VI.e - Outdoor Substation Conductor Ratings

Transmission and Substation Subcommittee

PJM Interconnection, LLC

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1.0 SCOPE / INTRODUCTION

The PJM Transmission and Substation Subcommittee (TSS) was requested to review and update the existing Outdoor Substation Conductor Ratings, Revision 2 from September 2010 issued by the Transmission and Substation Design Subcommittee (TSDS). This document contains ampacity ratings for tubular bus, stranded conductors, and bars 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 updating the document and reflecting changes associated with FERC Order 881 to apply Ambient Adjusted Ratings (AAR) over a wider range of temperatures in five (5) degree Fahrenheit increments for both day and night. The results of the task force work are incorporated into this new document. Revision 4 corrected an exponent in formula [6b] and added Appendix D.

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.
Maximum Allowable Conductor Temperature	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.
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° 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. Based upon FERC Order 881 and PJM requirements, conductors shall be rated between and including temperatures from 150F (65.5C) to -65F (-53.9C)

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 -65°F to 150°F in 5°F increments. For historical reference, the ratings in 5°C increments from -15°C to 40°C are also included.

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 "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. The 2023 task force modified the existing spreadsheet to calculate ratings over a wider range of ambient temperatures to address the needs of FERC Order 881.

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 and Appendix B of IEEE Standard 605 which references the IEEE transactions on 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:

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

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.

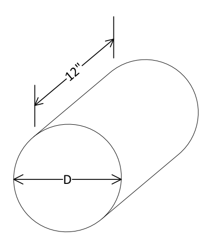
q_c = convective heat loss in watts per linear foot.

A more useful equation for spreadsheet application:

A = area = π * D * 12 in^2 / ft

l = length of conductor surface

= 12 * L = 12



Substituting into (eq. 1.) gives:

$q_c = 0.0022 * \Delta T^{1.25} * 12^{-0.25} * 12 * \pi * D$ $q_c = 0.0022 * \Delta T^{1.25} * 20.255166 * D$

(2.) $q_c = .044561 * D * \Delta T^{1.25}$ **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:

(3.) $q_{c0} = .283 * \rho_r^{0.5} * D^{0.75} * \Delta T^{1.25}$ **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:

(4.) $A = 24 * l * (N-1)$

A = effective conductor area

l = length of the conductor in inches

N = number of conductors

Substituting this expression for A in equation 1:

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

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:

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

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

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.] $\mathbf{q_{c2} = .1695 * (3600\ D\ \rho_r\ V/\mu_r)^{0.6} * k_f * (T_c - T_a)}$

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:

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

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

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

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 compare 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°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

Size	Conductor Temperature					
	80°C	90 °C	100 °C	110 °C	140 °C	150 °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

Size	Conductor Temperature					
	80ºC	90 ºC	100 ºC	110 ºC	140 ºC	150 ºC
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

Size	Conductor Temperature					
	80ºC	90 ºC	100 ºC	110 ºC	140 ºC	150 ºC
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:

$$q_c = 0.00367 h A \Delta T$$

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:

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

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 bein 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)[1] 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

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[1] ECAR was formed in 1967 to address the reliability of the bulk electric system and was the predecessor of Reliability First. The ECAR research and findings are still relevant to the calculation of outdoor substation conductor ratings.

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 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[2] 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.

It is recommended when a high temperature conductor is connected to substation equipment such a disconnect, caution should be used with respect to the conductor temperature versus the temperature rating of the substation equipment. The substation conductors should be sized to limit the temperature at the substation equipment. Larger or multiple conductors per phase or a plate used as a heatsink could mitigate the high temperatures.

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.

[2] This document refers to degrees Celsius since this is an industry standard. When calculations are made using the PJM bus conductor rating tool, calculation will be made in both degrees Fahrenheit and Celsius.

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)[3] 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

[3] ***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.

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).

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^{o}C without incurring either electrical or mechanical limitations. Several tests conducted by manufacturers showed that many conductor accessories operated at temperatures 50^{o}C to 100^{o}C lower than the conductor when operating at temperatures above 180^{o}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	-65°F to 150°F	
Wind Speed	2 Ft. per sec. (Normal & Emergency)	
Wind Direction	90° to the conductor	
Maximum allowable conductor Temp. range	70°C to 140°C	
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[4]	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[3]	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

[4] 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.

Maximum SHORT TERM (up to 1 hour) **emergency** operating temperature[3]	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

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. This data was 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 frompage A-19 of 1973 PJM Report, "Determination of Thermal Ratings for Bare Overhead Conductors".

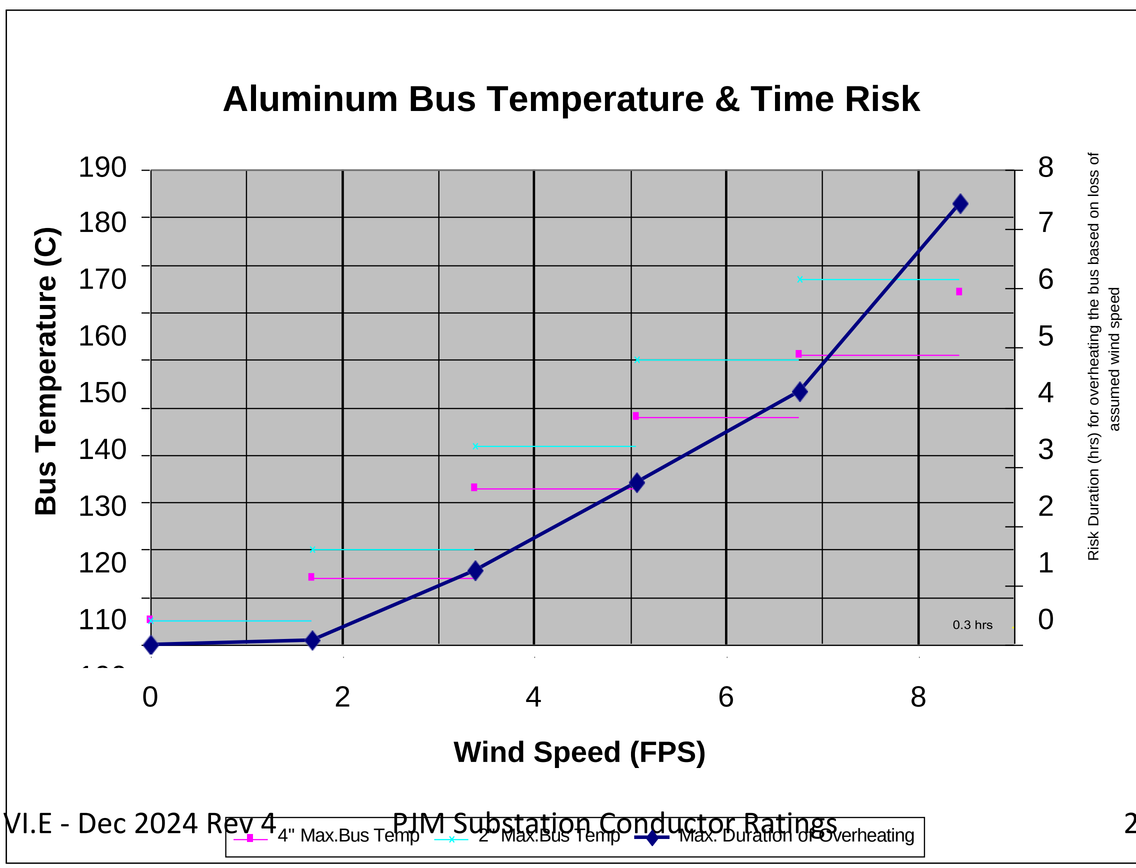
When rating bus conductors, the choice of wind speed used is important due to the significant effect on the rating. While a higher wind speed is desired for the higher rating, there is a cost. What happens if the wind speed that actually occurs at the substation is less than the assumed value? As the 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 90ºC 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 115ºC and may experience overheating above 90ºC 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.



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 summertime 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 summertime, 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.

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°C, 115°C and 130°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		1979/2004 PJM Value	2010/2024 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	Al Rigid	0.7	0.5	Decrease
	Al Stranded		0.7	N/A
	Cu Rigid	0.7	0.85	Increase
	Cu Stranded		0.7	N/A
Absorptivity	Al Rigid	0.9	0.5	Increase
	Al Stranded		0.9	N/A
	Cu Rigid	0.9	0.85	Increase
	Cu Stranded		0.9	N/A
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

Parameter		1979/2004 PJM Value	2010/2024 PJM Value	Resultant Effect On Ampacity
	Cu Wire, Strain	75°C	90°C	Increase
	Cu Wire, Non-Strain	75°C	130°C	Increase
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	100°C[5]	Increase
	Cu Wire, Non-Strain	95°C	130°C[6]	Increase
1 Hour Emergency Operating Temperature[7]	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	130°C[8]	Decrease
	Cu Wire, Strain	130°C	110°C[9]	Decrease
	Cu Wire, Non-Strain	140°C	140°C	Increase

[5] The 2010 version incorrectly identified this temperature as 115°C.

[6] The 2010 version incorrectly identified this temperature as 100°C.

[7] The 2010 version incorrectly identified this as 24 Hour.

[8] The 2010 version incorrectly identified this temperature as 140°C.

[9] The 2010 version incorrectly identified this temperature as 130°C.

Table 12-2

PJM Substation Bus Conductor Rating Comparison Table

Bus Size	Rating Condition	1979 PJM Ratings (Amperes) [10]	2010 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	Summer Normal	3340	3479	+4%
	Summer Emergency <24 Hrs.	4585	4365	**-5%**

[10] 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 70ºC and 120ºC. The ratings shown in the table above are based on 90ºC and represent typical values used. Individual substation owners may currently use different ratings due to the use of a different design temperature.

Bus Size	Rating Condition	1979 PJM Ratings (Amperes) [10]	2010 PJM Ratings (Amperes)	Change
Sch. 40 6061 Alloy	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%
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%

Bus Size	Rating Condition	1979 PJM Ratings (Amperes)[10]	2010 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%**
2” Aluminum Sch. 80	Summer Normal	1530	1722	+13%
	Summer Emergency <24 Hrs.	2280	2112	**-7%**
	Summer Emergency <1 Hr.	2435	2308	**-5%**
	Winter Normal	1760	2116	+20%

Bus Size	Rating Condition	1979 PJM Ratings (Amperes)[10]	2010 PJM Ratings (Amperes)	Change
6063 Alloy	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%**

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 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. Note, it is important to select the conductor from the dropdown bar and not manually type it in. Typing in this field could cause the conductor data not to update properly.

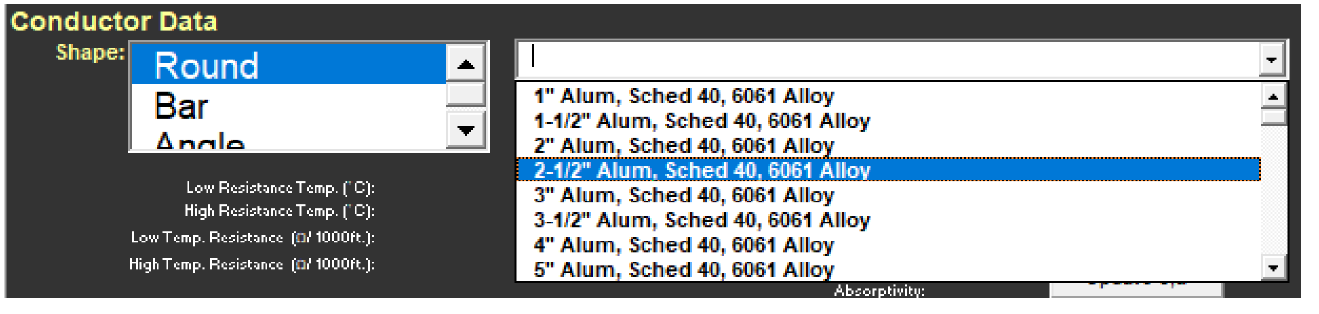


Figure 1: Bus Conductor Rating Program

- Review the month, day, time and atmospheric conditions parameters. The spreadsheet defaults to the PJM values. Adjust parameters as required and then click on the “Calculate” button.

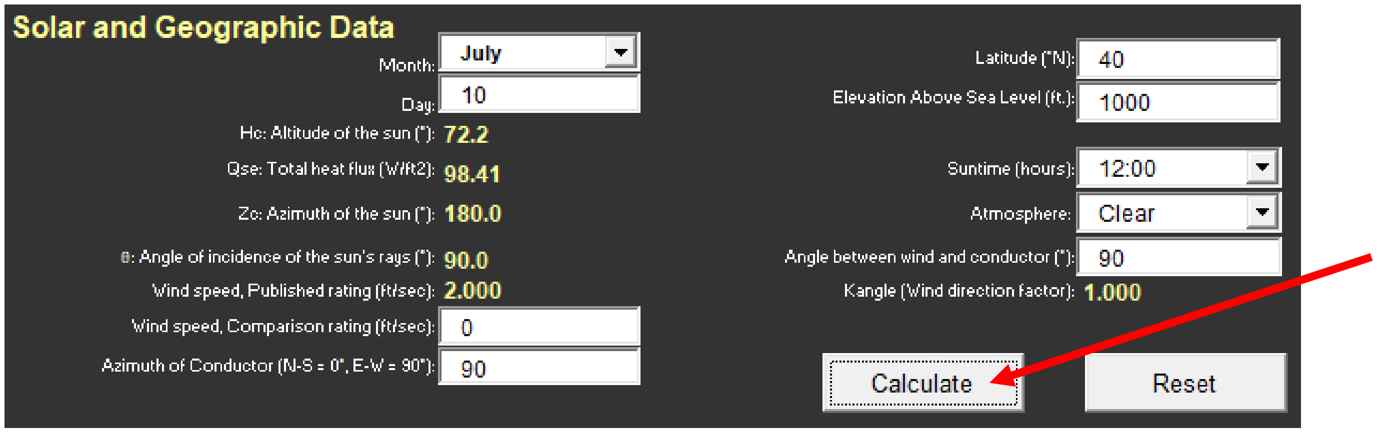


Figure 2: Calculation Set Up

- While remaining on the main page, one can view the **Ratings at a Glance** table at the bottom right. This table populates after clicking the “Calculate” button above.

At a Glance Rating Planning Rating (A)	Normal	Emergency 24 Hr	Emergency < 1 Hr
Summer Daytime	1729	2157	2373
Summer Nighttime	1955	2332	2529
Winter Daytime	2140	2482	2663
Winter Nighttime	2327	2636	2803
			2 ft/sec

Figure 3: Ratings at a Glance

To view the full ratings, navigate to the **Rating Report** page. It is the third tab. This tab calculates two sets of ratings, one for ambient temperatures in degrees Centigrade and one for ambient temperatures in degrees Fahrenheit.

Round Conductor Element

General data

Substation:	PJM Transmission & Substation Subcommittee (TSS)		
Bus description:	Substation Bus Conductors		
Element description:	-enter conductor info-		
Date prepared:	4-Jun-24	Prepared by:	PJM TSS

Conductor data

Name:	Round - 2-1/2" Alum, Sched 40, 6061 Alloy	Normal Temp. (°C):	90
Low Resistance Temp. (°C):	20	24 Hour Emergency Temp. (°C):	115
High Resisitance Temp. (°C):	70	4 Hour Emergency Temp. (°C):	130
Low Temp Resistance (Ω/1000ft.):	0.000012	Emissivity (e):	0.50
High Temp Resistance (Ω/1000ft.):	0.000014	Absorptivity (a):	0.50

Rating Parameters

Latitude (°N):	40	Wind speed, Published ratings (ft/s):	2.00
Elevation Above Sea Level (ft.):	1000	Wind speed, Comparison rating (ft/s):	0.00
Suntime (hours):	12:00	Kangle (Wind direction factor):	1.00
Atmosphere:	Clear	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 (Amps)

Ambient Temperature (°C)		Daytime Rating			Nighttime Rating		
Condition	Temp.	Normal	Emergency < 24 Hr	Emergency < 1 Hr	Normal	Emergency < 24 Hr	Emergency < 1 Hr
	-15	2472	2757	2914	2635	2897	3042
	-10	2410	2705	2866	2577	2847	2996
	-5	2346	2652	2817	2518	2796	2950
	0	2280	2597	2767	2456	2744	2902
	5	2212	2540	2716	2393	2691	2853
Winter Planning	10	2140	2482	2663	2327	2636	2803
	15	2066	2421	2608	2259	2579	2751
	20	1988	2359	2552	2188	2520	2698
	25	1906	2294	2495	2114	2460	2643
	30	1820	2227	2435	2036	2397	2587
Summer Planning	35	1729	2157	2373	1955	2332	2529
	40	1631	2084	2309	1869	2265	2469

Figure 4a: Rating Report in °C

Round Conductor Element

General data

Substation:	PJM Transmission & Substation Subcommittee (TSS)
Bus description:	Substation Bus Conductors
Element description:	-enter conductor info-
Date prepared:	4-Jun-24
Prepared by:	PJM TSS

Conductor data

Name:	Round - 2-1/2" Alum, Sched 40, 6061 Alloy	Normal Temp. (°C):	90
Low Resistance Temp. (°C):	20	24 Hour Emergency Temp. (°C):	115
High Resistance Temp. (°C):	70	4 Hour Emergency Temp. (°C):	130
Low Temp Resistance (Ω/1000ft.):	0.000012	Emissivity (e):	0.50
High Temp Resistance (Ω/1000ft.):	0.000014	Absorptivity (a):	0.50

Rating Parameters

Latitude (°N):	40	Wind speed, Published ratings (ft/s):	2.00
Elevation Above Sea Level (ft.):	1000	Wind speed, Comparison rating (ft/s):	0.00
Suntime (hours):	12:00	Kangle (Wind direction factor):	1.00
Atmosphere:	Clear	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 (Amps)

Ambient Temperature (°C)		Daytime Rating			Nighttime Rating		
Temp (°C)	Temp (°F)	Normal	Emergency < 24 Hr	Emergency < 1 Hr	Normal	Emergency < 24 Hr	Emergency < 1 Hr
-53.9	-65	2899	3125	3253	3039	3249	3368
-51.1	-60	2871	3101	3230	3012	3225	3346
-48.3	-55	2842	3076	3207	2985	3202	3324
-45.6	-50	2814	3051	3184	2958	3178	3302
-42.8	-45	2785	3026	3161	2930	3153	3279
-40.0	-40	2755	3000	3137	2903	3129	3257
-37.2	-35	2726	2975	3113	2874	3104	3234
-34.4	-30	2696	2949	3089	2846	3080	3211
-31.7	-25	2665	2922	3065	2817	3054	3187
-28.9	-20	2634	2896	3041	2788	3029	3164
-26.1	-15	2603	2869	3016	2758	3003	3140
-23.3	-10	2571	2842	2991	2728	2977	3116
-20.6	-5	2538	2814	2965	2697	2951	3091
-17.8	0	2505	2786	2940	2666	2924	3067
-15.0	5	2472	2757	2914	2635	2897	3042
-12.2	10	2438	2729	2887	2603	2869	3017
-9.4	15	2403	2699	2860	2571	2842	2991
-6.7	20	2368	2670	2833	2538	2814	2965
-3.9	25	2332	2640	2806	2504	2785	2939
-1.1	30	2295	2609	2778	2470	2756	2912

Figure 4b: Rating Report in °F

- For the next several tables, the tabs are color coded, yellow for round conductors, blue for bars and purple for angles.

Publication Table Bar (Night)	Publication Table Angle (Day)	Publication Table Angle (Night)	Publication Table Round (Day)

Figure 5: Color Codes Based on Shape

- The **Publication Tables** provide ratings charts which are shape specific and are completely copy-ready for simple transfer into other documents. Each tab has two charts, one for Celsius and one for Fahrenheit.

Round Bus Conductor: **2-1/2" Alum, Sched 40, 6061 Alloy**

***Note**: #NUM! Indicates that conductor cannot be operated at this temperature for the given ambient condition*

Celsius Table

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	2063	1983	1899	1810	1717	1617	1509	1392	1264	1119	951	743
	70	2210	2137	2062	1982	1899	1812	1719	1620	1513	1397	1270	1127
	80	2346	2279	2210	2138	2063	1984	1902	1815	1723	1625	1519	1404
Normal	**90**	2472	2410	2346	2280	2212	2140	2066	1988	1906	1820	1729	1631
	100	2591	2533	2474	2413	2350	2284	2216	2145	2072	1994	1913	1827
	110	2703	2649	2594	2537	2478	2418	2355	2290	2223	2152	2079	2002
Emergency (<24 hrs)	**115**	2757	2705	2652	2597	2540	2482	2421	2359	2294	2227	2157	2084
	120	2811	2760	2708	2655	2600	2544	2485	2425	2363	2298	2231	2162
Emergency (< 1 hr)	**130**	2914	2866	2817	2767	2716	2663	2608	2552	2495	2435	2373	2309
	140	3013	2968	2922	2874	2826	2776	2725	2673	2619	2563	2506	2446
	150	3109	3066	3023	2978	2932	2885	2837	2788	2737	2685	2632	2576
							WINTER					SUMMER	

Weather Assumptions:	Emissivity =	0.5	Suntime =	12:00
	Absorptivity =	0.5	Degrees North Latitude=	40
	Atmosphere =	Clear	Elevation Above Sea Level=	1000
	Azimuth of Conductor (N-S = 0, E-W = 90)	90	Z_1 (Angle between wind and conductor)	90
Conductor :	2-1/2" Alum, Sched 40, 6061 Alloy		Outside Diameter =	2.875 inches
	T_{low} =	20 °C	T_{high} =	70 °C
	R_{low} =	1.19500E-05 ohms/ft	R_{high} =	1.35300E-05 ohms/ft

Figure 6: Publication Table (Shape)

- The next set of tabs are comprised by the **Comparison Tables**. These tables are shape specific, and provide two rating tables for comparison. The first table shows the ratings at a wind speed of the user's designation. and the second shows the conductor ratings at the default wind speed of 2fps. It should be noted that the comparison wind speed is entered on the Main tab (first green tab). This wind speed will not impact the conductor ratings shown on the Rating Report tab (green).

Bus Conductor: **2-1/2" Alum, Sched 40, 6061 Alloy**

***Note**: #NUM! Indicates that conductor cannot be operated at this temperature for the given ambient condition*

Assumed Wind Speed = 0 fps

Rating	Rated Operating Temperature	Ambient Temperature (°C) -15	-10	-5	0	5	10	15	20	25	30	35	40
	60	1760	1674	1584	1490	1390	1284	1170	1045	905	742	536	170
	70	1921	1842	1761	1676	1588	1495	1397	1293	1181	1058	921	762
	80	2069	1996	1922	1844	1764	1681	1594	1503	1407	1304	1194	1073
Normal	**90**	**2207**	**2140**	**2070**	**1999**	**1925**	**1849**	**1771**	**1689**	**1603**	**1513**	**1418**	**1317**
	100	2338	2274	2209	2143	2075	2004	1932	1857	1780	1699	1614	1525
	110	2461	2401	2340	2278	2214	2149	2082	2013	1941	1867	1791	1711
Emergency (<24 hrs)	**115**	**2521**	**2463**	**2403**	**2343**	**2281**	**2218**	**2153**	**2086**	**2018**	**1947**	**1873**	**1797**
	120	2579	2522	2465	2406	2346	2285	2222	2158	2091	2023	1953	1880
Emergency (< 1 hr)	**130**	**2692**	**2638**	**2584**	**2528**	**2472**	**2414**	**2355**	**2294**	**2233**	**2169**	**2104**	**2036**
	140	2801	2750	2698	2645	2592	2537	2481	2424	2366	2307	2245	2183
	150	2907	2858	2808	2758	2707	2655	2602	2549	2494	2437	2380	2321
							WINTER					SUMMER	

Assumed Wind Speed = 2 fps

Rating	Operating Temperature	Ambient Temperature (°C) -15	-10	-5	0	5	10	15	20	25	30	35	40
	60	2063	1983	1899	1810	1717	1617	1509	1392	1264	1119	951	743
	70	2210	2137	2062	1982	1899	1812	1719	1620	1513	1397	1270	1127
	80	2346	2279	2210	2138	2063	1984	1902	1815	1723	1625	1519	1404
Normal	**90**	**2472**	**2410**	**2346**	**2280**	**2212**	**2140**	**2066**	**1988**	**1906**	**1820**	**1729**	**1631**
	100	2591	2533	2474	2413	2350	2284	2216	2145	2072	1994	1913	1827
	110	2703	2649	2594	2537	2478	2418	2355	2290	2223	2152	2079	2002
Emergency (<24 hrs)	**115**	**2757**	**2705**	**2652**	**2597**	**2540**	**2482**	**2421**	**2359**	**2294**	**2227**	**2157**	**2084**
	120	2811	2760	2708	2655	2600	2544	2485	2425	2363	2298	2231	2162
Emergency (< 1 hr)	**130**	**2914**	**2866**	**2817**	**2767**	**2716**	**2663**	**2608**	**2552**	**2495**	**2435**	**2373**	**2309**
	140	3013	2968	2922	2874	2826	2776	2725	2673	2619	2563	2506	2446
	150	3109	3066	3023	2978	2932	2885	2837	2788	2737	2685	2632	2576
							WINTER					SUMMER	

Figure 7: 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	H	I	J	K
1	**Conductor Data Table**		Note: FOR COPPER TUBES:								
2			R70c = 1.1925*R20c								
3							Rated Operating Temperatures			Emissivity	Absorptivity
4	Name	Outside Diam.	Rlow	Tlow	Rhigh	Thigh	Tnormal	ɘmergency<2	ɘmergency<1		
5		inches	u ohm/ft	deg C	u ohm/ft	deg C	deg C	deg C	deg C		
6											
7	1" Alum, Sched 40, 6061 Alloy	1.315	41.210	20	46.680	70	90	115	130	0.5	0.5
8	1-1/2" Alum, Sched 40, 6061 Alloy	1.900	25.450	20	28.820	70	90	115	130	0.5	0.5
9	2" Alum, Sched 40, 6061 Alloy	2.375	18.940	20	21.450	70	90	115	130	0.5	0.5
10	2-1/2" Alum, Sched 40, 6061 Alloy	2.875	11.950	20	13.530	70	90	115	130	0.5	0.5
11	3" Alum, Sched 40, 6061 Alloy	3.500	9.138	20	10.350	70	90	115	130	0.5	0.5
12	3-1/2" Alum, Sched 40, 6061 Alloy	4.000	7.957	20	8.613	70	90	115	130	0.5	0.5
123	User definable										
124	User definable										
125	User definable										
126	User definable										
127	User definable										

Figure 8: Conductor Data Table with User Definable Conductor Space

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

	A	B	C	D	E–J
1	**Weather Data**				
2					
3	Month	**July**			
4	Day	20			
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	0.85	0.5	*(selected when choosing conductor)*
10	Absorptivity (α)	0.5	0.85	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	**0**	(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/ft²)		To convert from Knots or mph to fps, enter below
21	Z_c (Azimuth of the sun)	180.00	°	Value used in	
22	θ (Effective angle of incidence of the sun's rays)	90.00	°	calculations and	2.00 Knots = 3.38 (ft/sec)
23				derived from the	30.00 miles/hr = 44.00 (ft/sec)
24				above data	
25					

Figure 9: 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		2-1/2" Alum, Sched 40, 6061 Alloy			0.25 x 4 inch copper bar		4 x 4 x 0.25 inch Aluminum Angle Alloy 6061-T6	
5	Diameter	2.875	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}	1.19500E-05	ohms/ft		8.72091E-06	ohms/ft	1.07959E-05	ohms/ft
13	Resistance@T_{high}	1.35300E-05	ohms/ft		1.04174E-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			0.85		0.5	
18	Absorptivity	0.5			0.85		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	4	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	14.6359195	Sq inches	60.35013895	Sq inches
25				Perimeter	8.5	inches	16	Sq inches

Figure 10: Conductor Data Table

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.

<u>The Ratings with Sun Tab:</u>

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: Round Conductor with SUN (Ampacity), Amperes

Atmosphere: **Clear**

2-1/2" Alum. Sched 40. 6061 Alloy **ε = 0.5** **α = 0.5**

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

Note *: #NUM! indicates that conductor cannot be operated at this temperature for the given ambient condition*

Ambient Temp (C)	-15	-10	-5	0	5	10.0 (Winter Planning)	15	20	25	30	35 (Summer Planning)	40
Max Op Temp (C)												
50	1583	1487	1385	1278	1161	1034	891	724	509	22	#NUM!	#NUM!
55	1673	1583	1488	1387	1281	1165	1039	898	733	522	121	#NUM!
60	1760	1674	1584	1490	1390	1284	1170	1045	905	742	536	170
65	1842	1760	1674	1585	1492	1393	1288	1175	1052	913	752	550
70	1921	1842	1761	1676	1588	1495	1397	1293	1181	1058	921	762
75	1996	1921	1843	1762	1678	1591	1499	1402	1298	1187	1065	930
80	2069	1996	1922	1844	1764	1681	1594	1503	1407	1304	1194	1073
85	2139	2069	1997	1923	1847	1767	1685	1598	1508	1412	1310	1201
90	2207	2140	2070	1999	1925	1849	1771	1689	1603	1513	1418	1317
95	2273	2208	2141	2072	2001	1928	1853	1775	1693	1608	1519	1425
100	2338	2274	2209	2143	2075	2004	1932	1857	1780	1699	1614	1525
105	2400	2339	2276	2211	2146	2078	2008	1936	1862	1785	1705	1621
110	2461	2401	2340	2278	2214	2149	2082	2013	1941	1867	1791	1711
115	2521	2463	2403	2343	2281	2218	2153	2086	2018	1947	1873	1797
120	2579	2522	2465	2406	2346	2285	2222	2158	2091	2023	1953	1880
125	2636	2581	2525	2468	2410	2350	2289	2227	2163	2097	2029	1959
130	2692	2638	2584	2528	2472	2414	2355	2294	2233	2169	2104	2036
135	2747	2695	2641	2587	2532	2476	2419	2360	2300	2239	2175	2110
140	2801	2750	2698	2645	2592	2537	2481	2424	2366	2307	2245	2183
145	2854	2804	2754	2702	2650	2597	2542	2487	2431	2373	2314	2253
150	2907	2858	2808	2758	2707	2655	2602	2549	2494	2437	2380	2321
155	2958	2910	2862	2813	2763	2713	2661	2609	2555	2501	2445	2388
160	3009	2962	2915	2867	2819	2769	2719	2668	2616	2563	2508	2453
165	3059	3014	2967	2921	2873	2825	2776	2726	2675	2624	2571	2517
170	3109	3064	3019	2973	2927	2880	2832	2783	2734	2683	2632	2579
175	3158	3114	3070	3025	2980	2934	2887	2839	2791	2742	2692	2641
180	3206	3164	3120	3076	3032	2987	2941	2895	2848	2800	2751	2701

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

Ambient Temp (C)	-15	-10	-5	0	5	10 (Winter Planning)	15	20	25	30	35 (Summer Planning)	40
Max Op Temp (C)												
50	1901	1811	1717	1616	1507	1389	1259	1113	943	732	422	#NUM!
55	1984	1900	1811	1716	1616	1508	1391	1261	1116	947	737	433
60	2063	1983	1899	1810	1717	1617	1509	1392	1264	1119	951	743
65	2138	2062	1982	1899	1811	1717	1618	1511	1395	1267	1123	956
70	2210	2137	2062	1982	1899	1812	1719	1620	1513	1397	1270	1127
75	2279	2210	2137	2062	1983	1900	1813	1721	1622	1516	1401	1274
80	2346	2279	2210	2138	2063	1984	1902	1815	1723	1625	1519	1404
85	2410	2346	2279	2210	2139	2064	1986	1904	1817	1726	1628	1522
90	2472	2410	2346	2280	2212	2140	2066	1988	1906	1820	1729	1631
95	2532	2473	2411	2348	2282	2214	2143	2069	1991	1910	1824	1732
100	2591	2533	2474	2413	2350	2284	2216	2145	2072	1994	1913	1827
105	2648	2592	2535	2476	2415	2352	2287	2219	2149	2075	1998	1917
110	2703	2649	2594	2537	2478	2418	2355	2290	2223	2152	2079	2002
115	2757	2705	2652	2597	2540	2482	2421	2359	2294	2227	2157	2084
120	2811	2760	2708	2655	2600	2544	2485	2425	2363	2298	2231	2162
125	2863	2813	2763	2711	2658	2604	2548	2490	2430	2368	2303	2236
130	2914	2866	2817	2767	2716	2663	2608	2552	2495	2435	2373	2309

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 nighttime since it is absent solar exposure. No user inputs are required.

Steady State Thermal Rating: Round Conductor without SUN (Ampacity), Amperes

Atmosphere: **Clear**

2-1/2" Alum, Sched 40, 6061 Alloy e= 0.5 a= 0.5

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

Note *: #NUM! indicates that conductor cannot be operated at this temperature for the given ambient condition*

					Winter Planning					Summer Planning	
Ambient Temp (C)	-15	-10	-5	0	5	10.0	15	20	25	30	35	40
Max Op Temp (C)												
50	1849	1768	1683	1596	1504	1408	1307	1199	1083	956	814	650
55	1924	1846	1765	1682	1595	1504	1408	1308	1200	1084	958	816
60	1997	1922	1844	1764	1681	1594	1504	1409	1308	1201	1086	960
65	2067	1995	1920	1843	1763	1680	1594	1504	1410	1310	1203	1088
70	2135	2065	1993	1918	1842	1763	1680	1595	1505	1411	1311	1205
75	2201	2133	2063	1992	1918	1842	1763	1681	1596	1507	1413	1314
80	2265	2199	2132	2062	1991	1918	1842	1764	1682	1598	1509	1415
85	2328	2264	2198	2131	2062	1991	1918	1843	1765	1684	1600	1511
90	2388	2326	2262	2197	2131	2062	1992	1919	1845	1767	1686	1602
95	2448	2387	2325	2262	2197	2131	2063	1993	1921	1847	1769	1689
100	2506	2447	2387	2325	2262	2198	2132	2065	1995	1924	1849	1772
105	2562	2505	2446	2387	2326	2263	2200	2134	2067	1998	1926	1852
110	2618	2562	2505	2447	2387	2327	2265	2202	2137	2070	2001	1930
115	2673	2618	2562	2506	2448	2389	2329	2267	2204	2140	2073	2004
120	2726	2673	2618	2563	2507	2450	2391	2331	2270	2208	2143	2077
125	2779	2727	2674	2620	2565	2509	2452	2394	2335	2274	2211	2147
130	2830	2779	2728	2675	2622	2567	2512	2455	2398	2338	2278	2216
135	2881	2832	2781	2730	2677	2624	2570	2515	2459	2402	2343	2283
140	2932	2883	2833	2783	2732	2681	2628	2574	2519	2464	2406	2348
145	2981	2934	2885	2836	2786	2736	2684	2632	2579	2524	2469	2412
150	3030	2983	2936	2888	2839	2790	2740	2689	2637	2584	2530	2474
155	3079	3033	2986	2939	2892	2844	2795	2745	2694	2642	2589	2535
160	3126	3082	3036	2990	2944	2896	2848	2800	2750	2700	2648	2596
165	3174	3130	3085	3040	2995	2948	2901	2854	2805	2756	2706	2655
170	3220	3177	3134	3090	3045	3000	2954	2907	2860	2812	2763	2713
175	3267	3225	3182	3139	3095	3051	3006	2960	2914	2867	2819	2770
180	3313	3271	3230	3187	3144	3101	3057	3012	2967	2921	2874	2827

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

					Winter Planning					Summer Planning	
Ambient Temp (C)	-15	-10	-5	0	5	10	15	20	25	30	35	40
Max Op Temp (C)												
50	2128	2048	1965	1877	1785	1686	1581	1467	1343	1204	1045	856
55	2200	2124	2045	1962	1875	1782	1684	1579	1466	1341	1203	1044
60	2269	2196	2121	2042	1959	1872	1780	1683	1578	1464	1340	1202
65	2335	2266	2193	2118	2040	1957	1871	1779	1681	1577	1464	1340
70	2399	2332	2263	2191	2116	2038	1956	1869	1778	1681	1576	1463
75	2461	2397	2330	2261	2189	2115	2037	1955	1869	1777	1680	1576
80	2521	2459	2395	2328	2260	2188	2114	2036	1954	1868	1777	1680
85	2579	2519	2457	2393	2327	2259	2188	2113	2036	1954	1868	1777
90	2635	2577	2518	2456	2393	2327	2259	2188	2114	2036	1955	1869
95	2690	2634	2576	2517	2456	2392	2327	2259	2188	2114	2037	1956
100	2743	2689	2633	2576	2517	2456	2393	2327	2260	2189	2115	2038
105	2796	2743	2689	2634	2576	2518	2457	2394	2329	2261	2190	2117
110	2847	2796	2743	2690	2634	2577	2519	2458	2395	2330	2263	2192
115	2897	2847	2796	2744	2691	2636	2579	2520	2460	2397	2332	2265
120	2946	2898	2848	2798	2746	2693	2638	2581	2523	2462	2400	2335

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)**

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

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) = $(T_c + T_a)/2$

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	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 (pf) 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 (ρ_f), (lb/ft³)

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	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

The Air Viscosity (uf) 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 (μ_f), (lb/ft*h)

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	0.043631	0.043921	0.04421	0.044498	0.044785	0.04507	0.045355	0.045638	0.04592	0.046201	0.046481	0.04676
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)

2-1/2" Alum, Sched 40, 6061 Alloy

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	31.19	28.10	25.09	22.18	19.36	16.64	14.03	11.52	9.14	6.88	4.79	2.87
V2	2	50	45.49	41.92	38.35	34.80	31.27	27.74	24.24	20.74	17.25	13.78	10.32	6.87
V1	0	55	34.07	30.92	27.86	24.88	22.00	19.20	16.51	13.91	11.43	9.06	6.83	4.75
V2	2	55	48.90	45.33	41.76	38.22	34.68	31.16	27.65	24.15	20.67	17.20	13.74	10.29
V1	0	60	36.98	33.78	30.66	27.63	24.68	21.82	19.05	16.37	13.80	11.34	8.99	6.78
V2	2	60	52.30	48.72	45.16	41.62	38.08	34.56	31.06	27.56	24.08	20.61	17.14	13.69
V1	0	65	39.92	36.67	33.50	30.41	27.40	24.48	21.64	18.90	16.25	13.69	11.25	8.92
V2	2	65	55.68	52.11	48.55	45.01	41.48	37.96	34.45	30.96	27.47	24.00	20.54	17.09
V1	0	70	42.88	39.58	36.37	33.23	30.16	27.18	24.28	21.47	18.75	16.12	13.59	11.16
V2	2	70	59.06	55.49	51.93	48.39	44.86	41.34	37.84	34.34	30.86	27.39	23.93	20.48
V1	0	75	45.86	42.53	39.26	36.07	32.96	29.92	26.97	24.09	21.30	18.60	16.00	13.48
V2	2	75	62.43	58.86	55.30	51.76	48.23	44.71	41.21	37.72	34.24	30.77	27.31	23.86
V1	0	80	48.87	45.49	42.18	38.95	35.78	32.70	29.69	26.76	23.91	21.14	18.46	15.87
V2	2	80	65.78	62.22	58.66	55.12	51.59	48.08	44.58	41.08	37.60	34.13	30.68	27.23

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 kf tab:

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

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	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 daytime ratings.

The q_s tab:

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

2-1/2" Alum, Sched 40, 6061 Alloy						0 ε= 0.5		α= 0.5						
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	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V2	2	50	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V1	0	55	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V2	2	55	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V1	0	60	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V2	2	60	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V1	0	65	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V2	2	65	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V1	0	70	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789
V2	2	70	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789	11.789

The q_r tab:

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.

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

2-1/2" Alum, Sched 40, 6061 Alloy ε= 0.5 α= 0.5

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	12.9056	12.1986	11.4500	10.6583	9.8220	8.9393	8.0085	7.0279	5.9959	4.9106	3.7702	2.5728
V2	2	50	12.9056	12.1986	11.4500	10.6583	9.8220	8.9393	8.0085	7.0279	5.9959	4.9106	3.7702	2.5728
V1	0	55	14.2850	13.5779	12.8293	12.0377	11.2013	10.3186	9.3878	8.4073	7.3752	6.2899	5.1495	3.9522
V2	2	55	14.2850	13.5779	12.8293	12.0377	11.2013	10.3186	9.3878	8.4073	7.3752	6.2899	5.1495	3.9522
V1	0	60	15.7289	15.0218	14.2732	13.4816	12.6452	11.7625	10.8317	9.8512	8.8191	7.7338	6.5934	5.3961
V2	2	60	15.7289	15.0218	14.2732	13.4816	12.6452	11.7625	10.8317	9.8512	8.8191	7.7338	6.5934	5.3961
V1	0	65	17.2393	16.5322	15.7837	14.9920	14.1556	13.2729	12.3421	11.3616	10.3295	9.2442	8.1038	6.9065
V2	2	65	17.2393	16.5322	15.7837	14.9920	14.1556	13.2729	12.3421	11.3616	10.3295	9.2442	8.1038	6.9065
V1	0	70	18.8182	18.1112	17.3626	16.5710	15.7346	14.8519	13.9211	12.9405	11.9085	10.8232	9.6828	8.4855
V2	2	70	18.8182	18.1112	17.3626	16.5710	15.7346	14.8519	13.9211	12.9405	11.9085	10.8232	9.6828	8.4855
V1	0	75	20.4678	19.7607	19.0122	18.2205	17.3841	16.5014	15.5706	14.5901	13.5580	12.4727	11.3323	10.1350
V2	2	75	20.4678	19.7607	19.0122	18.2205	17.3841	16.5014	15.5706	14.5901	13.5580	12.4727	11.3323	10.1350

The Resistance tab:

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.

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

2-1/2" Alum, Sched 40, 6061 Alloy

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	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05
V2	2	50	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05	1.290E-05
V1	0	55	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05
V2	2	55	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05	1.306E-05
V1	0	60	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05
V2	2	60	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05
V1	0	65	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05
V2	2	65	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05	1.337E-05
V1	0	70	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05
V2	2	70	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05
V1	0	75	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05
V2	2	75	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05	1.369E-05

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
2. *IEEE Guide for Design of Substation Rigid-Bus Structures*, IEEE Std 605
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, December 2022.
8. *PJM Manual 03: "Transmission Operations".*

APPENDIX D

Explanation of PJM Bus Rating Spreadsheet Formulas

When evaluating the formulas in the PJM Bus Rating Spreadsheet, the formulas may not seem to intuitively agree with the IEEE standards, upon further review, the formulas do appear correct. The following questions and answers is intended to help future users understand the spreadsheet formulas.

1. **Absolute viscosity of air**

   Question:

   The formula for dynamic viscosity from IEEE Standard 738 (eq 14) is:

$$\mu_f = 9.806 * 10^{-7} * \frac{\left(T_{film} + 273\right)^{1.5}}{T_{film} + 383.4} \frac{lb}{ft - s}$$

   The formula for the viscosity of air from the Excel spreadsheet (uf), on the other hand, is:

$$\mu_f = 0.0415 + 1.2034 * 10^{-4}(T_{film}) - 1.1442 * 10^{-7}\left(T_{film}\right)^2 + 1.9416 * 10^{-10}\left(T_{film}\right)^3$$

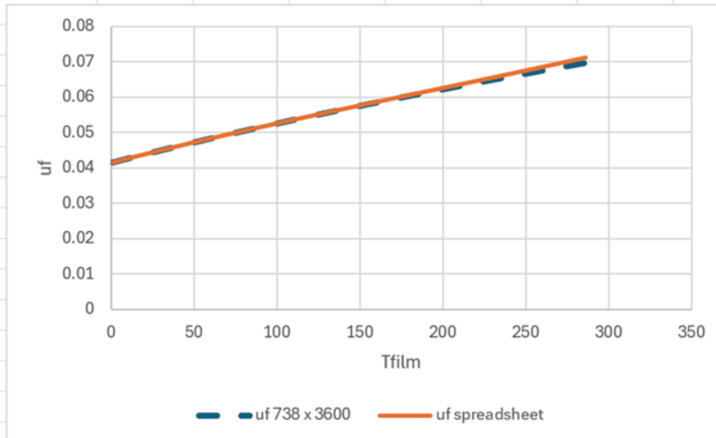
   Where did this formula come from? Is this a Taylor expansion of the first formula? Is it necessary to use a Taylor approximation when computers in this day and age are so powerful?

   Answer:

   It seems what is in the spreadsheet approximates the IEEE 738 standard (see picture below) scaled by approximately 3600 (seconds in an hour). I think the expanded equation could probably be replaced, my guess is that someone had datapoints for uf, and just did a line-of-best-fit.

   We suspect this is done in the spreadsheet because IEEE 738-1993 does not include a formula for μ_f but instead includes a table of μ_f for different values of T_{film}.

Tflim	uf 738 x 3600	uf spreadsheet
1	0.0416521	0.04162023
2	0.04177166	0.04174022
3	0.04189102	0.04186
4	0.04201017	0.04197954
5	0.04212912	0.04209886
6	0.04224786	0.04221796
7	0.04236641	0.04233684
8	0.04248475	0.0424555
9	0.04260289	0.04257393
10	0.04272083	0.04269215
11	0.04283857	0.04281015
12	0.04295612	0.04292794
13	0.04307346	0.04304551
14	0.04319061	0.04316287
15	0.04330757	0.04328001
16	0.04342433	0.04339694
17	0.04354089	0.04351367
18	0.04365726	0.04363018



2. Forced Convection of round conductor

Question:

The formula for convective heat loss of a round conductor at high wind speeds, as stated on page 10 of the PJM Outdoor Substation Conductors Ratings guide, is:

$$q_{c2} = 0.1695 * \left(3600\frac{D * \rho * V}{\mu_f}\right)^{0.52} * k_f * (T_c - T_a)$$

The formula in the Excel spreadsheet (qc) is slightly different. It is:

$$q_{c2} = K_{angle} * 0.1695 * \left(3600\frac{D * \rho * V}{\mu_f}\right)^{0.6} * k_f * (T_c - T_a)$$

Why is the exponent different? I noticed that this is the version of the formula from eq 10 of IEEE 738:

$$q_{c2} = K_{angle} * 0.754 * \left(\frac{D * \rho * V}{\mu_f}\right)^{0.6} * k_f * (T_c - T_a)$$

Answer:

The exponent in the q_{c2} formula in the PJM Outdoor Substation Conductor Ratings guide should be 0.6. The spreadsheet formula matches the IEEE 738-1998 version of the standard formulas (see below). (Note: In IEEE 738-1998 K_angle is not directly included in the qc formulas, but is mentioned elsewhere)

2.4.3 Forced convection heat loss

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

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

The reason the formulas are different is that IEEE 738-2023 and IEEE 738-1998 use different units for the inputs to the Reynolds number formula. Specifically:

Input Variable	Units in IEEE 738-2023	Units in Spreadsheet (IEEE 738-1993)
D_0 conductor diameter	ft	in
μ_f Absolute (dynamic) viscosity of air	lb/(ft-s)	lb/(ft-hr)

If we start from the formula for Reynold's number in IEEE 738-2023:

$$N_{Re} = \frac{D_0[ft] * \rho_f \left[\frac{lb}{ft^3}\right] * V_w \left[\frac{ft}{s}\right]}{\mu_f \left[\frac{lb}{ft - s}\right]}$$

And apply unit conversions:

$$N_{Re} = \frac{D_0[in] \left[\frac{1\ ft}{12\ in}\right] * \rho_f \left[\frac{lb}{ft^3}\right] * V_w \left[\frac{ft}{s}\right]}{\mu_f \left[\frac{lb}{ft - hr}\right] \left[\frac{1\ hr}{3600\ s}\right]}$$

We get the following formula (for D_0 in inches and μ_f in lb/(ft-hr))

$$N_{Re} = 3600 \frac{\frac{D_0}{12} * \rho_f * V_w}{\mu_f}$$

Revisiting the q_{c2} formula per IEEE 738-2023:

$$q_{c2} = K_{angle} * 0.754 * N_{Re}^{0.6} * k_f * (T_s - T_a)$$

Substituting the above equation for N_{Re}:

$$q_{c2} = K_{angle} * 0.754 * \left(3600 \frac{\frac{D_0}{12} * \rho_f * V_w}{\mu_f}\right)^{0.6} * k_f * (T_s - T_a)$$

For whatever reason, the Excel formula was re-arranged to keep the 3600 within the exponent, but pulled the 1/12 out, resulting in:

$$q_{c2} = K_{angle} * 0.754 * \left(\frac{1}{12}\right)^{0.6} \left(3600 \frac{D_0 * \rho_f * V_w}{\mu_f}\right)^{0.6} * k_f * (T_s - T_a)$$

$$q_{c2} = K_{angle} * 0.16977 \left(3600 \frac{D_0 * \rho_f * V_w}{\mu_f}\right)^{0.6} * k_f * (T_s - T_a)$$

While 0.16977 [above formula] $\neq 0.1695$ [spreadsheet], I suspect the IEEE 738-1993 standard made slightly different rounding steps.

3. Heat transfer coefficient:

Question:

The formula for the heat transfer coefficient, as stated on page 13 of the PJM Outdoor Substation Conductors Ratings guide, is:

$$H = .66 \left(\frac{Lv\rho_a}{\mu}\right)^{-\frac{1}{2}} \left(\frac{C_p\mu}{k}\right)^{-\frac{2}{3}} (C_p v \rho_a)$$

where

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

v = air velocity in feet/hr

ρ_a = density of air, lb/cubic feet

μ = vicosity of air, lb/ft-sec

C_p = heat capacity of air, BTU/lb-°F

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

$\frac{C_p\mu}{k}$ =the Prandtl number of air (dimensionless)

The formula that is in the tab (hflatsqrtL) is

$$H = .66 \left(\frac{3600v\rho_a}{\mu}\right)^{-\frac{1}{2}} (.74)^{-\frac{2}{3}} (.235 * 3600 * v\rho_a)$$

Answer:

- The 3600-conversion factor comes from having 3600 seconds in one hour.
- Do we assume that the length of flow path is always going to be one foot?
- This formula states that the Prandtl number of air is .74. According to Wikipedia, it is .71. https://en.wikipedia.org/wiki/Prandtl_number#:~:text=around%200.71%20for%20air%20and%20many%20other%20gases
- According to this formula, the heat capacity of air, $C_p = .235 \frac{BTU}{\text{lb} - {}^\circ\text{F}}$. According to the below website, it is $C_p = .2403 \frac{BTU}{\text{lb} - {}^\circ\text{F}}$.
- https://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html

Answer:

The heat transfer coefficient is very confusing in the spreadsheet and is tied directly to the forced convection equation. First, notice that the spreadsheet calculates hflatsqrtL, H(L^0.5), not H. Since L is the unit length for that dimension, it included in the forced convection equation, qcf Bar. These equations are described in the IEEE 605-1998 standard in section C.3.2.1, which I believe was the original source for the spreadsheet. For a more detailed derivation, please see the following figure where the units are in brackets [].

units from spreadsheet:

$u \rightarrow lb/fthr$; Absolute viscosity of air

$p^a \rightarrow lb/ft^3$; density of air

$Pr \rightarrow$ Prantl's number is unitless

$C_p \rightarrow .235\ btu/lbF^o$; Heat capacity of air

$L \rightarrow in$; L is given in inches, as a dimension of the conductor

$v \rightarrow ft/s$

$$h = .66\left(\frac{u[lb/fthr]/p^a[lb/ft^3]}{L[in]v[ft/s]}\right)^{1/2} Pr^{-2/3}(C_p[btu/lbF^o]v[ft/s]p^a[lb/ft^3]) \quad (8)$$

separate variables and units:

$$h = .66\left(\frac{u}{p^a}\frac{1}{Lv}\right)^{1/2}\left[\frac{lb}{ft\,hr}\frac{ft^3}{lb}\frac{s}{ft\,in}\right]^{1/2} Pr^{-2/3}(C_p\,v\,p^a)\left[\frac{btu}{lb\,F^o}\frac{ft}{s}\frac{lb}{ft^3}\right] \quad (9)$$

substitute to cancel units. We want h to have the units $\frac{BTU}{hr\,F^o\,ft^2}$

$$h = .66\left(\frac{u}{p^a}\frac{1}{Lv}\right)^{1/2}\left[\frac{lb}{ft\,hr}\frac{ft^3}{lb}\frac{s}{ft\,in}\frac{hr}{3600s}\frac{12in}{ft}\right]^{1/2} Pr^{-2/3}(C_p\,v\,p^a)\left[\frac{btu}{lb\,F^o}\frac{ft}{s}\frac{lb}{ft^3}\frac{3600s}{hr}\right] \quad (10)$$

$$h = .66\left(\frac{u}{p^a}\frac{1}{Lv}\right)^{1/2}\left[\frac{lb}{ft\,hr}\frac{ft^3}{lb}\frac{s}{ft\,in}\frac{hr\,in}{s\,ft}\right]^{1/2}\left(\frac{12}{3600}\right)^{1/2} Pr^{-2/3}(C_p\,v\,p^a)\left[\frac{btu}{lb\,F^o}\frac{ft}{s}\frac{lb}{ft^{3}}\frac{3600s}{hr}\right] \quad (11)$$

$$h = .66\left(\frac{u}{p^a}\frac{1}{Lv}\right)^{1/2}\left(\frac{12}{3600}\right)^{1/2} Pr^{-2/3}(C_p\,v\,p^a)3600\left[\frac{btu}{F^o\,ft^2\,hr}\right] \quad (12)$$

The 3600 multipliers to convert ft/s to ft/hr are included in the original calculation of h in the spreadsheet, but the $\sqrt{12}$ is not. Therefore, the spreadsheet calculations include the $\sqrt{12}$ later in the forced convection equation.

The formula that is in the tab (hflatsqrtL) is

$$H\ (L^{0.5}) = .66\left(\frac{3600v\rho_a}{\mu}\right)^{-\frac{1}{2}}(.74)^{-\frac{2}{3}}(.235 * 3600 * v\rho_a)$$

Q. Do we assume that the length of flow path is always going to be one foot?

A. The unit length conversion with the sqrt(12) is included in the forced convection equation

Q. This formula states that the Prandtl number of air is .74. According to Wikipedia, it is .71. https://en.wikipedia.org/wiki/Prandtl_number#:~:text=around%200.71%20for%20air%20and%20many%20other%20gases

A. The Prandtl number is assumed to be .74 in the IEEE 605-1998 Standard in section C.3.1

Q. According to this formula, the heat capacity of air, $C_p = .235 \frac{BTU}{\text{lb} - °\text{F}}$. According to the below website, it is $C_p = .2403 \frac{BTU}{\text{lb} - °\text{F}}$.
https://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html

$A.\ C_p = .235 \frac{BTU}{\text{lb} - °\text{F}}$. Is used in the IEEE 608-1998 Standard in section C.3.1

4. Natural convection of Angle conductors

Question:

The formula for the natural convection of angle conductors, as stated on page 9 of the PJM Outdoor Substation Conductors Ratings guide, is:

$$q_{c0} = 0.0462 * \Delta T^{1.25} * (l^{0.75} + w^{0.75})$$

The formula in the spreadsheet tab (qnat Angle) is

$$q_{c0} = 0.0462 * \Delta T^{1.25} * (w^{0.25} + h^{-0.75})(N - 1)$$

Where

$l =$ length of angle

$w =$ width of angle

$h =$ height of conductor

$N =$ number of conductors

Answer:

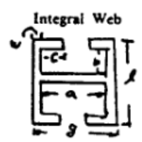
The forced and natural convection of angle conductors seems to be a combination of equations from IEEE 605-1998 section C.3.2.6. From the table on page 59 (see figure). The 3rd column (Area for Natural Convection) is usually 0, and due to the N-1, the result in the spreadsheet always produces 0 = qNat Angle. I would confirm that none of your substation angle conductors are double or more, otherwise, the natural convection should always be 0, and this strange (incorrect?) implementation would not affect your results.

C.3.2 6. Summation of convective losses

For each of the conventional types of bus conductor, the convective loss areas for which the formulas given in items 1, 2, and 3 apply are as follows.

qNat Angle

qcf Angle

Shape	Area for Forced Convection	Area for Natural Convection	Summation of Convection Losses
Single Rectangle	$24\ (l+t)$	0	$0.288\ \Delta T(l^{1/2} + t^{1/2})$
Multiple (N) Rectangles	$24(l+Nt)$	$24l(N-1)$	$0.288\ \Delta T(l^{1/2} + Nt^{1/2}) + 0.0528\ \Delta T^{1.25}\ l^{.75}\ (N-1)$
Round Tube or Bar	$12\pi d$	0	$0.377\ \Delta T\ d^{0.6}$
Square Tube	$48l$	0	$0.576\ \Delta T l^{1/2}$
Rectangular Tube ($l \times w$)	$24(l+w)$	0	$0.288\ \Delta T(l^{1/2} + w^{1/2})$
Universal Angle ($l \times w$)(ignoring thickness)	$24(l+w)$	0	$0.288\ \Delta T(l^{1/2} + w^{1/2})$
Double Angles (for 2 angles)	$24(l+w)$	$24(l+w)$*	$0.288\ \Delta T(l^{1/2} + w^{1/2}) + 0.0462\ \Delta T^{1.25}\ (l^{.75} + w^{.25})$
Single Channel	$24(l+2w)$	0	$0.288\ \Delta T(l^{1/2} + 2w^{1/2})$
Double Channel	$24(l+2w)$	$24(l+2w)$*	$0.288\ \Delta T(l^{1/2} + 2w^{1/2})$ $0.0462\ \Delta T^{1.25}\ (l^{.75} + 2w^{.75})$
Integral Web 	$24(l+2w)$	$24(a + 2b + 2c)$**	$0.288\ \Delta T(l^{1/2} + 2w^{1/2})$ $0.0264\ T^{1.25}\ (a^{.75} + 2b^{.75} + 2c^{.25})$

* Average over all surfaces on interior assuming equivalent of 3 favorably oriented surfaces and 1 unfavorable $\left[\frac{3(0.0022) + (0.0011)}{4}\right]24 = 0.0462$

The formula for the natural convection of angle conductors, as stated on page 9 of the PJM Outdoor Substation Conductors Ratings guide, is:

$$q_{c0} = 0.0462 * \Delta T^{1.25} * (l^{0.75} + w^{0.75})$$

The formula in the spreadsheet tab (qNat Angle) is

$$q_{c0} = 0.0462 * \Delta T^{1.25} * (w^{0.25} + h^{-0.75})(N - 1)$$

Where

l = length of angle

w = width of angle

h = height of conductor

N = number of conductors

5. Forced convection of Bar and Angle conductors

Question:

The formula for the forced convection of flat conductors, as stated on page 13 of the PJM Outdoor Substation Conductors Ratings guide, is:

$$q_{c0} = 0.00367HA\Delta T$$

where A is the area of the flat surface and H is the heat transfer coefficient (not the height of the conductor).

The formula on the spreadsheet tab (qcf Bar) is

$$q_{c0} = 0.305H\Delta T\left(\sqrt{w}+\sqrt{t}\right)N$$

Where

w = width of conductor

t = thickness of conductor

N = number of conductors

The formula on the spreadsheet tab (qcf Angle) is

$$q_{c0} = 0.305H\Delta T\left(\sqrt{w}+\sqrt{h}\right)$$

h = height of conductor

These do not look like the formulas for area, perimeter, or the Pythagorean theorem.

Answer:

Please see section C.3.2.1 in IEEE 605-1998. The sqrts for the width and heights, $\left(\sqrt{w}+\sqrt{h}\right)$, are due to the unit surface area (perimeter) divided by the sqrt of their unit length. The qcf Bar equation is a result of the surface area (perimeter), divided by the square root of the unit length L, for each dimension:

$$q_{c0} = 0.305\ (HL^{0.5})T\frac{A}{L^{0.5}} = 0.305\ (HL^{0.5})T(\frac{w}{\sqrt{w}}+\frac{h}{\sqrt{h}}) = \ 0.305H\Delta T\left(\sqrt{w}+\sqrt{h}\right)$$

The conversion for the inches to feet of the unit length L is applied in the forced convection equation in the spreadsheet. Note that $0.305 = .00367 * 12^{.5} * 24$ to include the unit length L conversion of inches to feet $12^{.5}$ and the perimeter inches to feet (2(w + h) *12).