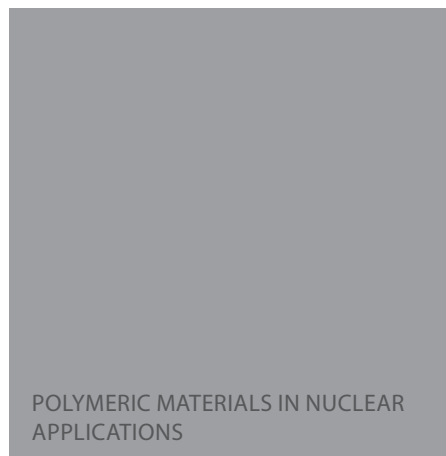
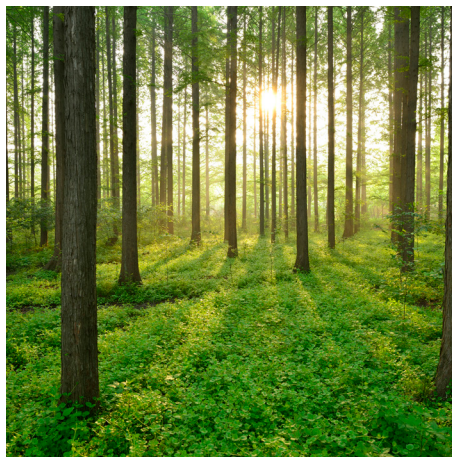
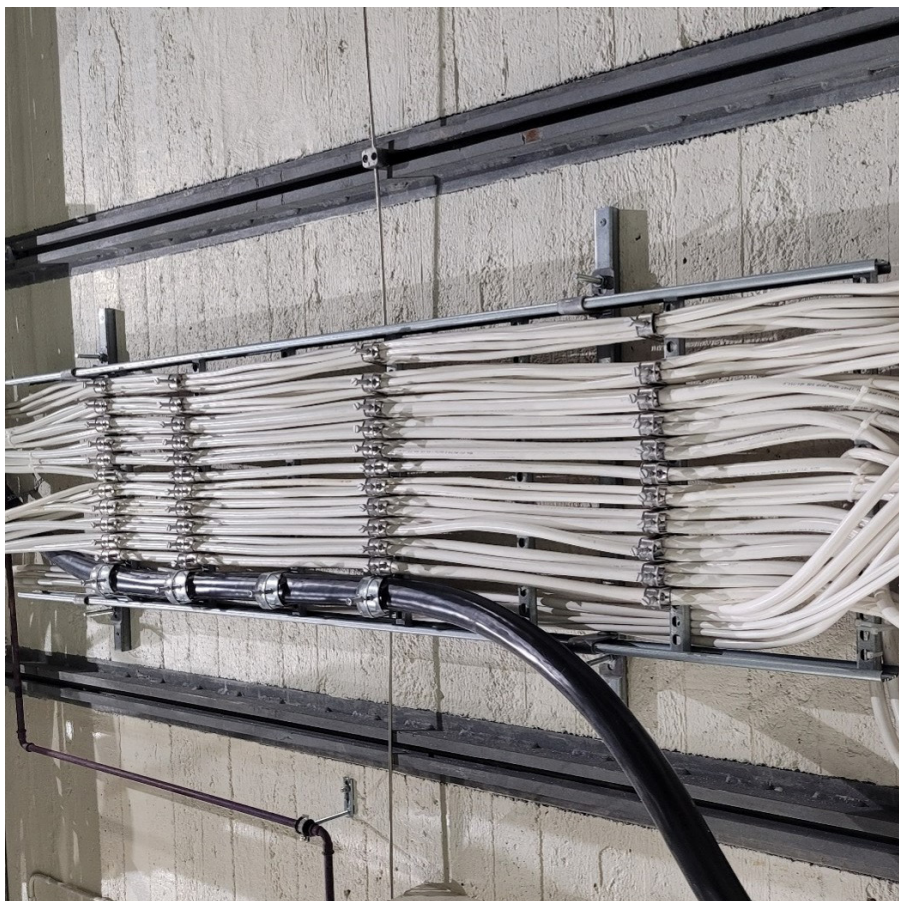
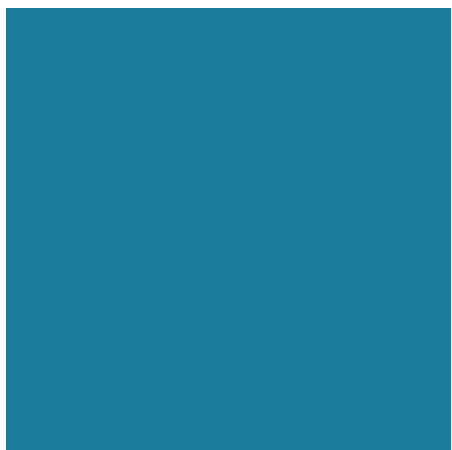


CABLE CONDITION MONITORING METHODS FOR NUCLEAR POWER PLANTS

REPORT 2024:1016



POLYMERIC MATERIALS IN NUCLEAR
APPLICATIONS



Cable condition monitoring methods for nuclear power plants

KONSTA SIPILÄ

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Foreword

The Energiforsk Polymers in Nuclear Applications Program aims to increase the knowledge of aspects affecting safety, maintenance and development of components containing polymers in the Nordic nuclear power plants. A part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

A single nuclear power plant contains approximately 1000-2000 km of low- and medium voltage cables. These are essential for purposes such as power supply and signal transmission. The degradation of the materials in these cables must be monitored to ensure their continued functionality. This study has investigated non-destructive monitoring and testing methods for both longer cable stretches and specific points.

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These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

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Summary

Low- and medium voltage cables are used in nuclear power plants as part of instrumentation and electrical equipment to supply electricity or for signal transfer. Typical estimates are that a single nuclear power plant contains approximately 1000-2000 km of such cables. Cables are subjected to ageing due to different environmental stressors like temperature, radiation and moisture. In order to monitor cable ageing accordingly, suitable condition monitoring methods are required.

Currently, elongation at break (EaB) is the material property that is universally accepted to be used as a condition indicator for cables. The definition of the cable EaB value requires destructive tensile testing, which limits the applicability of the condition indicator. Providing methods that could assess the cable condition non-destructively would be desirable.

Literature was reviewed to identify the most promising condition monitoring methods currently available. The cable condition monitoring techniques can be divided into globally and locally applied methods, where global methods can assess the cable condition or locating flaws on a longer cable length while local methods measure on limited spots.

From the globally applied methods, reflectometry methods have been demonstrated in real-service conditions with promising results. The dielectric spectroscopy method has been well demonstrated in laboratory conditions but seems to be missing demonstrations from real-service environment. This method would be particularly interesting as the method is similar to tan delta measurement, which has already been used at plants.

From the local methods, indenter modulus has been used in condition monitoring of cables in real service environments, and it has proven to be a suitable method for most types of polymer materials. OIT is another method that has been extensively tested in laboratory conditions, but measurement results with in-service cables have been inconclusive.

Keywords

Nuclear power plant cables, condition monitoring methods, ageing management

Sammanfattning

Låg- och medelspänningskablar är en del av kärnkraftverkens utrustning för att överföra elektricitet och signaler. En vanlig uppskattning är att ett enda kärnkraftverk innehåller ungefär 1000-2000 km kabel. Kablar åldras på grund av miljöfaktorer som t.ex. temperatur, strålning och fukt. För att övervaka kabelns åldrande på rätt sätt krävs lämpliga metoder.

För närvarande är förlängning vid brott (Elongation at Break, EaB) den mest allmänt accepterade metoden för kontroll av kabeltillstånd. Definitionen av kabelns EaB-värde kräver destruktiv dragprovning, vilket begränsar användbarheten vid tillståndskontroller av befintlig kabel. Att tillhandahålla icke-destruktiva metoder för tillståndskontroll av kabel är därför önskvärt.

En litteraturstudie utfördes för att identifiera de mest lovande metoderna för tillståndsovervakning som för närvarande är tillgängliga.

Kabeltillståndsovervakningsteknikerna kan delas upp i globalt och lokalt tillämpade metoder, där globala metoder syftar till att bedöma kabeltillståndet eller lokalisera fel på en längre kabelsträcka medan lokala metoder syftar till att mäta på avgränsade delar av en kabel.

Bland de globalt tillämpade metoderna har reflektometriska metoder provats under verkliga förhållanden med lovande resultat. Dielektrisk spektroskopi har provats i laboratorieförhållanden men tycks sakna resultat från provningar i från verkliga förhållanden. Denna metod skulle kunna vara särskilt intressant eftersom metoden liknar Tan Delta-mätning (TD), som är en metod som redan idag används.

Bland de lokala metoderna har indentermodul använts för tillståndsovervakning av kablar i verkliga miljöer, och har visat sig vara en lämplig metod för de flesta typer av polymermaterial. OIT är en annan metod som har testats omfattande i laboratorieförhållanden, men där mätresultat från kablar i drift däremot har varit motsägelsefulla.

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List of abbreviations

CSPE	Chlorosulfonated polyethylene
DBA	Design based accident
DLO	Diffusion limited oxidation
DSC	Differential scanning calorimetry
EaB	Elongation at break
EPDM	Ethylene propylene diene rubber
EPR	Ethylene propylene rubber
EVA	Ethylene vinyl acetate
FDR	Frequency domain reflectometry
FTIR	Fourier transform infrared spectroscopy
LIRA	Line resonance analysis
NMR	Nuclear magnetic resonance
NPP	Nuclear power plant
OIT	Oxidation induction time
OITp	Oxidation induction temperature
PD	Partial discharge
PDC	Polarisation-depolarisation current
PEEK	Polyether ether ketone
PVC	Polyvinylchloride
SiR	Silicon rubber
TDR	Time domain reflectometry
VLF	Very low frequency
XLEVA	Crosslinked ethylene vinyl acetate
XLPE	Crosslinked polyethylene
XLPO	Crosslinked polyolefin

1 Introduction

Low-, medium- and high voltage cables have all their typical application areas, ranging from low voltage signal supply and transfer to applications requiring larger power transmission (e.g., motors and electrical equipment) and all the way to transmission of electricity from power plants. In the context of nuclear power plant (NPP) cable condition monitoring, the focus is often on low- and medium voltage cables. A common way of defining different cable categories by the cable manufacturing industry is [Eland Cables 2024]:

- low voltage cables up to 1 kV
- medium voltage cables, from 1 to 45 kV
- high voltage cables above 45 kV

Cables are used in NPPs as part of instrumentation and electrical equipment to supply electricity or for signal transfer. Typical estimates are that a single NPP has approximately 1000-2000 km of such cables [Yamamoto et al. 2009, Simmons et al. 2013, OECD NEA 2011]. The cable structure consists of a metallic conductor or optical fibre, an insulator, possible metallic shielding and a jacket. The metallic conductor or optical fibre conducts electricity or transfers the signal. The insulator is used to electrically insulate the conductor from its environment, preventing grounding of the conductor. Additional metal shielding can be applied to the insulator to decrease outer disturbances affecting the signal quality. The outer jacket protects the cable internals from external stressors. A schematic illustration on a cable structure is presented Figure 1. Table 1 presents common polymer types applied in cable insulators and jackets based on [IAEA 2017] and [Penttilä et al. 2016].

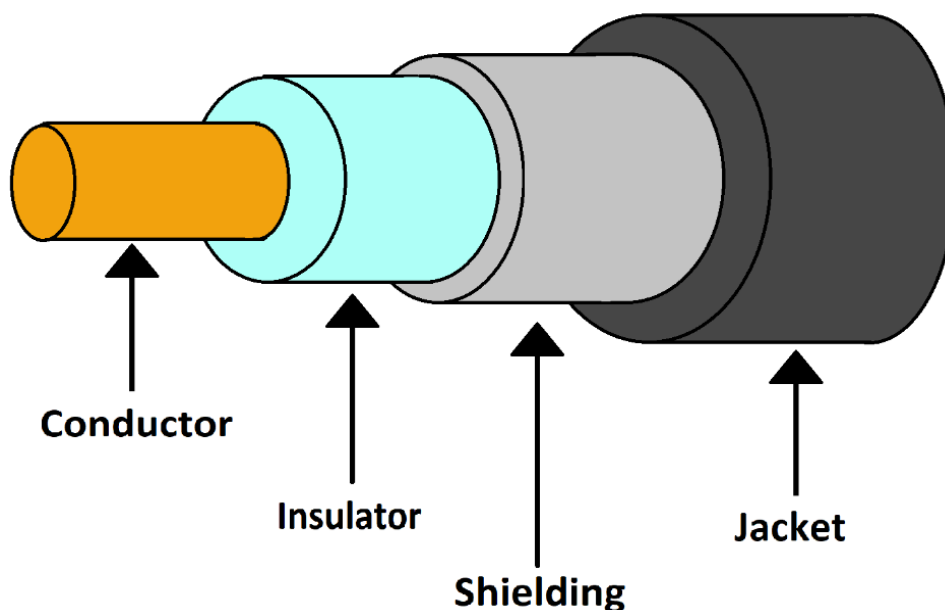


Figure 1 A schematic illustration on a cable structure.

Material	Insulator	Jacket	Manufacturer
CSPE		x	Lipalon, Hypalon
EPDM	x		Lipalon
EPR	x	x	Eupen, Changzhou Bayi Cable Co.
EVA		x	Eupen
PEEK	x		Habia
PVC	x	x	-
SiR	x	x	Hew
XLEVA		x	Rockbestos
XLPE	x		Rockbestos
XLPO	x	x	Acome, Shanghai Special Cable, Habia

Table 1. Typical insulator and jacket materials in NPP cables.

The degradation of the insulator is commonly considered to be more relevant compared to the jacket. This is due to the provided isolating properties that ensure proper cable functionality. The main ageing mechanism related to polymer degradation in nuclear applications is thermally or radiation induced oxidation, which results in polymer chain scission, crosslinking and the formation of oxidation products such as carbonyls and hydroperoxides [IAEA 2012]. Changes at the molecular scale affect the macroscopic properties and will ultimately result in the degradation of the functional properties of the polymer component, e.g., electrical insulation. The actual chemical reactions that govern the degradation can be complex in nature, and a more detailed presentation of the oxidation mechanisms and kinetics has been presented in [Verdu 2013] and in [Colin & Verdu 2012].

Condition monitoring methods are used as part of the ageing management of various voltage cables to improve the overall safety of operating NPPs. The importance of having a properly functioning ageing management programme is emphasised when the lifetime extension of NPPs is considered beyond the originally designed 40-year period. An example approach for cable condition monitoring at NPPs has been schematically illustrated in Figure 2. The cable inspections on low and medium voltage cables are not performed on the entire cable population located at individual NPPs, this would be laborious due to the vast number of cables present in a single NPP. The strategy would be merely to identify cable containing systems and components that have significant safety relevance and economic impact. Within this group of cables, those exposed to adverse environments, accelerating their ageing and increasing susceptibility to

localised failure modes, need to be identified and the condition monitoring efforts focused accordingly. A similar approach has been adopted by EPRI in the ageing management of low- and medium voltage cables [EPRI 2013, EPRI 2017].

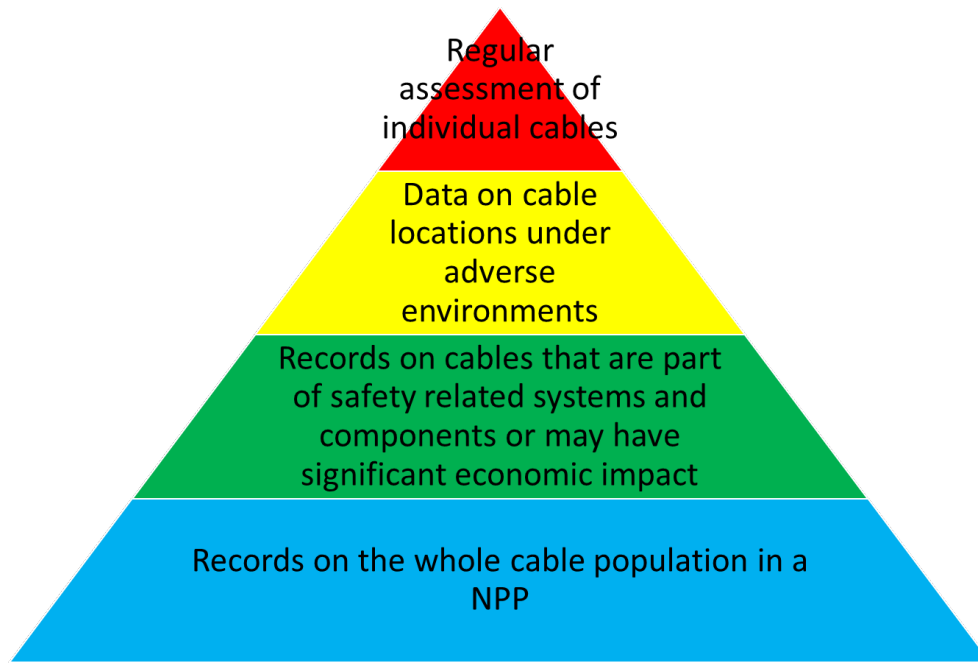


Figure 2. An approach for arranging cable condition assessments in NPPs.

Tensile testing is a commonly used method for assessing of the conditions of individual cables. An absolute elongation at break (EaB) value of 50% is commonly considered an acceptance criterion for a cable, as it has been estimated to be a conservative value for survival from a design based accident (DBA) [IAEA 2017]. DBA is a pre-defined test procedure where samples are tested in simulated accidental conditions for an extended period to assess the effect of irradiation, temperature and hot steam on the sample performance. See [ASTM D3911-16] for more details on DBA profiles. Using a destructive technique would require the removal of cables, which can be a complex operation [OECD NEA 2011], or the use of deposit samples. This limits the applicability of tensile testing in condition monitoring.

Application of non-destructive testing (NDT), or methods requiring minimal sample removal, would offer a possibility to circumnavigate the issues involved in cable condition monitoring related to the destructiveness of tensile testing. Even though there has been considerable progress in the development of NDT methods to be used on-site at NPPs, tensile testing remains the only universally acknowledged condition monitoring method. There seems to be a growing interest in more non-destructively applied methods that could be used instead or parallel with the tensile test. In this report, the most common techniques suggested for cable condition monitoring methods on low and medium voltage cables are briefly introduced, their applicability for on-site cable inspections at NPPs is assessed, and reported user experiences from actual NPP on-site use are summarised.

2 Cable condition monitoring methods

This section lists the various cable condition monitoring methods, discusses their measuring principles, and assesses their applicability as cable condition monitoring methods based on available literature. The methods can either assess the cable condition globally or locally, as schematically presented in Figure 1. In global methods, the measurement ends are usually connected to the conductor and shielding, and the insulator is measured through the whole cable length at once. Local methods measure only a limited area of the insulator or jacket.

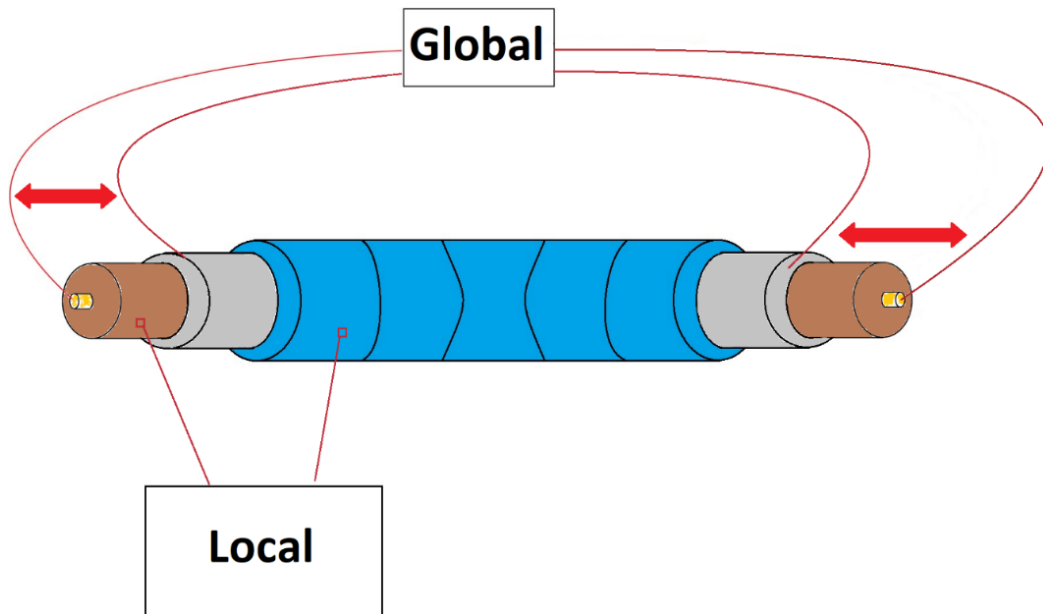


Figure 3. Schematic presentation of global and local cable condition monitoring measurement setups.

2.1 DIELECTRIC LOSS / TAN DELTA MEASUREMENT

In dielectric loss measurement, a low frequency AC voltage is applied between conductors around the insulator, and the resulting current response through the insulator is measured. This arrangement is described schematically in Figure 2. In this figure, measurement earths are connected to the conductor and shielding of the cable, and resistance and capacitance are measured over the insulator, as described by the capacitor and resistor drawn in the insulator. When the cable is new, the insulator has a very high resistance value. This would result in an almost fully capacitive response (I_C) in the measurement. As the insulator ages, the capacitive response decreases while the resistive response (I_R) increases. The relation between these two responses is measured during the measurement, and the relation is called the loss factor, or $\tan \delta$, which is dimensionless and solely determined by the structure of the insulator:

$$\tan \delta = \frac{I_R}{I_C} \quad (1)$$

Increased $\tan \delta$ values indicate the ageing of the insulator. This makes it a good parameter for ageing-induced changes in the structure [Kim et al. 2006].

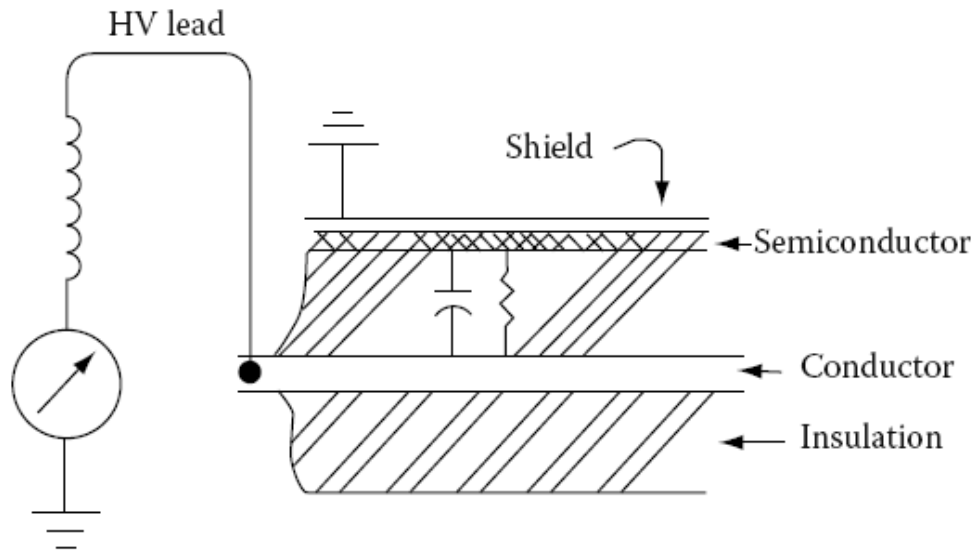


Figure 4. Schematic measurement arrangement in Tan delta measurement. [Your Electrical Guide 2024]

The method is considered to be sensitive to any excess moisture, e.g., water treeing, in the cable [IAEA 2017], and according to EPRI, it can identify water-related degradation [EPRI 2013]. $\tan \delta$ method is one of the methods EPRI has recommended to use in cable condition monitoring and has a broad range of on-site measurement data on various cable types [EPRI 2013]. The $\tan \delta$ measurement does not give location specific information on the degradation, nor can it assess the number or severity of individual faults in the insulator. Thus, in some cases it can be complemented by another method capable of locating flaws. $\tan \delta$ equipment and measurement services are commercially available [Simmons et al. 2013]. It can be applied to all types of cable materials.

2.2 DIELECTRIC SPECTROSCOPY

In dielectric spectroscopy measurements, the complex permittivity of the material is measured as a function of frequency. The measurement is in principle the same as the $\tan \delta$ measurement, except the applied frequency range is much broader. Figure 3 shows a schematic presentation of the measurement setup. The used equipment is usually designed for laboratory work and thus capable of producing a broadband dielectric spectrum, unlike the typical commercial $\tan \delta$ equipment. However, the laboratory-quality equipment is not necessarily suitable for on-site measurements. The broader frequency range enables a more comprehensive ageing assessment. To be more precise, dielectric spectroscopy enables the study of the frequency range at which dipolar polarisation takes place. Dipolar polarisation is the movement of dipoles in the direction of an electric field. This movement is affected by the polymer degradation as the number of dipolar species (i.e., oxidation products) increases in the insulator as a result of ageing. [Suraci et al. 2022]

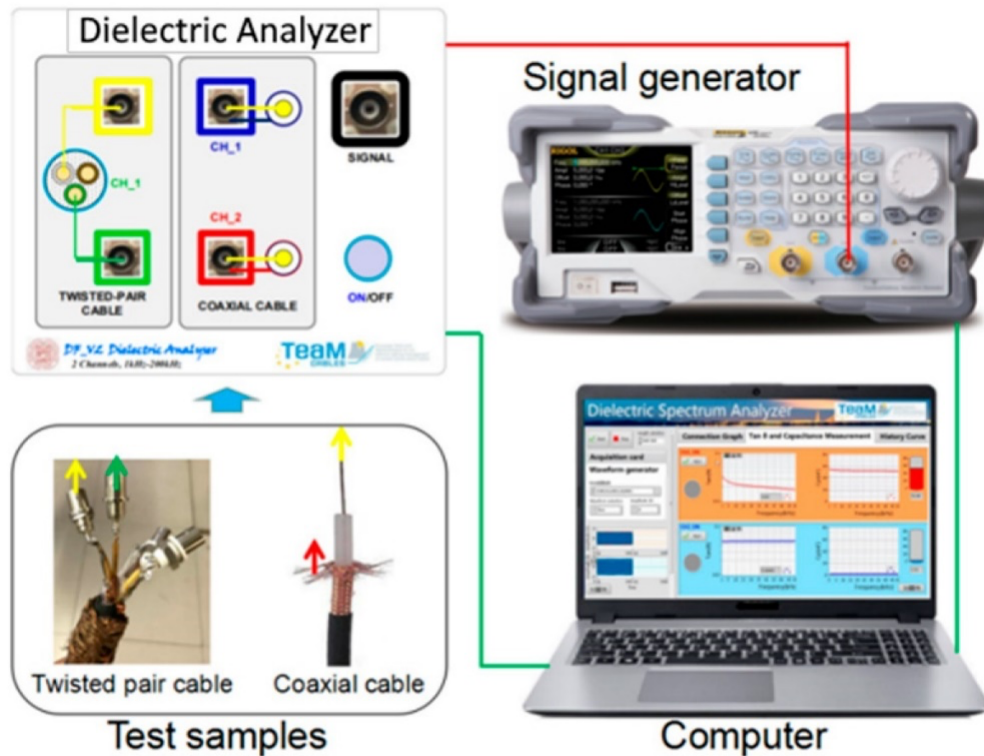


Figure 5. Schematic description of dielectric measurement setup according to [Suraci et al. 2022].

The method has been presented to provide promising results with low voltage cables aged globally [Fabiani and Suraci 2021]. Furthermore, it has been shown that the effect of local ageing can be seen in the measurement result with sufficient confidence when 35% of the cable length has suffered ageing [Suraci et al. 2022]. This indicates that the method cannot identify the locations of locally aged spots very accurately, and for this purpose, another method (e.g., TDR) is recommended to be combined for flaw location. The method is portable and thus suitable for on-site measurements. Further demonstrations are required with different cable types and measurements in on-site conditions.

2.3 DIFFERENTIAL SCANNING CALORIMETRY

Differential scanning calorimetry provides two possible measurement techniques: oxidation induction time (OIT) and oxidation induction temperature (OITp) for condition monitoring. Both measurement techniques require a small, 1-10 mg sample removal. The sample is heated in a chamber to a certain temperature in an inert atmosphere. The atmosphere is changed after a certain time interval to an oxygen atmosphere, which will cause oxidation of the sample after a certain induction time (i.e., OIT). The OIT is not a measure of degradation but merely an early ageing indicator that correlates with the antioxidant concentration, which is providing protection against the degradation of the polymer. The oxidation can be interpreted to begin when measurable exothermic heat flows can be measured. It can be stated that more aged samples tend to have shorter OITs than fresh

samples. Short OITs tend to be relevant in cases of low antioxidant content and vice versa [IAEA, 2012].

OITp can be used similarly to OIT. During OITp measurement, the sample is heated in an oxygen atmosphere with a certain temperature ramp. Again, the increasing exothermic heat flow is recorded, and the decreasing level of OITp indicates an increased level of degradation. OITp measurement also allows recording of endothermic peaks, which are related to the physical transitions of the sample material.

DSC equipment is commercially available from many vendors, and both OIT and OITp measurements are standardised [ISO 11357-6, ASTM D3895-14, IEC/IEEE 62582-4-2022]. Experienced equipment users typically can choose process parameters if standards are not applicable. The equipment needs some space, and it is not portable, as can be seen from the example equipment displayed in Figure 4.



Figure 6. DSC instrumentation. [Joki et al. 2021]

DSC analyses can be used as qualitative estimates of ageing. Since OIT and OITp are measures for the consumption of antioxidants, they could be potentially used as early ageing indicators. Correlating OIT with EaB could be problematic, as OIT is not a direct measure of polymer degradation. Some correlations have been suggested in the literature, for example, [Lungulescu et al. 2022] have provided a good correlation with irradiation time and OIT with LDPE, XLPE, EPR and EVA materials, but with these materials, the correlation is likely due to irradiation induced loss of stabilizer.

Fifield et al. suggest that DSC can provide meaningful data on the ageing of XLPE and EPR materials but would require additional methods to make full use of the data [Fifield et al. 2016]. Operational experience with OIT measurement has been reported by [Pirc 2016] in Slovenian Krško NPP, but the author did not include it as one of the most promising on-site testing methods.

Some limitations for the technique have been proposed by [Pauquet et al. 1993] and [Zweifel 1998]. The method is applicable only to systems of polyolefins and phenolic antioxidants. Furthermore, certain additives can contribute to the OIT measurement (secondary antioxidants and antacids) or do not contribute to OIT despite acting as long-term thermal stabilisers (e.g., hindered amine stabilisers).

2.4 DENSITY MEASUREMENT

Variations in density are characteristic when oxidation occurs in polymers. The oxidation products generated in the polymer tend to increase the density, and a higher increase in density indicates more severe ageing. Generally, two different approaches can be applied in density measurements of polymers, the Archimedes method and the density gradient column. While applying the Archimedes method, the sample is weighted in air, W_{air} , and in a liquid, W_{liq} , with a known density, ρ_{liq} , and the density of the sample can be thus calculated to be:

$$\rho = \left[\frac{W_{air}}{W_{air} - W_{liq}} \right] \rho_{liq}$$

The used sample size should be some tens of milligrams. Such a relatively small sample size is convenient when the polymer is degraded homogeneously, but in cases of heterogeneous ageing, there might be a risk of error in the measurements. [Gillen et al. 2005]

The principle of a density gradient column is based on creating a vertical liquid column, which itself has a density gradient in it. This density gradient column is usually created by mixing two miscible liquids (e.g., nitrate-water [Gillen et al. 2005]) with different densities in a long glass tube. The column is calibrated with reference samples with known densities, and based on the calibration, the density of the sample can be estimated. This method requires clearly smaller samples than the Archimedes method, and e.g., creating an ageing profile on a sample from thin scrapings from the sample is possible.

IAEA has reported a reasonable correlation between density measurements and ageing with CSPE [IAEA 2017], PE and silicon rubber [IAEA 2012, Simmons et al. 2013]. Contradictory results were obtained with EPR, and no correlation was found in PEEK, XLPO, EVA and XLPE. [IAEA 2017] A comprehensive ageing study where correlations between density and EaB with 10 different polymer-based cable materials were assessed was performed by [Gillen et al. 1999]. The results indicated that XLPE, CSPE, chloroprene, LDPE and PVC showed a good correlation with EaB, making density a potential ageing indicator for these materials. However, a later report concluded that variation in density can be rather small during ageing and scatter large.

2.5 FREQUENCY DOMAIN REFLECTOMETRY AND LINE RESONANCE ANALYSIS

Frequency domain reflectometry (FDR) is based on applying frequency signal sweeps to an electric cable circuit and analysing the reflected response. The reflectometry measurement principle is schematically presented in Figure 5. Reflections of the applied signal usually occur at discontinuous spots, such as junctions or defects. Reflection can be seen in the phase and magnitude of the measured impedance. FDR trace (reflective power vs. distance) is compared to a baseline measurement. The equipment is commercially available [Simmons et al. 2013].

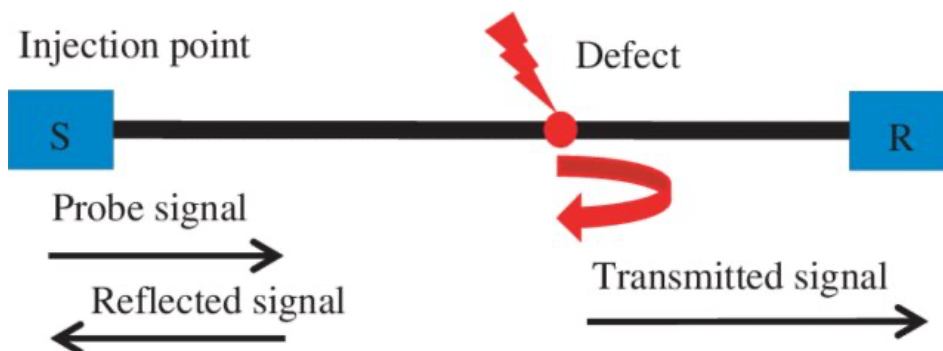


Figure 7. Schematic principle of reflectometry measurement. [Osman et al. 2020]

Line resonance analysis (LIRA) is one method that is based on FDR and tested in NPP environments [Toman & Fantoni 2008, Pirc 2016]. In LIRA, a specially designed algorithm analyses the measured data and provides information on cable degradation locally and globally. The measured data is indirectly linked to capacitance and inductance (to a lesser extent) via measurement of the complex line impedance. [IAEA 2012, OECD/NEA 2010]. Since capacitance and inductance are affected by ageing, it is possible to estimate the degradation of the cable insulator or jacket. A more detailed description of the LIRA has been given by [Ekelund et al. 2011].

LIRA has been shown to be useful in evaluating cables that are exposed to several different environments along their length and locally degraded cables [Fantoni 2009, Fantoni 2015, Glass et al. 2017]. It seems that LIRA has sufficient resolution to detect cables that will no longer pass a LOCA test and correlates quite well with EAB [OECD/NEA 2010]. The method is applicable to all types of materials.

2.6 GEL FRACTION AND SOLVENT UPTAKE FACTOR

Gel fraction and solvent uptake factor are both parameters that provide information on the amount of crosslinking occurring in the polymer due to ageing. Both parameters can be extracted with the same procedure, see Figure 6. The sample is set in a refluxing solvent (e.g., toluene, tetrahydrofuran or xylene) which will swell the sample. The weight of the sample is measured before insertion into the solvent, in its swollen state, and after the solvent is extracted from the sample in a vacuum chamber. The gel fraction is calculated by dividing the weight measured after the exposure and drying by the weight measured before the exposure to the solvent. The solvent uptake factor is calculated by dividing the weight measured in the swollen state by the weight after drying. An increasing gel fraction and a decreasing solvent uptake factor indicate an increase in crosslinking. The opposite behaviour would indicate an increase in chain scission.

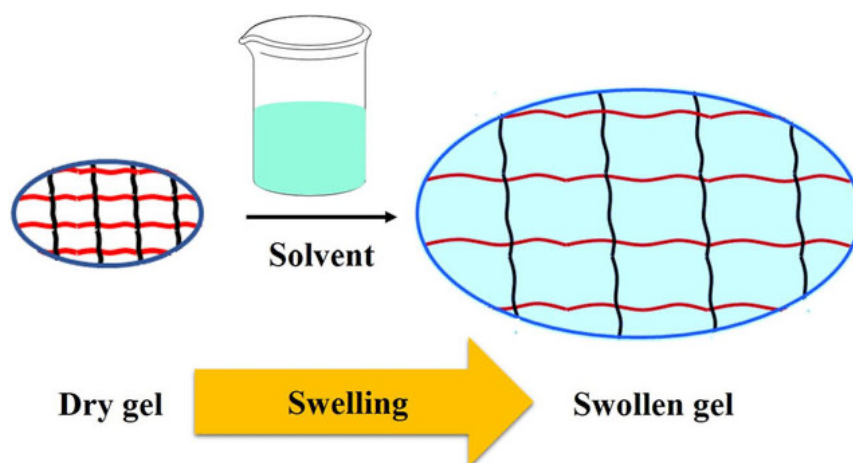


Figure 8. Schematic presentation performing solvent uptake test. [Bhattacharya et al. 2020]

Both methods require sample removal, but the sample size can be as small as 1 mg. The solvent uptake factor can be considered to be more sensitive to elastomers that already have a high crosslinking density than the gel fraction. Both crosslinking and chain scission are related to EaB, and the correlation of gel factor and solvent uptake to this property can be suggested for polyethylene, CSPE and polychloroprene [IAEA, 2012]. Also, correlation can be done with modulus profiling and NMR relaxation times since the measurement results obtained also depend on the crosslinking density. In the case of EPR and XLPO materials, the methods do not seem to be very feasible [Gillen et al. 2005].

2.7 INDENTER MODULUS

The indenter modulus can be considered as a parameter that describes the compressive stiffness of the polymer. A well-defined procedure has been developed for the measurement of indenter modulus, and it has been used at on-site measurements [Toman & Fantoni 2008, Pirc 2016]. The measurement is conducted as the equipment is clamped around the cable and the measurement probe is slowly inserted into the surface. Penetration depth and force are measured. An example of an indenter and measurement principle is shown in Figure 7.



Figure 9. Indenter equipment and schematic measurement principle according to [Pirc 2016].

The indenter modulus is calculated from the slope of the force-penetration depth data. Standard protocols for this calculation and how to conduct properly indenter modulus measurements are released by IEEE [IEC/IEEE 2011]. The same equipment can also be used to measure recovery time, which can be considered a measure of the viscoelastic properties of the material. Even though the recovery time has a good correlation with elongation, it is less frequently used than the standardized indenter modulus measurement.

The indenter modulus has been shown to be applicable to several elastomers including, CSPE and thermally aged PVC [IAEA 2012, EPRI 2005]. As part of the implementation of condition monitoring strategies at Krško NPP, indenter modulus was concluded to be one of the most useful and promising on-site testing methods [Pirc 2016]. There has been reported user experience in NPPs for this method [Toll et al. 2020] and U.S. Nuclear Regulatory Commission (NRC) has considered the use of indenter modulus acceptable for cable condition monitoring of PE, EPR, CSPE and neoprene [NRC 2012]. IAEA states that the method is suitable for a broad range of cable insulator materials. Only materials with higher initial hardness (e.g., PEEK) may not be applicable for indenter measurement as their hardness increases only discreetly due to ageing [IAEA 2017]. However, sufficient applicability has not been demonstrated for irradiated PVC and semi-crystalline materials. This is thought to be based on the different hardness related material properties of crystalline and amorphous regions as they degrade.

Indenter modulus can be applied to both jacketing and insulator materials as long as proper access is available, e.g. at the cable ends or switch boxes.

2.8 INFRARED ANALYSIS

Infrared analysis (commonly referred to as Fourier transform infrared spectroscopy, FTIR) is based on the absorption of the infrared light. An infrared spectrometer exposes thin samples to infrared light with a defined wavelength and presents the absorbance as a function of frequency, where the used unit is typically wavenumber instead of hertz. The wavenumber is defined as the number of complete wave cycles existing in one centimetre of matter, and depending on the

matter where the infrared wave propagates, the absorption can vary. The oxidation of polymers produces certain oxidation species that absorb infrared light with certain wavenumbers. Thus, the increase in absorbance at these wavenumbers can be interpreted to be due to ageing. A schematic illustration of FTIR measurement principle and data is shown in Figure 8.

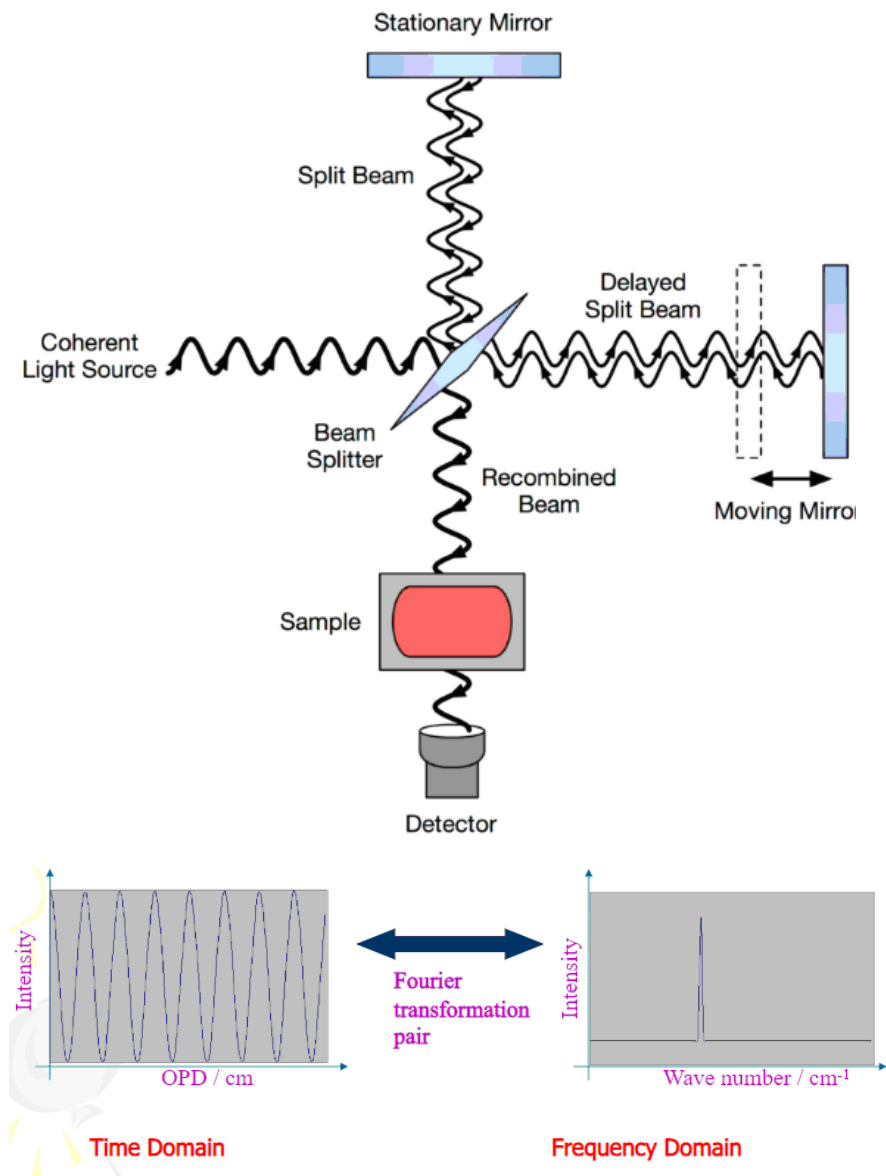


Figure 10. FTIR measurement principle and example data. [Bio-structure 2024]

The method has some limitations coming from material constituents, e.g., the presence of carbon black can complicate the measurement since it will absorb infrared light from all wavelengths. The method requires sample removal, although the sample is very thin (ca. 50-100 μm). [Gillen et. Al. 2005, IAEA 2012]

The IAEA states mostly a moderate correlation of infrared data to ageing, although it may be due to variations in the data analysis phase between different laboratories that cause variation in infrared results. [IAEA 2017] FTIR has been reported to be used for analysing cables from NPPs [Rouison et al 2019, Toll et al.

2020]. [Rouison et al 2019] considers the FTIR technique to be promising. FTIR equipment has traditionally been a laboratory method, but recently portable equipment has become commercially available [Rouison et al 2019].

2.9 INFRARED THERMOGRAPHY

Infrared thermography is based on measuring the wavelength of the electromagnetic radiation emitted by objects. Since the wavelength is affected by temperature, relatively low temperature differences between areas can be visually imaged. [Balakrishnan et al. 2022] An example of an infrared thermography image is shown in Figure 9. The method does not provide quantified information on cable condition, but it can be used to detect locations with elevated temperatures and thus allocate inspections efficiently. The technology is well developed, and infrared cameras are available commercially.

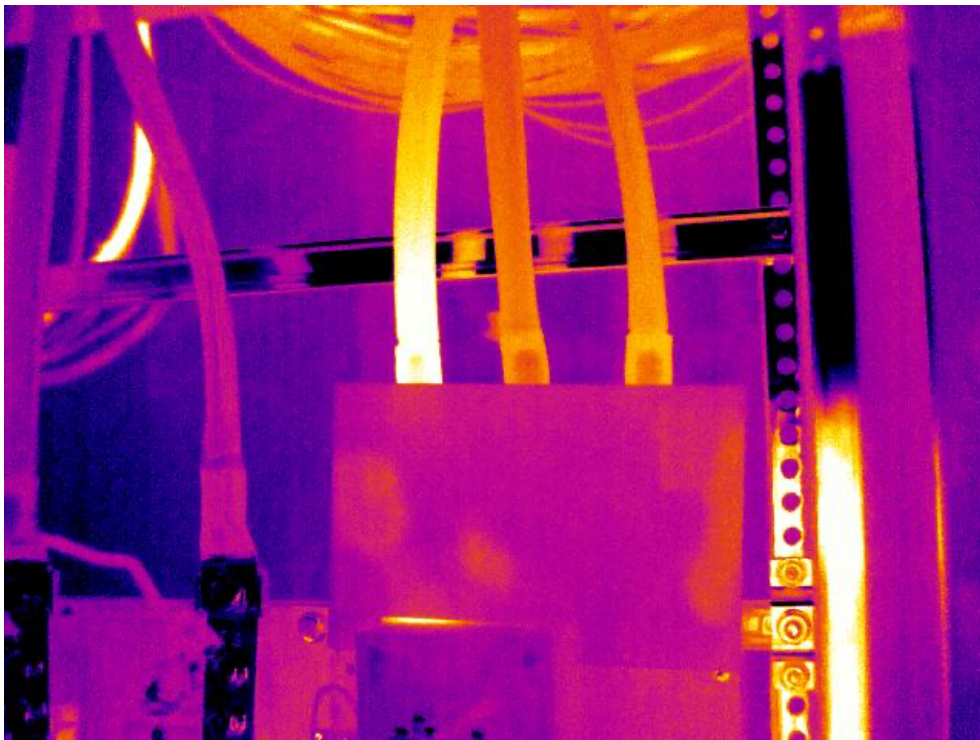


Figure 11. An example of an infrared thermography image. [Thermal Imaging Ltd 2024]

The method has been implemented as part of the condition monitoring strategy at Krško NPP, where temperature range classification has been defined. Four categories are applied, where the first one is advisory (in the vicinity of the reference temperature), followed by intermediate, serious and critical categories, which all are increasingly higher above the reference temperature. [Pirc 2016] NRC considers infrared thermography an acceptable condition monitoring method at NPPs [NRC 2012].

2.10 INSULATION RESISTANCE MEASUREMENT

Insulation resistance measurement is a rather simple measurement, and it is based on applying a voltage to the conductor and measuring the current flow across the insulator to ground, i.e., calculating a resistance for the insulator. The measured resistance changes as the cable insulator ages, and especially oxidation and moisture ingress-induced ageing can be detected. The applied voltage is usually lower than the maximum rated voltage of the cable. A schematic measurement setup is shown in Figure 10. Several standards have been published by ASTM (D257, D2801, D3554, D3555, D4245 and D4246) that define insulator resistance measurements for elastomeric and PVC insulators. IEC (NPP specific standard IEC 62582-6, IEC 60345, IEC 61196-1-102 and IEC 61557-2) EN (EN 3475-303), ISO (ISO 2951) and SFLC (SFLC STANDARD SPECIFICATION 3014) standards also exist. The equipment and measurement services are commercially available [Simmons et al. 2013].

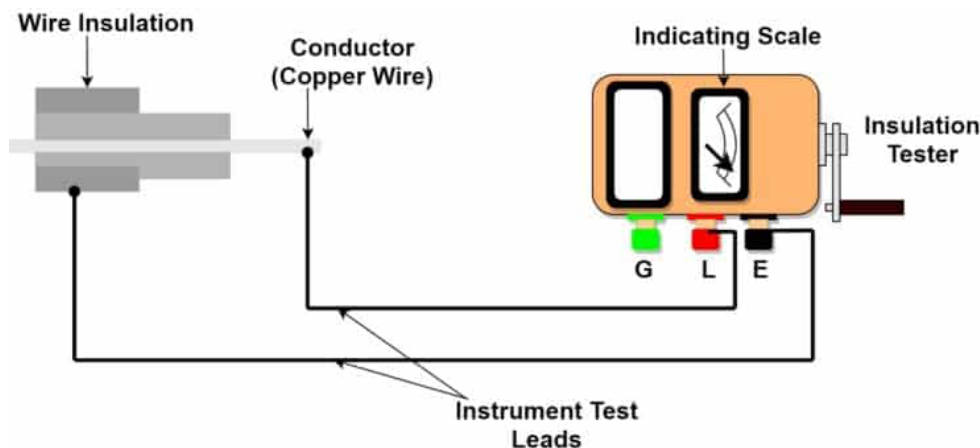


Figure 12. Schematic presentation of insulation resistance measurement. [Electrical Volt 2024]

NRC considers insulation resistance one of the acceptable condition monitoring methods at NPPs. Although the method is considered to be easy and simple to perform as it does not require access to the whole cable, it is not considered to be very accurate, and it is susceptible to environmental noise effects. [NRC 2012] User experience from Krško NPP indicated that insulation resistance measurement managed to identify only the most degraded cables [Pirc 2016].

2.11 NUCLEAR MAGNETIC RESONANCE

In nuclear magnetic resonance (NMR) spectrometric procedures, a sample is exposed to a magnetic field, which causes the atomic nuclei to align in a certain manner. External electromagnetic radiation is used to “excite” the aligned nuclei, and as the exposure of the external radiation is removed, the system relaxes, and fluctuations in the magnetic field are detected as resonance and converted to an NMR spectrum. A schematic diagram for NMR measurement is shown in Figure 11. A more detailed description of the technique and its capabilities is presented in [Duer, 2008].

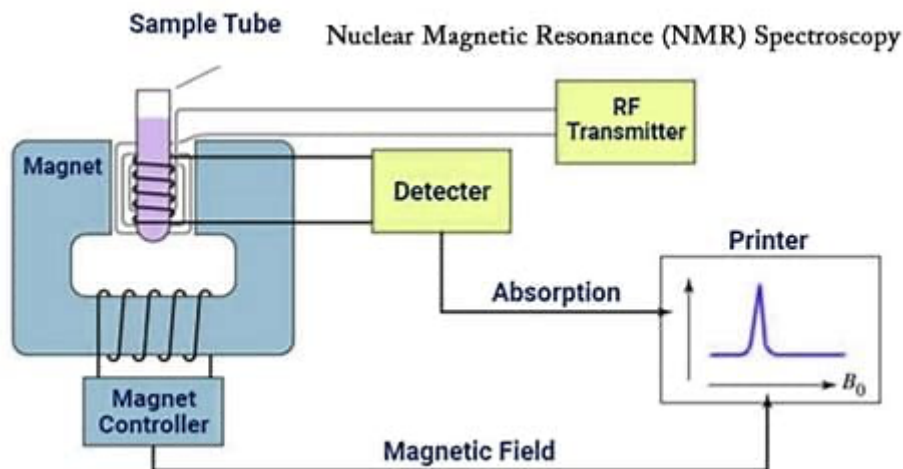


Figure 13. A schematic diagram for NMR measurement. [Microbe notes 2024]

NMR can provide information on the chain mobility of the polymer. Chain mobility is affected by ageing, and in NMR spectrometry relaxation time, T_2 , is a characteristic parameter for chain mobility. The sample size can vary from 10 to as low as 0,1 mg.

For certain cable materials, NMR relaxation measurements have been proven to have a good correlation with EAB measurements [Gillen et al. 2005]. KTH has developed a portable NMR sensor for on-site measurements that does not require sample removal at all. It has been tested on cables obtained from Forsmark and Ringhals NPPs. A correlation between EAB and intender modulus values could be established. However, the measurement data indicates that the portable sensor is currently capable of measuring only non-shielded cables, and further development is needed to perform fully non-destructive measurements with shielded cables. [Furo et al. 2021]

2.12 PARTIAL DISCHARGE

The partial discharge (PD) technique is based on the electrical discharges that occur in the gaseous inclusions of the polymer matrix. Such discharge causes high frequency currents, which can be measured with PD detection equipment. After the discharge, the inclusion walls have charge distribution, which interacts with the local electrical field, and the sinusoidal voltage applied to the conductor ultimately causes the next electrical discharge. Thus, a series of partial discharges can be monitored, each of which has its own characteristic properties. A typical measurement setup is described in Figure 12.

The parameter that correlates to the cable's overall condition is the PD inception voltage, which is the applied voltage at which PDs are observed at each cycle. Degradation of the studied material can be observed as the PD inception voltage is decreased. No general acceptance criterion exists for this technique, but generally, it is stated that a functioning cable has a PD at voltage levels that are twice as high as the operation voltage.

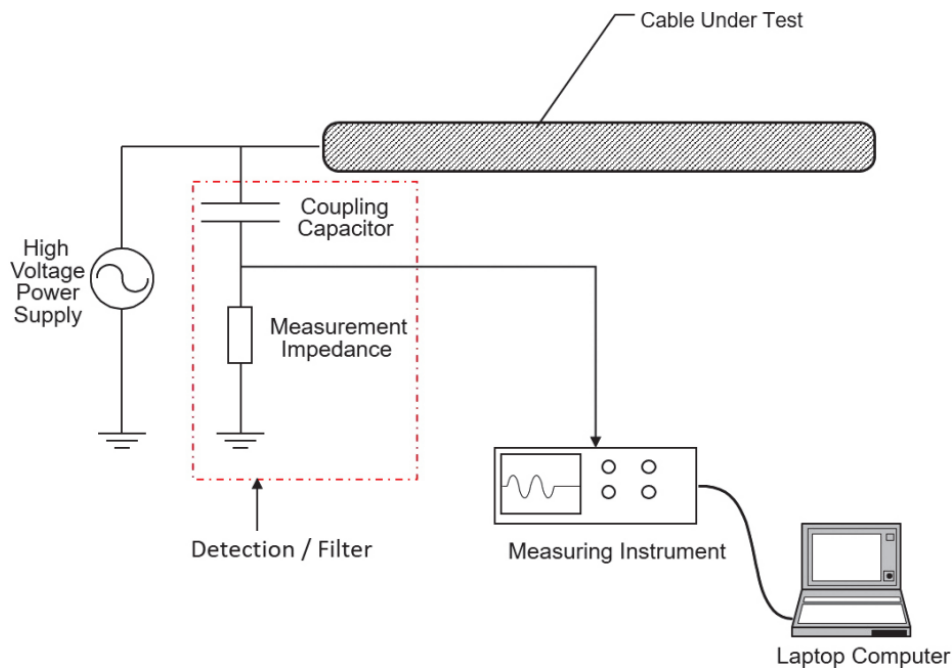


Figure 14. PD measurement setup. [EA Technology 2017]

The technique is rather well developed, some PD equipment is commercially available, and companies provide services (e.g., DEKRA Finland [Dekra 2024]). Also, general measurement procedures for the simplest cable designs are standardised (IEC 60270, IEC 60480 and IEC 62067). The recorded parameters (phase, magnitude and number of PDs) provide the possibility of detecting the source of the PDs, and the method provides information on the severity of the detected fault. However, the data analysis requires expertise. [NRC 2012] Even though the technique is considered non-destructive, applying a too large voltage during testing might result in damaging the cable insulator under inspection. EPRI has user experience data on this method and states that the PD method is not sensitive towards detecting water-based degradation modes [EPRI 2017].

2.13 POLARISATION-DEPOLARISATION CURRENT (PDC)

In PDC measurement, direct current step voltage is applied to the cable for a pre-defined time. The step voltage is shorted and the resulting polarisation current measured, as shown in Figure 13. The obtained data can be analysed in the time domain or transferred in the frequency domain. EPRI states that the method seems suitable for global characterization of cables and is recommended to be combined with reflectometry methods for fault location. More testing is still required to develop the method to be used in onsite cable assessments (e.g., the development of a cable specific acceptance criterion). [EPRI 2022]

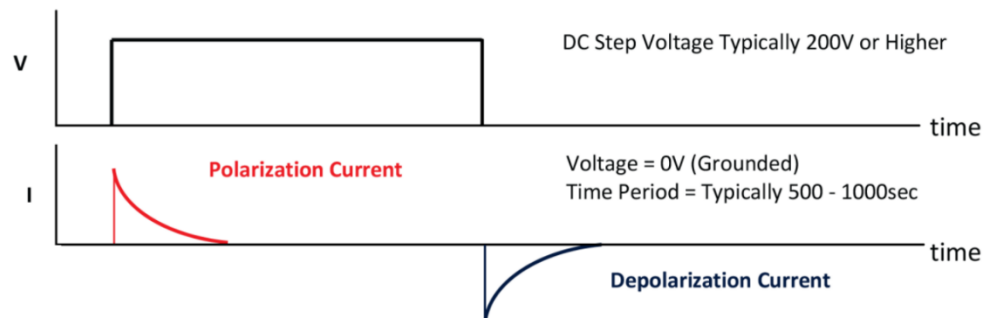


Figure 15. Presentation of a PDC test. [EPRI 2022]

2.14 THERMOGRAVIMETRIC ANALYSIS

The sample preparation in thermogravimetric analysis is similar to that in DSC analysis, and they both use a similar sample size, some milligrams. The technique itself differs from DSC since it measures the weight of the sample as it is heated in the sample chamber. See a schematic presentation of the setup in Figure 14. A decrease in mass can be correlated with the copolymer ratio, moisture content, the number of volatile additives, inorganic filler content and decomposition behaviour. [IAEA 2012, Simmons et al. 2013] The procedures for obtaining thermogravimetric data on polymers used as electrical insulators are defined in [ASTM D3850-12]. IAEA suggests that TGA analysis can be used in several ways: compositional analysis, analysing thermal and oxidative stabilities, lifetime estimation, effect of atmosphere, filler analysis, moisture and volatile compound analyses [IAEA 2017].

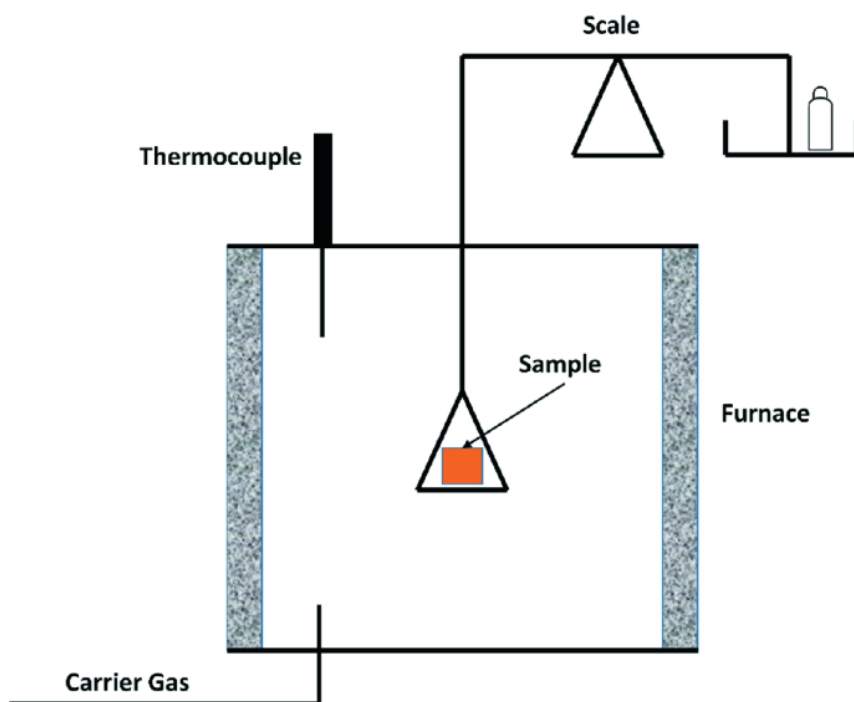


Figure 16. TGA measurement principle. [De Blasio 2019]

In IAEA benchmark tests two different acceptance criterion were chosen at which TGA results were correlated to EaB data: temperatures at 5% weight loss and maximum weight loss. IAEA states that when the 5 % TGA criterion was applied, the method did not correlate to ageing with most of the materials and the maximum weight loss criteria was not considered to be any better. This is most likely due to the sensitivity of the method to sample preparation. Also, sample loading should be taken into account in testing. [IAEA 2017] Another study with irradiation aged cables tested in isothermal conditions applying the 50% TGA criterion resulted in a better correlation with EaB [Boguski & Przybytniak 2016].

According to the experience from Krško NPP, TGA might be useful in measuring the relative degradation of polymers [Pirc 2016]. Toll et al. have also reported that the method has been applied in the analysis of cables obtained from NPPs [Toll et al. 2020].

2.15 TIME DOMAIN REFLECTOMETRY

Time domain reflectometry (TDR) is a very similar technique to FDR. It is a non-destructive technique that requires disconnecting the cables under inspection. The difference from FDR is in the applied signal. While in FDR the frequency of the signal is altered, in TDR the low voltage signal is in pulse form. Faults, connectors or end devices cause a reflection of the applied signal (reflections are relative to the cable impedance) and thus make it possible to diagnose the location of flaws, as exemplified in Figure 15. A typical TDR trace plots the reflection coefficient against cable distance, thus showing the location of any abnormalities. Faults located in the insulator can be detected to a greater extent than faults located in the jacket material, and diagnostic of the end device is possible. Just as in the case of the FDR technique, TDR also requires a baseline measurement to which measured data is compared. A NPP-specific standard exists for conducting TDR measurements with optical cables [IEC/IEEE 62582-6]. A variation of TDR, spread-spectrum time-domain reflectometry (SSTDOR) is a standardised test procedure used, e.g., in the aeroplane industry. [IAEA 2012]

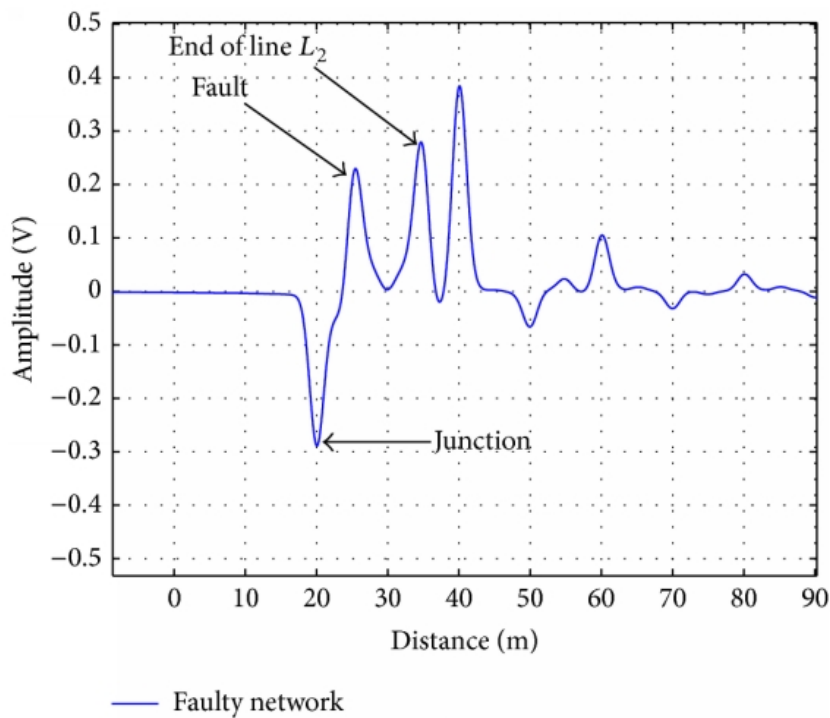


Figure 17. An example of a TDR measurement result on locally aged cable. [Ben Hassen et al. 2015]

Measuring devices are commercially available [Simmons et al. 2013]. Toll et al. have presented TDR data on real NPP cables, which demonstrate how the measured reflection coefficient changes from a baseline measurement [Toll et al. 2020].

2.16 TERAHERTZ METHOD

The terahertz method is based on the interaction of the applied terahertz waves (wavelengths ranging from a few mm to a few tens of m) with the material. There are two alternative ways to apply the measurement signal: THz time domain spectroscopy and THz continuous wave method. [Li et al. 2022] The measurement itself can be performed in four different modes, as presented in Figure 16. The collected measurement data can be imaged for visual presentation of the data [Zhenwei et al. 2022].

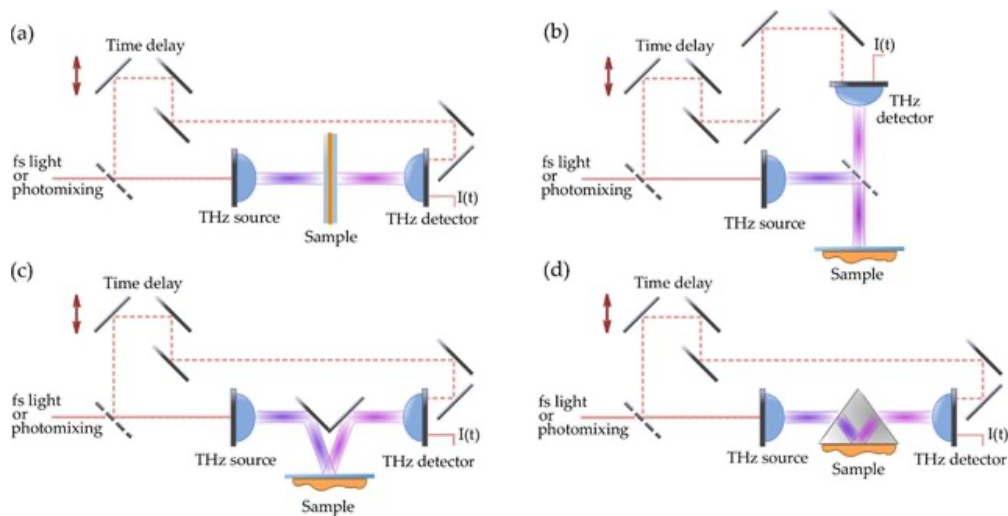


Figure 18. Different THz measurement modes: transmission mode (a) and various types of reflection modes (b, c and d). [Cherkasova et al. 2021]

The method has been demonstrated to work in laboratory conditions. It has been reported to be able to detect different types of defects, including air gaps, cracks and water trees. [Li et al. 2022] The ageing of a cable can be monitored based on permittivity and absorption coefficients. [Yan et al. 2017]

Good detection quality can be achieved with the method. An example of this is NASA's application in spacecraft inspections, where it is used to detect debonding defects. [Li et al. 2022] Otherwise, the method needs good access to the measured sample, which can be challenging in NPP. The required equipment is also expensive, and expertise is required to interpret the measurement data.

2.17 ULTRASONIC TECHNIQUE

The velocity of sound in a solid medium depends on the density and the modulus. Both of these properties are known to be affected by ageing, and thus it is possible to detect ageing as the velocity of sound in the material changes. In addition to these material properties, the form of the applied signal to the material (i.e., wave mode) also has an effect on the recorded response. Different wave modes used in ultrasonic inspection include longitudinal (or compressional) mode, horizontally and vertically polarised shear modes, and surface and plate wave modes. The type of wave mode is chosen based on the geometry of the inspected target and certain parameters related to material and transducer properties. [Rinta-Aho et al. 2021]

The instrumentation comprises piezoelectric transducers, which transmit and receive velocity signals. When the thickness of the sample is known and the measured signal transit times recorded, velocity can be calculated. Figure 17 shows schematically the measurement setup and an example of recorded measurement data.

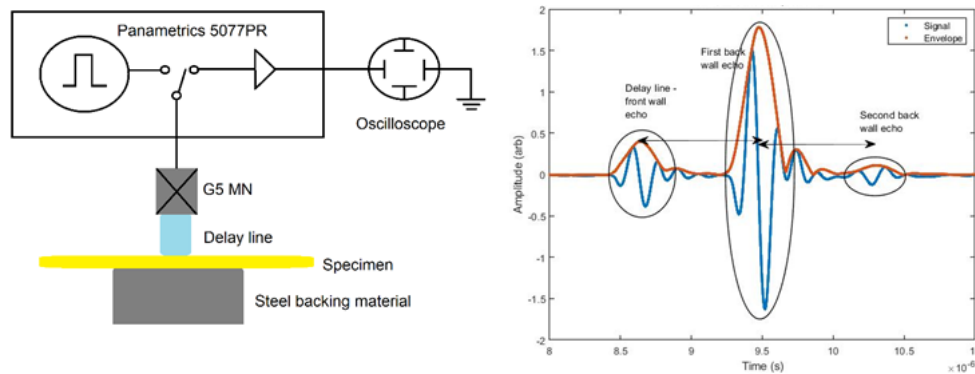


Figure 19. Schematic presentation on ultrasonic measurement setup on left and an example of measurement data on right. [Rinta-Aho et al. 2021a]

The technique is considered sensitive to detecting ageing, as pointed out with radiation aged XLPE in [Rinta-aho et al. 2021b]. However, there are a few complicating factors related to the signal behaviour. Firstly, the cable construction has an effect on how the wave introduced to the medium behaves, e.g., cable geometry, shielding and the structure of the polymer all have effect on the measured signal. Various parameters, such as transducer diameter, angle, frequency and their arrangement, can be adjusted to meet the properties of a specific cable type to obtain a good quality signal response [Simmons et al 2013]. Secondly, the technique is able to detect only ageing in the area where the transducers are placed, which is usually quite a small distance when compared to the overall length of cables (transducers can be easily moved by hand, so they are very suitable for onsite conditions). Thirdly, the technique requires baseline data for reference, as the cable composition can have a significant effect on the measured sound velocity.

The presence of metallic shielding in cables can limit the applicability of the method to only the jacket and certain locations where insulation is accessible (terminations and joints). The presence of additional multilayers affects the signal behaviour and may complicate the interpretation of the data.

2.18 VERY LOW FREQUENCY (VLF) WITHSTAND TEST

In this test, a constant voltage value is applied over the insulator for an elongated time period, and the cable should withstand without any local breakdown of the insulator. An example of a test setup is shown in Figure 18. The test result is simple: pass or fail.

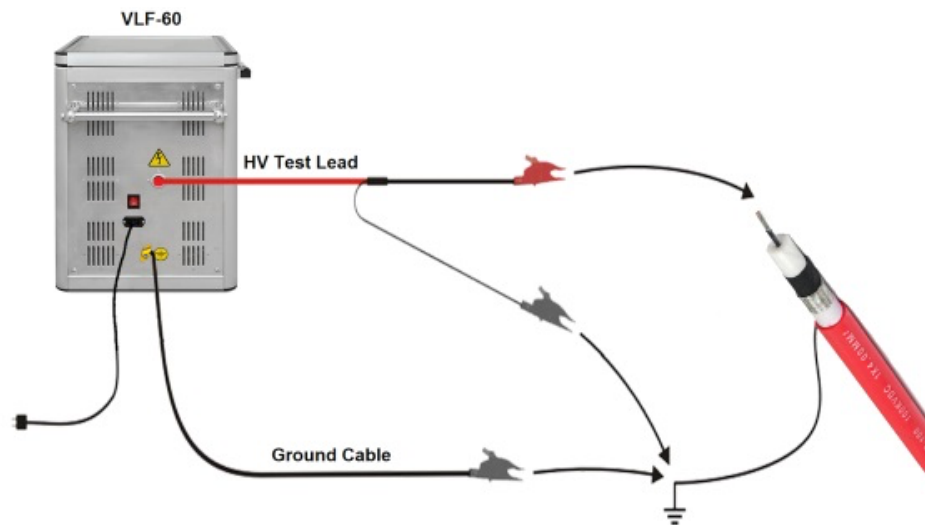


Figure 20. An example of a VLF test setup. [Rapid-Tech 2024]

The test is considered a viable option for detecting (significant) local defects in medium voltage cables, but it does not provide information on the global condition of the cable. [EPRI 2013] Additional condition monitoring methods are recommended to be combined with the VLF test in order to obtain a complete assessment of the cable condition [NRC 2012]. There are two standards, which define the test procedure for cable up to 35 kV and 69 kV [IEEE 400.2-2013, IEC 60502-1:2021]. No plant specific data was found on user experience, but the reports from EPRI and NRC [EPRI 2013, NRC 2012] indicate that the method can be used, at least in the U.S. plants.

3 Discussion on the most promising condition monitoring methods

3.1 COMPREHENSIVE REPORTS ON CABLE CONDITION MONITORING METHODS

Several summary reports on condition monitoring techniques have been published in the past years [EPRI 2005, Gillen et al. 2005, Yamamoto et al. 2009, OECD NEA 2010, Simmons et al. 2013, NRC 2014, IAEA 2017, Glass et al. 2020]. In the EPRI report from 2005, the use of 50 % of the EaB value as a condition monitoring method is discussed. The principle is that the cable should withstand handling during maintenance operations. Moderate bending of cables would allow as low as 11 % EaB value to be used as an acceptance criterion. However, in practice, when the cables are treated by hand during the maintenance procedure, they are subjected to local point loads that can cause higher elongations locally. Thus, a higher EaB value is considered reasonable, and the 50 % EaB value is commonly thought to provide sufficient margin to manipulate cables without cracking them during maintenance. [EPRI, 2005] The same report comprised a comparison between EaB and several non-destructive condition monitoring parameters performed with seven different cable materials. The results indicated the applicability of indenter modulus, micromodulus, sound velocity, DSC, density, gel fraction, uptake factor and NMR to assess the cable condition of certain cable material types. [EPRI 2005]

A broad report prepared by [Gillen et al. 2005] presents results from a 5-year cable ageing programme where life-time prediction and cable condition monitoring methods were assessed. The condition monitoring methods included in the study were indenter modulus, NMR, gel fraction, solvent uptake factor and density measurement. Based on the study results, indenter modulus seemed to be the most applicable condition monitoring method, while NMR and solvent uptake factor were also promising. Gel fraction and density measurement results seemed to be less promising, mostly due to measurement sensitivity issues, which can limit their applicability as condition monitoring techniques. [Gillen et al. 2005]

Indenter modulus was shown to be the most promising condition monitoring method out of the four candidates in the study performed by Yamamoto et al. [Yamamoto et al. 2009]. In the study, six different cable materials were artificially aged, and the material condition was tested as a function of the ageing time with EaB, ultrasonic technique, optical method (based on colour change), surface hardness and indenter modulus. The latter clearly showed the best correlation with EaB for all cable types studied. The other three methods were considered to be promising, but all had significant scatter in the results, which would require further development work to make them suitable for on-site condition monitoring.

The OECD NEA report lists 13 methods applied in condition monitoring of cables in NPPs around the world, including PD, current leak test, EaB, indenter modulus, IR, DSC (both oxidation induction time and temperature), potential decay, “system of electrical characterisation and diagnosis” (not opened in detail what it contains),

tan delta, TGA and visual inspections. [OECD NEA 2010] The report suggested further research in the field of cable condition monitoring techniques, including benchmarking procedures.

A study prepared by Simmons et al. [Simmons et al. 2013] reports that indenter modulus is applied in the nuclear industry for condition monitoring of cables. An interesting statistic is presented in the study, where the most promising condition monitoring techniques are listed based on literature references. EaB had clearly the greatest number of mentions (19) to be a suitable condition monitoring method, followed by FTIR with 13 mentions. The following methods with six or five mentions were DSC, volume resistivity, tan delta, gel fraction, dielectric spectroscopy and tensile strength.

NRC report from 2014 [NRC 2014] lists 20 condition monitoring methods that have shown to be suitable in laboratory conditions and could be potentially used in NPPs. The report divides the methods into three categories: techniques requiring sample removal, techniques not requiring sample removal and electrical techniques. From the destructive methods, EaB and DSC are mentioned as suitable to be used in condition monitoring at NPPs. The indenter modulus is considered a suitable method among the non-destructive methods. Although the electrical methods were considered to be good approaches for global and non-destructive evaluation of cables, they would require further validation.

IAEA published in 2017 a comprehensive report on condition monitoring methods applicable in NPPs. In the report, 14 different measurement techniques were tested with 12 different cable insulator and jacket materials to assess their applicability as condition monitoring methods. From the results, it seems that three condition monitoring methods appear to have a good or reasonable correlation with several cable materials. The report states that EaB has either good or at least reasonable correlation with ageing with the studied cable types, indicating its universal applicability as an ageing indicator. Indenter modulus seems to be even better than EaB with some materials, but with hard materials, no correlation with ageing was found. DSC methods showed a reasonable correlation with all materials under study. Insulation resistance and reflectometry methods were not considered to be very good in ageing monitoring, but their strength was merely seen in fault locating. Density, FTIR, ultrasound and dielectric spectroscopy methods were considered to be promising ageing monitoring methods, but TGA was not considered to be useful in this sense. [IAEA 2017]

A report focusing on online condition monitoring techniques has been published by [Glass et al. 2020]. The online methods applicable to NPPs are categorised into reflectometry methods, partial discharge measurement, fibre optic cable-specific methods and methods applied on the external jacket (interdigital capacitance, indenter modulus, ultrasound, FTIR and FT-Near IR). The report contains descriptions of cases where different online monitoring techniques have been applied on-site. TDR had successfully detected a cable failure that caused a control rod drop in the reactor core, causing a premature reactor shutdown and detection of faulty cable within reactor containment penetration. The PD method has been successfully used to detect a fault in the crimp connector in the middle parts of a cable that was more than 4 km long (the cable failed 20 days after the detection).

The listed comprehensive reports commonly use EaB as the most comprehensive property on the cable condition, and other material properties/parameters are compared to it. It seems that the indenter modulus correlates very well with it and can be applied to on-site measurements. TDR has been used successfully in fault detection and seems to be a similarly applicable condition monitoring method as the indenter modulus.

The Euratom funded project “European Tools and Methodologies for an efficient ageing management of NPP Cables” (Team Cables) contained a work package focusing on cable condition monitoring methods. The applicability of OIT, FTIR, terahertz, ultrasound, reflectometry and dielectric spectroscopy for in-situ inspections was assessed with XLPE insulator cables. The non-destructive technique deliverable report from the project suggests the application of OIT and FTIR as early ageing indicators and the application of a combination of global techniques in condition monitoring. Challenges are related to the interpretation of OIT measurement when the presence of fire retardant and the limited accessibility of local methods on the cable insulator was considered. The measurement procedures for different techniques were developed for on-site measurements. In the case of dielectric spectroscopy, the end-of-life criterion was possible to establish through correlation with other properties. [Team Cables consortium 2022]

3.2 REPORTED FIELD EXPERIENCE

In the previous section, long and comprehensive reports on condition monitoring methods were summarized. In this section, shorter publications on user experience in real service environments have been gathered.

LIRA has been applied in Ringhals NPP in 2006 [Fantoni et al. 2008]. Four 142 m long cables that had been in service more than 20 years were under test. No degradation was observed in the cables. Despite this, it was concluded that the method is functional in on-site conditions.

A 6-year cable ageing monitoring programme was implemented in Slovenian NPP Krsko [Pirc 2016]. Six different condition monitoring methods were applied (along with moisture, temperature and radiation measurements) and data gathered. Based on the results, indenter modulus and visual inspection gave the best results in fault identification. Tan delta and LIRA methods are mentioned as also being capable identifying aged cables in real service conditions. PD, on the other, hand did not result in fault indications. This might be since the cables did not necessarily contain any major faults detectable with the PD measurement.

A successful implementation of cable condition monitoring in Oyster Creek NPP has been reported by Kiger et al. [Kiger et al. 2017]. In this case, the plant had been suffering degradation of low voltage cables, resulting in significant plant impacts. The work was started by identifying the cables in the most severe environments and focusing the inspections on the identified cables, a principle that seems to be repeating throughout the related literature. The inspections were first planned to be performed as visual inspections, but due to the difficult routing of the cables, not all cables were accessible for visual inspection. Thus, a set of electrical tests were decided to be included in the test programme: TDR, FDR, and impedance

measurements. The approach was to use FDR to assess whether the cable had aged when exposed to severe environments, while the other methods were complementary providing data on the significance of the degradation. In FDR measurement, the cable condition was benchmarked against the cable locations in a milder environment successfully, as the FDR data showed an appropriate decrease in the reflection coefficient values in the harsher environments. The authors had developed a classification table identifying four different cable condition categories. In this specific test campaign, cables were identified to belong in categories 1 to 3, where category 3 was labelled as “Cable insulation has significant aging but is expected to function normally.”. The implementation of the measurements saved approximately 3.7 M\$ in costs and reduced the time required for the inspections from 14 to four days.

A second occasion where the same approach was applied in Oyster Creek NPP has been reported by Harmon et al. [Harmon et al. 2020] Again, similar ageing was detected in the cables, as reported by [Kiger et al. 2017] and similar cost savings were estimated.

Toll et al. [Toll et al. 2020] report three case studies where cable condition monitoring methods have been applied on-site. The first reported method was indenter modulus, which was applied to 10 different cables with a Neoprene jacket installed inside the reactor containment of a NPP, and comparison measurements were performed with seven corresponding cables that had been in a less severe service environment. The result was that after 43 years of service, a difference in the average indenter modulus values measured from the cables inside containment was slightly, but not significantly, higher compared to the reference samples, indicating only minor degradation.

In the second case study, the remaining useful lifetimes were determined for three different cable types removed from service by using a combination of EaB, OIT, visual inspection and TGA [Toll et al. 2020]. The condition of the cable was determined to be “as received” and these samples were artificially aged to obtain cable specific activation energy values. The Arrhenius equation was applied in calculating a conservative estimation of the remaining useful lifetime. For one of the cables, it was determined to be five years, which would not have been sufficient considering the lifetime extension of the plant.

The third case study presented by [Toll et al. 2020] focused on combining in-situ and laboratory condition monitoring methods on PVC cables exposed to moisture. The infrared method showed to be a sensitive method to detect moisture-related degradation. This was supported by another in-situ measurement data set obtained by using TDR. The moisture induced degradation was observable in EaB, permittivity, OIT and colour, so several methods can be used in estimating water related degradation.

3.3 SUMMARY ON THE CONDITION MONITORING METHODS

The condition monitoring methods have been divided into two parts depending on whether the measurement is applied to the cable locally (Table 1) or globally (Table

2 2). For each method, their strengths and limitations are summarised. Any monitoring data from cables that have been in service are reported.

Method	Strengths	Limitations	Data from plant conditions
DSC [time or temperature]	Sensitive to antioxidant content in laboratory conditions, simple procedure.	Requires microsampling, material specific limitations may exist, equipment not portable.	NPP user data available on various types of cables, but data inconclusive
Density [g/cm ³]	Simple method, good correlation with ageing with CSPE, PE and silicon rubber, cheap.	Microsampling required, high scatter, sensitive to DLO, non-portable.	No user data from NPPs was found.
Gel fraction and solvent uptake [%]	Simple method, correlates to EaB with PE, CSPE and PCP.	Microsampling required, a vacuum dryer (non-portable) required.	No user data from NPPs was found.
Indenter modulus [indentation depth and force]	Simple method, applies to several materials.	Limited accessibility to insulator, limited resolution to detect ageing with some polymers e.g. PEEK and XLPE, sensitive to operator.	NPP user data available on various types of cables.
Infrared analysis [absorbance]	Relatively simple method, available as portable version, portable equipment becoming available.	Requires microsampling, analysis of black materials can be complicated, correct interpretation of measurement data requires expertise.	Applied to real cables obtained from NPPs, it seems that the data analysis procedure needs to be standardised for different polymer types.
Infrared thermography [image]	Simple method, portable cameras commercially available, identification of hot spots.	Does not provide quantified data on cable condition.	Applied on-site to identified locations with elevated temperatures
Nuclear magnetic resonance [relaxation time]	Shown correlation with mechanical properties, portable.	The portable sensor can currently measure only non-shielded cables.	Cables obtained from NPPs tested.
Thermogravimetric analysis [weight]	Simple analysis, standardised methods are available.	No direct correlation with ageing has been presented so far, more of a complementary analysis method, non-portable.	Have been used in a few plants for cable condition analysis.

Method	Strengths	Limitations	Data from plant conditions
Terahertz method [attenuation or reflection]	Can be sensitive towards detecting defects.	Accessibility on insulator limited, cost, required expertise, non-portable.	No user data from NPPs was found.
Ultrasonic technique [sound velocity]	Relatively simple analysis, portable equipment, fast measurement.	Accessibility on insulator limited, some expertise required in data analysis.	No user data from NPPs was found.

Table 2. Summary of the local cable condition monitoring methods. The measured parameter is in brackets in the first column.

Method	Strengths	Limitations	Data from plant conditions
Tan delta [-]	Sensitive towards water-related degradation, commercially available equipment and inspection services, portable.	Does not provide locations for flaws, requires disconnecting.	NPP user data available on various types of cables.
Dielectric spectroscopy [impedance]	Seems to be a sensitive global cable condition assessment method, portable.	Not very suitable for detecting localised ageing.	Not available.
FDR/LIRA [reflection]	Can identify and locate faults on the whole cable length, portable.	Baseline measurements are usually required to monitor ageing, analysing data requires some expertise.	FDR have been shown to be able to detect ageing on thermally aged cables, LIRA has been applied to on-site condition monitoring.
Insulation resistance measurement [resistance]	Simple method, does not require access to the whole cable, portable.	Not very accurate and sensitive to environmental effects, requires disconnecting.	NPP user data available and according to it can detect mostly degraded cables.
Partial discharge [pass/fail]	Provides information on the fault location and severity, standardised procedures available, portable.	Requires high expertise level, too high applied voltages can damage cables, requires disconnecting, susceptible to environmental noises.	NPP user data available on various types of cables.

Method	Strengths	Limitations	Data from plant conditions
PDC [current]	More sensitive than traditional electrical methods such as tan delta, portable.	Only global characterization, acceptance criterion not yet well defined.	Applied for cables removed from NPPs.
TDR [reflection]	Been applied widely in other industries, portable.	Requires baseline measurements, requires disconnecting.	Have been used in NPPs.
Very low frequency withstand test [pass/fail]	Well established method for detecting localised flaws, portable.	Requires disconnecting, only for local fault detection, may progress already existing faults, not fully conclusive and often requires additional measurement methods.	Not available, although included in NRC and EPRI documents.

Table 3. Summary of the condition monitoring methods applied globally. The measured parameter is in brackets in the first column.

Table 3 presents the suitability of different condition monitoring methods for different materials. The globally applied methods do not seem to have material specific limitations. For locally applied methods, it was not possible to assess all method-material combinations within this framework, but it seems that there are knowledge gaps on their applicability. DSC may have some additional limitations regarding specific additive content, as discussed earlier. The infrared method may not be applicable to black materials, which is not shown in the table. NMR has been applied to various types of cables, but the material specific composition of cables has not been reported [Furo et al. 2021].

It seems there is currently no single method available that could be universally used in the assessment of cable condition. Thus, a combination of complementing methods would be recommendable. Methods capable of global condition characterization or fault detection could be first performed, followed by supportive local characterization at the aged locations.

Indenter modulus has been shown in many studies to correlate with cable condition, and its use has been demonstrated in NPPs. However, it assesses the cable condition only locally and additional methods would be required to allocate indenter measurement inspections properly. Another potential issue is that its accessibility is often limited to the jacket and the insulation could be accessed only at terminations and junctions. A proper understanding should be established of how well the jacket condition correlates with the insulation condition if the method is applied only to the jacket.

Method/Material	CSPE	EPDM	EPR	EVA	PEEK	PVC	SIR	XLEVA	XLPE	XLPO
Tan delta										
Dielectric spectroscopy										
DSC										
Density										
FDR/LIRA										
Gel fraction and solvent uptake										
Indenter modulus										
Infrared analysis										
Infrared thermography										
Insulation resistance measurement										
Nuclear magnetic resonance										
Partial discharge										
PDC										
Thermogravimetric analysis										
Time domain reflectometry										
Terahertz method										
Ultrasonic technique										
Very low frequency withstand test										

Table 4. Applicability of different condition monitoring methods for different materials. Green indicates good applicability, yellow indicates potential uncertainties in measurement, red indicates bad applicability and white indicates no suitable literature data was found.

OIT measurements performed in laboratory conditions have resulted in promising results. Especially using the method as an early warning sign for ageing would seem like an interesting approach. However, conclusive data from plant use was not found that could confirm its use as a on-site application. This seems like an area that would require more experience and studies with in-service samples.

Infrared thermography seems to be suitable method to identify local hot spots in temperature-wise and thus helpful coordinating condition monitoring measurement locations.

The rest of the local methods have shown promising laboratory results and some of them have been used in supporting analyses performed with cables obtained from service (e.g., FTIR and TGA). However, demonstrations in real-service conditions would still be required to show their applicability to be included in condition monitoring assessments.

Many of the globally applied methods have already been identified to be used at NPPs, as they have been listed by NRC and EPRI as suitable condition monitoring methods for NPPs [EPRI 2013, EPRI 2017, NRC 2012]. This can be taken as a measure of maturity for NPP cable condition monitoring. However, their limitations are acknowledged as well, and the best result is usually obtained by combining the strengths of the methods. FDR and LIRA methods have performed quite convincingly in plant conditions, based on what has been reported in the literature. Especially, they have shown their usefulness in accessing locations where visual inspection becomes nearly impossible due to challenging cable routing. When comparing the globally applied methods, it seems that the ones based on reflectometry seem currently the most advanced ones to characterise the cable condition globally or fault location. Simultaneously, it should be stated that dielectric spectroscopy has been demonstrated to function well in laboratory conditions and given the fact that it is in principle the same measurements as tan delta (although in a broader frequency range), it has the potential to provide

comprehensive data on the cable condition. It seems that the method is ready for plant trials, and it would be interesting to see its performance in real NPP conditions.

The other global methods (tan delta, insulation resistance, partial discharge and very low frequency withstand test) have been included in the NRC regulatory guide containing condition monitoring tests for NPP cables. Although these methods have been included in the NRC listing, they have limitations due to which they cannot be solely relied on in cable condition monitoring. They can be valuable techniques when complementing other condition monitoring methods.

3.4 CABLE AGEING MANAGEMENT LIFECYCLE APPROACH

Finally, it remains to be assessed how different methods could be used as part of the cable condition monitoring strategy at NPPs. It is not possible to suggest a detailed plan how to implement the use of the individual techniques as part of the condition monitoring strategy at NPPs within this framework, as there are method- and material-related uncertainties that would still require further analysis. However, some general principles can be suggested. Figure 19 shows an exemplary timeline and five stages for implementing a condition monitoring strategy.

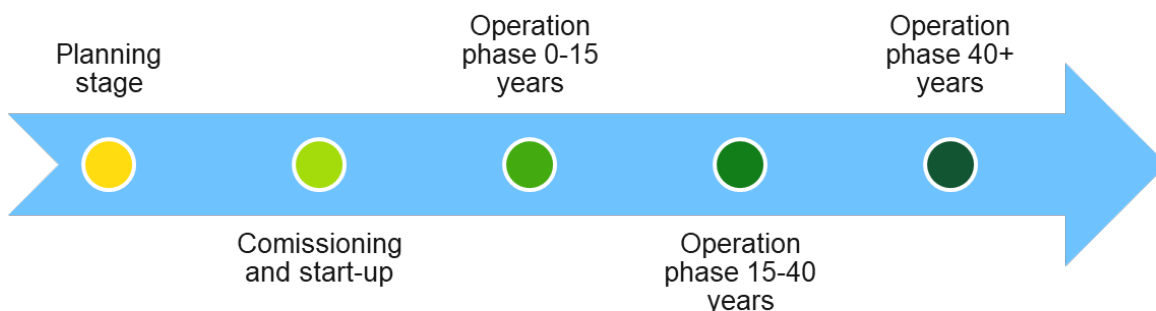


Figure 21. An example of a timeline of different stages in the cable condition monitoring strategy.

The first stage is the planning stage of the NPP. Here, the existing knowledge and good practices should be compiled as the basic principles of the strategy are planned. The applied condition monitoring methods and plans, including deposit samples in NPP, should be decided. At this stage, the cable manufacturers are contacted, and the used cable population is fixed.

The second stage is the commissioning of the NPP and start up. At this stage the initial properties of the cables are defined with different condition monitoring methods. This stage is of utmost importance since all the measurements performed later are compared to these baseline measurements. If the commissioning period is extended significantly, the environmental conditions where the cables are located should be recorded. Furthermore, emphasis should be put on data management to ensure that the data recorded in the early stages remains in readable/accessible form throughout the whole lifetime of the plant.

During the early operational phase, no significant ageing should be expected in the cable materials. The predetermined condition monitoring measurements should be performed accordingly.

During the second operational phase, more time has elapsed, and the focus of the condition monitoring is on cables exposed to the harshest environments. Methods capable of providing early ageing signs, such as DSC, should be considered along with the mixture of globally and locally applied methods.

During the third operational phase, after more than 40 years of time have elapsed, significant ageing of some of the cables can be expected. The predetermined condition monitoring measurements are continued accordingly. In addition, the condition monitoring data should be used, whenever feasible, to predict the remaining useful lifetime. This is particularly important if lifetime extensions are considered.

4 Conclusions

Low- and medium voltage cables are used in NPPs as part of instrumentation and electrical equipment to supply electricity or signal transfer. Condition monitoring methods are used as part of the ageing management of cables to improve the overall safety of operating NPPs. However, currently the only universally accepted condition monitoring method, EaB, is destructive, which would require the use of surveillance samples. Thus, methods capable of determining the cable condition non-destructively or by using only very small samples would be great interest.

The available literature on cable condition monitoring methods in NPPs has been reviewed in order to recognize the most promising non-destructive methods. The following conclusions are made:

- 1) It is utmost important to allocate the cable condition monitoring efforts properly based on environmental data (temperature, radiation, moisture) recorded. The inspections should be focused on the locations where the environment can accelerate ageing.
- 2) There is no single universal non-destructive cable condition monitoring method that could be applied in all situations to assess the cable condition. The most complete way to assess cable condition is to combine methods that assess the cable condition globally and locally.
- 3) Visual inspections and infrared thermography can be used to locate hot spots where the inspection should be concentrated.
- 4) Indenter modulus seems to be the most tested method in in-service conditions and has performed the best out of the local condition monitoring methods. The use of OIT measurement in the monitoring of in-service cables should be assessed in more detail due to the promising results obtained in laboratory conditions.
- 5) Reflectometry-based global methods can be used to assess cable condition throughout their whole length, even at locations hardly accessible by other methods. Promising in-service results have been demonstrated with the use of the FDR method. Another promising global method is dielectric spectroscopy, an advanced version of tan delta measurement that has been well demonstrated in laboratory conditions and is ready for on-site trials. Other global methods are feasible in terms of fault location, including water-related degradation.

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CABLE CONDITION MONITORING METHODS FOR NUCLEAR POWER PLANTS

Low- and medium voltage cables are used in nuclear power plants (NPPs) as part of instrumentation and electrical equipment to supply electricity or signal transfer. Typical estimates are that a single NPP contains such cables at approximately 1000-2000 km. Cables are subjected to ageing due to different environmental stressors like temperature, radiation and moisture. In order to monitor cable ageing accordingly, suitable condition monitoring methods are required. This report lists potential condition monitoring methods to be applied to NPP cables and assesses their strengths and weaknesses. The results can be used when suitable condition monitoring methods are chosen for NPP trials.

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