Duct Bank Heating Calculations are Essential for Critical Environments (Data Centers)

Electrical heating calculations may need to be performed when large amounts electrical duct banks with significant amounts of conduits and conductors are routed below grade in the earth. These heating calculations are performed to determine if any de rating of the conductors is required. This de rating is based on many factors including but not limited to the following:

1. Number and size of conduits and conductors
2. Configuration of the conduits and conductors
3. Spacing between the conduits in both the horizontal and vertical dimensions
4. Amount of earth above the conductors
5. The RHO factor and the amount of the back fill material
6. Load factor of the conductors
7. The actual design load

As in any situation, if the electrical conductors overheat past their rated use, the insulation protecting the conductor could burn off or degrade to a point where a short circuit condition could be precipitated.

As defined in this article the Load Factor plays a major role in defining if an installation will have a problem with overheating. A data center environment will typically have a very high Load Factor value, which will lead to significant problems if not designed properly. **At Lane Coburn & Associates, LLC, we are beginning to see existing data centers with significant overheating issues. The large underground feeders serving these data centers posed no problems before these critical environments were loaded up to the intended design loads. We are starting to see existing data centers that previously never achieved 50% of the design capacity, now running at or near capacity.**

Electrical conductor heating calculations can be very complicated based on many of the variables noted previously. There are various software programs available for determining the potential de rating of feeder conductors in large electrical duct banks. It is also critical to hire a Professional Electrical Engineer with expertise in both critical environments topology and on providing Neher-McGrath calculations.

Definitions utilized in the calculation

Load Factor - The ratio of the average load in kilowatts supplied during a designated period to the peak or maximum load in kilowatts taking place in that period. Load factor, in percent, also can be derived by multiplying the kilowatt hours (kWh) in the period by 100 and dividing by the product of the maximum demand in kilowatts and the number of hours in the period.

Example: Load Factor Calculation - *Load Factor = kilowatt hours/hours in period/kilowatts. Assume a 1 day billing period or 1 times 24 hours for a total of 24 hours. Assume a customer used 15,000 kWh and had a maximum demand of 1500 kW. The customer's load factor would be 41.6 percent ((15000 kWh/24 hours/1500 kW)*100). The 41.6 % load factor may be representative of a standard commercial building. The load factor in a data center with fairly constant load 24 hours of the day should be significantly higher.*

RHO – Thermal resistivity. Thermal resistivity, as used in the National Electrical Code annex, indicates the heat transfer capability through a substance in the trench by conduction. This value is the reciprocal of thermal conductivity and is typically expressed in the units C-cm/watt.

Where an underground electrical duct bank installation utilizes the configurations identified in the National Electrical Code examples, the National Electrical Code indicates in section 310-15 (b), that calculations can be accomplished to determine actual rating of the conductors. A formula is provided in the National Electrical Code that can be utilized under “Engineering Supervision” to provide these calculations. This formula is typically not sufficient because it does not include the effect of mutual heating between cables from other duct banks.

For distinctive duct bank configurations, an electrical system design engineer must utilize the Neher McGrath calculation method. The Neher-McGrath calculations are very complex and involve many calculations and equations and can be exceedingly time consuming. In addition, many of the calculations build on each other, so an error in one part of the calculation can result in a significant error in the final outcome. The hand calculations become even more complex if cable in the duct bank are of different sizes.

I have provided some of the pertinent information directly from the National Electrical Code below:

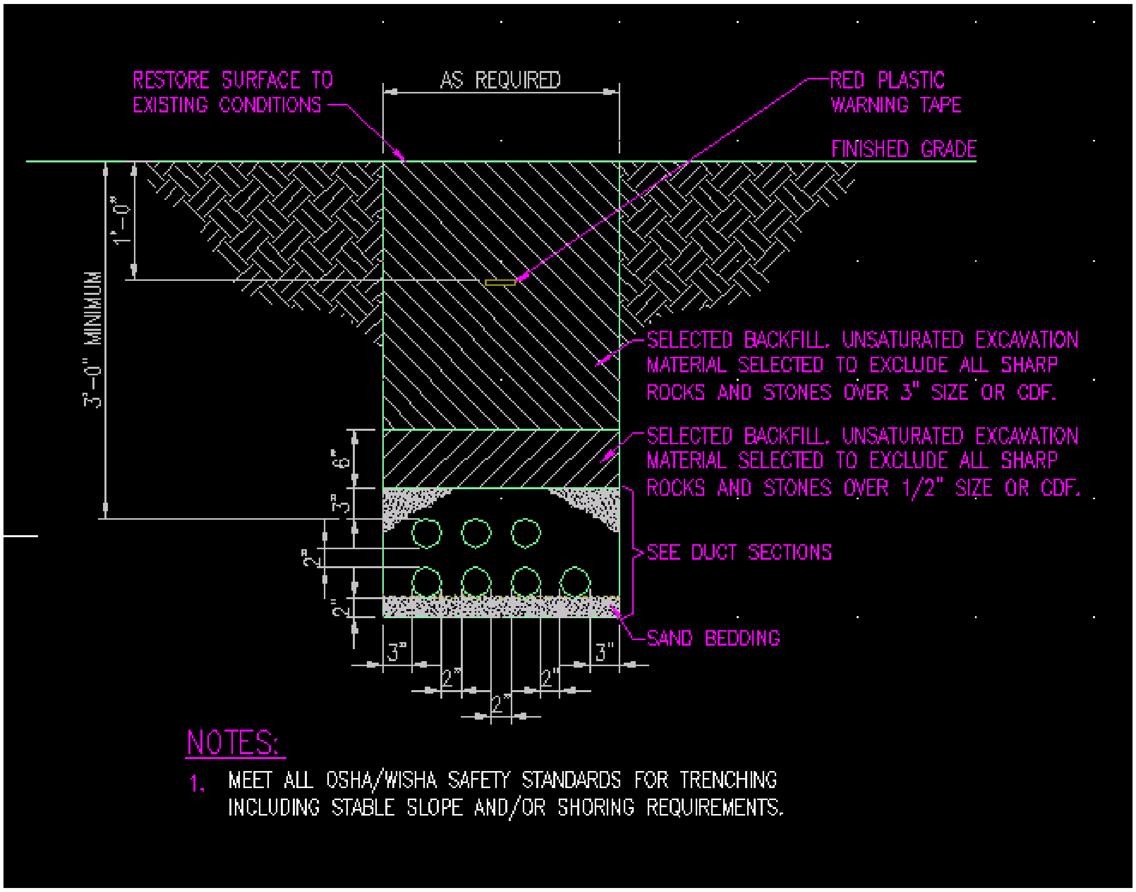
National Electrical Code : B.310.15 (B) (1) Formula Application Information. This NEC annex provides application information for ampacities calculated under engineering supervision. The data in Anex B is based on the Neher-McGrath method

NEC B.310.15 (B) (2) Typical Applications Covered by Tables. Typical ampacities for conductors rated 0 through 2000 volts are shown in Table B.310.1 through ***Table B.310.10.*** Underground electrical duct bank configurations, as detailed in Figure B.310.3, Figure B.310.4, and Figure B.310.5, are utilized for conductors rated 0 through 5000 volts. In Figure B.310.2 through Figure B.310.5, where adjacent duct banks are used, a separation of 1.5 m (5 ft) between the centerlines of the closest ducts in each bank or 1.2 m (4 ft) between the extremities of the concrete envelopes is sufficient to prevent de rating of the conductors due to mutual heating. These ampacities were calculated as detailed in the basic ampacity paper, AIEE Paper 57-660, The Calculation of the Temperature Rise and Load Capability of Cable Systems, by J. H. Neher and M. H. McGrath. For additional information concerning the application of these ampacities, see IEEE/ICEA Standard S-135/P-46-426, Power Cable Ampacities, and IEEE Standard 835-1994, Standard Power Cable Ampacity Tables.

You can see that the tables in the National Electrical Code for underground duct banks are very limited. If the RHO or Load Factor values are different that what is stated in the tables, then the tables do not apply. If the configuration of the conduits exceed the 6 electrical ducts as illustrated on Table B.310.7 the tables do not apply. Additionally if other duct banks are closer that 5 feet, the mutual heating effect of those conductors will not be taken into account.

As stated previously, a remedy to the complexity of these calculations is to utilize a software program. The software will make the math substantially easer but the data the soft input into the software and the calculated result need to be tureally analizedy by speciliced engineeres enperenced with this type of heating issue.

Figure #1



The diagram above is of a standard trench detail. Electrical heating becomes more of an issue when multiple rows of conduits are stacked on top of each other. Additionally, the separation of the conduits in both the vertical and horizontal planes as well as the total cover above the top row will all affect the potential de rating of the conductors. As stated above, both the load factor and the RHO value of the back fill also play large roles in determining the potential de rating of the conductors in the duct bank. See examples below.

The actual configuration of the conduits within a duct bank can be manipulated to reduce any potential de rating. By placing the conduits with the most amount of heat dissipation at certain locations within they duct bank or separating the conduits that will emanate the most heat from each other, total de rating can be reduced. Some of the software programs offered today will provide information on the optimum method of layering your conduits within your duct bank to reduce the total heating effect.

Fourier Law described the effects of heat transferred by conduction. The heat flux is proportional to the ratio of temperature over space. The air space within the conduit is the only area within a duct bank that does not conduct heat. In the air space convection occurs in lieu of conduction. The main method of heat transfer within a duct bank is conduction; therefore the air within the conduit will have less of an effect of heating.

One of the major components of this calculation is the RHO (See definitions previously). Selected backfill material can be utilized to manipulate the RHO value.

The following are typical RHO values for various materials:

Typical (reference) values of thermal resistivity (RHO) are as follows:

1. Average soil (90 percent of USA) = 90
2. Concrete = 55
3. Damp soil (coastal areas, high water table) = 60
4. Paper insulation = 550
5. Polyethylene (PE) = 450
6. Polyvinyl chloride (PVC) = 650
7. Rubber and rubber-like = 500
8. Very dry soil (rocky or sandy) = 120

There are methods of analyzing the actual thermal characteristics of the soil in lieu of just estimating these values based on common typical numbers. A thermal property analyzer can be utilized to measure the actual thermal characteristics of the soil. Additionally, the duct bank installer can utilize engineered backfill where these characteristics are specifically designed and known.

All of the heat created by an underground electrical cable must be dissipated through the adjacent soil. This is identified by the soil thermal resistivity coefficient (or thermal RHO, °C-cm/W). This value can typically fluctuate between 30 to 500°C-cm/W. Electrical engineers typically understand the characteristics of the electrical cable reasonably well. For the most part electrical engineers do not understand the behavior of soils. Generally, the electrical engineer will assume conservative values for RHO when performing these heating calculations.

The use of a soil thermal RHO of 90°C cm per W has become embedded in electrical engineering design practices. Soil studies performed many years ago have found that this was a conservative RHO value for the majority of moist soils in the United States. This RHO value is commonly utilized for electrical distribution cables when the native soil is reused as the backfill for the trench. When select backfill is utilized in lieu of the native backfill for the immediate area around the electrical conduits this backfill will generally have a lower RHO than the native soil.

The ability of the soil in the direct area around the electrical conduits to transmit the heat from the electrical cables establishes whether an electrical cable overheats or keeps cool. Over heating can lead to insulation failure or deterioration. Enhancing the peripheral thermal surroundings and precisely defining the soil and backfill thermal RHO values can result in a 10% to 15% increase in cable ampacity, with 30% improvements noted in some cases (3).

Most damp soils have a RHO of less than 90°C cm/W. Moist sands, which are frequently positioned around electrical distribution conduits, may even have a RHO of less than 50°C-cm/W. The dilemma is that many soils, particularly homogeneous sands, may dry considerably when heated from the electrical cables.

On the other hand, the thermal RHO of a dry soil can exceed 150°C-cm/W, and possibly reach levels of 300°C-cm/W. The dry thermal RHO of a properly designed and installed thermal backfill should be less than 100°C-cm/W and potentially as low as 75°C-cm/W.

Soils found in barren areas are, as you would expect are very dry. The assumption of a moist soil in your calculations is certainly not conservative. In certain parts of the country, the soils have a high inherent thermal RHO. Soil that is not properly compacted in the cable trench will be less dense and have a significantly elevated thermal RHO. Even your typical 480 volt electrical distribution or low voltage cables that are continuously under full load may dry the soil.

Inadequately compacted trench backfill can be an important issue. The thermal RHO of soil that is not compacted correctly can be much higher than soil that is correctly compacted. In addition, loose soil will dry more easily. The same effect can be developed when other cables are in close proximity. This effect is known as mutual heating.

I have provided a few examples below. As you can see, the duct configuration is the same in all of the examples. I have however changed the Load factor and the RHO factor. Modifying these values changes the amount of current that can be pushed through the electrical conductors without exceeding their temperature limits. As you can see, the amount of de rating can be significant.

Example #1 & Example #2 below

In this example, a 4,000 amperes duct bank with a design load of 3,600 amperes is simulated based on an Earth RHO factor of 90, **dirt RHO factor of 90 and a load factor of 100. In this analysis, 16 sets of 4" conduits with 3 #600 MCM copper conductors is required to feed the 3,600 ampere load. Each set of conductors is locked in at 225 amperes each (16 * 225 = 3,600). This essentially is a 60% de rating. 16 sets of 600 MCM conductors with no de rating would equate to 6,720 amperes. (4,000 / 6,720 = 60%). As you can see below, the maximum temperature of the hottest conductor is 66.73 degree Celsius. Per the National Electrical Code, the feeders need to stay below 75.0 degree Celsius. As you can see in Example #2, if we try to reduce the number of conductors to 14 in lieu of the 16, the temperature rises to 79.67 degree Celsius. As the temperature could rise above 75 degree Celsius, this example is not code compliant.

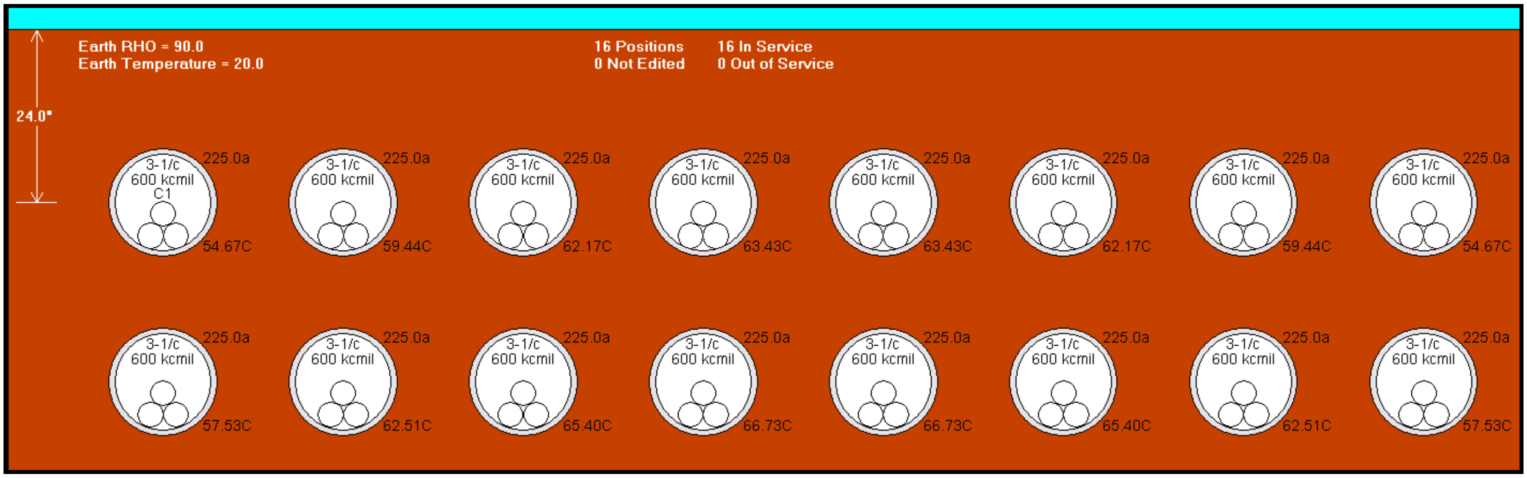
*** The dirt RHO is same as the earth RHO (typically 90) if native backfill is utilized to fill the area directly around the conduits. If select backfill is utilized around the conduits the dirt RHO could be less than the earth RHO. A dirt RHO of less than 90 can lead to less heating and less potential de rating.*

There is typically some discussion about utilizing the 90 degree Celsius rating of the conductors. Per National Electrical Code, section 110. 14 (C): "Conductors with temperature ratings higher than specified for terminations shall be permitted to be used for ampacity adjustments, corrections or both". This application is not typically applicable for 100% rated breakers. In fact, with most 100% rated circuit breakers, 90 Degree Celsius Cable is required, but it must be sized per the 75 Degree Celsius ampacity. These 100% rated breakers utilized the wire as a heat sync to be able to serve continuous loads at the full rating of the breaker.

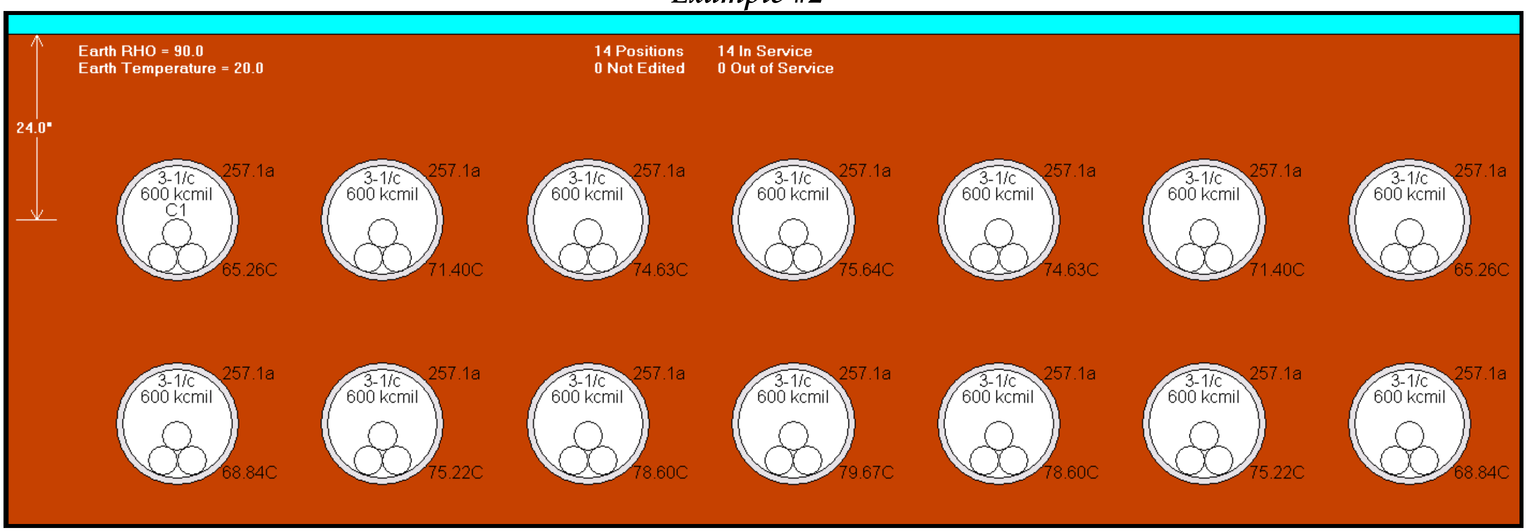
By evaluating the actual temperature of the conductors from the printout below, you can analyze the heat flow and determine the areas that will experience the most heating. which increases the possibility of thermal runaway. This is kind of a domino effect.

Cables that are in close proximity to heat producing equipment and infrastructure will experience elevated ambient temperatures and can operate at a hotter temperature.

Example #1



Example #2

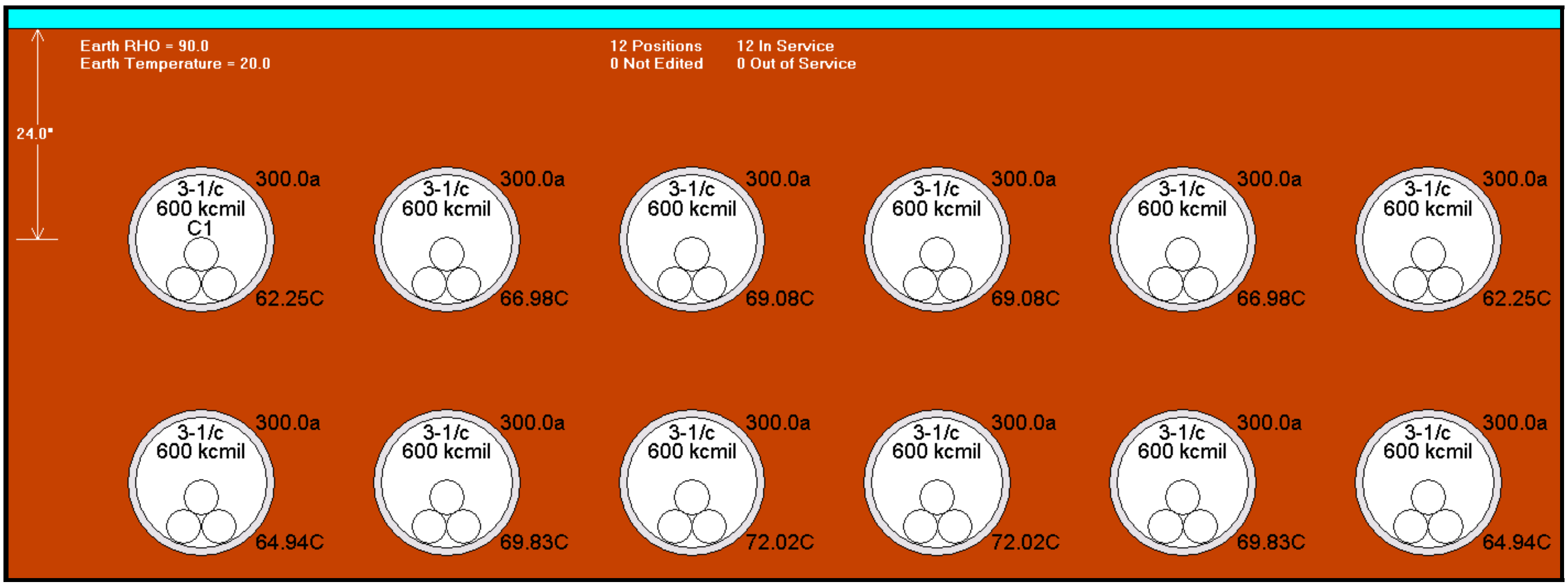


Example #3 below

In this next example, a 4,000 amperes duct bank with a design load of 3,600 amperes is simulated based on an Earth RHO factor of 90, dirt RHO factor of 90 and a load factor of 75. In this example, the load factor was reduced from 100 to 75, all other values are the same as in example #1.

In this analysis, 12 sets of 4" conduits with 3 #600 MCM conductors is required to feed the 3,600 ampere load. Each set of conductors is locked in at 300 amperes each (12 * 300 = 3,600). By reducing the load factor to 75, 4 – 4" conduits each with 3 #600 MCM conductors are not required. This is a very graphic example of how the assumption of load factor in the electrical system can have a significant effect on the total number of conduits and conductors that are required in your electrical distribution system.

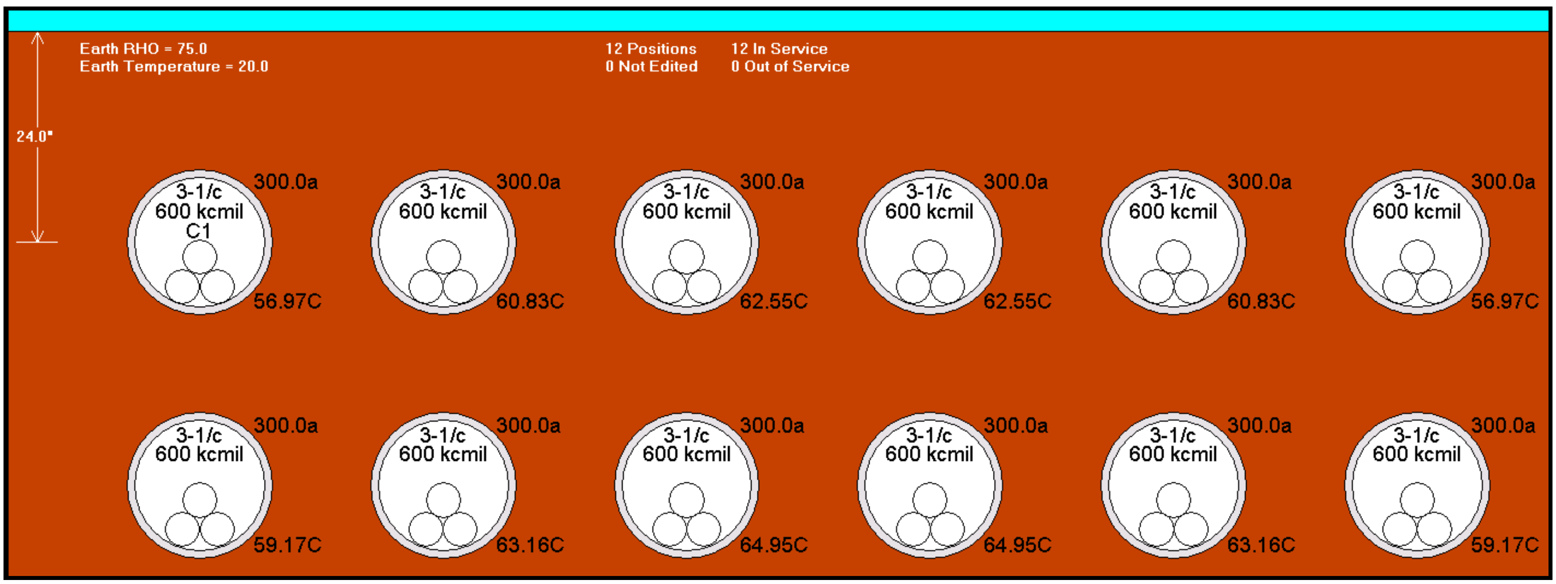
This essentially is a 79% de rating, example #1 above requires a 60% de rating. 12 sets of 600 MCM conductors with no de rating would equate to 5,040 amperes. (4,000 / 5,040 = 79%). As you can see below, the maximum temperature of the hottest conductor is 72.02 degree Celsius. The feeders need to stay below 75 degree Celsius. By evaluating the actual temperature of the conductors, you can analyze the heat flow and determine the areas that will experience the most heating. The hottest conductors are very close to the maximum 75 degree rating (72.02 degrees Celsius).



Example #4 below

In this example, a 4,000 amperes duct bank with a design load of 3,600 amperes is simulated based on an assumption that select backfill with an RHO of 75 is utilized. In this example, the load factor was reduced from 100 to 75 and the RHO of the concrete around the duct bank was reduced from 90 to 75.

In this analysis, 12 sets of 4” conduits with 3 #600 MCM conductors is still required to feed the 4,000 ampere load (Same as in example #3). Each set of conductors is locked in at 300 amperes each (12 * 300 = 3,600). By reducing the load factor to 75, 4 – 4” conduits each with 3 #600 MCM conductors are not required. This essentially is a 79% de rating. 12 sets of 600 MCM conductors with no de rating would equate to 5,040 amperes. (4,000 / 5,040 = 79%). As you can see below, the maximum temperature of the hottest conductor is reduced to less than 65 degree Celsius (In example #3, the hottest conductors are at 72.02 degrees Celsius, this accounts for a drop of over 7 degrees Celsius). The feeders need to stay below 75 degree Celsius. The change from the dirt RHO from 90 to 75, in this case, did not change the total number of conductors required to carry the 3,600 amperes of load. By evaluating the actual temperature of the conductors, you can analyze the heat flow and determine the areas that will experience the most heating.



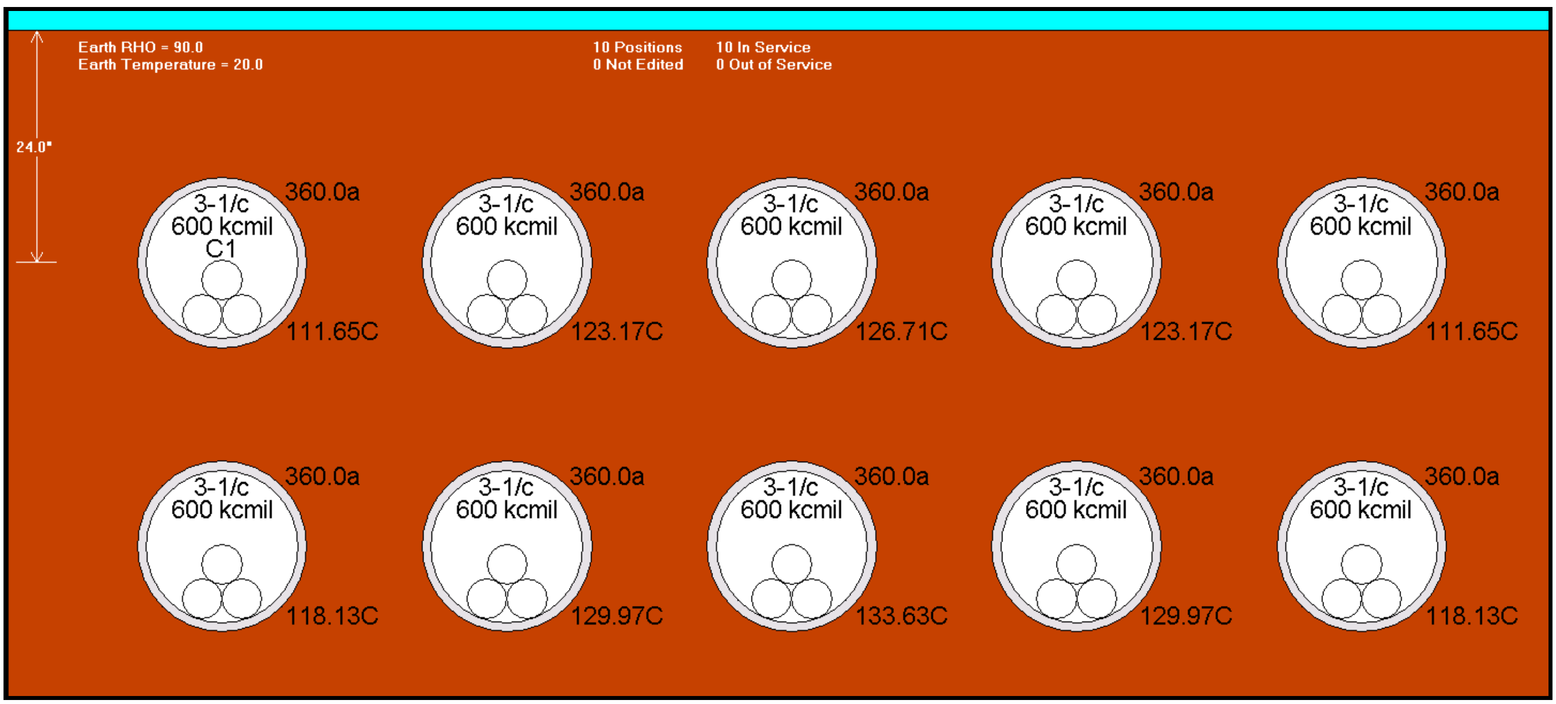
Additionally, these programs will calculate the total loss of energy due to heating and the voltage drop of the conductor. The energy wasted through the conductors due to heat loss can be a significant number and should be considered with any evaluation of these type of electrical duct banks.

The next example illustrates a situation that can occur when below grade electrical conductors with high usage and load factor are not sized in light of these heating calculations.

<u>Example #5 below</u>

A standard feeder schedule for a 4,000 ampere feeder based on the National Electrical Code section 310.16 would include 10 sets of 600 MCM copper conductors (10 x 420 amperes = 4,200). This does not include any de rating.

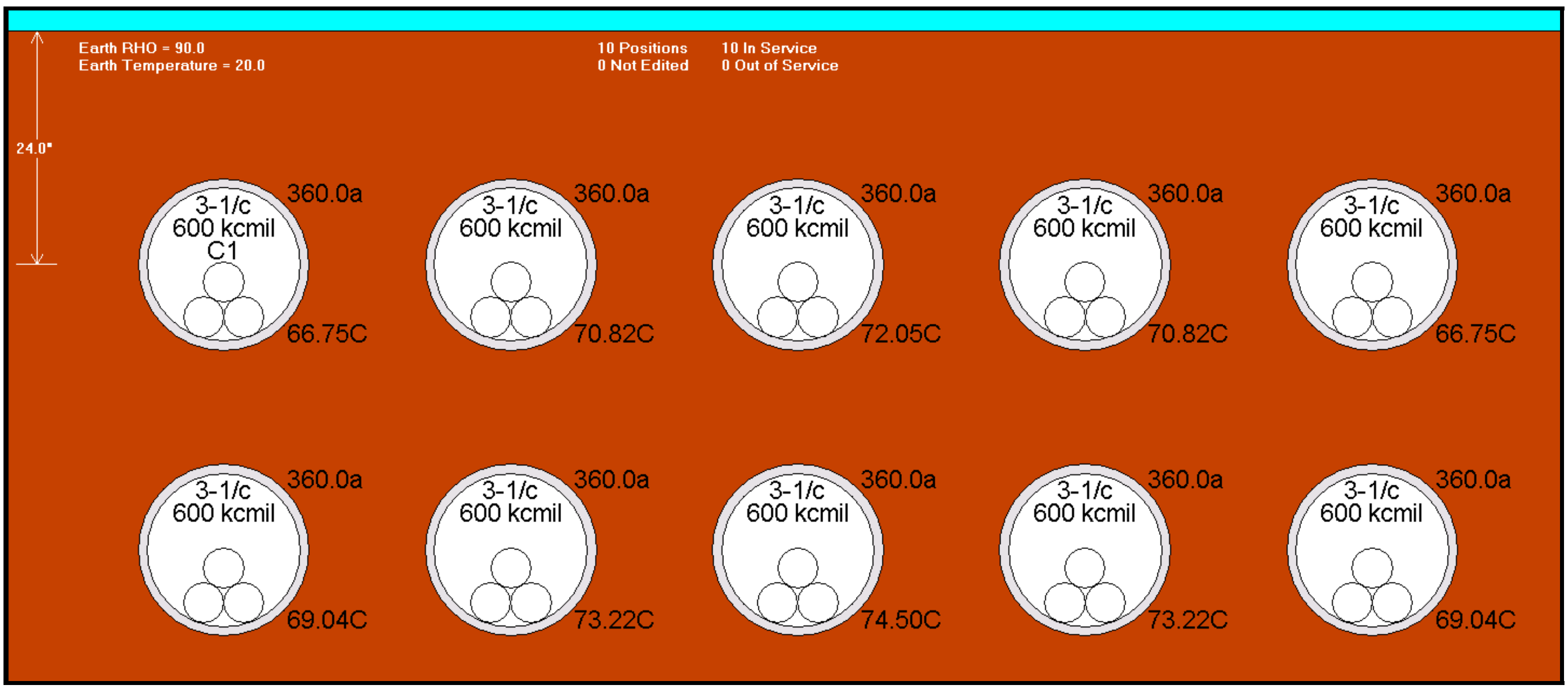
The example below illustrates 10 sets of 600 MCM copper conductors with an Earth RHO factor of 90, dirt RHO factor of 90 and a load factor of 100%. As you can see, if 3,600 amperes is required (360 amperes running through each of 10 conductors), the conductors will heat up to approximately 133.6 degrees Celsius. After prolonged heating, this could cause serious damage to the insulation. These are the temperatures that can be reached in a data center that reached design loads that has not been designed based on heating calculations.



This example is based on a conservative situation where the actual load is 3,600 amperes (86% of the rating of the conductors) and the load factor is 100 %. Actual current draw is typically significantly less than National electrical Code demand calculated load in most installation except data centers. In a data center environment, the actual loads and load factor can be very high. It is critical to determine if your existing data center was designed based on these Neher-McGrath calculations. It has been our experience that most have not been.

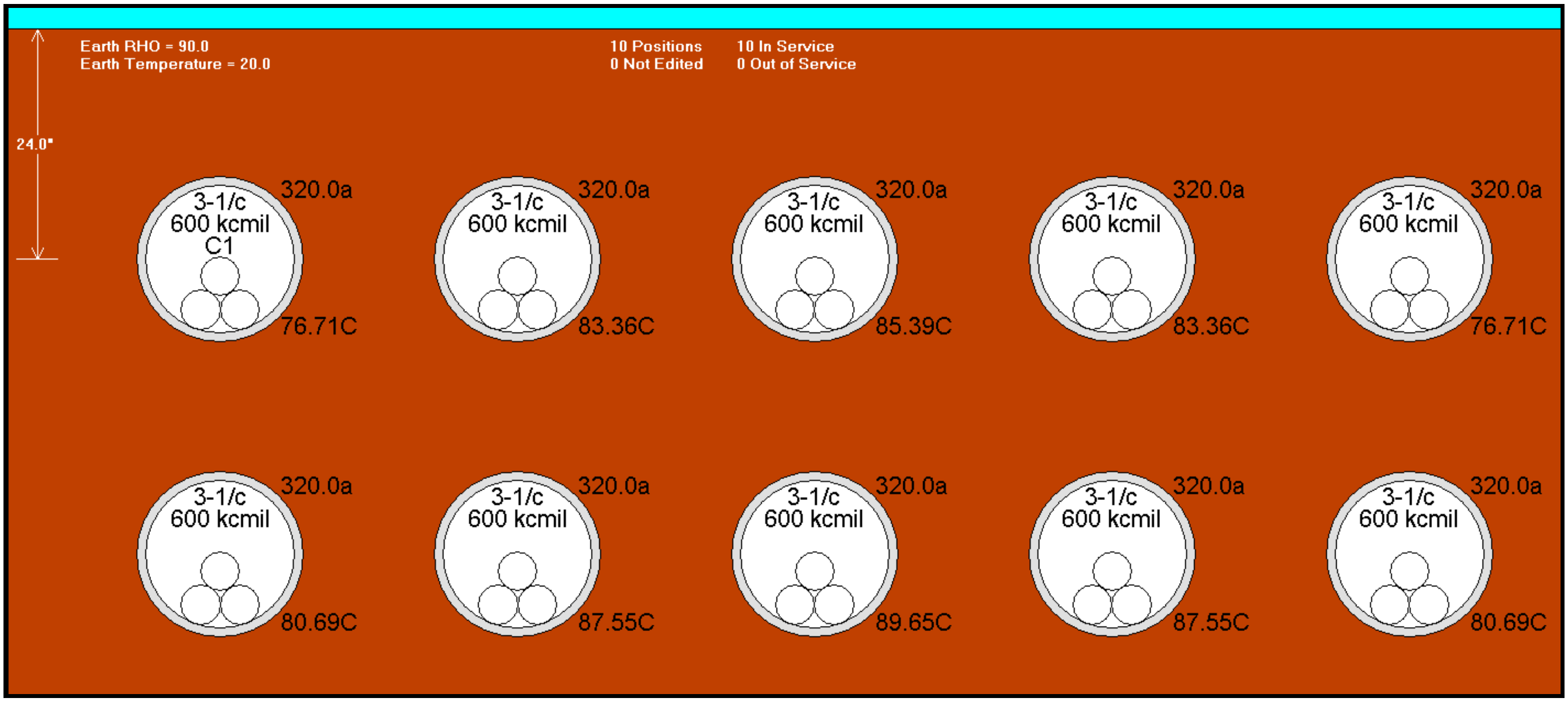
Example #6 below

In this example, I utilized a design load of 3,600 A and reduced the load factor to 60%. The earth and dirt RHO is set at the standard 90. In this example, the standard feeder schedule for a 4,000 ampere service (10 sets of 600 MCM copper conductors (10 x 420 amperes = 4,200)) will not heat up to more than 75 degree Celsius. This example illustrates that most electrical duct bank installations will typically not require any de rating based on the heating calculations. It has been our experience that most data center applications run above a 90% load factor.



Example #7

In this final example, I have utilized a 4,000 ampere duct bank with a design load of 3,200 amperes and increased the load factor to approximately 90%. The earth and dirt RHO are again set at the standard 90. In this example, the standard feeder schedule for a 4,000 ampere service (10 sets of 600 MCM copper conductors (10 x 420 amperes = 4,200)) will heat up to more than 75 degree Celsius.



Many data center installation may require de rating, these heating calculations may be critical to ensure that the designed electrical duct bank is adequate to serve the anticipated loads based on the assumed load factor, RHO factor and duct bank configurations.

It is important to note that not all feeders routed in electrical duct banks are going to require de rating, in fact, most will not require de rating. If the "design load" is less than the rating of the conductors and/or if the load factor is lower than 100, in many cases, de rating may not be required.

The reality is that most commercial installations have a load profile with a load factor of less than 50% and an actual current draw of somewhat less than the full rating of the conductors. Many data centers have actual measured loads that are 70% to 100% of the rating of the conductors and very high load factors.

With all of these factors and criteria involved, it is important to evaluate each electrical duct bank to determine if heating calculations are required and if any de rating will apply. Because of the complexity of these analysis, it is important to acquire the services of a qualified electrical design professional that utilizes the appropriate electrical design software. Additionally, as stated in the National Electrical code, the calculations should be performed under "Engineering Supervision" and should require the approval of a licensed professional engineer.

References

1. National Electrical Code 2005
2. AmpCalc from Calcware
3. Underground Cables Need a Proper Burial Apr 1, 2003 12:00 PM
   By Deepak Parmar and Jan Steinmanis, Geotherm Inc.

End of Article

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