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Heating

Electrical heating calculations might be necessary when large amounts of electrical duct bank are routed belowgrade.

When electrical duct banks with significant amounts of conduits and conductors are routed belowgrade, heating calculations are performed to determine if any conductor derating is required. Factors include the following:

- Number and size of conduits and conductors
- Configuration of the conduits and conductors
- Horizontal and vertical space between conductors
- Amount of earth above conductors
- RHO factor and the amount of the backfill material
- Load factor of the conductors
- Actual design load.

When electrical conductors overheat past their rated use, burning or degrading of normal insulation that protects conductors can precipitate a short circuit condition. Electrical conductor heating calculations can be complicated, but there are software programs for determining the potential derating of feeder conductors in large electrical duct banks. Any conceivable underground duct bank configuration can be input into the software. Additionally, various wire sizes can be used within the duct bank configurations.

Load factor is 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.

For example, load factor = kWh in period/kW. Assume a one-day billing period for a total of 24 hours. A customer uses 15,000 kWh with a maximum demand of 1,500 kW. The customer's load factor would be 41.6%: ((15,000 kWh/24 hrs/1,500 kW)*100). The 41.6% load factor represents a standard commercial building. The load factor in a data center would be significantly higher.

calculations for electrical duct bank

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.

NEC Section 310-15(b) indicates calculations to determine actual rating of the conductors, and provides a formula that can be used under "engineering supervision." But the formula typically is insufficient: It doesn't include the effect of mutual heating between cables from other duct banks.

For distinctive duct bank configurations, a system designer must use the Neher McGrath calculation method, which involves many calculations and equations. In addition, many of these calculations build on one another, 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.

The NEC tables for underground duct banks are limited. If the RHO or load factor values are different from what is stated, then the tables do not apply.

The actual configuration of the conduits within a duct bank can be manipulated to reduce any potential derating, by placing the conduits with the most amount of heat dissipation at certain locations within the duct bank or separating conduits that will emanate the most heat.

According to Fourier's law, heat flux is proportional to the ratio of temperature over space. In the air space within the conduit—the only area within a duct bank that does not conduct heat—convection occurs in lieu of conduction. Because the main method of heat transfer within a duct bank is conduction, the air within the conduit will have less of an effect.

One of the major components of this calculation is the RHO (see chart for typical RHO values for various types of fill). There are methods of analyzing the actual thermal characteristics of the soil, such as with a thermal property analyzer. Also, the duct bank installer can use engineered backfill with these characteristics specifically designed.

All 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 from 30 to 500 C-cm/W.

The use of a soil thermal RHO of 90 C-cm/W is standard practice. However, this is conservative for most moist soils in the U.S. This RHO value is commonly used for electrical distribution cables when the native soil is reused as the backfill, but select backfill generally has a lower RHO than native soil.

The ability of the soil in the direct area around the conduits to transmit heat from the electrical cables establishes whether an electrical cable overheats. 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.

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

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 properly designed and installed thermal backfill should be less than 100 C-cm/W, potentially as low as 75 C-cm/W.

Soils found in barren areas are dry. The assumption of a moist soil in the 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

Typical RHO values for various materials

- **Average soil = 90**
- **Concrete = 55**
- **Damp soil (coastal areas, high water table) = 60**
- **Paper insulation = 550**
- **Polyethylene (PE) = 450**
- **Polyvinyl chloride (PVC) = 650**
- **Rubber and rubber-like = 500**
- **Very dry soil (rocky or sandy) = 120**

elevated thermal RHO. Even typical 480-V electrical distribution or low voltage cables that are continuously under full load may dry the soil.

Inadequately compacted trench backfill also can be an issue. The thermal RHO of this soil can be much higher. In addition, loose soil will dry more easily, which increases the possibility of thermal runaway in 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. The same effect can be developed when other cables are in close proximity. This effect is known as mutual heating.

In the following examples, the duct configuration is the same, but load factor and RHO factor change. Modifying the values changes the amount of current that can be pushed through the electrical conductors without exceeding temperature limits. The amount of derating can be significant.

Examples 1 and 2. In the first example, a 4,000-amp duct bank with a design load of 3,600 amps is simulated based on an earth RHO factor of 90, dirt RHO factor of 90 and a load factor of 100 (Figure 2). Dirt RHO is same as earth RHO if native backfill is used directly around the conduits. If select backfill is used, dirt RHO might be less. Dirt RHO of less than 90 can lead to less heating and less potential derating.

In this analysis, 16 sets of 4-in. conduits with three #600 MCM copper conductors are required to feed the 3,600-amp load, each set locked in at 225 amps each (16 x 225 = 3,600). This essentially is a 60% derating. The 16 sets of conductors with no derating would equal 6,720 amps (4,000 / 6,720 = 60%). The maximum temperature of the hottest conductor is 66.73 C. Per NEC, feeders should stay below 75.0 C.

In Example 2 (Figure 3), I reduce the number of conductors to 14, and the temperature rises to 79.67 C. Because the temperature is above 75 C, the example is not code-compliant.

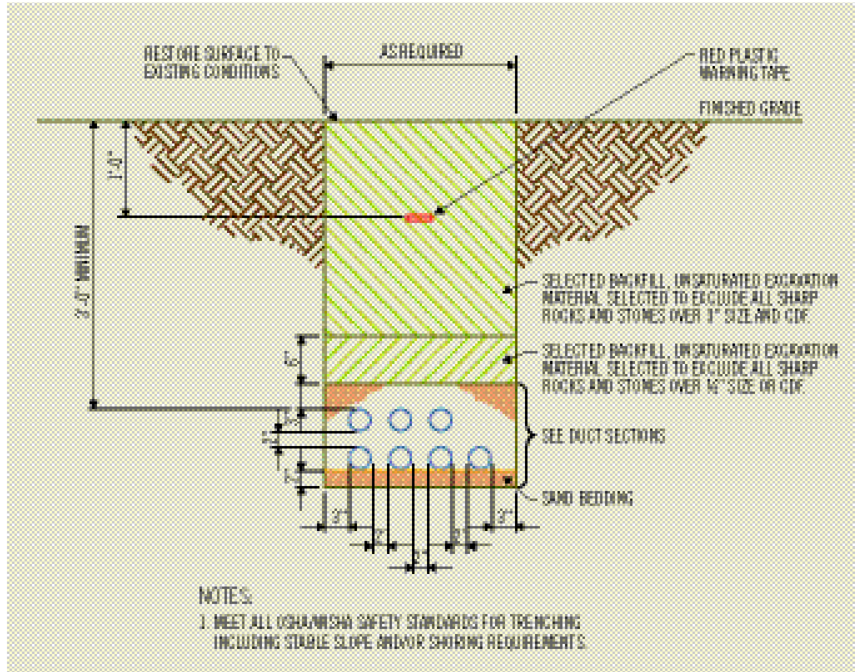


Figure 1 - Electrical heating becomes more of an issue when multiple rows of conduits are stacked on top of one another. Additionally, the separation of the conduits in both the vertical and horizontal planes, as well as the total cover above the top row, all affect the potential derating of the conductors. Both the load factor and the RHO value of the backfill also play large roles in determining the potential derating of the conductors in the duct bank.

NEC sections that reduce the effect of heating

NEC B.310.15 (B)(3) Criteria Modification (a). Where burial depths are increased in part of the electrical duct run to avoid underground obstructions, no decrease in the ampacity of the conductors is required, provided the total length of the part of the duct run increased in depth to avoid obstructions is less than 25% of the total run length.

B.310.15 (B) (6) If spacing between electrical ducts where electrical ducts enter equipment enclosures from underground, the ampacity of conductors contained within such electrical ducts need not be reduced.

The first allowance can have a significant reduction of the potential derating. The second can potentially remove any derating from large amounts of conductors that need tighter routing as they enter and leave the electrical gear.

Additionally, NEC Section 310-15, Ampacity of Conductors Rated 0 – 2000 V, includes no requirements for derating based on the use of electrical duct banks for conductors under 2,000 V. The basic requirements are given in Article 310.15 for conductors 0-2000 V. Any potential derating of conductors for voltages 2,000 V and less is not required and left to good engineering judgment.

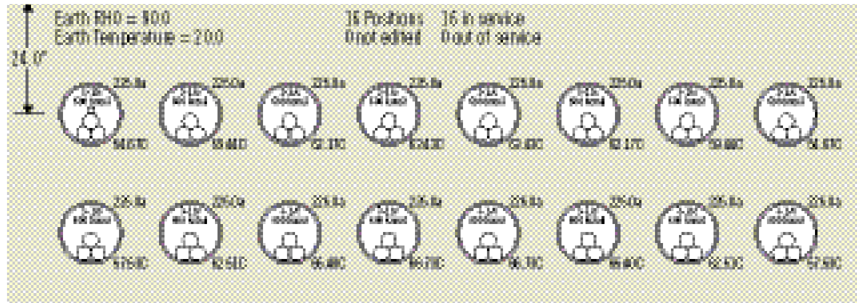
In NEC Article 310.60 for conductors rated 2,001 to 35,000 V, one finds the requirement and reference to 310.60 (C) and (D), along with other requirements that don't apply to lower voltages. The tables for 310.60 (C) and (D) for underground ducts include provisions for duct bank configurations, earth ambient temperature, load factor, and RHO.

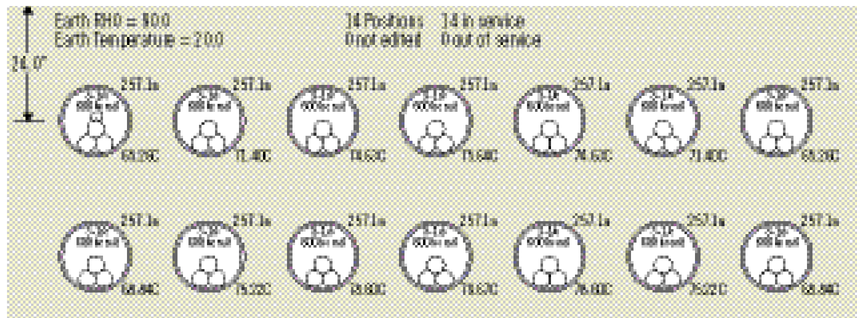
There is typically some discussion about utilizing the 90 C rating of the conductors. NEC Section 110.14 (C) states: "Conductors with temperature ratings higher than specified for terminations shall be permitted to be used for ampacity adjustments, corrections or both." This application typically isn't applicable for 100% rated breakers, where, in fact, 90 C cable is required. But it must be sized per the 75 C ampacity. These 100% rated breakers use the wire as a heat sync to serve continuous loads at the full rating of the breaker. By evaluating the actual temperature of the conductors from a printout, you can analyze the heat flow and determine the areas that will experience the most heating.

Example 3. All values are the same as in Example 1, except the load factor is reduced from 100 to 75. In this analysis, 12 sets of 4-in. conduits with three #600 MCM conductors are required to feed the 3,600-amp load. Each set is locked in at 300 amps each (12 x 300 = 3,600). By reducing the load factor to 75, four 4-in. 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% derating; Example 1 requires a 60% derating. Twelve sets of 600 MCM conductors with no derating would equal 5,040 amps (4,000 / 5,040 = 79%). The maximum temperature of the hottest conductor is 72.02 C—close to the maximum 75 C rating. By evaluating the actual temperature of the conductors, one can analyze the heat flow and determine the areas that will experience the most heating.

Example 4. Values are the same except that it uses select backfill with an RHO of 75. Once again, the load factor is reduced from 100 to 75 and the RHO of the concrete around the duct bank is reduced from 90 to 75.





Figures 2 and 3 - These figures show the printout for calculations of Examples 1 and 2 respectively. By evaluating the actual temperature of the conductors from the printout, the electrical engineer can use this type of data to analyze the heat flow and determine the areas that will experience the most heating.

As in Example 3, 12 sets of 4-in. conduits with 3 #600 MCM conductors are required to feed the 4,000-amp load. Each set of conductors is locked in at 300 amps each. By reducing the load factor to 75, four 4-in. conduits each with three #600 MCM conductors are not required. This essentially is a 79% derating. Twelve sets of 600 MCM conductors with no derating would equal 5,040 amps (4,000 / 5,040 = 79%). The maximum temperature of the hottest conductor is reduced to less than 65 C—a drop of over 7 C below Example 3. 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 amps of load.

Additionally, software 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.

Example 5. This example illustrates a situation where belowgrade electrical conductors with high usage and load factor are not sized in light of these heating calculations. A standard feeder schedule for a 4,000-amp feeder based on the NEC Section 310.16 would include 10 sets of #600 MCM copper conductors (10 x 420 amps = 4,200). This does not include any derating.

The example uses 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%. If 3,600 amps is required (360 amps running through each of 10 conductors), the conductors will heat up to approximately 133.6 C. After prolonged heating, this could cause serious damage to the insulation.

This example is based on a conservative situation where the actual load is 3,600 amps—almost the full rating of the conductors—and the load factor is 100%. Actual current draw is typically significantly less than NEC demand calculated load. This example only would occur in certain circumstances.

Example 6. In this example, I use a design load of 3,600 amps and reduce the load factor to 60%. The earth and dirt RHO is set at the standard 90. The standard feeder schedule for a 4,000-

amp service—10 sets of 600 MCM copper conductors (10 x 420 amps = 4,200)—does not heat up to more than 75 C. This example illustrates that most electrical duct bank installations will typically not require any derating based on the heating calculations.

Example 7. In this example, I use a 4,000-amp duct bank with a design load of 3,000 amps and increase the load factor to approximately 85%. The earth and dirt RHO are again set at the standard 90. The standard feeder schedule for a 4,000-amp service—10 sets of 600 MCM copper conductors (10 x 420 amps = 4,200)—will not heat up to more than 75 C. This is another example that illustrates that most electrical duct bank installations typically do not require any derating based on the heating calculations.

Example 8. The intent of this example is to illustrate the effect of allowing a 90 C temperature of the wire. I do not recommend allowing the wire/termination to go above 75 C. In this final example, I use a 4,000-amp duct bank with a design load of 3,200 amps and increase the load factor to approximately 90%. I am assuming a maximum of 80% loading on the breaker (3,200 amps) and not using the 100% rating of the breaker and I am using the full 90 degree rating of the THHN/THWN conductor. The earth and dirt RHO are again set at the standard 90. The standard feeder schedule for a 4,000-amp service—10 sets of 600 MCM copper conductors (10 x 420 amps = 4,200)—will not heat up to more than 90 C.

If this example used a non-power circuit breaker, the maximum termination rating is only 75 C, so the example would not be applicable. Additionally, based on my coordination with the breaker manufacturers, they will not guarantee that the breaker termination can go to 90 C even if the actual load is equal to or less than 80% of the rating. Therefore, I recommend, in all cases, not exceeding 75 C.

Although most installation may not require derating, 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. This is especially true for critical facilities such as data centers. A data center typically has a load factor between 90 and 100 and the load typically is managed to the peak design load. Additionally, in a data center application, the actual metered demand load could be very close to the NEC calculated load.

Not all feeders routed in electrical duct banks are going to require derating. In fact, most will not. 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 derating may not be required.

In reality, 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. Additionally, there are certain NEC sections that reduce the calculated effect of heating.

Another simplec way to look at AHJ requirements and good engineering judgment with respect to NEC load calculations is that there is significant amount of conservatism built in. If you provide your load calculations based on NEC 220, with good engineering judgment, some of the conservatism could be applied to the potential derating from the heating calculations.

In other words, if the load calculation indicates that you need 3,600 amps on a 4,000-amp service, the load realized once the facility is in operation is probably less than half of that number. Therefore you may be able to use 10 sets of #600 MCM THHN (420 amps each, per 310.16), for a total ampacity of 4,200 amps. You may be able to do this even if the conduits are in an electrical duct bank, because the negative effects of mutual heating at 1,800 amps or less will not be as bad as if one actually placed 3,600 amps through them.

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 derating will apply. Because of the complexity of the analysis, acquire the services of a design professional who uses the appropriate software. Additionally, the calculations should be performed under "engineering supervision" and approval of a licensed professional engineer. END

Pertinent information from the 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 Annex B is based on the Neher-McGrath method.

B.310.15 (B) (2) Typical Applications Covered by Tables. Typical ampacities for conductors rated 0 through 2,000 V are shown in Table B.310.1 through Table B.310.10. [NEC tables and figures are not shown.] Underground electrical duct bank configurationsare used for conductors rated 0 through 5,000 V. In Figure B.310.2 through Figure B.310.5, where adjacent duct banks are used, a separation of 5 ft between the centerlines of the closest ducts in each bank or 4 ft between the extremities of the concrete envelopes is sufficient to prevent derating 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.