THE MEASUREMENT OF SOIL THERMAL STABILITY, THERMAL RESISTIVITY, AND UNDERGROUND CABLE AMPACITY

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***Abstract* –** One of the most important factors affecting underground cable ampacity is the thermal resistivity of the soil. It is well known that thermal resistivity of the soil will vary with moisture content. It is also well known that the heat generated by cables can cause soil drying thus affecting the soil thermal resistivity. The ability of the soil to maintain its thermal resistivity in the presence of a heat source is known as thermal stability. Soil will increase in resistivity due to drying caused by heating from underground sources. This phenomenon makes it challenging for the design engineer to decide how to account for the drying effect in cable ampacity calculations. This paper will examine the information available from standard soil tests and the information these tests may provide relating to the migration of moisture in soil and the resulting changes in soil resistivity. Furthermore a method is suggested for including this information in underground cable ampacity calculations.

Index Terms – Soil Thermal Stability, Soil Thermal Resistivity, Cable Ampacity, Underground Cable Design,

I. INTRODUCTION

When a cable is buried in soil, whether direct buried or in an underground pipe, the heat generated by the I^2R losses in 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 great 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 that an engineer must know to calculate the amount of current any particular cable can be allowed to carry. 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].

II. 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. A soil sample is taken from the field and the in-place soil unit weight test gives the overall soil unit weight in lb/ft^3 as given in Equation 1. The water content of the soil sample is also tested and the results of this test gives the weight of water contained in the soil sample divided by the weight of dried soil and is given in percent as shown in Equation 2.

$$\text{Unit weight} = \gamma = \frac{\text{pounds of soil}}{\text{cubic foot of soil}}\ \text{lb/ft}^3$$

Equation 1

$$\%\text{Water content} = \omega = \frac{\text{Weight of water}}{\text{Weight of dry soil}} = \frac{W_w}{W_s}\times 100\%$$

Equation 2

The soil thermal resistivity is measured by inserting a heat generating thermal probe into the soil or soil sample (if done in a lab) and soil resistivity is measured as described in IEEE Std. 442 "IEEE Guide for Soil Thermal Resistivity" [2] [3]. A known heat rate in W/cm is injected into the probe and a plot is made of the temperature of the probe/soil interface versus time. Figure 1 shows an idealized example of the type of curve that may result from this type of test.

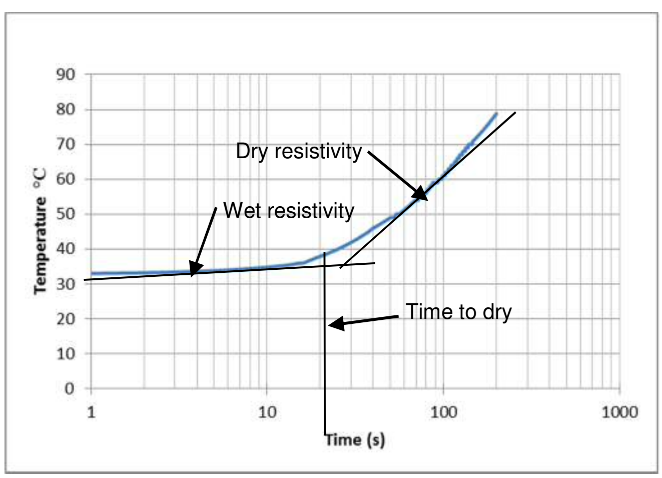

Figure 1: Soil drying curve.

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 the soil surrounding the probe dries. The resistivity of the soil in each condition is proportional to the slope of the respective curves. In the either condition, wet or dry, the soil resistivity may be found using Equation 3 [4].

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

Where

$\rho =$ soil resistivity $^{\circ}$C cm/W

q = heat input in W/cm

$T_1 =$ temperature at time t_1

$T_2 =$ temperature at time t_2

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

The effective drying time may also be found using this test. It will vary with 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. The diameter of the probe and the heat input of the probe per unit length must also be recorded.

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 Equation 4 [4] [5] [6].

$$t_2 = t_p\left[\frac{D_2}{D_p}\right]^2 \qquad \text{Equation 4}$$

Where

$t_2 =$ soil time to dry with heat source diameter D_2

$t_p =$ soil time to dry with probe diameter D_p

It is sometimes suggested that the time to try 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.

Laboratory tests are 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].

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 hours of a soil resistivity test taken with a 120 cm thermal probe with a heat input of 0.53 W/cm.

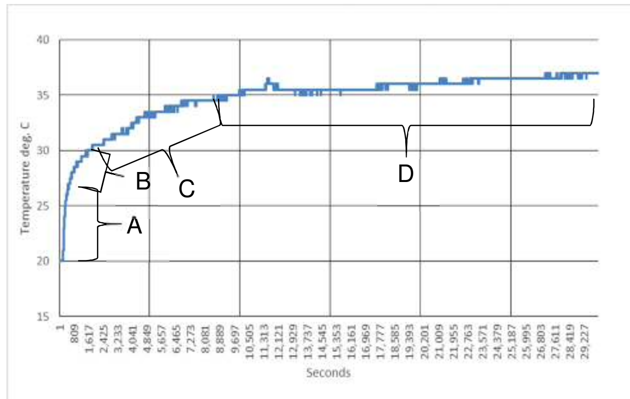

Figure 2: In situ soil resistivity test results.

There are four sections of data apparent from Figure 2. The following explanation is hypothesized to account for the measured data in this Figure. 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 for approximately 10 minutes 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 Sections "A" and "B" are extracted and plotted on a semi-log graph resulting in Figure 3.

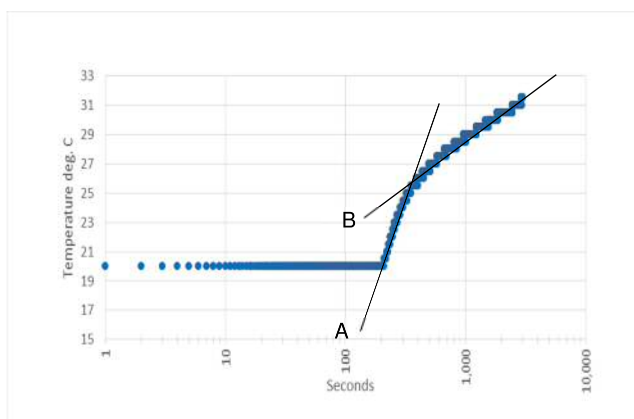

Figure 3: First 30 minutes of test.

For the first ten minutes 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 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 graphs is mainly due to heating the soil and the slope of "B" may be used with Equation 3 to determine soil resistivity.

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 heat source the slope of the resulting graph will be proportional to the soil thermal resistivity. However, at some point in time heat flow will no longer be one dimensional linear flow, and will transition into two dimensional heat flow. This transition region between one and two dimensional heat flow is represented by Section "C" in Figure 2. This transition occurs approximately 45 minutes after the probe begins heating and lasts approximately 3 hours. During this time the soil is slowly heating and two dimensional heat flow and end effects of the probe become important.

At the end of Section "C" and beginning of Section "D" the soil has reached a temperature of 36℃ and becomes nearly constant. It then gradually increased at a rate beginning at about 1 degree/day increasing to slightly more than 2.5 degrees/day and decreasing once again to 0.5 degrees/day after 7 days. The soil finally achieved a constant temperature of 54℃ at day 8. It stayed constant for the last 2 days of the test when the test was terminated. It is hypothesized that this gradual increase in temperature in Section "D" is due to a gradual reduction in moisture near the probe that resulted in the gradual increase in soil thermal resistivity near the probe thereby increasing the temperature of the probe. The soil finally achieved final equilibrium where this drying ceased and the soil achieved its final resistivity for the heat rate used.

Using the slope of line "B" in Figure 3 the soil resistivity may be found using Equation 3. It is suggested that when the in-field test is done and Equation 3 is used to determine resistivity that T_1 is taken after approximately 10 minutes of heating (for most standard type probes) and T_2 is taken after approximately 25 minutes [2] later 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 seconds T_1 was found to be 27.5℃ and T_2 was measured at 30.5℃ after 2100 seconds. The heat rate was 0.53 W/cm. Using Equation 3 results in the following soil thermal resistivity.

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

An equation permitting the calculation of steady-state conductive heat flow from the thermal probe may be found using the appropriate conduction shape factor [8]. If a cylinder is inserted vertically into 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.

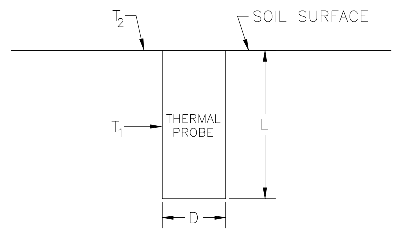

Figure 4: Thermal probe inserted vertically in soil.

If the diameter and length of the probe, D and L, and soil thermal resistivity are known and the probe surface temperature T_1 is measured and soil surface temperature T_2 can be found under steady state conditions then a solution to the two dimensional heat flow between the probe and the surface through an infinite soil layer bounded only at the surface may be found. It must be assumed that the thermal resistivity found is for a composite soil that can be assumed to be uniform, and 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.

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

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

Equation 5

The thermal resistance of the soil for two dimensional heat flow between the probe and the soil surface will be:

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

Equation 6

Where

ρ = Soil resistivity (cm-°C/W)

R = Thermal resistance (°C/W)

S = Shape factor from Equation 5 (cm)

D = Diameter of probe (cm)

L = Length of probe (cm)

The equation for heat flow using the shape factor for this condition will be:

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

$$\mathrm{Q_c} = \frac{2\pi\mathrm{L}(\mathrm{T_1} - \mathrm{T_2})}{\rho\ln\left(\frac{4\mathrm{L}}{\mathrm{D}}\right)} \quad \text{Watts}$$

Equation 7

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

The probe first achieves steady-state 2-dimensional heat flow at the beginning of Section "D" of Figure 2. Assuming no change in soil thermal resistivity has yet occurred at this time, and using Equation 7 the heat flow due to conduction during this time period may be found. The probe is 120 cm long, 1.5875 cm in diameter, T_1 was 36°C, and T_2 was soil ambient temperature—20°C.

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

Assuming the heat of conduction did not change with the final steady state condition after 8 days of testing the increase in soil resistivity may also be found using Equation 7. Combining this equation for the two cases of different temperature changes but constant heat flow the new thermal resistivity may be found using Equation 8.

$$\rho_2 = \rho_1 \frac{\Delta T_2}{\Delta T_1}$$

Equation 8

For the case where the initial soil resistivity was 57 °C-cm/W for the initial temperature change of 16°C, and the final temperature change after 8 days was 34°C, and assuming the heat of conduction through the soil did not change, the new apparent thermal resistivity would be:

$$\rho_2 = \rho_1 \frac{\Delta T_2}{\Delta T_1} = 57 \frac{34}{16} = 121 \text{ °C - cm/W}$$

From the measurements it appears that the soil has an initial resistivity to ambient earth of 57 °C-cm/W and due to moisture changes near the probe the resistivity increases to 121°C-cm/W after several days of the application of 0.53 W/cm. It should be noted that the results shown are only valid for one soil moisture content and would be expected to change at other soil moisture contents. As the water content varies, as can be expected during the year in most locations, the resistivity of the soil will also vary [9] .

Even more importantly, if the heat rate into the soil is increased soil will tend to dry more quickly and completely near the heat source changing the resistivity near the probe to a greater degree. The question that arises is which value of resistivity should be used in determining the ampacity of the underground cables? The moist value measured initially or the final dry value, or some intermediate value? It is clear 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 some intermediate value may be more accurate but more difficult to determine.

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

III. THE 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 though 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 particles increases resulting in 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.

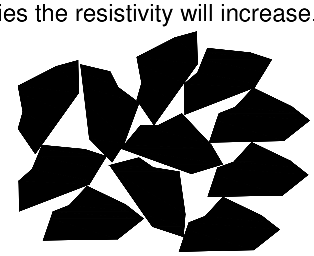

Figure 5: Soil particles with voids.

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 run away 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 of thermal instability that may occur which 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 soil. The first is movement in liquid form due to heat weakening 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 be a minor effect in the temperature change of cables [7] [12]. For this reason only the second mechanism, the movement of vapor through the soil, will be considered as an effective enough 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 vaporized and the increased pressure due to additional heating causes the vapor to move through the soil pores until it condenses in a cooler location [6]. As the water vapor leaves the area immediately surrounding the cable water in the soil in liquid form located further from the cable flows due to gravity and capillary action and hydraulic gradient into the dried soil as shown in Figure 6.

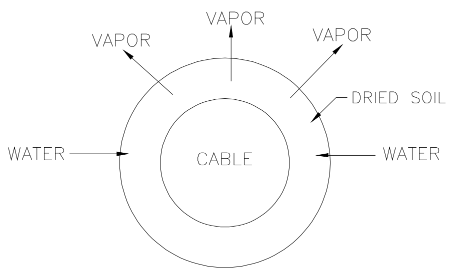

Figure 6: Vapor leaving and water entering a soil layer near a cable.

If the rate that heat enters the soil is slow enough that the surrounding water can replenish the water that migrates away then the resistivity of the soil will not change. If the heat source is large enough that water is vaporized and leaves the surroundings faster than the water can be replenished then the soil will dry and increase the soil resistivity near the cable. If the soil never dries out the wet value of resistivity as calculated in Figure 1, Figure 2, and Figure 3 can be used for cable ampacity calculations. If the soil does dry then for some distance from the cable the dry value of soil resistivity must be used surrounded by soil at the moist resistivity value. If the soil is partially dried, then it is suggested here that the use of a layer of some diameter of dried soil surrounded by soil of the moist value of thermal resistivity may still be used and will produce somewhat conservative results when determining cable ampacity.

IV. MEASURING THERMAL STABILITY; THE CRITICAL HEAT RATE AND NON-DRYING HEAT RATE

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

1. Critical heat rate (CHR)
2. Non-drying heat rate (NHR)

The critical heat rate 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 critical heat rate the heat input into the thermal probe could be increased in stages until a heat rate found that was just sufficient to cause this rapid increase in resistivity.

To determine the critical heat rate 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 prepared as shown in Figure 7. The heat rate at which the graph become horizontal, showing soil would not dry at this input even after a long time, will be the critical heat rate [6].

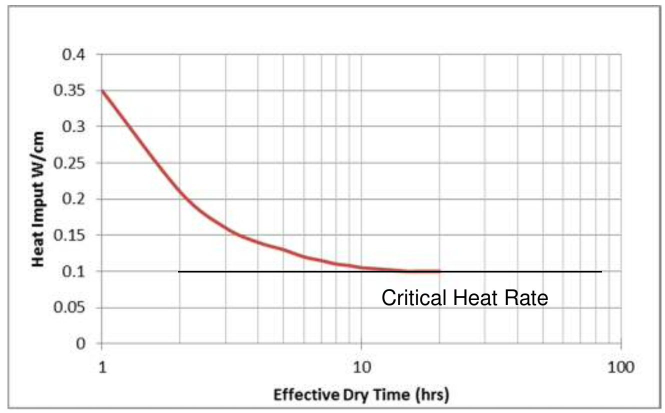

Figure 7: Thermal stability curve.

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 it would be expected 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 only be found in the field since it depends on the surrounding soil’s natural vapor and liquid diffusivity levels and the 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 some reduction in moisture, and therefore resistivity, gradually occurred. At exactly the NHR the water flowing back into the dried area would be returning at the maximum rate water could flow to a dried area through the soil. This would be the upper limit of the rate of moisture flow in the soil.

The NHR may be found in the field by starting 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. Heat input may then be increased in stages until the point where the temperature begins the slow trending up shown in Section “D” of Figure 2 occurs. If the temperature continues to trend up after the initial transient portion, it means that the soil is drying and changing in resistivity and the heat rate being applied must exceeding the NHR. To reduce the time takes to determine the NHR several thermal probes could be used simultaneously operating at different heat rates.

At the NHR the moisture content near the heat source is in equilibrium and the mass of water leaving the area surrounding heat source by evaporation will equal the mass of water entering the area. Were this not true the soil would dry. And if the NHR is known then the amount of moisture flowing back to the dried area would be the maximum the soil could supply. 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.

V. HEAT FLOW FROM THE THERMAL PROBE

For most cable ampacity calculations it is usually assumed that all heat leaving the cable is due to conduction through the soil. However, if the soil is drying then the water leaving the soil must also be absorbing heat and conduction is not the only method of heat transfer.

In the test shown in Figure 2 the heat input was 0.53 W/cm for a 120 cm probe this would be a total heat input of 63.6 W. However, from Equation 7 the heat of conduction was found to be only 37 W. For the thermal probe used in this test the heat flow up the probe to the air was estimated to be 1.5 W. This leaves 25.1W unaccounted for. It is hypothesized that this heat is used to increase the temperature of the inflowing water from ambient soil temperature to the temperature of the probe and then vaporizing the moisture which then leaves the area of the probe followed by the heating of the water flowing into the dried area. To simplify the following, it is also assumed that a steady-state condition has developed where the existing water near the probe has already heated to a constant temperature and 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 water and water vapor. It is also assumed that the heat transfer due to convection and radiation in the soil is negligible.

The following discussion is based upon 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 temperature and soil resistivity is 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 surrounding soil replacing the displaced vapor.

Equation 9 is the heat balance equation describing heat flow from the probe.

$$qL = Q_c + Q_w + Q_v$$

Equation 9

Where

q = heat rate into the probe (Watts/cm)

L = length of probe in cm

Q_c = heat carried away by conduction (Watts)

Q_w = heat absorbed by inflowing water (Watts)

Q_v = heat carried away by vapor (Watts)

The heat absorbed by the inflowing water and leaving by evaporation, assuming the temperature change of the water takes place as it moves from ambient earth to the heat source and evaporation takes place with no temperature change, would be:

$$Q_w = C_w m_w \Delta T$$

Equation 10

$$Q_v = h_v m_v$$

Equation 11

Where

Q_w = heat absorbed by inflowing water (Watts)

Q_v = heat carried away by vapor (Watts)

C_w = Specific heat of water - 4.18 kJ/kg°C = 1.89 kJ/lb°C

m_w = mass of water in kg or lb per second

h_v = latent heat of vaporization of water = 2260 kJ/kg = 1025 kJ/lb

m_v = mass of water evaporated in kg or lb per second

ΔT = The change in temperature of inflowing water from ambient temperature

Plugging Equation 10 and Equation 11 into Equation 9:

$$qL - Q_c = C_w m_w \Delta T + h_v m_v = (Q_w + Q_V)$$

Equation 12

If the NHR is known then to determine the rate vapor is leaving the soil and water is returning may be found by using the NHR for q in Equation 12. At the NHR the rate 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=NHR then the mass of water entering the soil must equal the mass of vapor leaving the soil: $m_w = m_v = m_{NHR}$ resulting in Equation 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 NHR. Making $qL = Q_{NHR}$:

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

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

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

Equation 13

If it is assumed 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 Equation 13 becomes:

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

Equation 14

Where

m_{NHR} = Mass of water or vapor in kg/sec or lb/sec at NHR

$Q_{NHR} = q_{NHR} L$ = Heat input of the probe at the NHR (Watts)

T_1 = The temperature of the probe (°C)

T_2 = Ambient soil temperature (°C)

To get the flow rate per cm of length this must be divided by the length of the probe.

It is clear from the 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 non-conservative if we estimating the NHR as 0.53 W/cm and Q_{NHR}=63.6 W and using Equation 14 results in the following maximum flow of water through the soil.

$$m_{NHR} = \frac{63.6 - 37}{1{,}890(36 - 20) + 1{,}025{,}000} = 0.0000252 \text{ lb/sec}$$

To get the mass per centimeter of probe length divide by the probe length of 120cm.

$$m'_{NHR} = \frac{0.0000252 \text{ lb/sec}}{120} = 0.00000021 \text{ lb/sec/cm}$$

This should represent the maximum rate at which liquid water can flow back into a dried area. If the soil is called upon to replenish the water at a greater rate than this due to more vapor leaving the soil, the soil will begin to dry. Using a density for water of 62.2 lb/ft^3 this would be 0.0000004 ft^3/sec or 0.011 gal/hour.

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. So the flow rate should be corrected for the minimum water content expected in the soil at a particular location.

VI. EXTENT OF SOIL DRYING

Referring once again to the test in Figure 2 the question arises that after the soil begins to dry and resistivity begins to increase in Section "D", why does the temperature once again level off and quit rising after about 8 days? 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 analysis it is assumed that the drying process will proceed in a manner that will completely dry a small annulus of soil next to the heat source and the diameter of this dried layer will gradually move outward as more soil dries. So a completely dry layer is produced next to the probe surrounded by soil at its natural moisture level. The dried area will increase in size and the soil effective resistivity in relation to the probe will gradually increase.

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. It is assumed that this hydraulic gradient will remain constant in the interface between wet and dry soil during the drying process. Furthermore it is assumed that the surrounding soil has sufficient moisture to replenish the dried area indefinitely without significantly affecting the ambient hydraulic gradient.

The maximum rate moisture can return to the dried area was determined using Equation 14. This value of water flow would be the amount of water flowing into a dried volume equal to the volume of the heated probe. This water must flow through an area of soil equal to the surface area of the probe. However, as soil dries a small annulus of dried soil will be created between the probe and the moist soil as shown in Figure 8.

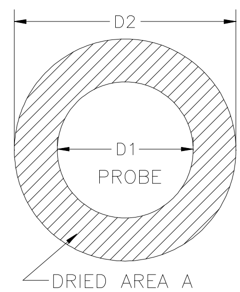

Figure 8: Dried soil surrounding probe.

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 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]. Darcy's law may be written as Equation 15.

$$q = kiA$$

Equation 15

Where

q = flow rate

k = soil permeability

i = hydraulic gradient = $\frac{\text{head}}{\text{length of flow path}}$

A = area through which water flows

Assuming the hydraulic gradient and permeability at the moist/dry interface will 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 would increase as the diameter of the dried area increases. The more dry soil exists and the farther we get from the heat source the larger the area becomes through which water can flow back to the dried area. Comparing the flow rate between any two areas using Darcy's law:

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

Equation 16

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

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

Equation 17

Where m_2=flow rate in kg/sec or lb/sec through a dried diameter of D_2 in cm if the diameter of the probe D_{probe} was given in cm. So 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 going outwards from the source until 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 to allow the moisture entering the dried area to just equal the moisture being vaporized by the new heat rate. At this point the drying process will once again cease. This accounts for the stabilization of soil resistivity that was witnessed after an 8 day period during the test shown in Figure 2.

The rate that heat is leaving the soil due to moisture being raised from ambient temperature to the temperature at the wet/dry soil interface and leaving the area as vapor would be:

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

If this occurs at the point where the diameter of the dry area has increased so a non-drying 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.

$$m = \frac{Q_w + Q_v}{h_v + C_w \Delta T} \text{ lb/sec}$$

Equation 18

Where

$m = m_w = m_v =$ flow rate of water or vapor (lb/sec)

$Q_v =$ heat input available to vaporize water (Watts)

$h_v =$ latent heat of vaporization

Substituting Equation 18 into Equation 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} is known.

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

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

Equation 19

If the heat rate is increased above the NHR the diameter of the dried area of 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 Equation 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 heat transfer due to water movement will both increase at the same rate that the total heat rate increased, then we can solve Equation 19 to determine the diameter of dried soil at the new heat rate using the following:

$$Q_c = \frac{Q_{new}}{Q_{NHR}} Q_{c\,NHR}$$

Equation 20

$$Q_w = \frac{Q_{new}}{Q_{NHR}} Q_{wNHR}$$

Equation 21

$$Q_v = \frac{Q_{new}}{Q_{NHR}} Q_{vNHR}$$

Equation 22

$$\left(Q_w + Q_v\right) = \frac{Q_{new}}{Q_{NHR}}\left(Q_{wNHR} + Q_{vNHR}\right)$$

Equation 23

Where:

Q_c=Heat transfer by conduction at the new heat input Q_{new}

Q_{cNHR}=Heat transfer by conduction at Q_{NHR}

Q_w=Heat transfer by inflowing water at the new heat input Q_{new}

Q_{wNHR}=Heat transfer by inflowing water at Q_{NHR}

Q_v=Heat transfer by vapor at the new heat input Q_{new}

Q_{vNHR}=Heat transfer by vapor at Q_{NHR}

Q_{new}=New heat input to the probe

For example, 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 127.2W, this would also double the conduction rate from 37 to 74 Watts leaving 50.2 Watts to be carried away by vaporization and heating of inflowing water (assuming 3W lost to air in the probe). So the new (Q_w + Q_v) = 50.2 W at the new heat rate using Equation 23. The heat probe used in the testing had a diameter of 1.5875 cm. Using Equation 19 to find the dried area:

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

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 dried soil is known, and the maximum flow rate back into the soil is known, then the time for a dried area to be completely returned 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 the flow rate at the maximum diameter according to Equation 17 would be:

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

The average flow rate back into the dried area will then be:

$$m_{avg} = \frac{m_{NHR} + m_2}{2} = \frac{m_{NHR} + \dfrac{D_2 m_{NHR}}{D_{probe}}}{2} = \frac{m_{NHR}}{2}\left(1 + \frac{D_2}{D_{probe}}\right)$$

Equation 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 maybe found.

γ = Unit weight of total soil sample (lb/ft^3)

γ_w = Weight of water per unit volume of soil sample (lb water/ft^3 of sample)

γ_s = Weight of dry soil per unit volume of soil sample (lb dry soil/ft^3 of sample)

$$\omega = \text{moisture content of the sample}(\%) = \frac{\text{weight of water}}{\text{weight of dry soil}}$$

$$\gamma = \gamma_s + \gamma_w$$

Equation 25

$$\gamma_w = \omega\gamma_s$$

$$\gamma_s = \frac{\gamma_w}{\omega}$$

Equation 26

Substituting Equation 26 into Equation 25 and solving for water weight of water per total volume of soil:

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

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

Equation 27

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

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

Equation 28

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

If the soil unit weight was measured at 120 lb/ft^3 (0.0042377 lb/cm^3) and the moisture content was 12% the weight of water originally in the volume V of dried soil before it was dried would be from Equation 27:

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

Using Equation 24 the average flow rate into the area would be:

$$m_{avg} = \frac{m_{NHR}}{2}\left(1 + \frac{D_2}{D_{probe}}\right) = \frac{0.0000252}{2}\left(1 + \frac{3}{1.5875}\right) = 0.0000364\ \text{lb/sec}$$

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

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

Equation 29

$$t = \frac{0.277}{0.0000364} = 7609\ \text{seconds} = 2.11\ \text{hours.}$$

So it would take approximately 2 hours for the moisture to flow back into the area that was dried by the increased heat rate after the heat was removed.

VII. 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 through the soil will be the same for the vertical and horizontal heat source. Equation 5, Equation 6, and Equation 7 describe the heat flow from a vertical cylinder in a semi-infinite medium. Their counterparts for heat flow in from a horizontal cylinder in a semi-infinite medium are:

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

Equation 30

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

Equation 31

$$Q_c = \frac{2\pi L(T_1 - T_2)}{\rho \ln\left(\frac{4z}{D}\right)} \quad \text{Watts}$$

Equation 32

In these equation 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 Equation 5, Equation 6, and Equation 7 with Equation 30, Equation 31, and Equation 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 heat rates, temperatures, and evaporation rates should be the same.

For a cable, however, the both the diameter and the burial depth may be vary from the vertical probe. This will change the amount of heat conducted away from the horizontal cable versus amount of heat leaving through vaporization to some degree 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 Equation 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. This 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. The result of increasing the diameter of the cable should be that the temperature of the cable will be reduced to some degree, but less than the value calculated using Equation 32 with 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 conduction will increase or evaporation decrease, if the original values calculated for the vertical probe for both 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 then 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 were increased to be below the surface more than the length of the test probe then according to Equation 31 the thermal resistance to ambient earth will increase. If the heat rate of conduction was assumed to be equal to the heat rate of conduction for the probe then then 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 Equation 32 to compute the heat transfer due to conduction from the buried cable, Q_{cNHR} (Q_c at the NHR) using the original probe temperature for T_1 at the new cable depth z, and then modify Q_{cNHR} using Equation 20 to get Q_c. Then the following heat balance equation is solved.

$$Q_{new} = Q_c + Q_w + Q_v$$
$$Q_w + Q_v = Q_{new} - Q_c$$

Equation 33

Where:

Q_{new}=The heat input in the cable (Watts)

Q_c = Heat transfer by conduction calculated as described using Equation 32

This value Q_w +Q_v determined using Equation 33 can then be used in Equation 19 to determine the diameter of 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 dried soil. It should be noted that the equations for heat flow may not be accurate for depths of cable less much less than the length of the probe. Care should be used in applying this method to shallow cables since actual temperatures may vary considerably from the assumptions made. Also, where long cables are involved rather than working with bulk values of heat and moisture the values in the above equations can be converted to values per unit length of cable by dividing by the length of the probe.

VIII. SUMMARY OF 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, the procedure suggested herein is:

1. Determine soil in-place unit weight γ using Equation 1 by any accepted method [14] [15] [16].

2. Determine water content ω using Equation 2 by any accepted method [17] [18] [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 hours, increase the heat input by 0.1 W/cm to 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 hours. The highest heat input at which an equilibrium temperature is achieved is the assumed non-drying heat rate q_{NHR}. At this heat rate under steady-state temperature conditions, record: the heat input (q_{NHR}) and calculate Q_{NHR} by multiplying by probe length L; steady state probe temperature (T_1); 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 Equation 3 (using T_2 at t_2=2400 seconds and T_1 at t_1=600 seconds 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 then a separate thermal resistivity measurement will be needed. A heat input of between 0.5 and 0.8 W/cm is suggested for this test. (Note: The values of T_1 and T_2 used in this step are not the same values 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 Equation 7. Use the results to compute the maximum mass of water flowing back to the dried area, m_{NHR}, using Equation 14.

6. Find (Q_W+Q_V) at the non-drying heat rate (NHR) using Equation 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 new maximum heat rate in W/cm that will be injected into the soil by the cable [1]. Determine the new value of heat transferred by water (Q_W+Q_V) using Equation 23 (and Equation 32 Equation 33 if needed).

8. Use the values calculated in Step 7 for (Q_W+Q_V) find the dried soil diameter at the new heat rate using Equation 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. Using the laboratory method [2] [20], or in field method if possible, determine the dried soil resistivity.

10. When preparing the soil thermal model to determine cable ampacity, model the soil resistivity surrounding the cable as a layer of dried soil of resistivity determined in Step 9 of 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.

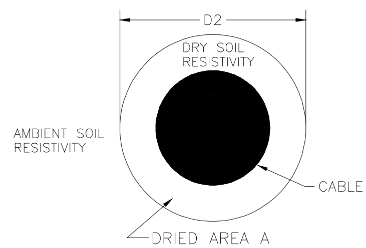

Figure 9

11. The thermal resistance of this dried soil layer is then added to Rca' in the Neher-McGrath equation. The value of thermal resistance to be added is computed using the equation:

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

Equation 34

Where D_2 is the computed maximum diameter of dried soil from step 8, and D_1 is the diameter of the cable or conduit including the insulation. The resistivity would be the soil dry 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 [1].

12. If it is desired to calculate the time it will take to replenish the moisture in this area of soil an approximate value can be calculated using equation 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.

IX. CONCLUSIONS

The same field tests often used to determine soil thermal resistivity may provide additional information that can help to determine the amount of dried soil surrounding a cable that may be expected for varying heat rates. The thermal probe can be used to determine the non-drying heat rate of the soil being studied. This value in turn can be used to determine the maximum rate water can flow into a dried area of soil from the surrounding soil. When this is known then the diameter of soil around a cable that will dry can be determined for any heat input rate.

The dried soil resistivity can sometimes be determined in the field, but may need to be found using laboratory tests. When this is determined then 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 consist of the cable surrounded by the thermal resistance of the insulation and jacket, conduit if used, plus the thermal resistance of the dried soil of the diameter calculated, plus 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].

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XI. VITA

Keith Malmedal received his BSEET degree from Metropolitan State College of Denver in 1995, a MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado- Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO. He has over 24 years combined experience in electrical power system design and system study, teaching, and research, and is presently the President of NEI Electric Power Engineering, Arvada, Colorado, a consulting firm specializing in all aspects of power system engineering and design. He has published over 25 technical papers and taught university courses and short courses related to power systems, machines, protection, renewable energy, and energy policy issues. Dr. Malmedal is also a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 25 states (US), Alberta and British Columbia, Canada.

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David Cain received his Associates of Applied Science degree with two Certificates of Completion from the Community College of Aurora concurrent with his graduation from high school in 2011. He is a registered electrical apprentice, with three years of field experience; one year of industrial, one year of commercial, and one year of residential. Currently David is attending the University of Colorado at Denver majoring in Electrical Engineering and expects to graduate with a BSEE by 2016.