$

2.5.3 Thermal conductivity of air (table 1)

$Y =$ thermal conductivity of air, k_f , in W/ft (°C)

$$\begin{aligned}
 X &= \text{temperature, } T_{\text{film}}(^{\circ}\text{C}) \\
 A &= 0.007388 \\
 B &= 2.27889 \cdot 10^{-5} \\
 C &= -1.34328 \cdot 10^{-9} \\
 D \text{ to } G &= 0
 \end{aligned}$$

Table 1 — Viscosity, density, and thermal conductivity of air

Temperature T_{film}			Absolute viscosity [B15] (lb/ft·hr) μ_r	Air density [B17] ρ_r (lb/ft ³)				Thermal con- ductivity of air [B18] (W/ft, °C) k_f
°F	°C	°K		Sea level	5 000 ft	10 000 ft	15 000 ft	
32	0	273	0.0415	0.0807	0.0671	0.0554	0.0455	0.00739
41	5	278	0.0421	0.0793	0.0660	0.0545	0.0447	0.00750
50	10	283	0.0427	0.0779	0.0648	0.0535	0.0439	0.00762
59	15	288	0.0433	0.0765	0.0636	0.0526	0.0431	0.00773
68	20	293	0.0439	0.0752	0.0626	0.0517	0.0424	0.00784
77	25	298	0.0444	0.0740	0.0616	0.0508	0.0417	0.00795
86	30	303	0.0450	0.0728	0.0606	0.0500	0.0411	0.00807
95	35	308	0.0456	0.0716	0.0596	0.0492	0.0404	0.00818
104	40	313	0.0461	0.0704	0.0586	0.0484	0.0397	0.00830
113	45	318	0.0467	0.0693	0.0577	0.0476	0.0391	0.00841
122	50	323	0.0473	0.0683	0.0568	0.0469	0.0385	0.00852
131	55	328	0.0478	0.0672	0.0559	0.0462	0.0379	0.00864
140	60	333	0.0484	0.0661	0.0550	0.0454	0.0373	0.00875
149	65	338	0.0489	0.0652	0.0542	0.0448	0.0367	0.00886
158	70	343	0.0494	0.0643	0.0535	0.0442	0.0363	0.00898
167	75	348	0.0500	0.0634	0.0527	0.0436	0.0358	0.00909
176	80	353	0.0505	0.0627	0.0522	0.0431	0.0354	0.00921
185	85	358	0.0510	0.0616	0.0513	0.0423	0.0347	0.00932
194	90	363	0.0515	0.0608	0.0506	0.0418	0.0343	0.00943
203	95	368	0.0521	0.0599	0.0498	0.0412	0.0338	0.00952
212	100	373	0.0526	0.0591	0.0492	0.0406	0.0333	0.00966