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CABLE-AGING MANAGEMENT PROGRAM IMPLEMENTATION IN NUCLEAR POWER PLANTS

NADZOR STARANJA ELEKTRIČNIH KABLOV V JEDRSKIH ELEKTRARNAH

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Keywords: nuclear cable aging, diagnostic testing criteria, residual life prediction model, risk ranking

Abstract

As a requirement for nuclear power plant life extension beyond 40 years, some additional Aging Management Programs (AMP) for passive equipment have to be implemented. This article presents an overview of Cable-Aging Management Program (CAMP) activities. The program defines basic rules and initial activities for the identification of adverse operation environment parameters that could lead to the accelerated aging of specific materials. 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. Acceptance criteria for environment parameters and diagnostic testing have been set. Initial visual inspection of cable conditions in an adverse environment and testing of sampled cables and environment yield results for on-time preventive measures. The first cable aging management program in Slovenia has been operating since 2010, and its experience could be adapted to other companies for which cables are key components.

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Povzetek

Podaljšanje življenjske dobe jedrske elektrarne nad 40 let zahteva vzpostavitev dodatnih programov nadzora stanja pasivnih komponent. Program nadzora staranja električnih kablov je vzpostavljen z namenom pravočasnega odkrivanja učinkov staranja in preprečevanja nepričakovanih odpovedi pri normalnem obratovanju. Program postavlja osnovna pravila in določa aktivnosti razpoznave vgrajenih materialov, obratovalnih pogojev in specifičnih parametrov, ki vplivajo na pospešeno staranje kablov. Vzorčenje kablov je izvedeno na osnovi zahtev po delovanju kritične varnostne opreme. Program določa kriterije sprejemljivosti ključnih parametrov okolice ter rezultatov nekaterih uporabnih merilnih metod. Začetna vizualna kontrola stanja izpostavljenih lokacij in izvedena diagnostična testiranja dajejo po šestih letih rezultate na osnovi katerih je mogoče pravočasno načrtovanje nadaljnjih preventivnih ukrepov. Prvi vzdrževalni program nadzora staranja električnih kablov v Sloveniji je koristen in se lahko prilagodi uporabi v drugih podjetjih, kjer je ta oprema ključna.

1 INTRODUCTION

The purpose of the Cable-Ageing Management Program (CAMP), *[1]*, is 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 are its main concern. The main goal is to confirm the functionality of cables for planned extended 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 Aging Management Program for cables uses two approaches. The first is a visual inspection of cable areas, to search for potential local adverse environments (harsh environments or “hot spots”), such as high temperature, humidity or submergence, chemical or mechanical wear. The second approach is to perform diagnostic testing of 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. Obviously, all cables cannot be inspected or tested, though the sampling approach of the most critical cables in adverse environments was conducted, as shown in Figure 1. CAMP is a continuing process, which concludes when all inspected and tested cables in a harsh environment meet the acceptance criteria; the whole population of cables is deemed functional until the next period of inspection.

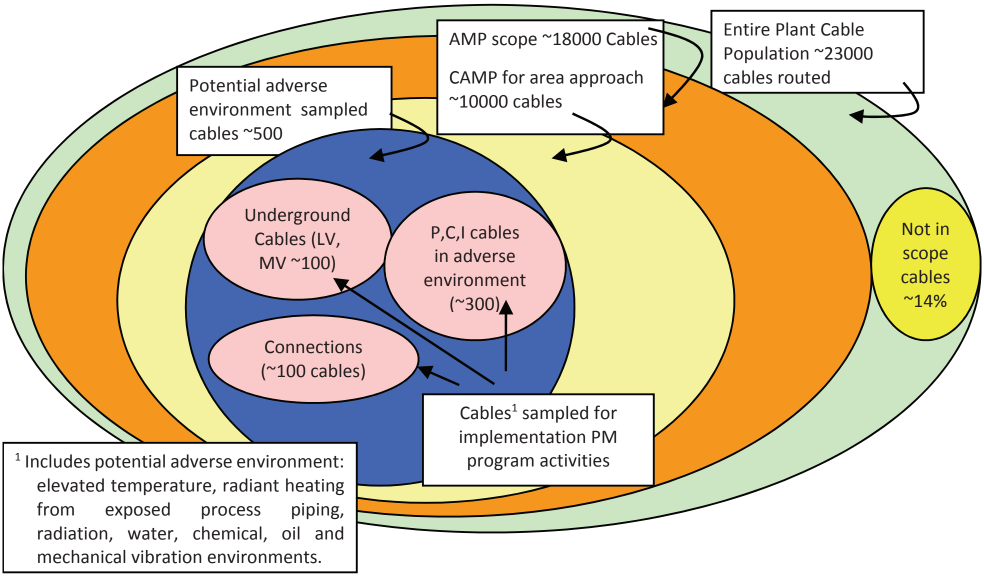

Figure 1: *Cable scoping and sampling process, [1]*

Most of the cables sampled in program scope are recognized as qualified safety-related class SR (1E). LOCA-qualified cables could be considered with a spaces approach, assuming all cables are installed in environmentally benign areas with all five of the following characteristics will remain operational for 40 years. If these environment conditions are met, there is no appreciable aging of cables for 60 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 in adverse environments: qualified safety-related cables (1E) purchased in accordance with technical specifications, operationally important cables (N1E), critical equipment and Operating Experience.

Different cable types are grouped based on voltage or type:

- Medium Voltage (MV) Power Cables (5 bills of material-BOM types, ~1%),
- Low Voltage (LV) Power Cables (42 BOM types, ~10% of cable),
- Control Cables (23 BOM types, 70% of cables),
- Instrumentation Cables (45 BOM, 19% of cables).

Several different manufacturers were identified. Three of them were recognized during construction time as the main producers of installed cables for SR (1E) circuits: Okonite for MV, Boston Insulated Wire (BIW) and Rockbestos 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 jacket material (Hypalone®) as the most vulnerable material, used for mechanical and fire protection, is a good indicating material for adverse environment effects.

2 LICENSING REQUIREMENTS AND PROGRAM OVERVIEW

NUREG-1801 Generic Aging Lessons Learned (GALL) 0 requires an aging management program to detect possible aging effects on electrical cables with appropriate consideration for low-voltage power, control, instrument and medium voltage cables with connections in a period of plant lifetime. Other licensing sources were considered: Maintenance Rule (10 CFR 50.65), License Renewal Rule (10 CFR 54) and Critical Components-reliability (INPO AP-913). Their additional requirements to be in scope are cables used to mitigate accidents or transients or support emergency operating procedures, cables whose failure could cause a reactor scram or actuation of a safety-related system, station blackout, fire protection, and reliability, i.e. cables supporting the function of critical components. The CAMP is conservative and specific in activities to identify adverse environments and requires the assessment of exposed and sampled cables by:

- Identification of locations and parameters where environments are more severe than the plant design environment for those areas and could cause premature aging effects;
- Visual inspection of sampled accessible cables located in adverse environments;
- Evaluation of calibration and surveillance testing results to identify deviations leading to direct testing of the circuits with involved cables and connections;
- Inspection for water collection in power cable manholes and draining water;
- Electrical test samples of inaccessible cables in identified adverse environments;
- Testing samples of power cable connections (i.e. IR camera, resistance testing, or other);
- If an unacceptable condition is identified at inspection or testing, a determination is made as to whether the same condition or situation applies to other (in) accessible cables;
- Estimating life prediction for exposed cables with site testing, theoretical calculations or laboratory testing to predict residual life of cable insulation.
- Corrective actions with repairing and replacing cables are planned to eliminate and prevent aging effects on cables (rerouting, thermal insulation, shielding, water pumping, etc.).

CAMP is a coordinated effort between different existing programs and organization departments of Technical Operation (TO), Engineering Support Division (ESD), Quality Assurance (QA), and Training. Responsibilities are defined with roles of personnel in specific departments.

3 CABLE-AGING DIAGNOSTIC TESTING METHODS

The focus of Cable Aging Management Program is to implement the best available inspection and testing method 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 2.

In the first place, visual inspection of the cable area was conducted to search for adverse environments and install environment monitors to measure specific parameters.

In the second phase, detailed in-service-inspection with diagnostic testing evaluation of electrical and mechanical properties was conducted to confirm cable functionality.

In the third phase, aged samples will be taken for a laboratory test to determine the actual scale of different properties change. Laboratories testing could be used for detailed modelling of remaining life prediction.

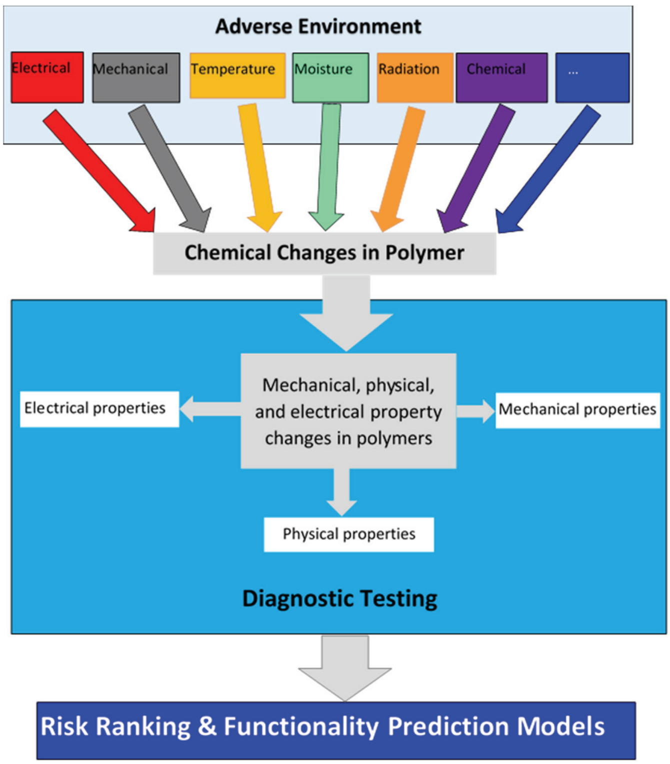

Figure 2: *Cable Aging Detection and Remaining Life Prediction, [4]*

3.1 Visual Inspection

Visual inspection is started with an area approach to look for adverse environment and service conditions looking for hot spots observable on the cable surface (colour change, hardening, cracking).

Basic adverse environment conditions are defined for an initial "hot spot":

- High Local Temperature: $T_{ambient}$>50 °C.
- High Radiation: >200 mSv/h.
- Long-term wetting: 75%-100% relative humidity.
- Mechanical: no hardening, cracking, no indentations, no cuts.
- Chemical: no softening, swallowing, swelling, no oil, acid, or base contamination.

Adverse service conditions for power cables are:

- High conductor temperature from ohmic heating.
- High resistance connections.

3.2 Temperature Monitoring

Elevated temperature is the most common cause of long-term aging of cable insulations and jackets in dry areas. For most insulation types and jackets identified in NEK, thermal aging causes the materials to harden, lose elongation properties, and eventually tensile properties. For low voltage power cables, operational ratings are based on a maximum conductor temperature of an assumed 40 °C ambient environment. Power cables have 90 °C conductor temperature ratings. Accordingly, power cables in areas with high ambient temperature (> 40 °C) will tend to thermally age more rapidly if operated close to ampacity if the elevated ambient temperature was not considered in the derating process. As the ambient temperature increases above 50 °C, the jacket materials of some power cables will begin to thermally age. Finding a hardened cable jacket would indicate that assessment of the aging of the cable is desirable to determine if the insulation has hardened and may be susceptible to cracking and failure. Table 1 provides approximate time to the point at which jacket aging would be detectable via tactile assessment for various ambient temperatures. The values are given to show that elevated temperatures significantly reduce lifespan. The table gives a rough indication of temperature sensitivity for identifying areas where cable condition should be assessed.

Table 1: *Approximate Time When Jacket Aging Would Be Detectable (hardened), [1]*

Jacket Material [1] \ Temperature	**50° C**	**60° C**	**70° C**
Neoprene	16–20 years	2–3 years	Very short
CSPE (Hypalon)	Very long life	25–30 years	9–11 years
PVC	14–22 years	5–8 years	2–3 years

[1] Generic material data used (not NEK-specific)

Appropriate tools for local temperature harsh environment finding are infrared camera, data logger and irreversible label memory sticker for one-time use in Figure 3-c for temperature range 37°C-65°C in 8 stages.

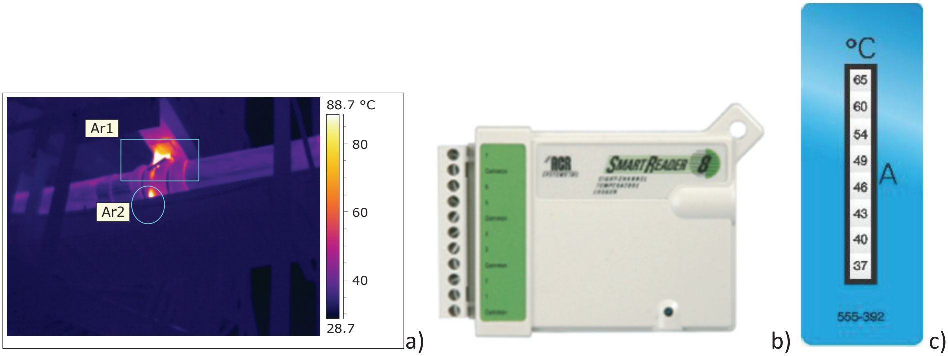

Figure 3: *Different temperature monitors: a) IR camera, b) data logger, c) irreversible label, [9]*

3.3 Radiation Monitoring

With respect to radiation effects, most cables will be in low-dose areas of the plant. However, some cables may be located in areas with appreciable doses. Some early Sandia research showed that effects on physical properties are not observable at 1-5 Mrad (10-50 kGy). The effects of radiation and temperature are to change the physical properties (loss of elongation and tensile properties) of the insulation and, after very severe aging, the electrical properties are eventually affected.

Radiation zone maps and environmental reports were reviewed and dose rates >200mSv/h were set for hot spot evaluation in the scope of CAMP. To determine if there are any additional zones where high radiation may exist, additional alanine pellets were set at 50 locations for gamma radiation and 5 neutron detectors. Conservative estimation suggested that the maximum radiation that cables would "see" in 60 years at selected hot spots would not reach more than 60-80 Mrad. Cables are qualified for 200 Mrad total dose. In general, high radiation conditions are expected to be accompanied by elevated thermal conditions and a few additional areas needing assessment should be identified by additional research about simultaneous effects of radiation and actual temperatures.

3.4 Humidity

There are two concerns associated with wet conditions. One is moisture in the vicinity of connections where conditions for corrosion of terminations is possible. Damp terminal blocks may also be subject to surface tracking that can lead to the failure of connections in damp areas. The second concern is long-term wetting of cables as could occur in underground applications. The duct/manhole system containing low and medium voltage power cables was reviewed, and long-term wetting of cable in adverse condition was determined. A conservative approach assumed that underground cables are wet. Underground systems have been designed to be drained naturally, with sloped ducts towards manholes structures, assuring cables are not submerged most of the operating time. Cables mounted on the trays and walls and not subject to wetting along their length are considered dry. Man holes are checked monthly, and water is pumped as needed to prevent the submergence of cables. Periodic exposures to moisture lasting less than a few days (i.e. normal rain and drain) are not significant. Significant voltage exposure is defined as exposed to system voltage for more than 25% of the time. Potentially wet cables are not energized for more than 25% of the time have a low likelihood of sustaining water-related degradation. As long as the continuously energized cables remain healthy, there is little concern that the normally de-energized cables have degraded. Conservatively, more than 75% relative humidity is calculated in the risk-ranking contribution.

3.5 Chemical

Most cables are not subject to contamination with oil or chemicals. Areas containing borates or other chemicals are inspected for being in touch with cables. With respect to borates, deterioration of exposed terminations is more of a concern than jacket/insulation deterioration.

Contamination with oil, in general, is more related to a spill. Cables subjected to oil contamination should be cleaned and evaluated for any effects on longevity around the turbine and large, oiled pumps.

Some traces of mineral oils were found in special sealants on a tray to a conduit that might affect the Hypalone jacket with softening and swallowing effects. Tests were conducted at different laboratories with no evidence on primary insulation confirmed. Visual inspection is planned for specific locations with repair and replacement as needed.

3.6 Ohmic Heating

Current in the conductor of power cable causes raised temperatures due to ohmic heating, mainly at connections. The power circuits loading current are checked. If the normal conservatism measures were applied during design, cables were applied with no more than 80% ampacity. The given temperature rise is proportional to the square of the current, 80% ampacity should result in 64% of the allowed temperature rise. In the case of a 90 °C cable in a 40 °C environment, the rise at 80% ampacity should be approximately 32 °C; the conductor temperature would thus be 72 °C.

Ohmic heating should be considered in conjunction with identified adverse thermal conditions in rooms especially if the ambient temperature coupled with the conductor rise results in temperatures approaching the rated temperature of the cable.

There are more approaches to evaluate the ohmic heating-induced aging of polymers or connections:

- Tests were conducted for different materials and resulting in a realistic calculated additional 14 °C to 17 °C temperature rise due to ohmic heating depending on material type, *[9]*.
- MV cables high electrical fields could impact impurities and voids in insulation, resulting in partial discharge as microscopic arcs leading to electrical trees resulting in dielectric failure or insulation breakdown. We start to use partial discharge testing.
- Infrared camera - Any temperature difference above reference (dT) is a concern. Table 2 provides suggested severity ranges for evaluating electrical power connections.

Table 2: Suggested Severity Ranges for Indoor Electrical Power Connections, [1]

Status	Range
Advisory	0.5 °C to 8°C Rise Above Reference
Intermediate	9 °C to 28 °C Rise Above Reference
Serious	29 °C to 56 °C Rise Above Reference
Critical	> 56 °C Rise Above Reference

3.7 On-Site Mechanical Test of Tensile Strength - Indenter Modulus

For the on-site mechanical test, evaluation of tensile strength (hardness), the Indenter Modulus (IM) testing method was implemented, and acceptance criteria developed[6]. This method, shown in Figure 4-a), 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 as shown in Figure 4-b). The indenter modulus of the material is the slope of the line relating the change in force ΔF to the change in deformation ΔX.

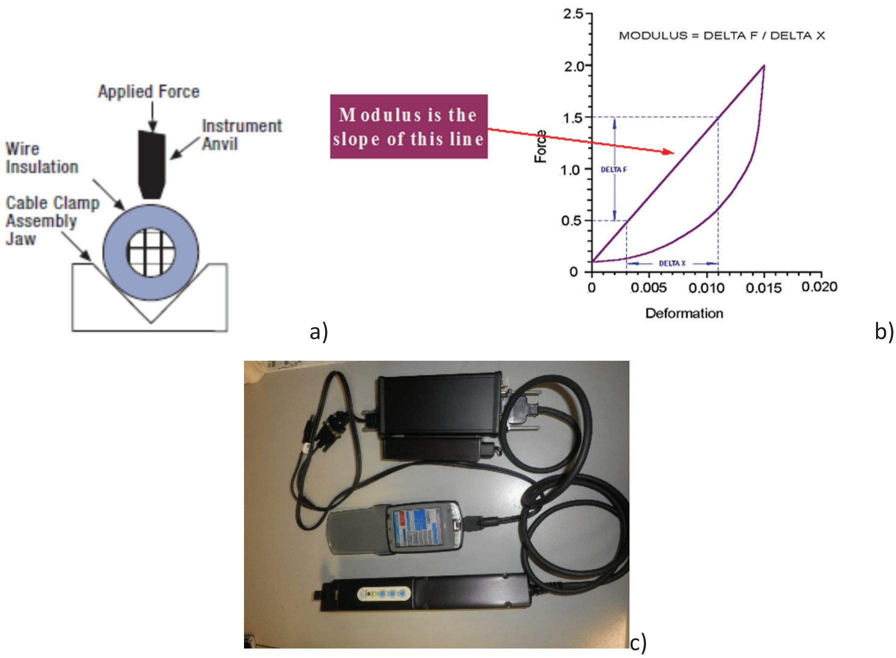

Figure 4: *Indenter Modulus Testing Equipment and functionality description, [6]*

Criteria were developed on 21 samples of cables from a warehouse and aged in an oven at 120°C for 9 different time stages; some visual aging results are shown in Figure 5, *[6]*:

- Sample #1 new cable: Indenter modulus measured from 10 to 13 N/mm NEW
- Sample #2 (72 h) and #3 (144 h): Modulus: 10-13 N/mm; no aging effects: OK
- Sample #4 (240 h) and #5 (360 h): 11-17 N/mm and 14-20 N/mm TRENDING

- Sample #6 (528 h): 85-118N/mm and #7 (1032 h): 151-206 /mm End of Life (EOL)-R&R
- Sample #8 (1872 h): 170-250N/mm and #9 (3264 h): 227-283N/mm EOL- Replace

Samples are used for training for visual inspection and acceptance criteria development for the IM of different materials. For jacket material CSPE (in all SR cables) three stages: up to 15 N/mm NEW material; from 16-80 N/mm initial degradation of jacket, insulation OK; 3 year – TRENDING; more than 80 N/mm End Of Life reached: Repair or Replace (R&R): Cable Jacket hardened and can crack; insulation possibly damaged.

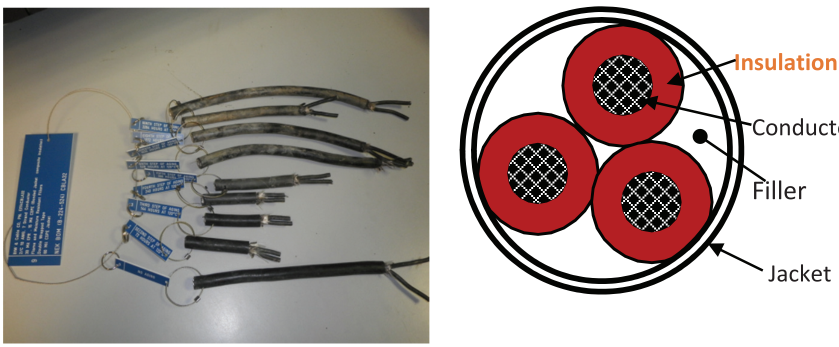

Figure 5*: Samples of 9 stages Owen Aged Control Cable (BIW 7C#14 AWG), [6], and description of cable jacket and insulation layers*

3.8 On-Site Electrical Tests

Evaluation of electrical properties is done using different testing methods depending on cable type and voltage (LV/MV). Some of the most useful techniques, with comparison in Table 3:

- Insulation resistance IR (R_{iz} > 2-100 MΩ) and polarisation index (PI=IR10'/IR1'<1,5)
- Connection Resistance (R<0,1 Ω); voltage drop at 100A (dU>0.1V deviation, asymmetry)
- Capacity (nF-pF)
- Dielectric Losses, tan δ using Power Frequency-50Hz or Very Low-Frequency VLF-0,1Hz (Acceptance criteria for EPR: tan δ<0,015 and XLPE: tan δ < 0,0015; Constant At Voltage Rise). Figure 6 compares both testing equipment.
- Partial Discharges, PD (as low as possible PD LAB<5pC and PD industry<500 pC for EPR)
- Time/Frequency Domain Reflectometry (TDR/FDR)
- Impedance, line impedance resonance analyse (LIRA)

Table 3: *Comparison of available cable inspection technique, [4]*

Inspection Method	Advantages	Disadvantages
Time-Frequency Domain Reflectometry (TDR and FDR)	Commonly used for the condition of inaccessible instrumentation, control and power cables.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Insulation Resistance	Commonly performed in industry to determine the condition of the cable insulation.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Inductance/Capacitance/ Resistance (LCR)	Good for detecting changes in cable and terminations by trending changes in inductance, capacitance and resistance.	Currently intrusive, requires disconnecting the cable at one end. Does not indicate location or cause of change in measurement.
Tan Delta (Tan δ)	Determines changes in insulation (dielectric) properties by measuring change in dielectric loss angle. Can measure aging effects over entire cable length.	Intrusive, requires disconnecting the cables at both ends. Single number from long cable makes isolating location of aging section difficult. Loss angle may be trended but single test insufficient to estimate remaining life.
Partial Discharge	Good in determining voids and defects in insulators of medium voltage cables.	Test can damage insulator with localized heating that causes degradation.
Line Impedance Resonance Analyse (LIRA)	Indicate location of change in measurement.	A lot of data setup and interpretation knowledge.

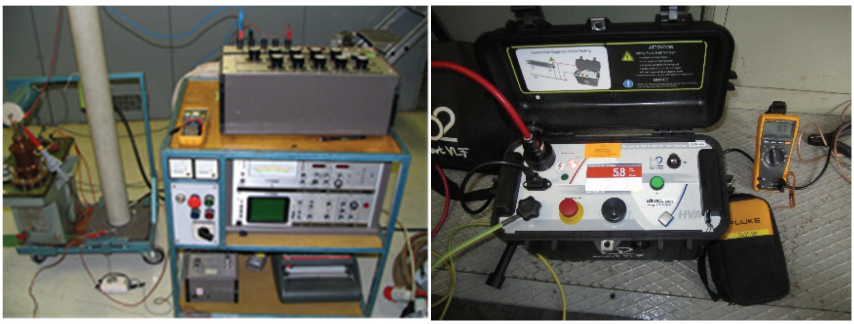

Figure 6: *Tan δ testing equipment with 50Hz (left) and 0.1Hz frequency*

3.9 Laboratory Testing Methods

Different methods are available for the laboratory testing of mechanical or chemical properties. The basic difference between methods is in the size of samples needed for the test (large=few m of cable insulation/small=few mg). This chapter gives a short overview of a few basic laboratory tests.

3.9.1 Elongation at Break (EaB)

Elongation at break is the ratio between changed length and initial length after breakage of the test specimen. The elongation at break defined by the EN ISO 527 standardized method for tensile mechanical properties of the polymer, used for End of Life (EoL) prediction, with known and predefined acceptance criteria for different materials (i.e. 300% for new cable and 50% for EoL).

Figure 7: *Testing equipment for EaB*

3.9.2 DSC Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) is a technique that is especially useful for the characterization of semi-crystalline polymer systems. DSC measures the flow of heat in and out of test samples over time as a function of sample temperature. Features in a DSC curve include phase change transitions. As illustrated in the DSC curve of different polymer materials in Figures 8, 9 and 10, [9], heat flows into a sample with rising temperature to effect endothermic transitions including the transition from 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 glass transition, is also related to chain scission and cross-linking that the polymer may have experienced.

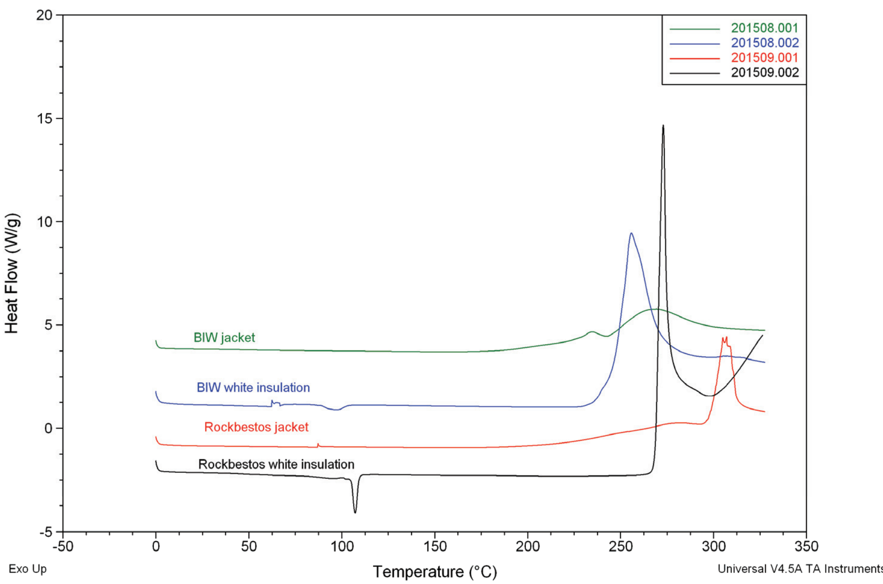

Figure 8: Dynamic method specific signature for insulation and jacket materials [9]

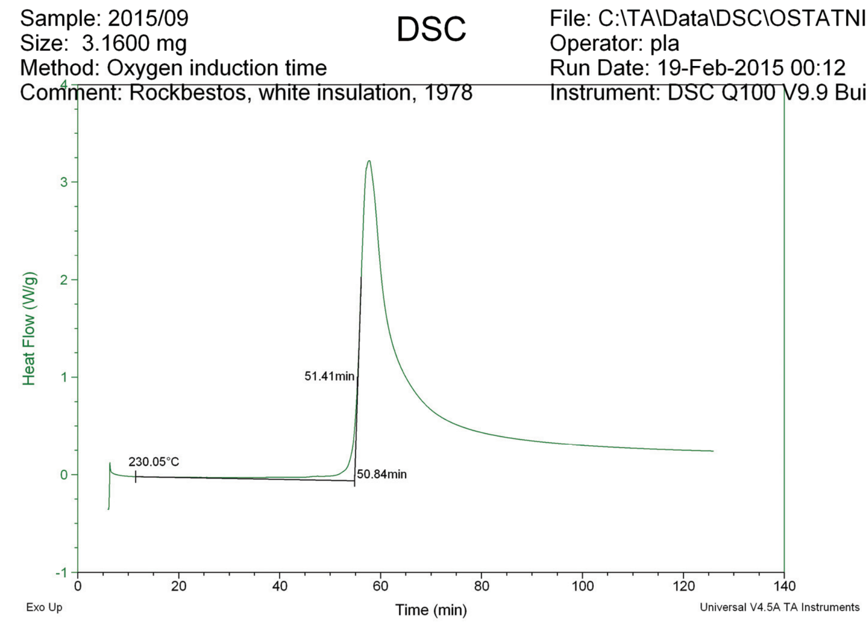

Figure 9: *Detailed analysis of results static method T=constant, [9]*

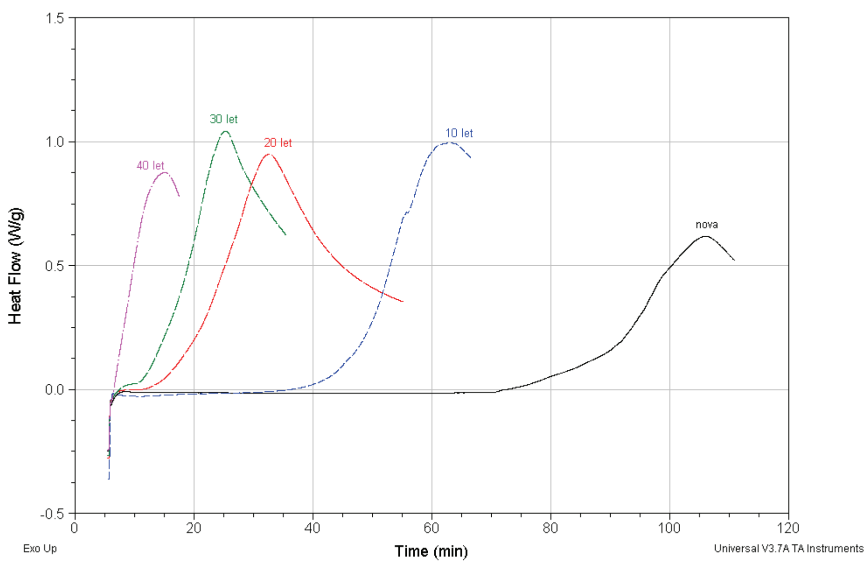

Figure 10: *DSC Heat Flow of different aged cables [9]*

3.9.3 Fourier Transform Infrared Spectroscopy (FTIR)

Oxidation and crosslinking of cable insulation polymers, such as EPR and XLPE, inherently introduce new chemical bonds within the material, including C=O carbonyl and C=C carbon bonds that have unique vibrational frequencies. A convenient method, therefore, for characterization of related polymer degradation is FTIR spectroscopy. The FTIR spectrum is shown in absolute values for different wavenumbers.

3.9.4 Thermogravimetric Analysis (TGA)

In thermogravimetric analysis (TGA), the mass of a sample is monitored as a function of temperature and time. The experiment may be performed under inert, reactive, or oxidizing atmospheres, and the TGA may be combined with a mass spectrometer to detect mass fragments of species volatilized during sample heating. Mass loss with heating can reveal copolymer ratio, moisture content, volatile additive content, and inorganic filler content. The decomposition behaviour of polymer samples at higher temperatures can also reveal information regarding the extent of chain scission and cross-linking in the polymer. Thermal decomposition in the TGA experiment may be a useful measure of the relative degradation and history of polymer samples.

4. DIAGNOSTIC TESTING RESULTS

Using all of the described onsite diagnostic methods, different tests were conducted and many results collected. After 6 years of CAMP implementation, we can summarize the results in Table 4 as follows *[5]*, *[7]*, *[8]*. We can summarize the most valuable techniques in visual inspection with temperature monitoring and IM hardness test. Among the electrical tests, tan δ and new LIRA give the best results with most deficiencies found.

Table 4: *Number of tests/findings/deficiencies (red) by diagnostic method [10]*

Diagnostic method / Cable type	Insulation resistance (IR)	Dielectric loss (tan δ)	LIRA	Partial discharge (PD)	Visual inspection	Humidity	Temperature (T)	Radiation	Indenter (IM)
MV(10 kV)	55/2	55/5	2/2	30/3	55/7	55/25/5	55/3	8/4/2	8/0
LV-P,C,I (<1000 V)	130/4	0	6/6	0	240/60/15	120/25/2	240/45/12	120/15/4	45/12

All cable areas were reviewed in buildings, and more than 45 temperature hot spots were considered and actions taken. Actions with rerouting cable from the hot spot and repair or replace as needed. More than 60 cables were rerouted and not in one had insulation failed but only the outer jacket; 12 cables were replaced due to jacket hardening/cracking.

In a 2015 outage, containment temperature and radiation adverse environment identification was finished after three years. Temperature data loggers (55) and alanine pellets for gamma radiation (50) and neutron detectors (5) near cable routes were analysed. Six hot spots were identified: 2 for temperature and 4 for radiation will be considered in the future.

As a standardized test, insulation resistance (IR) or the Megger test does not give very useful results, finding mainly severely damaged, failed cables: 3 LV power cables failure found dueto mechanical damage in the tray (all triplex power cables without jacket) shown on Figure 11 and c) one N1E underground failure in the splice.

a) 2005 b) 2015 c) 2016

Figure 11: *Failures of LV power cables found with IR test*

A total of 55 MV cables were tested with 5 findings in trending criteria for tan δ results (all underground with accessories – connections and splices).

The only qualified cable trending results for the last three tests conducted in 2012, 2013 and 2015 on Figure 12 do not show significant changes from lower trending limits (same for both testing methods: power frequency and VLF). Tape splices are most contributing factor of higher tan δ results.

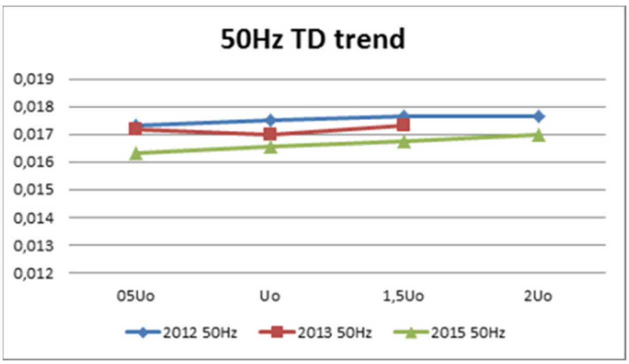

Figure 12: Trending results for tan δ at power frequency 50Hz

The explanation of lowering trend results in recent years, was a fact, the underground trenches (manholes) are keeping dry all the time for the last 6 years as much is possible. Preventive maintenance activities are conducted regularly, twice per month inspections and water pumping as needed before water reaches level of 0,2m. Trended cable with splice connections are in trays, raised from manhole floor for more than 1m.

Non-qualified Medium voltage (MV) cable N1E with XLPE insulation found bad connection at termination on Figure 13.

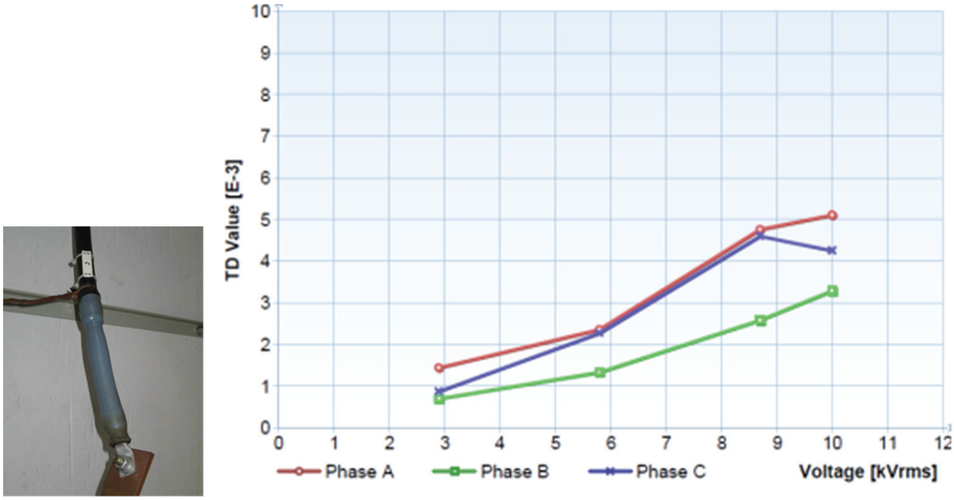

Figure 13: *Found deficiency on XLPE cable connection with diagnostic test*

Time Domain Reflectometry (TDR) signature results of primary cycle temperature detector cables in Figure 14..

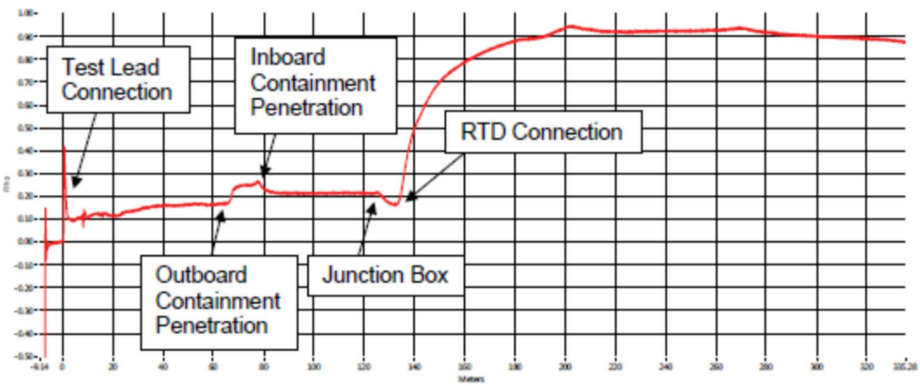

Figure 14: *TDR test plot with route configuration description, [9]*

Method is usable mainly as comparison signatures of aged cable with same new cable plot. Other possibility is to compare same type of cables routed in exact same configuration (conduit or tray). In any case, initial tests of new routed cables have to be plotted to have baseline for comparison to track any age related deviation in insulation or connection

MV cable partial discharge test results in Figure 15.

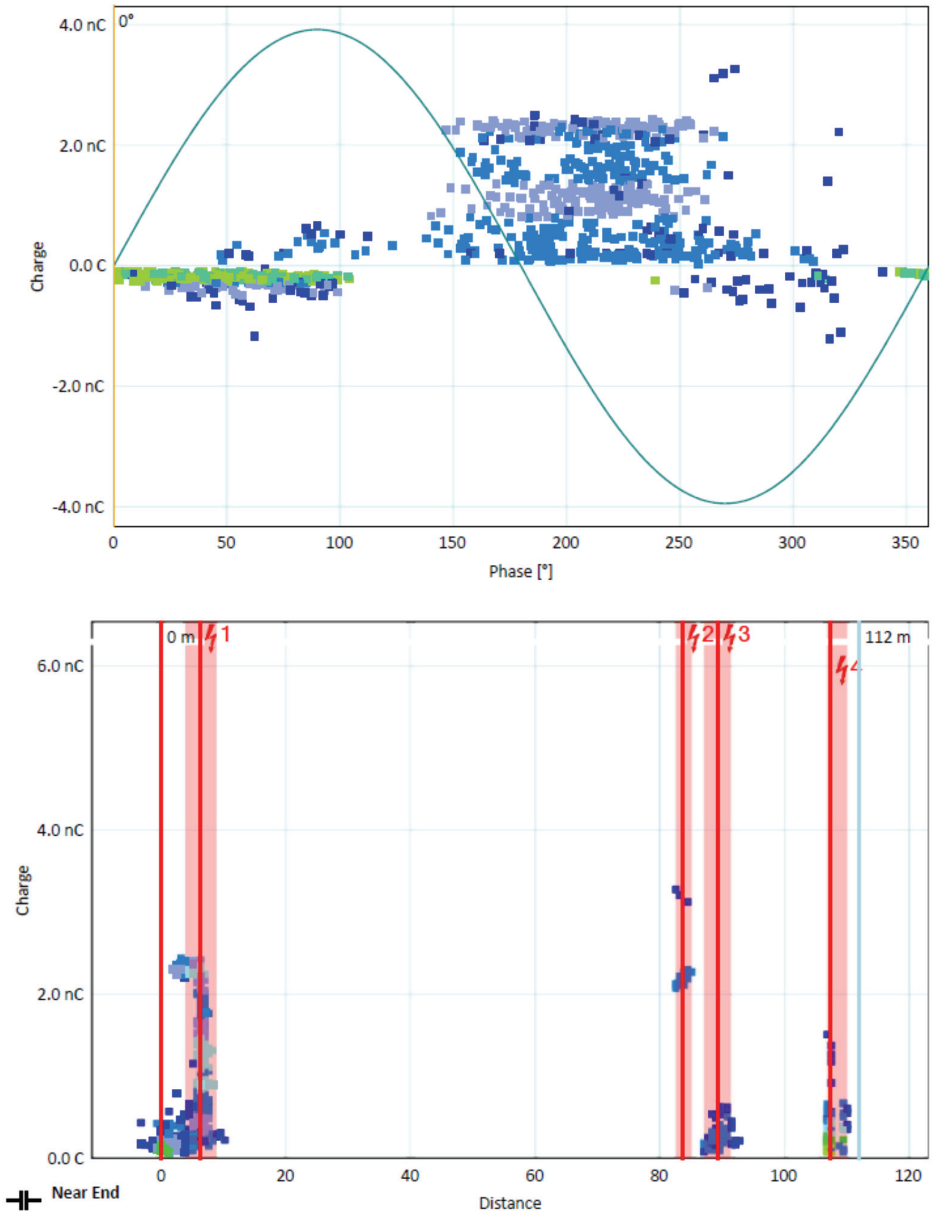

Figure 15: Significant PD events: XLPE cable failure at 5 m from cable near end

Line Impedance Resonance Analysis (LIRA) testing of 8 cables resulted in 8 findings and deviations: 3 on field cables and 5 at the instrument testing with the known location of cable damage (short circuit, bad connection, cut in insulation, local burned insulation). In Figure 16, a Spot Signature (dB) is shown with deficiencies at two locations. The short circuit in Figure 11-c) was found 30 m from cable end that is marked in left peak on Figure 16, second was indentation.

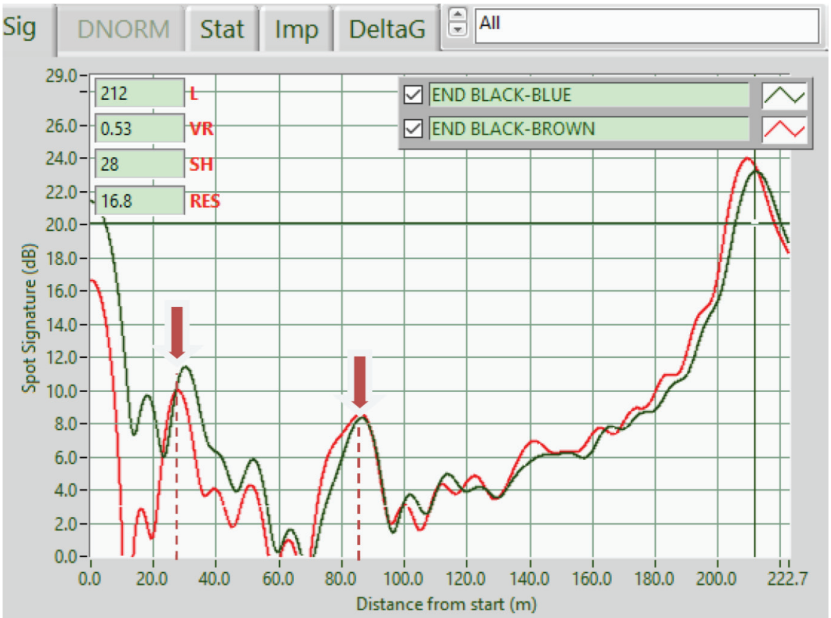

Figure 16: LIRA located two deviations on LV cable insulation, [10]

5 CONCLUSION

CAMP has been in the implementation phase for the last 6 years. Diagnostic testing results are promising and trending with immediate actions taken as needed. The most useful and promising on-site testing methods in NEK are an infrared camera, hardness test-Indenter Modulus, dielectric Losses- tan δ and LIRA.

Laboratory testing has not been required nor implemented at a larger scale. It will be used only in some specific examples for additional evaluation of specific effects that might be found in the future.

Additional diagnostic on site and laboratory tests will aid in residual life-time prediction and risk ranking according to deviations between qualification test methods and real environmental conditions including simultaneous aging effects of radiation, temperature, humidity, chemical environment, and mechanical load. Additional testing would also help to control functionality and possible different failure mechanisms, such as LOCA testing condition in a low oxygen atmosphere or inverse temperature effect including Arrhenius calculation for temperature calculation with activation energy (E_a) as temperature dependant, where a small difference in material constant yields significant change (10% change results in double residual life-time), [3].

Program health report and risk-ranking tools are in the development phase and are planned to be implemented after a testing period in 2016.

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Nomenclature

(Symbols)	(Symbol meaning)
NEK	Nuklearna elekrarna Krško
CAMP	Cable Aging Management Program
SR	Safety Related, Nuclear Qualified (1E)
LOCA	Loss Of Coolant Accident
MV	Medium Voltage (6,3kV or 10kV)
LV	Low Voltage (up to 1000 V); P - power; C - control; I - instrument
EPR	Ethylene Propylene Rubber (EPDM)
XLPE	Cross-Linked Polyethylene
CSPE	Chlorosulfonated Polyethylene (Hypalone®)
TD	Tan δ, Dielectric Losses
PD	Partial Discharge
IR	Insulation Resistance
LIRA	Line Impedance Resonance Analyse
TDR	Time Domain Reflectometry
E_a	Activation Energy
IM	Indenter Modulus
EoL	End Of Life