Calculation of Water Ingress in a HV Subsea XLPE Cable with a Layered Water Barrier Sheath System

S. M. Hellesø,[1] S. Hvidsten,[1] G. Balog,[2] K. M. Furuheim[2]

[1]*Department of Electric Power Technology, SINTEF Energy Research, NO-7465 Trondheim, Norway*
[2]*Technical Department Nexans Norway, 1751 Halden, Norway*

ABSTRACT: The main aging mechanism of electrical cables with polymeric electrical insulation is the growth of water trees. Water trees are initiated if the relative humidity (RH) in the electrical insulation is above a critical level. Delaying the water ingress into the electrical insulation system delays the water tree initiation and reduces water tree growth, thus extending the service life of the cable. For a cable without any metallic water barrier, the water ingress can be significantly delayed by the use of an outer sheath material with low water permeability. An even greater delay in the water ingress into the electrical insulation can be achieved using a layered sheath system. To explore the possibilities of a layered sheath system, calculations of water ingress into a typical cable cross section has been performed using a finite element method. The water diffusion and sorption data used in the calculation has been measured for typical cable materials. Calculations have been performed for uniform temperature conditions and for a temperature gradient due to resistive current heating. The time to reach critical humidity levels and stationary humidity levels in the insulation system has been determined for several different arrangements of the sheath system. A sheath system with an outer layer of a material with low water permeability and an inner layer of a material with a high water absorption capacity is shown to give a significant delay of the water ingress into the electrical insulation. For the sheath materials used in this study, there is an optimum distribution of thickness of each layer. The calculations also show that a temperature gradient across the insulation system of a cable in operation gives an advantageous RH profile. With a temperature gradient the equilibrium RH level in parts of the electrical insulation can be lower than the critical value for water tree initiation. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 2127–2133, 2011

Key words: water diffusion; cables; barrier; modeling; simulations

INTRODUCTION

Medium voltage cables consists today of predominantly polymeric materials, with an insulation system of typically crosslinked polyethylene (XLPE). The major aging mechanism in polymeric medium voltage alternating current AC cable insulation is the growth of water trees in the electrical insulation.[1] Water trees can be a precursor for electrical tree growth through the insulation, finally leading to breakdown of the insulation.

Water trees can only be initiated if the relative humidity (RH) in the insulation is above a critical level. The critical level for initiation in XLPE is about 70% RH. The growth rate of water trees is also strongly reduced if the RH is below 100%.[2] The initiation and growth of water trees can thus be delayed by reducing the amount of water that enters the electrical insulation for as long as possible, thereby extending the operational life of the cable.

The design of a polymeric medium voltage distribution cable typically includes the following parts: conductor core of either aluminum or copper, a semiconducting conductor screen, electrical insulation of usually XLPE, insulation screen, ground shield wires, and outer sheath. The outer sheath mechanically protects the electrical insulation system and the ground wires from external damage through handling and exposure to liquid water. For high voltage transmission cables a metallic barrier (e.g., an aluminum foil), completely impervious to water, is included in the design. However, for some applications, it can be very advantageous to omit the metallic barrier.[3]

The amount of water that reaches the electrical insulation in a cable without any metallic water barrier can be reduced by careful selection of sheath materials with advantageous water permeability and solubility characteristic. The time it takes to reach critical humidity levels for water tree initiation in the electrical insulation can be greatly extended by combining an outer sheath layer of a material having low water permeability with an inner sheath layer of material that has a high water absorption capacity.[4]

Results from the simulation of the water ingress into a subsea cable system are presented for several

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Correspondence to: S. M. Hellesø (svein.helleso@sintef.no).

combinations of outer and inner sheath materials and for several temperature profiles across the cable cross section.

Theory of water diffusion in polymers

The sorption and diffusion of water in a polymeric material is highly dependent on the type of polymer, the morphology of the polymer, and the temperature. It is usual to define a solubility coefficient S as[5]

$$\rho = S \cdot p \qquad (1)$$

Where ρ is the mass of water absorbed per unit volume of the polymer, and p is the water vapor partial pressure just above the surface of the polymer. If the solubility coefficient is independent of the partial pressure, (1) describes Henry's Law. For some materials, for example, polymers filled with carbon black, the solubility coefficient can be dependent on the water vapor partial pressure.

The diffusive mass flux of water j in a polymer can usually be assumed to follow Ficks first law

$$j = -D\nabla\rho \qquad (2)$$

where D is the diffusion coefficient. If the diffusion coefficient is independent of the concentration of water in the polymer, the diffusion is called Fickian. However, for some polymers, the diffusion coefficient is dependent on the water concentration in the polymer.

The diffusion and solubility coefficients might be nonconstant for instance through a cable cross section because different materials have different properties, temperature gradients or diffusion or solubility coefficients being dependent on the amount of adsorbed water.[6]

The temperature dependence of both the solubility and diffusion coefficients can usually be expressed as an Arrhenius equation (since both processes are thermally activated) with pre-exponential factors S_0 or D_0 and activation energies E_S or E_D

$$S = S_0 e^{-\frac{E_S}{RT}} \qquad (3)$$

$$D = D_0 e^{-\frac{E_D}{RT}}. \qquad (4)$$

The diffusion of water through the polymer has to fulfill the continuity equation that can be expressed as

$$\frac{\partial\rho}{\partial t} + \nabla \cdot (\rho V) = \frac{\partial\rho}{\partial t} + \nabla \cdot (\rho V_{avg} + j) = 0 \qquad (5)$$

where V is the velocity vector of the water, V_{avg} is the mass average velocity vector and ρ is still the

mass of water per unit volume. For diffusion of water in polymers, it is reasonable to assume that the mass-average velocity is negligible as the bulk polymer is stationary. Combining (2) with (5) and neglecting the convective contribution from the mass-average velocity results in

$$\frac{\partial\rho}{\partial t} + \nabla \cdot (-D\nabla\rho) = 0, \qquad (6)$$

a form of Ficks second law, which can be used for calculating the time evolution of the water concentration in the polymer.

Different methods may be used to solve (6) for a specified geometry, with specified boundary and initial conditions. For simple geometries, with constant diffusion and solubility coefficients, it is possible to find analytical solutions.[7] However, for practical applications with arbitrary geometries with nonconstant diffusion and solubility coefficients, it is generally not possible to find a suitable analytical solution. In such cases, (6) has to be solved by a suitable numerical method. In the present work, a commercial finite element method code has been used.[8]

Calculation of the water diffusion into a cable with a "wet design," that is, without any metallic water barrier, has been performed for a cable with a two-layered sheath system. Sensitivity analysis has been performed by varying the thickness of the layers as well as their radial position and the service temperature. In particular, the time to reach 70% RH in the electrical insulation has been determined for different configurations. The time for the humidity in the cable to reach equilibrium conditions has also been determined for the different cases.

METHODS AND MATERIALS

Cable geometry and materials

The calculations were performed for a cable geometry that represented a XLPE insulated cable with 52 kV voltage rating. The cable was of a "wet design" with a copper conductor with a cross section of 1200 mm[2,9] A schematic figure of the cable is shown in Figure 1; the cable dimensions and materials are given in Table I.

Material data

The water absorption and diffusion properties of the cable materials have been determined using the freeze-drying[10] or weighing method. The absorption was determined by measuring the water uptake in material samples with thickness of 1 mm and area 5 cm[2] soaked in water-filled vessels at a constant
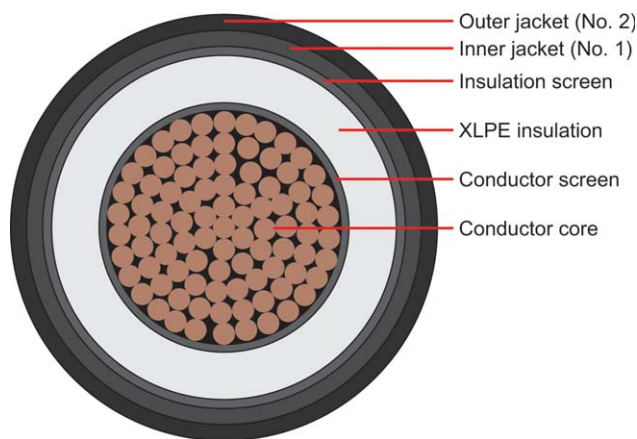
Figure 1 High voltage XLPE insulated cable used as basis for the geometrical model. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

temperature. After removing the samples from the vessels they were immediately soaked in ice water in order to reduce the further adsorption/desorption of water. Then, the samples were carefully dried by using blotting paper. The water content was measured either by using a weight (Mettler AB 240) with a resolution of 100 μg or the freeze-drying method with a resolution of 5 μg. The diffusion and solubility coefficients were determined from the transient and stationary mass uptake. The permeability coefficient was determined by measuring the mass flow rate of water through a polymer cable sheet with thickness of 1 mm and an area of 7 cm^2. The measurements were performed at 20, 40, 65, and 90°C.

A summary of diffusion and sorption data for the materials is given in Table II[11]: It was found that Henry's Law was valid for all materials in the temperature range used in the calculations (i.e., no concentration dependence).

The thermal conductivity of the polymeric materials was assumed equal to the thermal conductivity of XLPE as the difference in thermal conductivity of the polymeric cable materials is relative small. The temperature dependence of the thermal conductivity of XLPE is low. Therefore, a value of 0.26 W/(m K) has been used in the calculations.[12]

Equations and finite element method

The governing equation for calculating the time evolution (6) is to be solved for the insulation system from the surface of the outer sheath to the interface between the conductor screen and the conductor core. It is assumed that the conductor is solid, that is, no water enters the conductor core. Solving (6) directly for the entire insulation system is complicated, as the dependent variable ρ is discontinuous over material boundaries. To simplify the modeling, (1) is introduced into (6) resulting in

$$S\frac{\partial p}{\partial t} + \nabla \cdot (-D\nabla Sp) = 0 \qquad (7)$$

which is a partial differential equation with the water vapor partial pressure p as the dependent variable. The water vapor pressure is continuous over material boundaries.

The temperature profile through the cable insulation system was calculated assuming stationary conditions. The stationary heat equation is

$$\nabla(-k\nabla T) = 0, \qquad (8)$$

where k is the thermal conductivity. The temperature of the conductor and at the surface of the sheath was prescribed as boundary conditions when solving (8).

Initial and boundary values

At the surface of the outer sheath the boundary condition was set to 100% RH. The inner boundary of the calculation area was to be impervious, that is, no water entered the conductor core (solid conductor). The initial condition for the calculations was set to no initial water in the insulation system.

Simulation cases and temperatures

The calculations were performed for several different designs. The simulations cases are described in Table III. In all cases, the conductor and insulation screen was of the same semiconducting material while the electrical insulation was XLPE.

TABLE I
Cable Dimensions and Materials

Cable layer	Material	Code	Thickness [mm]
Conductor	Copper	–	22.7
Conductor screen	Polymer with carbon black filler	SC	1.5
Electrical insulation	Cross-linked polyethylene	XLPE	9.2
Insulation screen	Polymer with carbon black filler	SC	1.75
Outer jacket (combined)	Jacket no. 1 (J1) Jacket no. 2 (J2)	LP/HS[a]	6.2

[a] LP: Low water permeability material, HS: High water solubility material.

TABLE II
Diffusion and Solubility Data

	Arrhenius parameters			
	D_0	E_D	S_0	E_S
Material	[m²/s]	[kJ/ (mol K)]	[kg/ (m³ Pa)]	[kJ/ (mol K)]
XLPE	$3.30 \times \cdot 10^{-1}$	55.7	$1.80 \times \cdot 10^{-7}$	−9.90
SC	$2.55 \times \cdot 10^{-2}$	58.0	$9.75 \times \cdot 10^{-11}$	−42.15
HS	$2.77 \times \cdot 10^{-6}$	28.7	$4.34 \times \cdot 10^{-11}$	−37.1
LP	$1.40 \cdot \times 10^{2}$	81.37	$7.21 \times \cdot 10^{-11}$	−35.92

Simulations were performed for several temperature conditions. Typical sea water temperatures for northern latitudes is in the range from −1 to 10°C, and because of the ocean currents the heat transfer from the cable to the water is very good due to convective cooling. Thus, a temperature of 5°C at the surface of the outer sheath was set to represent typical conditions. For buried cables on the seabed, the temperatures could be higher. Complete calculations for all cases in Table III were performed for uniform temperatures of 5 and 25°C throughout the insulation system, and for a temperature profile with 50°C at the conductor screen and 5°C on the surface of the outer sheath. The temperature profile through the cable cross section was calculated assuming very good thermal contact between the different cable material layers.

The results from the simulations are the time-varying partial water vapor pressure. As the RH level in the electrical insulation system is an important factor for water tree growth, the results are presented as RH. Some examples of results from the simulations are presented in more detail. For all cases, the time to reach 70% RH and equilibrium close to the conductor and insulation screen of the

TABLE III
Simulation Cases

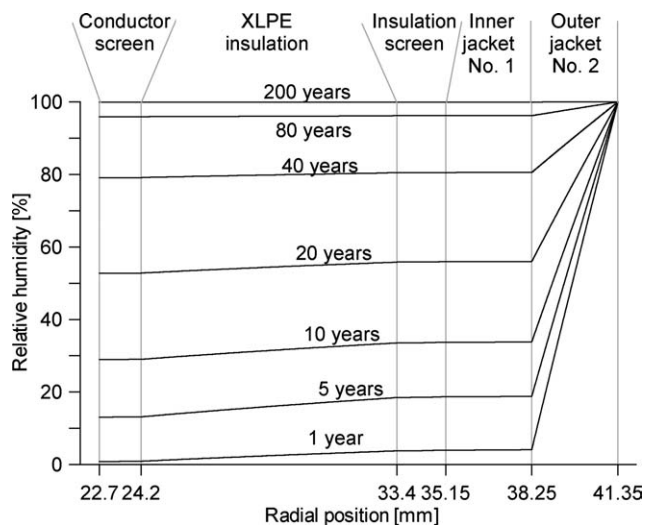| Case	Inner jacket no. 1 material (thickness) (mm)	Outer jacket No. 2 material (thickness) (mm)
1	–	XLPE (6.2)
2	–	LP (6.2)
3	HS (1.1)	LP (5.1)
4	HS (2.1)	LP (4.1)
5	HS (3.1)	LP (3.1)
6	HS (4.1)	LP (2.1)
7	HS (5.1)	LP (1.1)
8	HS (6.2)	–
9	LP (1.1)	HS (5.1)
10	LP (2.1)	HS (4.1)
11	LP (3.1)	HS (3.1)
12	LP (4.1)	HS (2.1)
13	LP (5.1)	HS (1.1)
14	HS (5.1)	LP (5.1)

Figure 2 RH across the insulation system for different times for Case 5 with a uniform temperature of 25°C. The major gradient in RH is across the LP outer sheath.

cable is presented (if applicable). Equilibrium is in the calculations defined as the humidity reaching a value of 99% of the stationary value.

RESULTS

Result for uniform temperature 25°C

The RH across the insulation system for selected times for Case 5 at a uniform temperature of 25°C is shown in Figure 2. It can be seen that the major gradient in RH occurs across the outer sheath system. The RH at the conductor and insulation screens is plotted as a function of time in Figure 3, where the
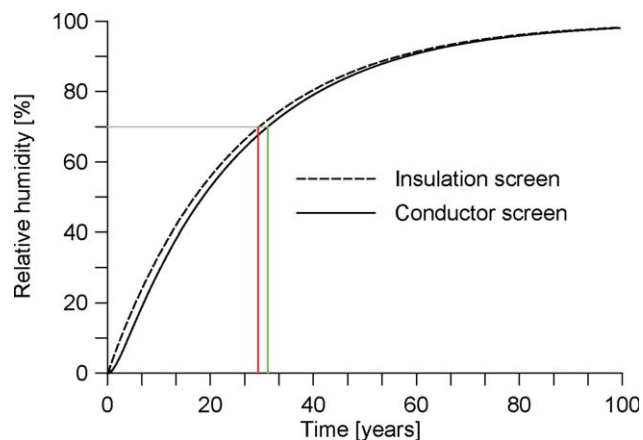

Figure 3 RH levels at the conductor and insulation screen for Case 5 with a uniform temperature of 25°C. The time to reach 70% RH at the insulation and conductor screen is shown as the red and green lines, respectively. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
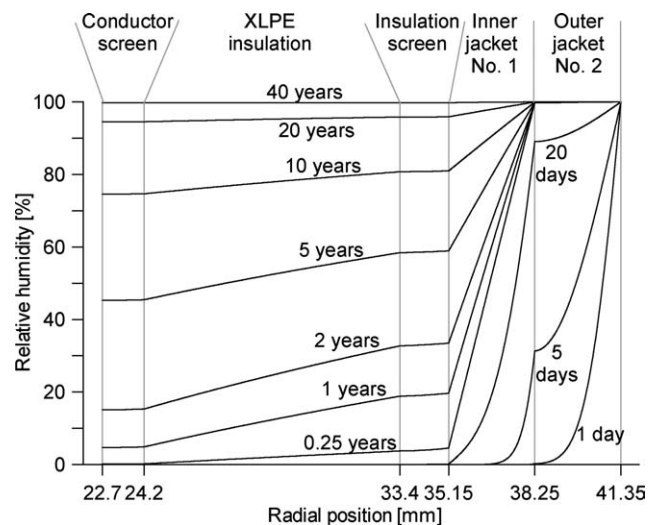
Figure 4 RH across the cable for different times for Case 11 with a uniform temperature of 25°C. The major gradient in RH is across the inner sheath of LP, the outer sheath of HS is quickly saturated by humidity.

time to reach 70% RH is also indicated for the insulation and conductor screen.

For Case 11, where the materials of the two layers of the outer sheath is interchanged compared to Case 5, i.e. the outer sheath is of high solubility (HS) material and the inner sheath is of low of low permeability (LP) material, the RH across the insulation system is shown in Figure 4. As can be seen, the outer sheath layer of HS is quickly saturated (in a matter of weeks) by water, and the major gradient in humidity is still across the LP layer.

The time to reach 70% RH at the insulation and conductor screens at a temperature of 25°C for the other cases in Table III is shown in Table IV, together with the time to reach equilibrium conditions.

It can be seen that the time to reach 70% RH in the insulation is very dependent on the arrangement

TABLE IV
Time to Reach 70 % RH and Equilibrium Conditions in the Insulation for Uniform Temperature 25°C

Case	Time to 70% RH [years]	Time to equilibrium [years]
1	2.4–4.4	13–15
2	14–16	54–57
3	22–24	92–95
4	29–30	112–113
5	30–32	110–112
6	25–26	95–98
7	16–17	60–63
8	0.18–2.1	1.9–7.6
9	2.2–4.1	12–15
10	5.0–7.0	21–23
11	7.0–9.0	29–31
12	9.5–11	38–41
13	12–14	44–48
14	71	260–270

of the outer sheath layers. By having a sheath of only LP (Case 2), the time to reach 70% RH in the insulation is about 15 years. However, a longer time to reach 70% RH can be achieved by replacing some of the LP with an inner layer of HS (which is comparably more permeable than LP but absorbs more water). For the current cable configuration, there seems to be an optimum when the sheath consists of half the thickness of both materials. Interchanging the order of the materials, that is, replacing some of the LP with an outer layer of HS, does not give any similar synergetic effects, for this arrangement the increase in time to reach 70% RH is proportional to the thickness of the LP layer. Increasing the total thickness of the sheath to 10.2 mm (Case 14) increases the time to reach 70% RH significantly.

The time to reach equilibrium condition is significantly longer than the time to reach 70% RH, which will contribute to reduce the growth rate of water trees in the insulation.[2]

Result for uniform temperature 5°C

The RH across the insulation system for selected times for Case 5 at a uniform temperature of 5°C is plotted in Figure 5. The time to reach 70% RH is greatly increased compared to a uniform temperature of 25°C. The major drop in humidity is still across the outer sheath of LP.

The time to reach 70% RH and equilibrium conditions at a temperature of 5°C for the other cases in Table III is shown in Table V. Similarly to the situation at 25°C, there seems to be an optimal distribution of the total thickness of the sheath between LP and HS.
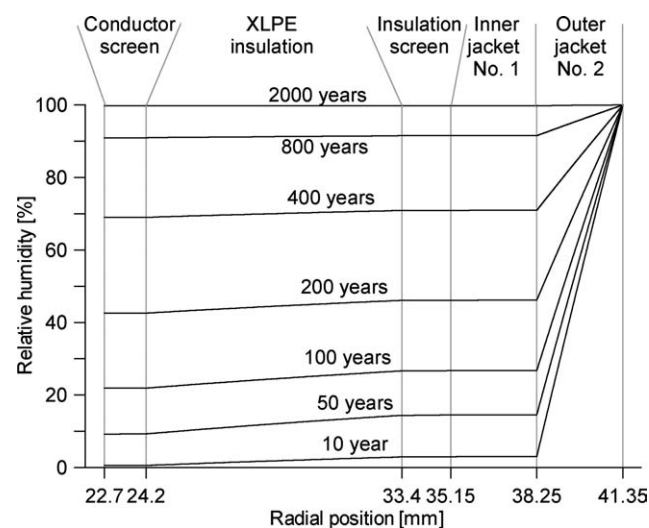

Figure 5 RH across the cable for different times. Case 5, uniform temperature 5°C. The major drop in RH is across the outer sheath of LP.

TABLE V
Time to Reach 70% RH and Equilibrium Conditions in the Insulation for Uniform Temperature of 5°C

Case	Time to 70% RH [years]	Time to equilibrium [years]
1	32–57	160–190
2	170–200	700
3	320–350	1200
4	380–410	1500
5	380–410	1500
6	350–350	1300
7	210–230	790–820
8	0.73–25	3.5–92
9	29–54	160–180
10	60–82	260–290
11	89–110	380–3800
12	120–140	480–510
13	150–170	570–600
14	900–950	3600

Result for temperature gradient

If there is a temperature gradient across the insulation system, which typically occurs for a cable in operation where the conductor is heated by resistive losses, the results are a bit different. The temperature profile across the insulation system for a temperature at the conductor of 50°C, and a temperature at the surface of the sheath of 5°C is shown in Figure 6.

For a cylinder symmetrical temperature gradient across the cable, the equilibrium condition is that the radial mass flow is zero. The radial mass flow is given by

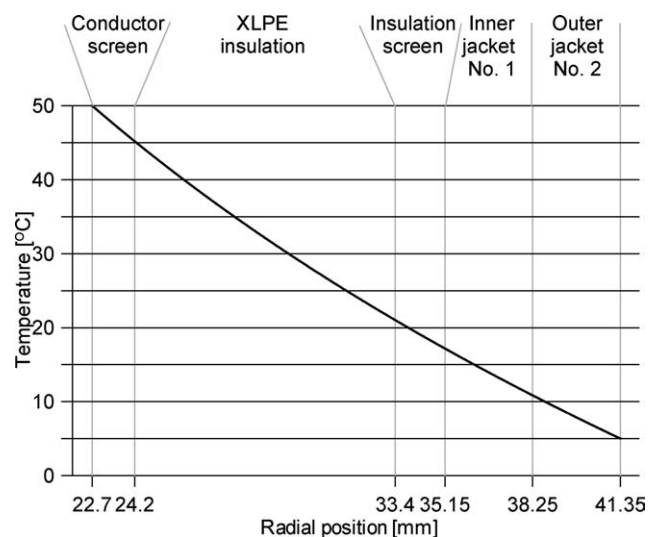$$j_r = -D\frac{1}{r}\frac{\partial Sp}{\partial r} = 0. \qquad (9)$$

Figure 6 Temperature profile across the cable for a temperature at the conductor of 50°C and a temperature at the surface of the sheath of 5°C (seawater).
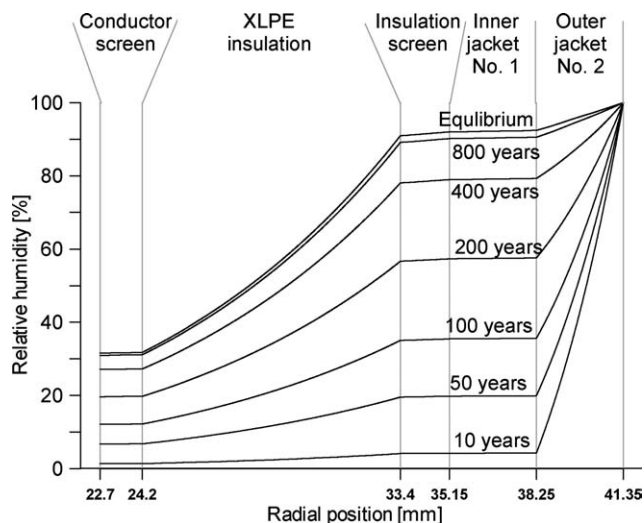
Figure 7 RH across the cable for different times. Case 5, with a temperature at the conductor of 50 and 5°C at the outer sheath. The major drop in RH is across the outer sheath of LP.

This means that the product Sp has to be constant. This means that for a typical service condition (current heating) the RH decreases toward the conductor, as the solubility coefficient decreases faster than the increase in water vapor saturation pressure.

An example of the time varying RH across the insulation system for a temperature gradient from 50°C at the conductor core to 5°C at the surface of the outer sheath for Case 5 is shown in Figure 7.

At equilibrium the RH is less than 100% in the insulation system due to the temperature gradient. In the electrical insulation, the equilibrium RH is between 32 and 90%. This means that for this temperature profile the RH in most of the electrical insulation is below the critical value for water tree
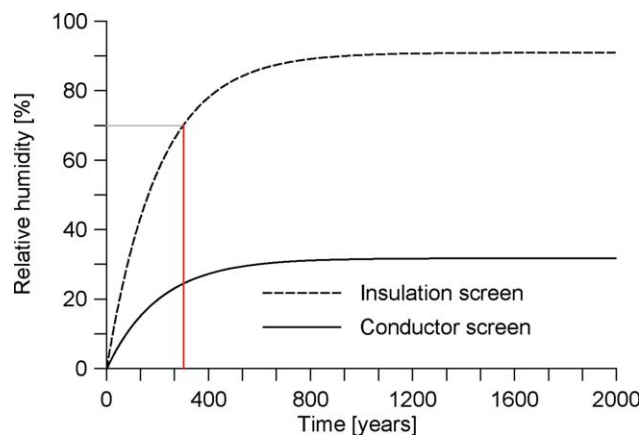
Figure 8 Results from the simulations for Case 5 for the RH levels close to the conductor and insulation screen for a temperature gradient, 50°C at the conductor core, 5°C at the surface of the outer sheath. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE VI
Time to Reach 70% RH and Equilibrium Conditions in the Insulation for a Temperature Gradient, 50°C at the Conductor Core, 5°C at the Surface of the Outer Sheath

Case	Time to 70% RH [years]	Time to equilibrium [years]
1	0	0.70–0.72
2	95	35
3	210	240
4	270	570
5	300	820
6	280	950
7	190	670
8	0.51	1.8–2.8
9	6.3	23
10	20	63
11	26	79–82
12	41	120
13	63	170
14	640	1700

growth. The RH at the interfaces between the electrical insulation and the conductor and insulation screens is plotted as a function of time in Figure 8, where the time to reach 70% RH is also indicated for the outer part of the insulation.

The time to reach 70% RH in the outer parts of the electrical insulation for this temperature profile for the cases in Table III is shown in Table VI, as is also the time to reach equilibrium conditions. Also here, there seems to be an optimal distribution of the total thickness of the sheath between LP and HS, and the optimal thickness distribution is the same as for the uniform temperature.

DISCUSSION AND CONCLUSIONS

The main finding from the simulations is that even at 25°C it is possible to maintain a low RH for a long time in the electrical insulation by carefully selecting the materials and design of the outer sheath. The first (and obvious) step is to use a material with low permeability coefficient for the sheath. This is exemplified by Case 1, where the sheath material is XLPE, compared with Case 2, where the sheath material is LP, where a increase in the time to reach 70% RH of 12 years obtained by selecting the less permeable LP.

However, it is possible to get even a better performance by using a layered outer sheath, where the materials in each layer are selected based on their water permeability and water solubility properties. The outermost layer (outer sheath) should be made from a material with low water permeability, while the inner layer of the sheath (inner sheath) should be made of a material with high water solubility. The results show that there is an optimum thickness for each layer of the sheath that maximizes the time it takes to reach critical humidity levels in the electrical insulation.

The simulations also show that for a cable in operation the temperature gradient across the insulation system has a profound effect on the humidity levels in the electrical insulation. The humidity level in the major part of the electrical insulation does not reach the critical level for water tree growth if there is a temperature gradient across the insulation. This effect can probably be enhanced by suitable thermal design of the cable.

Work is now in progress to verify the numerical calculations by measurements of water diffusion into full-sized XLPE cables equipped with a two-layered outer sheath system.

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