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ONE OF THE MOST IMPORtant factors affecting underground cable ampacity is the thermal resistivity of the soil. A soil's thermal resistivity varies with moisture content, and the heat generated by cables can cause the soil to dry, increasing its resistivity. The ability of the soil to maintain its thermal resistivity in the presence of a heat source is known as *thermal stability*. Since no soil has perfect stability, accounting for the fluctuating thermal resistivity of soil makes the cable ampacity calculations difficult. This article will examine the information available from standard soil tests and the information these tests may provide relating to the migration of moisture in the soil and the resulting changes in soil resistivity. Furthermore, we suggest a method for including this information in underground cable ampacity calculations.

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A method to help determine underground cable ampacity

THE HEAT AND BURIED CABLE CONUNDRUM

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Soil Thermal Resistivity

When a cable is buried in the soil, whether directly buried or in an underground pipe, the heat generated by the resistive losses in the cable must be carried away through the soil surrounding the cable. The rate at which this heat can be carried away determines the temperature the cable will reach during any loading condition. If this temperature becomes too high, the cable can be damaged. The thermal resistivity of the soil surrounding the cable is the main factor in determining the rate at which heat can be conducted away from the cable and, therefore, the ultimate amount of current the cable can carry.

Soil thermal resistivity is one of the most important values an engineer must know to calculate the cable ampacity. Once the thermal resistivity of the surrounding soil is known, the Neher–McGrath method is commonly used to determine the amount of current a cable can carry without exceeding its allowable temperature [1].

SOIL THERMAL RESISTIVITY IS ONE OF THE MOST IMPORTANT VALUES AN ENGINEER MUST KNOW TO CALCULATE THE CABLE AMPACITY.

Measurement of Soil Properties

Thermal resistivity is a measure of the ability of a material to resist the flow of heat. In the case of soil, this property is commonly measured using either laboratory or field tests. Several soil tests are commonly performed to characterize a soil's properties. One common test performed determines the soil density and moisture content. To perform this test, a soil sample is taken from the field, and the in-place soil unit weight test gives the overall soil unit weight in pounds per cubic foot, as given in (1). The water content of the soil sample is also tested, and the result of this test gives the weight of water contained in the soil sample divided by the weight of the dried soil and is given in a percentage, as shown in (2)

$$\text{Unit Weight} = \gamma = \frac{\text{Pounds of Soil}}{\text{Cubic Feet of Soil}} \ \text{lb/ft}^3 \quad (1)$$

$$\%\ \text{Water Content} = \omega = \frac{\text{Weight of Water}}{\text{Weight of Dry Soil}} = \frac{W_w}{W_s} \times 100\%. \quad (2)$$

Once the density and moisture content are known, a soil's thermal resistivity is measured by inserting a heat-generating thermal probe into the soil or, if done in a lab, the soil sample, and soil resistivity is measured as described in IEEE Standard 442, *IEEE Guide for Soil Thermal Resistivity* [2], [3]. A known heat rate in watts per centimeter is injected into the probe, and a plot is made of the temperature of the probe/soil interface versus time. Figure 1 illustrates an idealized example of the results, often called a "dry-out" curve.

The graph in Figure 1 shows two fairly linear parts of this logarithmic temperature versus time curve. The part of the curve with the flatter slope represents the resistivity of the soil before it begins to dry. The part of the curve with the steeper slope represents the resistivity of the soil as the soil surrounding the probe dries. A soil's resistivity in each condition is proportional to the slope of the respective curves as described in [2]. In either condition, wet or dry, we may find the soil resistivity using

$$\rho = \frac{4\pi}{q}\left[\frac{T_2 - T_1}{\ln\left(\frac{t_2}{t_1}\right)}\right], \quad (3)$$

where ρ is the soil resistivity (°c-cm/W), q is the heat input (W/cm), T_1 is the temperature at time t_1, and T_2 is the temperature at time t_2.

Applying (3) to the case shown in Figure 1, the thermal resistivity on the wet part of the curve, assuming a 0.3-W/cm heat input, is approximately 80 °C cm/W, and, on the dry part of the curve, the thermal resistivity is approximately 200 °C cm/W.

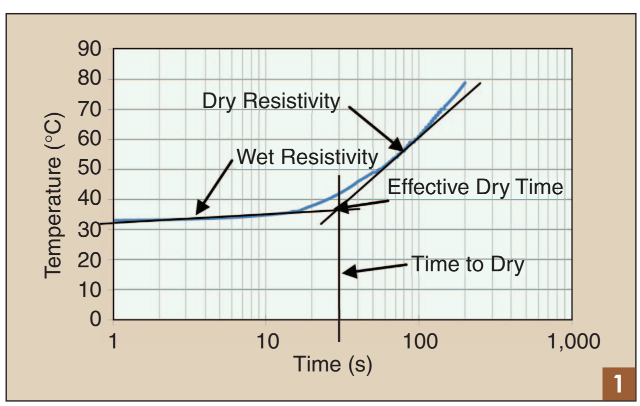
We may also find the effective drying time using this test. It will vary with the heat input and soil moisture and will be the time measured to the knee point of the curve just before the resistivity of the soil changes, as shown in Figure 1.

As the diameter of the heat source increases, it is often claimed that the drying time will also increase. Some sources suggest that, for a particular heat rate, the drying time of the soil can be adjusted for a larger-diameter heat source such as a cable, using the measured drying time for the smaller-diameter probe using [4]–[6]

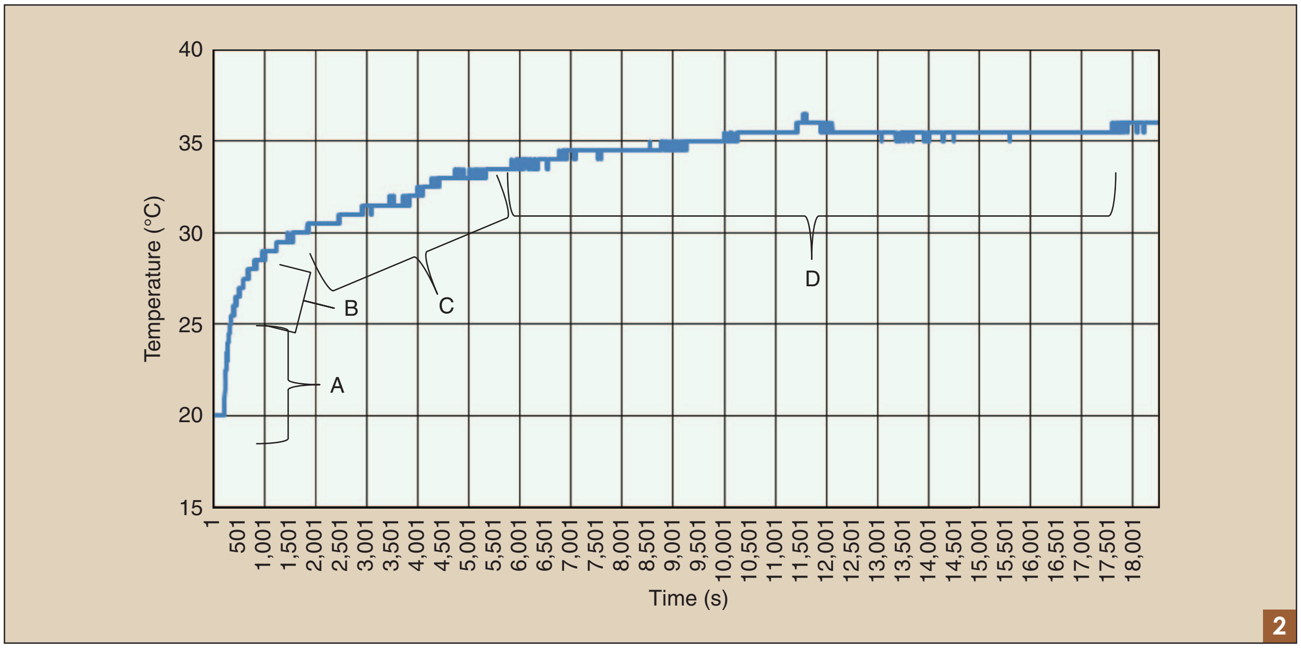
$$t_2 = t_p\left[\frac{D_2}{D_p}\right]^2, \quad (4)$$

where t_2 is the soil time to dry with the heat source diameter D_2 and t_p is the soil time to dry with the probe diameter D_p.

It is sometimes suggested that the time to dry for a particular diameter of cable being installed may be used to assess the stability of the soil resistivity [4]. However, the criteria used for such an assessment are difficult to define, and caution is advised when using it (4). Laboratory tests are



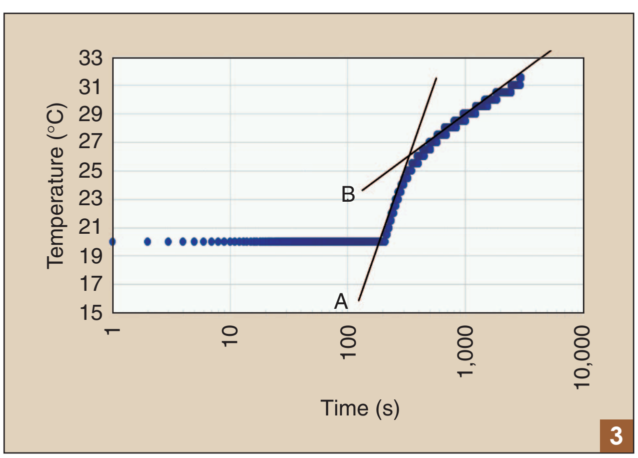
The soil drying curve.



In situ soil resistivity test results.

limited in the amount of information they can provide, especially about moisture and its movement in the soil. Since the soil in the lab is not subject to natural moisture, it cannot provide information about water movement and the effect of that moisture movement on the heat source. It is reported that laboratory and field tests consistently provide differing results for the resistivity of soil [7]. The lab test may give a resistivity that is two to three times that of field tests. While a curve similar to the one shown in Figure 1 is often used as an example of how soil resistivity is measured, when resistivity tests are performed in the field, curves of this nature will seldom be observed. In situ tests will more frequently produce a curve similar to that shown in Figure 2, which shows data from the first 8 h of a soil resistivity test taken with a 120-cm thermal probe with a heat input of 0.53 W/cm.

There are four sections of data apparent from Figure 2. We hypothesize the following explanation to account for the measured data in this figure. Data section A begins when heat is applied to the probe. The soil ambient temperature at this time is 20 °C. This section is the transient portion of the heating test and lasts approximately 10 min for the probe used. This represents the time the probe takes to heat up and cannot be used to determine the resistivity of the soil. For clarity, we extract and plot sections A and B on a semilog graph, resulting in Figure 3. For the first 10 min, the probe and soil are heated, producing slope A in this figure. After the probe finishes absorbing heat and reaches a quasi–steady-state condition compared to the rate heat is being extracted by the soil, the slope of the graph changes from section A to section B. At this point, the slope of the graph is mainly due to heating the soil, and the slope of B may be used with (3) to determine the soil resistivity. We can make this assumption because the thermal time constant for the probe–soil interface is much smaller than the time constant of the soil itself. This is also briefly described in [2].



The first 30 min of the test.

The theory that permits using the slope of section B to determine the resistivity of the soil assumes an infinitely long line source of heat. As long as the thermal probe conducts heat in such a way that it approximates an infinitely long line of heat source, the slope of the resulting graph will be proportional to the soil thermal resistivity. At some point in time, however, heat will no longer flow in a one-dimensional, linear fashion but will transition to a two-dimensional flow. This transition region between one- and two-dimensional flow is represented by section C in Figure 2. This transition occurs approximately 45 min after the probe begins heating and lasts about 3 h. During this time, the soil is slowly heating, and the two-dimensional heat flow and end effects of the probe become important.

At the end of section C and the beginning of section D, the soil reaches a temperature of 36 °C and becomes nearly constant. It then gradually increases at a rate beginning at about 1°/day, rising to slightly more than 2.5°/day and decreasing once again to 0.5°/day after seven days. The soil finally achieves a constant temperature of 54 °C on day eight. It stays constant for the last two days of the test, at which point the test was terminated. We hypothesize that this gradual increase in temperature in section D is due to a gradual reduction in moisture near the probe that results in the gradual increase in soil thermal resistivity near the probe, thereby increasing the temperature of the probe. The soil finally achieves equilibrium when this drying ceases and the soil achieves its final resistivity for the heat rate used.

Using the slope of line B in Figure 3, we find the soil resistivity using (3). When the in-field test is done and (3) is used to determine the resistivity, we suggest that T_1 be taken after approximately 10 min of heating (for most standard probes) and T_2 be taken after approximately 25 min [2] to avoid two-dimensional heating effects. In any case, these values must be measured at two times, when the data is as linear as possible but beyond the initial equipment-controlled transient state. After 600 s, T_1 was found to be 27.5 °C, and T_2 was measured at 30.5 °C after 2,100 s. The heat rate was 0.53 W/cm. Using (3) results in the following soil thermal resistivity:

$$\rho = \frac{4\pi}{q}\left[\frac{T_2 - T_1}{\ln\left(\frac{t_2}{t_1}\right)}\right] = \frac{4\pi}{0.53}\left[\frac{30.5 - 27.5}{\ln\left(\frac{2100}{600}\right)}\right] = 57\,^\circ\mathrm{C\ cm/W}.$$

Now that the resistivity is known, we may find an equation permitting the calculation of the steady-state conductive heat flow from the thermal probe using the appropriate conduction shape factor [8]. If a cylinder is inserted vertically into the soil of a single thermal resistivity, the common heat flow case shown in Figure 4 will result. This is the case of a vertical cylinder in a semi-infinite medium.

If the diameter D and length L of the probe and the soil thermal resistivity are known, and, if the probe surface temperature T_1 is measured and the soil surface temperature T_2 can be found under steady-state conditions, then we may find a solution to the two-dimensional conductive heat flow between the probe and the surface through an infinite soil layer bounded only at the surface. We must assume that the thermal resistivity found is for a composite soil that can be assumed to be uniform, and that the temperature T_2 will be assumed to be the ambient temperature of the soil at the depth of interest. During the time used for most testing, and at the soil depths of interest, these assumptions will be approximately true and are the same assumptions in [2].

The shape factor for this condition, where all dimensions are measured in centimeters and temperatures in degrees Celsius, is [8]

$$S = \frac{2\pi L}{\ln\left(\frac{4L}{D}\right)}. \tag{5}$$

The thermal resistance of the soil for two-dimensional conductive heat flow between the probe and the soil surface is

$$R = \frac{\rho}{S} = \rho\frac{\ln\left(\frac{4L}{D}\right)}{2\pi L}, \tag{6}$$

where ρ is the soil resistivity (cm–°C/W), R is the thermal resistivity (°C/W), S is the shape factor from (5) (cm), D is the diameter of the probe (cm), and L is the length of the probe (cm).

The equation for heat flow using the shape factor for this condition is

$$Q_c = \frac{\Delta T}{R} = \frac{S(T_1 - T_2)}{\rho} = \frac{2\pi \mathrm{L}(T_1 - T_2)}{\rho\ \ln\left(\frac{4L}{D}\right)}$$

$$Q_c = \frac{2\pi L(T_1 - T_2)}{\rho\ \ln\left(\frac{4L}{D}\right)}. \tag{7}$$

The value of Q_c in (7) measured in watts is the amount of heat that is leaving the probe due to the pure conduction in the soil.

The probe first achieves steady-state two-dimensional heat flow at the beginning of section D in Figure 2. Assuming that the soil thermal resistivity has not changed yet, we use (7) to find the heat flow due to conduction during this time period. The probe is 120 cm long, 1.5875 cm in diameter, T_1 is 36 °C, and T_2 is a soil ambient temperature of 20 °C:

$$Q_c = \frac{2\pi L(T_1 - T_2)}{\rho\ \ln\left(\frac{4L}{D}\right)} = \frac{2\pi(120)(36 - 20)}{57\ \ln\left(\frac{4(120)}{1.5875}\right)} = 37\ \mathrm{W}.$$

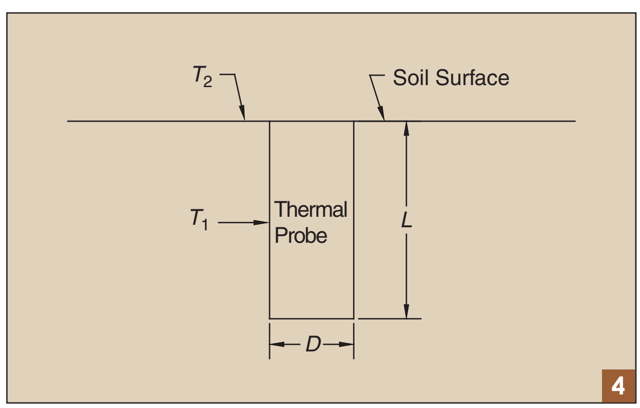
Assuming that the heat of conduction did not change with the final steady-state condition after eight days of testing, the increase in soil resistivity may also be found using (7). Combining these equations to use for the two cases of different temperature changes, while heat flow is kept constant, the new thermal resistivity may be found using

$$\rho_2 = \rho_1\frac{\Delta T_2}{\Delta T_1}. \tag{8}$$

Continuing the example, where the soil's initial resistivity is 57 °C cm/W for the initial temperature change of 16 °C, and the final temperature change after eight days was 34 °C, the new apparent thermal resistivity is

$$\rho_2 = \rho_1\frac{\Delta T_2}{\Delta T_1} = 57\frac{34}{16} = 121\ ^\circ\mathrm{C\ cm/W}.$$

From the measurements, it appears that the soil has an initial resistivity of 57 °C cm/W, and, due to moisture changes near the probe, the resistivity increases to 121 °C cm/W due to continuous heating. It should be noted that the results shown are valid only for one soil



The thermal probe inserted vertically in the soil.

moisture content and would be expected to change at other soil moisture contents. The resistivity of the soil will also vary [9] as the water content varies, as can be expected during the year in most locations.

More importantly, if the heat rate into the soil is increased, the soil will tend to dry more quickly near the heat source, changing the resistivity near the probe to a greater degree. The question that arises then is which value of resistivity should be used to determine the ampacity of the underground cables: the moist value measured initially, the final dry value, or some intermediate value? It is clear that using the initial moist value will result in lower cable temperatures, and using the final dry resistivity will result in much higher cable temperatures and lower allowable ampacities, and that some intermediate value may be more accurate but more difficult to determine.

IF A HEAT SOURCE SUCH AS A CURRENT-CARRYING CABLE IS INTRODUCED INTO THE SOIL, THE HEAT FROM THE CABLE WILL CAUSE THE SOIL TO DRY OUT NEAR THE CABLE.

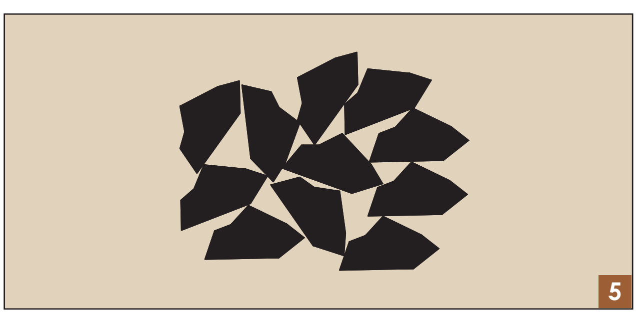
To answer this question, more than the soil resistivity needs to be measured. It is important to know if the soil will dry and, if so, how this drying will affect the soil resistivity and thus the cable ampacity calculations. The soil thermal stability must also be characterized so that the design engineer can determine which value or values of thermal resistivity should be used and how. The question arises of whether we can extract any useful information from existing testing that will aid the engineer in determining the effects of soil drying on a cable's ampacity.

Mechanism of Heat Transfer Through Soil

Soil is made of solid particles in contact with each other at relatively small contact points, as shown in Figure 5. The voids between the particles may contain either air or water. In dry soil, the voids between particles are filled with air. Heat is conducted through the particles and between particles at the contact points. Some heat is also conducted through the air, which has much more resistance to heat flow than the soil particles. If the voids start to fill with water, the effective contact area between the particles increases, resulting in an increased conduction of heat. This reduces the resistivity of the soil. For this reason, an increase in water content means a decrease in soil resistivity, and as the soil dries, the resistivity will increase. If a heat source such as a current-carrying cable is introduced into the soil, the heat from the cable will cause the soil to dry out near the cable. As the soil dries, its resistivity increases, causing the temperature of the cable to increase. If the soil reaches some critical temperature and heat rate, it may dry quickly, allowing a type of thermal runaway condition where the dry soil increases in resistivity, causing the cable temperature to increase, which in turn more quickly forces the remaining moisture out of the soil. This is the basis for the possible occurrence of thermal instability that may cause the temperature of the cable to quickly increase until damage occurs.

There are two mechanisms by which moisture may move away from a heat source in the soil. The first is movement in liquid form due to heat weakening the surface tension between water and soil particles, and the second mechanism is due to vapor movement through the soil [10], [11]. Movement of moisture in the liquid state has been found to have only a minor effect on the temperature change of cables [7], [12]. For this reason, we will consider only the second mechanism, the movement of vapor through the soil, as an effective mechanism to produce the type of drying seen in soils surrounding cables. As the heat source heats the surrounding soil, the soil dries through evaporation. The water near the cable will vaporize, and the increased pressure due to additional heating causes the vapor to move through the soil voids until it condenses in a cooler location [6]. As the water vapor leaves the area immediately surrounding the cable, water located further from the cable flows back into the dried area due to the soil's hydraulic gradient, as shown in Figure 6.

If the heat is low enough for the surrounding water to replenish the water that migrates away, then the resistivity of the soil will not change. If the heat is high enough for water to be vaporized and to leave the cable surroundings faster



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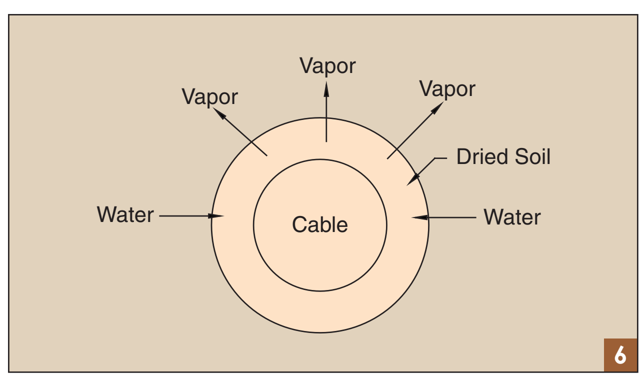
The soil particles with voids.



6

The vapor leaving and the water entering a soil layer near a cable.

than it can be replenished, then the soil will dry and increase the soil resistivity near the cable. So for cable ampacity calculations, if the soil never dries out, we use the wet value of resistivity, as calculated in Figures 1–3. If the soil does dry out, then, for some distance from the cable, the dry value of soil resistivity must be used surrounded by soil at the moist resistivity value. In other words, the dry soil will form a cylindrical shell around the cable and be surrounded by moist soil. If the soil is partially dried, then we suggest that the use of a layer of some diameter of the dried soil, surrounded by the soil of the moist value of thermal resistivity, may still be used and will produce somewhat conservative results when determining cable ampacity. The question is, what is the diameter of this dried soil layer for a given heat rate?

IT IS IMPORTANT TO KNOW IF THE SOIL WILL DRY, AND, IF SO, HOW THIS DRYING WILL AFFECT THE SOIL RESISTIVITY AND THUS THE CABLE AMPACITY CALCULATIONS.

Measuring Thermal Stability

After the moist thermal resistivity is known, the next requirement is to determine the rate at which water can flow into a dried area from the surrounding soil. Two heat rates of interest are as follows:

1) critical heat rate (CHR)
2) nondrying heat rate (NHR).

The CHR is the maximum heat rate at which the soil will not be dried completely and enter the area in Figure 1 beyond the "Time to Dry" line. This "Time to Dry" line is the time for the soil to reach a dried state. While this point is most easily seen in laboratory tests, it may also occur in field tests that apply sufficiently high heat rates for a long enough period of time. Below the CHR, the soil may begin to dry but will not dry to the point that the rapid increase in temperature shown in Figure 1 occurs. To find the value of the CHR, the heat input into the thermal probe could be increased in stages until a heat rate is found that is just sufficient to cause this rapid increase in resistivity. To determine the CHR in the lab, the soil sample is divided into several equal parts, and the time to dry is measured using a different heat rate input for each sample. A time to dry versus heat input graph is shown in Figure 7. The heat rate at which the graph becomes horizontal, showing that the soil would not dry at this input even after a long time, will be the CHR [6].

The NHR is defined as the maximum heat rate at which the soil will not begin to dry. If the heat input used in the tests in Figure 2 had been slightly lower, the temperature of the soil would have leveled off at 36 °C and not increased. This would mean that the moisture leaving the area of the probe would be exactly balanced by the liquid flowing into the area around the probe; hence, the soil would not dry. At and below the NHR; we would expect that soil resistivity would never change and the soil would not dry, so the temperature of the probe will be constant no matter how long heat is applied. The NHR can be found only in the field, since it depends on the surrounding soil's natural vapor, liquid diffusivity levels, moisture level, and the soil's ability to supply moisture back to a drying area.

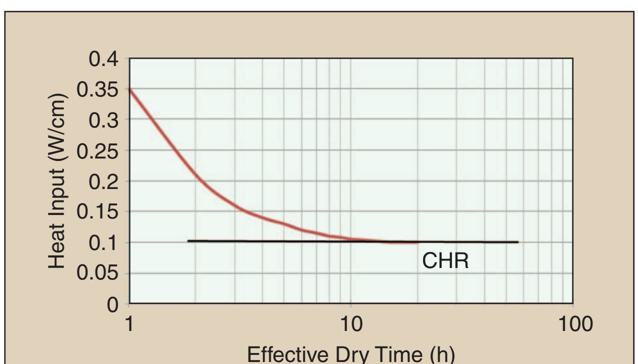
The rise in temperature in section D of Figure 2 shows that the heat rate used was above the NHR; since there was a gradual reduction in the moisture and an increase in the resistivity. At the NHR, the water flowing back into the dried area returns at the maximum rate for that specific soil. This is the upper limit of the rate of the moisture flow in the soil.

To find the NHR in the field, we start the probe at a low heat rate. If the temperature levels off after the transient portion of the curve and does not increase thereafter, the heat input must be at or below the NHR. The heat input may then be increased in stages until the point where the temperature begins to slowly trend upward, as shown in section D of Figure 2. If the temperature continues to trend up after the initial transient portion, it indicates that the soil is drying and changing in resistivity. Therefore, the applied heat rate exceeds the NHR. To reduce the time it takes to determine the NHR; several thermal probes could be used simultaneously at different heat rates.

At the NHR, the moisture content near the heat source is in equilibrium because the mass of water leaving the area surrounding the heat source by evaporation equals the mass of water entering the area. Using this knowledge will allow us to approximate the rate that water flows through the soil and the amount of soil that will dry at other heat rates.

Heat Flow from the Thermal Probe

For most cable ampacity calculations, it is assumed that all heat leaving the cable is due to conduction through the soil. However, if the soil is drying, the water leaving the soil must also be transferring heat, so conduction is not the only method of heat transfer. In the test shown in Figure 2, the heat input is 0.53 W/cm for a 120-cm probe, which is a total heat input of 63.6 W. However, from (7), the heat of conduction was found to be only



7

The thermal stability curve.

37 W. For the thermal probe used in this test, the heat flow up the probe to the air was calculated to be approximately 1.5 W, which leaves 25.1 W unaccounted for. We hypothesize that this heat is used to vaporize the water near the cable, which then leaves the area of the probe, followed by the heating of the water flowing into the dried area. To simplify the following calculations, we assume that a steady-state condition has developed where the existing water near the probe has already heated to a constant temperature. We assume that an equilibrium condition exists where the temperature gradients, due to conduction in the soil, have stabilized, and the only movement of heat is through conduction and the movement of liquid water and water vapor. We also assume that the heat transfer due to convection and radiation in the soil is negligible.

IF THE SOIL IS DRYING, THE WATER LEAVING THE SOIL MUST ALSO BE TRANSFERRING HEAT, SO CONDUCTION IS NOT THE ONLY METHOD OF HEAT TRANSFER.

The following discussion is based on the hypothesis that there are only three ways heat transfer occurs from a heat source buried in the soil:

1) conduction, which can be calculated if the temperature and soil resistivity are known
2) the latent heat of vaporization due to evaporation near the heat source, followed by movement away from the source through the soil
3) the heating of the water flowing back into the area from the surrounding soil, replacing the displaced vapor.

In (9), we find the heat balance equation describing the heat flow from the probe

$$qL = Q_c + Q_w + Q_v, \tag{9}$$

where q is the heat rate into the probe (W/cm), L is the length of the probe (cm), Q_c is the heat carried away by conduction (W), Q_w is the heat absorbed by inflowing water (W), and Q_v is the heat carried away by vapor (W). Assuming the temperature change of the water takes place as it moves from ambient earth to the heat source and that evaporation takes place with no temperature change, the heat absorbed by the inflowing water and the heat leaving by evaporation is

$$Q_w = C_w m_w \Delta T, \tag{10}$$

$$Q_v = h_v m_v, \tag{11}$$

where

- Q_w is the heat absorbed by inflowing water (W).
- Q_v is the heat carried away by vapor (W).
- C_w is the specific heat of water (4.18 J/g °C), which is 1,890 J/lb °C.
- m_w is the mass of water (kg or lb/s).
- h_v is the latent heat of vaporization of water, which is 2,260 J/g, which is 1,025,000 J/lb.
- m_v is the mass of water evaporated (kg or lb/s).
- ΔT is the change in temperature of inflowing of water from ambient temperature.

Combining (10) and (11) with (9), we get

$$qL - Q_c = C_w m_w \Delta T + h_v m_v = (Q_w + Q_V). \tag{12}$$

If we know the NHR; then we may determine the rate that vapor is leaving the soil and water is returning by using the NHR for q in (12). At the NHR; the soil will not dry, no matter how long the heat source is applied, because the mass of water leaving the soil as vapor will equal the mass of water flowing back as liquid, preventing drying and any change in soil resistivity. For this condition, where $q = \text{NHR}$, the mass of water entering the soil must equal the mass of vapor leaving the soil, i.e., $m_w = m_v = m_{\text{NHR}}$, resulting in

$$Q_{\text{NHR}} - Q_c = C_w m \Delta T + h_v m$$

$$Q_{\text{NHR}} - Q_c = m(C_w \Delta T + h_v)$$

$$m_{\text{NHR}} = \frac{Q_{\text{NHR}} - Q_c}{C_w \Delta T + h_v}. \tag{13}$$

This equation is the mass of either vapor leaving the soil or water returning to the dried area at equilibrium due to being at the NHR; making $qL = Q_{\text{NHR}}$.

If we assume that ΔT, the change in temperature of the inflowing water, will be the temperature difference between the soil ambient temperature and the probe temperature, then referring once again to Figure 4, (13) becomes

$$m_{\text{NHR}} = \frac{Q_{\text{NHR}} - Q_c}{C_w(T_1 - T_2) + h_v}, \tag{14}$$

where m_{NHR} is the mass of water or vapor (kg/s or lb/s) at NHR; Q_{NHR} is $q_{\text{NHR}}L$, which is the heat input of the probe at the NHR (W); T_1 is the temperature of the probe (°C); and T_2 is the ambient soil temperature (°C). To determine the flow rate per centimeter of length, this must be divided by the length of the probe.

It is clear from Figure 2 that the heat rate used for the test was slightly higher than the NHR. The heat rate used was probably not far above the NHR; since the soil remained at 36 °C for several hours and the subsequent increase in temperature was very slow. Understanding that using these values may be slightly nonconservative, if we estimate the NHR as 0.53 W/cm and $Q_{\text{NHR}} = 63.6$ W, using (14) results in the following maximum flow of water through the soil:

$$m_{\text{NHR}} = \frac{63.6 - 37}{1{,}890(36-20) + 1{,}025{,}000}$$
$$= 2.52 \times 10^{-5} \text{ lb/s}.$$

To get the mass per centimeter of probe length, we divide by the probe length of 120 cm:

$$m'_{\text{NHR}} = \frac{0.0000252 \text{ lb/s}}{120} = 2.1\times10^{-7} \text{ lb/s/cm}.$$

This represents the maximum rate at which liquid water can flow back into a dried area. The soil will begin to dry if the heat driving the water away increases. Using a density for water of 62.2 lb/ft^3, this would be 4×10^{-7} ft^3/s or 0.011 gal/h.

If the moisture content of the soil during the determination of the NHR is known and it is desired to find the flow rate at other moisture contents, the flow rate should increase or decrease proportionally to the moisture content of the soil, assuming the hydraulic gradient will increase or decrease in the same manner. Therefore, the flow rate should be corrected for the minimum moisture content expected in the soil at a particular location.

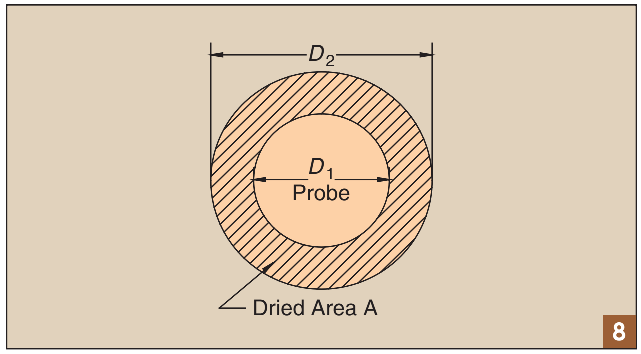
Extent of Soil Drying

Referring once again to the test in Figure 2, a question arises: why does the temperature achieve a second steady-state condition about eight days after the soil begins to dry and resistivity begins to increase in section D? Why does the soil not continue to dry until it reaches its dry resistivity? The moisture leaving the area of the thermal probe will migrate fastest from the warmest temperature next to the probe. To simplify the analysis, we assume that the drying process will proceed in a manner that will completely dry a small annulus of soil next to the heat source and that the diameter of this dried layer will gradually move outward as more soil dries. Thus, a completely dry layer is produced next to the probe surrounded by soil at its natural moisture level as shown in Figure 8. The dried area will increase in size, and the soil's effective resistivity to ambient earth will gradually increase. Realistically, the soil moisture will decrease in a continuous gradient rather than a discrete step, but will be modeled discretely in this article to simplify the analysis.

The water replenishing the vapor that leaves the vicinity of the heat source flows into the dried area because of the hydraulic gradient that exists in the moist soil. We assume that this hydraulic gradient will remain constant in the interface between the ambient soil and the dried annulus of soil during the drying process. Furthermore, we assume that the ambient soil has sufficient moisture to replenish the dried area indefinitely without significantly affecting the ambient hydraulic gradient. The maximum rate that the moisture can return to the dried area was determined using (14). This value of the water flow is the amount of water flowing into a dried volume that is equal to the volume of the heated probe. This water must flow through an area of soil that is equal to the surface area of the probe. However, as the soil dries, a small annulus of dried soil will be created between the probe and the moist soil, as shown in Figure 8. The drying process will increase the area through which moisture may flow back into the dried area. Where the original area was equal to πD_1 (for a unit length of the probe), the new area after slight drying would be equal to πD_2.

Darcy's law describes the flow rate of a liquid through soil [13]. This law may be written as

$$q = \text{kiA}, \tag{15}$$



The dried soil surrounding the probe.

where q is the flow rate; k is the soil permeability; i is the hydraulic gradient, which is the head/length of the flow path; and A is the area through which water flows. Assuming that the hydraulic gradient and the permeability at the moist/dry interface remain nearly constant, the only thing that will change as the dried soil area expands and moves away from the heat source is the area through which the replenishing water flows back into the dried area, and this area increases as the diameter of the dried area increases. The larger the dried soil is, the larger the area becomes through which water can flow back to the dried area. We compare the flow rate between any two areas using Darcy's laws

$$\frac{q_1}{q_2} = \frac{kiA_1}{kiA_2} = \frac{A_1}{A_2}. \tag{16}$$

Using the computed flow rate at the NHR as the flow rate at the original probe diameter, and assuming that the length of the dried area remains the same, this becomes

$$\frac{m_{\text{NHR}}}{\pi D_{\text{probe}}} = \frac{m_2}{\pi D_2}, \tag{17}$$

where m_2 is the flow rate in kilograms per second or pounds per second through a dried diameter of D_2 in centimeters, if the diameter of the probe D_{probe} was given in centimeters. Therefore, as the dried area increases in size, the flow rate of water into the dried area will also increase proportionally.

If the heat rate into the heat source is increased to some level above the NHR; the soil will dry until an equilibrium is once again established between the mass of vaporized water and the amount of water that can return to the dried area. The circumference of the dried soil will increase until it is sufficiently large enough to allow the moisture entering the dried area to equal the moisture being vaporized by the new heat rate. At this point, the drying process will cease. This accounts for the stabilization of soil resistivity that was witnessed after an eight-day period during the test shown in Figure 2.

The rate at which heat leaves the soil due to moisture being raised from ambient temperature to the temperature at the wet/dry soil interface and leaves the area as vapor is

$$Q_w + Q_v = C_w m_w \Delta T + h_v m_v.$$

If this occurs at the point where the diameter of the dry area has increased so a nondrying equilibrium is once again established, then the mass of water entering the soil equals the mass of water leaving, and $m_w = m_v = m$

$$m = \frac{Q_w + Q_v}{h_v + C_w \Delta T} \text{ lb/s}, \quad (18)$$

where m is m_w, or m_v, which is the flow rate of liquid water or vapor (lb/s), respectively; Q_v is the heat input available to vaporize water (W); and h_v is the latent heat of vaporization; and Q_w is the heat absorbed by the inflowing water.

Substituting (18) into (17) results in an equation for the diameter of dried soil D_2 that would result from moisture being vaporized by a heat rate equal to any arbitrary Q for the soil at which m_{NHR} and D_{probe} are known

$$\frac{m_{\text{NHR}}}{\pi D_{\text{probe}}} = \frac{\left(\dfrac{Q_w + Q_v}{h_v + C_w \Delta T}\right)}{\pi D_2}$$

$$D_2 = \frac{D_{\text{probe}}\,(Q_w + Q_v)}{m_{\text{NHR}}\,(h_v + C_w \Delta T)}. \quad (19)$$

If the heat rate is increased above the NHR; the diameter of the dried area of the soil will increase and the temperature of the probe will increase due to the increase in soil resistivity next to the probe. An increase in heat rate would also be expected to increase the temperature at the moist/dry soil interface above that measured at the NHR. The increase in diameter would slightly decrease the resistivity between the moist/dry soil interface and ambient earth by increasing D in (7). Both of these effects would increase the heat conducted away from the heat source. However, the increase in temperature would also tend to increase the rate of evaporation from the moist/dry soil interface. It is unknown whether one effect will outweigh the other, i.e., whether the heat carried away by evaporation will increase more than the heat carried away by conduction or whether the converse will be true.

This also means that ΔT is not precisely known for a new heat rate. However, if we make the conservative assumption that the temperature of the water entering the moist/dry interface will increase at least as much as before the increase in heat rate, and furthermore assume that the heat transfer by conduction and the heat transfer due to water movement will both increase at the same rate that the total heat rate increased, then we can solve (19) to determine the diameter of dried soil at the new heat rate using the following:

$$Q_c = \frac{Q_{\text{new}}}{Q_{\text{NHR}}} Q_{c\,\text{NHR}}, \quad (20)$$

$$Q_w = \frac{Q_{\text{new}}}{Q_{\text{NHR}}} Q_{w\text{NHR}}, \quad (21)$$

$$Q_v = \frac{Q_{\text{new}}}{Q_{\text{NHR}}} Q_{v\text{NHR}}, \quad (22)$$

$$(Q_w + Q_v) = \frac{Q_{\text{new}}}{Q_{\text{NHR}}} (Q_{w\text{NHR}} + Q_{v\text{NHR}}), \quad (23)$$

where
- Q_c is the heat transfer by conduction at the new heat input Q_{new}.
- $Q_{c\text{NHR}}$ is the heat transfer by conduction at Q_{NHR}.
- Q_w is the heat transfer by inflowing water at the new heat input Q_{new}.
- $Q_{w\text{NHR}}$ is the heat transfer by inflowing water at Q_{NHR}.
- Q_v is the heat transfer by vapor at the new heat input Q_{new}.
- $Q_{v\text{NHR}}$ is the heat transfer by vapor at Q_{NHR}.
- Q_{new} is the new heat input to the probe.

Using the example given earlier, if we doubled the heat rate into the probe from the NHR of 0.53 W/cm to 1.06 W/cm, for a change from 63.6 to 127.2 W, this would also double the conduction rate from 37 to 74 W, leaving 50.2 W to be carried away by vaporization and heating of the inflowing water (assuming that 3 W is lost to air in the probe). So the new $(Q_w + Q_v) = 50.2$ W at the new heat rate using (23). The heat probe used in the testing had a diameter of 1.5875 cm. We may use (19) to find the dried area

$$D_2 = \frac{1.5875\,(50.2)}{0.0000252\,(1{,}025{,}000 + 1890(36 - 20))} = 3\,\text{cm}.$$

So, a dried area with a diameter of 3 cm would have resulted from this increase in heat rate. This would be a layer of dried soil of approximately 0.71 cm surrounding the probe on all sides.

If the volume of the dried soil and the maximum flow rate back into the soil are known, then the time for a dried area to completely return to its natural moisture level after the removal of the heat source can be found. If m_{NHR} is the maximum flow rate at the original probe diameter and D_2 is the maximum diameter of the dried area, then, according to (17), the flow rate at the maximum diameter is

$$m_2 = \frac{D_2 m_{\text{NHR}}}{D_{\text{probe}}}.$$

The average flow rate back into the dried area is then

$$m_{\text{avg}} = \frac{m_{\text{NHR}} + m_2}{2} = \frac{m_{\text{NHR}} + \dfrac{D_2 m_{\text{NHR}}}{D_{\text{probe}}}}{2}$$

$$= \frac{m_{\text{NHR}}}{2}\left(1 + \frac{D_2}{D_{\text{probe}}}\right). \quad (24)$$

If the in-place unit weight of soil and the moisture content of the soil are known, then the amount of water originally contained in the area of the soil around the probe may be found using

$$\gamma = \gamma_s + \gamma_w, \quad (25)$$

$$\gamma_w = \omega \gamma_s,$$

$$\gamma_s = \frac{\gamma_w}{\omega}, \quad (26)$$

where γ is the unit weight of the total soil sample (lb/ft^3), γ_w is the weight of water per unit volume of soil sample (lb water/ft^3 of sample), γ_s is the weight of dry soil per unit volume of soil sample (lb dry soil/ft^3 of sample), and ω is the moisture content of the sample (%), which is the weight of water/weight of dry soil. We substitute (26) into (25) and solve for the weight of water per total volume of soil:

$$\gamma = \frac{\gamma_w}{\omega} + \gamma_w = \gamma_w\left(1+\frac{1}{\omega}\right) = \gamma_w\left(\frac{\omega+1}{\omega}\right)$$

$$\gamma_w = \frac{\gamma\omega}{(1+\omega)} \text{ lb water/ft}^3 \text{ of total soil.} \tag{27}$$

For a cylinder of dried soil that is 3 cm in diameter surrounding the probe that is 1.5875 cm in diameter and 120 cm long, the volume of the dried cylinder of soil is

$$V = \left(\frac{\pi D_2{}^2}{4} - \frac{\pi D_{\text{probe}}^2}{4}\right)L$$

$$V = \frac{\pi}{4}(3^2 - 1.5875^2)\ 120 = 610.7 \text{ cm}^3. \tag{28}$$

Using the soil unit weight measured at 120 lb/ft^3 (0.0042377 lb/cm^3) and the moisture content of 12%, and using (27) the weight of water originally in the volume V of dried soil before it was dried, yields

$$V\gamma_w = 610.7\frac{\gamma\omega}{(1+\omega)} = 610.7\frac{0.0042377(0.12)}{1+0.12}$$
$$= 0.277 \text{ lb.}$$

Using (24), the average flow rate into the area is

$$m_{\text{avg}} = \frac{m_{\text{NHR}}}{2}\left(1+\frac{D_2}{D_{\text{probe}}}\right) = \frac{0.0000252}{2}\left(1+\frac{3}{1.5875}\right)$$
$$= 3.64 \times 10^{-5} \text{ lb/s.}$$

This would result in a time to replenish the moisture in this area of dried soil of

$$t = \frac{V\gamma_w}{m_{\text{avg}}}$$

$$t = \frac{0.277}{0.0000364} = 7{,}609 \text{ s} = 2.11 \text{ h.} \tag{29}$$

Therefore, it would take approximately 2 h for the moisture to flow back into the area that was dried by the increased heat rate after the heat is removed.

Vertical Probe Test Results Used for Horizontal Cables

The values we have measured using the vertical probe may be used for calculations for a horizontal cable buried in the earth. Both the soil resistivity and the maximum water-flow rate will be the same for the vertical and horizontal heat source. Equations (5)–(7) describe the heat flow from a vertical cylinder in a semi-infinite medium. Their counterparts for heat flow from a horizontal cylinder of length L in a semi-infinite medium are

$$S = \frac{2\pi L}{\ln\left(\frac{4z}{D}\right)}, \tag{30}$$

$$R = \frac{\rho}{S} = \rho\frac{\ln\left(\frac{4z}{D}\right)}{2\pi L}, \tag{31}$$

$$Q_c = \frac{2\pi L(T_1 - T_2)}{\rho\ \ln\left(\frac{4z}{D}\right)}. \tag{32}$$

In these equations, z is the depth of the center of the cable below the surface, and D is the cable diameter. Equation (32) is known as the short form of the Kennelly equation and is a valid approximation for cases where z is more the 1.5 times the cable diameter [7].

A comparison of (5)–(7) with (30)–(32) shows that they are identical if the depth of burial of the horizontal cable z is equal to the length L of the vertical probe. So a cable of the same diameter as the probe buried at the depth equal to the length of the probe and supplying the same heat rate should perform identically with the vertical probe. All of the heat rates, temperatures, and evaporation rates will be the same.

For a cable, however, both the diameter and the burial depth may differ from the vertical probe. This will change the amount of heat conducted away from the horizontal cable versus the amount of heat leaving through vaporization from the values computed. It is unlikely that the diameter of an underground cable will be less than the diameter of the vertical probe. If the underground cable of interest is larger than the vertical probe, the result will be that the thermal resistance to ambient earth will decrease according to (31). This would mean that, for the same heat rate used for the smaller-diameter probe, the temperature of the cable/soil interface would be less than the temperature of the probe. This lower temperature would tend to reduce the evaporation rate, which would decrease the heat carried away by vapor and increase the amount of heat conducted away, resulting in an increase in the temperature of the cable/soil interface for any condition above the NHR. Increasing the diameter of the cable should decrease the temperature of the cable to some degree but by less than the value calculated using (32) assuming the same heat rate of conduction used in the probe. Furthermore, the rate of evaporation will also decrease to some degree. While it is unknown exactly how much the conduction will increase or the evaporation will decrease, if the original values calculated for the vertical probe for both the conduction and evaporation are used, a conservative result will be expected. Using these assumptions, the diameter of dried soil calculated should be more than what will actually occur, since the evaporation rate is reduced. It should also be noted that, if the calculated diameter of dry soil is less than the diameter of the cable, the soil around the cable would be expected to never dry out at the heat rate used in the calculations.

If the depth of the cable in question was increased to set the cable below the surface and deeper than the length of the test probe, then, according to (31), the thermal resistance to ambient earth would increase. If the heat rate of conduction was assumed to be equal to the heat rate of conduction for the probe, the temperature of the cable/soil interface must increase from the temperature of the probe. This higher temperature will tend to increase the evaporation rate and increase the amount of heat carried away by water. Since more heat is being carried away by the water vapor, this leaves less heat needing to be transferred by conduction. This will, in turn, tend to reduce the heat transfer by conduction. A suggested approach is to use (32) to compute the heat transfer due to conduction from the buried cable, $Q_{c\mathrm{NHR}}$ (Q_c at the NHR), using the original probe temperature for T_1 at the new cable depth z, and then to modify $Q_{c\mathrm{NHR}}$ using (20) to get Q_c. Then the following heat balance equation is solved:

$$Q_{\mathrm{new}} = Q_c + Q_w + Q_v$$
$$Q_w + Q_v = Q_{\mathrm{new}} - Q_c, \quad (33)$$

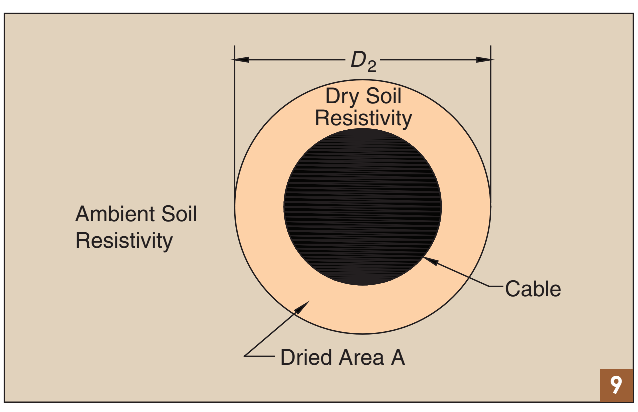
where Q_{new} is the heat input in the cable (W), and Q_c is the heat transfer by conduction, calculated as described using (32).

This value $Q_w + Q_v$ that is determined using (33) can then be used in (19) to determine the diameter of the dried soil for a cable deeper than the length of the probe. A cable buried at a depth less than the length of the probe should present the opposite case, and using the original values computed for the probe should result in a conservative estimate for the diameter of the dried soil. It should be noted that the equations for heat flow may not be accurate for the depths of the cable much less than the length of the probe. Use care when applying this method to shallow cables, since actual temperatures may vary considerably from the assumptions made. Also, when long cables are involved, the heat and moisture values can be converted to per unit length of cable by dividing by the probe length rather than working with bulk values.

Summary of the Procedure

To find the thermal resistivity of the dried soil surrounding a direct-buried cable at any expected heat rate and the expected diameter of this dried soil around the cable, we suggest the following procedure:

1) Determine the soil in-place unit weight using (1) by any accepted method [14]–[16].



A diagram of the thermal model.

2) Determine the water content ω using (2) by any accepted method [17]–[19].
3) Using the in-the-field thermal resistivity test equipment [2], start with a heat input of 0.1 W/cm. If the probe temperature reaches an equilibrium temperature and does not change for a period of 3 h, increase the heat input by 0.1–0.2 W/cm. Repeat this process, increasing by the same step size until the point where the temperature slowly increases and does not reach an equilibrium temperature in 3 h. The highest heat input at which an equilibrium temperature is achieved is the assumed NHR q_{NHR}. At this heat rate under steady-state temperature conditions, record a) the heat input (q_{NHR}) and calculate Q_{NHR} by multiplying by the probe length L, b) the steady-state probe temperature (T_1), and c) the beginning probe temperature (soil ambient temperature T_2).
4) Calculate the soil thermal resistivity using the data measured in step 3 for the initial application of heat and using (3) (using T_2 at $t_2 = 2{,}400$ s and T_1 at $t_1 = 600$ s after the application of heat in this equation). If the initial heat input in step 3 does not produce a large enough temperature variation in the time suggested to produce an accurate result, a separate thermal resistivity measurement will be needed. A heat input between 0.5 and 0.8 W/cm is suggested for this test. (Note that the values of T_1 and T_2 used in this step are not the same as those recorded in step 3. See the method for calculating resistivity for these values.)
5) At the steady-state temperature reached at Q_{NHR} and using the data recorded in step 3, calculate the heat carried away by conduction Q_c using (7). Use the results to compute the maximum mass of water flowing back to the dried area, m_{NHR}, using (14).
6) Find $(Q_W + Q_V)$ at the NHR using (12). This value should be reduced by the heat loss in the system that is not transferred to the soil, if it can be estimated.
7) Find the design heat rate in watts per centimeter that will be injected into the soil by the cable [1]. This is calculated using the expected design current and cable resistivity. Determine the new value of heat transferred by water $(Q_W + Q_V)$ using (23) [and (32) and (33) if needed].
8) Using the values calculated in step 7 for $(Q_W + Q_V)$, find the dried soil diameter at the new heat rate using (19). If the diameter of dried soil is less than the diameter of the cable, then soil drying will not occur at the heat rate used.
9) Determine the dry soil resistivity using the laboratory method [2], [20] or the in-field method if possible.
10) When preparing the soil thermal model to determine the cable ampacity, model the soil resistivity surrounding the cable as a layer of dried soil with a resistivity determined in step 9 and a diameter determined in step 7. This will be surrounded by soil of ambient thermal resistivity as determined in step 4. The final soil thermal model is shown in Figure 9.
11) Add the thermal resistance of this dried soil layer to R_{ca} (or to R_{sd} if conduit or electrical ducts are involved) in the Neher–McGrath equation. The value of the thermal resistance to be added is computed using

$$R = 0.012\, \rho_{\text{dry soil}}\, \log\left(\frac{D_2}{D_1}\right)\, \Omega\text{-ft}, \tag{34}$$

where D_2 is the computed maximum diameter of the dried soil from step 8, and D_1 is the diameter of the cable or conduit including the insulation. The resistivity would be the dry soil resistivity determined in step 9. The value used for D_e in the Neher–McGrath calculations would also change from the diameter of the beginning of the earth portion of the thermal circuit to the diameter of the beginning of the earth circuit surrounding the dried soil, i.e., D_e is now D_2 stated above [1].

12) If you desire to calculate the time it will take to replenish the moisture in this area of the soil, an approximate value can be calculated using (29) and using the diameter of the cable rather than the diameter of the probe and the moisture rate per 1-cm length of cable.

THE DRIED SOIL RESISTIVITY CAN SOMETIMES BE DETERMINED IN THE FIELD BUT MAY NEED TO BE FOUND USING LABORATORY TESTS.

Conclusions

The same field tests that are often used to determine soil thermal resistivity may provide additional information that can help to determine the amount of soil drying around a cable that may be expected for varying heat rates. The IEEE 442 [2] standard thermal probe can be used to determine the NHR of the soil being studied. This value, in turn, can be used to determine the maximum rate that water can flow into a dried area of soil from the surrounding soil. When this is known, the diameter of the soil around a cable that will dry can be determined for any heat input rate. This process will dramatically help the design engineer in properly sizing the cable. Currently, the engineer typically assumes a worst-case thermal runaway resistance that results in cable sizes that may be too large.

The dried soil resistivity can sometimes be determined in the field but may need to be found using laboratory tests. When this is determined, a thermal model can be built that includes the typical values used in Neher–McGrath calculations plus the thermal model of the worst-case dried soil layer that is expected at the heat rate of interest. This model will use the typical design parameters including the thermal resistance of the insulation, jacket, and the conduit (if it is used). The model will also use the calculated dried soil annulus and the thermal resistance of the unaffected soil surrounding the dried area. These values can then be included in the normal methods of determining cable ampacity [1]. Further discussion of (4) and its questionable use for estimating the time to dry is provided in [21].

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