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https://doi.org/10.21278/TOF.42Si108
ISSN 1333-1124
eISSN 1849-1391

CABLE AGING MONITORING WITH DIFFERENTIAL SCANNING CALORIMETRY (DSC) IN NUCLEAR POWER PLANTS

Summary

As a requirement for plant life extension for more than 40 years, additional Cable Aging Management Program (CAMP) has to be implemented in Nuclear Power Plant Krško. Samples of cables are selected based on nuclear safety and electrical equipment criticality for inspection and testing, to check functionality and prevent unexpected failure during normal operation. Different onsite testing equipment and methods are implemented to find harsh environment due to temperature, radiation, humidity and chemical effects that could affect insulation lifetime. Infrared thermography is used for determining and evaluating temperature hot spots.

The article presents a development of laboratory testing of cable insulation using Differential Scanning Calorimetry (DSC). Thirty-six samples of different nuclear qualified cables made of most frequently used materials, ethylene propylene rubber (EPR) and cross linked polyethylene (XLPE) – all with chlorosulfonated polyethylene (CSPE) jacket, were tested. Samples were 35 years old and additionally temperature aged in several steps with an intention to get acceptance criteria. Similar tests were conducted in two testing laboratories.

The results showed an evident decrease in oxidation stability of the inner EPR insulation; the onset temperature of oxidation processes has been shifted from 238 ^{o}C (unaged samples) to 175 ^{o}C (most aged samples). A decrease in oxidation stability was also observed for XPLE insulation; the onset oxidation temperature decreased from 266 ^{o}C for unaged samples to 213 ^{o}C (most aged samples). For the jacket material CSPE used as the insulation protection nearly no changes were observed.

Key words: *Cable ageing, cable maintenance, nuclear technology, laboratory testing, DSC, thermal calorimetry*

1. Introduction

Cable-Ageing Management Program (CAMP) was implemented in 2010 at Krško Nuclear Power Plant (NEK) [1] to provide reasonable assurance of functionality of the electrical cables with connections exposed to localized adverse environments. Identification of potential adverse localized environments or adverse service conditions and management of cable insulation and connections were its main concern. The main goal is to confirm the functionality of cables for planned extended plant life operation for beyond 40 years.

CAMP defines activities on low voltage power, control, instrument and medium voltage cables with associated connections to safety-related equipment (1E), critical equipment and cables identified in the operating experience of the plant as exposed to adverse localized environments.

The CAMP uses visual inspection and measurements of environment parameters at cable areas to search for potential local adverse environments (harsh environments or "hot spots"), such as high temperature, radiation, humidity or submergence, chemical or mechanical wear. Onsite diagnostic testing of electrical and mechanical parameters is performed on selected cables in specific local adverse environments. In a typical nuclear power plant, there are more than 1000 km of installed cables in more than 20 000 circuits and hundreds of different cable types, with regard to construction, material, and manufacturer.

Most of the cables sampled in the CAMP scope are recognized as nuclear qualified safety-related class SR (1E) [2] and as such could be considered with a spaces approach, assuming all cables are installed in environmentally benign areas. There is no appreciable aging of cables for 60 years if these environment conditions are met for 40 years:

- room ambient temperature never exceeds 40 °C,
- no close, hot process lines,
- no radiation sources,
- no connections frequently manipulated,
- the area is always dry.

The program applies to different cable groups based on voltage or type in adverse environments Medium Voltage (MV) Power Cables (~1% of cables), Low Voltage (LV) Power Cables (~10% of cables), Control Cables (~70% of cables) and Instrumentation Cables (~ 19% of cables).

Three different manufacturers were recognized from the end of 1970's during construction time as the main producers of installed cables for SR (1E) circuits: Okonite (OK) for MV, Boston Insulated Wire (BIW) and Rockbestos (RB) for LV. Most of the cable materials identified for insulation used in safety-related 1E qualified cables are ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) with CSPE (Hypalone®) for the jacket. All materials have good thermal, radiation and moisture resistance for long-term operation of more than 40 years under normal designed temperature and radiation. The CSPE jacket material (Hypalone®) as the most vulnerable material, used for mechanical and fire protection, is a good indicating material for adverse environment effects [3].

Different samples of commonly used nuclear qualified cable insulation materials (EPR and XLPE) and jacket (CSPE), were taken from a warehouse. Samples were temperature aged in an air-controlled oven at 120 °C in different stages to evaluate mechanical, calorimetric and chemical properties of polymers. Main goals of the oven temperature aging was to develop acceptance criteria for a visual control, considering colour change and mechanical properties of polymers detected with Indenter Modulus (IM) and correlate results with DSC results. Some preliminary results are presented.

2. Temperature cable aging diagnostic and testing methods

One of the CAMP focuses is to implement the best available inspection and testing methods with predefined acceptance criteria to detect cable aging on time with appropriate action based on a risk-ranking model or remaining-life prediction. An overview of the concept is shown in Figure 1.

Visual in-service inspection of the cable area and diagnostic testing of electrical and mechanical properties was conducted to confirm cable functionality.

This article represents the third phase of activities when artificially aged samples have been taken for laboratory tests in order to determine the actual scale of different properties change. Laboratories testing could be used for detailed modelling of remaining life prediction.

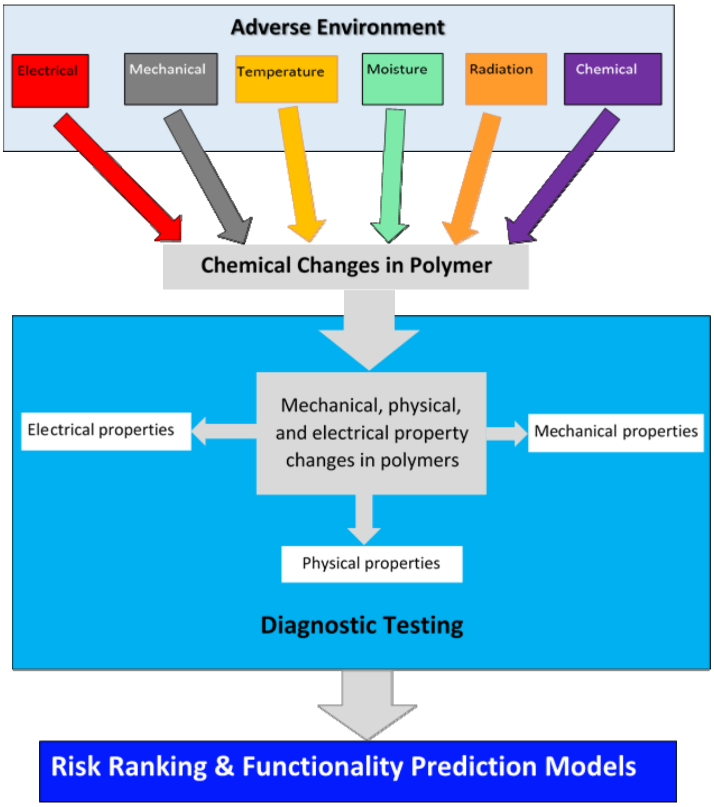


Fig. 1 Cable Aging Detection and Remaining Life Prediction [4,5]

In this paper, main consideration is temperature aging as one of common aging affect identified at plant. Different testing methods used will be presented in this paper such as temperature monitoring, artificial aging and indenter modulus acceptance criteria development to research any correlation with chemical material diagnostic technique such as Differential Scanning Calorimetry (DSC).

2.1 Temperature hot spot identification in field

Infrared thermography-IR camera, contact and IR temperature meters, data loggers and memory label were used to determine hot spots temperatures. Infrared camera is mainly used for temperature hot spot identification to get a big picture of localized hot spots. Some of techniques used at the Krško plant are shown in Figure 2.

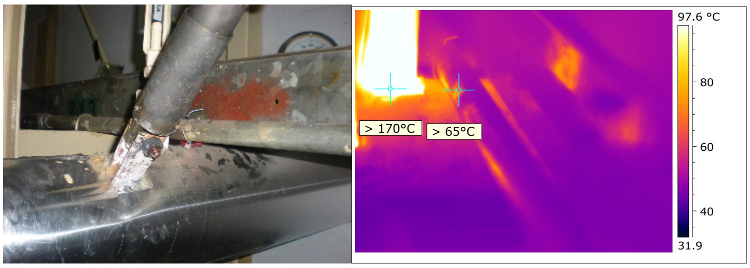


Fig. 2 Temperature monitoring using IR camera

2.2 Accelerated temperature aging

The goal of extrapolated predictions is to take accelerated thermal aging at higher temperature and use this data to generate predictions at lower operating temperatures.

Accelerated thermal aging of specific polymeric materials was conducted in a laboratory air circulated oven. The Arrhenius model relates the rate of degradation (reaction) to temperature through the exponential function (1) and is commonly used for thermal aging evaluation of polymers in nuclear qualified cables. Arrhenius equation describes relation between rate of degradation, aging temperature and exposure duration [6, 7, 8]. This model was used for determination of different ambient temperature influence to cable polymer materials. Aged samples are taken for indenter modulus testing and acceptance criteria development, as described in 2.3.

$$R = A \cdot e^{\frac{-E_a}{k_B \cdot T}} \tag{1}$$

where

R - Specific rate of degradation reactions between molecules
A - Constant velocity of the molecules (property of the material)
T - Absolute temperature
k_B - Boltzmann's constant (0,8617 x 10^{-4} eV/K)
E_a - Activation energy (eV, J/mol) of the process depending on specific reaction and may vary for thermal aging of different polymers from 0.9 to 1.8 eV

The activation energy, E_a is a measure of the energy required to produce a given type of endothermic reaction within the material. This parameter can be correlated to the rate of degradation; that is, materials with higher activation energies will thermally degrade at a slower rate than those with lower activation energies [3]. Specific values of activation energy, used in Table 1, are obtained from cable qualification reports, used at the Krško NPP – NEK [9], and are valid for the instrument and control cables with very low currents, less than 1% of its ampacity.

A common form of the Arrhenius equation (2) relates the degradation time for a material at one temperature to that at another temperature.

$$\frac{t_s}{t_a} = e^{\frac{E_a}{k_B}\left(\frac{1}{T_s} - \frac{1}{T_a}\right)} \tag{2}$$

where

T_s - Ambient operating temperature (K)
T_a - Accelerated aging temperature (K)
t_s - Operating time at ambient temperature T_s
t_a - Time of accelerated aging at temperature T_a
E_a - Activation energy

According to this form of the equation, exposure of a material of activation energy E_a to temperature T_s for a period of t_s produces degradation equivalent to exposure at T_a for period t_a. Implicit in this relationship is the idea that exposure of a material at higher temperature for shorter duration will result in degradation equivalent to that resulting from longer exposure at lower temperature [3, 6, 7, 8].

For demonstration, the impact of temperature aging of polymer materials' properties of nuclear cable insulation during operating lifetime are calculated and presented in Table 1.

Table 1 Arrhenius Aging model for EPR / XLPE insulations Lifetime prediction at various operating temperatures

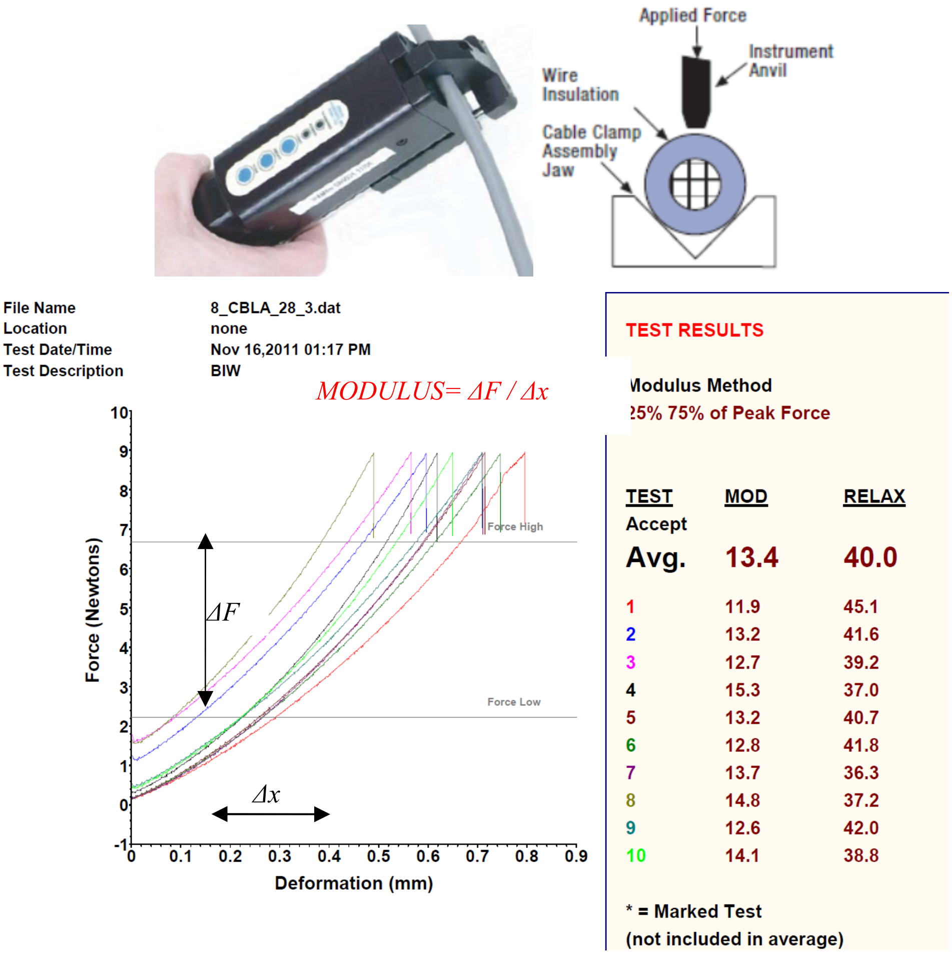
Operating Temperature Ts (°C)	Qualification Aging Temperature EPR / XLPE Ta (°C)	Aging Time EPR / XLPE ta (Year)	Activation Energy Ea EPR / XLPE (eV)	Operating Lifetime prediction EPR / XLPE ts (Years)
60	135 / 150	0.2 / 0.1	1.15 / 1.24	315 / 977
70				98 / 278
80				33 / 85
90				12 / 27

As evident from calculated results, the main insulation material can withstand long-term operation at normal ambient temperature below 50 °C which is the case in most cable areas in plants. For two insulation materials, EPR and XLPE, calculations considered more conservative activation energy of the material than in references [3, 6]. Arrhenius calculated limited temperature for 60 years lifetime for both materials: EPR at 74 °C and XLPE at 83 °C. In most of the references, end life of insulation is considered at 50 % Elongation at Break [3, 6, 7, 8]. This value was also used as a reference considering development of Indenter Modulus (*IM*) criteria for field and laboratory determination of polymer degradation due to aging effects. Such temperature and radiation causing hardening and embrittlement is described in the next paragraph.

2.3 Indenter Polymer Aging Monitor (IPAM)

The Indenter Polymer Aging Monitor (IPAM) is a portable test instrument for testing the cables installed in the Krško nuclear power plant. The Indenter test data enables characterisation of the condition of plant cables. Data gathered by Indenter provides a means to track polymer degradation due to thermal, radiation, and other environmental stressors. Indenter measures the embrittlement (hardening) of the cable jacket and insulation. This is achieved by recording force and deformation readings as a small instrument anvil is pressed against the insulation or jacket at constant velocity. The change in force divided by the change of deformation is called the (compressive) “modulus” or Indener Modulus – *IM*. For cable materials that harden with age, the Indenter modulus will also increase to reflect the change in cable properties [8]. Indenter Modulus data can be correlated with elongation-at-break (EAB) for given material type to quantify the cable insulation condition to accepted standard. This correlation allows the Indenter to acquire cable condition information with a non-destructive test. The method was implemented at the Krško NPP with acceptance criteria developed [9]. This method, shown in Figure 3, uses a small-diameter probe (anvil) to press against a cable. The force needed to compress the polymer jacket to a limited, defined extent is measured. The force F used and the displacement X are plotted against each other. The indenter modulus IM of the material is the slope of the line relating the change in force ΔF to the change in deformation ΔX (or velocity in time slope) (3). Ten measurements of the cable, rotated for 90°, were calculated to obtain the average value IM_{avg}.

$$IM=\Delta F/\Delta X \tag{3}$$



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TEST RESULTS

odulus Method
5% 75% of Peak Force

TEST	MOD	RELAX
Accept		
Avg.	13.4	40.0
1	11.9	45.1
2	13.2	41.6
3	12.7	39.2
4	15.3	37.0
5	13.2	40.7
6	12.8	41.8
7	13.7	36.3
8	14.8	37.2
9	12.6	42.0
10	14.1	38.8

* = Marked Test
(not included in average)

Fig. 3 Indenter Modulus Testing Equipment and functionality description [9]

Acceptance criteria for indenter modulus (*IM*) were developed in 2011 based on 21 samples of different nuclear-qualified cables, and on specific manufacturers and materials. The sampled cables were taken from a warehouse and artificially temperature aged in an air circulated oven at 120 °C at 9 different time stages. The summarized results of the experiment with *IM* measurements criteria are described in Table 2 and Figure 4 [9, 10, 11].

Table 2 Indenter Modulus Average Results for general evaluation of CSPE jacket condition

Stage	Time (h)	IM_{avg} CSPEjacket (N/mm)	IM_{avg} EPR (N/mm)	IM_{avg} XLPE (N/mm)	Equivalent Operation time at 50 °C (years)	Evaluation Criteria
#1*	0	10-12	12.9	103	/	NEW-Good
#2	72	12	--	--	12	Good
#3	144	13	--	--	24	Good
#4	240	16	--	--	40	Trend
#5	360	19	--	--	60	Trend
#6*	528	80	15.2	--	89	Trend&Analysis
#7*	1032	100	--	80	174	Aged - Action
#8	1872	150	--	--	315	Aged - Action
#9*	3264	250	20.1	78	549	Aged - Action

* Sampled for the first DSC analysis

-- Values not used for the first DSC analysis

For the first DSC measurement, only three representative samples of three different jacket and insulation materials were used. Main changes in material are demonstrated between stage #1 for new cable, stages #6 for trending value and stages #7 or #9 for aged polymers.

Fig. 4 Samples of 9 stages labelled oven aged cables with EPR insulation and CSPE jacket [9]

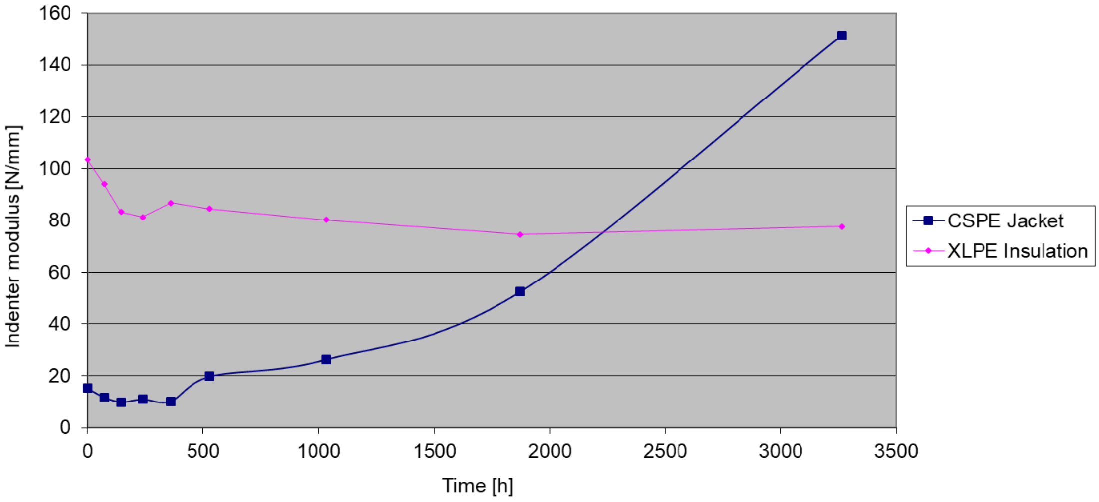

Fig. 5 Indenter modulus of XLPE insulation and CSPE jacket; oven-aged cable: 3264 hours at 120 °C [9]

The numbers in Table 2 and characteristics of the CSPE jacket in Figure 5 demonstrate the value of *IM* ranging from 12-20 N/mm. After approx. 400 hours of oven aging, *IM* of CSPE jacket start to grow rapidly to a value of over 150 N/mm. *IM* values for EPR increase with aging but XLPE insulation decreases at the beginning of aging and remains almost constant. That means that the aging time should be much longer until degradation is notable and the slope of the curve starts to increase.

3. Experiment for DSC

Different samples of commonly used nuclear qualified cable insulation materials (EPR and XLPE) and jacket (CSPE) were taken from a warehouse. Samples were temperature aged in an air controlled oven at 120 °C in different stages to evaluate mechanical, calorimetric and chemical properties of polymers. Main goals of the oven temperature aging was to develop acceptance criteria for a visual control, considering color change and mechanical properties of polymers detected with Indenter Modulus (*IM*) and to correlate results with the DSC results. Some preliminary results are presented.

3.1 Instrumental

DSC measurements were performed using a Mettler Toledo DSC 1 Instrument. Measuring conditions were chosen according to ISO 11357-6:2008(E) standard [12].

For oxidation induction temperature (dynamic OIT) measurements approximately 3-4 mg sample was placed in a 40 μL aluminum crucibles and covered with a pierced lid. Programmed heating started at 25 °C with a heating rate of 10 °C /min in an oxygen (5.0 purity) atmosphere with flow-rate of 30 mL min^{-1}. End temperature was 325 °C. The intercept point (dynamic OIT) was determined by tangent method.

Oxidation induction time (isothermal OIT) measurements started from 25 °C under nitrogen (5.0 purity) atmosphere to the test temperature at a heating rate of 20 °C /min. The instrument was pre-purged with nitrogen for 5 minutes prior to the beginning of the heating cycle. After reaching the test temperature, the sample was isothermally treated for another 3 minutes in nitrogen before the gas was switched to oxygen at a same flow-rate (30 mL min^{-1}). The test temperature was selected from 15 to 25 °C below the oxidation induction temperature, so specimens provided an oxidation induction time between 10 to 60 minutes before the oxidative decomposition.

4. Results and discussion

Laboratory oven temperature aging, correlated with findings on cables in the plant, confirmed degradation of cable insulation, i.e. discoloration and embrittlement, and resulted in cracking and a loss of dielectric strength [13]. Polymeric materials, used for nuclear qualified cable (XLPE and EPR) insulation, which were exposed to accelerated ageing over a period of time, resulted in lower oxidation induction temperature, i.e. aged polymers were more prone to oxidation. Similar conclusions are confirmed in previous research studies and publications[14].

In Figure 6, dynamic DSC curves of XLPE wire insulation, aged to different degrees (unaged, 6th and 9th stage ageing), are shown. From the obtained results (Figure 6, Table 3) it is clearly seen that the OIT temperature of this insulation, composed of cross-linked polyethylene (XLPE), was lowered from 266 °C (unaged) to 213 °C (most aged) . In Figure 7, oxidation induction time of the same samples is presented. Condition temperature was chosen on the basis of dynamic OIT and ISO 11357-6:2008(E) standard [12]. For unaged sample, the OIT was 21.6 minutes when exposed to 240 °C, while for the most aged the OIT was 23.0 minutes after exposure to 200 °C (Table 3).

The results of dynamic and isothermal OIT for Okonite insulation, composed of ethylene propylene rubber (EPR), are also presented in Table 3 showing similar behavior. For this type of insulation oxidation processes start at lower temperatures comparing to XPLE insulation type (approximately 30 to 40 degrees), but the tendency is the same.

It was already shown that the OIT measurements had to be very sensitive to detect the initiation and subsequent degradation of XLPE and EPR insulation [13]. Since only a few milligrams of the sample are needed for the DSC measurement, deterioration of cable insulation can be monitored without affecting the function of the cable. Additionally, we also measured dynamic OIT for jackets of the mentioned unaged and aged samples, composed of chlorosulfonated polyethylene (CSPE), but almost no changes were detected for jacket materials, aged to different degrees. Further researches (FTIR, chemiluminescence) are planned for the determination of CSPE deterioration during ageing.

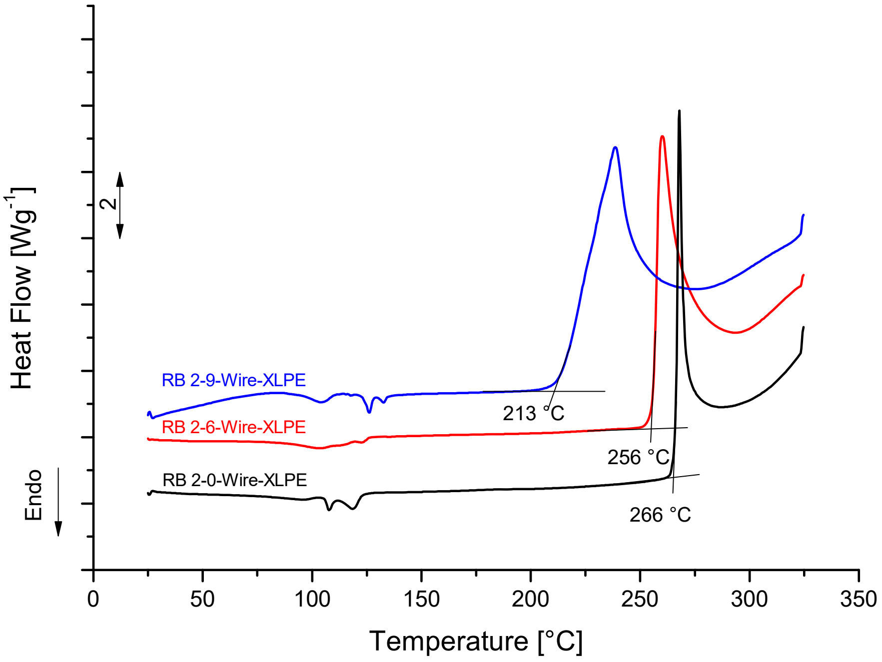

Fig. 6 Dynamic OIT of XLPE aged samples 0, 6, 9 in oxygen atmosphere

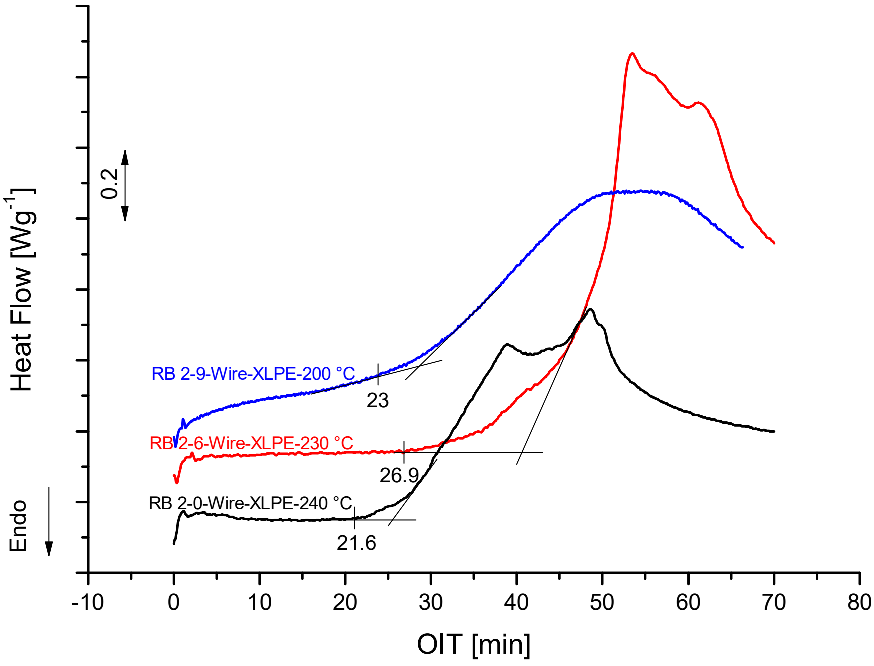

Fig. 7 4th segment of isothermal OIT method of XLPE aged samples 0, 6, 9 – time determination by isothermal heating in oxygen atmosphere at test temperature

Table 3 OIT temperature (T_{OIT} or Ton) and time by isothermal heating at T_{ISO} for XLPE and EPR aged samples 0, 6, 7, 9

XLPE			**EPR**		
Sample name	T_{OIT} /°C	t_{OIT} /min (T_{ISO})	Sample name	T_{OIT} /°C	t_{OIT} /min (T_{ISO})
2-**0**-Wire-XLPE	266	21.6 (240 °C)	3-**0**-EPR	238	32 (220 °C)
2-**6**-Wire-XLPE	256	26.9 (230 °C)	3-**7**-EPR	215	23 (190 °C)
2-**9**-Wire-XLPE	213	23.0 (200 °C)	3-**9**-EPR	175	10 (150 °C)

Legend:

2-**0**-Wire-XLPE unaged, grey, flexible insulation (RB)

2-**6**-Wire-XLPE 6th stage aged, grey, flexible insulation (RB)

2-**9**-Wire-XLPE 9th stage aged, grey, hardened-flexible insulation (RB)

3-**0**-EPR unaged, red, flexible insulation (OK)

3-**7**-EPR 7th stage aged, red, hardened-flexible insulation (OK)

3-**9**-EPR 9th stage aged, red, hardened-flexible insulation (OK)

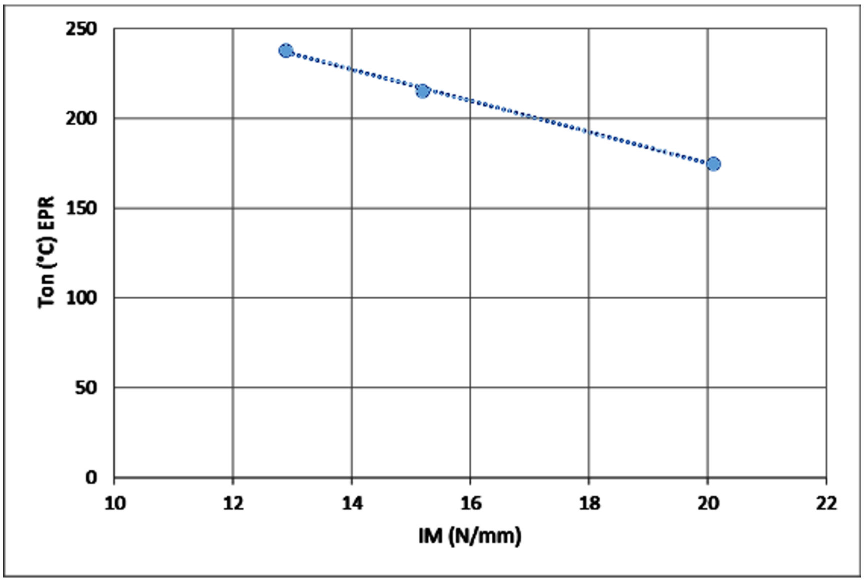

Fig. 8 Correlation between Indenter Modulus (IM) and OIT temperature (Ton) for EPR

5. Conclusion

The DSC measurements of EPR and XLPE used for insulation in nuclear qualified cables reveals preliminary test results. Compared to indenter modulus OIT, the onset time showed good correlation for EPR as can be seen in Figure 8 and might be used as a remaining life model if more testing samples and different methods, such as FTIR, TGA and chemiluminescence, would be used.

NOMENCLATURE

NEK Krško Nuclear Power Plant
SR Safety Related (1E) in accordance with [2]
EPR Ethylene Propylene Rubber
XLPE CrossLinked PolyEthylene
CSPE ChloroSulfonated PolyEthylene
RB Rockbestos
OK Okonite
BIW Boston Insulating Wire
IM Indenter Modulus
DSC Digital Scanning Calorimetry
OIT Oxidation Induction Time
Ton Onset Time – time of melting
FTIR Fourier Transform Infrared Spectroscopy
TGA Thermogravimetric analysis

REFERENCES

[1] M. Pirc, Cable Aging Management Program, TD-2D, rev.2, NEK, 2016
[2] IEEE 323-2003, Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations

[3] SAND96-0344, Aging Management Guideline for Commercial Nuclear Power Plants - Electric Cable and Terminations, Ogden Environmental and Energy Services under contract to Sandia National Laboratories for the U.S. Department of Energy

[4] M. Pirc and J. Avsec, Cable-Aging Management Program Implementation in Nuclear Power Plants, JET Volume 9, Issue 2, p.p. 73 – 90, 2016

[5] K. L. Simmons, Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Study FY13, PNNL for US DOE, September 2013

[6] NP-7485 Power Plant Practices to ensure cable Operability, Electric Power Research Institute, 1992

[7] IEEE Std. 1205-2000, Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations

[8] NP-T-3.6, International Atomic Energy Agency, Assessing and Managing Cable Ageing in Nuclear Power Plants, 2012

[9] M. Pirc, Development of acceptance criteria for Indenter Modulus, HS-2011-02-T-IM, NEK, 2011

[10] M.Pirc, Vzpostavljanje programa nadzora staranja električnih kablov v NEK, CIGRE, 2011

[11] M. Pirc, Rezultati diagnostičnih testiranj kablov v NEK, CIGRE, 2015

[12] ISO 11357-6: 2008 (E), Plastics – Differential scanning calorimetry (DSC), Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)

[13] K. Anandakumaran, D. J. Stonkus: Assessment of Oxidative Thermal Degradation of Crosslinked Polyethylene end Ethylene Propylene Rubber Cable Insulation, Polymer Engineering and Science, 32, 1992, 1386-1393. https://doi.org/10.1002/pen.760321808

[14] K. Anandakumaran, W. Seidl and P.V.Castaldo, Condition Assessment of Cable insulation Systems in Operating Nuclear Power Plants, IEEE Transactions on Dielectrics and Electrical Insulations, Vol. 6 No.3, 1999, p. 376-384. https://doi.org/10.1109/94.775626

Submitted: 20.6.2017

Accepted: 15.02.2018

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