JOURNAL OF ENERGY TECHNOLOGY
Vol. 18, No. 1, pp. 35–54, May 2025

Original Scientific Article

CHEMICAL ANALYSIS OF THERMALLY AGED CABLES IN NUCLEAR POWER PLANTS

MARKO PIRC,[1] JURIJ AVSEC,[2] DIJANA VRSALJKO[3]
[1] Nuclear Power Plant Krško (NEK), Krško, Slovenia
marko.pirc@nek.si
[2] University of Maribor, Faculty of Energy Technology, Krško, Slovenia
Jurij.avsec@um.si
[3] KONČAR - Electrical Engineering Institute, Zagreb, Croatia
dvrsaljko@koncar-institut.hr

CORRESPONDING AUTHOR
marko.pirc@nek.si

Submitted
10. 4. 2025

Accepted
13. 4. 2025

Published
30. 5. 2025

Abstract The paper presents findings on the implementation of various mechanical and chemical diagnostic procedures aimed at enhancing the monitoring of cable insulation conditions in Krško Nuclear Power Plant (NEK). This article introduces the advancement of four novel diagnostic testing methodologies for evaluating the mechanical and chemical properties of cable insulation: Indenter Modulus (IM), Differential Scanning Calorimetry (DSC), Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric analysis (TGA) and X-Ray Fluorescence Spectral Analysis (XRF). Experiments were performed on diverse samples of widely used nuclear-qualified cable polymer materials, including Ethylene Propylene Rubber (EPR) and Crosslinked Polyethylene (XLPE), all with a Chlorosulphonated Polyethylene (CSPE) jacket. Samples from various vintages were subjected to additional temperature ageing in many stages, to establish field testing acceptability requirements and assess the remaining lifespan of the polymer insulation. Diagnostic tests were performed and some preliminary results are reported.

Keywords
cable,
ageing,
nuclear,
diagnostic testing criteria,
chemical condition monitoring

https://doi.org/10.18690/jet.18.1.35-54.2025

University of Maribor Press

1 Introducton

Safe operation is one of most important topics in the nuclear power industry. Electrical cables are installed and connected to every electrical component, and are essential for its functionality and overall system operation as well. More than 1,000 kilometres of installed cables in more than 20,000 circuits and hundreds of distinct cable types based on function, construction, material, and manufacturer can be found in a typical nuclear power station. It makes electrical cables one of the critical subcomponents, and the operator needs to provide reasonable assurance of their functionality. In order to achieve this goal, Krško Nuclear Power Plant (NEK) launched the Cable-Ageing Management Program (CAMP) [1]. Its key concerns were managing cable insulation and connections, and identifying potentially harmful localised surroundings or unfavourable service circumstances. The primary objective is to assess key cable reliability for up to 60 years of extended plant life operation. The CAMP uses visual inspection and measurements of environment parameters at cable areas to search for potential local adverse environments, such as high temperature, radiation, humidity or submergence, chemical or mechanical wear. Field diagnostic testing of electrical and mechanical parameters is being performed on selected cables sampled in specific local adverse environments.

Most of the cables sampled in the CAMP scope are recognised 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. If these environmental parameters are met—that is, the room ambient temperature never rises beyond 40 °C, there are no close hot process lines, radiation sources, no submergence or regularly manipulated connections—the cables won't age noticeably. Control cables, instrumentation cables, and medium- and low-voltage power cables are the cable categories to which the program is applicable, depending on the voltage or material type. The program applies to commonly used nuclear qualified cable insulation materials (EPR and XLPE) and jacket (CSPE and Neoprene). Based on proved existing diagnostic testing methods for field testing of electrical, physical and mechanical parameters, this work presents some available advanced testing of thermal and chemical properties with the initial results.

2 Methodology

For this research we selected two material manufacturers: Boston Insulated Wire (BIW) and Rockbestos (RB), which represent the majority of installed cables in NEK nuclear Safety Related (SR) circuits [1]. The predominant insulating materials in NEK safety-related, environmentally qualified cables [2] are cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR), together with chlorosulphonated polyethylene (CSPE, Hypalon®) and Neoprene for the outer jacket. For over 60 years of operation under typical design temperature and radiation, all the materials have extremely good thermal, radiation and moisture resistance. The materials employed most commonly for mechanical and fire protection, as well as indicating materials for harmful environmental effects, are CSPE and Neoprene jackets [3].

Samples of the specified materials were prepared for thermal ageing. Nine different time stages of temperature aged samples were evaluated for the mechanical and chemical properties of polymers. In this article the focus was temperature ageing at 120°C in an air circulating oven, with the initial goal to develop acceptance criteria for a visual control, considering change of polymer colour and mechanical properties detected with the Indenter Modulus (IM). The results were correlated with a standardised elongation at break (EAB) test with acceptance criteria defined and described in the program [1], [4], [9] and implementation testing procedures. This article presents the initial results obtained from various chemical laboratory instruments and analytical methods, including Differential Scanning Calorimetry (DSC), Fourier Transform Infrared spectroscopy (FTIR), Thermogravimetric analysis (TGA) and X-Ray Fluorescence Spectral Analysis (XRF).

Temperature ageing is described as implemented for the purpose of this work. The main intention for the ageing of the samples to be taken for laboratory tests, was in order to determine the actual scale of different properties` changes. The laboratories testing results of mechanical and chemical properties could be used for acceptance criteria, and also for detailed modelling of the remaining life prediction [5]. The main concept is described in Figure 1.

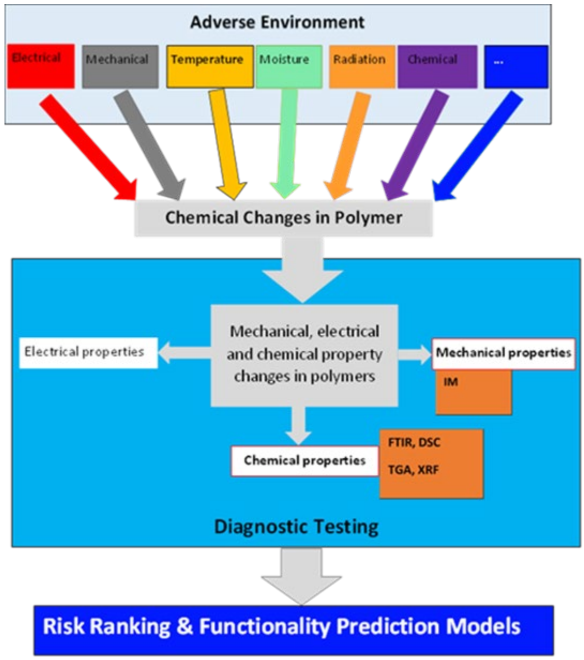

Figure 1: Cable Life Prediction and Ageing Detection model
Source: [4, 5, 13]

2.1 Accelerated temperature Ageing

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

Accelerated thermal ageing of specific polymeric materials was conducted in a laboratory air circulated oven. In accordance with IEEE 1205-2000, the Arrhenius model relates the rate of degradation (reaction) to temperature through the exponential function (2.1) [7], and is used commonly for thermal ageing evaluation of polymers in nuclear qualified cables. The Arrhenius equation describes the relation between the rate of degradation, ageing temperature and exposure duration [6], [7], [8]. This model was used for determination of different ambient temperature influence on cable polymer materials. The aged samples were taken for indenter modulus testing and acceptance criteria development, as described in the next paragraph.

$$R = A \cdot e^{\frac{-E_a}{k_B \cdot T}} \tag{2.1}$$

Where

R - Specific rate of degradation reactions between molecules
A - Constant velocity of the molecules (property of the material)
T - Absolute temperature (K)
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 ageing 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; the material with higher activation energy will degrade thermally at a slower rate than one with lower activation energies [3]. The specific values of activation energy, used in Table 1, were obtained from the cable qualification reports used at the NEK [1, 3, 13], 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 (2.2) often correlates the degradation durations of a material at two distinct temperatures [7].

$$\frac{t_s}{t_a} = e^{\frac{E_a}{k_B}\left(\frac{1}{T_s} - \frac{1}{T_a}\right)} \tag{2.2}$$

Where

T_s - Ambient operating temperature (K)
T_a - Accelerated ageing temperature (K)
t_s - Operating time at the ambient temperature T_s
t_a - Time of accelerated ageing at temperature T_a
E_a - Activation energy (eV, J/mol)

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 ta. Implicit in this relationship is the idea that exposure of a material at a higher temperature for a shorter duration will result in degradation equivalent to that resulting from longer exposure at a lower temperature [3, 6, 7, 8, 13]. For demonstration, the impact of temperature ageing of polymer materials' properties of nuclear cable insulation during its operating lifetime are calculated and presented in Table 1.

Table 1: Calculated temperature lifetime using the Arrhenius model for EPR / XLPE

Operating Temperature T_s (°C)	Qualification Ageing Temperature EPR/XLPE/CSPE T_a (°C)	Ageing time EPR/XLPE/CSPE t_a (Year)	Activation Energy EPR/XLPE/CSPE E_a (eV)	Operating Lifetime prediction EPR / XLPE/ CSPE t_s (Years)
60	135 / 150 / 80	0,2 / 0,1/ 13,5	1,15 / 1,24/ 1,14	315 / 977 / 128
70				98 / 278 / 40
80				33 / 85 / 13
90				12 / 27 / 5

The primary polymer material can tolerate long-term operation at a normal ambient temperature below 50 °C, as shown by the computed findings, which is the case in the majority of cable areas in plants. The calculations took into account the material's activation energy more conservatively than in references [3, 6] for the polymers XLPE, EPR and CSPE. For a material with a 60-year lifespan, Arrhenius determined the following limiting temperatures: CSPE at 66 °C, EPR at 74 °C, and XLPE at 83 °C. The end life of insulation is typically taken into account at 50 % elongation at break in the majority of references [3, 6, 7, 8]. The acceptance criteria have been established and validated for the Indenter Modulus (IM) to evaluate polymer deterioration due to temperature impacts in the field.

2.2 Indenter Polymer Ageing Monitor (IPAM)

The Indenter Polymer Aging Monitor (IPAM) is a portable test instrument for field testing the cables installed in the NEK. The Indenter test data enable characterisation of the condition of the plant cables. The data gathered by the Indenter provide a means to track polymer degradation due to thermal, radiation, and other environmental stressors. The 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 Indenter Modulus – IM. For aged cable materials, the Indenter modulus will also increase to reflect the change in polymer properties [8]. The Indenter Modulus data can be correlated with elongation-at-break (EAB) for a given material type to quantify the cable insulation condition to an accepted Standard. This correlation allows the Indenter to acquire cable condition information with a non-destructive test. The method was implemented at the NEK with the acceptance criteria developed in [1]. This method 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 slope of the line connecting the change in force (ΔF) to the change in deformation (ΔX) (2.3) is the material's indenter modulus (IM) [13]. Ten measurements of the cable, rotated by 90°, were calculated to obtain the average value IM_{avg}.

Table 2: Results of the Indenter Modulus with acceptance criteria evaluation for four stages ageing of different polymers

Ageing Stage	Thermal Ageing time (h) at 120°C	IM_{avg} CSPE jacket (N/mm)	IM_{avg} EPR (N/mm)	IM_{avg} XLPE (N/mm)	Equivalent Operation time at 50°C CSPE (years)	Evaluation Acceptance Criteria of remaining life time
# 0 (1)	0	10-12	12.9	103	/	Unaged - Good
# 6	528	80	15.2	84	89	Trend & Analysis
# 7	1032	100	/	80	174	Aged – Action
# 9	3264	250	20.1	78	549	Aged - Action

a Samples for chemical analysis using DSC, FTIR, TGA, XFR.

$$IM = \Delta F / \Delta X \ [N/mm] \tag{2.3}$$

Four samples of aged cables were selected for this study. Thermal ageing was carried out in a convection oven at 120 °C throughout four distinct time intervals. Table 2 [9, 11, 13] presents the summarised results based on the IM measurement criteria for particular materials.

Four aged typical samples of various jacket and insulation materials were chosen for the first thermal and chemical examination in the laboratory. Stage #0 (1) for unaged cable, stage #6 for trending value, and stages #7 or #9 for the aged polymers with equal operating time calculated in Table 2 illustrate the main material changes. The figures in Table 2 and the features of the CSPE jacket show that $IM_{avg,}$ with values between 12 and 20 N/mm, is acceptable. The IM of the CSPE jacket began to grow quickly after 528 hours of oven ageing, reaching a value of more than 170 N/mm 1032 hours. When EPR ages, the IM values rise, but the XLPE insulation falls off at the start of ageing and stays nearly constant. This implies that, until degradation becomes apparent and the curve's slope starts to rise, the ageing period should be significantly longer.

3 Laboratory test of the thermal and chemical parameters

3.1 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) is used for the characterisation of semi-crystalline polymer systems [10]. DSC measures the flow of heat in and out of the test samples over time as a function of the sample temperature. The features in a DSC curve include phase change transitions. In the DSC curve of Oxidation Induction Time (OIT), heat flows into a sample with rising temperature to effect endothermic transitions, including the transition from a solid to a glassy state, the glass transition, and from a glassy solid to a melted liquid. Heat is also consumed in the evaporation of volatile compounds such as added processing aids. In a semi-crystalline polymer, it is the material in the crystalline regions that undergoes a distinct melting transition. The integral of the melting peak in the DSC curve is, thus, a direct measure of the crystalline content of the system. The shape of the DSC curve, including the location of the glass transition, is also related to chain scission and cross-linking that the polymer may have experienced [10].

Three different samples set of commonly used cable insulation materials (EPR and XLPE) and jacket (CSPE and Neoprene) were preaged in an air-controlled oven in different stages to evaluate the mechanical, calorimetric and chemical properties of the polymers. Temperature aged cable polymers were tested with an Indenter Modulus (IM) and the results were corelated with the DSC results OIT and OITP [13], [14]. The samples were prepared and delivered into a laboratory as described in Table 3. Samples 2015/08, 09 and 10 were aged in three stages for test as stated in Table 2: Stage #0/1 (Non-aged), stage #6 (528 hours at 125 °C) and stage #9 (3264 hours at 125 °C). The test procedure and instructions were based on standard IEC-IEEE 62582-4 and ASTM D3895-95 [14].

Table 3: Test samples` identification and description [14]

Manufacturer designation	Sample id. No.	Description
CBL: B-8	2015/08	BIW, 1978, CSPE + (EPR + Hypalon) Stg.0/1,6,9
CBL: B-8RB FW III	2015/09	RB, 1979, Neoprene + (XLPE) Stg.0/1,6,9
CBL: C-1	2015/10	BIW, 1976 CSPE + (EPR + Hypalon) Stg.0/1,6,9

The measurements were conducted with a calibrated testing machine, DSC Q100 TA Instruments, with aluminum sample pans for the autosampler with a gas flow of Nitrogen and Oxygen. A Mettler Toledo Balance, AX 205 DR/A, was used, with sample slices cut as a cross-section in a mass range from 1 to 4 mg; detailed information is in the Tables with results. The procedure was carried out by two different test types, and gave a description of a typical profile for D - Dynamic test (Ramp) and I – Isothermal measurement. The experiment runs in oxygen atmosphere and is recorded at the D - Dynamic test (Ramp). The temperature was increased in a defined speed and temperature interval to the temperature above the degradation point of the sample, at a heating rate of 10 °C/min, in an oxygen atmosphere. For the I-Isothermal measurement, for example, I185 (ISO-185) at a temperature increase up to a set temperature of 185 °C, while the temperature in the nitrogen increased at a higher heating rate 50 °C/min. At this temperature nitrogen is replaced by oxygen and the experimental data were recorded for a defined time, so it is possible to determine the oxidation induction time [14].

3.2 Fourier Transform Infrared spectroscopy (FTIR)

An FTIR spectrum is a plot of absorbance (or transmittance) versus wavenumber (cm^{-1}). Each peak in the graph corresponds to a specific molecular vibration. The position (wavenumber) and intensity of these peaks provide information about the molecular structure. Different functional groups absorb IR radiation at characteristic wavenumbers. For example: the region below 1500 cm^{-1} is known as the fingerprint region. It contains complex absorption patterns unique to each molecule, making it useful for identification. Fourier Transform IR measurements were used to determine the level of oxidation in a range of polymeric materials by measuring the height (or area) of the absorption related to oxidative species, e.g., the –C=O carbonyl group stretch around 1700 cm^{-1}, the O-H stretch around 3200-3600 cm^{-1}, the C-H stretch around 2800-3000 cm^{-1}. The ratio of the height (or area) of the carbonyl absorption near 1720 cm^{-1} and the –C-H absorption near 1370 cm^{-1} is the oxidation index [10]. The specific peaks that monitor ageing in the cable materials being tested best cannot be specified initially, but will be determined on the basis of all of the ageing data obtained. Materials containing carbon black are difficult to measure, because of the high absorption observed across the IR frequency range [10].

3.3 Thermogravimetric analysis (TGA)

TGA measures the weight loss of a micro-sample during nitrogen heating using conventional thermal analysis equipment. TGA assesses sample weight and mass as a function of temperature. TGA measures mass changes (gain or loss), assesses stepwise mass changes (typically as a percentage of the starting sample mass), and identifies temperatures that define a mass loss or gain curve step.

Samples were taken as a through thickness slice of the insulation or jacket material being tested. Each sample for TGA measurement was in the range ~5 mg in weight. The test parameters for each TGA sample should be heated in flowing nitrogen at a temperature ramp rate of 10° C/min. The temperature should be reported at the maximum rate of weight loss and at 5% weight loss [8, 10, 13].

3.4 X-Ray Fluorescence Spectral Analysis (XRF)

X-Ray Fluorescence Spectral Analysis (XRF) is an analytical technique for determination of the elemental composition of materials. The detector uses a dispersive system to measure the different energies of the characteristic radiation from the sample, and it can separate signals to different elements. XRF aims to estimate the degradation of polymer insulation based on measurements of the presence or absence of individual atoms [15]. In this work the initial acceptance criteria were drafted for the BIW CSPE jacket specific elements in relation to temperature aged interval correlated to the IM values.

4 Results and discussion

4.1 Results for Differential Scanning Calorimetry (DSC)

The initial results for DSC are described in Tables 4-9, where the results were averaged after 3 tests in the required 10 % deviation range [14]. Figures 4, 5 and 6 show the evaluation of sample 2015/09 (jacket and insulation) by the D or ISO experiments. Figure 8 shows the evaluation of sample 2015/10 (insulation) by the D experiment.

During the isothermal experiments, the oxidation induction time (OIT) and peak extreme were evaluated (the maximum value Max is described only in the Figures, but not in the Tables). In the dynamic experiments, the characteristic points at curve of heat flux versus temperature, e.g., peak extremes were evaluated, such as minimum (Min), maximum (Max), oxidation induction temperature (OITP) [14]. The DSC test results of OITP on Tables 5, 6 and Fig.2 and 3 for RB insulation and Jacket did not correlate to the IM results of different ageing steps as expected for Neoprene and XLPE, and are conditionally appropriate for this testing procedure only in the final stages, and it is recommended to compare them to other stages.

Table 4: Results of the dynamic and isothermal tests on sample BIW Id. No. 2015/08 [14]

Sample description	Test type	OITP [°C] OIT [min]
BIW jacket CSPE	D	179.7
Insulation white EPR	D	243.7
BIW jacket CSPE	I180	11.78
Insulation white EPR	I215	13.78

Table 5: Results of the dynamic tests on sample Id. No. 2015/09 – insulation (compared with Fig. 2) [14]

Sample description	Test type	OITP [°C]
Insulation white, non-aged	D	268.7
Insulation white, aged, Stg. 6	D	198.7 ± 0.7
Insulation white, aged, Stg. 9	D	244.9 ± 1.5

The DSC test results of OIT in Tab.7, 8 and Fig.7 for RB insulation and Jacket correlated to the IM results of different ageing steps, leading to the conclusion that Neoprene and XLPE are appropriate for this testing procedure, and could be used as future acceptance criteria for both materials

Table 6: Results of the dynamic tests on sample Id. No. 2015/09 – jacket (compared with Fig. 3) [14]

Sample description	Test type	OITP [°C]
RB neoprene jacket, non-aged	D	209.7
RB jacket, aged, Stg. 6	D	209.3 ± 5.2
RB jacket, aged, Stg. 9	D	208.4 ± 1.8

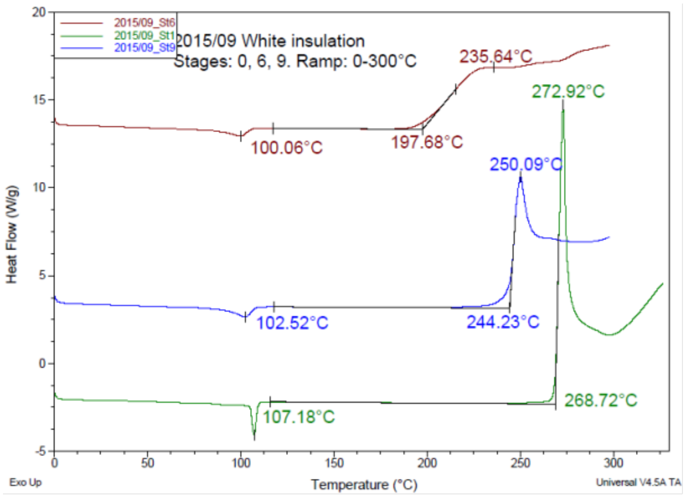

Figure 2: Dynamic test of RB 2015/09 – aged to stage 0, 6 and 9 XLPE insulation white

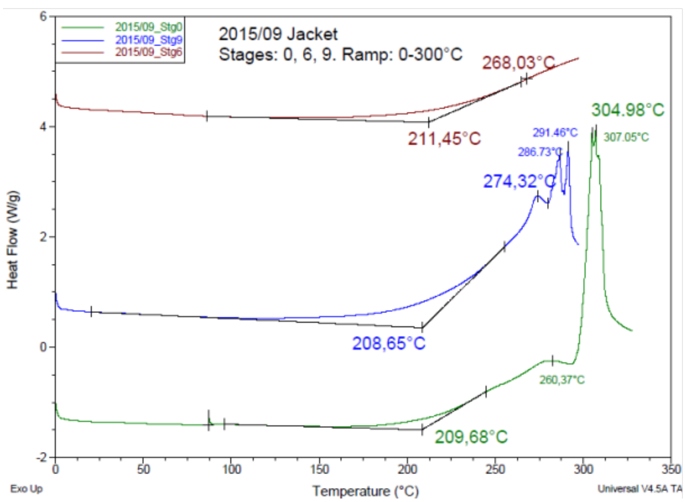

Figure 3: Dynamic test of RB 2015/09 – aged to stage 0, 6 and 9 Neoprene Jacket

Table 7: Results of the dynamic tests of 2015/09 – white insulation (compared with Fig. 4) [14]

Sample description	Test type	OIT [min]
RB XLPE white ins. -non-aged	I225	61.2 ± 1.0
RB XLPE white ins.-aged, Stg. 6	I225	6.85
RB XLPE white ins.-aged, Stg. 9	I225	4.96

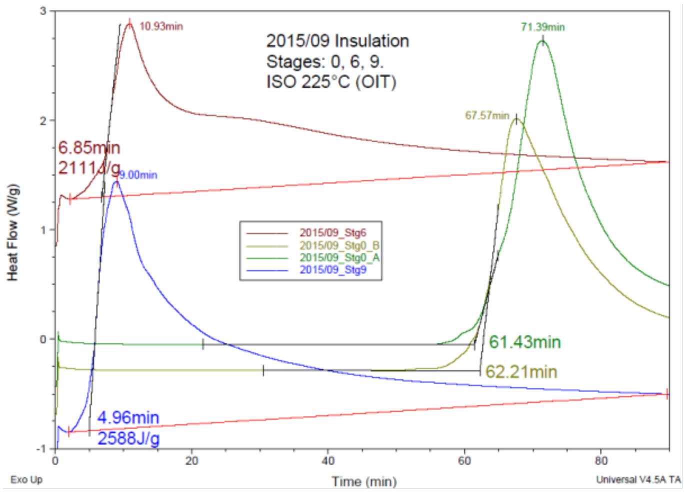

Figure 4: Isothermal test of RB Cable 2015/09 aged to 0,6 and 9 XLPE Insulation
Note: it was possible to determine OIT for stage 0 only; the other times are too short for evaluation

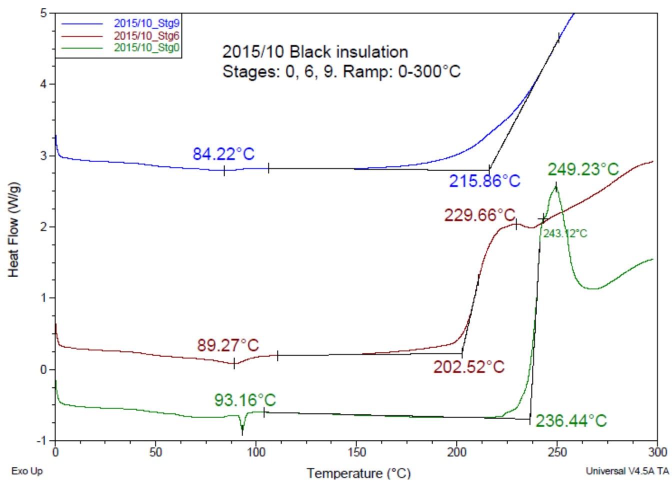

Figure 5: Isothermal test of BIW Cable 2015/10 at 225 °C for bonded EPR-CSPE Insulation

Table 8: Results of the D and ISO tests on sample Id. No. 2015/10 (compared with Fig. 5)

Sample description	Test type	OITP [°C] OIT [min]
BIW CSPE jacket non-aged	D	209.7
Insulation white, non-aged	D	268.6
Insulation black, non-aged	D	234.4 ± 3.2
Insulation black, aged, Stg. 6	D	205.5 ± 0.7
Insulation black, aged, Stg. 9	D	212 ± 10
BIW CSPE jacket non-aged	I220	80.76
Insulation white, non-aged	I230	50.84
Insulation black, aged	I185	70.2 ± 2.6
Insulation black, aged, Stg. 6	I185	5.65
Insulation black, aged, Stg. 9	I185	7.54

The DSC test results of OIT and OITP on Tab.8 and Fig.5 for BIW EPR bonded CSPE insulation and CSPE Jacket correlated sporadically to the IM results of different ageing steps. This leads to a recommendation for additional tests of the materials and check for other available test procedures before the method could be used as acceptance criteria for both materials [14].

4.2 Results for Fourier Transform Infrared spectroscopy (FTIR)

The initial results of FTIR, TGA and XRF analysis of aged samples are preliminary compared with the basic description in Figures 6 -10 [16]. Identification of the testing samples as shown in Figures 6 and 7 are described in Tab.9

Table 9: Identification and description of the test samples for FTIR, TGA and XRF [16]

Manufacturer designation	Ageing Stage No.	Sample description
BIW	1	BIW CBLA-29, 1987, Unaged: CSPE Jacket
BIW	6	BIW CBLA-29, 1987 Aged #6: 528h at 120 °C CSPE Jacket
BIW	9	BIW CBLA-29 1987 Aged #9: 3264h at 120 °C CSPE Jacket
RB	1	Rockbestos, 2005, C51-030 FW III: Unaged: CSPE Jacket
RB	6	Rockbestos, FWIII Aged #6: 528h at120 °C: CSPE Jacket
RB	9	Rockbestos, FWIII, Aged #9: 3264h- 120 °C: CSPE Jacket

From the FTIR spectra for the BIW CSPE jacket in Fig. 6, it is evident that the material samples show changes due to the ageing effect of temperature degradation, resulting primarily in the reduction of signals characteristic of C-H (-CH2-) bonds: 3000-2850 cm^{-1}; 1470-1450 cm^{-1}; 725-650 cm^{-1} and S=O bonds in the region around 1000 cm^{-1} [16].

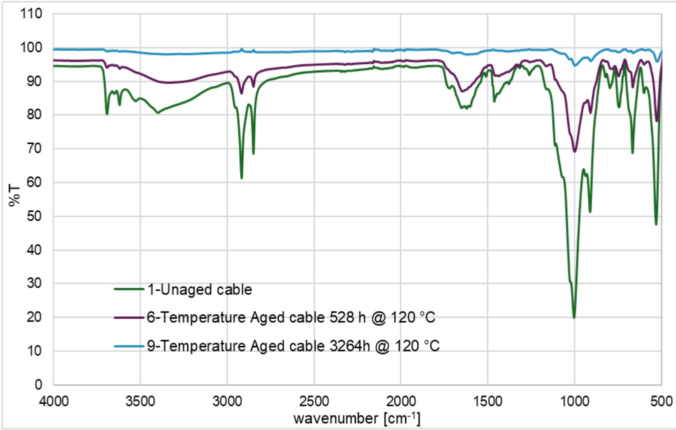

Figure 6: FTIR spectra of the BIW CSPE cable jacket
Source: [16]

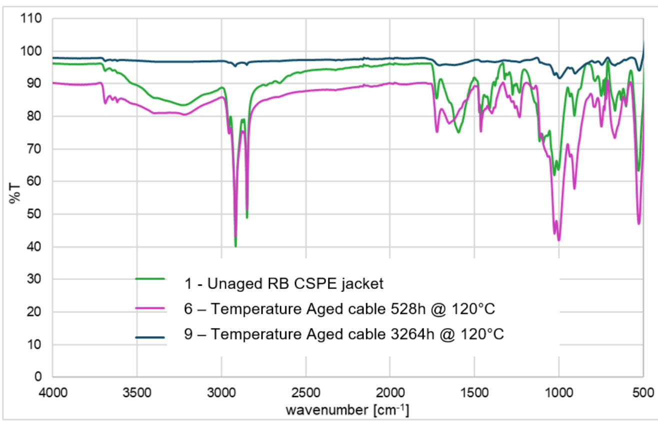

Figure 7: FTIR spectra of the RB CSPE cable jacket
Source: [16]

The main conclusion, based on the graphs in Fig. 7 for the RB jacket CSPE degradation is in accordance with ageing time, and could be used as acceptance criteria: the highest characteristic peaks for unaged material after 528 hours of ageing at 120 °C and all the peaks are lowering and at final ageing stage #9 the FTIR graph is almost flat – without any remaining characteristic peaks hardly observable at 1000 and 500 cm^{-1} [16].

The results for the BIW jacket indicate alignment with expectations, and acceptability criteria may be formulated; however, for RB, more testing will be required on additional samples from various vintages.

4.3 Results of Thermogravimetric analysis (TGA)

The initial results of TGA on Fig. 8 are showing some temperature degradation effects in the CSPE jacket in both stages, and are promising, resulting primarily in the reduction of signals at different temperatures 280 °C for unaged cable, 290 °C for 528 hours of ageing and 310 °C, and, at the second transition, 440 °C-450 °C-460 °C [16]. Consequently, they are applicable for the acceptance criteria that will be used and confirmed after recommended additional tests to be accomplished for different ageing stages and different materials to confirm the exact values.

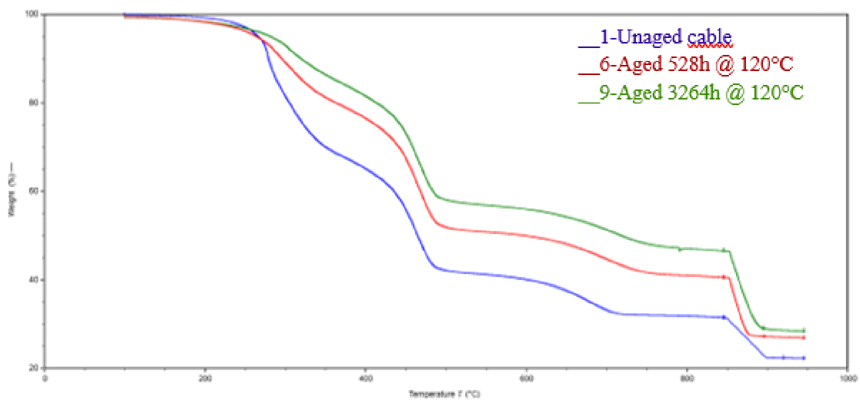

Figure 8: Thermograms of the cable CSPE jacket, new and aged

Source: [16]

4.4 Results for the X-Ray Fluorescence Spectral Analysis (XRF)

XRF analyses were conducted on the outer surface of the main BIW cable CSPE Jacket. The results of the XRF analysis are presented graphically in Fig.9; all the detected elements are listed in mass %, and a trend of changes in the chemical composition due to temperature degradation is easily observable. Due to the effect of temperature over time, migration, release, degradation and recombination occurs of certain components and compounds. Considering that it is a chlorosulphonated polymer, observing the XRF results for the Jacket, it could be concluded that significant changes occur in the content of chlorine (-80 %) and lead (Pb), silicon and sulphur (as well as other elements) due to the thermal ageing effect [16].

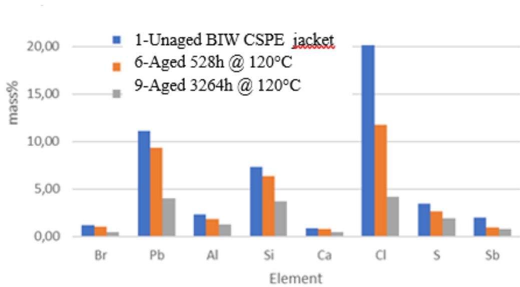

Figure 9: XRF results of the BIW CSPE jacket material depending on the thermal ageing time of the BIW cable. Without PE content (60-80 mass%)
Source: [16]

5 Conclusions

The outcomes of various mechanical and chemical diagnostic testing methods indicated a significant alteration in the properties of electrical cable polymers, which might be utilised for the remaining life prediction models. Advanced chemical testing methodologies have been implemented to promote their utilisation among users and researchers of electrical cables in nuclear power plants. These technologies provide enhanced understanding of the condition of the polymer insulation.

The primary conclusion of the research presentation is that certain chemical laboratory testing procedures may be employed to monitor and predict the reliability of polymers. Variations were identified and validated in various materials and testing methodologies. The preliminary conclusions on the acceptance requirements for the specified testing techniques validate that the indenter modulus (IM) is highly effective and suitable for field testing of prevalent jacket materials, including CSPE and NEOPRENE, as well as insulation materials like EPR. The acceptance criteria were established and validated in practice. Certain limitations of the XLPE material have been observed that require further assessment.

XRF demonstrates a highly promising association with IM for CSPE jackets, thereby rendering it suitable for field diagnostic purposes. It would be advisable to use a portable XRF tester that has been verified for accuracy using comparison on laboratory test samples.

DSC OIT has a favourable association with IM for some Neoprene and XLPE materials. Restricted use of DSC OITP with EPR, XLPE, and CSPE materials was seen, and further testing is advised. FTIR and TGA demonstrated a strong association with IM for some jacket CSPE (BIW), and the values may be utilised for acceptance criteria. The insulation materials EPR and XLPE are less promising for FTIR, warranting further research.

Additionally, it would be intriguing to assess the distinct impacts of ionising radiation under moderate heat conditions, and to establish particular metrics that could aid in identifying the radiation-induced breakdown of cable polymers.

Acknowledgment

The authors of this article wish to convey their appreciation to the Krško Nuclear Power Plant - NEK, Končar - Electrical Engineering Institute Zagreb, University of Maribor - Faculty of Energy Technology, and numerous specialists and experts in chemical and other laboratories for their assistance and support in further development of advanced cable condition monitoring techniques.

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Nomenclature

(Symbols)	(Symbol meaning)
NEK	Nuklearna elekrarna Krško
CAMP	Cable Ageing Management Program
SR	Safety Related, Nuclear Qualified (1E)
IM	Indenter Modulus
EPR	Ethylene Propylene Rubber (EPDM)
XLPE	Cross-Linked Polyethylene
CSPE	Chlorosulphonated Polyethylene (Hypalone®)
DSC OIT/OITP	Differential Scanning Calorimetry, Oxidation Induction Time / Temperature
FTIR	Fourier Transform Infrared Spectroscopy
TGA	Thermogravimetric analysis
XRF	X-Ray Fluorescence Spectral Analysis

Povzetek v slovenskem jeziku

Kemijske analize temperaturno staranih kablov v jedrskih elektrarnah. Prispevek predstavlja ugotovitve o izvajanju različnih mehanskih in kemijskih diagnostičnih postopkov za izboljšanje spremljanja stanja izolacije kablov v Nuklearni elektrarni Krško (NEK). Članek predstavlja uvajanje in razvoj štirih novih metod diagnostičnega testiranja za ocenjevanje mehanskih in kemijskih lastnosti izolacije kablov: indenter modul (IM), diferenčna dinamična kalorimetrija (DSC), Fourierjeva transformacijska infrardeča spektroskopija (FTIR), termogravimetrična analiza (TGA) in rentgenska fluorescenčna spektralna analiza (XRF). Eksperimenti so bili izvedeni na različnih vzorcih široko uporabljanih jedrsko kvalificiranih polimernih materialov kablov, vključno z etilen-propilen gumo (EPR) in zamreženim polietilenom (XLPE), vsi s plaščem iz klorosulfoniranega polietilena (CSPE). Vzorci iz različnih obdobij so bili dodatno termično starani v več stopnjah, da bi določili zahteve za kriterije sprejemljivosti terenskih testiranj in ocenili preostalo življenjsko dobo polimerne izolacije. Izvedeni so bili diagnostični testi in v članku poročamo o nekaterih preliminarnih rezultatih.