Quantifying Possible Transmission Network Benefits from Higher Cable Conductor Temperatures

J A Pilgrim[1*], P L Lewin[1], A Gorwadia[2], F Waite[2], D Payne[2]

[1] Tony Davies High Voltage Laboratory, University of Southampton, Southampton, SO17 1BJ, UK. (*Corresponding Author: jp2@ecs.soton.ac.uk)

[2] National Grid, Warwick Technology Park, Gallows Hill, Warwick, CV34 6DA.

Abstract

The maximum current rating of high voltage power cables is limited by the allowable conductor temperature, in order to prevent damage to the adjacent dielectric material. Cross-linked polyethylene dielectrics are generally subject to a thermal limit of 90°C in the UK. The use of novel new dielectric materials may allow this temperature limit to be raised considerably. This paper examines the possible thermal rating benefits available from 400kV cable systems capable of conductor temperatures of up to 150°C in a number of common deployment scenarios, including direct burial and installation in ventilated tunnels. The results of the analysis show a divide between modest improvements in continuous rating and much more utilizable gains in short term emergency ratings which could offer the possibilities of single cable circuits being able to match the current carrying capacity of overhead lines over 24hr periods.

1. Nomenclature

The following symbols are used in the equations which follow:

C	Volumetric specific heat capacity (kJm^{-3}°C^{-1})
D_T	Thermal diffusivity (m^{2}s^{-1}°C^{-1})
D_θ	Isothermal diffusivity (m^{2}s^{-1})
$D_{\theta v}$	Isothermal vapour diffusivity (m^{2}s^{-1})
K_c	hydraulic conductivity (ms^{-1})
L	Volumetric heat of vaporization (Jm^{-3})
T	Temperature (°C)
k_{unsat}	Unsaturated hydraulic conductivity (ms^{-1})
ε	Porosity
η	Dynamic viscosity of water (Pa.s)
θ	Volumetric moisture content
λ	Thermal conductivity (Wm^{-1}°C^{-1})

ρ_d Dry density (kgm^{-3})

ρ_w Density of water (kgm^{-3})

σ Surface tension of water (Jm^{-3})

2. Introduction

The maximum current rating of a cable circuit is limited by the permissible operating temperature of the dielectric material used within the cable. Within the UK transmission network, cables constructed with a cross-linked polyethylene (XLPE) dielectric are typically restricted to a maximum temperature of 90°C in order to avoid premature ageing of the dielectric. Recent research has suggested that advanced polypropylene based systems may have the potential to offer operation at temperatures of up to 120°C without the need for cross-linking, although development of such materials is still at an early stage [1]. In addition, some cable systems which are now commercially available at lower voltage levels are considered to withstand conductor temperatures of up to 130°C in emergency conditions [2].

This paper seeks to identify the possible operational benefits to a transmission network operator of the deployment of 400kV cable systems capable of higher operating temperatures. Two specifications of 'HT' cable are examined, based on the same cable design but with conductor temperature limits of either 120°C or 150°C. Analysis of the benefits is achieved through performing a series of cable rating studies to benchmark the potential of 'HT' cables against an existing XLPE reference design. Both continuous (steady state) ratings and short term emergency ratings are analysed to consider the possible impacts of the 'HT' cables on realistic network scenarios.

Although the circuit length of 400kV cable system in UK represents a relatively low percentage of overall transmission route length, many cable links form part of longer circuits consisting mainly of overhead line (OHL). In these instances the cable can frequently present the limit to the continuous rating, with the overhead line often not becoming the limiting factor until short term emergency ratings of less than 6hrs duration are considered.

3. Deployment Scenarios

The two deployment scenarios selected here are the most common in the UK in terms of circuit length, namely direct burial and installation in forced cooled tunnels. In order to calculate ratings for cables operating at higher temperatures, different approaches to the rating calculation may be required. The calculation approaches for the two deployment scenarios are discussed in detail in the following sections.

3.1 Directly Buried Cables

Increased conductor temperatures will naturally lead to increased oversheath temperatures, which can lead to excessive drying of the cable circuit backfill. Such behaviour leads to an increase in the local thermal resistance, reducing the rate of heat flow away from the cables and hence adversely impacting their rating [3]. Any rating methodology used for buried HT cables clearly must take account of this. Traditionally continuous ratings for buried cables have been calculated using the IEC

60287 standard [4], with the transient ratings calculated according to IEC 853 [5]. Both methods are analytical in nature and can be solved by hand or through a simple computer program. Limited provision is made in [4] for the consideration of moisture migration effects through the use of the two zone model published in Electra 104 [6]. This model assumes two zones of uniform soil (one nominally wet, the other dry), bounded by an isotherm. Applicability is restricted to the case of one circuit, with a significant assumption of an isothermal ground surface. Making this assumption for cables buried at depths of less than 1.5m has previously been demonstrated to be overly optimistic [7]. In the case of IEC 853, the properties of the soil must be assumed to be constant. While this is unlikely to be a problem for shorter duration transients, over longer periods the increase in cable losses would induce further moisture migration. As a result of these factors, a dynamic backfill model has been produced using finite element techniques.

3.1.1 Dynamic Backfill Model

A number of authors have previously modelled moisture migration around power cables using FEA techniques. Work by Anders and Radhakrishna has demonstrated the use of the Philip and DeVries equations [8], obtaining reasonable agreement between theoretical temperatures and those measured experimentally [9]. The relevant diffusion coefficients were implemented according to the methods discussed by Groeneveld in [10]. Similar work by Freitas utilizes the finite volume method to solve generalized forms of Fick's Law and Darcy's Law for a number of cable load profiles [11]. Both of these methods show that the nonlinear dependence of the hydraulic parameters on temperature and moisture content must be accounted for, as previously shown by [12]. Some simpler methods also exist, for instance that of [13] which assumes both axial and radial symmetry, meaning that both gravity and changes at the ground surface can not be modelled. As the Philip and DeVries model is perhaps the most well developed, it is selected for use in this study.

The Philip and DeVries model permits the modelling of heat and moisture transport through two coupled differential equations [13]. Modelling of the moisture transport through means of both liquid and vapour is achieved by consideration of effects due to Fick's Law and Darcy's Law. In this case an extended version of Fick's Law is used to improve its applicability to porous materials [14]. This results in the defining equation for the transport of moisture, θ,

$$\frac{\partial \theta}{\partial t} = \nabla.(D_t \nabla T) + \nabla.(D_\theta \nabla \theta) + \frac{\partial k_{unsat}}{\partial z} \quad (1)$$

Where D_t is the thermal diffusivity of moisture (in both liquid and vapour phase (m^2s^{-1})), D_θ is the isothermal diffusivity of moisture in both phases (m^2s^{-1}) and k_{unsat} is the unsaturated permeability of the soil. This equation is coupled to a modified expression for heat transport,

$$C\frac{\partial T}{\partial t} = \nabla.(\lambda \nabla T) + L\rho_w \nabla.(D_{\theta v} \nabla \theta) \quad (2)$$

which accounts for the latent heat within the water vapour. Here C is the specific heat capacity ($Jkg^{-1}K^{-1}$), λ is thermal conductivity ($Wm^{-1}K^{-1}$), L is the latent heat of vaporization of water (Jkg^{-1}), ρ_w is the density of water and $D_{\theta v}$ is the isothermal diffusivity of water vapour (m^2s^{-1}). Whilst such an equation system appears straightforward, complications arise due to the nonlinearity of the coefficients. Both D_T and D_θ must be considered as a function of both temperature and volumetric moisture content. The appropriate characterisations and derivations are presented in the Appendix.

3.1.2 FEA Model Construction

A 2D finite element analysis model has been developed to calculate circuit ratings using the dynamic backfill model. The cable is buried at a constant depth of 1.05m, with a phase spacing of 385mm. There are no external heat sources which might affect the cable at any point along its route. The basic specification of the model is similar to that reported in [7].

The modelling of the cable itself is as [7], but with the conductor ac resistance being modelled as a function of temperature according to [4]. The joule losses are distributed uniformly along the outer boundary of the conductor, while the sheath losses are distributed uniformly along the inner boundary of the sheath region. The dielectric losses are distributed across the dielectric region using the voltage dependent function described in [7].

The modelling of the thermal environment around the cable is as [7], but with the modelling procedure described in Section 3.1.1 being used for the thermal conductivity of the backfill. The overall size of the soil zone modelled is 50m in width by 26.05m deep, with an isothermal boundary specified 25m below the cables. This remote ground isotherm is set to 12°C which has been judged a suitable temperature for most UK regions. The thermal initial condition for the model is a uniform 12°C in keeping with this isotherm. Tests have been undertaken which verify that the position of these remote boundaries do not artificially constrain the solution obtained. The area immediately around the cables, measuring 1m by 0.4m, consists of a cement-bound sand (CBS) backfill. The thermal properties of the CBS are assumed constant, with a thermal conductivity of 0.833W/m.K and a specific heat capacity of 1.9MJ/m^{3}K. Given the very high conductor temperatures studied here, it is not appropriate to force an isothermal boundary at the ground surface. Instead a still air convection boundary is specified based on an assumed air temperature of 15°C, as discussed in [7]. All external boundaries are considered to be insulating to moisture, hence no account is made for either evaporation or rainfall at the ground surface.

3.2 Ventilated Tunnels

Ventilated tunnels have become the installation method of choice in densely populated urban areas, such as London (where an additional 33km of tunnels are currently under construction), in the past decade. The present internationally standard method for calculating cable ratings in forced-ventilated tunnels is that published in Electra 143 [15]. In order to model fully tunnels containing multiple cable types operating on independent load cycles, it is necessary to make some modifications to the original method as detailed in [16]. These changes are particularly important in the application considered here, where the conductor temperatures of different circuits may be markedly different.

3.3 Cable Specification

All of the calculations presented in this paper are based on a common cable system, as described in Table I. The cable design adopted is based on existing 400kV systems and is for a 3 phase 50Hz ac system with 2500mm^2 conductor and polymeric dielectric. The sheath is constructed from copper wires, surrounded by a thin aluminium foil water barrier, encased in an outer sheath of polyethylene.

TABLE I

PROPERTIES OF CANDIDATE 400KV CABLE

CABLE PROPERTY	VALUE
Conductor Diameter	64mm
Dielectric Thickness	31mm
Outer Sheath Diameter	132mm
External Diameter	148mm
Dielectric Thermal Resistivity	3.5 $K.mW^{-1}$
Outer Sheath Thermal Resistivity	3.5 $K.mW^{-1}$
Conductor ks Coefficient	0.62
Conductor kp Coefficient	0.8
Sheath Loss Factor (lead/centre/lag)	0.0111/0.0433/0.0105
Conductor Electrical Resistivity	1.7241×10^{-8} Ωm
Temperature coefficient of resistance	0.00393 K^{-1}
Tangent of dielectric loss angle	0.001
Dielectric relative permittivity	2.4

4. Buried Cable Circuits

This section presents the results of the rating analysis undertaken on the HT cables systems in the direct buried deployment scenario. A number of 400kV cable circuits in rural areas are installed in this manner. Results are presented for both continuous and emergency ratings.

4.1 Continuous Rating Results

Continuous ratings were obtained for the buried cable circuit using the dynamic backfill model discussed in Section 3.1. The rating is obtained by iteratively solving the FEA model for higher conductor currents until the maximum conductor temperature criterion is reached at the end of a 40 year time period (40 years is chosen as the average asset life for such a cable system). Results are obtained for initial moisture contents of between 3% and 15% by volume, with the results summarised in Fig. 1.

Fig. 1. Buried cable continuous ratings with respect to moisture content

As expected, the continuous circuit rating increases with increasing volumetric moisture content due to the higher backfill thermal conductivity. The largest gain in rating between the XLPE and 150°C 'HT' cable is 35% for the lowest moisture content studied, reducing to 20% at 15% moisture content (the reduced percentage increase at high temperatures is due to the heat output broadly being a function of current squared). Comparing the results of the FEA model to the IEC 60287 two-zone approximation, Fig. 2 shows a distinct wet/dry boundary in the vicinity of the 20°C isotherm. However, Fig. 3 for the 15% moisture content shows a much more graduated change in moisture content away from the cable circuit. In this case the dry zone appears to be delimited by the 35°C isotherm. This suggests that the size of the dry zone is also a function not only of temperature, but also of the overall moisture content in the soil.

Fig. 2. Steady State Moisture Distribution for XLPE cable (3% initial moisture content)

Fig. 3. Steady State Moisture Distribution for XLPE cable (15% initial moisture content)

Previously in the UK, where high continuous cable ratings have been needed, they have been achieved using conventional cable surrounded by water pipes [17]. While these systems can offer very high ratings, they do so at the expense of increased maintenance overheads and reduced availability (due to cooling system repairs etc.). However, they remain a valuable comparator. To generate data for comparison, a water cooled cable circuit matching the geometry of Fig. 4 has been modelled according to the scheme of [18], but with modelling of moisture migration in the backfill. The cooling section length is 2.7km, with a flow rate of $1ls^{-1}$ per pipe and an inlet temperature of 15°C. The continuous rating obtained is 2564A (assuming that joint bays are not limiting) for the lowest soil moisture content of 3%, which is vastly higher than the continuous rating for the 'HT' cable circuits. For buried cable circuits it is clearly more beneficial to the continuous rating to employ forced cooling rather than deploy an 'HT' cable.

Fig. 4. Layout of cooling pipes around cable circuit (inlet pipes 2 & 3, outlet pipes 1 & 4)

4.2 Emergency Rating Results

While the continuous rating is important to overall network planning, on an operational basis the ability of a network link to carry more than its continuous rated load for a short time period becomes vital in avoiding constraints. The ratings calculated here are for either 6hr or 24hr durations, based on prior continuous operation at a percentage of the steady state rating. Fig. 5 shows the results for both the 6hr and 24hr ratings at a preload of 60%, with Fig. 6 showing the results for a 75% preload. It should be noted that this definition means that the preload current carried by the 'HT' cables is hence higher than that of the XLPE circuits. A number of conclusions can be drawn from these results – firstly, it can be seen that the magnitude of the emergency ratings hardly increases above an initial moisture content of 7.5%. This is due to the fact that the initial conductor temperatures are very similar. However the most important conclusion comes from the comparison of the 6hr rating of the conventional XLPE cable, against the 24hr rating of the 150°C cable. As the 24hr rating of the 150°C is at least equal to the 6hr rating of the conventional cable, it would mean that the existing 6hr rating of a circuit could be maintained for a 24hr period. Such a facility could be valuable in avoiding network constraints.

Fig. 5. 6hr and 24hr ratings of buried cable circuit as a function of moisture content, given prior operation at 60% of continuous rating

Fig. 6. 6hr and 24hr ratings of buried cable circuit as a function of moisture content, given prior operation at 75% of continuous rating

4.3 Constraint Example

In order to determine whether the 'HT' cables could prove valuable operationally, existing network locations which are constrained (i.e. where power transfer is limited) by buried cable circuits have been evaluated. One example within constraint Zone 8 contains 4GW generation capacity. If more than 2GW of generation is scheduled inside the constraint zone, but an outage is in place on one of the 400kV circuits, thermal limits would be exceeded. As a result a generation intertrip arrangement would need to be agreed (at a cost) to manage power flows in the event of a fault on one circuit.

In one example from 2010, given a planned outage on one cable circuit and a downrating on an adjacent OHL, the second cable circuit would be preloaded to 75% of continuous rating (1800MVA). Had a fault occurred, the circuit would have been required to support a flow of 2620MVA. The corresponding 6hr rating for the cable circuit was only 2450MVA, which would have required the intertrip arrangement to be deployed, removing one generating set. Based on the emergency rating results calculated in Section 4.2, it is clear that with the extra power transfer capability of the HT120 cable, such a constraint could have been avoided.

5. Cables in Ventilated Tunnels

Cable tunnels are becoming increasingly common in urban areas of the UK, as the challenges associated with direct burial of cables begin to make tunnelling more desirable, despite the high capital expenditure required. The tunnel modelled here is a 3km length of 4m diameter, with two shafts of 30m depth at each end. Cooling is achieved through forced air ventilation with a flow rate of 5m/s in the 4m tunnel sections. Two tunnel options are modelled, with the first containing one 400kV double circuit of the construction outlined in Table I. The second tunnel option also includes a second 400kV double circuit and 3 circuits of 132kV XLPE cable with a 1600mm^2 copper conductor. The ratings are calculated according to the method discussed in [9]. During the summer season the tunnel is assumed to have a constant air inlet temperature of 20°C, while the corresponding value for winter is 5°C.

5.1 Continuous Rating Results

For transmission class cable tunnels in the UK, there are two possible thermal limits on the cable circuit rating. The first is that the conductor temperature reaches its limit, while the second is that the outlet air temperature reaches 50°C. For shorter, more lightly utilized tunnels (Option 1 in this study) it is typically the conductor temperature which limits, whereas for the more heavily loaded tunnel of Option 2 it is normally the air temperature which is the constraint.

The continuous rating of the Option 1 tunnel, shown in Table II, is easily calculated as there is only one circuit to consider. In this particular case, switching to a HT120 cable would increase the available continuous rating by 14.2% in the summer season, but the additional increase given by a HT150 cable would be negligible given the air temperature limit. For the winter season the full capability of the HT150 cable can be used, however the increase on the HT120 rating is only 9%.

TABLE II
OPTION 1 TUNNEL CONTINUOUS RATINGS (S=SUMMER, W=WINTER)

CABLE TYPE	CURRENT PER CABLE	CONDUCTOR TEMPERATURE (°C)	OUTLET AIR TEMPERATURE (°C)
XLPE (S)	2832A	90	40.8
HT120 (S)	3301A	120	49.8
HT150 (S)	3312A	121	50.0
XLPE (W)	3087A	90	31.6
HT120 (W)	3511A	120	40.5
HT 150 (W)	3853A	150	49.3

Calculation of the continuous ratings for the Option 2 tunnel is more complex, with the rating solution being a trade-off between the two groups of circuits at different voltage levels. Fig. 7 shows the summer and winter rating curves for the Option 2 tunnel. As any point along the line represents a valid rating combination, it is considered that the most operationally effective would be for the 132kV circuits to be rated at 300MVA (1312A), giving the 400kV circuits a rating of 4070A per circuit in summer and 5122A per circuit in winter. Fig. 8 illustrates why the HT cables may not provide a continuous rating increase in a heavily utilized tunnel. For the summer season, it is clear that the air temperature is at the 50°C limit for every rating combination studied, with the conductor temperature still being below 90°C even where the load on the 132kV cables is very low. Plotting the same results for the winter season shows that the conductor temperature is actually the limiting factor where the 132kV loads are below 1500A.

Fig. 7. Continuous ratings of Option 2 tunnel configuration

Fig. 8. Temperature curves for Option 2 tunnel under steady state loads

5.2 Emergency Rating Results

As with the analysis of buried cables, the primary emergency ratings of interest in this study are the 6hr and 24hr ratings. These are calculated by determining the steady state temperature distribution in the tunnels for a defined pre-fault load (taken here as 60% of the continuous rating), then setting this as the initial condition for a transient solution. For Option 1, the deployment of cable capable of a conductor temperature greater than 120°C did not produce a continuous rating benefit. However the air temperature limit of the tunnel rarely limits the emergency ratings, due to the large thermal time constant of the tunnel wall. The most important conclusion from Table III is that the 24hr ratings of the HT120 circuits are higher than the 6hr ratings of the XLPE circuits. Considering the results for the HT150 cables, both the 6hr and 24hr ratings are sufficiently high that the cable would no longer be the thermal limit (due to much of the protection being rated at 4kA over these durations).

TABLE III
OPTION 1 TUNNEL EMERGENCY RATINGS (S=SUMMER, W=WINTER)

CABLE TYPE	PRE-FAULT LOAD PER CABLE (A)	6HR RATING PER CABLE (A)	24HR RATING PER CABLE (A)
XLPE (S)	1699A	3427A	3145A
HT120 (S)	1981A	4079A	3734A
HT150 (S)	1987A	4688A	4252A
XLPE (W)	1852A	3776A	3459A
HT120 (W)	2107A	4385A	4007A
HT 150 (W)	2312A	4909A	4474A

While the deployment potential looks to be very high for the HT cables in the Option 1 tunnel configuration in steady state and emergency rating scenarios, little potential was identified to improve continuous ratings in the Option 2 case. Despite this, there are some benefits available for the emergency rating cases. Fig. 9 shows the results for the case where an emergency rating is required on one 400kV circuit, while the other operates at its pre-fault load and the 132kV circuits are loaded to full continuous rating. The gain in emergency rating when moving from XLPE to the HT120 cable is in the region of 700A per cable (1400A for a double circuit).

Fig. 9. 6hr emergency ratings for Option 2 configuration, summer season

The results of the 24hr calculations are shown in Fig. 10. In this case, the 24hr rating of the HT120 cable exceeds the 6hr rating of the XLPE cable, a very clear benefit from the viewpoint of network operation. Unlike the 6hr ratings of Fig. 9, some of the 24hr ratings are air temperature limited, as can be seen from the curves for the HT120 and HT150 cables. At higher preloads the rating of these cables is identical as the cable temperature is not the limiting factor on the operation of the circuit.

Fig. 10. 24hr emergency ratings for Option 2 configuration, summer season

5.3 Constraint Example

The majority of UK cable tunnels outside of London itself are installed under rivers or estuaries where an OHL crossing would prove impractical. One such example is the Medway tunnel, which forms part of the Zone 15 constraint group containing 6 major generating plants. The tunnel network consists of two separate tunnels, each carrying a 400kV double circuit. Although many different operational modes could exist in this area, the most onerous was identified to be where export to France via the channel DC link was at its peak of 2GW. During one case in summer 2010, two of the circuits at the constraint boundary were out of service and the majority of the generation within the constraint group was scheduled to meet the lunchtime peak. In this scenario, the Medway tunnel circuits experience a preload of 75%. If one of the circuits experienced a fault, contingency analysis suggests that the remaining circuit would need to support a load of 2750MVA. The appropriate 6hr rating is almost 500MVA lower than this requirement, leading to the requirement to constrain generation within the Zone 15 group. This example matches well with that of the Option 1 tunnel, where the indicative gain in rating in the summer season was 19% for moving to HT120 and 36% for HT150 cables. This would mean that the necessary load flow could almost be supported for 6hrs with the HT120 cable, while it would be easily achievable for the HT150 cable. In this case, the ability to allow the conductor temperature to reach 150°C would prevent the need to apply generation constraints during the peak period.

6. Viability of High Conductor Temperature Cables

The work presented in this paper has demonstrated that, were a suitable cable system available, the concept of 'HT' cable could be useful in lifting some network constraints – especially those over short time periods. This said, there are a number of key technical difficulties in deploying such a technology. Significant thermo-mechanical issues must be addressed as permitting a conductor temperature of up to 150°C would lead to a large increase in conductor thrust. It is likely that a significant upgrade in joint design would be necessary to cope with the increased forces. A second issue is that of terminations, for instance at a transformer, where it would be undesirable for excess heat from the conductor to be conducted into the adjacent item of plant. The introduction of additional cooling at a termination would be undesirable, but potentially unavoidable. A final consideration is that the HT dielectric would also need to be suitable for use in accessories.

7. Conclusions

This paper has analysed the potential benefits to a transmission system operator of 400kV cable circuits capable of operation at conductor temperatures of up to 150°C. A method for rating buried HT cables is presented which enables full account to be taken of changes in soil thermal resistivity arising from moisture migration. This is particularly important for emergency ratings, where the initial conductor temperature has a strong influence on the final result and hence the thermal state under pre-fault conditions must be well defined. The standard IEC 853 method can't be reliably used to rate HT installations as failing to model the change in soil thermal resistivity will overstate the emergency rating benefits available. The model presented takes full account of the non-isothermal condition at the ground surface – this is essential for consideration of HT cables, meaning that the conventional IEC 62087 method is not suitable. The rating study undertaken has shown that existing continuous ratings of buried circuits could be increased by up to 35%, but this may not represent the best use of the additional thermal capability owing to higher system losses. However improved emergency rating capability (particularly over the 6hr and 24hr periods) could prove valuable in mitigating network constraints, as shown by the constraint evaluation at existing 400kV circuit locations. In tunnels which are lightly utilized (in terms of cable volumes), continuous rating gains can be achieved – however for any tunnel limited by air temperature, the additional cable performance would not be usable. Despite this, the increases in emergency ratings (including the potential to extend the 6hr rating of an XLPE cable to a period of 24hrs) could still represent a valuable addition to the operational flexibility of the transmission network by permitting longer maintenance outages and providing capacity to deal with greater short term peaks in generation. The value of such a capability is likely to increase given the increasing penetration of intermittent generation across the network.

8. Acknowledgement

The authors gratefully acknowledge the assistance of H. Skinner and J. Smethurst for providing geotechnical advice and facilities. This work was supported by the UK Technology Strategy Board project "Sustainable Power Cable Materials Technologies with Improved Whole Life Performance" (Grant TS/G000239/1) and National Grid plc.

9. References

[1] Hosier, I.L., Reaud, S., Vaughan, A.S. and Swingler,S.G.: 'Morphology, thermal, mechanical and electrical properties of propylene-based materials for cable applications'. Proc. IEEE Int. Symp. Electrical Insulation, Vancouver, Canada, June 2008. pp.502-505.

[2] Belli, S., Perego, G., Bareggi, A., Caimi, L., Donazzi, F. and Zaccone, E: 'P-Laser: Breakthrough in Power Cable Systems'. Proc. IEEE Int. Symp. Electrical Insulation, San Diego, California, June 2010. pp1-5.

[3] Milne, A.G. and Mochlinski, K.: 'Characteristics of soil affecting cable ratings,' Proc. Inst. Electrical Engineers, 1964, 11, (5), pp1017-1039.

[4] IEC 60287-1-1: 'Electric Cables – calculation of the current rating, part 1-1: Current rating equations (100% load factor) and calculation of losses', 2006.

[5] IEC 60853-2: 'Calculation of the cyclic and emergency current rating of cables: Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages', 1989.

[6] Cigré Working Group 21.08: 'Current ratings of cables in partially dried out soil, part 1,' Electra, 104, pp11-22. 1986.

[7] Swaffield, D.J, Lewin, P.L. and Sutton, S.J.: 'Methods for rating directly buried high voltage cable circuits.' IET Generation, Transmission and Distribution, 2008, 2, (3), pp393-401.

[8] Philip, J.R. and deVries, D.A.:, 'Moisture movement in porous soils under temperature gradients.' Trans. of the American Geophysical Union, 1957, 38, (2), pp222-232.

[9] Anders, G.J. and Radhakrishna, H.S.: 'Power cable thermal analysis with consideration of heat and moisture transfer.' IEEE Trans. Power Delivery, 1988, 3, (4), pp1280-1288.

[10] Groeneveld, G.J., Snijders, A.L., Koopmans, G., Vermeer, J.: 'Improved Method to Calculate the Critical Conditions for Drying Out Sandy Soils Around Power Cables'. IEE Proceedings Part C, 1984, 131, (2), pp.42-53.

[11] Freitas, D.S., Prata, A.T. and de Lima,A.J.: 'Thermal performance of underground power cables with constant and cyclic currents in presence of moisture migration in the surrounding soil.' IEEE Trans. Power Delivery, 1996, 11, (3), pp1159-1170.

[12] Preece, R.J. and Hitchcock, J.A.: 'Simultaneous diffusion of heat and moisture around a normally buried EHV cable system.' IEE Conf. Pub.176, 1979. pp262-267.

[13] Hartley, J.G. and Black, W.Z.: 'Transient simultaneous heat and mass transfer in moist unsaturated soils,' Trans. of the ASME, 1981, 103, pp376-382.

[14] Carman, P.C.: 'Properties of capillary held liquids.' Journal of Physical Chemistry, 1953, 57, (1), pp56-64.

[15] Cigré WG08-SC21: 'Calculation of temperatures in ventilated cable tunnels.' Electra, 1992, 143, pp.38-59.

[16] Pilgrim, J.A., Swaffield, D.J, Lewin, P.L., Larsen, S.T., Waite, F. and Payne, D.: 'Rating Independent Cable Circuits in Forced Ventilated Cable Tunnels.' IEEE Trans. Power Delivery, 2010, 25, (4), pp2046-2053.

[17] Ball, E.H., Reilly, M., Skipper, D.J., Yates, J.B.: 'Connecting Dinorwic pumped storage power station to the grid system by 400kV underground cables', Proc. IEE, 1979, 126, (3), pp239-245.

[18] Swaffield, D.J., Lewin, P.L., Payne, D. and Larsen, S.T.: 'Effects of modeling assumptions on the rating calculation for externally forced cooled high voltage cables,' IET Generation, Transmission & Distribution, 2009, 3, (5), pp496-507.

Appendix

Analysis of the moisture transport properties of backfills is not a straightforward undertaking, despite the fact that most of the moisture transport coefficients are described as functions of physical properties. In order to maximize the accuracy of the dynamic backfill model, a number of laboratory characterizations were undertaken to assist in the derivation of the diffusion coefficients. This paper does not enter into great detail as to the theory underpinning the Philip and de Vries model, however ample references are provided for the interested reader. In order to calculate the diffusion coefficients, it is first necessary to determine the soil water characteristic curve (SWCC) and the hydraulic permeability.

A.1 Soil Water Characteristic Curve

The SWCC relates volumetric moisture to soil suction and has been determined through the use of a pressure plate extractor test. Figure A1 illustrates the experimental data, against which a curve has been plotted using the technique presented by Fredlund [1A]. The backfill porosity was determined to be 0.4. In addition the soil suction, Ψ (kPa), is also a function of temperature, due to the temperature dependence of the surface tension of water, σ. This is accounted for by describing the temperature dependent relationship as

$$\psi(\theta,T) = \frac{\sigma_{ref}}{\sigma_T}\psi(\theta)_{ref} \quad \text{(I)}$$

$$\sigma_T = 0.122 - 0.0002(T + 273.15) \quad \text{(II)}$$

Fig. A1. Soil Water Characteristic Curve at 20°C, with Fredlund and Xing curve fitted

A.2 Hydraulic Permeability

There are two components to the hydraulic permeability, with differences between saturated and unsaturated behavior. The saturated behavior can easily be derived from a laboratory test using a constant head permeameter. Averaging across five samples, the saturated permeability was found to be 2.297ms^{-1}. As it is extremely difficult to obtain a laboratory characterization of unsaturated permeability, the theory presented in [2A] was utilized to derive the curve of Fig. A2 from the SWCC. As with soil suction, there is an additional consideration regarding the dependence of temperature due to the relationship between permeability and the dynamic viscosity of water as demonstrated by

$$k_{unsat} = \frac{\eta_{ref}}{\eta_T} k_{unsat(\theta)ref} \quad \text{(III)}$$

$$\eta_T = 0.0014e^{-0.0177T} \quad \text{(IV)}$$

Where T is the temperature (°C) and η is the dynamic viscosity of water (Pa.s). The reference temperature is 20°C.

Fig. A2. Unsaturated permeability plot at reference temperature

A.3 Thermal Diffusivity

The thermal diffusivity, D_T, accounts for the diffusion of moisture in a soil due solely to a temperature gradient. It is made up of two separate components, the thermal liquid diffusivity (derived using the SWCC as per [8]) and the thermal vapour diffusivity (derived as per [12] using the experimental SWCC), with the curve shown in Fig. A3 representing the sum of these components between the fully dry and saturated states.

Fig. A3. Thermal Diffusivity with varying temperature and moisture content

4.3.4 Isothermal Diffusivity

The isothermal diffusivity, D_θ, accounts for the diffusion of moisture in a soil due solely to a concentration gradient. As with the thermal diffusivity, there are components due to both liquid and vapour, the sum of which is shown in Fig. A4. Both components are derived from the SWCC using the relations given in [8].

Fig. A4. Thermal Diffusivity with varying temperature and moisture content

A.5 Thermal Conductivity

One of the main couplings between the two differential equations used to represent the moisture migration process is the dependence of the backfill thermal conductivity on its moisture content. To obtain a continuous thermal conductivity function for use in the FEA models, the soil thermal conductivity is determined experimentally at different moisture contents using the thermal needle approach recommended by IEEE Std 442 [3A]. The volumetric specific heat capacity of a backfill may be obtained by calculating the sum of the volumetric heat capacities of its individual constituent's weighted by their volume fractions [4A].

Fig. A5. Thermal Conductivity with volumetric moisture content

[1A] Fredlund, D.G. and Xing, A.: 'Equations for the soil-water characteristic curve,' Canadian Geotechnical Journal, 1994, 31, (4), pp521-531.

[2A] Fredlund, D.G., Xing, A. and Huang, S: 'Predicting the permeability function for unsaturated soil using the soil water characteristic curve,' Canadian Geotechnical Journal, 1994, 31, (4), pp533-546.

[3A] IEEE Std 442: 'IEEE guide for soil thermal resistivity measurements', 1996.

[4A] Farouki, O.: 'Thermal properties of soils,' CRREL Monograph 81-1, US Army Corps of Engineers. 1981.

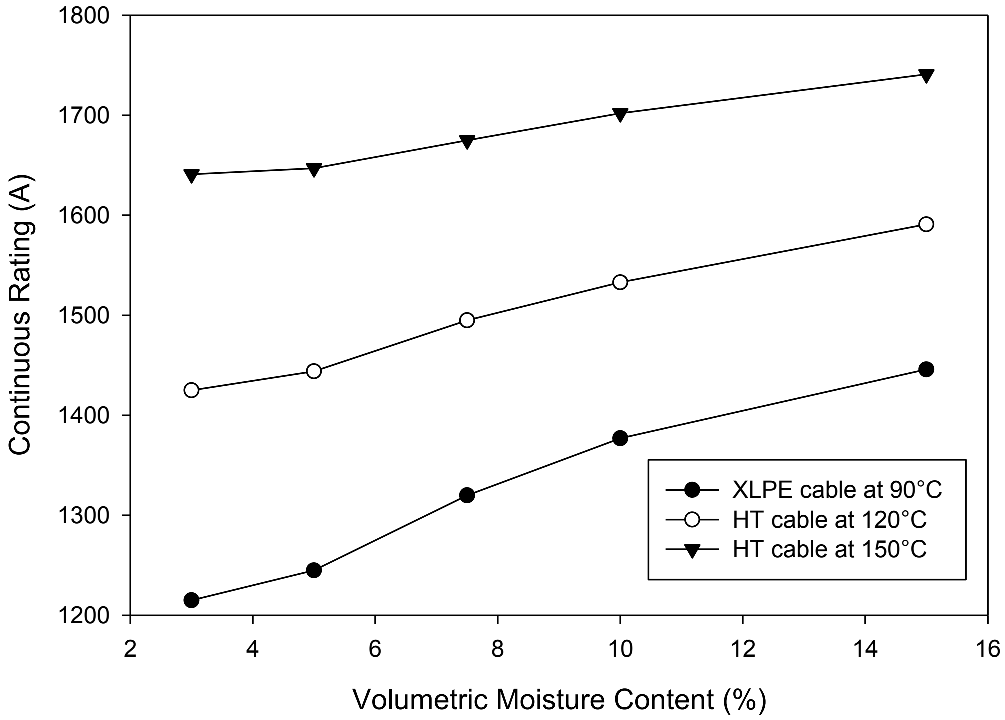

Fig. 1. Buried cable continuous ratings with respect to moisture content

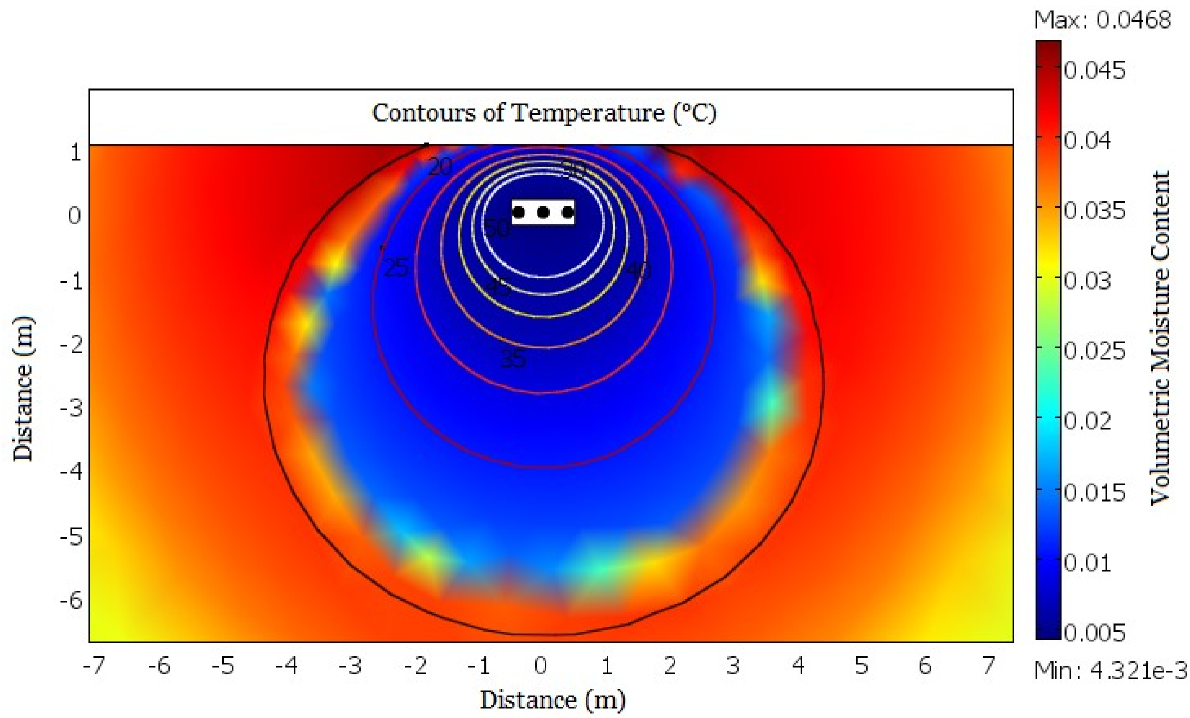

Fig. 2. Steady State Moisture Distribution for XLPE cable (3% initial moisture content)

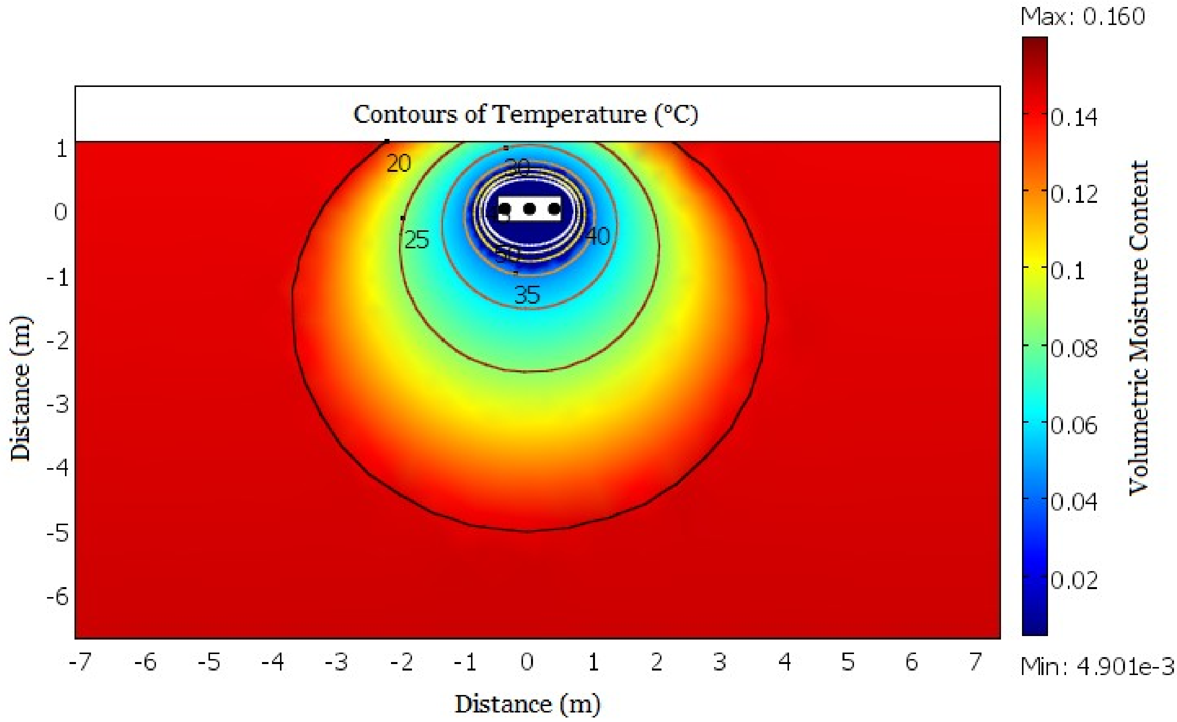

Fig. 3. Steady State Moisture Distribution for XLPE cable (15% initial moisture content)

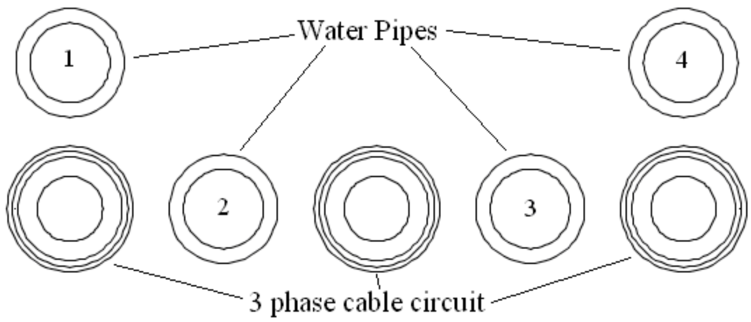

Fig. 4. Layout of cooling pipes around cable circuit (inlet pipes 2 & 3, outlet pipes 1 & 4)

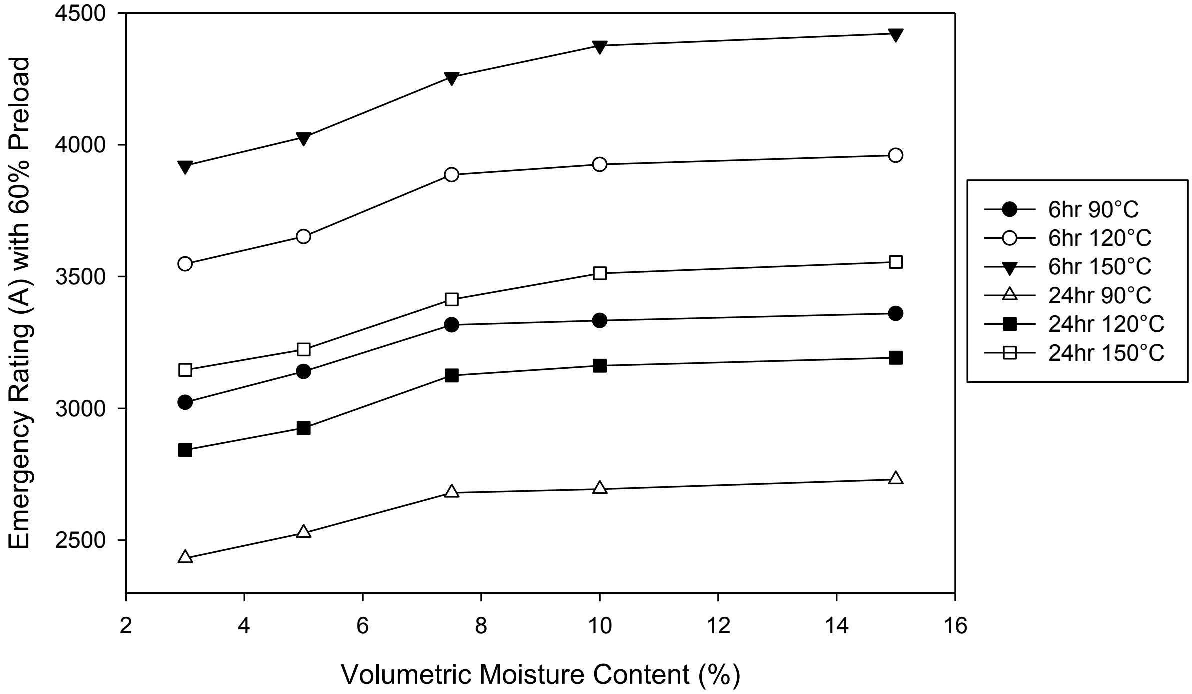

Fig. 5. 6hr and 24hr ratings of buried cable circuit as a function of moisture content, given prior operation at 60% of continuous rating

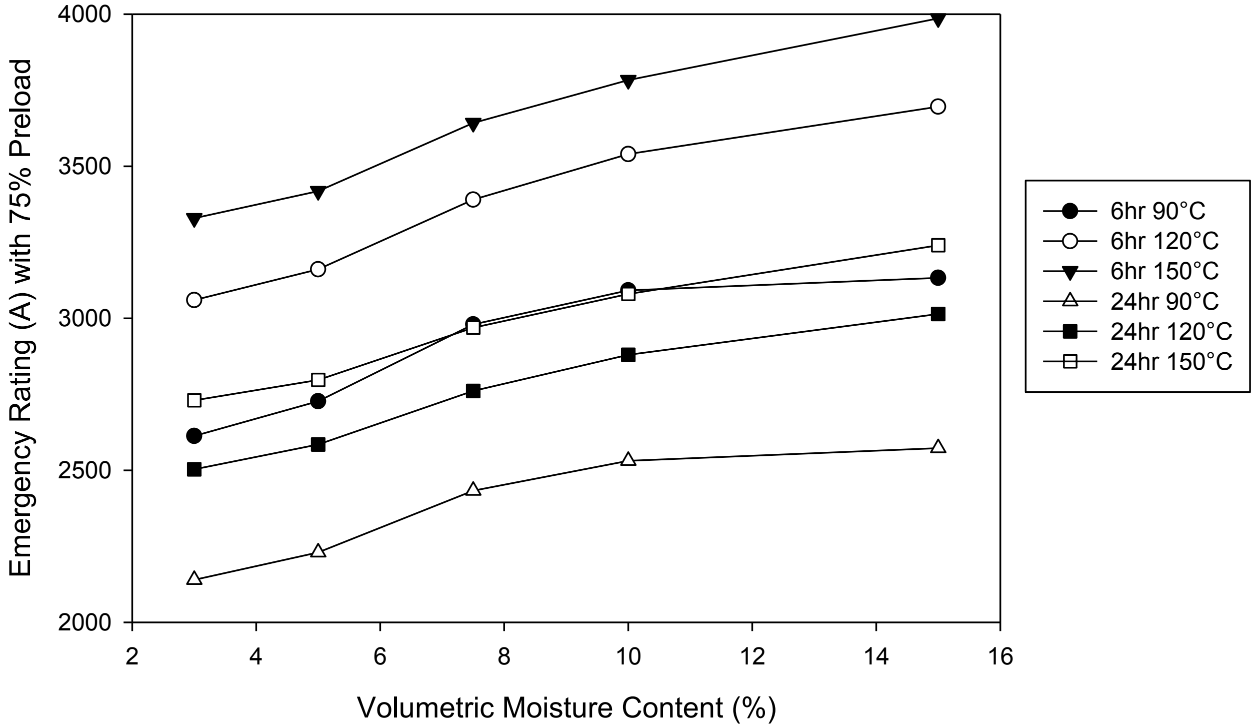

Fig. 6. 6hr and 24hr ratings of buried cable circuit as a function of moisture content, given prior operation at 75% of continuous rating

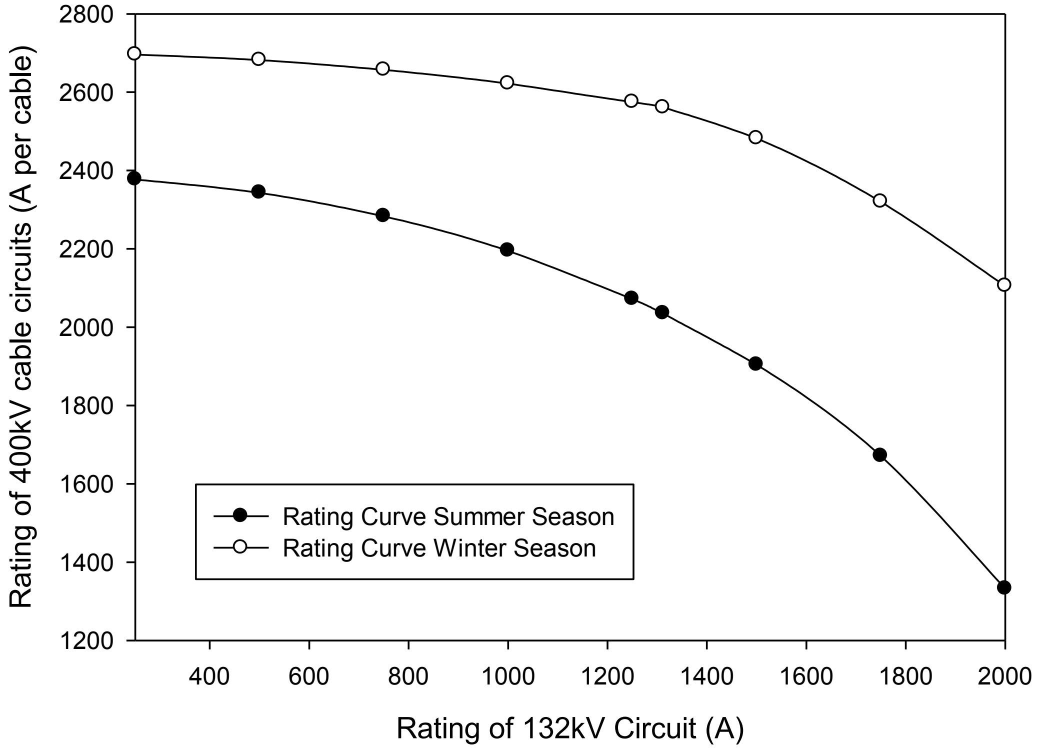

Fig. 7. Continuous ratings of Option 2 tunnel configuration

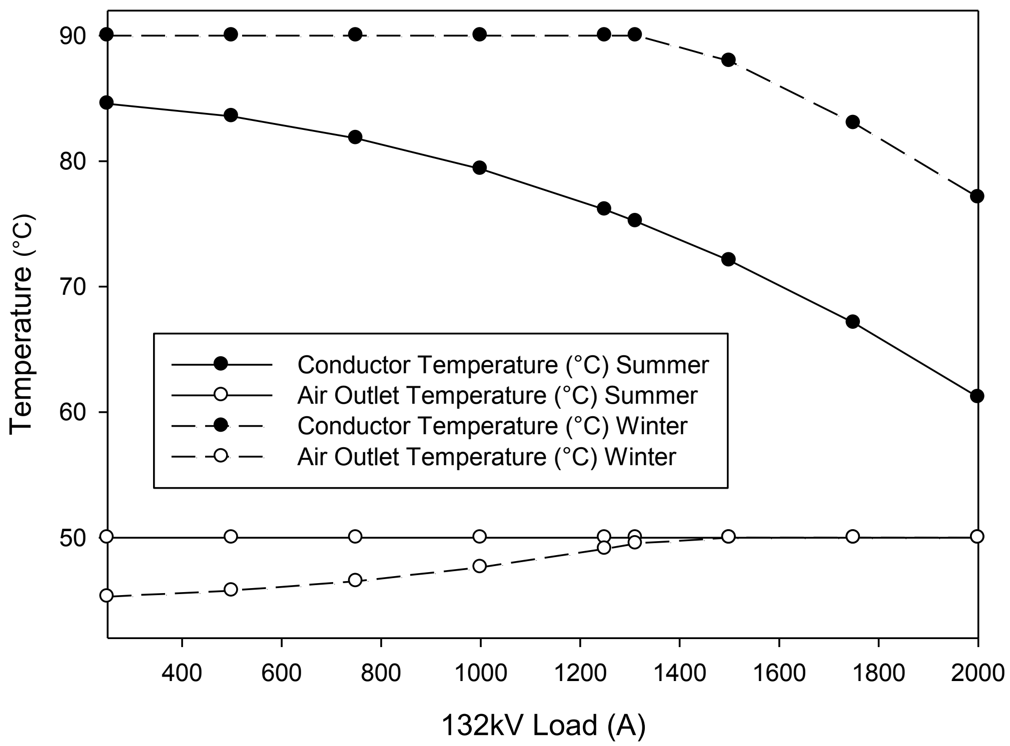

Fig. 8. Temperature curves for Option 2 tunnel under steady state loads

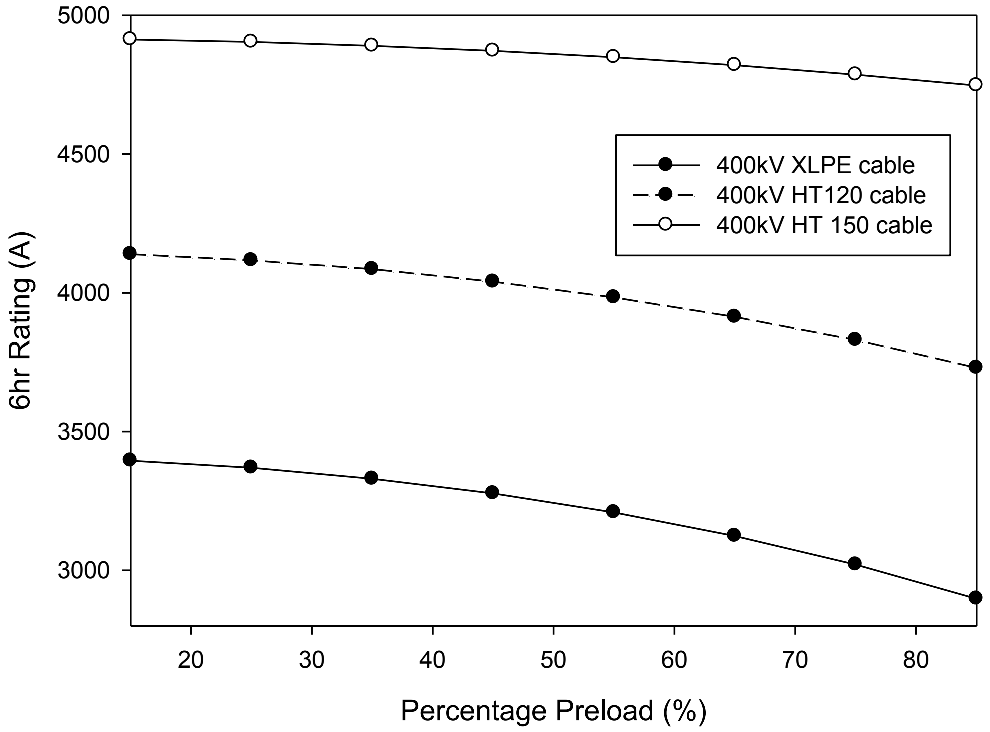

Fig. 9. 6hr emergency ratings for Option 2 configuration, summer season

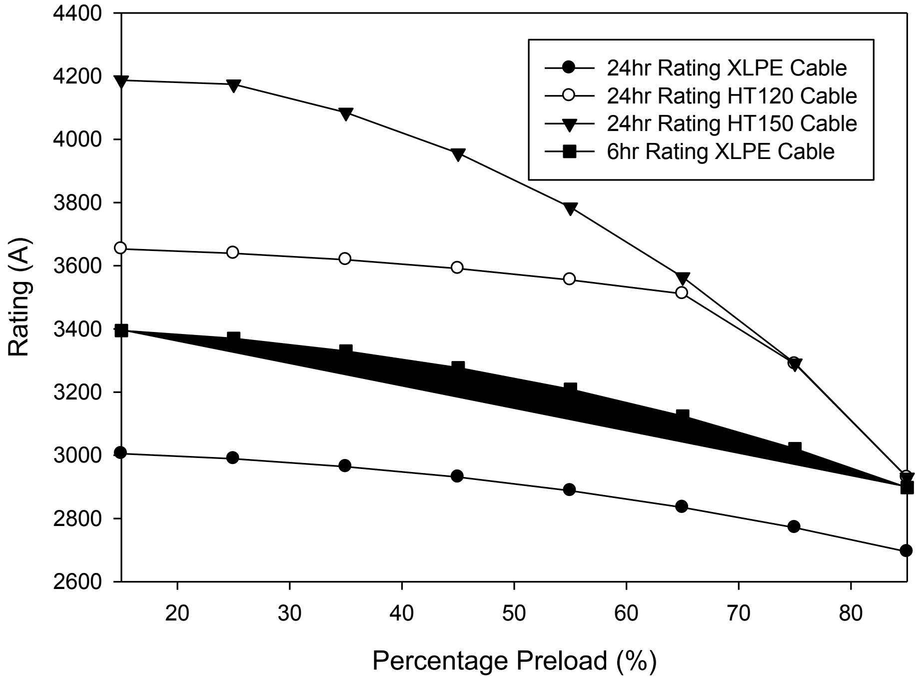

Fig. 10. 24hr emergency ratings for Option 2 configuration, summer season

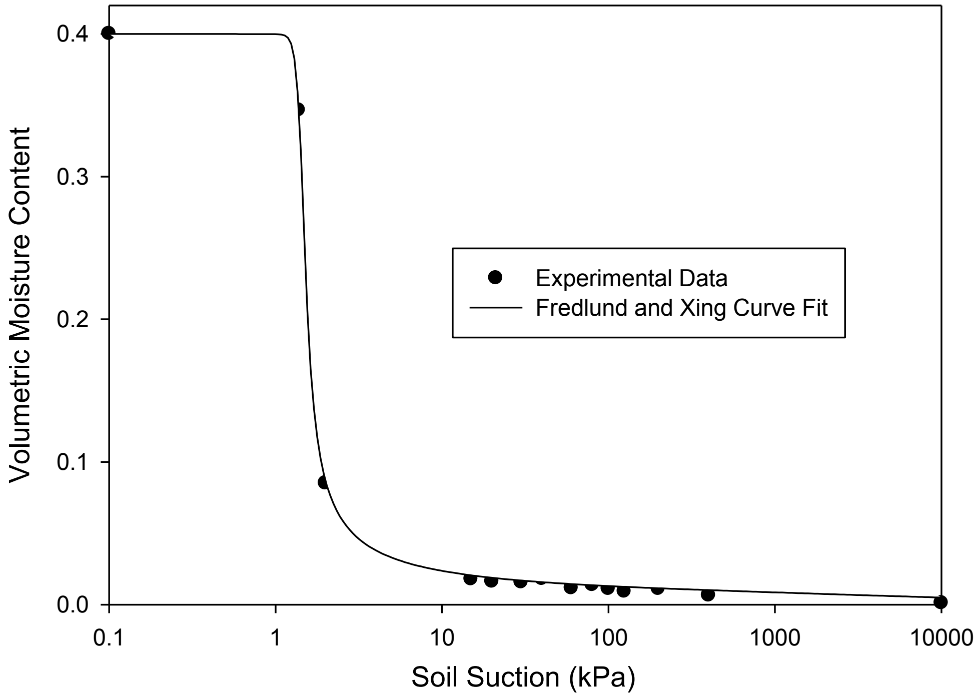

Fig. A1. Soil Water Characteristic Curve at 20°C, with Fredlund and Xing curve fitted

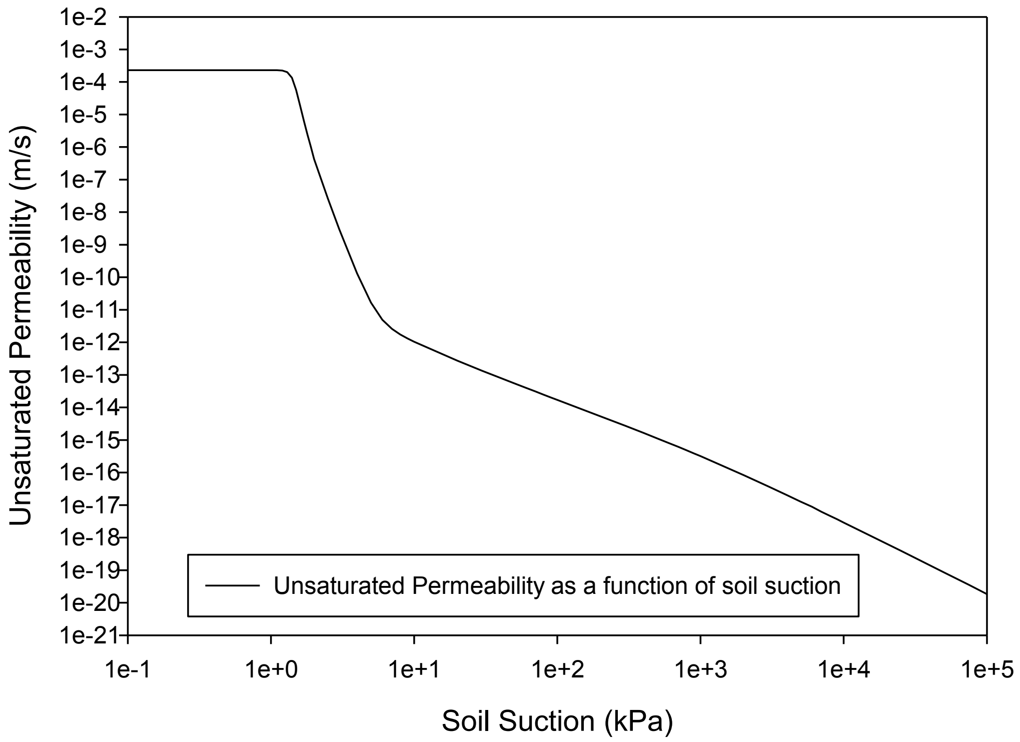

Fig. A2. Unsaturated permeability plot at reference temperature

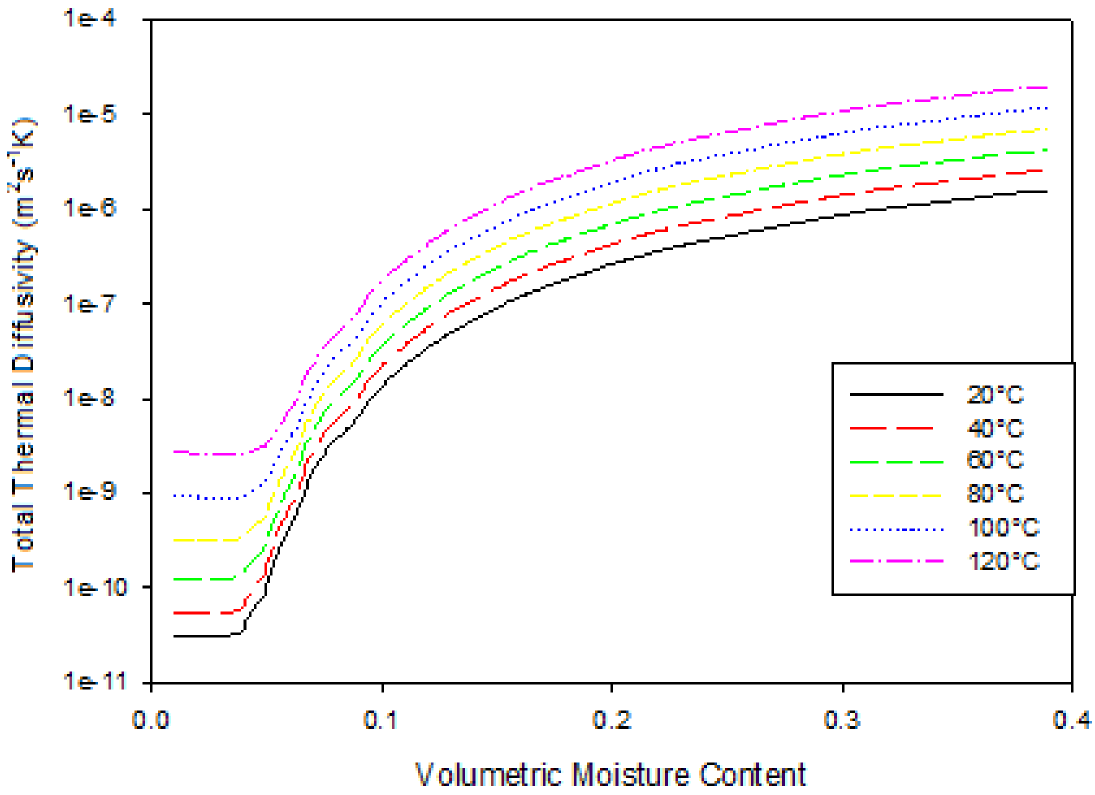

Fig. A3. Thermal Diffusivity with varying temperature and moisture content

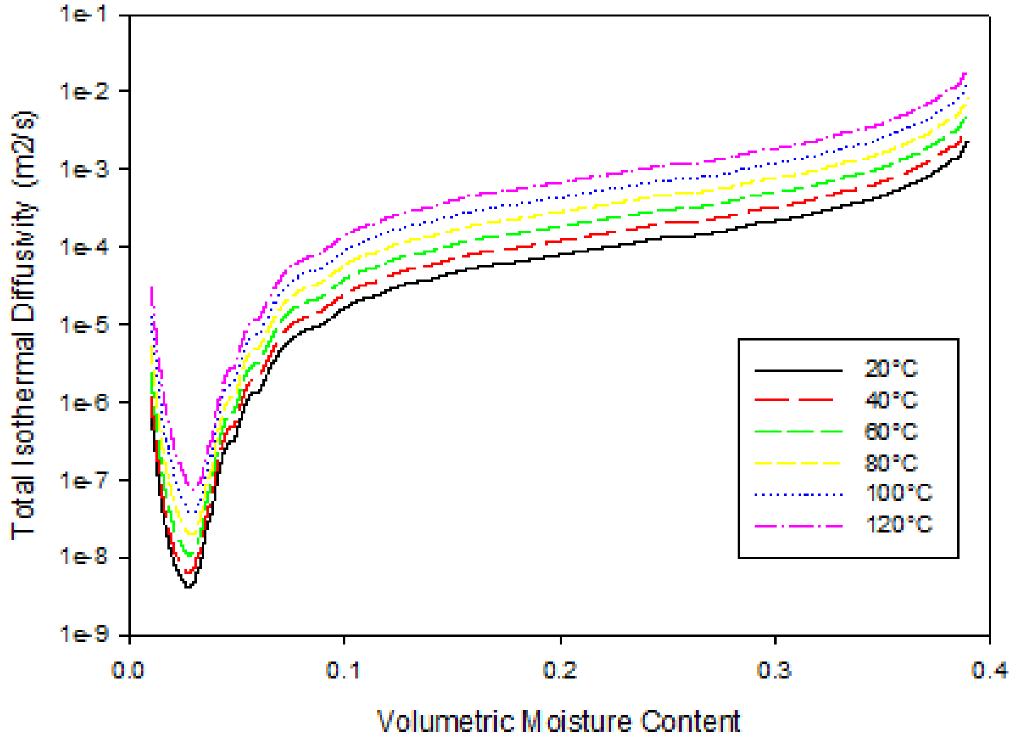

Fig. A4. Thermal Diffusivity with varying temperature and moisture content

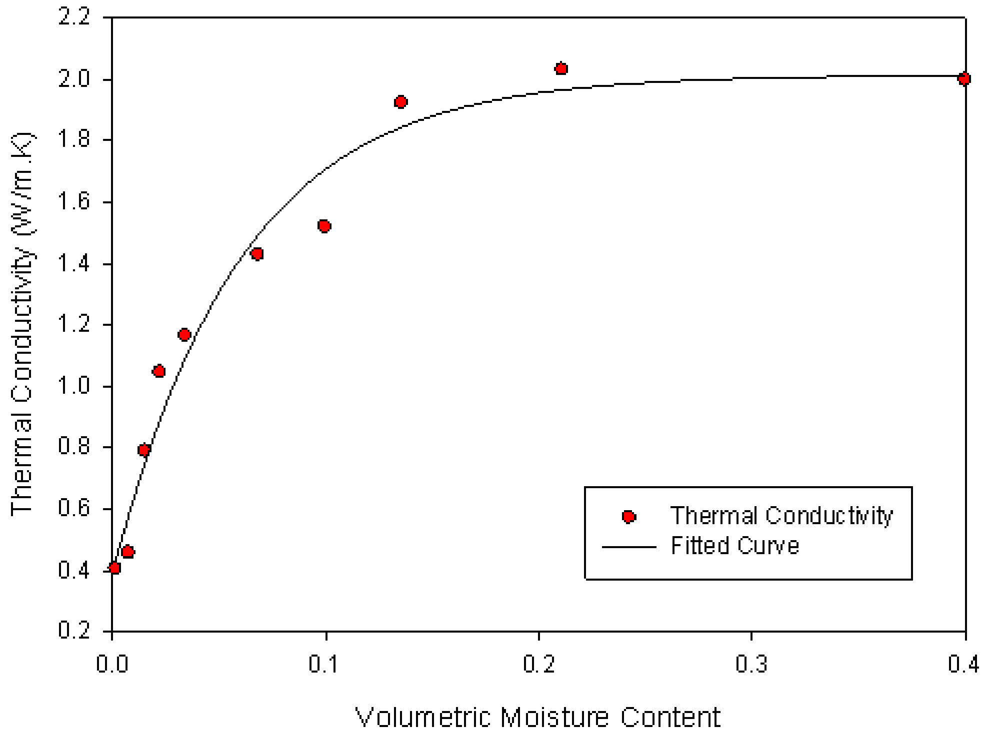

Fig. A5. Thermal Conductivity with volumetric moisture content