Molecular Thermodynamics of Water in Direct-Buried Power Cables

Key Words: Polyethylene cables, soil moisture, water solubility, permeation, voids, dielectrophoresis, strand blocking, cable jackets

Glen J. Bertini
Novinium, Inc.

Water, which is almost always present at 100% relative humidity at the typical 1 meter burial depth of direct-buried power cables, moves very quickly through any polymeric layers.

Introduction

From our common experience, we learn that warmth dries things. It is understandable that many believe a cable carrying considerable load and warms above the ambient ground temperature in which it is buried might dry in comparison to an unloaded and cooler neighbor.

Water vapor pressure rises (see Figure 1) as temperature increases. The vapor pressure is 1 atmosphere or 760 mmHg (i.e., the boiling point) at 100°C. If two identical wet items (e.g., cables or laundry) were placed in nonwater-saturated air at two different temperatures, of course, the one at the higher temperature will dry more quickly.

Although the drying laundry metaphor is appropriate for the soil in which cable is buried, the explicit assumption of this example is false for a typical, direct-buried cable. The buried cable is not in dry air — it is in wet soil. In fact at 1 m in depth most, soil has a relative humidity of 100% for most of the year.

Using the methodology of the U.S. National Oceanic and Atmospheric Administration (NOAA) described in [2], average soil moisture for the driest month of the year for the three decades encompassing 1961 to 1990 is plotted to a resolution of 0.25° of latitude and longitude in Figure 2. As described by [2] the model was validated by soil moisture data gathered throughout Illinois over 1984–1998. The model does not include the local effects of irrigation and, hence, generally understates the water present in the soil. In most cases in which cables are buried, communities provide irrigation during the driest months.

Excluding lakes, which are shown in white, there are very few other white areas that would indicate a complete absence of water in the top 2 meters of the soil. There are very few of these bone-dry areas near population centers in which buried cable is likely to be found in abundance. Model predictions are available from [2] for individual months and years. There are, of course, periods of drought; but, on average, most direct-buried cables lay in soil at 100% relative humidity almost all of the time. It is important to recognize that because underground air does not freely circulate with atmospheric air below the top few

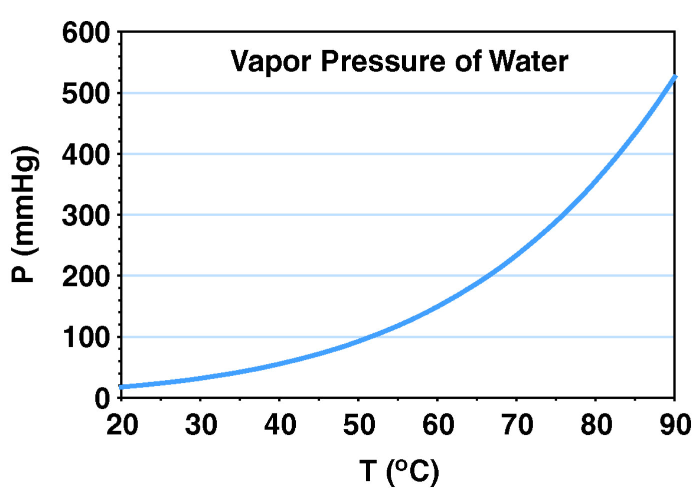

Figure 1. Vapor pressure of water as a function of temperature [1].

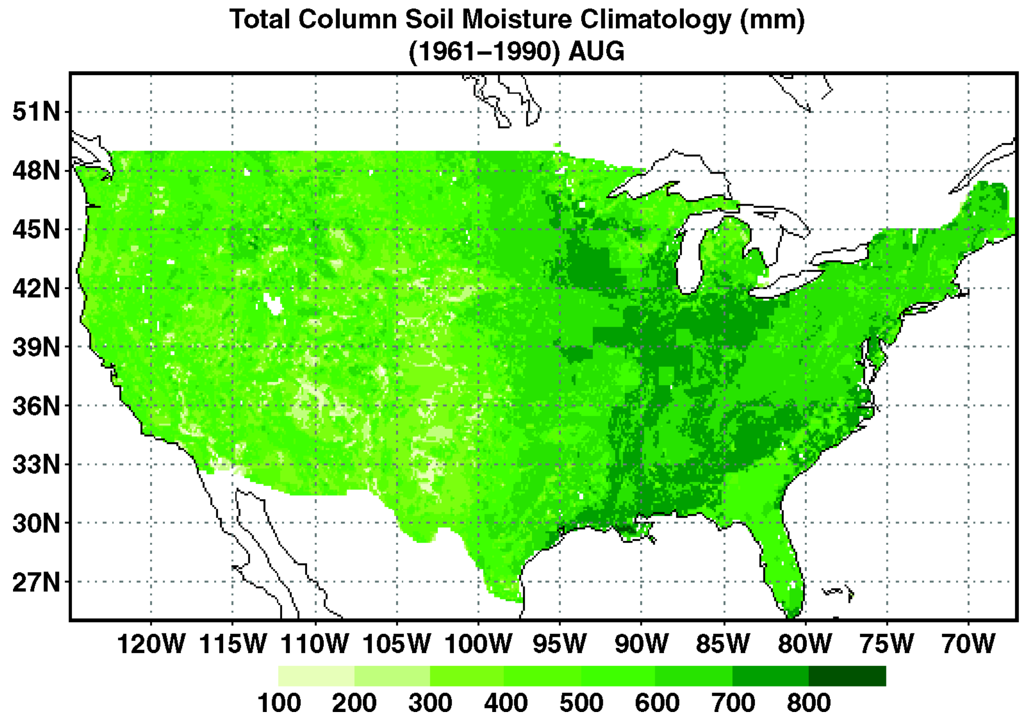

Figure 2. Water (mm) in the top 2 meters of U.S. soil in the driest month of the year (August). Depending on soil types, 700-800 mm of water represents fully saturated soil (i.e., no gaseous air present).

centimeters of soil, the relative humidity of the soil with any liquid water present is 100%. Adding more water to the soil does nothing to increase the thermodynamic impetus for water to permeate a cable. The bulk of almost all direct-buried cables are exposed to the same saturated humidity conditions almost all the time. However, micro-soil climates abound in real world situations. For example, a cable passing under a well-drained roadway may experience much lower local humidity than the balance of the cable installed below irrigated grass.

The balance of this article examines what actually happens to water within a direct-buried cable throughout the day and year as the cable temperature, the soil temperature, and the water content of the soil vary.

Water Solubility

An increase in water vapor pressure by itself would support a thermodynamic tendency to redistribute water from high temperature regions to lower temperature regions of a chemically homogeneous system. A cable directly buried in soil, however, is anything but homogeneous. And the vapor pressure plays a secondary role in determining the thermodynamic equilibrium of the system. The driving force for the movement of any solute in any solvent is a concentration gradient adjusted with a fugacity coefficient to account for nonideal behavior. The fugacity represents the tendency of a fluid to escape or expand isothermally and has units of pressure. The fugacity coefficient, ϕ is the ratio f/P between the fugacity f and the pressure. For an ideal gas, the fugacity coefficient is 1. For a given temperature, T, the fugacity satisfies the following differential relation:

$$d \ln \frac{f}{f_0} = \frac{dG}{RT} = \frac{\tilde{V} dP}{RT} ,$$

where G is the Gibbs free energy, R is the gas constant, $\tilde{V}$ is the fluid's molar volume, and f_0 is a reference fugacity generally taken as that of an ideal gas at 1 bar. For an ideal gas, when $f = P$ this equation reduces to the ideal gas law.

Thus, for any two mutually isothermal physical states, represented by subscripts 1 and 2, the ratio of the two fugacities is as follows:

$$f_2/f_1 = exp\left(\frac{1}{RT}\int_{G_1}^{G_2} dG\right) = exp\left(\frac{1}{RT}\int_{P_1}^{P_2} \tilde{V} dP\right).$$

Put another way, diffusion occurs from high-fugacity regions to lower fugacity regions to minimize the free energy of the system as required by the second law of thermodynamics. Figure 3 is a compilation of measured solubility data of the pure component (water) in the medium (PE) from Soma and Kuma [3] and Sletbak and Ildstad [4] showing the increase in solubility of water in polyethylene as the temperature increases.

Solubility generally increases (gases in liquids being the notable exception) with increasing temperature and the solubility

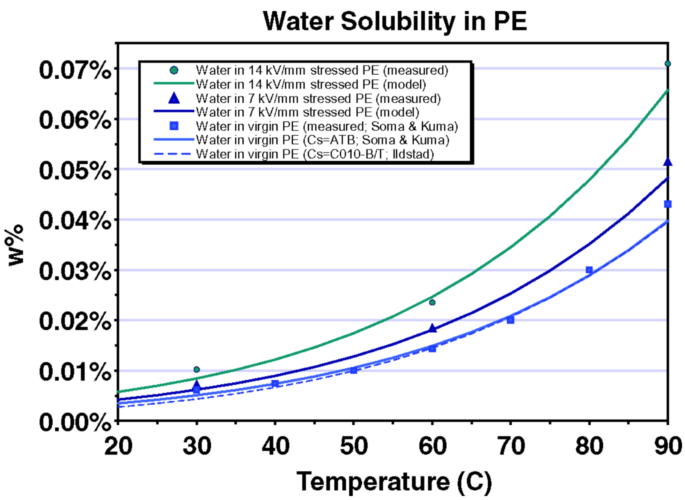

Figure 3. Water solubility as a function of temperature and divergent electrical field strength.

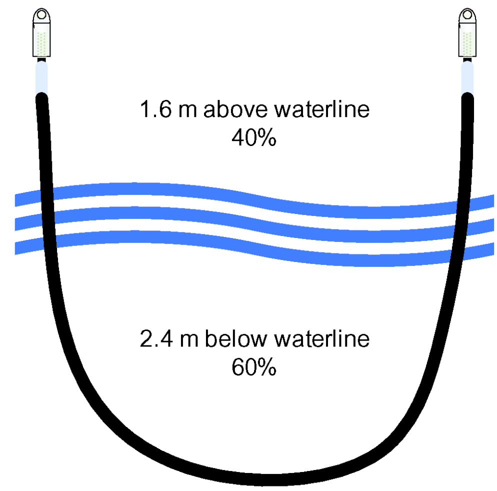

Figure 4. General layout of the Pélissou experiment.

of water in polyethylene (PE) comports with this generalization. This solubility increase is counter to the increasing vapor pressure. In other words, the increasing affinity with temperature of water for PE outweighs the increasing vapor pressure of water. In the case of PE not only does the solubility of water in the amorphous phase of the polymer increase as the temperature increases, but the ratio of amorphous to crystalline polymer also increases with temperature. A consequence of this phase change over the relevant operating temperature range of a typical cable is an accelerating increase in solubility with each incremental increase in temperature as demonstrated by Figure 3. The same generalization holds for the semiconductive shield layers and, if present, polymeric jackets.

Pélissou and St. Antoine [5] and Onodi [6] reported that higher temperatures or thermal cycling reduced the water content of the insulation. Neither considered the loss of water from the air-exposed termination in their experimental designs. Figure 4 shows the general layout of the Pélissou experiment in which about 40% of the cable is above the waterline (i.e., in air at 22 ± 2°C and the humidity 60 ± 10%) of a tank, and 60% of the cable is submerged.

Figure 5 shows a detail of a termination. The cable had an encapsulating jacket with hydroscopic powder. Althoughe there was a stress cone, there was no termination. At the beginning of the experiment, the cable was quite dry. But time and high temperature quickly infused each of the layers of the cable below the water line until they reached saturation — except that, once water reached the interstitial spaces of the conductor, there were strong convective forces and vapor-phase concentration gradients that transported water rapidly along the cable axis toward the terminations. These vapor phase phenomena occur at least two orders of magnitude faster than the solid-phase permeation. The axial transport did not limit the exodus of water from the cable interior. Once the water was transported away from the submerged portion of the cable, it would have left the system by convection at the exposed strands and by permeation out of the cable above the water line. About 75% of the cable length above the water line had been stripped of its jacket, facilitating outward permeation.

Although the ratio of submerged to unsubmerged cable was 1.5 to 1, the ratio of the maximum radial permeation outward in the unsubmerged portion to the maximum radial permeation inward in the submerged portion is at least 25 to 1. This large ratio is due to the difference in permeation rates of about a factor of three for each 10°C, as can be demonstrated by multiplying the solubility from Figure 3 with the diffusion from Figure 10 at two temperatures of interest. The likely difference is over 30°C between the portion of cable insulation immersed in water at 30-31°C and the portion in the less thermally conductive ambient air. A more precise calculation is not trivial as there was no attempt to measure the surface temperature of the exposed cable. Precision is not required, however, because the jacket was largely removed from the unsubmerged portion thereby increasing the relative permeation rate. Additionally, convective exodus from the strands would have proceeded in parallel to the permeation. In short, the total flux of water was limited by the rate that water diffused into the submerged cable. Once the water reached the strands, it quickly was transported out. The conditions of these experiments are not consistent with typical field conditions in which a much larger fraction of the cable is buried and the temperature differences are much less. Nonetheless for unblocked cable strands, the same phenomenon works at keeping the strands dry.

The polymer in aged cables is not the same as the virgin PE used to generate the data of Figure 3. Over the years water treeing and halo formation create physical voids in the insulation and regions of chemically changed polymer that support higher water solubility than virgin PE. Figure 6 is just such a cable prior to silicone treatment in about 1989. The microinfrared spectrographic technique of [8] generally understates the water concentration because water is lost in the sampling process, especially after a sample is sliced with microtome exposing a large

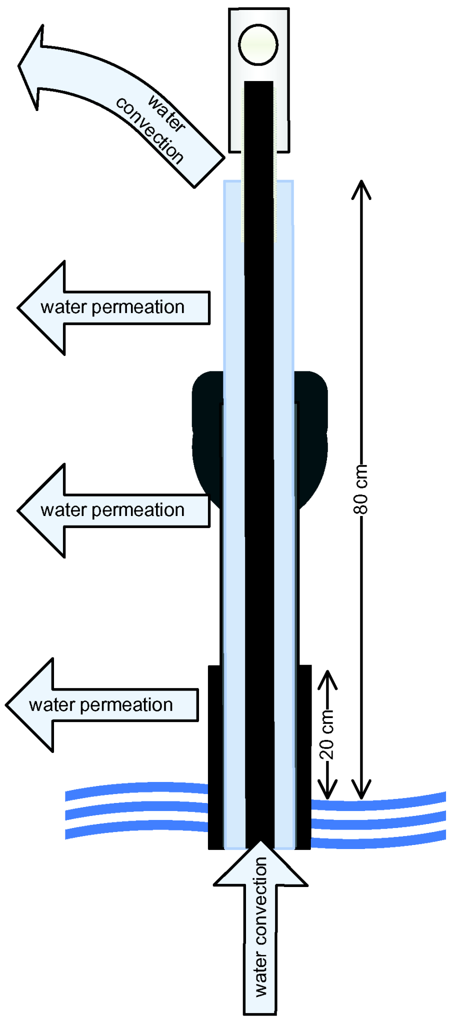

Figure 5. Termination detail of the Pélissou experiment.

surface area for evaporation. The amount of water actually present in aged cables as exemplified by Figure 6 far exceeds the solubility of water in virgin PE with or without an electrical field in comparison to Figure 3.

Voids

Figure 3 demonstrates another complexity regarding thermodynamic equilibrium of water in cables. Water solubility in PE increases in divergent AC fields due to dielectrophoresis, as predicted by the Clausius-Clapeyron equation and as measured by Soma and Kuma [3]. This solubility increase is driven by the large difference in dielectric constants for water and PE.

Water in the insulation portion of a cable exists in three states:

- There is some liquid water on the gravitational bottom of most voids. Water has a much higher surface energy than PE, so the water beads and does not coat the surface.
- There is water in the vapor phase within the gas-filled void.
- There is water dissolved in the PE. There is even more water dissolved in the PE near defects such as voids supported by strongly divergent electrical fields.

If the void and surrounding PE in Figure 7 experience a temperature increase, the increased solubility of the water in the PE drives the liquid water out of the void into the vapor phase within the void, and more importantly into the surrounding PE. This warm, energized state is illustrated by Figure 8.

In this condition, the gas-filled void volume has increased. This increase in void volume likely will have an impact on the partial discharge (PD) inception voltage.

When the temperature decreases, the thermodynamic driving force reverses, and the water is driven out of the PE and out of the vapor phase within the voids to the liquid phase. If the water molecule is close to the outer cable surface, it can exit the cable into the soil. If the water molecule is close to a stranded and unblocked conductor, it can exit the polymeric layers and enter the strand interstices. However, if the water is near the center of the insulation, the water cannot exit the insulation fast enough and the insulation becomes supersaturated with water. If a solid-core or effectively strand-blocked conductor is used the region of supersaturation is likely expanded radially inward. The water phase creates a large number of voids near the center of the insulation that are collectively referred to as a halo with a concentration profile generally consistent with the example of Figure 6. The water condensing into the voids decreases the gas-filled void volume and may impact the PD inception voltage.

For brevity, Figure 9 illustrates the low temperature case and includes the additional effect of taking the cable off line. The two effects together are obviously greater than either effect alone. Except for the magnitude, the results of each alone are consistent with the illustration.

When voltage is removed from a cable the dielectrophoresis effect — which dynamically increases the solubility of water in PE — ends abruptly, and the water molecules previously in so-

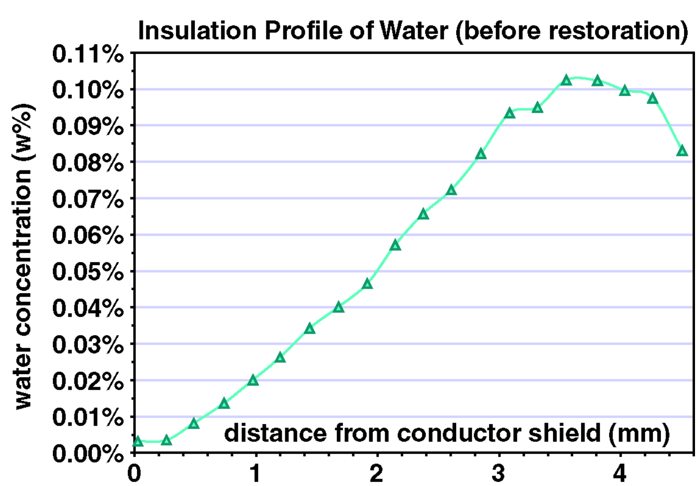

Figure 6. Water concentration profile obtained by micro-IR of 250 mm² (500 kcmil) 15kV field-aged cable.

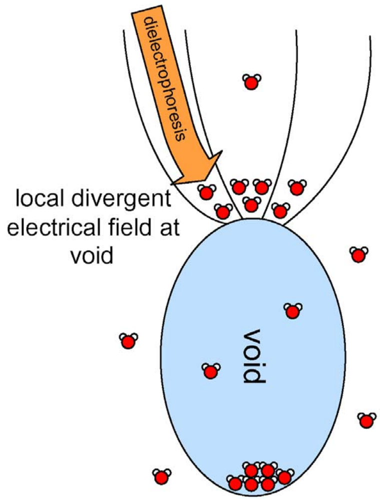

Figure 7. Model void with divergent electrical fields, dielectrophoresis, and the resulting local concentrations of water (H_2O molecules illustrated as "mouse head" icons) at a moderate temperature.

lution must migrate quickly to the liquid phase. If there is not a void nearby, the accumulating liquid-phase water will condense, creating mechanical pressure that may spawn or enlarge a void.

Temperature decreases are more gradual — compared to instantaneous loss of voltage — in normal operation. Hence, the prospective damage from each thermal cycle is less severe and generally limited to the portions of the cable not immediately adjacent to the exterior of the cable or strand interstices. Cutting the load on a moderate-to-highly loaded cable creates a quicker change in temperature than normal operations, and the consequential damage to the insulation is commensurately greater.

Permeation

Figure 10 shows the diffusion coefficient of water through PE as measured by Sletbak and Ildstad [4].

The diffusion coefficient can be used to calculate a lag time for a cable as a function of temperature. The lag time is the time it takes a diffusing molecule to traverse the width of a membrane. Consider for illustration purposes an unjacketed, 500 mm^2 (1000 kcmil), 25 kV cable. At 20°C the lag time of water from the soil to the strands (across the insulation shield, the insulation, and the conductor shield) is approximately 6 hours, at 90°C the lag time is less than 6 minutes. A jacket may increase those lag times by 10 to 50%, depending upon the material and design.

Cable Reliability Implications

The immutable second law of thermodynamics and the dynamics of water in particular have profound implications on cable reliability. An understanding of those dynamics has dozens of implications on cable design and operations. The rest of this article examines three implications: strand blocking, jackets, and partial discharge testing.

The strand interstices are in thermodynamic equilibrium with the soil. Water moves from high fugacity regions to low fugacity regions radially with such rapidity in a cable that excess water in the strands of a cable will exit the cable in short order. Unless water is being supplied to the strands of a cable from a leaky termination, it cannot remain in bulk within the strands for long. This theoretical conclusion is confirmed by thousands of observations made by the author in treating cables when there is no water in the strands. Indeed, submarine cables submerged for decades typically have dry strands. Strand filling may reduce water from installation problems or dig-ins, but it does not exclude water from the cable or the strands and may have little impact on the life of a typical cable in service. Using the market data of Dudas and Fletcher [9] and Forrest [10] and assuming strand blocking cables adds 23¢ per conductor meter to the cost of cable, approximately $170M dollars have been expended on strand-blocking from 1975 to 2006 in the U.S. power utility market. An unanswered but related question: what is the net effect the water-swellable compounds and carbon-black filled thermoplastic have on the equilibrium concentration of water in the strands? Both of these materials can support higher water concentrations than the air they replace. Another unintended consequence of blocked strands or solid core cable is the halting of the convective exodus of water along the cable axis to cable ends exposed to relatively dry atmospheric air. Althoughe this mechanism is not as large in typical installations as demonstrated in short laboratory sections, the elimination of this mechanism can result only in more water in the insulation.

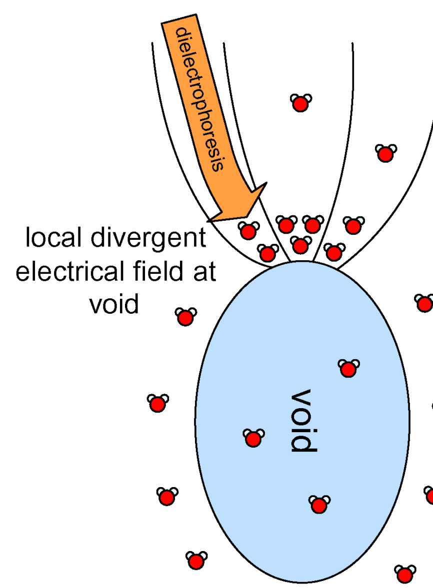

Figure 8. Model void with divergent electrical fields, dielectrophoresis, and the resulting local concentrations of water at a higher temperature.

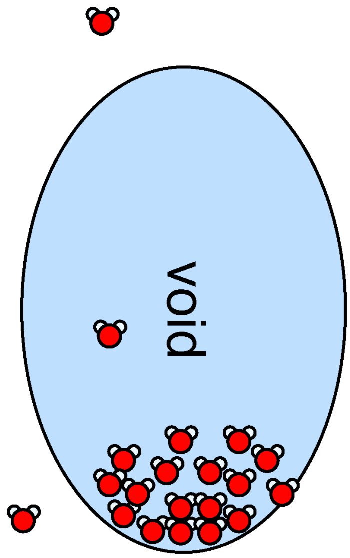

Figure 9. Model void with electrical field removed and/or a lower temperature.

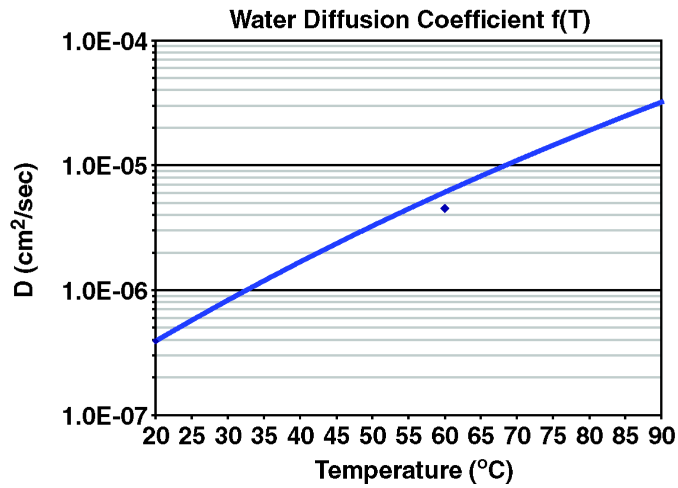

Figure 10. The diffusion of water in PE as a function of temperature. Measured values are diamonds and the model of Sletbak and Ildsatd is represented by the solid line.

Although there may be many good reasons to specify jacketed cable such as protecting the neutral from corrosion and the cable from damage during installation, the often cited reason to halt the ingress of water has little merit. As shown in [5], the presence of the jacket increases the insulation temperature and, hence, increases the solubility of water in the insulation. The transient benefit of slower initial water penetration is lost within a few short months of installation. As the cable nears saturation the jacket acts to retard the equilibration of the cable interior with the soil, the latter almost always is saturated. In other words, over the lifetime of the cable, the jacket is just as likely to hold water in (exasperating halo formation) as it is to keep water out.

Water is ubiquitous in the soil in which cables are buried. Soil is almost always at 100% relative humidity at the 1 m depth at which most directly buried medium voltage power cables are found. Contrary to common belief, as the temperature of a cable increases, the amount of water in the cable increases too. The only exception to that generalization is when the soil at cable depth contains no more liquid water and the relative humidity drops below 100%. This condition can occur only when there is little or no rain or irrigation for a sustained period. Partial discharge activity may be affected by prolonged periods of low rainfall and high temperatures. In most of the temperate regions of the globe, these conditions occur in late summer and early fall and coincide with the failure season of most utilities. The author is quick to warn that cable failures are not a single-mode phenomenon and certainly cable buried in perpetually wet soils fail too. Often times these perpetually wet areas experience a proportionately higher lightning strike density than the cable located in more arid areas.

Summary

Water is ubiquitous in the environment and is almost always present at 100% relative humidity at the typical 1 m depth of direct-buried power cables. Water moves very quickly through any polymeric layers. Contrary to popular wisdom, the warmer a typical, direct-buried cable operates, the wetter the insulation becomes. Temperature gradients create fugacity gradients that draw water radially inward. The retardation of radial water permeation as cable temperature fluctuates by solid or blocked conductors, and by low permeability jackets, likely increase the magnitude of water halos – precisely the opposite of the intended effect. Polymeric jackets also increase the cable average operating temperature for a given load profile that increases the water concentration in the insulation.

Temperature cycling, abrupt temperature decreases, and loss of voltage on cables spawn and enlarge voids, which may precipitate failures on marginal insulation.

Unless water is supplied to the strands of a cable via a leaky termination, unblocked strands will not support a significant amount of liquid moisture. Strand-blocking cables cannot reduce the amount of water in the insulation over the cable life. It is unlikely that strand-blocking direct-buried cable increases its life. Leak-free devices on exposed life-front terminations are a small fraction of the cost of purchasing strand-blocked cables.

Care should be taken in interpreting PD measurements of aged, wet cables as those results likely will vary with season. For moderate-to-heavily loaded cables, they may vary depending upon the time of the day. Off-line measurements also may vary with the elapsed time from the circuit going off-line to the time the measurement is made.

There is no paradox to be found in the fact that warmer cable operation may accelerate the drying of soil, while increasing the water concentration in the direct-buried cable. Only after the soil adjacent the cable is entirely free of liquid water will there be a net radial permeation of water out of the cable. This seasonal drying is generally possible for only a couple of months of the year and may contribute to the overlap of failure season and the dry season at many locations.

In the early 1980s, considerable progress in cable design and manufacture were commercialized and rapidly adopted. Simultaneous improvements were made in insulation cleanliness, conductor shield cleanliness and smoothness, improved tree-retardant properties of insulation compounds, dry curing, triple extrusion, and others. The simultaneous introduction of these improvements with the gradual adoption of strand filling and more widespread use of jackets confound the anecdotal results cited by the proponents of strand-filled conductors. Although jacketing suffers from the same confounding, other benefits of jacketing likely support its widespread adoption. However, any attempt at slowing water permeation, short of stopping it with a solid metallic sheath, is likely unjustified and may even shorten the life of a direct-buried cable. Jacket design should be optimized to meet its other laudable purposes.

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Glen J. Bertini is the President, CEO, and Chairman of Novinium, Inc. He has spent the last two decades working with cable rejuvenation technology, beginning with its development at Dow Corning in 1985 and continuing through its commercialization and growth to over 75 million feet of cable rejuvenated so far. Mr. Bertini was employed by Dow Corning, a silicon chemical manufacturer, as a development engineer, where he focused on the thermodynamics of multicomponent systems and was part of a small team that developed and commercialized the first cable rejuvenation products. Mr. Bertini is the world's foremost authority on the business and technology of cable rejuvenation. He holds a total of 15 patents on cable rejuvenation and related technologies and has 8 more patents pending. In 1992, he was co-recipient of the prestigious R&D 100 award for cable rejuvenation. In 2006 Mr. Bertini and Novinium won the $100,000 Zino Zillionaire Investment Forum award for the best investment opportunity in the Pacific Northwest. Mr. Bertini holds a B.S. in chemical engineering from Michigan Technological University, Houghton, Michigan, is a senior Member of the IEEE, and a voting member of the IEEE ICC.