Outdoor Substation Conductor Ratings

Transmission and Substation Design Committee
Substation Conductor Rating Task Force

PJM Interconnection, LLC

September, 2010 – Revision 2

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December 16, 2004 – Revision 1

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1.0 Scope / Introduction

The PJM Transmission and Substation Design Subcommittee (TSDS) was requested to review and update the existing Outdoor Substation Conductor Ratings, Revision 1 document issued by the TSDS on December 16, 2004. This document contains ampacity ratings for tubular bus and stranded conductors used in substations and was based on calculations performed using a similar methodology and set of parameters determined for transmission line conductors. A task force consisting of representatives from PJM member operating companies was assigned the task of adding bus ratings for non-tubular rigid bus conductor shapes, as well as revisiting certain rating parameters and assumptions used for stranded and tubular conductors. The results of the task force work are incorporated into this new document.

For this guide, it is assumed that system power levels will be maintained and managed within the requirements of PJM Manual 3, Section 2, "Thermal Operating Guidelines". PJM operating philosophy strives to restore loads to below the Normal Rating in four hours or less. The intent of this guide is that equipment loading will not be above the Normal Rating for greater than four hours. It is understood that under a single event restoration, cumulative time of loading, in excess of the Normal Rating, beyond four hours may occur. Operating in excess of four hours above the Normal Rating for a single event restoration should be evaluated by the equipment owner.

The task force utilized the information and methodology contained in IEEE Std 605-2008, "Guide for Design of Substation Rigid-Bus Structures" as a primary reference in developing ampacity ratings for non-tubular rigid bus shapes, specifically bar and angle shaped conductors.

The task force retained the recommended values adopted in Revision 1 for the key parameters used in calculating bar and angle shaped conductor ampacity. These parameters include wind speed and direction, ambient temperature, solar gain, emissivity, absorptivity, and maximum conductor temperature limitations for conditions of normal (continuous), emergency (one hour and 24-hour) ratings. The report also contains a discussion on the calculation methodology, conductor materials, fittings and accessories, other ampacity considerations, and the risk associated with wind speeds which are different than those that are assumed for the calculations.

Lastly, this report includes new revised ampacity ratings for substation conductors used in facilities under the control of PJM. **The ratings provided in this document are for outdoor applications of aluminum and copper tubular bus, aluminum and copper bar, aluminum universal angle bus (UAB), and bare aluminum and copper wire of various sizes.**

2.0 Definitions and Terms

Normal Conditions	All equipment in normal configuration, and normally expected range of ambient weather conditions.
Normal Rating	The maximum permissible constant load at normal conditions, at the maximum allowable conductor temperature for that conductor.
Emergency Conditions	Equipment has been operating at Normal Rating. The equipment is then exposed to an out of configuration condition.
Emergency Rating	The maximum permissible constant load at emergency conditions, at the maximum allowable conductor temperature. (for a period longer than 1 hour, but not to exceed 24 hours)
Weather Conditions	Ambient temperature, solar and sky radiated heat flux, wind speed, wind direction, and elevation above sea level.
Max. Allowable Condr. Temp.	The maximum temperature limit that is selected in order to minimize loss of strength, conductor sag, line losses, or a combination of the above.
Time Risk	The time during which the conductor is vulnerable to operation at temperatures greater than the design temperature.
Temperature Risk	The maximum increase in conductor temperature above design temperature which can be experienced if the conductor carries its rated current simultaneously with an occurrence of the most severe set of ambient conditions.
Transition Point	Regardless of the installation method, the transition point is the connection of the insulator string to the overhead conductor at the dead end structure. The dead end referenced should be the structure that transitions the line to any type of substation equipment. Underground cable transition is at the end of the pot head. The intent of the point of demarcation is to prevent a high temperature overhead conductor from overheating temperature sensitive substation

	equipment. Conductor drops from a take-off tower may be rated as line conductor if attached to non-temperature sensitive substation components.
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Load Dump Rating	The maximum permissible transient load at emergency conditions, at the maximum allowable conductor temperature. for a period of 15 minutes. This is a transient rating, since the conductor will normally not achieve a constant temperature within 15 minutes. Load is returned to pre-load dump conditions at 15 minutes.

3.0 Weather Assumptions

Ambient weather conditions have a major effect on thermal ratings of a substation conductor. There are many factors to consider when determining the precise weather model to utilize in the ampacity calculations of substation bus conductors. However, wind (speed and direction) and ambient temperature are major variables to consider and have the most effect in determining the final thermal ratings of substation conductors. The following sections will outline these major variables that are critical in the calculation of the overall thermal rating.

It is important to note that weather data was collected and analyzed in PJM work performed by the original transmission line conductor rating task force in 1973. The weather data included 10 years of data from Pittsburgh from January 1, 1949 through December 31, 1958 and 16 years of data from Ronald Reagan Washington National Airport (formerly Washington D.C. National Airport) from January 1, 1949 through December 31, 1964. All of the data was combined to form an hourly composite record that was representative of the entire PJM service territory. The previous task force evaluated this original data and believed it to remain representative of the weather conditions that exist within the present PJM territory. The present task force made no change to the weather assumptions.

3.1. Wind Speed

Wind speed is an important variable in determining the ratings of a substation conductor. This document follows Section C.3 (Heat Transfer) in Annex C of the IEEE Standard 605 document which states that a wind speed of 2 fps is used for all substation conductor thermal rating calculations. In IEEE Standard 605, it is concluded that assumption of a 2 fps wind is a conservative, yet realistic approach and was chosen for the basis of the IEEE document. The inherent risks associated with utilizing this wind speed are discussed in Section 11 of this document.

3.2. Wind Direction

Both the 1979 PJM bus rating work and the IEEE Standard 605 agree in the utilization of a wind perpendicular to the substation conductor. A perpendicular wind (a 90^{o} cross wind) was recommended by the previous task force for the calculations of substation conductor thermal ratings and is used in the published tables.

The composite weather data supporting the above statistics can be found in Section 11. The inherent risk associated with utilizing the various ambient temperature parameters can be found in Section 11 of this document.

3.3. Ambient Temperature

Ambient temperature is an important parameter to consider when calculating substation conductor thermal ratings. As stated in the 1979 PJM bus rating document, for the summer rating period, an ambient temperature of 35°C is to be used for substation conductor thermal rating calculations. Examination of the original PJM weather data indicates that the actual summer temperatures are less than or equal to 35°C over 99% of the time.

For the winter rating period an ambient temperature of 10°C is to be used for substation conductor thermal rating calculations. This is a reduction in ambient temperature versus the 1979 PJM work (10°C versus 20°C) and is believed to be a conservative, yet realistic selection. Examination of the original PJM weather data indicates that the actual winter temperatures are less than or equal to 10°C over 88% of the time.

The composite weather data supporting the above statistics can be found in Section 11. The inherent risk associated with utilizing the various ambient temperature parameters can be found in Section 11 of this document.

3.4. Rating Tables

A conductor rating report for each type of substation conductor can be generated by the MS Excel Spreadsheet that is described in appendix A of this document. The conductor rating report will provide a specific thermal rating based on the wind and ambient temperature recommendations discussed above. The reports are ambient temperature adjusted so as to allow the system operator to determine the ampacity of a substation conductor based on real time information. Each conductor rating report provides thermal ratings based on ambient temperatures from -15°C to +40°C in 5° increments.

3.5. Solar Gain & Atmosphere

The model utilized by the PJM task force is based upon the solar gain (solar heating) equations used in both IEEE Standard 605 and IEEE Standard 738-1993 “IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors”. Both of these standards allow for adjustments in solar gain effects due to varying atmosphere clarity. The atmosphere clarity varies between a clear atmosphere and a hazy industrial atmosphere. The clear atmosphere allows for more solar heating of the bus conductor and results in a slightly lower bus ampacity rating when compared to the industrial atmosphere assumption. The bus ampacity tables published in IEEE Standard 605 are based upon a clear atmosphere. Utilizing this flexibility, the task force chose to utilize a clear atmosphere for ampacity calculations as defined by IEEE Standards 738 and 605. The task force believes this is a conservative, yet realistic approach and is chosen for the basis of this document.

4.0 Method of Calculation

4.1.Calculating the Current-Temperature Relationship of Conductors

The task force retained the method of IEEE Standard 605. Copies of the standard are widely available and earlier IEEE source documents discuss the calculations in greater detail than the standard. IEEE Standard 605 is widely accepted as a standard within the industry and forms a commonly accepted basis for calculations. With this in mind, the 2004 task force developed a Microsoft Excel © Spreadsheet to accommodate a wide base of possible users. The spreadsheet applies the IEEE Standard 605 approach to these calculations for use by all PJM member companies. The 2010 task force modified the existing spreadsheet to calculate bar and angle shaped ampacities.

4.2.Description of IEEE Standard 605-2008

This standard presents a method of calculating the current-temperature relationship of bare substation rigid-bus conductors based on a 2 fps wind perpendicular to the length of the conductors. The authors of the standard chose a 2 fps wind because it was, "conservative, yet realistic."

The conductor temperature is a function of:

a. Conductor material
b. Conductor shape with diameter or width and thickness
c. Conductor surface condition
d. Ambient weather conditions
e. Conductor electrical current

IEEE Standard 605 includes mathematical models to calculate conductor temperatures and conductor thermal ratings. The standard contains calculated tables with numerous temperature-current relationships for specific conductors and weather conditions. Each user of the standard must determine weather data and conductor characteristics appropriate for their needs.

The source document for the ampacity calculation and table portion of IEEE Standard 605, Power Apparatus & Systems (PAS) 96, No. 4, July/August 1977, Page 1341, "Thermal Considerations for Outdoor Bus Conductor Design Ampacity Tables," notes an elevation of sea level was used in preparing the ampacity tables.

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 for a given conductor temperature (by iteration)

The Standard's approach to calculating ampacity requires first calculating the convective heat loss (q_c), the radiation loss (q_r), and the solar heat gain (q_s), of the conductor under investigation. Since the Task Force decided that calculations should be able to be performed at any wind speed, the convection equations contained in IEEE Standard 605 were modified to be suitable for variable wind speeds. The modifications were based on IEEE Standard 738.

Since both standards use the same sets of equations to calculate the radiation loss and the solar heat gain for round shapes, the balance of this discussion will focus on convective heat loss considerations for all shapes, and radiation loss and solar heat gain for non-tubular shapes.

4.3. Convective Heat Loss Considerations

Convective heat loss, or the cooling due to air movement, is a major factor in determining the thermal rating of a conductor. There are two conditions to consider: (a) cooling due to natural convection – or a zero wind speed, and (b) cooling due to forced convection – or a non-zero wind speed. This section reviews material taken from IEEE Standards 605 and 738, to permit bus ampacity calculations for any wind speed.

4.3.1. Natural Convection

4.3.1.1. Cylindrical Surfaces

Natural convection applies to surfaces shielded from direct exposure to the wind. Assuming, however, that there is enough space for natural convection to occur, then surface heat loss can be calculated using generally accepted equations for natural convection. According to IEEE 605 natural convection is not consider for single round or flat conductors since they are not shielded from the wind. In Section C.3.2.3, IEEE Standard 605 (Substation Rigid-Bus Structures) gives equation (1.) below for natural convection over a cylindrical surface:

$$\textbf{(1.)}\quad \mathbf{q_c = 0.0022 * \Delta T^{1.25} * l^{-0.25} * A}$$

ΔT = temperature difference between the conductor surface and the surrounding air in degrees Celsius.

l = length of conductor surface in inches = 12 for a one foot length of conductor.

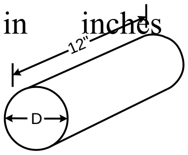
A = conductor surface area in inches^2 / foot length.

q_c = convective heat loss in watts per linear foot.

A more useful equation for spreadsheet application:

A = area = $\pi * D * 12$ in^2 / ft

l = length of conductor surface in inches = $12 * L = 12$



Substituting into (eq. 1.) gives:

$$q_c = 0.0022 * \Delta T^{1.25} * 12^{-0.25} * 12 * \pi * D$$

$$q_c = 0.0022 * \Delta T^{1.25} * 20.255166 * D$$

$$\textbf{(2.)} \quad q_c = .044561 * D * \Delta T^{1.25} \text{ watts / ft}$$

By comparison, IEEE Standard 738 (Bare Overhead Conductors) explicitly recognizes more of the factors involved in natural convection heat loss. As noted in Section 2.4.4 of that Standard:

$$\textbf{(3.)} \quad q_{c0} = .283 * \rho_r^{0.5} * D^{0.75} * \Delta T^{1.25} \text{ watts/ft}$$

q_{c0} = convective heat loss due to zero wind
ρ_r= density of air in lb/ft^3
D= conductor outer diameter in inches
ΔT= temperature difference between the conductor surface and the surrounding air in degrees Celsius

Since the spreadsheet developed by the task force is based on the work of the previous Conductor Rating Task Force, equation (3.) above is used. This facilitates recognizing the effect of elevation upon conductor ratings (higher elevation results in lower air density and therefore lower heat transfer, all else being equal.).

4.3.1.2. Bars & Rectangular Shapes

Equation 1, above, is applicable to upward facing surfaces while surfaces facing down experience one-half this heat loss. Natural convection for a single rectangle or bar is assumed to be zero per the table in C.3.2.6 of IEEE 605-1998. The table also gives the area for natural convection of multiple (N) rectangles as:

$$\textbf{(4.)} \quad A = 24 * l * (N-1)$$

A = effective conductor area
l = length of the conductor in inches
N = number of conductors

Substituting this expression for A in equation 1:

$$\textbf{(5.)} \quad q_{c0} = .0528 * \Delta T^{1.25} * l^{0.75} * (N-1)$$

4.3.1.3. Single & Double Angles

As noted in 4.3.1.2, Equation 1, above, is applicable to upward facing (favorable) surfaces while surfaces facing down (unfavorable) experience one-half this heat loss. Natural convection for a single angle is assumed to be zero per the table in C.3.2.6 of IEEE 605-1998. The table also gives the area for natural convection of 2 angles as:

$$\textbf{(6.)} \quad A = 24 * (l + w)$$

A = effective conductor area
l = length of the angle in inches
w = width of the angle

Equation 1 is multiplied by a factor of 7/8 to average the loss of 3 favorable and 1 unfavorable surfaces. Substituting this expression for A and applying the multiplier to equation 1:

(7.) $q_{c0} = .0462 * \Delta T^{1.25} * (1^{0.75} + w^{0.75})$

4.3.2. Forced Convection

4.3.2.1. Forced Convection for Cylindrical Shapes

IEEE Standard 605, section C.3.2 2 gives the following equation for heat transfer where there is a 2 fps wind.

(8.) $\mathbf{q_c = .010 * (D^{-0.4}) * A * \Delta T}$

D = outer diameter of cylinder in inches
A = surface area of cylinder in inches^2 per foot length
ΔT = temperature difference in degrees Celsius between the conductor surface and the ambient air temperature.

Remembering that the surface area of a 12 inch long cylinder = 12 * π * D and then substituting in equation (4.) gives:

(9.) $\mathbf{q_c = 0.376991 * D^{0.6} * \Delta T}$

This equation, again, is valid only for a 2 fps wind. As stated in section C.3 of IEEE Standard 605, an assumption of a 2 fps wind is a conservative, yet realistic approach, and it will be used in the examples given herein.

IEEE Standard 738 notes in section 2.6.1.2, "Since the wind velocity is greater than 0 ft/second, the forced convection heat loss for perpendicular wind is calculated according to equations [6a.] and [6b.] corrected for wind direction, and compared to the natural convection heat loss. The larger of the heat losses due to both natural and forced convection is then used in calculating the thermal rating."

[6a.] $\mathbf{q_{c1} = [\,1.01 + 0.371 * (3600\,D\,\rho_r\,V/\mu_r)^{0.52}\,] * k_f * (T_c - T_a)}$

[6b.] $\mathbf{q_{c2} = .1695 * (3600\,D\,\rho_r\,V/\mu_r)^{0.52} * k_f * (T_c - T_a)}$

where V = wind velocity in feet per second.

Taking this guidance leads to the conclusion that the proper method of calculating q_c is to use the specific equations for q_{c0}, q_{c1}, and q_{c2} and then pick the one yielding the greatest value. To recap, q_{c0} is the convective heat loss due to zero wind, and q_{c1} is the convective heat loss due to low wind velocity. The q_{c1} equation applies at low wind speeds, but gives values that are too low at high wind speeds. q_{c2} is the convective heat loss due to high wind speed. This equation gives values that are too low at low wind speeds. Hence the largest heat loss value is chosen.

In the spreadsheet, the following equations will be used for the calculations:

$$\mathbf{q_c = Maximum\ (\ q_{c0},\ q_{c1},\ and\ q_{c2}\ )}$$

$$\mathbf{q_{c0} = Equation\ (3.) = .283 * \rho_r^{0.5} * D^{0.75} * \Delta T^{1.25}\ watts/ft}$$

$$\mathbf{q_{c1} = Equation\ (6a.) = [\ 1.01 + 0.371*(\ 3600\ D\ \rho_r\ V/\mu_r)^{0.52}\ ] * k_f * (T_c - T_a)\ watts/ft}$$

$$\mathbf{q_{c2} = Equation\ (6b.) = .1695 * (3600\ D\ \rho_r\ V/\mu_r)^{0.52} * k_f * (T_c - T_a)\ watts/ft}$$

The tables below compares the values of q_c obtained for a 2 fps wind speed using the equations of IEEE Standard 605 and the Task Force's spreadsheet for various diameter pipes.

6" Diameter Pipes

Tc	Ta	q_c 605	q_c spreadsheet	605/spreadsheet
60	40	22.09	21.29	3.77%
80	40	44.19	42.34	4.36%
100	40	66.28	63.16	4.94%
120	40	88.37	83.78	5.48%
150	40	121.51	114.36	6.26%
180	40	154.65	144.46	7.06%

4" Diameter Pipes

Tc	Ta	q_c 605	q_c spreadsheet	605/spreadsheet
60	40	17.32	16.70	3.73%
80	40	34.64	33.20	4.35%
100	40	51.97	49.52	4.94%
120	40	69.29	65.69	5.48%
150	40	95.27	89.66	6.26%
180	40	121.26	113.34	6.98%

2” Diameter Pipes

Tc	Ta	q_c 605	q_c spreadsheet	605/spreadsheet
60	40	11.43	11.09	3.05%
80	40	22.86	22.15	3.19%
100	40	34.29	33.19	3.30%
120	40	45.71	44.22	3.38%
150	40	62.86	60.76	3.45%
180	40	80.00	77.28	3.52%

In conclusion, the q_c calculation in the spreadsheet gives q_c values that are between 3% and 7% lower than those calculated by the formula of IEEE Standard 605. The practical impact of these upon conductor ampacity is minimal, as shown in the tables below. These tables compare the spreadsheet against the values in IEEE Standard 605, Table B.3 for schedule 40 aluminum (6063 alloy – 53.0 % conductivity) tubular bus at a 40^{o}C ambient at sea level. The small differences are attributable to rounding errors, errors due to curve fitting to data in the standard, and unavailability of the actual conductor constants that were used in preparing the original tables.

6” Diameter Pipes

	Conductor Temperature					
Size	**80^{o}C**	**90 ^{o}C**	**100 ^{o}C**	**110 ^{o}C**	**140 ^{o}C**	**150 ^{o}C**
6” from 605	3771	4435	5003	5506	6382	7144
6” spdsht	3876	4506	5047	5528	6366	7096
Difference	**105 amps**	**71 amps**	**44 amps**	**22 amps**	**-16 amps**	**-48 amps**

4” Diameter Pipes

	Conductor Temperature					
Size	**80^{o}C**	**90 ^{o}C**	**100 ^{o}C**	**110 ^{o}C**	**140 ^{o}C**	**150 ^{o}C**
4” from 605	2534	2954	3315	3535	4192	4675
4” spdsht	2589	2990	3335	3642	4176	4640
Difference	**55 amps**	**46 amps**	**20 amps**	**7 amps**	**-16 amps**	**-35 amps**

2” Diameter Pipes

	Conductor Temperature					
Size	**80^{o}C**	**90 ^{o}C**	**100 ^{o}C**	**110 ^{o}C**	**140 ^{o}C**	**150 ^{o}C**
2” from 605	1217	1402	1561	1703	1949	2161
2” spdsht	1235	1413	1566	1702	1942	2150
Difference	**18 amps**	**11 amps**	**5 amps**	**-1 amp**	**-7 amps**	**-11 amps**

4.3.2.2. Forced Convection for Flat Surfaces

IEEE Standard 605, section C.3.2.1 gives the following equation for the total heat transfer (in watts/ft) due to forced convection when air flows parallel to and over a flat planar surface:

$$q_c = 0.00367 hA\Delta T$$

where

q_c = convection losses, watts/ft

h = heat transfer coefficient, BTU/hr °F ft^2

A = area of flat surfaces, square inches/linear foot

ΔT = temperature difference between the surface of the conductor and surrounding air, °C

The heat transfer coefficient, *h*, is given by the following equation:

$$h = 0.66(L v \rho_a / \mu)^{-1/2} (C_\rho \, \mu / k)^{-2/3} (C_\rho v \rho_a)$$

where

L = length of flow path over conductor (normally the width or thickness) in feet

v = air velocity, feet/hour

ρ_a = density of air, lb/cubic ft

μ/ρ_a = kinematic viscosity, ft^2/sec

C_ρ = heat capacity of air, BTU/lb-°F

k = thermal conductivity of air, BTU/hr-ft^2-°F

$C_\rho \mu/k$ = Prandtl number of air (dimensionless)

μ = viscosity of air, lb/ft-sec

According to IEEE Standard 605, the formula above for q_c "applies to air flow parallel to the surface. Outdoor air flow is seldom unidirectional and cannot always be parallel to the surface. However, it is assumed that air circulating around the conductor will be in more turbulent flow and provide on the average greater heat transfer that would be calculated using the … equation" for q_c given. This equation "must be applied to each surface of the conductor."

For multiple bars or angles, facing surfaces are treated as shielded from forced convection, being separated by about one thickness of the bar or angle, with natural convection being applied to those surfaces.

5.0 Emissivity and Absorptivity

For all ampacity calculations within this guide, the emissivity and absorptivity of rigid bus conductors are considered to be equal. The values used for emissivity and absorptivity for copper bus are 0.85 and for aluminum bus are 0.50. These values are typical after extended outdoor exposure resulting in weathered conductors and are in alignment with IEEE Standard 605.

The values of emissivity and absorptivity used in the original PJM document for tubular bus were based upon tests made on stranded aluminum conductors. As stated above, the task force has chosen to utilize the values for emissivity and absorptivity from IEEE Standard 605. These changes have a small impact on the ampacity of the bus.

For stranded aluminum and copper conductors used in a substation, an emissivity value of 0.7 and an absorptivity value of 0.9 will be used for both materials. These values are based on the 1973 study titled *"Determination of Bare Overhead Conductor Ratings"* and are identical to the values used in the previous tubular bus rating guide.

6.0 Maximum Conductor Temperature Limitations

Maximum conductor temperature limitations are based on different criteria for the various types and applications of the conductors treated in this guide. For stranded conductors under tension, the loss of tensile strength (annealing) due to high operating temperatures is a major factor in limiting maximum conductor temperature. For rigid conductor maximum span length designs, annealing may be an issue due to the loss of bending strength. For stranded conductors in low-tension applications, such as leads to circuit breaker or transformer bushings or to switch terminals, annealing is not an issue, but rather the maximum temperature limits of the bushings or switch terminals may dictate the maximum conductor temperature limits.

ECAR (East Central Area Reliability) reports 74-TFP-37, "*Transmission Conductors Loss of Strength Due To Elevated Temperature"*, and 74-EEP-42, "*A Uniform Method For the Determination of Load Capability of Line Terminal Equipment,*" and IEEE 605-2008, "IEEE Guide for Bus Design in Air Insulated Substations," have all been used to assist the task force in selecting the recommendations for substation conductor maximum operating temperatures.

The annealing process causes a loss of the conductor strength, which occurs whenever the conductor is exposed to elevated temperature operation for a period of time. After a conductor is operated at an elevated temperature, there is no recovery of the amount of strength lost when the conductor is allowed to cool. Additional loss of strength from subsequent heating cycle will begin with the loss established by the previous heating cycle and will continue to accumulate as long as the elevated temperatures exist. The amount of loss of strength will increase rapidly under extreme emergency operating conditions and can be calculated if sufficient information on the conductor materials and operating history is available with respect to temperatures.

6.1.Stranded Conductors Under Tension

In choosing maximum operating temperatures for stranded conductors under tension, it is important to choose values that will not cause significant reduction in the conductors' mechanical strength or life. Many studies have been performed to determine the temperatures at which conductors can operate without loss of strength or life, the results of which are reported in documents such as the ECAR reports cited above.

ECAR report 74-TFP-37 provides a method for performing loss of strength calculations for stranded conductors. Conductor loss of strength is a function of the conductor temperature and the duration of time the conductor is at that temperature. For stranded conductors, factors considered in the determination of conductor loss of strength include the loss of strength factor, the strength ratio of conductor components, the strength adjustment due to stranding or cabling factor, and the adjustment to test strand data. The loss of strength factor is a percent loss of strength of test strands taken from suppliers' data. The ratios of the strength of each component part of a cable to the total strength of the cable are given in ECAR report 74-TFP-37, and reflect the composite effect of the rated strength of strands, cabling reduction, and metal proportions. The cabling process reduces the effective strength of the individual components of the cable relative to the sum of the individual strands. This factor is given by ASTM standards. The adjustment to test strand factor is needed since the entire cable is composed of strands that may not be of identical type and strength. The initial strength of strands is a function of the cold drawing process at the wire mill. The final strength in the fully annealed state is related only to the metal alloy. Consequently, the portion of the initial strength that can be lost through annealing will be greater for the higher strength strands than for the lower strength strands.

The conductor temperature limitations chosen by the task force are based on ECAR report 74-EEP-42, except for stranded copper, as noted in the next paragraph. The temperature limits are based on the annealing characteristics of hard-drawn copper and two representative aluminum conductor materials. The maximum normal conductor temperatures chosen are based on a normal temperature limit at which operation will result in no reduction of conductor strength.

It is important to note that most strain buses in substations are not strung at tensions comparable to tensions typically used on transmission lines. This is primarily because the spans are usually not as long in a substation bus as in a transmission line. Therefore, for copper conductors, the task force chose higher temperature limitations than those recommended in the ECAR documents.

The recommended maximum normal operating temperatures for conductors under strain are 90°C for copper wire and 105°C for aluminum wire (AAC, AAAC, ACAR, and ACSR). The recommended maximum 24 hour conductor emergency operating temperatures are based on a temperature limit at which operation at this temperature for 24 hours will rarely result in more than one percent loss of strength. (As explained in the previous paragraph, a slightly greater amount of loss of strength may be tolerated for copper.) The recommended maximum emergency 24 hour operating temperatures are 100°C for copper wire and 130°C for aluminum wire of all types. The recommended maximum one hour conductor emergency operating temperatures are based on a temperature limit at which operation at this temperature for one hour will rarely result in more than one percent loss of strength. The emergency one hour operating temperatures chosen are 110°C for copper wire and 140°C for aluminum wire.

A ten to fifteen percent loss of initial conductor tensile strength over the lifespan of the conductor is considered to be the limit for maintaining safe mechanical integrity of the conductor.

6.2.Rigid Conductors

The maximum normal recommended operating temperature for rigid copper and aluminum conductors (i.e., pipe, bar, and angle) is 90°C, based on IEEE 605-2008, Section 8.2.1. (Note that this task force feels the statement in this same IEEE 605 section concerning excessive oxidation of copper that may occur if operated above 80°C should not normally be a concern in substation applications.) The maximum 24 hour conductor emergency operating temperature is 115°C. The maximum one hour conductor emergency operating temperature is 130°C. These temperatures are the same as those used for pipe in the previous version of this document.

6.3.Stranded Conductors in Non-Strain Applications

The recommended maximum normal operating temperature chosen for stranded conductors under no strain is 130°C for all copper and aluminum conductor types. The recommended maximum 24 hour conductor emergency operating temperature is the same as the recommended normal operating temperature, due to the concern of exceeding the limit of observable temperature rise of connected equipment due to conductive heat transfer from the conductor. The maximum one hour conductor emergency operating temperature is 140°C. In all cases, care should be taken to ensure that the recommended limits of observable temperature rise of connected equipment are not exceeded.

7.0 Conductor Materials

Copper and aluminum are the main basic materials used in commercial manufacturing of most types of electrical conductors for current carrying applications in electric power systems.

Conductivity standards of copper (percent International Annealed Copper Standard (IACS)[1]) apply to pure copper in the annealed or unrestrained condition, for as the metal is cold worked its resistance is increased and conductivity decreased. The cold working of copper greatly increases its ultimate tensile strength. Likewise, greater strength is obtained if certain alloying ingredients are added, but its conductivity is decreased. Commercial hard drawn copper conductor is considered as having conductivity ranging between 97%-99% IACS.

Pure aluminum has an electrical conductivity of 65% IACS. Commercial high-purity aluminum alloys such as 1350, 6063, and 6061 are the forms of aluminum most widely used for electrical conductors. They have a conductivity of approximately 61, 55, and 43 % IACS respectively. Again, greater strength is obtained if certain alloying ingredients are added, but its conductivity is decreased. Aluminum conductors are manufactured to meet appropriate ASTM (American Society for Testing and Materials) specifications.

In general, a high strength metallic alloy can only be produced at the expense of conductivity. Conversely, a high conductivity metallic alloy can only be produced at the expense of high strength. Improvement of strength may be achieved by: addition of alloying elements, cold working, or heat treatment (i.e., temper).

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[1] ***Note*** : International Annealed Copper Standard (IACS) – In 1913 the International Electro-Technical Commission established an annealed copper standard (IACS) which in terms of weight resistivity specifies the resistance of a copper wire one meter long that weighs one gram. The reference temperature is taken to be at 20ºC.

8.0 Other Considerations

The purpose of this document is to define the ampacity rating method to be used for substation conductors. It is not intended to be a comprehensive bus design standard. Other elements of bus design are the responsibility of the design engineer. Some of the other elements that need to be considered are described below:

8.1. Connections to Station Equipment

Bus ratings within this document are based on maximum allowable conductor temperatures over the specified time period to prevent significant loss of conductor strength. It is important to recognize that the heat generated by a bus conductor may be conducted to any attached equipment. While fittings and connectors often act as heat sinks and can dissipate heat generated by the bus, equipment temperature limitations must be considered to insure proper bus design. Equipment temperature limitations should be obtained from the applicable specification or equipment manufacturer.

8.2. Thermal Expansion

Bus conductors expand and contract as their temperature changes. This expansion and contraction, if not properly designed for, can induce significant loadings on bus supports. For long bus spans, provisions should be made to allow for expansion and contraction of bus conductors over the operating temperature range through the use of expansion fittings.

8.3. De-rating of Parallel Busses or Conductors

All ratings within this guide apply to bus configuration with one conductor per phase and sufficient spacing between phases as to not impact the conductor rating. When more than one conductor per phase is used and the conductors are in close proximity, the conductors' ability to radiate heat is reduced. Consequently, the ampacity of the bus conductor is reduced. In these situations an appropriate ampacity rating reduction should be taken.

8.4. Uneven Loading of Parallel Conductors

Parallel conductors are often used to increase the ampacity of a bus. Depending on their physical configuration, mutual inductance between conductors can result in an impedance imbalance and uneven loading. The uneven loading of parallel conductors should be considered when calculating the overall ampacity rating of the bus.

9.0 Fittings and Accessories

The 1979 PJM Tubular Bus Rating task force contacted several manufacturers and electric utility companies to determine the effect of elevated temperatures on bus fittings and accessories. Replies confirmed that properly installed bus fittings and accessories can be operated at temperatures up to 120°C without incurring either electrical or mechanical limitations. Several tests conducted by manufacturers showed that many conductor accessories operated at temperatures 50°C to 100°C lower than the conductor when operating at temperatures above 180°C. This property is mainly dependent on the large mass and surface area of the fittings. The current PJM Substation Bus Rating task force believes this information to still be valid or conservative. Overall, the quality of workmanship installing the fittings and accessories will directly affect the ability to operate at elevated temperatures. Therefore, it is imperative that fittings and accessories be properly installed in accordance with manufacturer's recommendations to insure the desired performance.

10.0 Rating Assumptions

Assumptions for Calculations shown in the results tables

Design Ambient Temperatures	35°C summer 10°C winter
Ambient Temperature Range	-15°C to 40°C
Wind Speed	2 Ft. per sec. (Normal & Emergency)
Wind Direction	90° to the conductor
Maximum allowable conductor Temp. range	70°C to 140°C (table 12-1, pg. 23)
Solar / Sky Radiated Heat Flux	Day Time / Clear
Elevation	1000 Ft. above sea level
Latitude	40° North Latitude
Sun Time	14:00 Hrs.

Maximum **normal** operating temperature[#]

Aluminum, rigid	90°C
Aluminum wire, strain	105°C
Aluminum wire, non-strain	130 °C
Copper, rigid	90°C
Copper wire, strain	90°C
Copper wire, non-strain	130 °C

Maximum **emergency** (up to 24 hours) operating temperature[#]

Aluminum, rigid	115°C
Aluminum wire, strain	130°C
Aluminum wire, non-strain	130 °C
Copper, rigid	115°C
Copper wire, strain	100°C
Copper wire, non-strain	130 °C

Maximum SHORT TERM (up to 1 hour) **emergency** operating temperature[#]

Aluminum, rigid	130°C
Aluminum wire, strain	140°C
Aluminum wire, non-strain	140 °C
Copper, rigid	130°C
Copper wire, strain	110°C
Copper wire, non-strain	140 °C

[#] Since heat generated in the bus conductor may be conducted to attached equipment, allowable conductor temperatures may be governed by the temperature limitations of the attached equipment. Equipment temperature limitations should be obtained from the applicable specification or equipment manufacturer.

11.0 Risk

As discussed previously, bus conductor ratings are affected by many factors. The most significant of these is wind speed. Unlike many of the other factors such as absorptivity, ambient temperature, conductor resistance, etc., wind speed is truly variable in magnitude and direction. In the early PJM work on transmission line conductors, summarized by the "Determination of Thermal Ratings for Bare Overhead Conductor, 1973", weather data was collected from Washington DC over a period of 16 years, and from Pittsburgh over a 10 year period. These data were pooled to represent a 26-year span of conditions in the PJM service territory. The weather data were summarized on pages A18 and A19 in the 1973 Report in a table format for the frequency distribution of wind and ambient temperature conditions. The tables are reprinted below. In these tables each row lists the probability of occurrence of a given wind speed at a specified ambient temperature. Alternately, each row gives the probability of occurrence of different ambient temperatures given the particular wind speed.

COMPOSITE WEATHER DATA
PITTSBURGH AND WASHINGTON, D.C.
PITTSBURGH 1/1/49 – 12/31/58 - 10 YEARS
NATIONAL AIRPORT 1/1/49 – 12/31/64 - 16 YEARS
TOTAL COMPOSITE HOURLY RECORD - 26 YEARS

FREQUENCY OF OCCURRENCE (PERCENT)

SUMMER DAYS

	WIND SPEED-KNOTS						
AMBIENT TEMP.°C	***0***	***1***	***2***	***3***	***4***	***5***	***OVER 5***
0	0.009	0.025	0.042	0.024	0.059	0.070	1.830
5	0.038	0.115	0.195	0.247	0.326	0.427	6.455
10	0.059	0.176	0.299	0.345	0.519	0.634	8.811
15	0.070	0.209	0.355	0.484	0.741	0.955	11.147
20	0.103	0.311	0.528	0.655	1.049	1.401	14.559
25	0.109	0.324	0.550	0.791	1.405	1.743	17.949
30	0.059	0.178	0.302	0.496	0.962	1.381	14.708
35	0.012	0.034	0.058	0.127	0.261	0.389	4.650
Over 35	0.000	0.001	0.001	0.003	0.009	0.010	0.187
Total	**0.459**	**1.373**	**2.330**	**3.172**	**5.331**	**7.010**	**80.296**

SUMMER NIGHTS

	WIND SPEED-KNOTS						
AMBIENT TEMP.°C	***0***	***1***	***2***	***3***	***4***	***5***	***OVER 5***
0	0.031	0.090	0.153	0.114	0.248	0.271	2.998
5	0.125	0.373	0.632	0.659	0.921	1.135	8.495
10	0.174	0.524	0.887	0.987	1.340	1.453	10.003
15	0.257	0.773	1.312	1.174	1.654	2.089	11.975
20	0.351	1.020	1.730	1.582	2.254	2.600	13.952
25	0.236	0.711	1.207	1.671	2.205	2.582	12.846
30	0.037	0.112	0.188	0.342	0.426	0.516	2.490
35	0.000	0.001	0.002	0.006	0.013	0.011	0.064
Over 35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**1.211**	**3.604**	**6.111**	**6.535**	**9.061**	**10.657**	**62.823**

Note: Data is taken from page A-18 of 1973 PJM Report, "Determination of Thermal Ratings for Bare Overhead Conductors".

COMPOSITE WEATHER DATA
PITTSBURGH AND WASHINGTON, D.C.
PITTSBURGH 1/1/49 – 12/31/58 - 10 YEARS
NATIONAL AIRPORT 1/1/49 – 12/31/64 - 16 YEARS
TOTAL COMPOSITE HOURLY RECORD - 26 YEARS

FREQUENCY OF OCCURRENCE (PERCENT)

WINTER DAYS

	WIND SPEED-KNOTS						
AMBIENT TEMP.°C	***0***	***1***	***2***	***3***	***4***	***5***	***OVER 5***
0	0.105	0.321	0.541	0.751	1.315	1.649	22.146
5	0.233	0.695	1.184	1.633	2.380	2.912	31.418
10	0.118	0.354	0.600	0.875	1.079	1.351	16.749
15	0.046	0.134	0.230	0.282	0.344	0.433	7.302
20	0.007	0.023	0.039	0.062	0.062	0.082	2.164
25	0.000	0.000	0.000	0.003	0.000	0.003	0.348
30	0.000	0.000	0.000	0.000	0.000	0.000	0.007
35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Over 35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**0.509**	**1.527**	**2.594**	**3.606**	**5.180**	**6.430**	**80.134**

WINTER NIGHTS

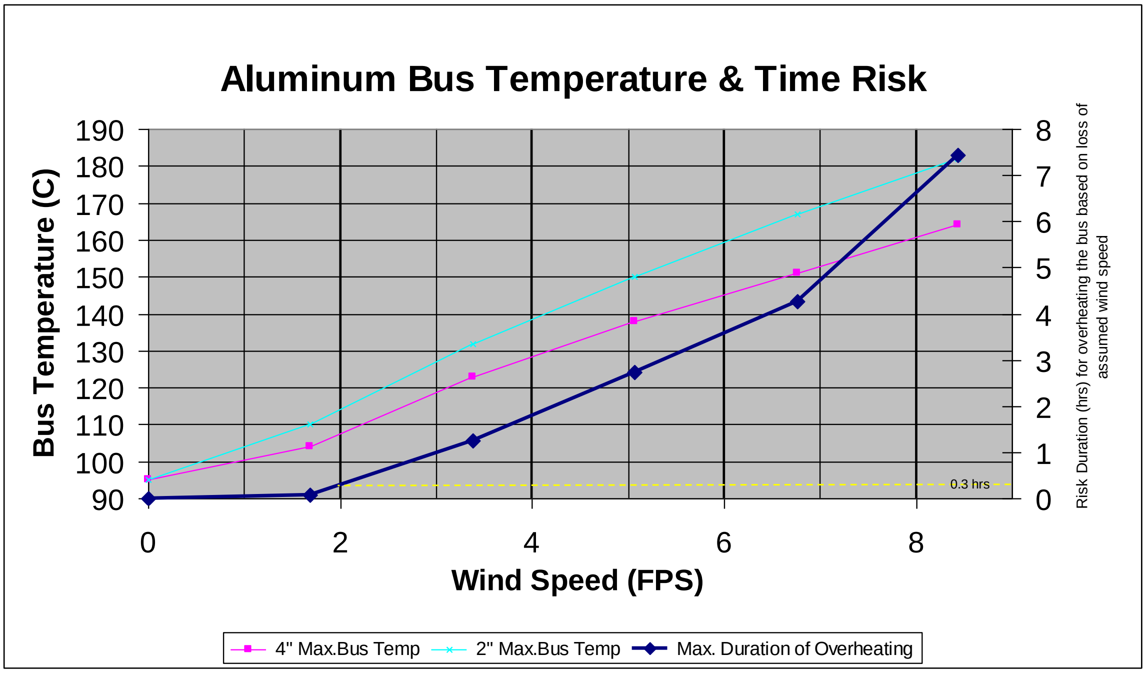
	WIND SPEED-KNOTS						
AMBIENT TEMP.°C	***0***	***1***	***2***	***3***	***4***	***5***	***OVER 5***
0	0.287	0.856	1.453	1.581	2.709	3.038	27.265
5	0.450	1.345	2.282	2.778	3.286	3.592	28.548
10	0.136	0.411	0.791	0.709	0.884	1.073	10.873
15	0.023	0.078	0.132	0.151	0.213	0.190	3.953
20	0.004	0.008	0.016	0.004	0.012	0.012	0.918
25	0.000	0.000	0.000	0.000	0.000	0.000	0.008
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Over 35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**0.900**	**2.698**	**4.674**	**5.223**	**7.104**	**7.905**	**71.565**

Note: Data is taken from page A-19 of 1973 PJM Report, “Determination of Thermal Ratings for Bare Overhead Conductors”.

When rating bus conductors, the choice of wind speed used is important due to the significant effect on the rating. While a higher wind speed is desired for the higher rating, there is a cost. What happens if the wind speed that actually occurs at the substation is less than the assumed value? As the original PJM work showed, the wind speed is characterized by a distribution of wind speeds with higher and lower values. A wind speed lower than assumed would result in a higher bus temperature than designed. For example, if a rating were based upon 100°C with 2 feet/sec. of wind and a lesser wind were to occur it would cause an increase in conductor temperature to a temperature above 100°C. The risk due to the magnitude of the over temperature condition is called temperature risk.

The duration of these lower wind speeds is also of concern. The acceptability of a particular temperature risk changes with the duration of that risk. For example, while a temperature overrun of 25°C would not be of major concern for 5 minutes, it would be more problematic if it were for 6 hours during mid-day. The risk due to the duration of the over temperature condition is called time risk.

The figure shown below illustrates these risks. On the horizontal axis are listed the wind speeds that could be used for the basis of a bus rating. On the left vertical axis are the bus temperatures that would result if the assumed wind conditions were not achieved. On the right are the durations for the wind speeds at or less than the rated values. For example with a rating of a section of 2" aluminum bus based upon 90°C and a wind speed of 2 feet per second, for times when the wind speed drops below 2 fps, the bus could rise in temperature up to approximately 115°C and may experience overheating above 90°C for about 0.25% of the time.



From this chart it can be seen that the magnitude of over temperature condition is higher with small bus sizes, and reduced with large bus sizes. Additionally, it can be seen that the duration of an over temperature condition does not vary by bus size.

While the original PJM transmission line work evaluated these risks and developed a reasonable approach to manage these risks using normal ratings based upon 0 knots of wind, this approach is not applicable for substation bus conductor. It is not appropriate for substation ratings because transmission conductors are often sag limited. The maximum sags are controlled by operating and legal limitations. For substation bus, sag limitations do not typically exist, but thermal expansion issues and loss of mechanical strength is of concern.

11.1 Normal Ratings

The task force recommends normal ratings based upon 2 fps at normal bus operating temperatures of 90°C for rigid aluminum, 105°C for aluminum wire in strain, 90°C for rigid copper, and 90°C for copper wire in strain. These temperatures have been chosen to generally mitigate loss of mechanical strength of the aluminum or copper conductors through annealing. (Higher temperatures were chosen for aluminum and copper wire in non-strain applications, where loss of strength is normally not an issue.) This philosophy includes an inherent temperature risk of overheating that can be quantified. For example, 4" schedule 80, 6063 aluminum bus has a proposed summer normal rating of 3713 amperes. This is based on a 35°C ambient temperature, a wind of 2 fps, and a bus operating temperature of 90°C. If during this period the wind speed were to fall to zero, then the bus temperature would rise due to the decrease in heat loss from the bus. In this case the bus temperature would rise to approximately 108°C. This represents a temperature risk of 18°C. While this may be relatively small, ratings based upon higher wind speeds will have commensurately higher temperature risk. The substation designer must consider the magnitude of temperature risk when designing for expansion and contraction of the bus over the wide range of possible operating temperatures. The temperature risk will change with changes in bus conductor size.

Once the temperature risk has been evaluated, the next logical question is how long will this over temperature condition exist. There are discrete probabilities that exist for weather conditions that will cause an overheated conductor based upon the assumed conditions. For a summer time assumed ambient temperature of 35°C and a wind speed of 2 fps, there is a possibility that the ambient temperature could actually be higher than 35°C and winds at or below 2 fps. From the composite weather figures shown earlier, it is possible to calculate the joint probability of summer daytime temperatures above 35°C and wind speeds of 2 fps. It is also possible to calculate the joint probabilities of occurrence for lesser wind speeds and ambient temperature combinations that result in bus overheating. These probabilities can then be summed to calculate the total probability of bus overheating for an assumed set of ambient conditions such as 35°C and 2 fps of wind. For the 4" aluminum bus described above, this calculation summing probabilities result in any bus overheating above 90°C yields a 0.3% duration of risk for summer daylight hours. Assuming 15 daylight hours per day in the summer time, and 180 days of summertime rating, this equates to 8 hours of risk per year.

Therefore, the bus conductor could be expected to overheat by up to 18°C for up to 0.3% of the time or about 8 hours per summer. This quantifies the magnitude of temperature and time risk in this example. In reality the probability is small of the bus operating at the rated load concurrently and with less than assumed wind.

Based on this type of analysis, it is possible to calculate the cumulative time and temperature risk for a 40 year expected lifetime of substation bus, and use these results to make a judgment about any concerns of loss of bus strength due to annealing. The task force believes the time and temperature risk in the magnitude depicted in this example does not represent a significant design concern for the substation bus conductor. The substation designer must make this evaluation for each individual substation design to determine what maximum operating temperature to utilize.

11.2 Emergency Ratings

Emergency ratings are provided for abnormal out of configuration system conditions. The duration of emergency conditions is much shorter, and based upon previous PJM work on transmission line conductors; PJM assumes emergency operations could exist for up to 4 hours per year. This is also a reasonable assumption for substation bus conductors. To help manage abnormal conditions, emergency ratings with durations of 24 hours and 1 hour are provided by this document.

While there is some non-zero additional time and temperature risk that is accumulated by emergency operation, the various emergency operating temperatures ($100^{o}C$, $115^{o}C$ and $130^{o}C$) do not significantly increase loss of strength from annealing above the values previously described because the duration of temperatures above normal operating temperatures are small in the overall bus lifespan. The concern with emergency operations at high temperature becomes the adequate management of the expansion of the bus. Emergency rating periods are not to exceed 24 hours.

12.0 PJM Method Comparison

In the previous sections, the task force has detailed the changes recommended in the method and parameters for the calculation of substation bus conductor ratings.

Table 12-1 summarizes the changes in input parameters and provides a qualitative impact to the ratings for the change. The effect of any change in individual parameter should not be considered excessively, but the cumulative effect of all of the changes needs to be evaluated.

Table 12-2 summarizes the effective changes in ratings for 3 sizes of aluminum tubular bus between the original PJM ratings and the proposed ratings recommended in this document. It can be seen from the table that while the new ratings generally show an increase in capability when compared to the original PJM ratings, the table shows that there is a reduction in rating by between 5% and 8% for summer emergency conditions. The task force generally believes this reduction to be tolerable for a number of reasons. Firstly, some utility companies utilize the normal ratings for both normal and emergency conditions which render this concern meaningless. Second, some utility companies utilize a lower bus design temperature which provides a lower rating and therefore eliminates the concern.

The task force believes that there will be an inherent variance between any old method and a new one due to rounding issues, and variability in the bus resistance and temperature values. As a result of these alone, the task force believes that ratings that are within a few percent tolerance essentially represent identical ratings. As a result, the 5% to 8% reduction shown for summer emergency conditions in Table 12-2 are not only negligible, but more conservative.

Table 12-1
PJM Substation Bus Conductor Ampacity Parameter Summary

Parameter		Original PJM Value	New PJM Value	Resultant Effect on Ampacity
Wind Speed	Normal	0 fps	2 fps	Increase
	Emergency	3.38 fps	2 fps	Decrease
Summer Ambient	Normal	35°C	35°C	No change
	Emergency	20°C	35°C	Decrease
Winter Ambient	Normal	20°C	10°C	Increase
	Emergency	10°C	10°C	No change
Emissivity	All	0.7	0.5	Decrease
	Cu	0.7	0.85	Increase
Absorptivity	All	0.9	0.5	Increase
	Cu	0.9	0.85	Increase
Atmosphere Clarity		Clear	Clear	No change
Normal Operating Temperature	Al Rigid	90°C	90°C	No change
	Al Wire, Strain	105°C	105°C	No change
	Al Wire, Non-Strain	105°C	130°C	Increase
	Cu Rigid	90°C	90°C	Increase
	Cu Wire, Strain	75°C	90°C	Increase
	Cu Wire, Non-Strain	75°C	130°C	Increase

Table 12-1 (cont'd)
PJM Substation Bus Conductor Ampacity Parameter Summary

Parameter		Original PJM Value	New PJM Value	Resultant Effect on Ampacity
24 Hour Emergency Operating Temperature	Al Rigid	115°C	115°C	No change
	Al Wire, Strain	130°C	130°C	No change
	Al Wire, Non-Strain	130°C	130°C	No change
	Cu Rigid	115°C	115°C	No change
	Cu Wire, Strain	95°C	115°C	Increase
	Cu Wire, Non-Strain	95°C	100°C	Increase
24 Hour Emergency Operating Temperature	Al Rigid	130°C	130°C	No change
	Al Wire, Strain	140°C	140°C	No change
	Al Wire, Non-Strain	140°C	140°C	No change
	Cu Rigid	140°C	140°C	No change
	Cu Wire, Strain	130°C	130°C	No change
	Cu Wire, Non-Strain	140°C	140°C	Increase

* Operating temperatures were selected by individual utility companies in the range of 70°C to 120°C

Table 12-2
PJM Substation Bus Conductor Rating Comparison Table

Bus Size	Rating Condition	Original PJM (Amperes) *(See Note Below)*	New PJM Ratings (Amperes)	Change
2" Aluminum Sch. 40 6061 Alloy	Summer Normal	1170	1313	+12%
	Summer Emergency <24 Hrs.	1740	1623	**-7%**
	Summer Emergency <1 Hr.	1855	1781	**-4%**
	Winter Normal	1345	1614	+20%
	Winter Emergency <24 Hrs.	1855	1860	0%
	Winter Emergency <1 Hr.	1855	1991	+7%
4" Aluminum Sch. 40 6061 Alloy	Summer Normal	2620	2783	+6%
	Summer Emergency <24 Hrs.	3665	3477	**-5%**
	Summer Emergency <1 Hr.	4030	3829	**-5%**
	Winter Normal	3015	3434	+14%
	Winter Emergency <24 Hrs.	3910	3989	+2%
	Winter Emergency <1 Hr.	4030	4285	+6%
5" Aluminum Sch. 40 6061 Alloy	Summer Normal	3340	3479	+4%
	Summer Emergency <24 Hrs.	4585	4365	**-5%**
	Summer Emergency <1 Hr.	5135	4816	**-6%**
	Winter Normal	3840	4298	+12%
	Winter Emergency <24 Hrs.	4890	5008	+2%
	Winter Emergency <1 Hr.	5135	5387	+5%

Note: The original PJM ratings published in the "Determination of Ratings for Tubular Bus" dated 1979 establish bus conductor ratings based upon a bus conductor design temperature ranging between 70°C and 120°C. The ratings shown in the table above are based on 90°C and represent typical values used. Individual substation owners may currently use different ratings due to the use of a different design temperature.

Table 12-2 (cont'd)
PJM Substation Bus Conductor Rating Comparison Table

Bus Size	Rating Condition	Original PJM (Amperes) *(See Note Below)*	New PJM Ratings (Amperes)	Change
2" Aluminum Sch. 40 6063 Alloy	Summer Normal	1310	1473	+12%
	Summer Emergency <24 Hrs.	1950	1808	**-7%**
	Summer Emergency <1 Hr.	2085	1977	**-5%**
	Winter Normal	1505	1811	+20%
	Winter Emergency <24 Hrs.	2080	2073	0%
	Winter Emergency <1 Hr.	2085	2211	+6%
4" Aluminum Sch. 40 6063 Alloy	Summer Normal	2940	3122	+6%
	Summer Emergency <24 Hrs.	4115	3872	**-6%**
	Summer Emergency <1 Hr.	4555	4248	**-7%**
	Winter Normal	3380	3852	+14%
	Winter Emergency <24 Hrs.	4385	4443	+1%
	Winter Emergency <1 Hr.	4555	4754	+4%
5" Aluminum Sch. 40 6063 Alloy	Summer Normal	3740	3899	+4%
	Summer Emergency <24 Hrs.	5135	4857	**-5%**
	Summer Emergency <1 Hr.	5825	5338	**-8%**
	Winter Normal	4300	4817	+12%
	Winter Emergency <24 Hrs.	5475	5572	+2%
	Winter Emergency <1 Hr.	5825	5971	+3%

Note: The original PJM ratings published in the "Determination of Ratings for Tubular Bus" dated 1979 establish bus conductor ratings based upon a bus conductor design temperature ranging between 70^{o}C and 120^{o}C. The ratings shown in the table above are based on 90^{o}C and represent typical values used. Individual substation owners may currently use different ratings due to the use of a different design temperature.

Table 12-2 (cont'd)
PJM Substation Bus Conductor Rating Comparison Table

Bus Size	Rating Condition	Original PJM (Amperes) *(See Note Below)*	New PJM Ratings (Amperes)	Change
2" Aluminum Sch. 80 6061 Alloy	Summer Normal	1370	1539	+12%
	Summer Emergency <24 Hrs.	2040	1902	**-7%**
	Summer Emergency <1 Hr.	2175	2087	**-4%**
	Winter Normal	1575	1892	+20%
	Winter Emergency <24 Hrs.	2175	2180	0%
	Winter Emergency <1 Hr.	2175	2334	+7%
4" Aluminum Sch. 80 6061 Alloy	Summer Normal	3075	3263	+6%
	Summer Emergency <24 Hrs.	4305	4070	**-5%**
	Summer Emergency <1 Hr.	4980	4479	**-10%**
	Winter Normal	3540	4025	+14%
	Winter Emergency <24 Hrs.	4590	4669	+2%
	Winter Emergency <1 Hr.	4980	5012	+1%
5" Aluminum Sch. 80 6061 Alloy	Summer Normal	3955	4115	+4%
	Summer Emergency <24 Hrs.	5425	5159	**-5%**
	Summer Emergency <1 Hr.	6495	5689	**-12%**
	Winter Normal	4545	5084	+12%
	Winter Emergency <24 Hrs.	5785	5918	+2%
	Winter Emergency <1 Hr.	6495	6364	**-2%**

Note: The original PJM ratings published in the "Determination of Ratings for Tubular Bus" dated 1979 establish bus conductor ratings based upon a bus conductor design temperature ranging between 70^{o}C and 120^{o}C. The ratings shown in the table above are based on 90^{o}C and represent typical values used. Individual substation owners may currently use different ratings due to the use of a different design temperature.

Table 12-2 (cont'd)
PJM Substation Bus Conductor Rating Comparison Table

Bus Size	Rating Condition	Original PJM (Amperes) *(See Note Below)*	New PJM Ratings (Amperes)	Change
2" Aluminum Sch. 80 6063 Alloy	Summer Normal	1530	1722	+13%
	Summer Emergency <24 Hrs.	2280	2112	**-7%**
	Summer Emergency <1 Hr.	2435	2308	**-5%**
	Winter Normal	1760	2116	+20%
	Winter Emergency <24 Hrs.	2435	2421	**-1%**
	Winter Emergency <1 Hr.	2435	2581	+6%
4" Aluminum Sch. 80 6063 Alloy	Summer Normal	3445	3713	+8%
	Summer Emergency <24 Hrs.	4815	4617	**-4%**
	Summer Emergency <1 Hr.	5575	5072	**-9%**
	Winter Normal	3960	4580	+16%
	Winter Emergency <24 Hrs.	5135	5296	+3%
	Winter Emergency <1 Hr.	5575	5676	+2%
5" Aluminum Sch. 80 6063 Alloy	Summer Normal	4420	4586	+4%
	Summer Emergency <24 Hrs.	6065	5693	**-6%**
	Summer Emergency <1 Hr.	7265	6244	**-14%**
	Winter Normal	5080	5665	+12%
	Winter Emergency <24 Hrs.	6470	6530	+1%
	Winter Emergency <1 Hr.	7265	6984	**-4%**

Note: The original PJM ratings published in the "Determination of Ratings for Tubular Bus" dated 1979 establish bus conductor ratings based upon a bus conductor design temperature ranging between 70°C and 120°C. The ratings shown in the table above are based on 90°C and represent typical values used. Individual substation owners may currently use different ratings due to the use of a different design temperature.

Appendix A

Instructions for using PJM Bus Conductor Ratings Spreadsheet

This Excel Program is designed to generate ratings for Substation Bus conductors following the methodology defined in IEEE 605. This spreadsheet was originally produced for round shape conductors by the first PJM Substation Bus Conductor Task Force. The bar and angle shapes are now included in the latest revision of the Substation Bus Conductors Ratings Spreadsheet.

- Open the spreadsheet and select the desired conductor **Shape**. Then choose the correct combination of options from the dropdown bar on the right.

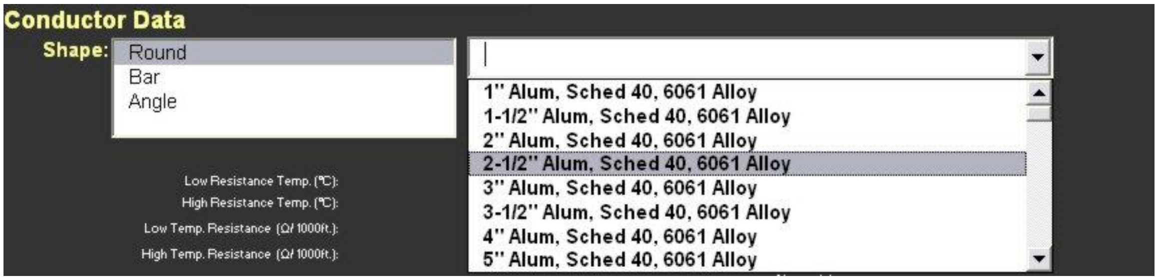
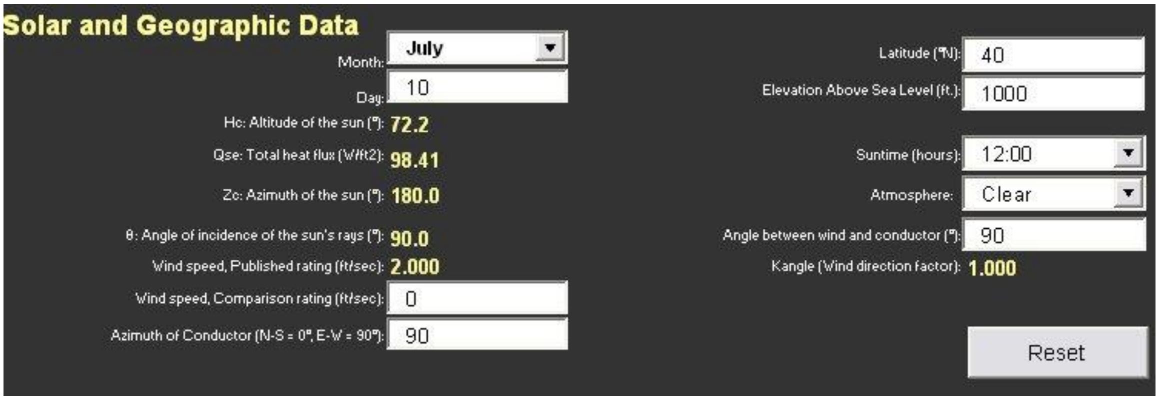


Figure 1: Bus Conductor Rating Program

- Review the month, day, time and atmospheric conditions parameters. The spreadsheet defaults to the PJM values. Adjust parameters as required.



Solar and Geographic Data

Month: July
Day: 10
Hc: Altitude of the sun (°): 72.2
Qse: Total heat flux (W/ft2): 98.41
Zc: Azimuth of the sun (°): 180.0
θ: Angle of incidence of the sun's rays (°): 90.0
Wind speed, Published rating (ft/sec): 2.000
Wind speed, Comparison rating (ft/sec): 0
Azimuth of Conductor (N-S = 0°, E-W = 90°): 90
Latitude (°N): 40
Elevation Above Sea Level (ft.): 1000
Suntime (hours): 12:00
Atmosphere: Clear
Angle between wind and conductor (°): 90
Kangle (Wind direction factor): 1.000

__Figure 2: Calculation Set Up__

- While remaining on the main page, one can view the **Ratings at a Glance** table at the bottom right. This table populates as soon as the conductor shape and specifications have been selected.

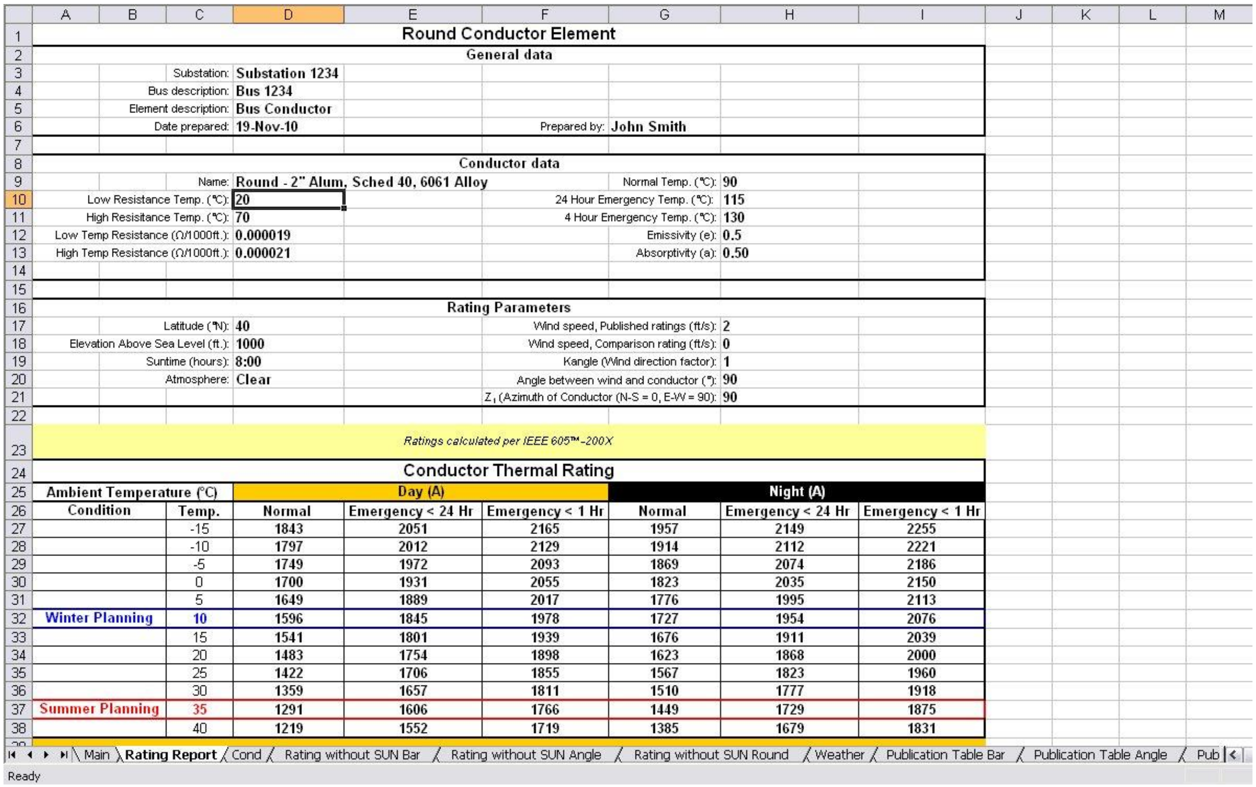
At a Glance Rating

Planning Rating (A)	Normal	Emergency 24 Hr	Emergency < 1 Hr
Summer Daytime	1291	1606	1766
Summer Nighttime	1449	1729	1875
Winter Daytime	1596	1845	1978
Winter Nighttime	1727	1954	2076

2 ft/sec

__Figure 3: Ratings at a Glance__

- To view the full ratings, navigate to the **Rating Report** page. It is the second tab, directly next to the main page.



Round Conductor Element

General data

Substation: Substation 1234
Bus description: Bus 1234
Element description: Bus Conductor
Date prepared: 19-Nov-10
Prepared by: John Smith

Conductor data

Name: Round - 2" Alum, Sched 40, 6061 Alloy
Low Resistance Temp. (°C): 20
High Resisitance Temp. (°C): 70
Low Temp Resistance (Ω/1000ft.): 0.000019
High Temp Resistance (Ω/1000ft.): 0.000021
Normal Temp. (°C): 90
24 Hour Emergency Temp. (°C): 115
4 Hour Emergency Temp. (°C): 130
Emissivity (e): 0.5
Absorptivity (a): 0.50

Rating Parameters

Latitude (°N): 40
Elevation Above Sea Level (ft.): 1000
Suntime (hours): 8:00
Atmosphere: Clear
Wind speed, Published ratings (ft/s): 2
Wind speed, Comparison rating (ft/s): 0
Kangle (Wind direction factor): 1
Angle between wind and conductor (°): 90
Z_1 (Azimuth of Conductor (N-S = 0, E-W = 90): 90

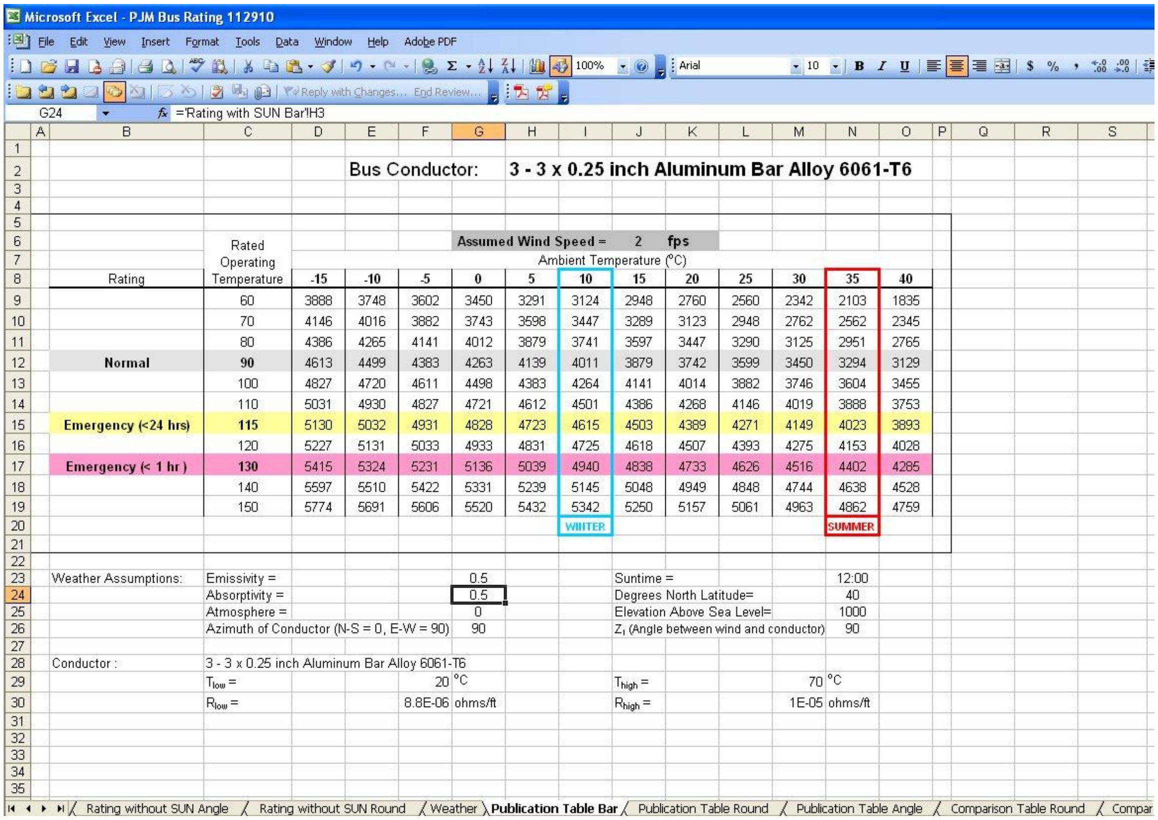
Ratings calculated per IEEE 605™-200X

Conductor Thermal Rating

Ambient Temperature (°C)		Day (A)			Night (A)		
Condition	Temp.	Normal	Emergency < 24 Hr	Emergency < 1 Hr	Normal	Emergency < 24 Hr	Emergency < 1 Hr
	-15	1843	2051	2165	1957	2149	2255
	-10	1797	2012	2129	1914	2112	2221
	-5	1749	1972	2093	1869	2074	2186
	0	1700	1931	2055	1823	2035	2150
	5	1649	1889	2017	1776	1995	2113
Winter Planning	10	1596	1845	1978	1727	1954	2076
	15	1541	1801	1939	1676	1911	2039
	20	1483	1754	1898	1623	1868	2000
	25	1422	1706	1855	1567	1823	1960
	30	1359	1657	1811	1510	1777	1918
Summer Planning	35	1291	1606	1766	1449	1729	1875
	40	1219	1552	1719	1385	1679	1831

Figure 4: Rating Report

- The eighth, ninth and tenth tabs contain **Publication Tables**. These ratings charts are shape specific, and are completely copy-ready for simple transfer into other documents.



Bus Conductor: **3 - 3 x 0.25 inch Aluminum Bar Alloy 6061-T6**

Assumed Wind Speed = 2 fps

Rating	Rated Operating Temperature	Ambient Temperature (°C)											
		-15	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	60	3888	3748	3602	3450	3291	3124	2948	2760	2560	2342	2103	1835
	70	4146	4016	3882	3743	3598	3447	3289	3123	2948	2762	2562	2345
	80	4386	4265	4141	4012	3879	3741	3597	3447	3290	3125	2951	2765
Normal	**90**	4613	4499	4383	4263	4139	4011	3879	3742	3599	3450	3294	3129
	100	4827	4720	4611	4498	4383	4264	4141	4014	3882	3746	3604	3455
	110	5031	4930	4827	4721	4612	4501	4386	4268	4146	4019	3888	3753
Emergency (<24 hrs)	**115**	5130	5032	4931	4828	4723	4615	4503	4389	4271	4149	4023	3893
	120	5227	5131	5033	4933	4831	4725	4618	4507	4393	4275	4153	4028
Emergency (< 1 hr)	**130**	5415	5324	5231	5136	5039	4940	4838	4733	4626	4516	4402	4285
	140	5597	5510	5422	5331	5239	5145	5048	4949	4848	4744	4638	4528
	150	5774	5691	5606	5520	5432	5342	5250	5157	5061	4963	4862	4759
							WINTER					SUMMER	

Weather Assumptions:	Emissivity =	0.5	Suntime =	12:00
	Absorptivity =	0.5	Degrees North Latitude=	40
	Atmosphere =	0	Elevation Above Sea Level=	1000
	Azimuth of Conductor (N-S = 0, E-W = 90)	90	Z_1 (Angle between wind and conductor)	90

Conductor : 3 - 3 x 0.25 inch Aluminum Bar Alloy 6061-T6

T_{low} = 20 °C

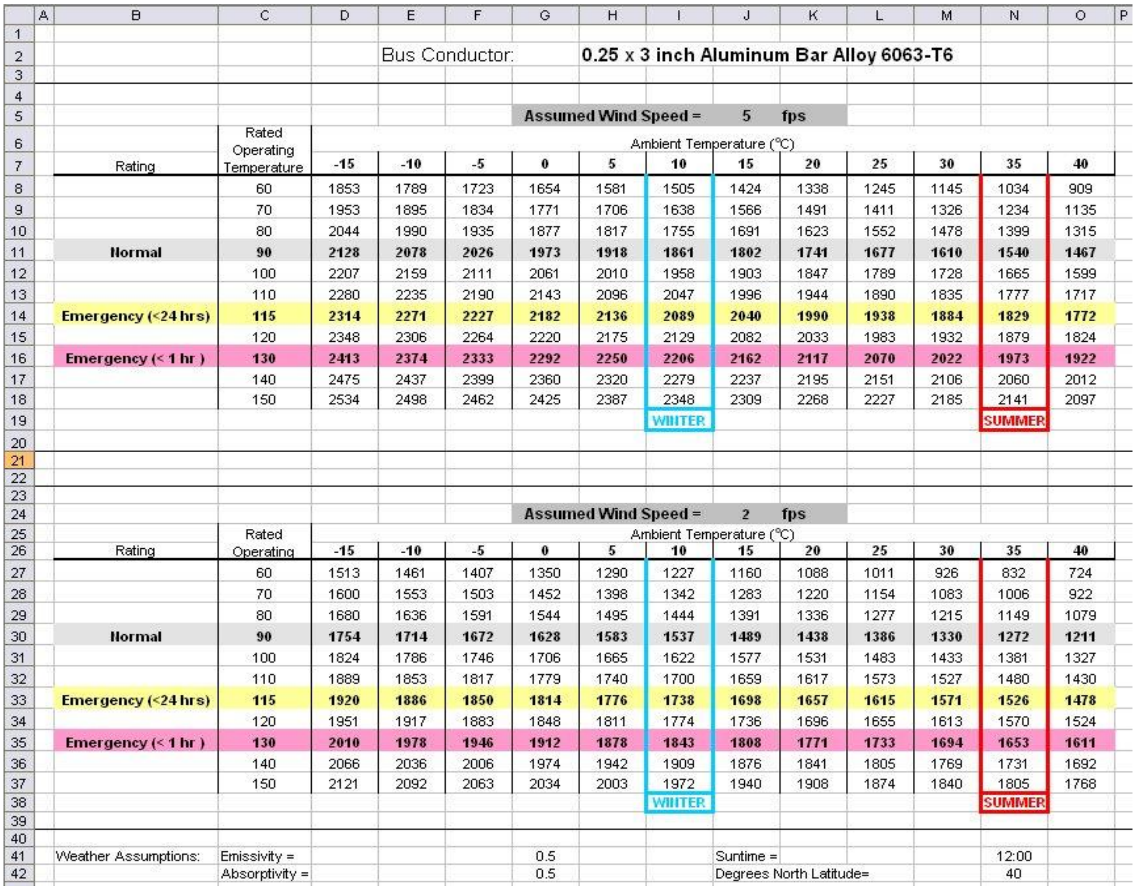
R_{low} = 8.8E-06 ohms/ft

T_{high} = 70 °C

R_{high} = 1E-05 ohms/ft

Figure 5: Publication Table (Shape)

- The eleventh, twelfth and thirteenth tabs are comprised by the **Comparison Tables**. These tables are shape specific, and provide two rating tables for comparison. The first table shows the conductor ratings at the default wind speed of 2fps and the second shows the ratings at a wind speed of the user's designation.



Bus Conductor: **0.25 x 3 inch Aluminum Bar Alloy 6063-T6**

Assumed Wind Speed = 5 fps

Rating	Rated Operating Temperature	Ambient Temperature (°C) **-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	60	1853	1789	1723	1654	1581	1505	1424	1338	1245	1145	1034	909
	70	1953	1895	1834	1771	1706	1638	1566	1491	1411	1326	1234	1135
	80	2044	1990	1935	1877	1817	1755	1691	1623	1552	1478	1399	1315
Normal	**90**	**2128**	**2078**	**2026**	**1973**	**1918**	**1861**	**1802**	**1741**	**1677**	**1610**	**1540**	**1467**
	100	2207	2159	2111	2061	2010	1958	1903	1847	1789	1728	1665	1599
	110	2280	2235	2190	2143	2096	2047	1996	1944	1890	1835	1777	1717
Emergency (<24 hrs)	**115**	**2314**	**2271**	**2227**	**2182**	**2136**	**2089**	**2040**	**1990**	**1938**	**1884**	**1829**	**1772**
	120	2348	2306	2264	2220	2175	2129	2082	2033	1983	1932	1879	1824
Emergency (< 1 hr)	**130**	**2413**	**2374**	**2333**	**2292**	**2250**	**2206**	**2162**	**2117**	**2070**	**2022**	**1973**	**1922**
	140	2475	2437	2399	2360	2320	2279	2237	2195	2151	2106	2060	2012
	150	2534	2498	2462	2425	2387	2348	2309	2268	2227	2185	2141	2097
							WINTER					SUMMER	

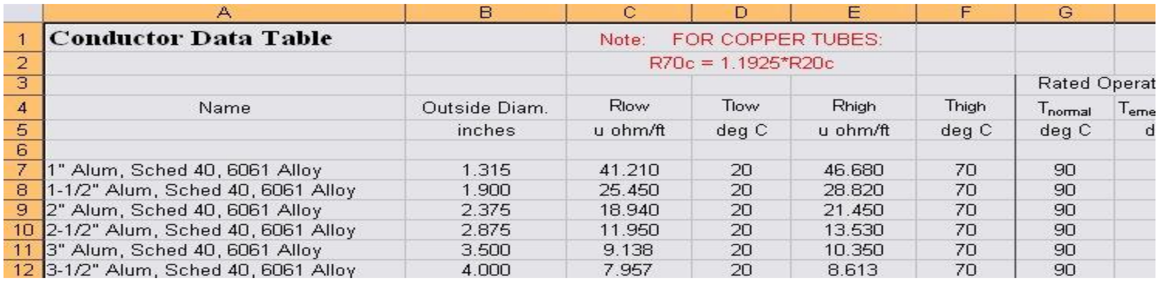
Assumed Wind Speed = 2 fps

Rating	Rated Operating	Ambient Temperature (°C) **-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
	60	1513	1461	1407	1350	1290	1227	1160	1088	1011	926	832	724
	70	1600	1553	1503	1452	1398	1342	1283	1220	1154	1083	1006	922
	80	1680	1636	1591	1544	1495	1444	1391	1336	1277	1215	1149	1079
Normal	**90**	**1754**	**1714**	**1672**	**1628**	**1583**	**1537**	**1489**	**1438**	**1386**	**1330**	**1272**	**1211**
	100	1824	1786	1746	1706	1665	1622	1577	1531	1483	1433	1381	1327
	110	1889	1853	1817	1779	1740	1700	1659	1617	1573	1527	1480	1430
Emergency (<24 hrs)	**115**	**1920**	**1886**	**1850**	**1814**	**1776**	**1738**	**1698**	**1657**	**1615**	**1571**	**1526**	**1478**
	120	1951	1917	1883	1848	1811	1774	1736	1696	1655	1613	1570	1524
Emergency (< 1 hr)	**130**	**2010**	**1978**	**1946**	**1912**	**1878**	**1843**	**1808**	**1771**	**1733**	**1694**	**1653**	**1611**
	140	2066	2036	2006	1974	1942	1909	1876	1841	1805	1769	1731	1692
	150	2121	2092	2063	2034	2003	1972	1940	1908	1874	1840	1805	1768
							WINTER					SUMMER	

Weather Assumptions:
Emissivity = 0.5
Absorptivity = 0.5
Suntime = 12:00
Degrees North Latitude= 40

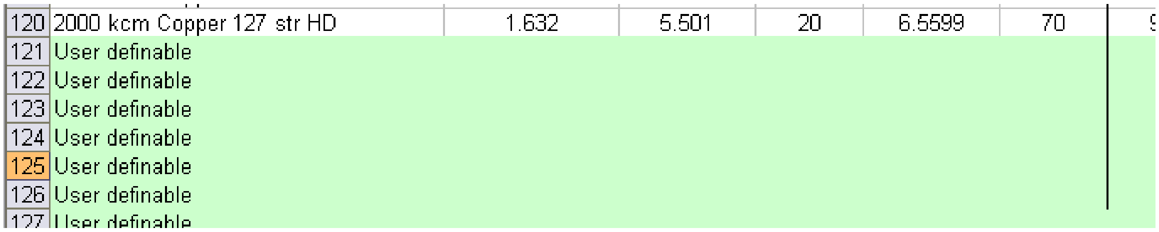
Figure 6: Comparison Table (Shape)

- The **Conductor Data Table** tabs show the stored values for each conductor, and provide space for the user to enter new parameters for an unlisted conductor.



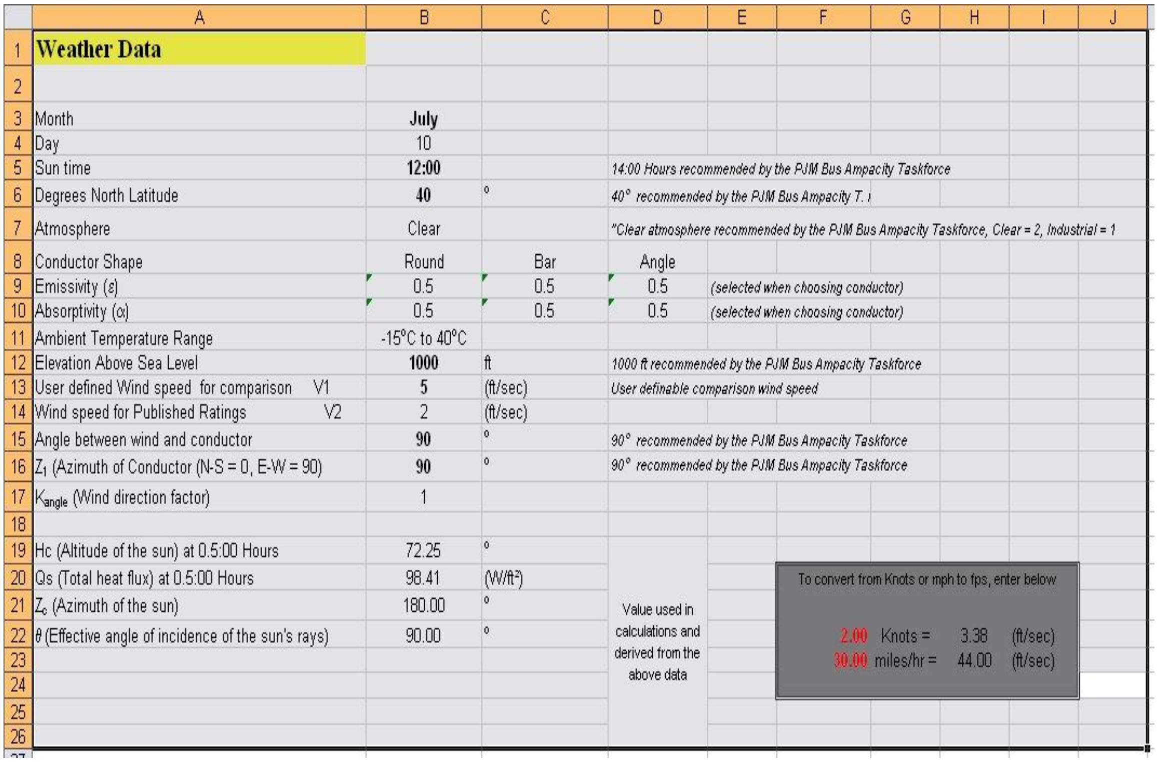
	A	B	C	D	E	F	G
1	**Conductor Data Table**		Note: FOR COPPER TUBES:				
2			R70c = 1.1925*R20c				
3							Rated Operat
4	Name	Outside Diam.	Rlow	Tlow	Rhigh	Thigh	T_{normal}
5		inches	u ohm/ft	deg C	u ohm/ft	deg C	deg C
6							
7	1" Alum, Sched 40, 6061 Alloy	1.315	41.210	20	46.680	70	90
8	1-1/2" Alum, Sched 40, 6061 Alloy	1.900	25.450	20	28.820	70	90
9	2" Alum, Sched 40, 6061 Alloy	2.375	18.940	20	21.450	70	90
10	2-1/2" Alum, Sched 40, 6061 Alloy	2.875	11.950	20	13.530	70	90
11	3" Alum, Sched 40, 6061 Alloy	3.500	9.138	20	10.350	70	90
12	3-1/2" Alum, Sched 40, 6061 Alloy	4.000	7.957	20	8.613	70	90

Figure 7: Conductor Data Table with User Definable Conductor Space



120	2000 kcm Copper 127 str HD	1.632	5.501	20	6.5599	70
121	User definable					
122	User definable					
123	User definable					
124	User definable					
125	User definable					
126	User definable					
127	User definable					

- The **Weather Data** table shows values for all of the weather related variables used to calculate the conductor ratings. It lies on the seventh tab.



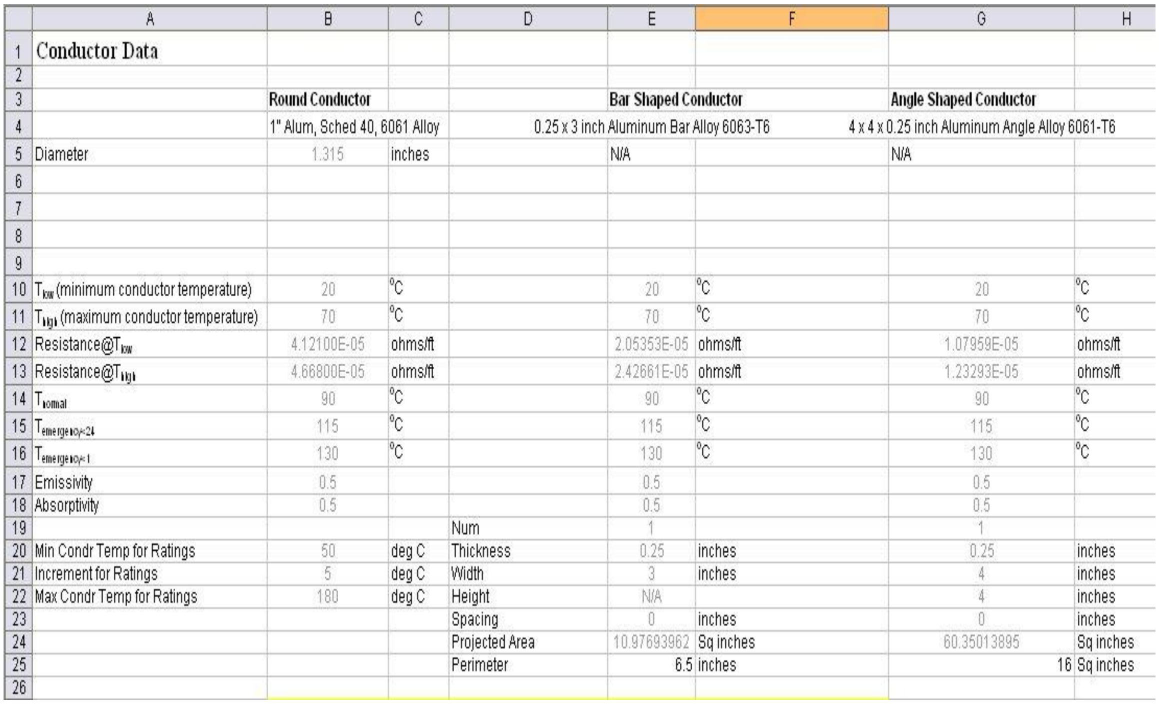
	A	B	C	D	E
1	**Weather Data**				
2					
3	Month	**July**			
4	Day	10			
5	Sun time	**12:00**		*14:00 Hours recommended by the PJM Bus Ampacity Taskforce*	
6	Degrees North Latitude	**40**	°	*40° recommended by the PJM Bus Ampacity T. i*	
7	Atmosphere	Clear		*"Clear atmosphere recommended by the PJM Bus Ampacity Taskforce, Clear = 2, Industrial = 1*	
8	Conductor Shape	Round	Bar	Angle	
9	Emissivity (ε)	0.5	0.5	0.5	*(selected when choosing conductor)*
10	Absorptivity (α)	0.5	0.5	0.5	*(selected when choosing conductor)*
11	Ambient Temperature Range	-15°C to 40°C			
12	Elevation Above Sea Level	**1000**	ft	*1000 ft recommended by the PJM Bus Ampacity Taskforce*	
13	User defined Wind speed for comparison V1	**5**	(ft/sec)	*User definable comparison wind speed*	
14	Wind speed for Published Ratings V2	2	(ft/sec)		
15	Angle between wind and conductor	**90**	°	*90° recommended by the PJM Bus Ampacity Taskforce*	
16	Z_1 (Azimuth of Conductor (N-S = 0, E-W = 90)	**90**	°	*90° recommended by the PJM Bus Ampacity Taskforce*	
17	K_{angle} (Wind direction factor)	1			
18					
19	Hc (Altitude of the sun) at 0.5:00 Hours	72.25	°		
20	Qs (Total heat flux) at 0.5:00 Hours	98.41	(W/ft^2)		
21	Z_c (Azimuth of the sun)	180.00	°	Value used in calculations and derived from the above data	
22	θ (Effective angle of incidence of the sun's rays)	90.00	°		
23					
24					
25					
26					

To convert from Knots or mph to fps, enter below

2.00	Knots =	3.38	(ft/sec)
30.00	miles/hr =	44.00	(ft/sec)

Figure 8: Weather Data Table

- The **Cond** tab or **conductor data** shows characteristics of the conductor the spreadsheet is rating. Only the shape chosen on the main page will have a complete set of data.



	A	B	C	D	E	F	G	H
1	Conductor Data							
2								
3		**Round Conductor**			**Bar Shaped Conductor**		**Angle Shaped Conductor**	
4		1" Alum, Sched 40, 6061 Alloy			0.25 x 3 inch Aluminum Bar Alloy 6063-T6		4 x 4 x 0.25 inch Aluminum Angle Alloy 6061-T6	
5	Diameter	1.315	inches		N/A		N/A	
6								
7								
8								
9								
10	T_{low} (minimum conductor temperature)	20	°C		20	°C	20	°C
11	T_{high} (maximum conductor temperature)	70	°C		70	°C	70	°C
12	Resistance@T_{low}	4.12100E-05	ohms/ft		2.05353E-05	ohms/ft	1.07959E-05	ohms/ft
13	Resistance@T_{high}	4.66800E-05	ohms/ft		2.42661E-05	ohms/ft	1.23293E-05	ohms/ft
14	T_{normal}	90	°C		90	°C	90	°C
15	$T_{emergency<24}$	115	°C		115	°C	115	°C
16	$T_{emergency<1}$	130	°C		130	°C	130	°C
17	Emissivity	0.5			0.5		0.5	
18	Absorptivity	0.5			0.5		0.5	
19				Num	1		1	
20	Min Condr Temp for Ratings	50	deg C	Thickness	0.25	inches	0.25	inches
21	Increment for Ratings	5	deg C	Width	3	inches	4	inches
22	Max Condr Temp for Ratings	180	deg C	Height	N/A		4	inches
23				Spacing	0	inches	0	inches
24				Projected Area	10.97693962	Sq inches	60.35013895	Sq inches
25				Perimeter	6.5	inches	16	Sq inches
26								

<u>Figure 9: Conductor Data Table</u>

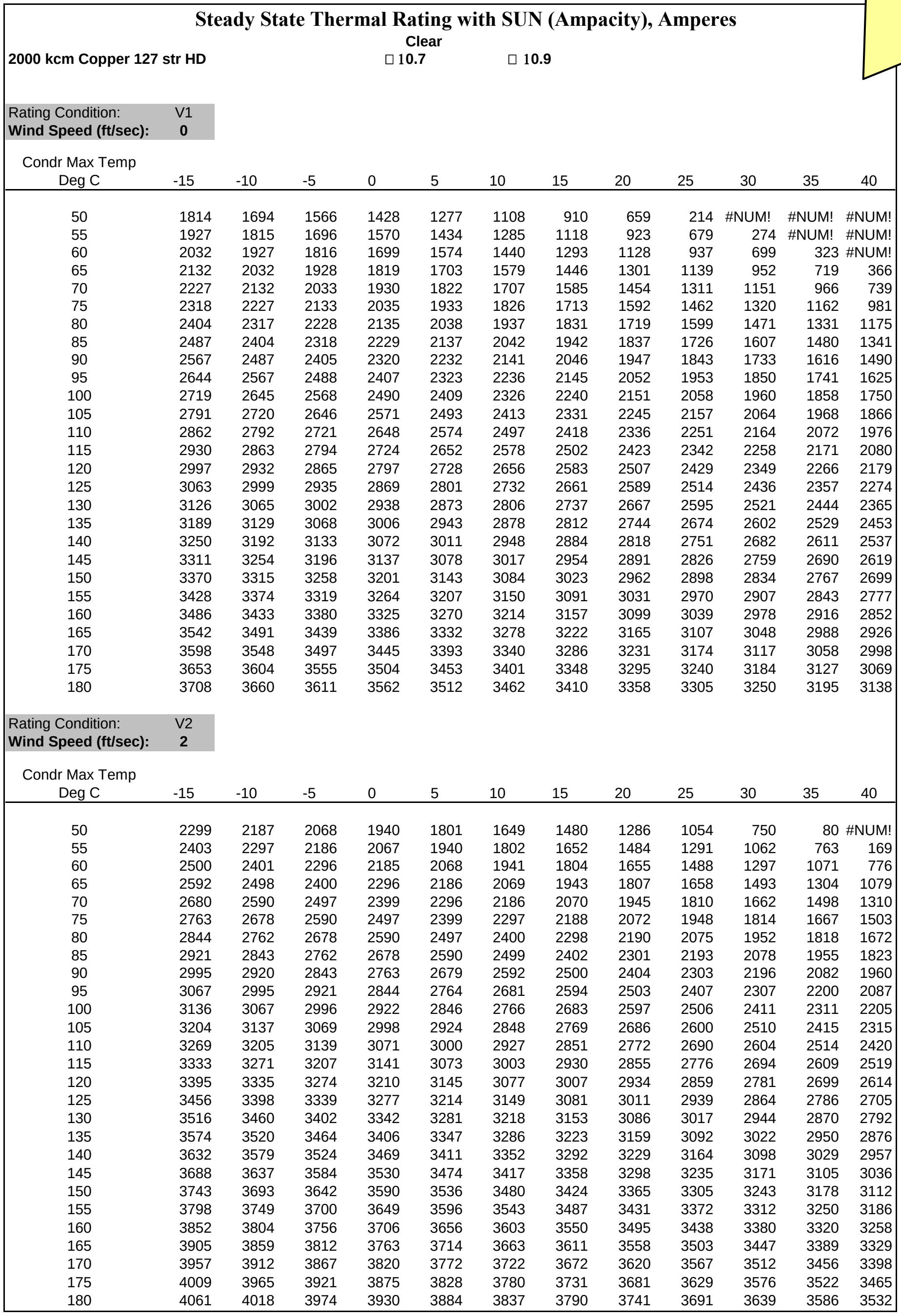
Appendix B

PJM Bus Conductor Ratings Spreadsheet:Tab by tab Instructions

This section described the various sections or tabs of the spreadsheet software. No user inputs are required.

The Ratings with Sun Tab:

This table is one of the results tables and shows conductor ratings for the range of operating temperatures, ambient temperatures for each of the two different wind speeds. This table is for daytime since it is based upon solar exposure. No user inputs are required.



Steady State Thermal Rating with SUN (Ampacity), Amperes

Clear

2000 kcm Copper 127 str HD ☐ 10.7 ☐ 10.9

Rating Condition: V1
Wind Speed (ft/sec): 0

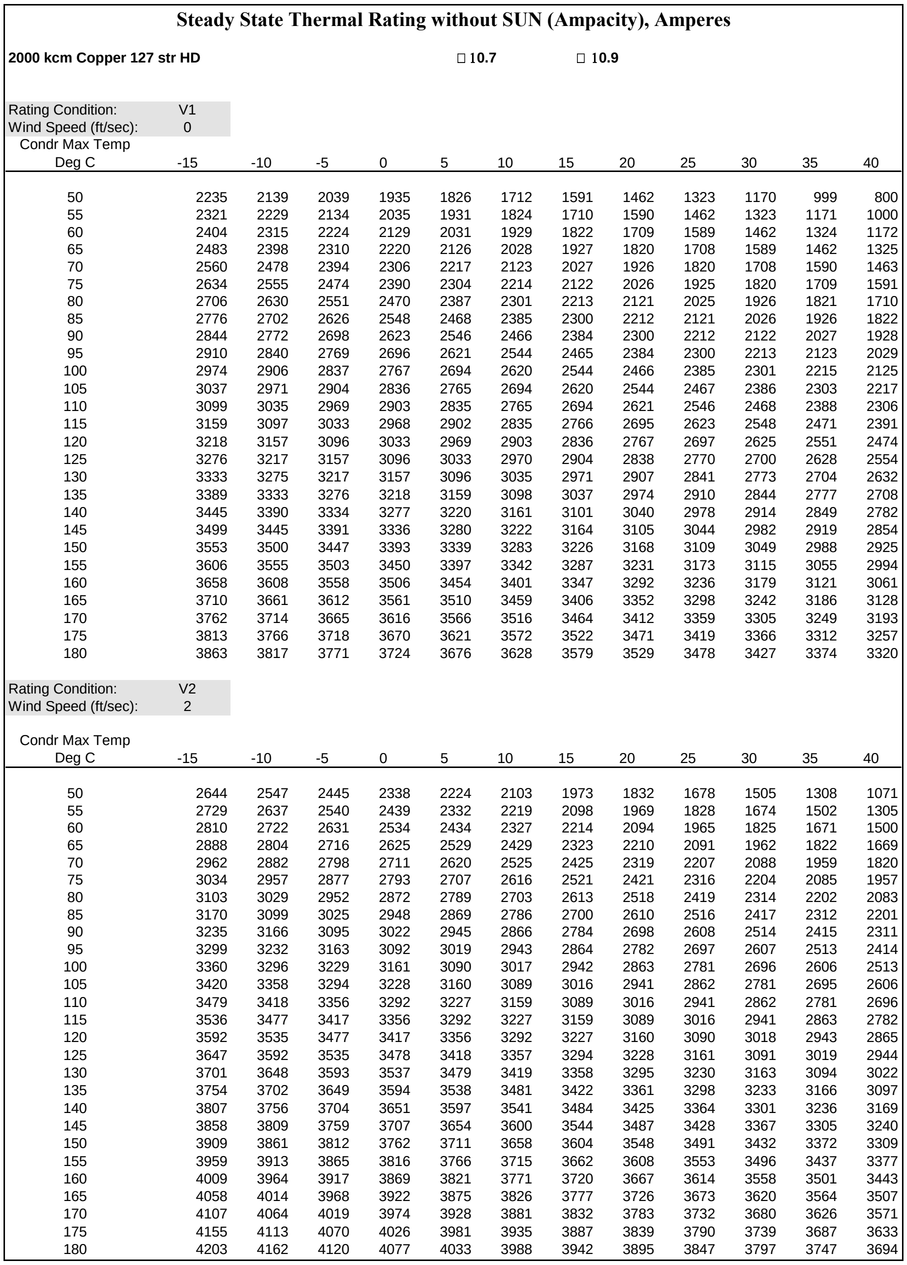
Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
50	1814	1694	1566	1428	1277	1108	910	659	214	#NUM!	#NUM!	#NUM!
55	1927	1815	1696	1570	1434	1285	1118	923	679	274	#NUM!	#NUM!
60	2032	1927	1816	1699	1574	1440	1293	1128	937	699	323	#NUM!
65	2132	2032	1928	1819	1703	1579	1446	1301	1139	952	719	366
70	2227	2132	2033	1930	1822	1707	1585	1454	1311	1151	966	739
75	2318	2227	2133	2035	1933	1826	1713	1592	1462	1320	1162	981
80	2404	2317	2228	2135	2038	1937	1831	1719	1599	1471	1331	1175
85	2487	2404	2318	2229	2137	2042	1942	1837	1726	1607	1480	1341
90	2567	2487	2405	2320	2232	2141	2046	1947	1843	1733	1616	1490
95	2644	2567	2488	2407	2323	2236	2145	2052	1953	1850	1741	1625
100	2719	2645	2568	2490	2409	2326	2240	2151	2058	1960	1858	1750
105	2791	2720	2646	2571	2493	2413	2331	2245	2157	2064	1968	1866
110	2862	2792	2721	2648	2574	2497	2418	2336	2251	2164	2072	1976
115	2930	2863	2794	2724	2652	2578	2502	2423	2342	2258	2171	2080
120	2997	2932	2865	2797	2728	2656	2583	2507	2429	2349	2266	2179
125	3063	2999	2935	2869	2801	2732	2661	2589	2514	2436	2357	2274
130	3126	3065	3002	2938	2873	2806	2737	2667	2595	2521	2444	2365
135	3189	3129	3068	3006	2943	2878	2812	2744	2674	2602	2529	2453
140	3250	3192	3133	3072	3011	2948	2884	2818	2751	2682	2611	2537
145	3311	3254	3196	3137	3078	3017	2954	2891	2826	2759	2690	2619
150	3370	3315	3258	3201	3143	3084	3023	2962	2898	2834	2767	2699
155	3428	3374	3319	3264	3207	3150	3091	3031	2970	2907	2843	2777
160	3486	3433	3380	3325	3270	3214	3157	3099	3039	2978	2916	2852
165	3542	3491	3439	3386	3332	3278	3222	3165	3107	3048	2988	2926
170	3598	3548	3497	3445	3393	3340	3286	3231	3174	3117	3058	2998
175	3653	3604	3555	3504	3453	3401	3348	3295	3240	3184	3127	3069
180	3708	3660	3611	3562	3512	3462	3410	3358	3305	3250	3195	3138

Rating Condition: V2
Wind Speed (ft/sec): 2

Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
50	2299	2187	2068	1940	1801	1649	1480	1286	1054	750	80	#NUM!
55	2403	2297	2186	2067	1940	1802	1652	1484	1291	1062	763	169
60	2500	2401	2296	2185	2068	1941	1804	1655	1488	1297	1071	776
65	2592	2498	2400	2296	2186	2069	1943	1807	1658	1493	1304	1079
70	2680	2590	2497	2399	2296	2186	2070	1945	1810	1662	1498	1310
75	2763	2678	2590	2497	2399	2297	2188	2072	1948	1814	1667	1503
80	2844	2762	2678	2590	2497	2400	2298	2190	2075	1952	1818	1672
85	2921	2843	2762	2678	2590	2499	2402	2301	2193	2078	1955	1823
90	2995	2920	2843	2763	2679	2592	2500	2404	2303	2196	2082	1960
95	3067	2995	2921	2844	2764	2681	2594	2503	2407	2307	2200	2087
100	3136	3067	2996	2922	2846	2766	2683	2597	2506	2411	2311	2205
105	3204	3137	3069	2998	2924	2848	2769	2686	2600	2510	2415	2315
110	3269	3205	3139	3071	3000	2927	2851	2772	2690	2604	2514	2420
115	3333	3271	3207	3141	3073	3003	2930	2855	2776	2694	2609	2519
120	3395	3335	3274	3210	3145	3077	3007	2934	2859	2781	2699	2614
125	3456	3398	3339	3277	3214	3149	3081	3011	2939	2864	2786	2705
130	3516	3460	3402	3342	3281	3218	3153	3086	3017	2944	2870	2792
135	3574	3520	3464	3406	3347	3286	3223	3159	3092	3022	2950	2876
140	3632	3579	3524	3469	3411	3352	3292	3229	3164	3098	3029	2957
145	3688	3637	3584	3530	3474	3417	3358	3298	3235	3171	3105	3036
150	3743	3693	3642	3590	3536	3480	3424	3365	3305	3243	3178	3112
155	3798	3749	3700	3649	3596	3543	3487	3431	3372	3312	3250	3186
160	3852	3804	3756	3706	3656	3603	3550	3495	3438	3380	3320	3258
165	3905	3859	3812	3763	3714	3663	3611	3558	3503	3447	3389	3329
170	3957	3912	3867	3820	3772	3722	3672	3620	3567	3512	3456	3398
175	4009	3965	3921	3875	3828	3780	3731	3681	3629	3576	3522	3465
180	4061	4018	3974	3930	3884	3837	3790	3741	3691	3639	3586	3532

The Ratings without Sun Tab:

This table is another of the results tables and shows conductor ratings for the range of operating temperatures, ambient temperatures for each of the two different wind speeds. This table is for night time since it is absent solar exposure. No user inputs are required.



Steady State Thermal Rating without SUN (Ampacity), Amperes

2000 kcm Copper 127 str HD ☐ 10.7 ☐ 10.9

Rating Condition: V1
Wind Speed (ft/sec): 0

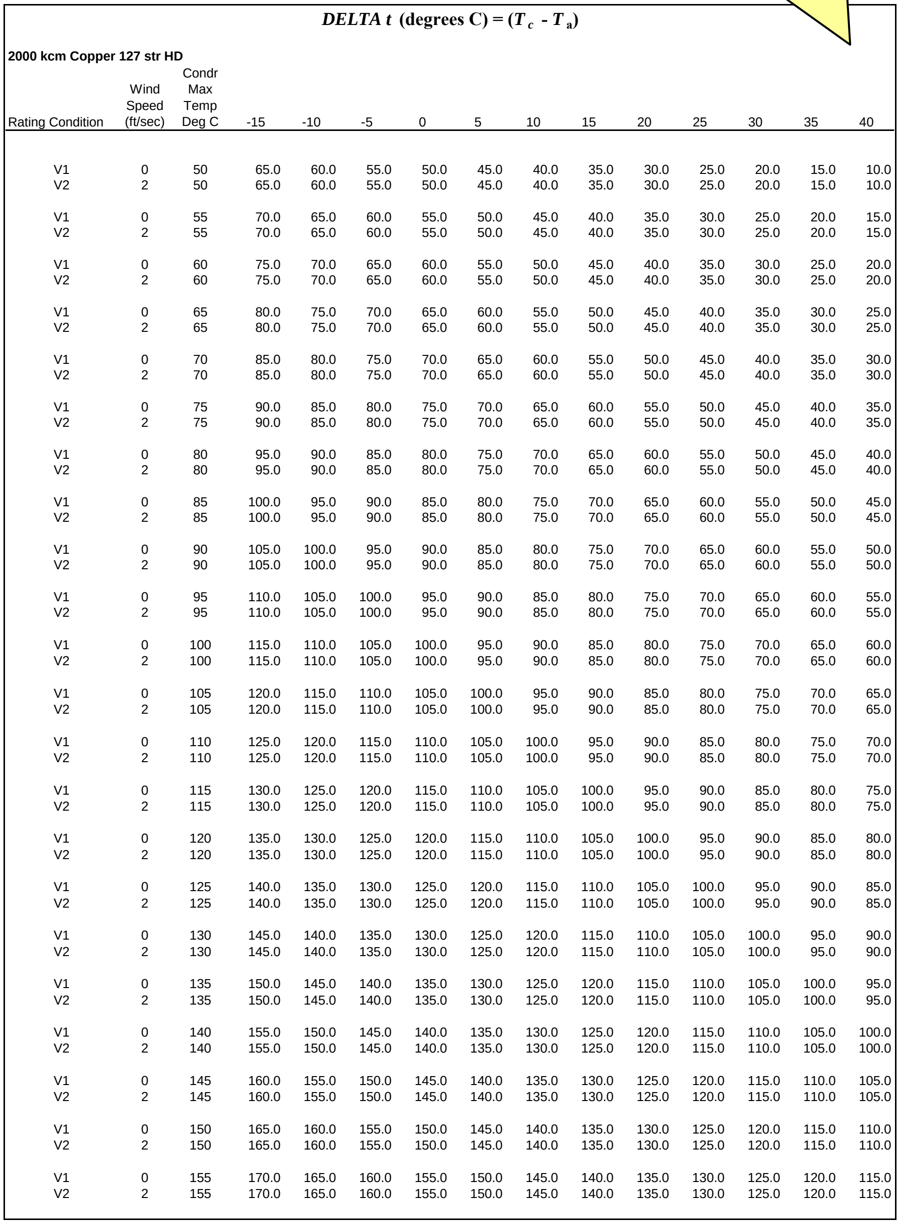
Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
50	2235	2139	2039	1935	1826	1712	1591	1462	1323	1170	999	800
55	2321	2229	2134	2035	1931	1824	1710	1590	1462	1323	1171	1000
60	2404	2315	2224	2129	2031	1929	1822	1709	1589	1462	1324	1172
65	2483	2398	2310	2220	2126	2028	1927	1820	1708	1589	1462	1325
70	2560	2478	2394	2306	2217	2123	2027	1926	1820	1708	1590	1463
75	2634	2555	2474	2390	2304	2214	2122	2026	1925	1820	1709	1591
80	2706	2630	2551	2470	2387	2301	2213	2121	2025	1926	1821	1710
85	2776	2702	2626	2548	2468	2385	2300	2212	2121	2026	1926	1822
90	2844	2772	2698	2623	2546	2466	2384	2300	2212	2122	2027	1928
95	2910	2840	2769	2696	2621	2544	2465	2384	2300	2213	2123	2029
100	2974	2906	2837	2767	2694	2620	2544	2466	2385	2301	2215	2125
105	3037	2971	2904	2836	2765	2694	2620	2544	2467	2386	2303	2217
110	3099	3035	2969	2903	2835	2765	2694	2621	2546	2468	2388	2306
115	3159	3097	3033	2968	2902	2835	2766	2695	2623	2548	2471	2391
120	3218	3157	3096	3033	2969	2903	2836	2767	2697	2625	2551	2474
125	3276	3217	3157	3096	3033	2970	2904	2838	2770	2700	2628	2554
130	3333	3275	3217	3157	3096	3035	2971	2907	2841	2773	2704	2632
135	3389	3333	3276	3218	3159	3098	3037	2974	2910	2844	2777	2708
140	3445	3390	3334	3277	3220	3161	3101	3040	2978	2914	2849	2782
145	3499	3445	3391	3336	3280	3222	3164	3105	3044	2982	2919	2854
150	3553	3500	3447	3393	3339	3283	3226	3168	3109	3049	2988	2925
155	3606	3555	3503	3450	3397	3342	3287	3231	3173	3115	3055	2994
160	3658	3608	3558	3506	3454	3401	3347	3292	3236	3179	3121	3061
165	3710	3661	3612	3561	3510	3459	3406	3352	3298	3242	3186	3128
170	3762	3714	3665	3616	3566	3516	3464	3412	3359	3305	3249	3193
175	3813	3766	3718	3670	3621	3572	3522	3471	3419	3366	3312	3257
180	3863	3817	3771	3724	3676	3628	3579	3529	3478	3427	3374	3320

Rating Condition: V2
Wind Speed (ft/sec): 2

Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
50	2644	2547	2445	2338	2224	2103	1973	1832	1678	1505	1308	1071
55	2729	2637	2540	2439	2332	2219	2098	1969	1828	1674	1502	1305
60	2810	2722	2631	2534	2434	2327	2214	2094	1965	1825	1671	1500
65	2888	2804	2716	2625	2529	2429	2323	2210	2091	1962	1822	1669
70	2962	2882	2798	2711	2620	2525	2425	2319	2207	2088	1959	1820
75	3034	2957	2877	2793	2707	2616	2521	2421	2316	2204	2085	1957
80	3103	3029	2952	2872	2789	2703	2613	2518	2419	2314	2202	2083
85	3170	3099	3025	2948	2869	2786	2700	2610	2516	2417	2312	2201
90	3235	3166	3095	3022	2945	2866	2784	2698	2608	2514	2415	2311
95	3299	3232	3163	3092	3019	2943	2864	2782	2697	2607	2513	2414
100	3360	3296	3229	3161	3090	3017	2942	2863	2781	2696	2606	2513
105	3420	3358	3294	3228	3160	3089	3016	2941	2862	2781	2695	2606
110	3479	3418	3356	3292	3227	3159	3089	3016	2941	2862	2781	2696
115	3536	3477	3417	3356	3292	3227	3159	3089	3016	2941	2863	2782
120	3592	3535	3477	3417	3356	3292	3227	3160	3090	3018	2943	2865
125	3647	3592	3535	3478	3418	3357	3294	3228	3161	3091	3019	2944
130	3701	3648	3593	3537	3479	3419	3358	3295	3230	3163	3094	3022
135	3754	3702	3649	3594	3538	3481	3422	3361	3298	3233	3166	3097
140	3807	3756	3704	3651	3597	3541	3484	3425	3364	3301	3236	3169
145	3858	3809	3759	3707	3654	3600	3544	3487	3428	3367	3305	3240
150	3909	3861	3812	3762	3711	3658	3604	3548	3491	3432	3372	3309
155	3959	3913	3865	3816	3766	3715	3662	3608	3553	3496	3437	3377
160	4009	3964	3917	3869	3821	3771	3720	3667	3614	3558	3501	3443
165	4058	4014	3968	3922	3875	3826	3777	3726	3673	3620	3564	3507
170	4107	4064	4019	3974	3928	3881	3832	3783	3732	3680	3626	3571
175	4155	4113	4070	4026	3981	3935	3887	3839	3790	3739	3687	3633
180	4203	4162	4120	4077	4033	3988	3942	3895	3847	3797	3747	3694

The DeltaT Tab:

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the difference in temperature between the conductor temperature and ambient temperature.



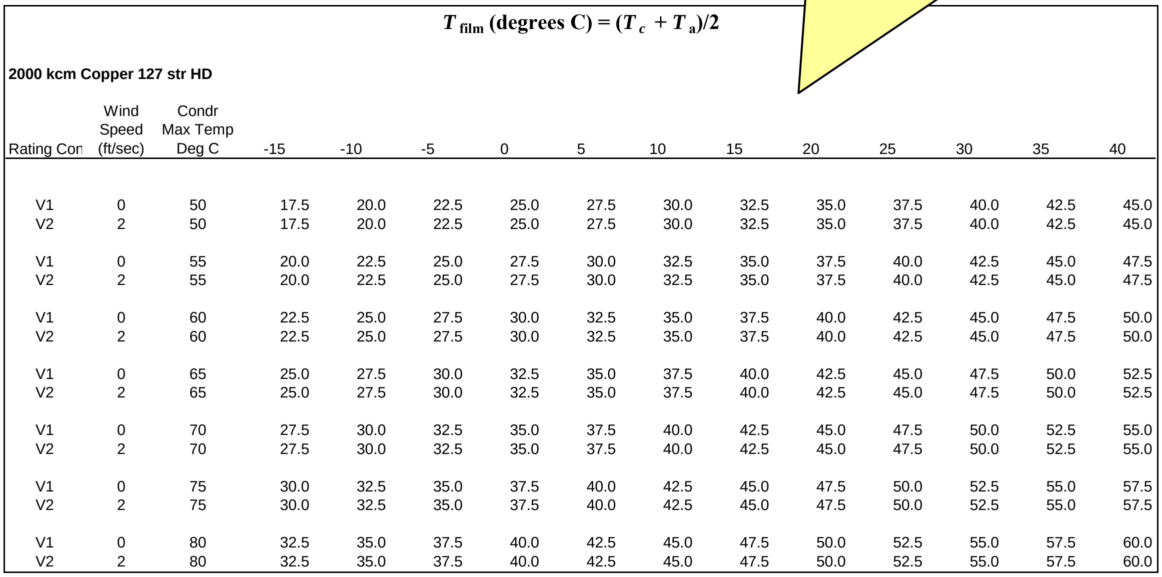
DELTA *t* (degrees C) = (T_c - T_a)

2000 kcm Copper 127 str HD

Rating Condition	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0	10.0
V2	2	50	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0	10.0
V1	0	55	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0
V2	2	55	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0	15.0
V1	0	60	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0
V2	2	60	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0	20.0
V1	0	65	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0
V2	2	65	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0	25.0
V1	0	70	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0
V2	2	70	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0	30.0
V1	0	75	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0
V2	2	75	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0	35.0
V1	0	80	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0
V2	2	80	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0	40.0
V1	0	85	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0
V2	2	85	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0	45.0
V1	0	90	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0
V2	2	90	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0	50.0
V1	0	95	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0
V2	2	95	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0	55.0
V1	0	100	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0
V2	2	100	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0
V1	0	105	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0
V2	2	105	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0
V1	0	110	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0
V2	2	110	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0
V1	0	115	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0
V2	2	115	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0
V1	0	120	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0
V2	2	120	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0
V1	0	125	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0
V2	2	125	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0
V1	0	130	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0
V2	2	130	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0
V1	0	135	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0
V2	2	135	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0
V1	0	140	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0
V2	2	140	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0
V1	0	145	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0
V2	2	145	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0	105.0
V1	0	150	165.0	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0
V2	2	150	165.0	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0	110.0
V1	0	155	170.0	165.0	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0
V2	2	155	170.0	165.0	160.0	155.0	150.0	145.0	140.0	135.0	130.0	125.0	120.0	115.0

The TFilm tab:

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the temperature of the air film between the conductor and ambient environment.



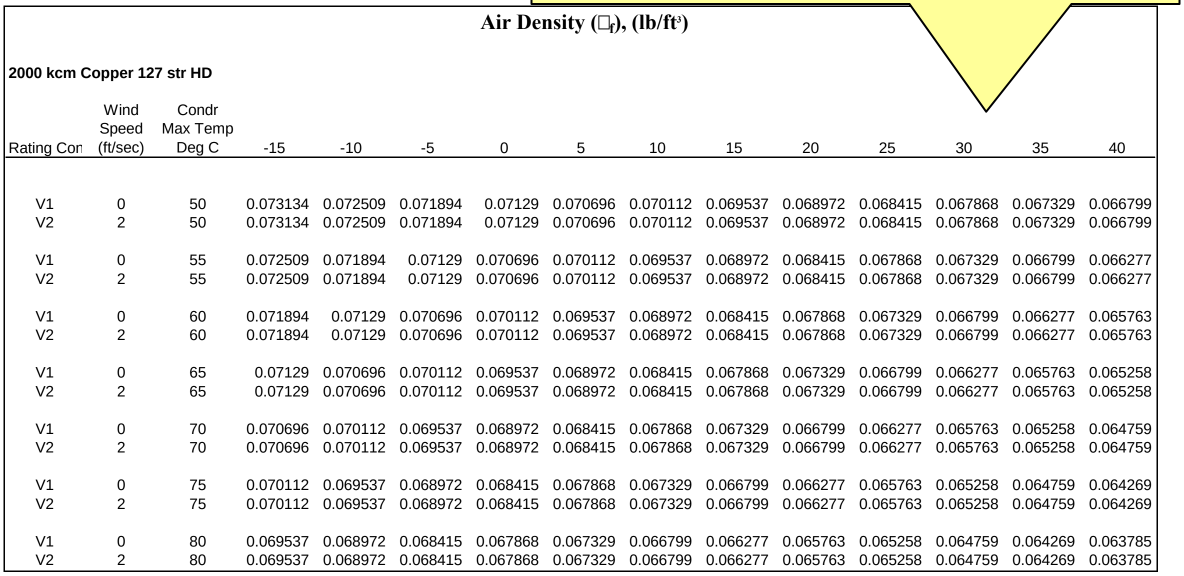
T_{film} (degrees C) = (T_c + T_a)/2

2000 kcm Copper 127 str HD

Rating Con	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0
V2	2	50	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0
V1	0	55	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5
V2	2	55	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5
V1	0	60	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0
V2	2	60	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0
V1	0	65	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5
V2	2	65	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5
V1	0	70	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0
V2	2	70	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0
V1	0	75	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5
V2	2	75	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5
V1	0	80	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0
V2	2	80	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0

The Air Density tab:

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the air density around the conductor based on temperature.



Air Density (□$_f$), (lb/ft^3)

2000 kcm Copper 127 str HD

Rating Con	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	0.073134	0.072509	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799
V2	2	50	0.073134	0.072509	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799
V1	0	55	0.072509	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277
V2	2	55	0.072509	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277
V1	0	60	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763
V2	2	60	0.071894	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763
V1	0	65	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258
V2	2	65	0.07129	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258
V1	0	70	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759
V2	2	70	0.070696	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759
V1	0	75	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759	0.064269
V2	2	75	0.070112	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759	0.064269
V1	0	80	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759	0.064269	0.063785
V2	2	80	0.069537	0.068972	0.068415	0.067868	0.067329	0.066799	0.066277	0.065763	0.065258	0.064759	0.064269	0.063785

The Air Viscosity tab:

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the viscosity of the air around the conductor.

Absolute Viscosity of Air ($\square_f$), (lb/ft*h)

2000 kcm Copper 127 str HD

Rating Con	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	0.043572	0.043863	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701
V2	2	50	0.043572	0.043863	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701
V1	0	55	0.043863	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979
V2	2	55	0.043863	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979
V1	0	60	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255
V2	2	60	0.044152	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255
V1	0	65	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531
V2	2	65	0.04444	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531
V1	0	70	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805
V2	2	70	0.044727	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805
V1	0	75	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805	0.048078
V2	2	75	0.045012	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805	0.048078
V1	0	80	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805	0.048078	0.04835
V2	2	80	0.045297	0.04558	0.045862	0.046143	0.046423	0.046701	0.046979	0.047255	0.047531	0.047805	0.048078	0.04835

The q_c tab:

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the convection heat loss from a 1 foot length of conductor.

Convected Heat Loss (q_c), Watts Per Foot of Conductor (max of qc0, kqc1, or kqc2)

2000 kcm Copper 127 str HD

Rating Condition	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	20.40	18.37	16.41	14.51	12.66	10.88	9.17	7.53	5.97	4.50	3.13	1.88
V2	2	50	32.65	30.12	27.60	25.08	22.56	20.04	17.53	15.02	12.51	10.01	7.50	5.00
V1	0	55	22.28	20.22	18.22	16.27	14.39	12.56	10.80	9.10	7.47	5.93	4.47	3.11
V2	2	55	35.14	32.61	30.09	27.57	25.05	22.54	20.03	17.52	15.01	12.50	10.00	7.50
V1	0	60	24.18	22.09	20.05	18.07	16.14	14.27	12.46	10.71	9.03	7.42	5.88	4.43
V2	2	60	37.63	35.11	32.58	30.06	27.55	25.03	22.52	20.01	17.50	15.00	12.49	9.99
V1	0	65	26.10	23.98	21.91	19.89	17.92	16.01	14.15	12.36	10.62	8.96	7.36	5.84
V2	2	65	40.12	37.60	35.08	32.56	30.04	27.53	25.01	22.50	20.00	17.49	14.99	12.49
V1	0	70	28.04	25.89	23.78	21.73	19.73	17.78	15.88	14.04	12.26	10.54	8.89	7.30
V2	2	70	42.61	40.09	37.56	35.05	32.53	30.02	27.51	25.00	22.49	19.98	17.48	14.98
V1	0	75	29.99	27.81	25.68	23.59	21.55	19.57	17.64	15.76	13.93	12.17	10.46	8.82
V2	2	75	45.10	42.57	40.05	37.53	35.02	32.51	30.00	27.49	24.98	22.48	19.97	17.47
V1	0	80	31.96	29.75	27.59	25.47	23.40	21.38	19.42	17.50	15.63	13.83	12.07	10.38
V2	2	80	47.58	45.06	42.54	40.02	37.51	35.00	32.49	29.98	27.47	24.97	22.46	19.96

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the thermal conductivity of the air around the conductor.

The μ_r tab:

Thermal Conductivity of Air (k_f) at Temperature , T_{film} W/ft (degrees C)

2000 kcm Copper 127 str HD

Rating Con	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	0.007786	0.007843	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411
V2	2	50	0.007786	0.007843	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411
V1	0	55	0.007843	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467
V2	2	55	0.007843	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467
V1	0	60	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524
V2	2	60	0.0079	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524
V1	0	65	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581
V2	2	65	0.007957	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581
V1	0	70	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637
V2	2	70	0.008014	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637
V1	0	75	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637	0.008694
V2	2	75	0.00807	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637	0.008694
V1	0	80	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637	0.008694	0.00875
V2	2	80	0.008127	0.008184	0.008241	0.008297	0.008354	0.008411	0.008467	0.008524	0.008581	0.008637	0.008694	0.00875

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the heat gain to the conductor due to solar heat input. This is only used for day time ratings.

The q_s tab:

Solar Heat Gain (q_s), Watts Per Foot of Conductor

Clear

2000 kcm Copper 127 str HD **□ [0.7** **□ [0.9**

Rating Condition	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	50	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	55	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	55	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	60	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	60	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	65	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	65	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	70	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	70	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	75	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	75	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V1	0	80	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458
V2	2	80	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458	10.458

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the heat loss due to radiation from the hot conductor.

The q_r tab:

Radiated Heat Loss (q_r), Watts Per Foot of Conductor

2000 kcm Copper 127 str HD						**□ [0.7**	**□ [0.9**							
Rating Condition	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	10.2563	9.6944	9.0995	8.4703	7.8057	7.1041	6.3644	5.5852	4.7650	3.9025	2.9962	2.0447
V2	2	50	10.2563	9.6944	9.0995	8.4703	7.8057	7.1041	6.3644	5.5852	4.7650	3.9025	2.9962	2.0447
V1	0	55	11.3525	10.7905	10.1957	9.5665	8.9018	8.2003	7.4606	6.6814	5.8612	4.9987	4.0924	3.1409
V2	2	55	11.3525	10.7905	10.1957	9.5665	8.9018	8.2003	7.4606	6.6814	5.8612	4.9987	4.0924	3.1409
V1	0	60	12.4999	11.9380	11.3431	10.7140	10.0493	9.3478	8.6081	7.8289	7.0087	6.1462	5.2399	4.2883
V2	2	60	12.4999	11.9380	11.3431	10.7140	10.0493	9.3478	8.6081	7.8289	7.0087	6.1462	5.2399	4.2883
V1	0	65	13.7003	13.1384	12.5435	11.9143	11.2497	10.5482	9.8085	9.0292	8.2090	7.3465	6.4402	5.4887
V2	2	65	13.7003	13.1384	12.5435	11.9143	11.2497	10.5482	9.8085	9.0292	8.2090	7.3465	6.4402	5.4887
V1	0	70	14.9551	14.3932	13.7983	13.1692	12.5045	11.8030	11.0633	10.2840	9.4638	8.6013	7.6950	6.7435
V2	2	70	14.9551	14.3932	13.7983	13.1692	12.5045	11.8030	11.0633	10.2840	9.4638	8.6013	7.6950	6.7435
V1	0	75	16.2660	15.7041	15.1092	14.4801	13.8154	13.1139	12.3742	11.5949	10.7747	9.9122	9.0059	8.0544
V2	2	75	16.2660	15.7041	15.1092	14.4801	13.8154	13.1139	12.3742	11.5949	10.7747	9.9122	9.0059	8.0544
V1	0	80	17.6347	17.0727	16.4779	15.8487	15.1840	14.4825	13.7428	12.9636	12.1434	11.2809	10.3746	9.4231
V2	2	80	17.6347	17.0727	16.4779	15.8487	15.1840	14.4825	13.7428	12.9636	12.1434	11.2809	10.3746	9.4231

This tab is used for intermediate steps in the calculation. No user inputs are required. The table shows the resistance of the conductor based upon the conductor temperature.

The Resistance tab:

Conductor Electrical Resistance (R), (Ohms/ft.)

2000 kcm Copper 127 str HD														
Rating Condition	Wind Speed (ft/sec)	Condr Max Temp Deg C	-15	-10	-5	0	5	10	15	20	25	30	35	40
V1	0	50	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06
V2	2	50	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06	6.1E-06
V1	0	55	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06
V2	2	55	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06	6.2E-06
V1	0	60	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06
V2	2	60	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06	6.3E-06
V1	0	65	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06
V2	2	65	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06	6.5E-06
V1	0	70	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06
V2	2	70	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06	6.6E-06
V1	0	75	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06
V2	2	75	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06	6.7E-06
V1	0	80	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06
V2	2	80	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06	6.8E-06

Appendix C

References

This PJM Substation Conductor Rating document was prepared using various industry standards as guides and references. These referenced documents are:

1. *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*, IEEE Std 738-1993
2. *IEEE Guide for Design of Substation Rigid-Bus Structures*, IEEE Std 605-1998
3. *A Uniform Method for the determination of load capability of line terminal equipment*, ECAR 74-EEP-42, revised June 1974.
4. *ECAR Transmission Conductors Loss of Strength Due to Elevated Temperature, ECAR 74-TFP-37*, May 1974.
5. *Determining the Loadability of Line Terminal Equipment*, ECAR 88-EEP-42, July 1988
6. *Transmission Conductor Thermal Ratings, ECAR 89-TFP-28, October 1989*
7. *Bare Overhead Transmission Conductor Ratings,* PJM Interconnection, November 2000.
8. *PJM Manual 03: “Transmission Operations”,* Revision 37, June 18, 2010.