Impact of Emergency Operating Temperatures on the Integrity of XLPE Transmission Cable Systems

Technical Report

Impact of Emergency Operating Temperatures on the Integrity of XLPE Transmission Cable Systems

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Final Report, December 2003

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REPORT SUMMARY

This report describes a research project that was carried out to develop an understanding of the mechanical properties of XLPE transmission cables at high temperatures. This will provide some of the basic information necessary to recommend maximum emergency operating temperatures for such cables. The report includes a survey of cables in use, some work aimed at understanding the properties of XLPE under service conditions, and several validation tests in which cable segments were tested under mechanical and thermal stresses.

Results & Findings

The project determined that the XLPE component of an XLPE transmission system can be operated at up to 130°C conductor temperature without suffering mechanical degradation. A hysteresis effect was found when XLPE is cycled repeatedly through its softening temperature, and this should be investigated further. The properties of jackets, duct and accessories must be considered before recommending increased emergency operating temperatures in XLPE transmission cables.

Challenges & Objectives

The objective is to learn as much as possible about temperature limits of the key link in the cable system, the insulation, with a view to making it possible to operate cables beyond their ratings for emergency periods. It must be understood that a full answer will depend on additional factors such as the details of the duct, the terminations and splices.

Applications, Values & Use

EPRI's ultimate goal is to provide utilities with information so that a prudent decision can be made about emergency operation of cables at current levels above their ratings. Recent years have seen increased demands on a system that is not growing as fast as loads so more cases are arising in which utilities have a need to deliver more power over existing facilities. Often this need is strongest for only a limited peak time and so corresponds to the aim of this study.

EPRI Perspective

Recent years have seen a notable effort on the part of EPRI to stretch ratings on the basis of a fuller understanding of temperature effects on materials and systems. In particular EPRI has found cases where a significant increase can be made in ratings which assume that one or more limiting conditions have occurred, which may well not be the case. This study is an important step in gaining confidence that XLPE cables can be used above their ratings for short times. This is not the final step, however, because the current rating depends not only on the cable, but on the entire system which includes the jacket, the duct, the splices and the terminations.

Approach

A user survey was conducted to identify the characteristics of transmission cables presently in service. After this, a series of lab tests were performed to characterize the high temperature behavior of XLPE and to develop an understanding of possible failure mechanisms and long-term aging effects. Four validation tests were carried out on cable samples with peak conductor temperatures of 130°C.

Keywords
XLPE,
Transmission Cable,
Emergency Operating Temperature

ABSTRACT

Emergency operating temperature limits for XLPE transmission cables are largely based on historical values mainly derived from experience with distribution cables. This report describes the results of a project to systematically analyze the characteristics of XLPE transmission cables and develop recommended limits for emergency operating temperatures for 100 and 300 hour durations at 75% and 100% daily load factor. A user survey was conducted to identify the characteristics of transmission cables presently in service. A series of tests were performed to characterize the high temperature behavior of XLPE and to develop an understanding of possible failure mechanisms and long-term aging effects. Four validation tests were carried out on cable samples with peak conductor temperatures of 130°C. The conclusion of the work was that for the types of cables studied in this project no mechanical failure or deterioration of the cable was observed for emergency conductor temperatures up to 130°C. Cables are only one part of an operating cable system. Further work is necessary to investigate the impact of splices, terminations, jacket and duct characteristics on emergency operating limits.

ACKNOWLEDGMENTS

The successful completion of this project was largely due to the competence and hard work of Powertech staff W. Anthoine, V. Buchholz, C. Morton, L. Ogawa, and R. Pidcock.

Cable samples were provided for the project by Jim Voss of BC Hydro, Vince Curci of LADWP and Shantanu Nandi of Commonwealth Edison.

Throughout the project, the team drew heavily on the expertise and experience of project manager Walter Zenger and technical monitor Takashi Kojima. They were always available to provide immediate advice and guidance as needed, and their critical review greatly improved the quality of the final report.

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1 INTRODUCTION

There is a need to identify maximum allowable emergency operating temperatures for XLPE transmission cables. Cable manufacturers have carried out electrical tests up to 130°C conductor temperatures and have shown that XLPE cables maintain high electrical strength. There is much less information available on the ability of these cables to withstand mechanical stresses at high temperatures, and there is no industry consensus on maximum allowable emergency operating temperatures.

The objective of this project is to identify suitable conductor temperature limits for XLPE transmission cables for 100 hour and 300 hour emergency operation, based on daily load factors of 75% and 100% and taking into account mechanical factors. The emergency operating temperatures identified should be applicable to cable designs and installation configurations commonly used by EPRI member utilities.

The present AEIC CS7 specification [1] limits the emergency conductor temperature to between 105ºC and 130°C for a 72-hour duration. Considering that emergency loading is often required for the duration of repair of other circuits, 72 hours is often insufficient, especially for high voltage cables.

Important factors to be considered in determining the maximum allowable emergency operating temperature include the high coefficient of thermal expansion of XLPE and mechanical properties of XLPE that change significantly between 80°C and 110°C. At these temperatures the XLPE insulation is starting to become soft. Deformation of XLPE cables at high temperatures could be cumulative if thermal expansion is restrained excessively. Exposure of XLPE cable to these high temperatures for prolonged time could lead to insulation deformation resulting in premature failure. Optimized emergency operating temperature limits for XLPE cable systems must be established to manage the risk of premature failures.

A survey of EPRI members was carried out to characterize the cable and installation types in use by the member utilities, and the results are described in Chapter 2. A literature search was carried out to identify published information on the mechanical properties of XLPE at high temperatures. To validate that information, an oven expansion test was performed and compared with computer simulations of cable expansion up to 120°C. The results of the test and simulation are presented in Chapter 3, along with tables of mechanical properties of XLPE that were used for the subsequent work.

Chapter 4 describes the work that was done to investigate the behavior of XLPE at high temperatures, including work on inelastic deformation (creep or flow) as well as the effect of long-term aging on the material properties. This work led to the recommendation of a maximum conductor temperature limit of 130°C, which was used for validation tests to demonstrate that cables could successfully survive this temperature under operational conditions.

Chapter 5 describes the long term aging test that was performed to investigate the possibility of long term deterioration of XLPE at elevated temperature. A cable sample was aged at conductor temperatures up to 150°C for 2400 hours and then dissected.

Chapter 6 presents the results of the validation tests, in which cable samples were subjected to thermal and mechanical stress for up to 300 hours at conductor temperatures of 130°C. The cables were examined and dissected after the tests and the XLPE was found to be undamaged.

Chapter 7 of the report includes the recommendations and conclusions, along with a discussion of other factors that should be considered in setting maximum allowable emergency operating temperature limits for emergency operation of XLPE insulated transmission cables.

2
USER SURVEY

A web based survey was carried out to identify the types of cable and installation in use and to determine what guidelines are being followed by EPRI members to set emergency operating temperature limits on their XLPE transmission cable installations. A survey web page was created and 17 EPRI members with XLPE transmission cable installed were asked to respond with information about the XLPE transmission cables installed in or planned for their system. Two weeks after the initial message, members who had not responded were sent individual messages requesting their information. In total, eight utilities responded, describing the emergency operating temperature guidelines and installation and construction details for 31 transmission class XLPE cables. Appendix A contains a sample of the survey questionnaire and the detailed results.

The results are summarized in Table 2-1. Of the survey returns, 50% of the cables are 69 kV, 40% are138 kV, and 10% are higher voltage. About 70% have copper conductors and 30% aluminum. For 80% of the cables, the maximum emergency temperature rating was 105°C, with the remainder evenly divided between lower temperatures (90°C) and higher temperatures (120°C-130°C). Most of the respondents use AEIC CS7 guidelines for emergency operating temperature, but some use manufacturer's guidelines or their own. All but one of the responses indicated that cable clamps are used; the remaining one used cable anchors. A few of the fields had diverse responses not amenable to statistical analysis; for instance, the maximum overload time was variously given as 10 hours/month, 72 hours/year, indefinite, 100/300, and 'depends on backfill material'.

The mechanical behavior of the cables depends on the type of sheath, so the survey results have been further broken down by sheath type in Tables 2-2 through 2-4. The overall results are shown graphically in Figures 2-1 and 2-2.

The survey results were used to help ensure that the validation tests were relevant to the cables in use at EPRI member utilities. In addition, the survey results made it clear that there is no clear consensus or standard practice for emergency temperature limits, either in terms of maximum allowable emergency temperature or allowable duration. This confirms that this work, along with future extensions of the research, can provide much needed information to allow the development of standard practices for emergency temperature operation of XLPE transmission cables.

Table 2-1
Overall Utility Survey Results

Rated kV	69 kV (16)	138 kV (11)	>138 kV (3)	
Conductor Materials	Copper (22)	Aluminum (8)		
Conductor sizes	350-1000 kcm (13)	1001-2000 kcm (11)	>2000 kcm (5)	
Conductor constructions	Concentric compact round (16)	Compact segmental (13)	Concentric regular strand (2)	
Sheath/laminated metal foil	Corrugated aluminum (6)	Lead (10)	Metal foil (13)	Other (2)
Phase configuration	Single phases (29)	Three phase (2)		
Max allowable emergency temp	90°C (3)	105°C (24)	120°C (2)	130°C (1)
Guidelines for max allowable emergency temp	AEIC CS7 (19)	Manufacturer's (7)	Internal (4)	
Installation types	Direct buried (2)	In plastic duct (23)	Other (6)	
Minimum bending radius:diameter ratio - pulling	14-16 (15)	19-22 (6)	25 (3)	32 (1)
Minimum bending radius:diameter ratio - trained	11-13 (5)	14-16 (17)	20 (2)	28 (1)

Table 2-2
Survey Results for Corrugated Aluminum Sheathed Cables

Rated kV	69 kV (5)	161 kV (1)	
Conductor materials	Copper (6)		
Conductor sizes	500 (1)	1000 (1)	1750-2000 (4)
Conductor constructions	Compact segmental (5)	Concentric compact round (1)	
Phase configuration	Single phases (5)	Three phase (1)	
Max allowable emergency temp	105°C (4)	130°C (1)	
Guidelines for max allowable emergency temp	AEIC CS7 (2)	Manufacturer's (2)	Internal (1)
Installation types	In plastic duct (4)	Other (2)	
Minimum bending radius:diameter ratio - pulling	14 (2)	16-20 (3)	22 (1)
Minimum bending radius:diameter ratio - trained	13-15 (4)	20 (1)	28 (1)

Table 2-3
Survey Results for Lead Sheathed Cables

Rated kV	69 kV (2)	138 kV (5)	230 kV (2)
Conductor materials	Copper (8)	Aluminum (1)	
Conductor sizes	<=1000 (3)	1500 (3)	1750-2500 (3)
Conductor constructions	Compact segmental (6)	Concentric compact round (3)	Concentric regular strand (1)
Phase configuration	Single phases (9)	Three phase (1)	
Max allowable emergency temp	105°C (6)		
Guidelines for max allowable emergency temp	AEIC CS7 (3)	Manufacturer's (4)	Internal (3)
Installation types	In plastic duct (5)	Other (4)	
Minimum bending radius:diameter ratio - pulling	20 (2)	25 (3)	>25 (1)
Minimum bending radius:diameter ratio - trained	<13 (4)	15 (1)	20 (1)

Table 2-4
Survey Results for Foil Covered Cables

Rated kV	69 kV (8)	138 kV (5)	
Conductor materials	Copper (6)	Aluminum (7)	
Conductor sizes	350-800 (7)	1000-1500 (3)	>1500 (2)
Conductor constructions	Compact segmental (1)	Concentric compact round (12)	
Phase configuration	Single phases (13)		
Max allowable emergency temp	105°C (13)		
Guidelines for max allowable emergency temp	AEIC CS7 (13)		
Installation types	In plastic duct (12)	Direct buried (1)	
Minimum bending radius:diameter ratio - pulling	15 (12)	22 (1)	
Minimum bending radius:diameter ratio - trained	14 (1)	15 (12)	

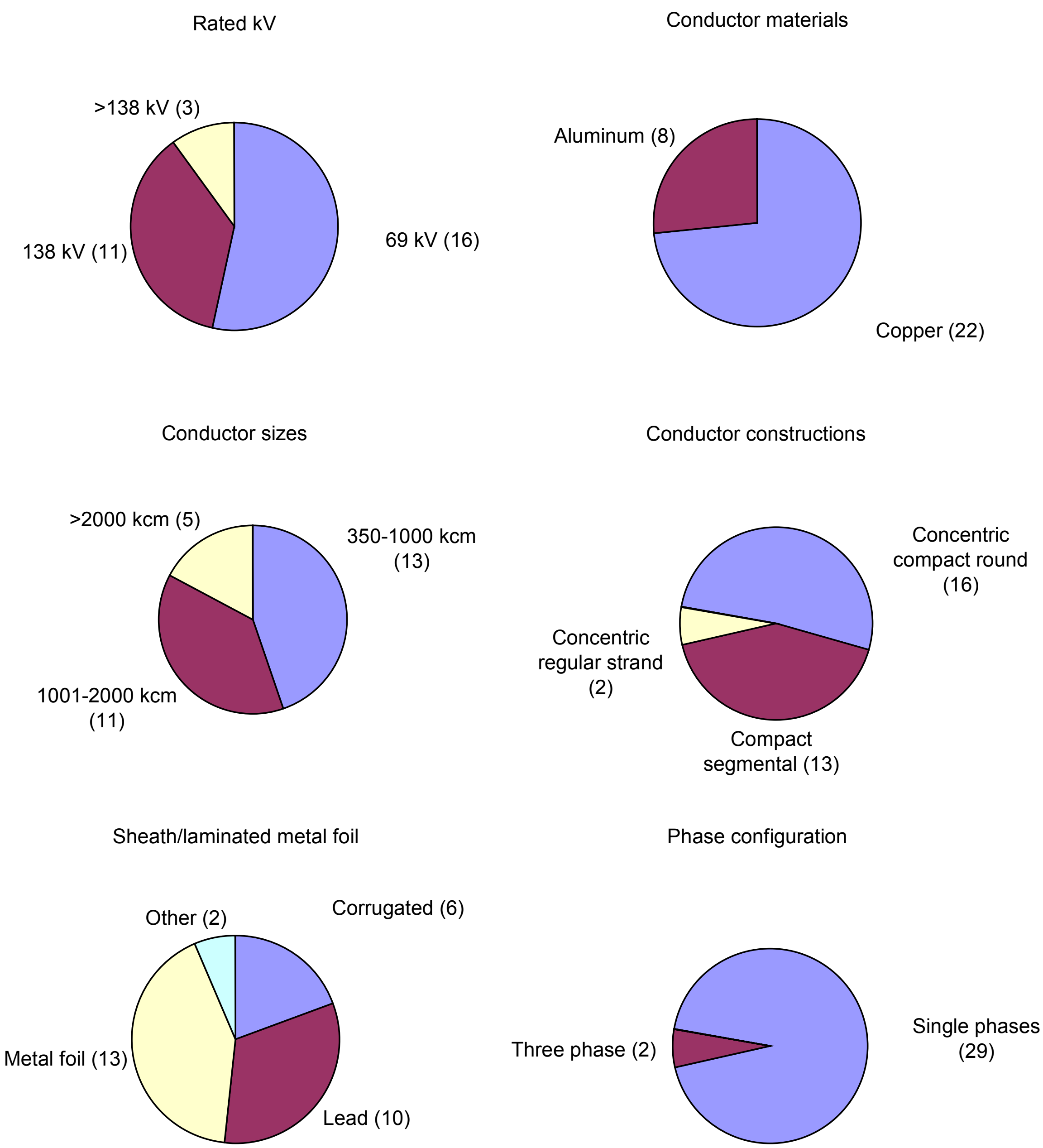


Figure 2-1
Pie Charts Showing Survey Results Breakdown

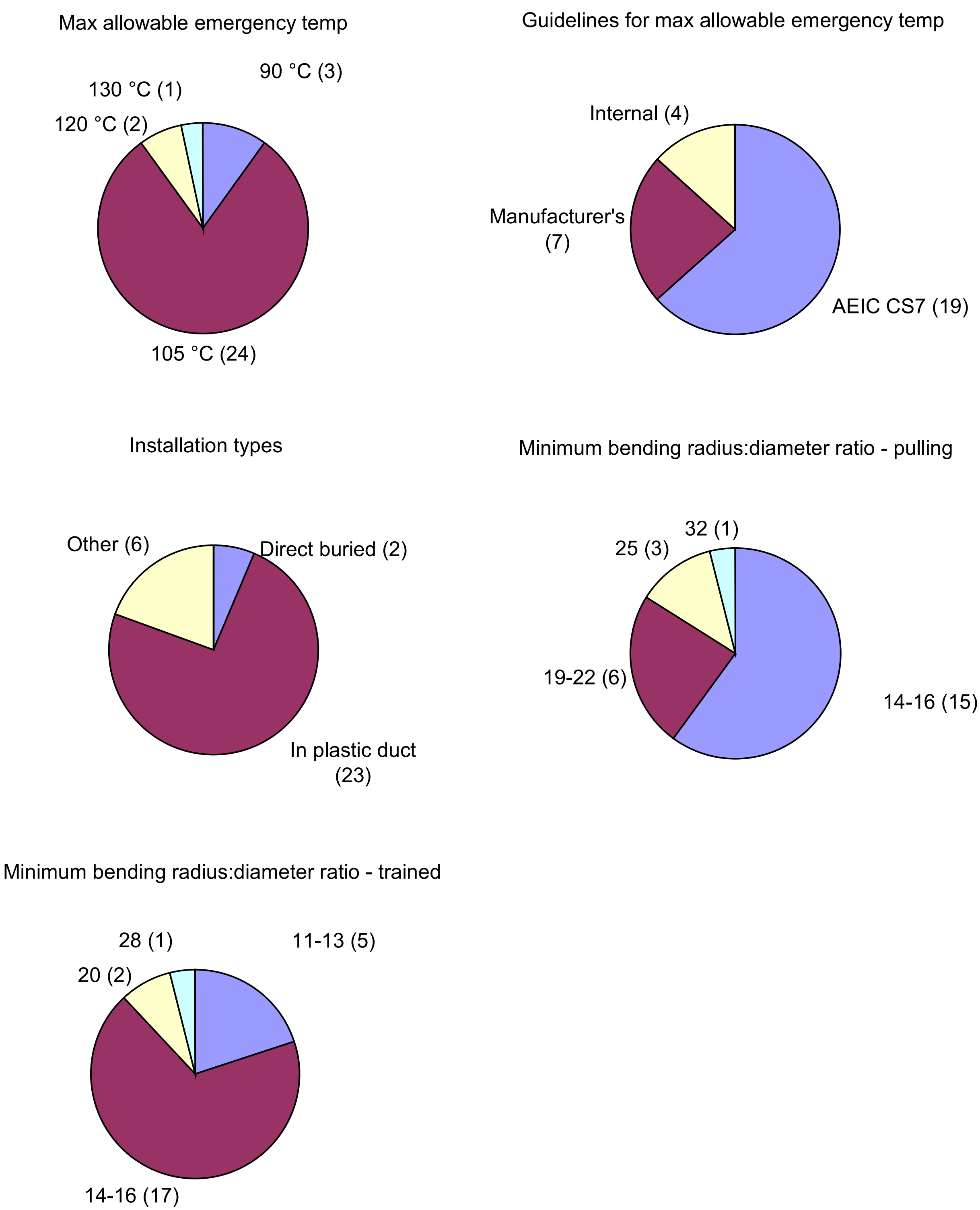


Figure 2-2
Pie Charts Showing Additional Survey Results

3 MECHANICAL PROPERTIES OF XLPE

Literature Search

A literature search was carried out to identify published work describing research into high temperature limits for XLPE cables and the high temperature properties of XLPE. A dozen or so publications were examined, and their references investigated [2-8]. It appears that the only original research available on high temperature XLPE properties is an EPRI report carried out by IREQ in 1978, *Research to Determine the Acceptable Emergency Operating Temperatures for Extruded Dielectric Cables,* [2] (EPRI EL-938). Several subsequent papers had references to, or data extracted from, the EL-938 report. Another useful source of information on high temperature cable behavior was a pair of CEA reports, *Maximum Temperature Operation of XLPE Distribution Cable systems,* [3] and *Elevated Temperature Operation of Distribution Cable Systems,* [4]. Tokyo Electric Power Company and Mitsubishi Cable Industries, Ltd. both of Japan carried out a series of tests to investigate impacts of conductor temperature variations between room temperature and 105°C on XLPE cables at cable clamps and bends. The test was based on the present practice of allowing 105°C conductor temperature for a duration of 10 hours/month. The report concluded that there was no appreciable impact on the cable [8]. There are several references to high temperature testing in the minutes of the Insulated Conductor Committee (ICC), but we were unable to locate any published reports of the work beyond mention in the minutes of tests that had been done by manufacturers. A paper has been found that describes deformation and creep in XLPE cables at high temperatures [5]. This paper describes mechanical tests carried out at temperatures from 90°C to 120°C in which the degree of compression and deformation of XLPE insulation was measured as a function of loading and temperature.

In subsequent phases of this project, mechanical stress calculations were carried out, and it was necessary to establish the mechanical parameters of XLPE. These values were extracted from graphs published in EPRI EL-938, as listed in Table 3-1.

Table 3-1
Properties of XLPE Interpolated from EPRI EL-938 Graphs

T (°C)	Modulus (psi)	Modulus (kPa)	Average Coefficient of Linear Expansion (1/K)
20	2.45E+04	1.69E+05	
40	1.29E+04	8.86E+04	2.23E-04
60	6.81E+03	4.69E+04	2.48E-04
80	3.57E+03	2.46E+04	2.97E-04
100	6.71E+02	4.63E+03	3.81E-04
120	1.24E+02	8.55E+02	4.71E-04
140	1.24E+02	8.55E+02	4.34E-04

Oven Heating Test

To verify that these values shown in Table 3-1 are realistic and appropriate to our test cables, we performed a simple test in which several samples were oven heated to temperatures from 40° to 120°C, and their dimensions measured. This test was not intended as a rigorous determination of parameters, which would be outside the scope of the project, but rather as a validation check, and as such the work was done with limited accuracy using simple methods and a minimum number of samples. Two short cable segments and two blocks of XLPE cut from a cable sample were tested. The cable was 69 kV rated, 1750 kcm copper conductor cable with 13.3 mm insulation thickness, and corrugated aluminum sheath. Full details of the cable are given in Table 6-1, where it is identified as sample A.

The two cable segments were cut to about 10 cm long and both ends turned smooth on a lathe. One segment (S) had the aluminum sheath and jacket removed, and the other (F) was tested as a complete cable segment. Two XLPE block samples were cut to smooth rectangular blocks about 7 x 1 x 2 cm, with the long dimension along the axis of the cable. A sketch of the block samples is shown in Figure 3-1.

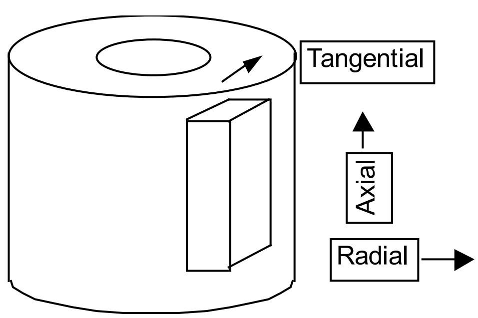


Figure 3-1
Orientation of XLPE Block Samples Cut from Cable Insulation

The lengths of the cable samples were measured at 6 locations each and the diameters over the extruded XLPE semicon insulation shielding at 3 locations with a digital caliper or micrometer at room temperature. The three dimensions of the XLPE blocks were also measured at two locations each with a digital caliper. All four samples were heated in an oven at 40°C for 2 hours, then removed from the oven one at a time and measured as quickly as possible. The oven temperature was raised to 60°C, and after two hours the measurement was repeated. This process was continued in 20°C increments to 120°C. The samples were left for 2 additional hours at 120°C, then cooled and measured in 20°C decrements down to room temperature. The measured dimensions (averaged over duplicate measurement locations) are listed in Table 3-2. The changes in measurements for the XLPE blocks are plotted in Figure 3-2. Each curve starts at zero at room temperature, and shows the expansion during heating followed by the contraction during cooling. There is significant distortion and hysteresis in the XLPE at high temperature, and at 120°C the material was observed to soften and change color. On examination of the results it was observed that the curves during cooling are much more consistent with the theoretical coefficients of linear thermal expansion than during heating. When the contraction measured during cooling was plotted beside the calculated curves, as shown in Figure 3-3, satisfactory agreement was obtained.

Table 3-2
Measurements of Sample Dimensions in mm During Heating Stage of Oven Expansion Test, Averaged Over Multiple Measurements

	T (°C)	22.5	40	60	80	100	120
Rectangular block sample	Radial	10.84	10.96	11.07	11.16	11.37	11.85
	Tangential	15.77	15.86	15.97	16.06	16.13	16.13
	Axial	74.52	74.89	74.93	74.98	75.13	73.75
Complete cable sample (F)	XLPE length	88.20	88.62	88.87	89.34	90.59	94.46
	Conductor length	88.22	88.40	88.42	88.45	88.35	88.48
	Diameter of semicon	70.88	71.03	71.43	71.95	72.51	73.09
Cable sample with jacket and sheath removed (S)	XLPE length	89.50	89.92	90.27	90.55	90.64	89.86
	Conductor length	89.45	89.57	89.58	89.59	89.64	89.66
	Diameter of semicon	73.46	73.77	73.99	74.56	75.32	76.39

Table 3-3
Measurements of Sample Dimensions in mm During Cooling Stage of Oven Expansion Test, Averaged Over Multiple Measurements

	T (°C)	120	100	80	60	40	22
Rectangular block sample	Radial	11.87	11.80	11.72	11.67	11.58	11.52
	Tangential	16.07	15.90	15.82	15.69	15.63	15.52
	Axial	73.80	72.97	72.30	71.73	71.45	71.19
Complete cable sample (F)	XLPE length	94.44	92.47	91.57	90.16	89.36	88.67
	Conductor length	88.45	88.44	88.42	88.34	88.31	88.31
	Diameter of semicon	72.89	73.30	73.21	73.07	72.89	72.90
Cable sample with jacket and sheath removed (S)	XLPE length	89.74	89.29	88.32	87.41	86.95	86.31
	Conductor length	89.68	89.63	89.52	89.53	89.45	89.46
	Diameter of semicon	76.51	76.02	75.17	74.94	74.50	74.36

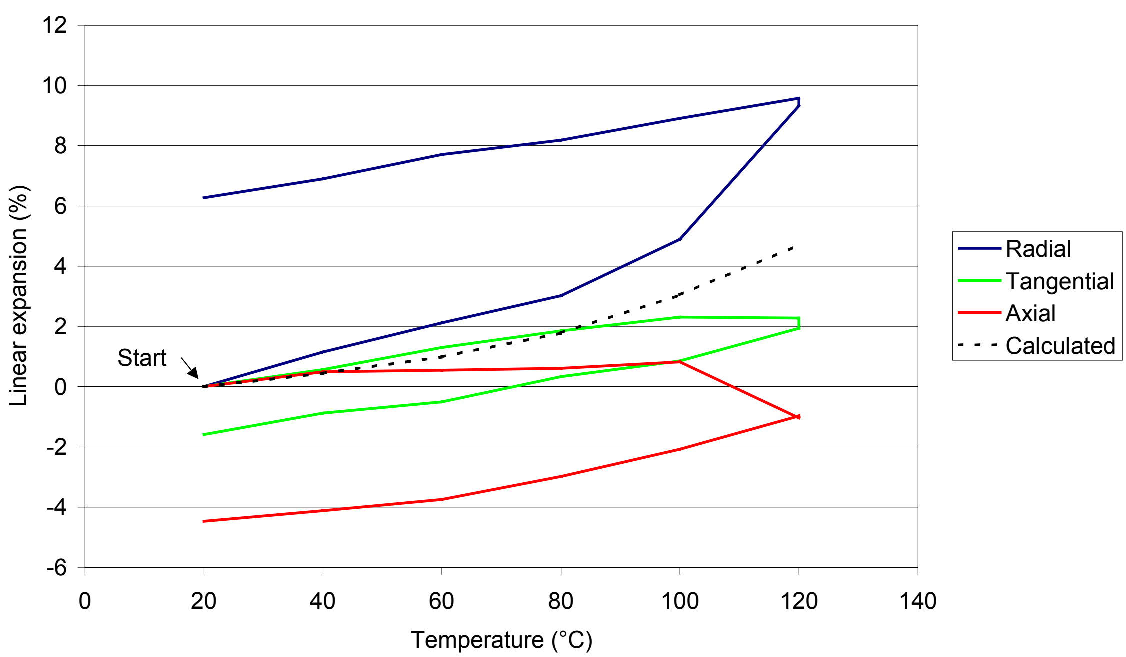


Figure 3-2
Linear Expansion of XLPE Block Samples During the Oven Heating Test

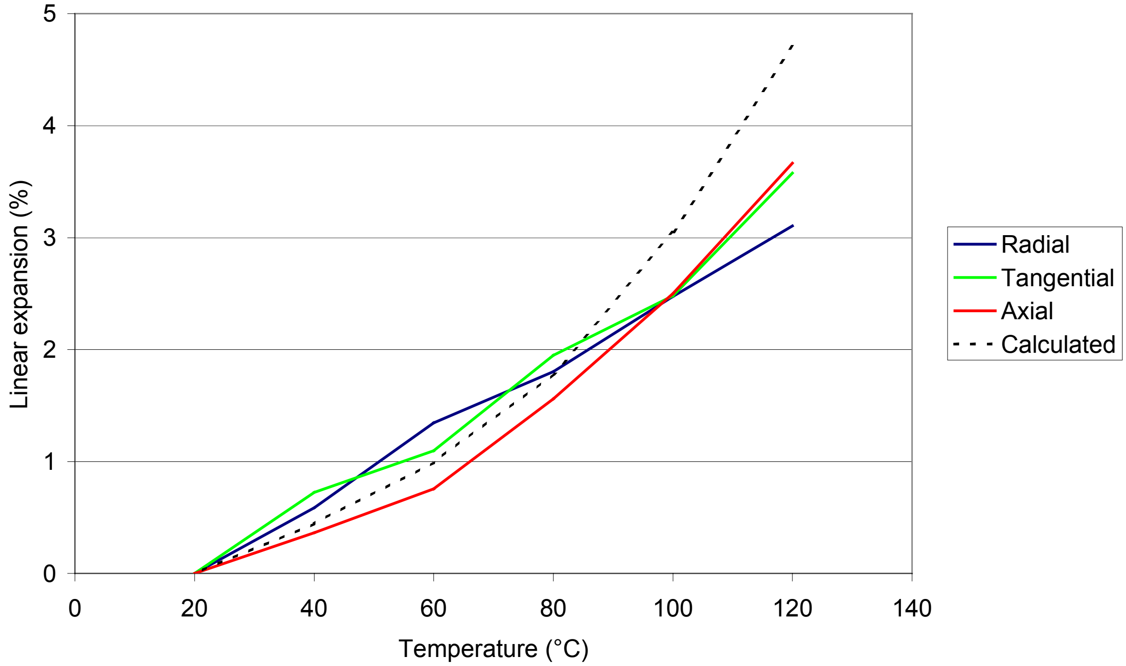


Figure 3-3
Linear Expansion of XLPE Block Samples During Cooling in the Oven Test

Finite Element Analysis

Analysis of the changes in dimension of the cable segments is more complicated, since the effect of the conductor and sheath must be taken into account. These measurements were used to check the finite element model that was later used to calculate mechanical movement and stresses in the complete cables. A finite element model was constructed using the Cosmos program to simulate each of the cable segments used in the oven test. For the complete cable segment (F), the axial expansion as constrained by a corrugated aluminum sheath was calculated. For the segment with the jacket and sheath removed (S) curve, the unconstrained axial expansion was calculated. For the diameter modeling, the unconstrained expansion in the diameter was calculated. As with the XLPE block samples, there were large differences between the heating and cooling curves, indicating hysteresis and an effect that could be called ‘slumping’, in which the hot polyethylene flows under the effect of gravitational force and expansion, and then hardens in the new shape. These effects are evident in Figure 3-4. These curves illustrate the complicated behavior of this material during heating and cooling. The diameter of the complete cable, constrained by the aluminum sheath, showed a large hysteresis, while the relatively unconstrained length showed less hysteresis. The cable with the jacket and sheath removed behaved very differently, as gravity caused the material to slump, reducing the expansion in length, and a large hysteresis occurred in the length, while the hysteresis in diameter was much less. As before, the linear expansion during cooling (except for the diameter of the complete cable, where the heating curve was used) was more consistent and produced the best match with the finite element model calculations, as shown in Figure 3-5.

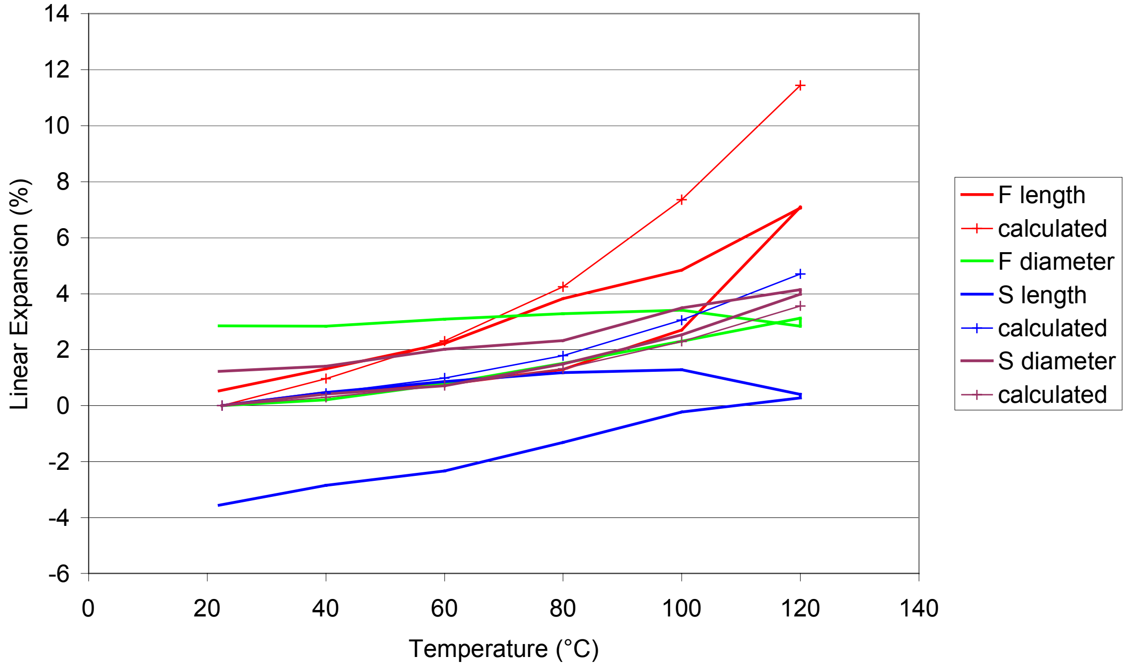


Figure 3-4
Linear Thermal Expansion of Cable Samples. Curves Labeled F Relate to the Complete Cable and Curves Labeled S Relate to the Cable with Jacket and Sheath Removed

When the calculated and measured curves are plotted together in Figure 3-5, there are obvious discrepancies. The core diameter of the complete sample (from heating), and the length and diameter (from cooling) match the finite element curves reasonably well, but the measured length of the sample with jacket and sheath removed does not fit the model curve. If the actual heating and cooling curves are considered, the discrepancies are even worse. These discrepancies illustrate one of the major lessons of this project, that the tools of conventional finite element analysis are insufficient to model the observed hysteresis effects in XLPE insulation. The finite element program did not have any tools capable of modeling the irreversible temperature and force dependent distortions that were observed, nor do we have the theoretical understanding to model these forces even if we had the tools. Attempts to duplicate this behavior in a computer model were unsuccessful, and it must be left to a future research project to study and develop an understanding of hysteresis effects in XLPE. While one of the goals of this project was to develop tools for modeling the behavior of cables at high temperatures and mechanical stress, this information appeared to move that goal out of reach. Before the modeling tools can be developed, some fundamental research is required on the irreversible distortion, or hysteresis that occurs in XLPE after cycling to high temperatures.

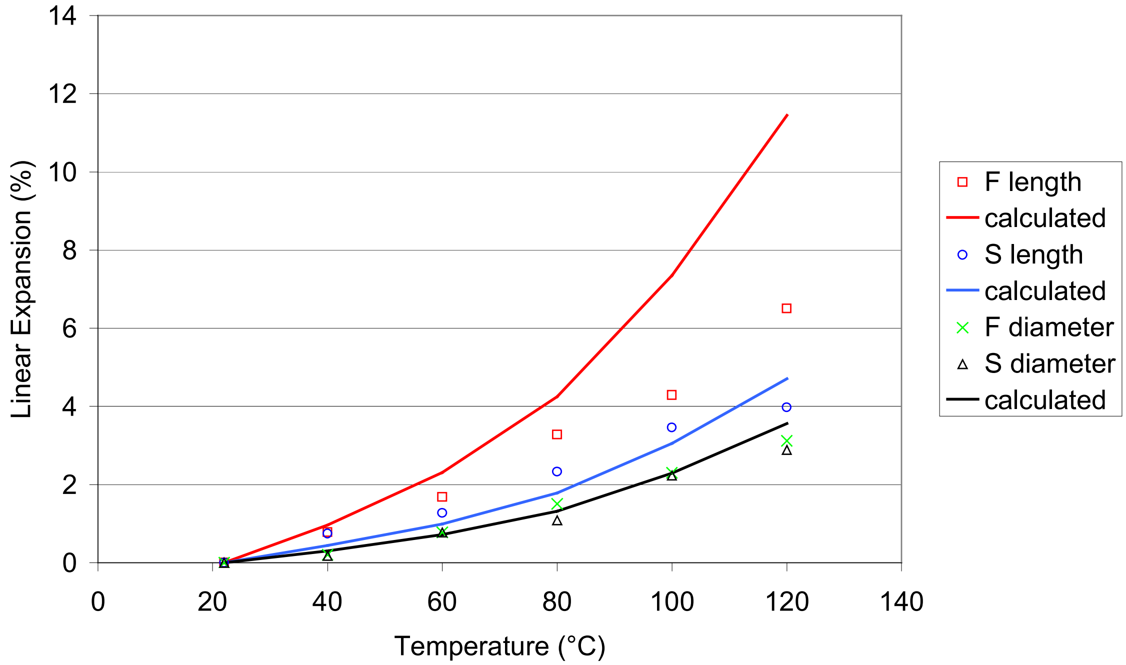


Figure 3-5
Cable Sample Linear Expansion During Cooling from the Oven Expansion Test. Curves Labeled F Relate to the Complete Cable and Curves Labeled S Relate to the Cable with Jacket and Sheath Removed

Figure 3-6 shows a color contour map of the internal stresses in the constrained finite element model, with the bottom end fixed and the upper end allowed to expand. This illustrates the finite element techniques that were used to calculate the expansion of the cable segments as a function of temperature.

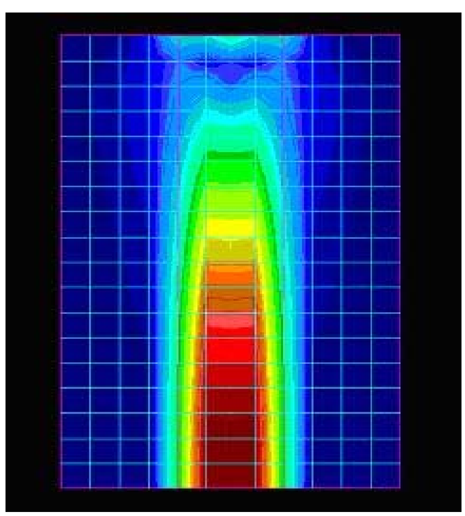


Figure 3-6
Color Contour Plot of the Stresses in the Constrained Finite Element Model

4
BEHAVIOUR OF XLPE AT HIGH TEMPERATURES

Since very limited information is available on the mechanical behavior of XLPE insulation at temperatures above 100°C, some tests were performed to investigate how XLPE changes under stress at temperatures up to 200°C. XLPE insulation could be mechanically compromised through one of three possible mechanisms. *Elastic deformation* occurs when the material is deformed reversibly by stress, returning to its original shape when the stress is removed. As observed in the previous chapter, the elastic modulus of XLPE drops steeply at temperatures around 110°C, leading to a substantial increase in elastic deformation. When elastic limits of stress or temperature are exceeded, *inelastic deformation* will occur, typically as a function of stress, temperature and time. Some evidence for this type of behavior was seen in the oven heating tests as the material slumped during heating. Finally, *mechanical property changes* may occur after the insulation is heated to elevated temperatures for sufficient time. This could create problems if the material becomes brittle or soft after long term heating.

Elastic Deformation

Elastic deformation was studied through finite element analysis. The results showed that in all cases studied, the stress inside the XLPE insulation of transmission cables is quite symmetrical. As the temperature increases, the unconstrained expansion of XLPE is about 10 times greater than that of copper or aluminum. The result of heating a coaxial cable with a metallic sheath or neutral wires is that pressure develops in the XLPE as a result of the differential expansion. Since the XLPE is much more elastic than the metal, becoming even softer at high temperatures, the result is that the insulation expands to press tightly against the surrounding metal and is then held in position by the generated pressure, which is low relative to the strength of the metal components. The XLPE behaves rather like a fluid, deforming to accommodate any minor movement of the conductor or sheath.

Inelastic Deformation

While elastic deformation is amenable to numerical modeling, inelastic deformation is a much more difficult phenomenon to model. Under a combination of sufficient temperature and stress, many materials deform permanently, sometimes undergoing structural or chemical changes in the process, so that the history of a body influences its future behavior. Many metals and plastics behave this way. PVC and non-crosslinked polyethylene are thermoplastic materials, which when heated can readily be deformed under relatively low pressure. XLPE, in which the polymers are locked in place more rigidly by the cross linking of the polymer chains, has a structure more resistant to inelastic deformation than either crystalline metals or non crosslinked plastics. The XLPE may still deform or fail, but only when subjected to a sufficiently high combination of temperature, stress, and time. In order to study this possibility, a series of tests were performed using XLPE samples cut from a 69 kV cable (Sample A in Table 6-1), as shown in Figure 4-1. The jacket, sheath and conductor were removed from a length of cable, and the XLPE was cut into three inch long samples. The inside was bored out slightly to a 1.5 inch diameter to make a sliding fit on the tubular steel core, which was electrically heated while an asymmetrical transverse load was applied to the samples by means of hanging weights. The samples were subjected to steadily increasing temperatures up to 200°C and stresses up to 313 kPa. The stress (pressure underneath the top part of the support strap) was calculated using the formula $S = \frac{Mg}{2Rw}$, where Mg is the applied weight, R is the outer radius, and w is the width of the support strap. Preliminary tests showed elastic deformation as expected, but no long term creep or plastic failure. After the first hour or two, no further deformation occurred, even at temperatures up to 200°C with the stress maintained continuously for several days. The preliminary tests did reveal hysteresis that occurred when the temperature was cycled, so additional tests were performed to investigate this phenomenon.

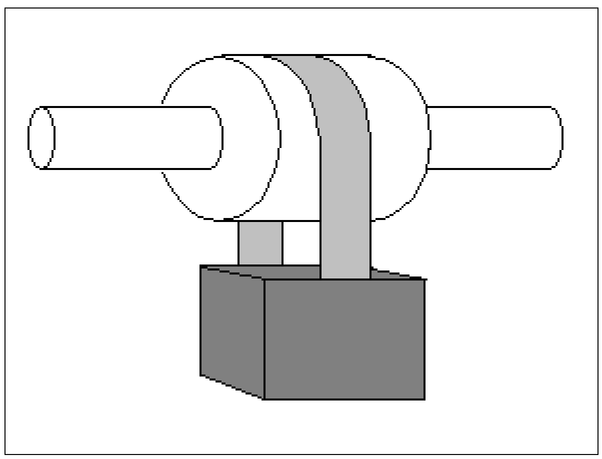


Figure 4-1
Diagram of Loaded Temperature Cycling Tests

In the second round of tests, two samples were tested, one loaded at 162 kPa (23 psi) and the other at 313 kPa (45 psi). These stresses were selected based on the maximum load that could be applied using the test stand, and were well above the expected stresses in an installed cable. The samples were mounted on a conductor that could be heated to 195°C. The outside was wrapped in thermal insulation to obtain a maximum temperature difference across the XLPE of about 25°C. The samples were subjected to four cycles, each comprising 8 hours of heating and 16 hours of cooling, to investigate inelastic distortion and hysteresis. The measured temperatures and the movement of the top surface of the samples are shown in Figure 4-2. A photograph of the test setup (with the insulation removed) is shown in Figure 4-4.

At room temperature loads of this magnitude will cause a compression of less than 0.5% in the thickness. During the first heating interval, two opposing forces are at work. The XLPE has a large coefficient of thermal expansion and will therefore tend to expand, but the elastic modulus drops with heating, and so the softer material is compressed by the load. During the first heating interval, the deformation depends mainly on the stress. When the material is unloaded, it expands substantially, consistent with the high thermal expansion coefficient, which was predicted at a free expansion of 5% to 10%. When a moderate compression stress is applied (162 kPa), the amount of increased compression is roughly equal to the thermal expansion, so there is very little change in thickness (red curve in Figure 4-2). When a higher compression stress is applied (313 kPa), the increased compression is greater than the thermal expansion, and there is a substantial net compression of the material as it is heated (blue curve in Figure 4-2). During the subsequent cooling interval, in which the stress was maintained constant, both samples contracted by the expected 5 to 10% as they cooled under load. In the next heating, both samples showed a relatively small compression followed by thermal expansion. In subsequent heating and cooling cycles, there was no more hysteresis, and samples showed a fairly consistent behavior of expansion during heating and contraction during cooling, with a magnitude in the 5 to 15% range. At the end of the process the samples were allowed to cool and the weights were removed. The measured insulation thickness had decreased by 10% at low stress and 25% at high stress under the support straps, as shown in Figure 4-3.

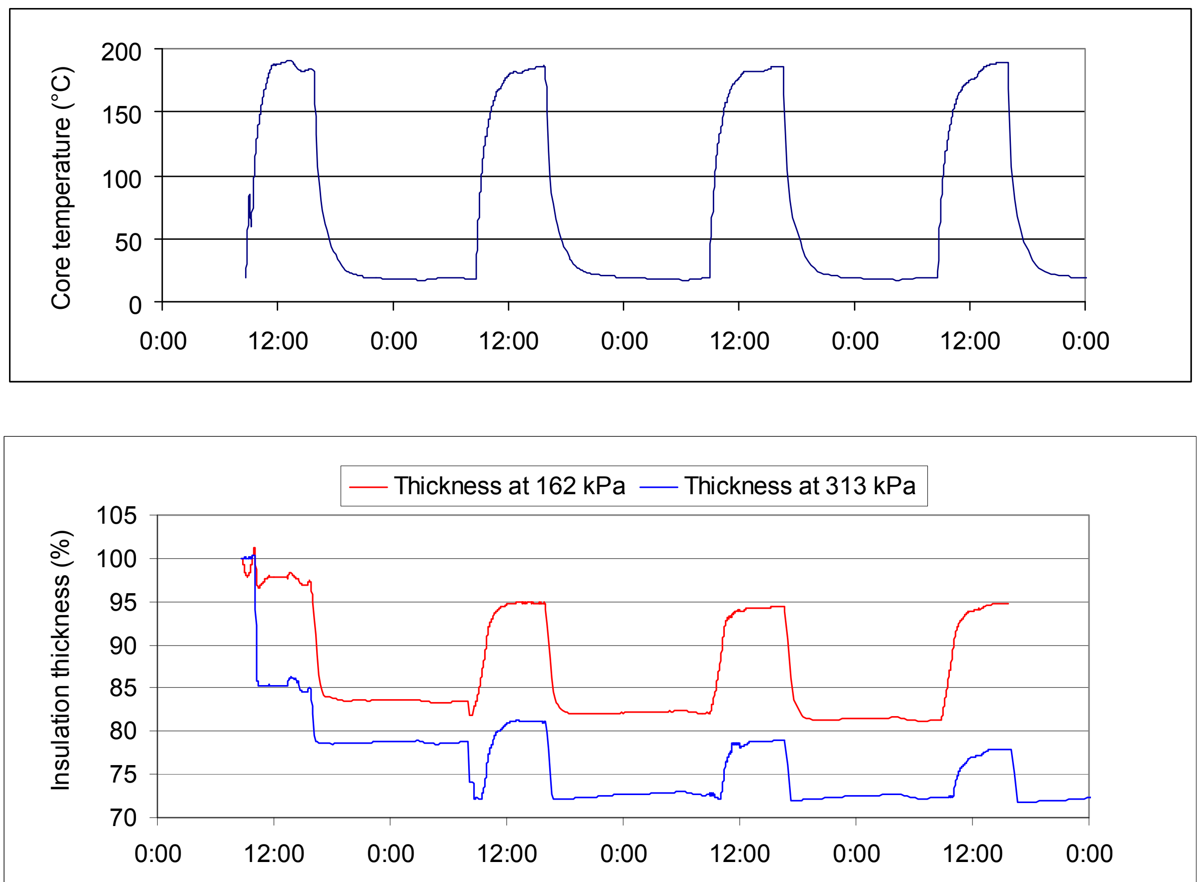


Figure 4-2
Variation of Thickness During Loaded Temperature Cycling

Figure 4-3
Photos of Samples After Testing, Showing Permanent Deformation
(313 kPa Sample on the Left, 162 kPa Sample on the Right)

Figure 4-4
The Test Setup for Loaded Temperature Cycling

The dimensional changes in these samples were not simple compression, but rather three-dimensional deformation; the samples were unconstrained, so that material flowed out of the high stress region towards the ends of the samples or around the support rod. It appears that during the initial heating under stress the material deformed, and that continued heating locked the material into the new shape. This phenomenon is interesting, and warrants further investigation, but it falls outside the scope of the current project and must be left as a topic for future study. In subsequent testing it was observed that the thermal properties of complete cables change as a result of temperature cycling in a manner consistent with irreversible deformation. Those observations are discussed further in the following chapters.

Mechanical Property Changes

The loaded temperature cycling tests demonstrated that the physical properties of XLPE can change with time at high temperature. After several days of heating to almost 200°C the samples showed discoloration as shown in Figure 4-5, and some hardening. This suggested the possibility of a failure mechanism in which the insulation becomes brittle as a result of heating over long periods. The brittle insulation might then be subject to failure when stressed by cable movement or expansion and contraction. It should be noted that the conditions were unusual, since these samples were exposed to the air during the heating, while in normal operation air is excluded from the interior of the cable.

Table 4-1
Compression Modulus of XLPE After Aging

Oven aging		Compression Modulus (MPa) at		
Hours	**Temperature**	**20°C**	**100°C**	**120°C**
0		146.0	9.3	0.9
100	105	152.6		
300	105	134.2		
100	125	113.0		
200	125	111.1		
300	125	110.3	10.5	0.8
100	150	114.4		
200	150	122.7		
300	150	113.8	11.3	0.7
2400	150	135.3		
2400 (duplicate)	150	119.0	9.1	1.8

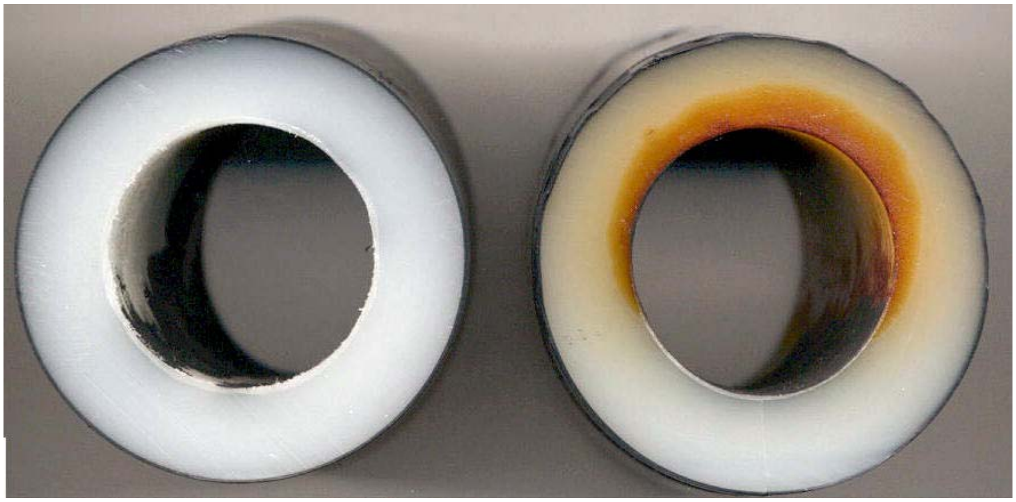
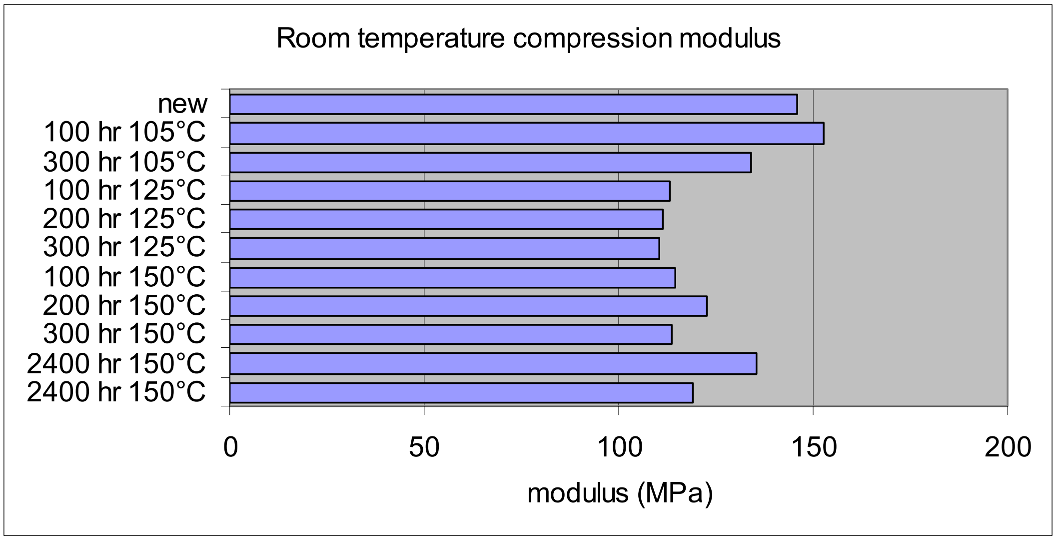


Figure 4-5
Insulation Color Before and After Loaded Temperature Cycling Test

To investigate this possibility, a series of oven heating tests was carried out at different combinations of temperature and duration up to 150°C and 300 hours, and a long term aging test was carried out for 2400 hours (see next chapter). Cylindrical shell samples were baked in an oven for times ranging from 100 to 300 hours, and then the compression modulus of each sample at room temperature was measured to determine whether the elasticity had changed. Additional modulus measurements were made on some of the samples at 100 and 120°C to look for changes to the elasticity at higher temperature. The results of the testing are listed in Table 4-1 and shown graphically in Figure 4-6. Aging caused minor changes in the modulus at a given temperature, including a slight decrease in room temperature modulus on initial aging and a slight increase in the high temperature modulus after 2400 hours of aging, but the changes were not large enough to suggest any threat to the insulation integrity. From these tests we concluded that the mechanical properties of the XLPE do not deteriorate significantly at temperatures and durations of interest for this project.



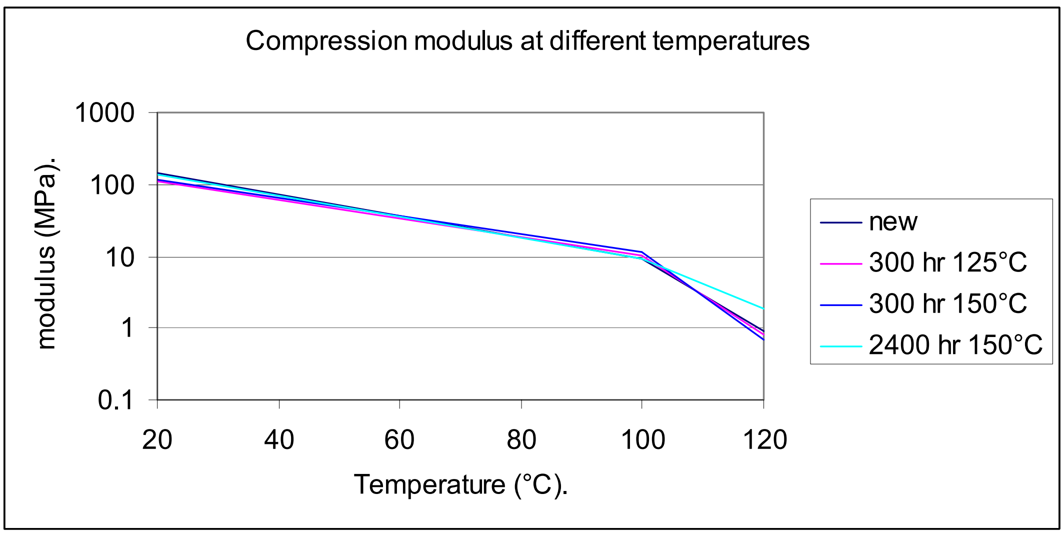


Figure 4-6
Compression Modulus of XLPE After Aging for the Time and Temperature Shown on Y axis

5
LONG TERM AGING TEST

To further investigate the long term aging behavior, a 2400 hour long term aging test was done on a 4 m length of cable with a peak conductor temperature of 150°C. The cable used was the same 69 kV aluminum sheathed cable as described previously, sample A in Table 6-1. During the test, the current was cycled periodically to simulate emergency service with a 75% daily load factor. Core, jacket and ambient temperature and current were measured and logged by computer at 5 minute intervals. The daily cycle consisted of 16 hours at 2300 A and 8 hours at 575 A, and after every 13 days of cycling the current was turned off for a 24 hour cooling period. A typical cycle is shown in Figure 5-1.

During the early stages of this test the observations confirmed the effects of hysteresis that were measured during the loaded temperature cycling test as shown in Figure 4-2. Figure 5-2 shows the current and temperatures measured during the first few cycles of the test.

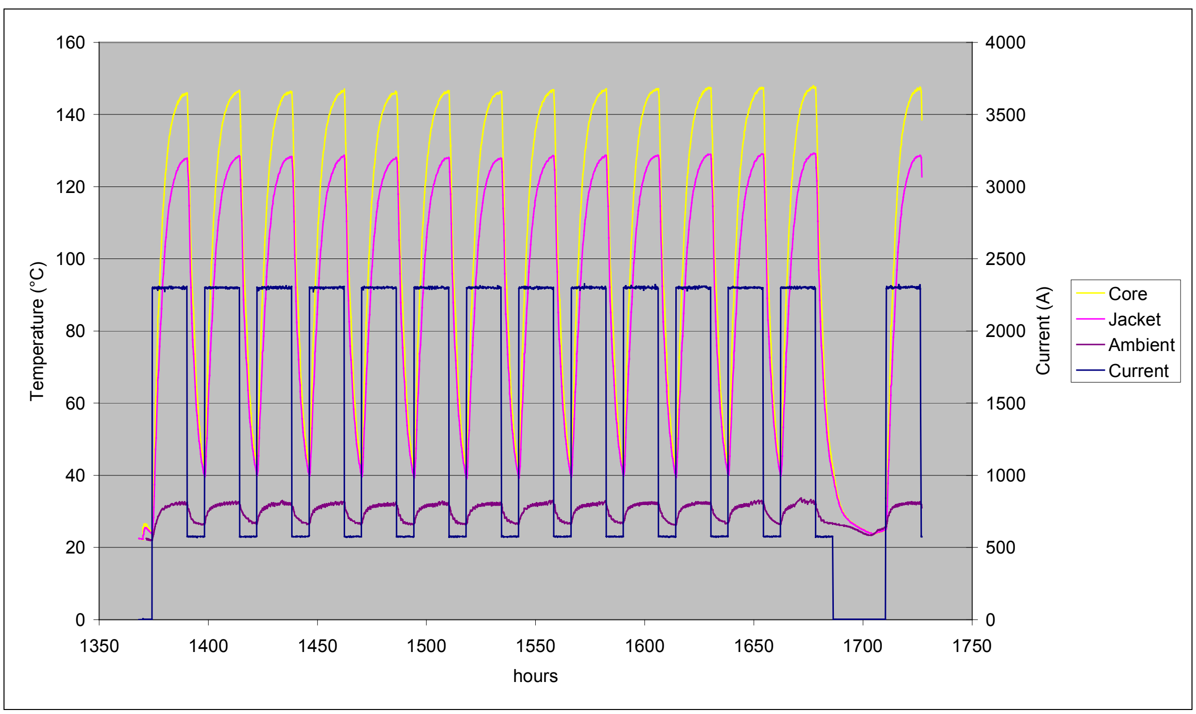


Figure 5-1
A Typical Two Week Cycle of the Long Term Aging Test

In the first cycle the current was set at 2300 A, but the cable quickly overheated and the test was shut down automatically on over-temperature. The current was reduced to 2220 A, but over the next few cycles the peak temperature dropped steadily. After 8 cycles the current was restored to 2300 A, and the temperature approached the target of 150°C.

The best explanation for this phenomenon is that in the first few thermal cycles the XLPE insulation deforms to make better thermal contact with the sheath, and then settles permanently in that shape. The result is much improved heat transfer to the sheath and the ambient air, so that the conductor temperature drops, and the cable is subsequently able to carry higher current at a given peak temperature. This has interesting implications on ampacity rating calculations for this type of cable, and should be investigated further, since it is clear that thermally cycled cable may have rather different thermal properties than cable that has never been heated above the softening point. The change in thermal properties will likely depend on the mechanical construction of the cable, in particular the type of sheath and the details of the interface between XLPE and sheath. This is probably only a factor in cables with a corrugated aluminum sheath in which the heat transfer properties of the XLPE/sheath interface may change substantially on thermal cycling. Lead sheathed or foil covered cables would probably be affected much less, if at all.

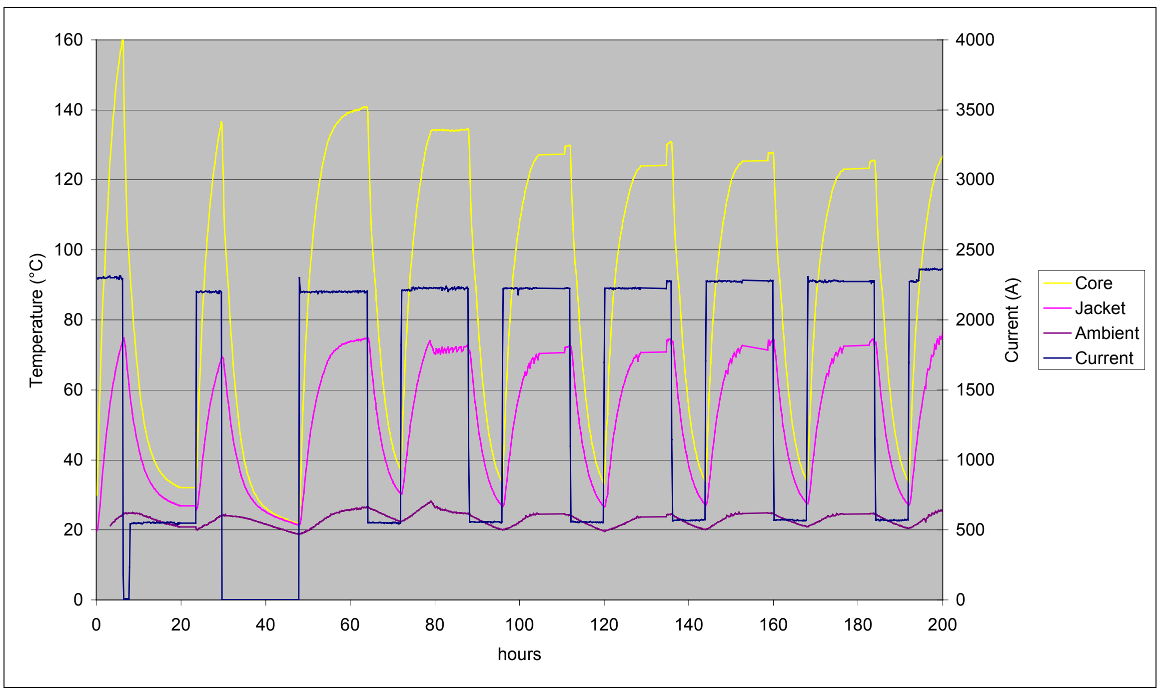


Figure 5-2
The First 200 Hours of the Long Term Aging Test

The long term aging test was actually carried out for 8 weeks, logging 2450 hours with current on plus 237 hours of cooling with current off. At the end of the test several XLPE samples were cut from the center of the cable for examination and elastic modulus testing, as described in the previous chapter. The material had darkened visibly, but did not show enough change in elastic properties to raise concerns for the insulation integrity in normal service, as shown in Figure 4-6. The progressive darkening of the material during aging is shown in Figure 5-3 below.

Figure 5-3
Progressive Darkening of Thermally Aged XLPE Samples (Left to Right): Not Aged, Oven Aged 300 Hours at 125°C, Oven Aged 330 Hours at 150°C, and Cycled for 2450 Hours at up to 150°C

6 VALIDATION TESTS

Based on the results of the initial work, a tentative determination was made that the maximum emergency temperature (based only on mechanical considerations) should not exceed 130°C. Validation tests were designed to test realistic worst-case scenarios on different cable types with a 130°C maximum conductor temperature. These validation tests were intended to provide experimental evidence of how well the cables can survive these situations.

The first test, the minimum bending radius test, involved maximum axial stress in a cable with a corrugated aluminum sheath constrained in a duct bent at the minimum allowable radius. A major unexpected failure occurred 6 days into the test when the PVC duct softened and failed under the applied stress, causing the cable to extrude through the side of the duct. The test cable and much of the test equipment were severely damaged by the failure. A decision was made to rebuild the test setup and repeat the test using aluminum duct and a fresh cable sample, thus adding a fourth validation test to the list.

The other two tests evaluated the impact of cable clamps on two cables, one with a lead sheath and the other with a copper foil laminate and concentric neutral wires. All of the tests were run with a standard current profile based on a 75% daily load factor (average current equal to 75% of peak current). For 16 hours each day the cable was run at constant current, at a magnitude designed to generate a 130°C maximum conductor temperature. For the remaining 8 hours of the day, the current was reduced to 25% of that value. This cycle was maintained for 13 days, giving 312 hours under test. The conductor and jacket temperatures were monitored with thermocouples, and there was a period of adjustment during the first few cycles in which the current was adjusted to give the correct peak temperature. As previously noted, expansion of the XLPE can cause the thermal properties of the cables to change as they age, and the long thermal time constant of the cables also complicates matters, since it requires a full 16 hours of heating to determine whether the current level is correct. At the end of each validation test, the cables were dissected to determine if any deformation or mechanical damage had occurred and if any gaps had formed in the insulation.

Minimum Bending Radius Test in PVC Duct

This test was extremely challenging to perform, involving a combination of high current heating and large time dependent axial forces on the cable. The cable sample was a 4 meter length of 69 kV cable with copper conductor and a corrugated aluminum sheath. This cable is listed as type A in Table 6-1. The cable was inserted in a PVC duct with a 2 m straight section and a 2 m bent section, bent at 1.3 m radius, or 13.5 times the cable overall diameter, as shown in Figure 6-1.

Table 6-1
Details of Validation Test Samples

Sample	A	B	D
Rated kV	69	230	138
Conductor	Copper	Copper	Copper
Strands	Compact 4 segment	Compact 5 segment	Compact 4 segment
Cross section, mm^2 (kcmil)	886 (1750)	1266 (2500)	1520 (3000)
Conductor diameter, mm (inch)	36.6 (1.44")	44.2 (1.74")	49 (1.93")
Insulation thickness, mm (mil)	13.3 (524)	27 (1063)	16.5 (650)
Degree of cross-linking (by solvent extraction method)	80 %	85 %	83 %
Diameter over insulation shield, mm (inch)	64 (2.51")	100 (3.94")	82 (3.23")
Sheath type	Corrugated Aluminum	Extruded Lead	N/A
Foil lamination type	N/A	N/A	Copper foil and shield wires
Outer jacket	Polyethylene	Polyethylene	Polyethylene
Overall diameter, mm (inch)	96 (3.78")	129 (5.08")	110 (4.33")
Mass of cable, kg/m (lb/ft)	14 (9)	34 (22)	20 (13)

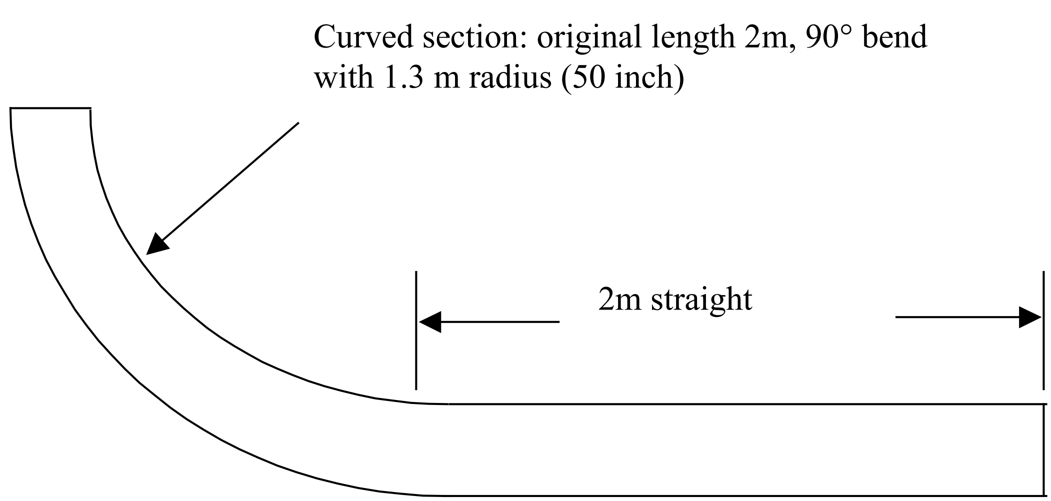


Figure 6-1
Drawing of the Duct Design for the Minimum Bending Radius Test

Figure 6-2
Photograph of the Minimum Bending Radius Test Setup

Fittings were fabricated to hold the cable ends, fixing the relative position of conductor and sheath by clamping both in the same aluminum end fitting. The upper end was fixed in place, while force was applied to the lower end (the straight section) with a motorized screw jack, similar to a bench vise. The whole structure was supported by a wooden support bolted to the floor and ceiling of the test laboratory. Figure 6-2 shows a photograph of the complete assembly.

After some discussion, it was determined that the applied force to be used in the test should be based on friction forces that would develop in a cable due to thermal expansion and contraction. The calculation was based on a 500 m length of cable with a mass of 14 kg/m sliding in a duct with a maximum coefficient of friction of 0.35, giving a total force of 24 kN (around 5400 pounds). As the cable heats, very large expansion forces are generated, and are relieved by snaking of the cable in the duct and in manholes. The maximum force that a termination could experience would be limited by the force required to slide the full length of the cable in the duct and relieve the stress. As the stress builds up, it will also be relieved to some extent by snaking of the cable within the duct, particularly as the cable softens from heating. During heating, the force would be compressive, and during cooling the cable would experience a tension force. For the test, the axial force was monitored with a load cell, and a computer was used to drive the screw jack in and out to maintain the target force. A force profile was programmed to match the heating profile based on a 24 kN maximum force.

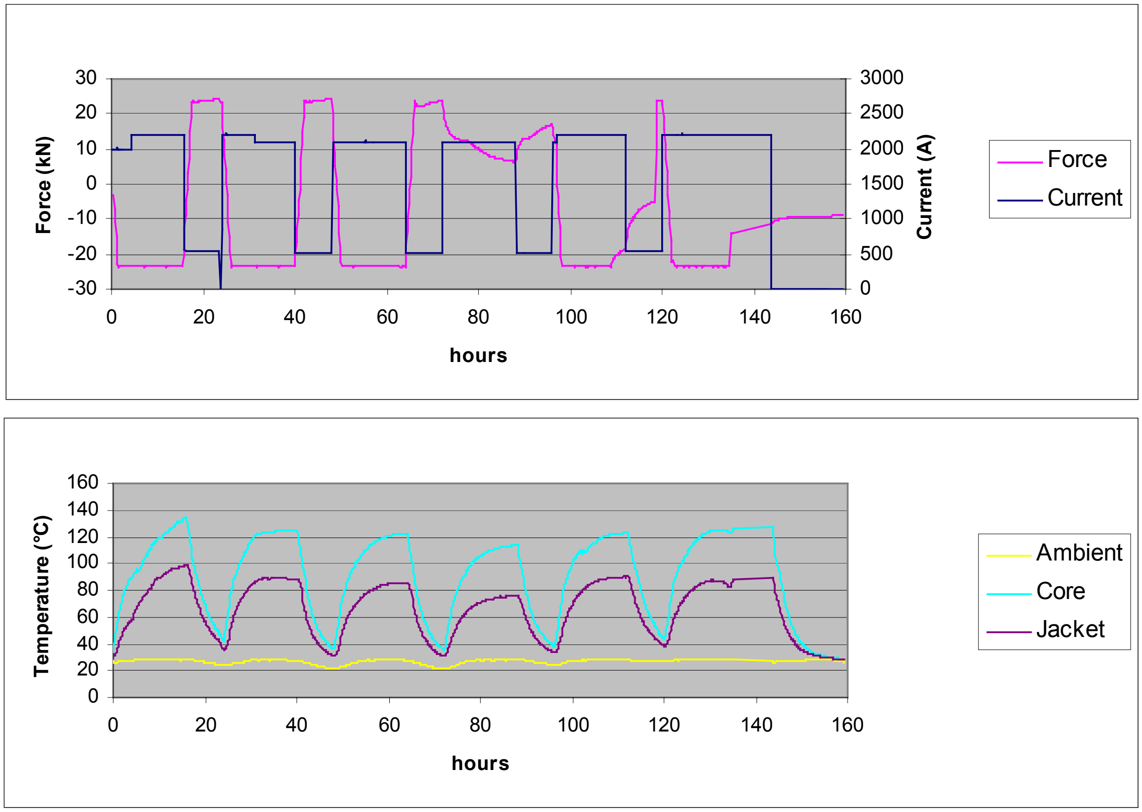


Figure 6-3
Temperature and Force Measurements from the Minimum Bending Radius Test

After the cable was installed and terminated, the duct was wrapped with a layer of fiberglass insulation to simulate burial and maintain a realistic temperature drop of about 40°C between the conductor and jacket. The test was started, and progressed satisfactorily for several days, as shown in the profile in Figure 6-3. On the fourth and fifth nights the applied forces were disturbed by limit switch operations, but adjustments were made and the test continued.

At midnight on the sixth night a catastrophic failure occurred when a section of the PVC duct softened enough to allow the cable to push through under the 24 kN force, causing damage to the test cable, support structure, and screw drive mechanism.

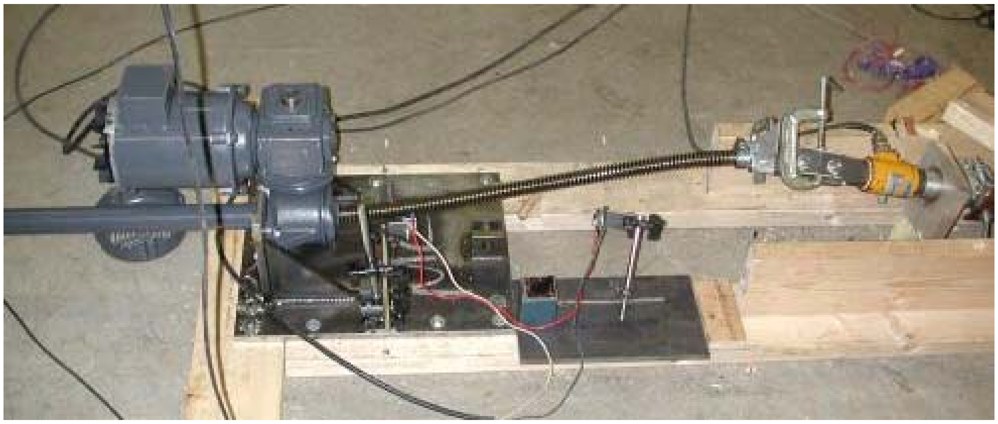


Figure 6-4
The Damaged Drive Shaft After the PVC Duct Failure

Much of the cable was undamaged, but the section that pushed through the duct was bent at an acute angle. A composite picture of the test cable is shown in Figure 6-5. The cable was cut in sections as shown in Figure 6-6 and the insulation thickness was measured at each cut to determine how much the insulation had been deformed during the test and failure. While there was significant deformation at the two sites that had pushed through the duct, the bulk of the cable was in relatively good condition and showed no change in insulation thickness. Figure 6-7 shows a photograph of the most heavily damaged section of cable after it was cut along the axis for examination. This section is heavily damaged and would be very likely to fail, but this is far more severe bending than would be experienced in service, even during a heavy overload.

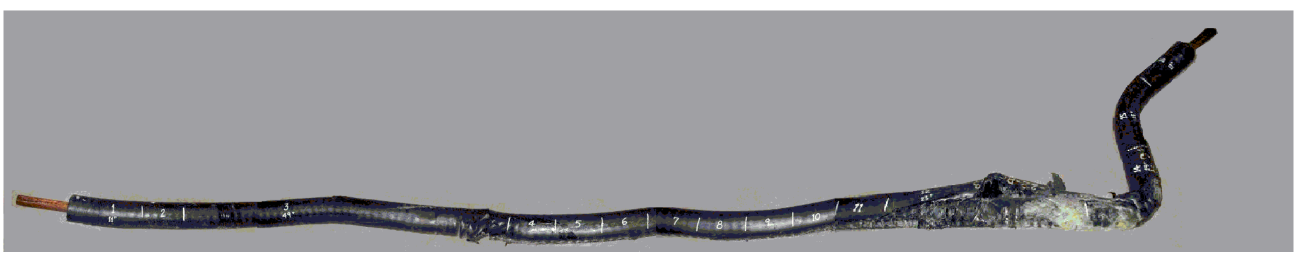


Figure 6-5
A Composite Photograph of the Damaged Cable

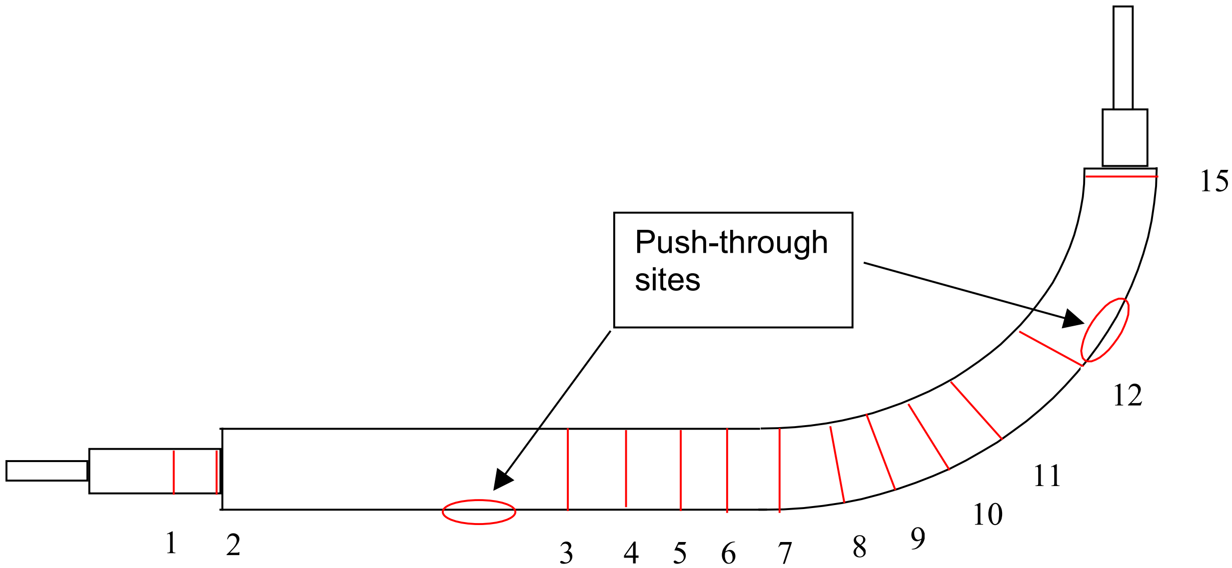


Figure 6-6
A Drawing of the Damaged Cable and Duct Showing Dissection Locations and Push-Through Sites

Table 6-2
XLPE Thickness Measurements on Damaged Cable (mm)

Cut	Top	Bottom	Right	Left	Range
1	15.5	13.5	14.5	13	2.5
2	14	14	14	13	1
3	15.5	11	14	12	4.5
4	13.5	12	13.5	13	1.5
5	14	12.5	13	14	1.5
6	14	13	13.5	13	1
7	13	13	14	13	1
8	13.5	13	13.5	13.5	0.5
9	13.5	13	13	13	0.5
10	14	13.5	13	13	1
11	13.5	13	13	13	0.5
12	14	13	14	13.5	1
15	13	14	13	14	1

Insulation thickness measurements were made at the top, bottom, right and left side of each cross-sectional cut. There was significant distortion at location 1, where the cable was highly stressed as it left the duct, and at location 3, where it pushed through the bottom of the duct, as well as in the highly bent region shown in Figure 6-7, but in the areas away from duct failure sites the insulation shows no sign of deterioration or distortion, and the thickness remains within measurement error of the nominal 13.3 mm. Based on the results of this test, there is no suggestion that the insulation integrity would have been impacted by the stresses if the duct failure had not occurred. Clearly the duct failure raises an important issue, and the impact of over-temperature operation on ducts, jackets and supporting structures must be considered when deciding on a maximum emergency operating temperature. In this case, the duct temperature reached 90°C to 100°C, and the duct was unable to support the loading at that temperature. As might also be expected in service, the duct is hidden from view, and can easily be overlooked when analyzing the ability of the cable to survive high temperature operation. It should be noted that PVC duct would normally be buried in concrete or similarly supported in service and it would behave differently from that used in the test. Temperature limitations related to duct operating temperatures should be investigated further before final recommendations are made on emergency operating temperatures.

Figure 6-7
A Photograph of the Dissected Cable at the Sharp Bend

Clamping Test Procedure

The clamping tests were intended to determine whether any damage or distortion could result from the stresses introduced by cable clamps applied to the cables. For cables with strong sheaths, such as corrugated aluminum, the small forces from cable clamps will not be transmitted to the insulation, so these tests were done on lead sheathed or foil laminated cable, samples B and D in Table 6-1. Two 3 meter sections of each cable were tested, connected in series, with a clamp in the center of each section. One of the clamps was spring loaded, with 500 lbs/inch springs compressed to approximately 250 lbs force. Both clamps were mounted over 6 mm neoprene linings as recommended by the manufacturer. End plates were clamped on the cut ends to prevent the insulation from extruding. The cables were subjected to the standard current profile, 16 hours at full current and 8 hours at 25% current repeated for 13 days. Thermocouples were inserted into the conductors and mounted on the jackets to measure the conductor and jacket temperature, and the cables were covered with a layer of fiberglass insulation to create a realistic temperature rise on the jacket.

After 13 days (312 hours) of testing, the cables were cooled down and cut into sections where the clamps had been mounted. One section from each cable was cut axially and examined and photographed.

Clamping Test on Lead Sheathed Cable

The lead sheathed cable, sample B in Table 6-1, 230 kV class with 27 mm insulation thickness, was the largest of the cables tested. It was set up for the clamp test as described above, and as usual there was some trial and error involved in adjusting the current level to achieve a peak conductor temperature of 130°C. This test ran at a significantly higher current level than previous tests due to the larger copper cross-section, and there were problems controlling the ambient temperature. The weather at the time was unusually hot, and the lab air conditioner was unable to cope with the heat dissipation and iced up, causing the ambient temperature to run away and the test to trip on over-temperature. The test was delayed while an air bypass was installed to relieve the loading on the air conditioner. The test was restarted, but the next day a computer problem shut down the test during the weekend. It was restarted without incident, but ambient temperature control continued to be a problem, and it took several days before the peak temperature could be stabilized at 130°C. Despite the problems, the cable was eventually subjected to 13 cycles with peak temperatures between 120°C and 133°C. The record of temperatures and currents during the test is shown in Figure 6-8.

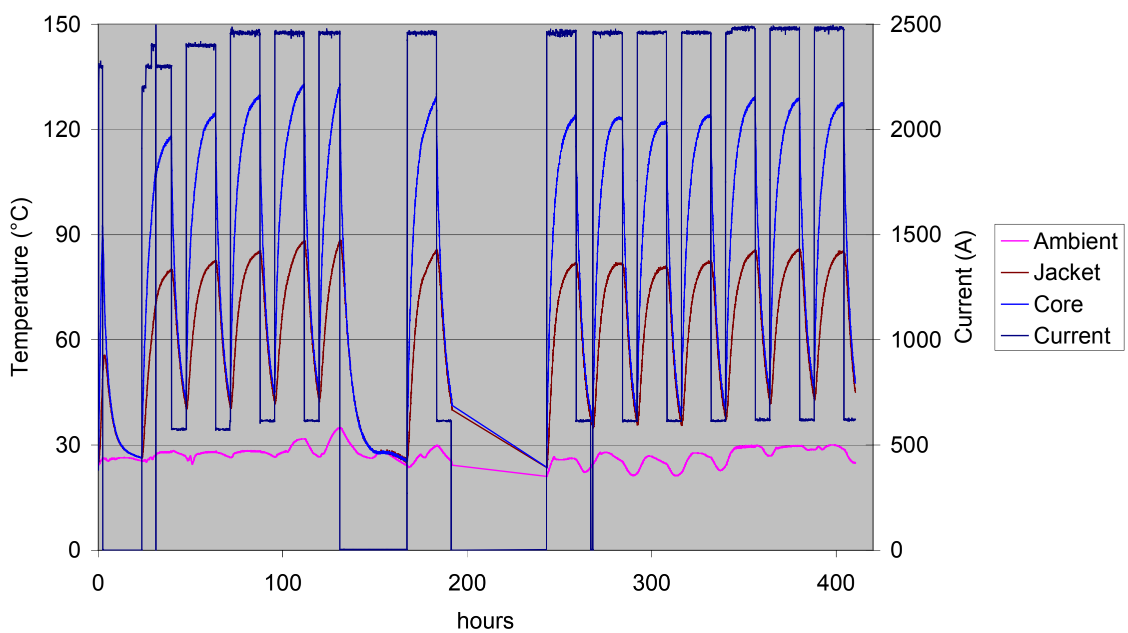


Figure 6-8
Current and Temperature Profile for Lead Sheathed Cable

When the clamps were removed, slight indentations could be observed where they had been, but the exterior of the jacket did not show any other signs of damage or deterioration. A section of cable around each clamp was cut out, and a cross-section cut through the center of where the clamp had been. One half of the clamped section was then cut axially to look for signs of deformation, gaps in the insulation, or any other changes that might impact the insulation performance. The XLPE showed no visible indentation or deformation, and no sign of anything to suggest that the electrical or mechanical performance might be impaired. Photographs of the cables after the test, whole and dissected, are shown in Figures 6-9 to 6-11.

Figure 6-9
Lead Sheathed Cable Samples After the Test, Ready for Dissection

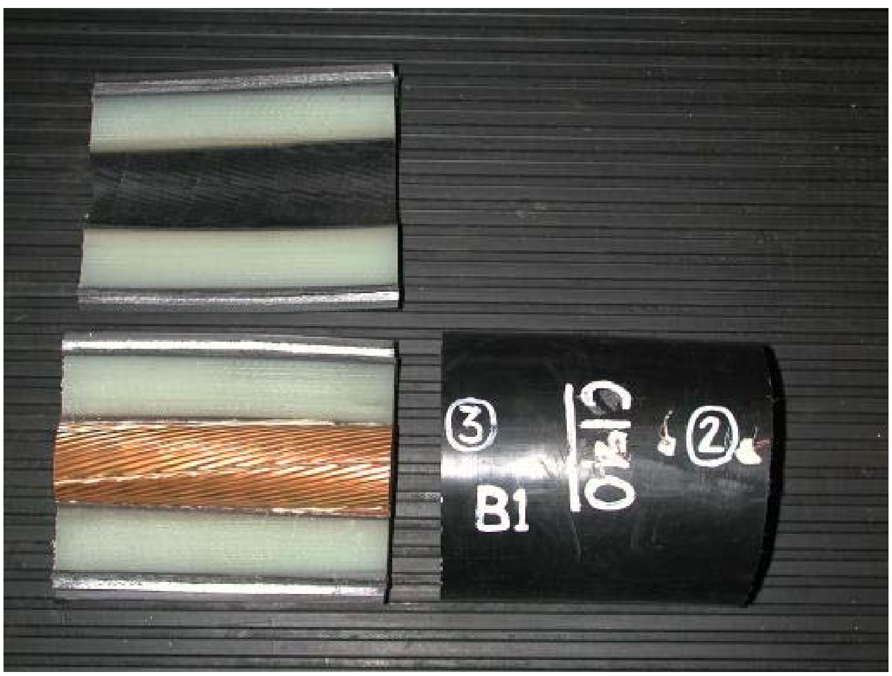


Figure 6-10
Dissected Lead Sheathed Cable Sample After the Clamping Test

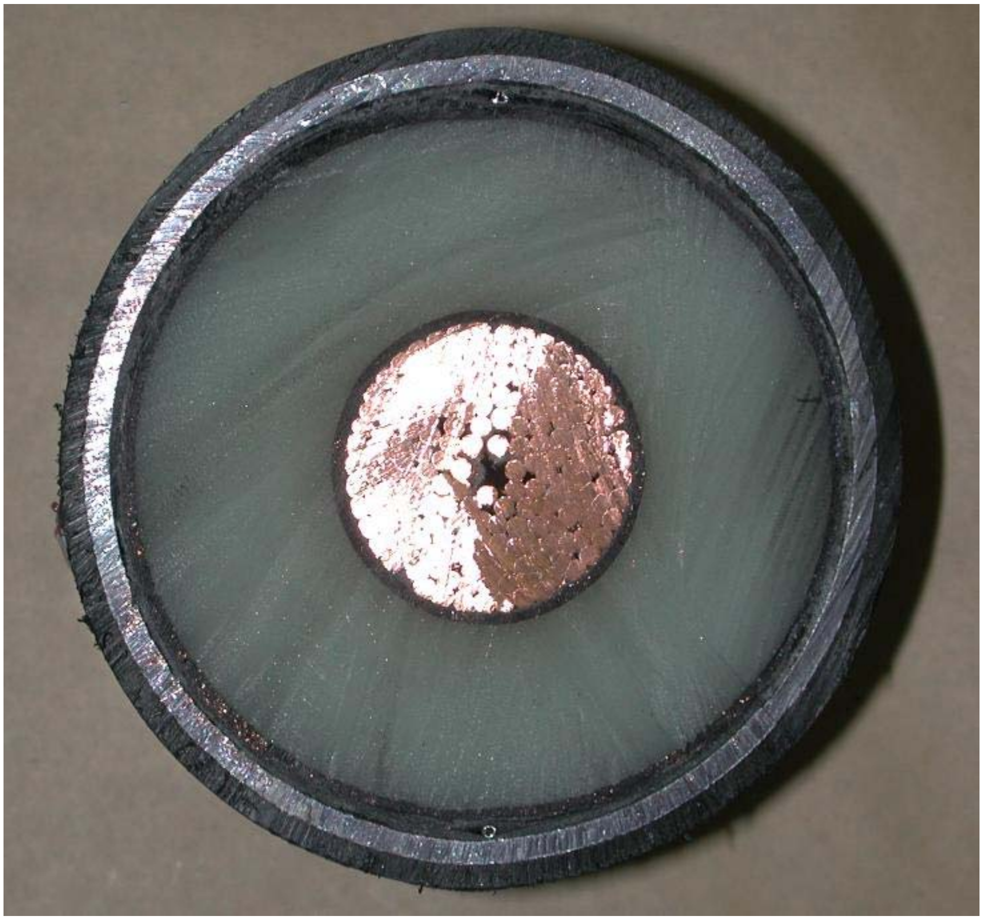


Figure 6-11
Cross-Section Photo of Cable B1 Under the Center of the Clamp After the Test

To confirm the qualitative observation that the XLPE was unaffected by the clamping test, measurements were made of the cable overall diameter in two directions and of the insulation thickness at four points around the perimeter. The measurements were made under the center of the clamp and at the outer cut, about 10 cm away from the clamp. Both cables showed a 3-4 mm compression in the overall diameter, but there were no significant differences in the insulation thickness under the clamps. It should be noted that the insulation thickness varied by about 1-2 mm at different points around the circumference, and there was some uncertainty in identifying the edges of the insulation as well. The measured dimensions are shown in Table 6-3.

Table 6-3
Dimensions (mm) of Lead Sheathed Cable Samples

Sample and Location	Overall Diameter		Insulation Thickness			
	(Top-Bottom)	(Side-Side)	Top	Right	Bottom	Left
B1 under clamp	124.1	130.8	28.8	30.0	28.2	29.9
B1 outside clamp	127.9	130.3	29.9	28.3	29.2	29.4
B2 under clamp	126.5	128.8	29.9	29.6	28.8	28.4
B2 outside clamp	129.2	127.6	29.5	29.5	28.3	28.9

Clamping Test on Foil Laminated Cable

The second clamping test was done on a sample of 138 kV foil laminated cable with copper neutral wires, labeled sample D in Table 6-1. The cable was tested in the same manner as the lead sheathed cable. To minimize end effects, end plates were clamped on to contain the XLPE and the neutral wires were soldered to a ring at each end to maintain them in a fixed position with respect to the conductor and insulation. With the benefit of experience, the test ran smoothly without any interruptions, as shown by the current and temperature profiles in Figure 6-12 below.

When the clamps were removed, the imprint on the cable jacket was less than had been observed on the lead sheathed cable, and there were no indications of damage or deterioration on the cable jacket. A section of cable around each clamp was cut out, and a cross-section cut through the center of where the clamp had been. One half of the clamped section was then cut axially to look for signs of deformation, gaps in the insulation, or any other changes that might impact the insulation performance. The XLPE showed no visible indentation or deformation, and no sign of anything to suggest that the electrical or mechanical performance might be impaired. Photographs of the cables after the test, whole and dissected, are shown in Figures 6-13 through 6-16.

Measurements were made of the cable exterior and the XLPE insulation thickness, as listed in Table 6-4. Unfortunately, the jacket of sample D1 was removed before external diameter measurements had been made, so those measurements are missing from the table, but the results should be very similar to sample D2. The dissected samples were examined to see if the neutral wires had pushed into the insulation, but they did not shift from their normal position, and the integrity of the cable insulation did not seem to have been impaired in any way by the test.

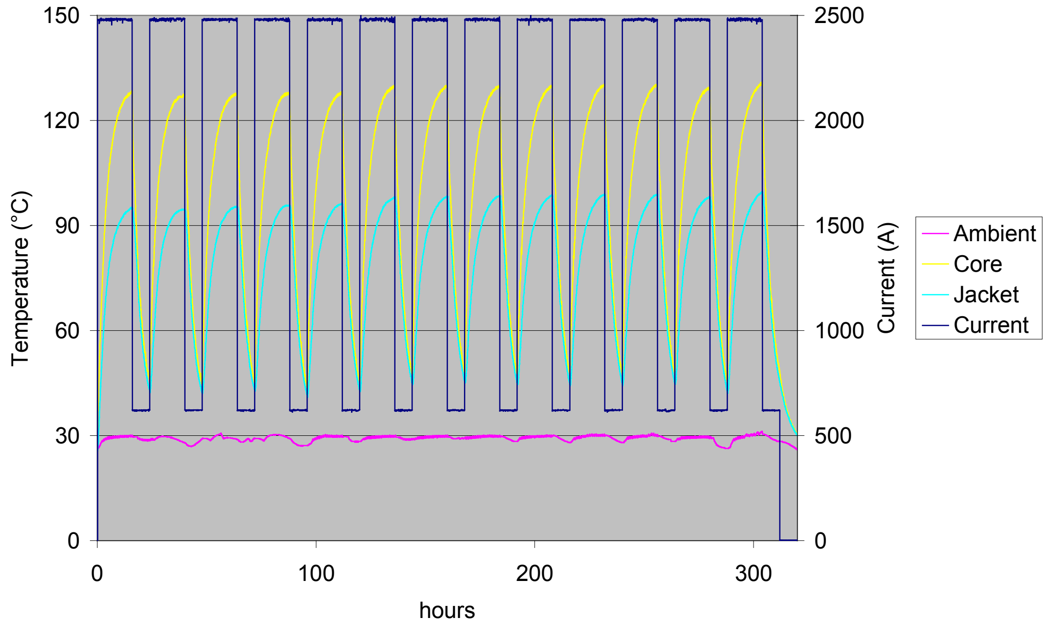


Figure 6-12
Current and Temperature Profiles for Copper Foil Sheathed Cable

Figure 6-13
Copper Foil Sheathed Cables After the Test, Ready for Dissection

Figure 6-14
Dissected Copper Foil Laminated Cable with Jacket and Neutral Wires Removed

Figure 6-15
Dissected Copper Foil Laminated Cable with Jacket and Neutral Wires in Place

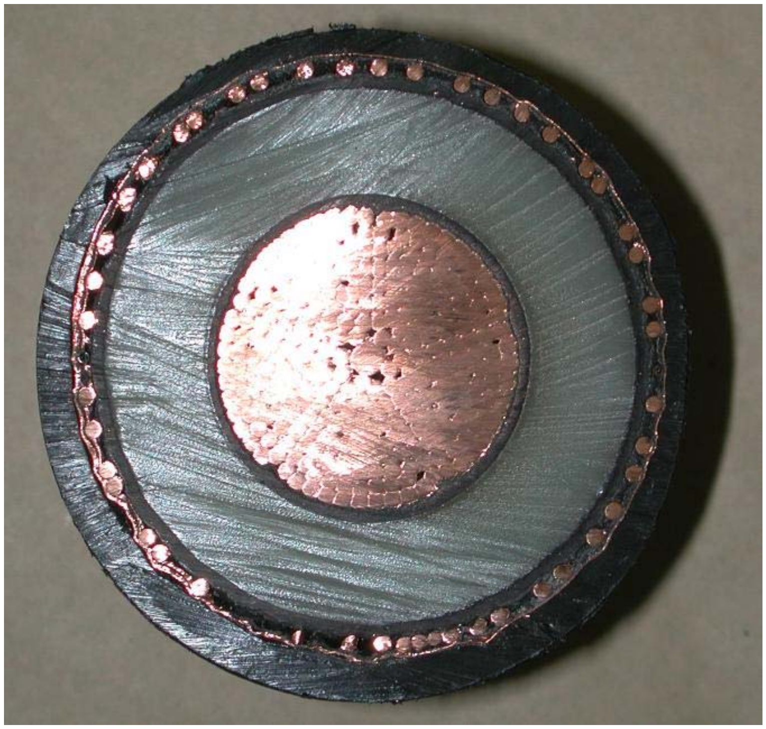


Figure 6-16
Cross Section Photo of Cable D2 Under the Center of the Clamp After the Test

Table 6-4
Dimensional Measurements (mm) of Copper Foil Sheathed Samples After Load Cycle Test

Sample and Location	Overall Diameter		Insulation Thickness			
	(Top-Bottom)	(Side-Side)	Top	Right	Bottom	Left
D1 under clamp	n/a	n/a	17.1	16.3	18.1	17.4
D1 outside clamp	n/a	n/a	16.9	16.5	16.9	17.7
D2 under clamp	106.9	108.6	15.6	18.8	16.5	16.5
D2 outside clamp	108.2	108.5	16.0	18.2	17.4	16.9

Minimum Bending Radius Test in Aluminum Duct

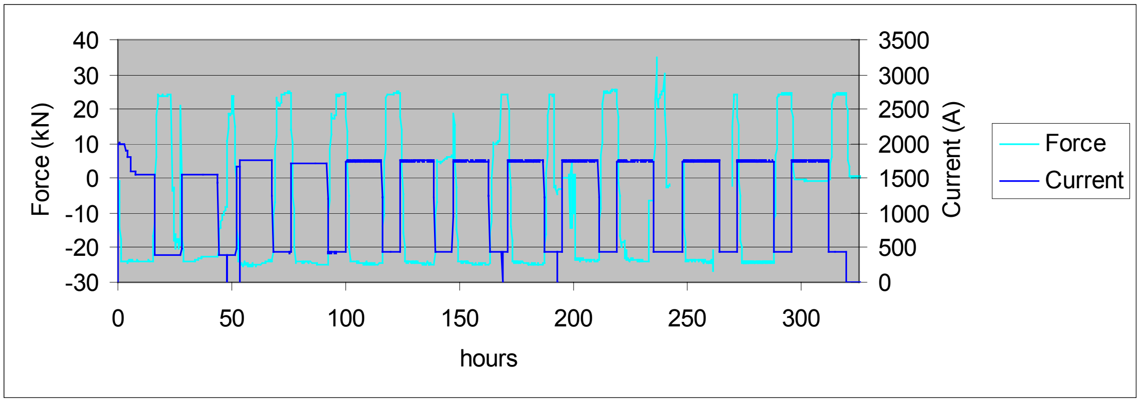
After repair of the test bed and drive motor, the minimum bending radius test was repeated with an aluminum pipe in place of the plastic duct, as shown in Figure 6-17. As before, the plan was to apply 13 heating and cooling cycles with a peak temperature of 130°C. During heating, a compression force of 24.5 kN was applied to simulate cable expansion, and during cooling the same force was applied in tension. The control software was modified to provide software limits that prevented excessive movement of the screw drive by limiting the maximum travel in both directions.

Figure 6-17
Setup for Repeat Minimum Bending Radius Test

Two thermocouples were inserted into the conductor near the middle of the cable, and thermocouples were mounted on the jacket, the aluminum duct, and in ambient air. As before, the thermal conductance of the cable changed during the first few cycles, so the current values had to be adjusted to achieve the target maximum temperature of 130°C. The logged values of current, force, and temperature are shown in Figure 6-18 below.

Despite a number of problems, the test provided thermal and mechanical stresses close to planned levels. Thirteen heating and cooling cycles were run over 320 hours, and on all but the second cycle, the peak conductor temperature was between 122°C and 134°C, although thermocouple problems caused some low readings. The target compression force was applied in all but the last cycle, and the target tension force was applied during every cycle, although in half the cycles the full tension force was only applied for part of the cooling stage.

Relative movement of the core and sheath caused one thermocouple to fail during the first cycle, and the second one to fail during the fourth cycle. A new thermocouple was installed after the seventh cycle, and it survived the balance of the test. Although the core temperature was not recorded for cycles 5-7, and the indicated temperatures were low for the last few cycles, we believe that peak conductor temperatures were within a few degrees of 130°C for the last 9 cycles.



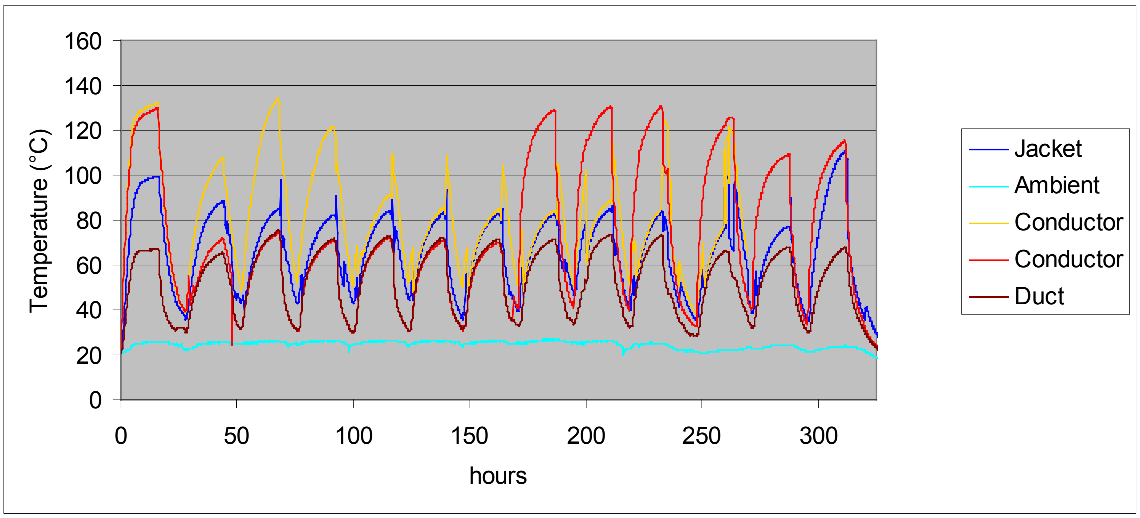


Figure 6-18
Logged Data from Repeat Minimum Bending Radius Test

Problems with software limits and end fittings caused some deviations in the planned force. Near the end of the tenth heating cycle, the load cell that was used to monitor and control the force failed. The failure was such that an error of 20 kN was introduced in the measurement, so that the controller reduced the load to near zero during the heating stage, then attempted to apply 44 kN of tension for the cooling stage, nearly twice the design force. At a tension of approximately 40 kN, the fixed end support broke, relieving the tension. The software limiter controlled the damage. The structure was repaired, and the load cell was removed and examined. It was determined that a solder joint had failed, and the load cell was repaired and judged fit for service. It was reinstalled by the end of the day, and the test was continued. The next night the load cell failed again, and this time the readings went to very large values, causing the controller to apply tension until the software limiter stopped it. The force was close to normal judging by the cable end position, although the exact value could not be determined. The load cell was again removed and examined, and it appeared that another solder joint had failed. After analyzing the failures we found the problem. Some improvements that had been made to the end grips to reduce slip had also improved the thermal contact, and the load cell was now overheating, causing the solder joints to fail. A thermal break was inserted, and a radiator fin and cooling fan were attached to the load cell for the last two cycles, as shown in Figure 6-19. This solved the problem, but an incorrect software limit prevented compression from being applied during the last cycle.

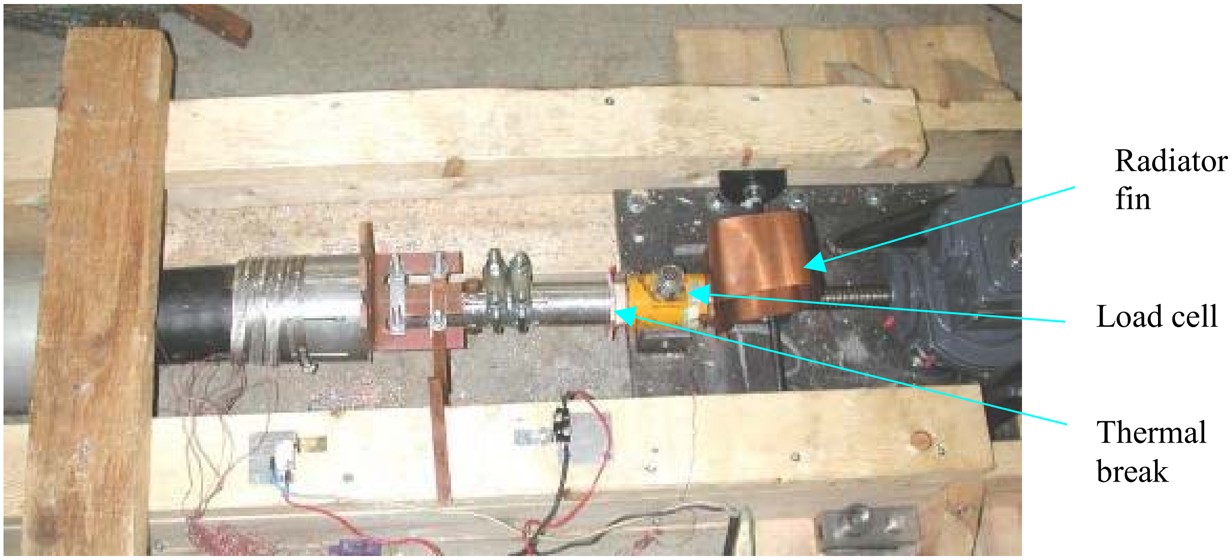


Figure 6-19
The Load Cell with Thermal Break and Radiator Fin Installed

The changes to the load cell reduced the measured peak temperatures during the last two cycles. It is likely that the conductor temperature in the middle of the test sample would not have been affected much by this change. The replacement thermocouple was close to the end of the cable, and the changes would have had considerably more effect on the temperatures near the end of the cable than in the bent section far from the load cell.

After surviving the cycling test, the cable was dissected for examination. Cross-sectional cuts were made every 50 cm along the cable, as shown in Figure 6-20. The insulation thickness was measured at the top, bottom, left and right at each cross-section. The cuts are numbered from the fixed (top) end, so cuts 1-5 are in the bent section and 6-9 are in the straight section of the duct. The results are listed in Table 6-5 and shown graphically in Figure 6-21. Photographs are shown in Figures 6-22 and 6-23.

Some deformation of the cable occurred during the test; the top insulation thickness (inside edge of the bend) was reduced throughout the bent part of the cable by an average of 1.7 mm and the side thickness was increased by an average of 0.9 mm. The bottom thickness was unaffected. There were no gaps or defects that might affect the performance of the cable. The thinnest top wall thickness found, the inside wall near the center of the bend, was 11 mm, 1.6 mm less than the thinnest wall thickness in the straight section.

The impact of this worst-case test on the insulation thickness was a 1.7 mm (13%) reduction in insulation thickness in the most highly stressed area. There were no electrical stress enhancements observed that might lead to any further reduction in electrical strength. Previous tests have showed that this deformation occurs in the first few thermal cycles and that the material does not undergo long term deterioration from operation in this temperature range.

Using the analytic formula for peak field, $E_{\max} = \dfrac{V}{R_1 \ln(R_2/R_1)}$ where R_1 is the inner radius and R_2 is the outer radius of the insulation, this implies an increase of 11% in electrical stress for the cable under test. This result may vary for different cable geometry. In reality, the insulation deformation occurs in only a small fraction of the cable length, so unless the weakest point of the cable is already in the stressed region, the peak stress will be increased by less than this amount. If the cable is designed with a safety margin for electrical breakdown that is large compared to this 11% stress enhancement, and the electrical strength is not compromised at high temperature, increased emergency operating temperatures up to 130°C should be tolerable.

Table 6-5
Measured Insulation Thickness (mm) After Repeat Minimum Bending Radius Test

Cut	Top	Bottom	Right	Left	Range
1	13.8	13.2	12.7	13.9	1.2
2	11.6	13.1	13.6	14.3	2.7
3	11.8	13.3	14.0	16.4	4.6
4	12.6	13.9	14.5	14.1	1.9
5	11.0	12.8	13.5	14.4	3.4
6	13.2	13.1	13.4	14.3	1.2
7	13.6	14.4	13.9	14.2	0.8
8	13.3	12.9	13.5	13.0	0.6
9	13.6	13.6	12.6	14.6	2.0

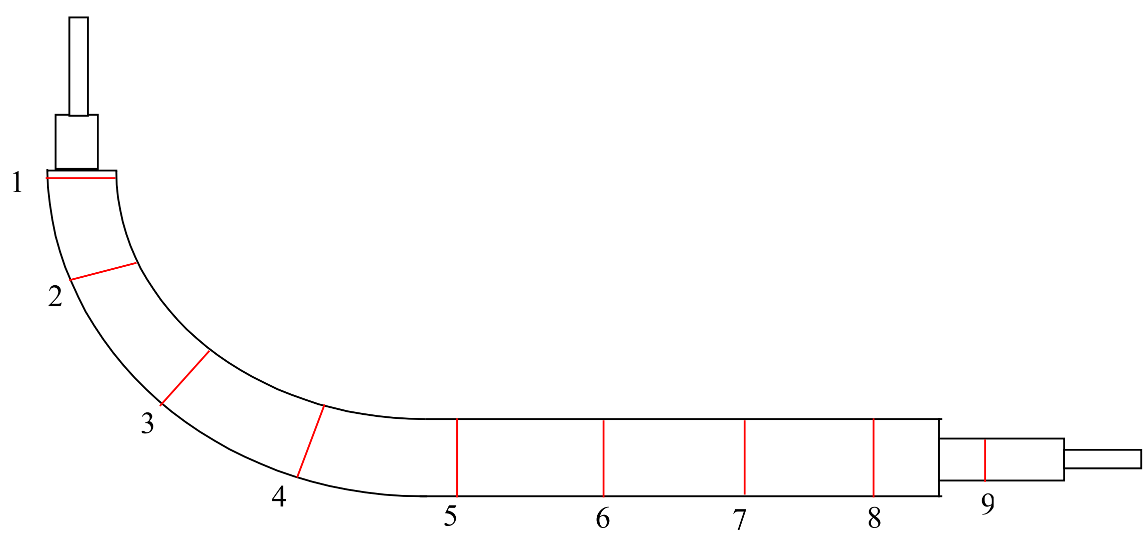


Figure 6-20
Dissection Cut Locations After Bending Test

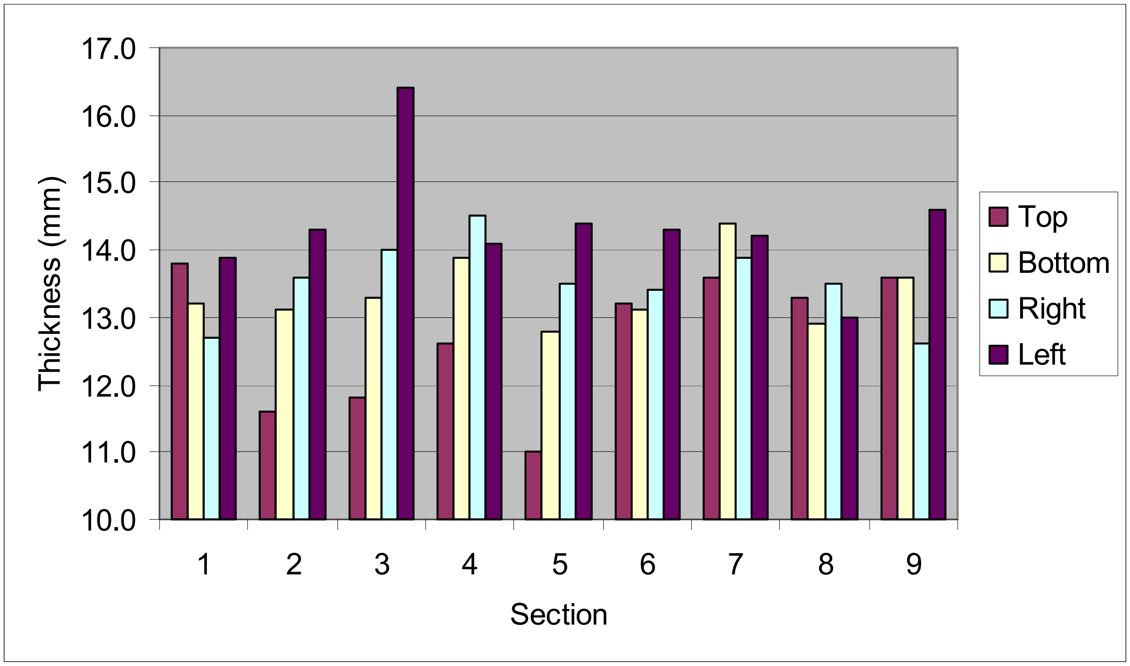


Figure 6-21
Variations in Insulation Thickness at Different Sections

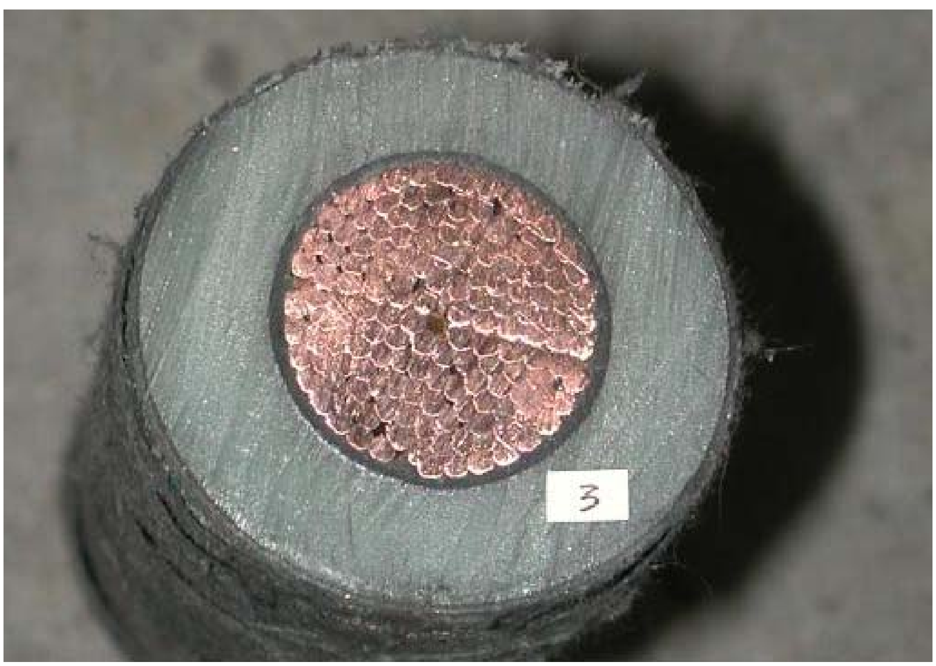


Figure 6-22
Cross-Section View of Cut 3 in the Center of the Bent Section

Figure 6-23
Cross-Section View of Cut 6 in the Straight Section

7 CONCLUSIONS AND RECOMMENDATIONS

Both the analytic work and the validation tests confirm that XLPE insulation in cables of the types tested in this program will not be mechanically compromised when operated for short periods at a peak temperature of 130°C at 75% daily load factor. Some reduction in insulation thickness can be expected. It must be stressed that this work has examined the XLPE cable insulation only, and further research is essential to determine whether the interface between cables and accessories, accessories, jackets and ducts can also tolerate increased operating temperature. Transmission cables are very much a system with multiple components, and it is not enough to study only the cable insulating material.

Validation tests have been run for 300 hours, and long term aging tests for 2400 hours, to investigate the short term effects for a 300 hour emergency period, and the cumulative effects of 2400 hours over the cable lifetime. We have seen that XLPE dimensional changes are caused primarily by temperature cycling (passing through the softening temperature) rather than by long term heating. This implies that a 75% daily load factor (with larger temperature swings) will be more likely to cause problems than a 100% daily load factor with the same peak temperature. A 2400 hour test confirmed that long term aging does not degrade the mechanical properties of XLPE, even at conductor temperatures as high as 150°C. What remains to be evaluated is the impact of emergency operating temperatures on accessories, jackets and ducts. The most serious failure encountered in this project was the failure of a PVC duct in the minimum bending radius test, a failure that emphasizes the need to consider these other factors in setting maximum allowable operating temperatures. Obviously it is also essential to consider the electrical strength of the insulation during and after emergency temperature operation, a subject that is outside the scope of this project.

Hysteresis

The study of XLPE properties has uncovered some interesting behavior that occurs when the material is repeatedly heated above the softening temperature and then cooled. These cycles can cause permanent changes in the shape of the material, changes that depend on the stress applied during the heating and cooling cycles. These changes can have a significant impact on cable conductor temperatures by changing the thermal conductivity of the system, and may also affect the electrical strength and the mechanical and electrical stresses inside the cable. This phenomenon is too complex and poorly understood to allow the use of conventional finite element methods to model the behavior. Research should be undertaken to study the effect and develop a theoretical understanding and computational methods for modeling cable behavior.

Jackets and Ducts

As illustrated by the failure in the minimum bending radius test, thermoplastic materials such as PVC and non-crosslinked polyethylene with low melting temperatures are often used for cable jacket and duct material, and are sometimes forgotten in the analysis. Any determination of maximum operating temperature must take into account the presence of these materials, and must ensure that their maximum operating temperature is not exceeded. This requires an accurate prediction of the jacket and duct temperature. For cables with corrugated aluminum sheaths we have learned that this prediction must take into account the hysteresis effect as well as the initial cable properties.

Accessories

Cable accessories, i.e. joints and terminations, are an essential part of any XLPE cable system, and must be considered when setting maximum allowable emergency operating temperature limits. There are a variety of systems in use, including prefabricated, rubber premolded, in-situ molded, and tape-wrapped joints, and they have different high temperature characteristics. Especially if a maximum cable temperature above the softening temperature is being considered, analysis and testing should be done to predict and evaluate the accessory performance at high temperatures.

While this project has demonstrated that from a mechanical point of view uniform XLPE insulated cable can be safely operated at 130°C, the introduction of interfaces and other materials introduces a whole new set of concerns. The following factors should be included in a future research program to determine the maximum safe temperature for accessories.

- Longitudinal expansion and contraction of the conductor and sheath can generate large forces, which might cause accessories to buckle or pull apart.
- The high expansion coefficient of XLPE could create gaps in interfaces with lower expansion coefficient materials.
- XLPE loses elasticity above the softening temperature, which might cause interfaces to lose contact pressure and cause electrical failure.
- Accessory materials may similarly lose elasticity, and softening of accessories in combination may also cause interface problems.
- The hysteresis effect after thermal cycling can cause dimensional changes in the XLPE, which must be accommodated.
- The accessory temperature may be higher or lower than the cable temperature, depending on the design.
- The maximum working temperatures of accessory materials should be assessed to ensure that they can tolerate the maximum temperature without breaking down or losing strength.

There is still much work to be done to determine the maximum safe temperature for the other components of the system. A follow-up project should be initiated to determine whether the different types of accessories can operate to the same temperature, or whether restrictions should be imposed for certain types of accessories.

Conclusions

Taking into account mechanical considerations alone, and subject to analysis of the electrical strength and the maximum temperature limits of jacket, duct and accessories, XLPE transmission cables with a low electrical stress design can safely be operated at conductor temperatures up to 130°C for emergency operations. Emergency operations are taken to mean short term operation up to 300 hours at 75% to 100% daily load factor, with a cumulative duration up to 2400 hours over the life of the cable.

Aside from a visible darkening, there is no significant deterioration in mechanical properties after 2400 hours at 150°C. The impact on electrical properties was not analyzed.

The elastic properties of XLPE at high temperatures are reasonably well understood, but when the temperature is cycled under mechanical stress, a hysteresis effect occurs which plays a significant role in the behavior of cables under emergency conditions. The most significant changes occur during the first few temperature cycles. Further work will be necessary to fully understand this effect.

The properties of jackets, duct and accessories must be considered before recommending increased emergency operating temperatures in XLPE transmission cables.

Recommendations

Further work should be done to develop an understanding of the hysteresis effect so that it can be included in cable thermal calculations and mechanical modeling.

A research project should be carried out to determine the suitability of different types of accessories (splices and terminations) at temperatures up to 130°C.

After the study of accessory temperature limits is complete, the results should be considered and recommendations made on maximum emergency operating temperature limits for XLPE transmission cable systems, including accessories, jacket and duct.

8
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A
SAMPLE OF THE USER SURVEY

EPRI has commissioned Powertech Labs to carry out a project to determine the impact of emergency operating temperatures on the integrity of XLPE transmission cable systems.

This survey is intended to identify the types of XLPE transmission cable installation that are in use by EPRI members. The results will be used to direct the work of the project toward the most commonly used cables. The objective is to recommend emergency temperature limits that will optimize the use of XLPE cables while minimizing the risk of premature failure.

These questions relate to the underground transmission cable in use or planned for installation in your company. If you are not the most appropriate person to fill out the survey, please refer it to the person in your organization most able to provide the information. We need your feedback to ensure that the project results will be useful to you!

Please fill in the table on the following page and return the completed form by fax. If you have more than one type of cable in use, please fill in one form for each type.

We appreciate your taking the time to complete the survey. This information will be kept strictly confidential and will not be used for any purpose other than the EPRI project.

Only the following cables are covered by the survey:

- 60 kV or higher
- XLPE insulated
- Underground (not underwater)

Please fax completed forms by October 18, 2002 to:

Bruce Neilson, Powertech Labs

Fax (604) 597-6656

Phone (604) 590-7454

Respondents are encouraged to fill out the survey electronically instead of on paper.
To do so, visit the following web site and fill out the form on line:

http://ftp.powertech.bc.ca/survey.htm

Fax to: (604) 597-6656

Name	
Email Address (for follow-up)	
Company & Location	

Nominal cable voltage (kV line-line):	
Conductor size or range of sizes (kcmil):	
Approximate miles of cable in service:	
Cable installation type: direct buried | in plastic duct | in steel pipe | suspended (hangars) | tray or trench (no fill)	
Phase grouping: individual phases | three phases together	
Restraining devices installed: cable clamps | cable anchors	
Conductor material: copper | aluminum | other	
Conductor strands: concentric | compact round | compact segmental	
Metallic shield design: wire | tape | other	
Sheath type: smooth aluminum | corrugated aluminum | lead | Corrugated copper | corrugated stainless | metal foil | none	
Jacket: polyethylene | pvc | other	
Minimum bending radius for pulling (ratio to diameter):	
Minimum bending radius for post bending (ratio to diameter):	
Maximum permitted emergency operating temperature (°C):	
Duration for emergency operating temperature (hours):	
Guidelines used for emergency operating temperature: Internal guidelines | manufacturer's | none | don't know	

Please add any comments, or give more details for your previous answers

B
USER SURVEY RESULTS

Company	A	A	A	A	A	A
kV	69	69	69	69	69	69
Burial	Other	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct
Grouping	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases
Restraints	Other					
Size	500	1750	2000	1750	1750	1750
Conductor	Copper	Copper	Copper	Copper	Copper	Copper
Strands	Compact stranded	Compact segmental	Compact segmental	Compact segmental	Compact segmental	Compact segmental
Shield						
Sheath	Corrugated aluminum, LDPE	Corrugated aluminum, MDPE	Corrugated aluminum, LDPE	Corrugated aluminum, LDPE	Corrugated aluminum, LDPE	Lead, LDPE
Pull radius	22	16	14	19	14	32
Post radius	15	14	14	13	28	11
Max temp		105	105	105	130	105
Max hours		less than 10hrs/month	less than 10hrs/month	72hrs/year		
Guideline		Manufacturer's limits	Manufacturer's limits	AEIC CS7	AEIC CS7	AEIC CS7
Note	1					

Company	A	B	C	D	D	D	E
kV	69	161	115	138	230	230	138
Burial	In plastic duct	Other	In plastic duct	Other	Other	Other	In plastic duct
Grouping	Individual phases	Three phases together	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases
Restraints		Cable clamps	Other	Cable clamps	Cable clamps	Other	Cable clamps
Size	500	1000		1500	1000	2500	3500
Conductor	Copper	Copper	Copper	Copper	Copper	Copper	Copper
Strands	Concentric	Compact segmental	Compact segmental	Compact round	Compact round	Compact segmental	Compact round
Shield		Wire shield	Tape shield		Wire shield		Wire shield
Sheath	Lead, LDPE	Corrugated aluminum, LDPE	Lead, LDPE	Lead, MDPE	Lead, MDPE	Lead, HDPE	Metal foil, MDPE
Pull radius	20	20	20	25	25	25	15
Post radius	15	20	20	12	12	12	15
Max temp	105	105	105	90	90	90	105
Max hours		24	indefinite	300	300	300	See note below
Guideline	AEIC CS7	Internal guidelines	AEIC CS7	Internal guidelines	Internal guidelines	Internal guidelines	AEIC CS7
Note		2	3	4	5	6	7

Company	E	E	E	E	E	E	E	E	E
kV	138	138	138	69	69	69	69	69	69
Burial	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct	In plastic duct
Grouping	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases
Restraints	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps
Size	2500	790	750	400	1250	500	1500	1000	750
Conductor	Copper	Copper	Copper	Copper	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Strands	Compact round	Compact round	Compact round	Compact round	Compact round	Compact round	Compact round	Compact round	Compact round
Shield	Wire shield	Wire shield	Wire shield	Wire shield	Wire shield	Wire shield	Wire shield	Wire shield	Wire shield
Sheath	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE	Metal foil, MDPE
Pull radius	15	15	15	15	15	15	15	15	15
Post radius	15	15	15	15	15	15	15	15	15
Max temp	105	105	105	105	105	105	105	105	105
Max hours	See note below	See note	See note	See note	See note	See note	See note	See note	See note
Guideline	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7
Note	7	7	7	7	7	7	7	7	7

Company	E	E	F	G	H	H	H	H	H
kV	69	69	138	69	138	138	138	138	138
Burial	Direct buried	In plastic duct	In plastic duct	In plastic duct	Direct buried	Other	In plastic duct	In plastic duct	In plastic duct
Grouping	Individual phases	Individual phases	Individual phases	Individual phases	Individual phases	Three phases together	Individual phases	Individual phases	Individual phases
Restraints	Cable clamps	Cable clamps	Cable anchors	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps	Cable clamps
Size	650	350		1500	750	1500	1500	3000	2400
Conductor	Aluminum	Aluminum	Copper	Copper	Aluminum	Other	Copper	Copper	Copper
Strands	Compact round	Compact round	Compact segmental	Concentric	Compact round	Compact segmental	Compact segmental	Compact segmental	Compact segmental
Shield	Wire shield	Wire shield	Wire shield	Other	Other	Other	Other	Other	Other
Sheath	Metal foil, MDPE	Metal foil, MDPE	Metal foil, HDPE	Other, LDPE	Lead, LDPE	Lead, MDPE	Lead, HDPE	Other, HDPE	Lead, HDPE
Pull radius	15	15	22						
Post radius	15	15	14						
Max temp	105	105	105	105	105	105	105	120	120
Max hours	See note	See note below	Vague	SEE BELOW	100 hr/300hr	100 hr/300hr	100 hr/300hr	100 hr/300hr	100 hr/300hr
Guideline	AEIC CS7	AEIC CS7	AEIC CS7	AEIC CS7	Manufacturer's limits	Manufacturer's limits	Manufacturer's limits	Manufacturer's limits	Manufacturer's limits
Note	7	7	8	9		10	10	11	12

Note	Comments
1	Tie Cables. Installed in a combination. - Direct buried at top of hill (cables snaked before burial) - In duct bank down steep hill.
2	Below grade cable trough granular thermal fill capped with pre-cast lids acting as sidewalk and driveway. Clamps installed above ground.
3	Use cable clamps for risers, no other restraints.
4	Cables are in older fiber (wood fibers in coal tar base) ducts.
5	Individual cable phases will be in fiberglass epoxy-reinforced type ducts. Circuit will be completed in March 2004.
6	Individual cable phases are in Fiberglass epoxy-reinforced type ducts.
7	Under sheath type, metal foil can serve as metallic shield if sized to handle fault current. Duration (hours) for emergency depends on thermal properties of backfill to limit expected conductor temperature to 105 degrees C.
8	Side wall pressure 1500 lbs/ft Retrofit constructions have pull-thru manholes, average cable length 1500' New construction, no pull through manholes, Av length 1500'.
9	1. 75% of our 69kv cable has a lead sheath, the remaining 25% of 69kv cable has copper shield wires with an aluminum foil moisture barrier. Both are accepted by the specification. 2. Emergency rating is cumulative, the emergency rating may not be used for more than 300 hours in any 12 month period and for a total of 1500 hours during the life of the cable.
10	Cable system consists of 2 - 3x630mm2 cables and 6 - 1X 800mm2 cables. The 3 core cables are submarine cables and the 800mm2 cable are land cables. Approx 900ft of the 3 - core cable is land cable. The 3 - core cable is not armored. Conductor shield - probably semi-con XLPE Insulation shield - probably semi-con XLPE
11	This project is in the design phase with construction planned for 2004. Lead or corrugated cooper sheath Conductor shield - probably semi-con XLPE Insulation shield - probably semi-con XLPE
12	Conductor shield - Semi-conducting XLPE Insulation shield - Semi-conducting XLPE.

Program:
Underground Transmission Systems

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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