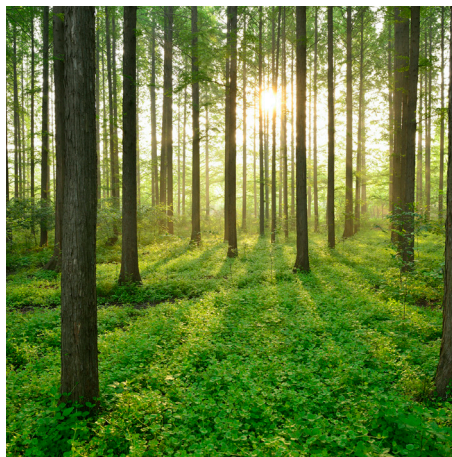
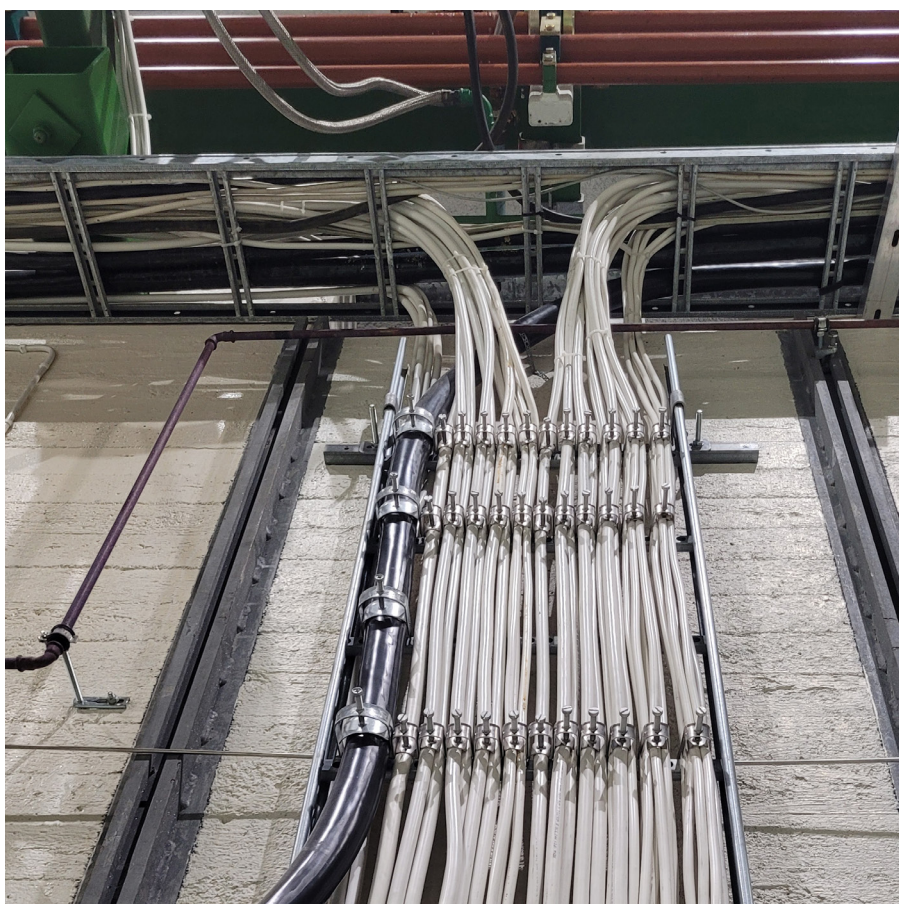


CABLE CONDITION MONITORING EXPERIENCES AT NUCLEAR POWER PLANTS

REPORT 2025:1124



POLYMERIC MATERIALS IN
NUCLEAR APPLICATIONS



Cable Condition Monitoring Experiences at Nuclear Power Plants

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Foreword

This report forms the results of a project performed within the Energiforsk Polymers in Nuclear Applications Program. The Polymers 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 nuclear power plant can contain up to 2 000 km of cables necessary for signal or electricity transfer, which makes it important but also time and resource consuming to ensure their proper function throughout the lifetime of the plant.

The purpose of this study was to analyse current practices in cable condition management, to identify good practices and possible areas for improvement. The report lists a wide variety of condition monitoring methods and good practices, making it possible for the power plants to benchmark and improve in this important area.

The study was carried out by Konsta Sipilä, VTT and Anna Bondeson, RISE. The study was performed within the Energiforsk Polymers Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

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

Summary

Nuclear power plants have various systems and components that contain cables as part of signal or electricity transfer. These cables are subjected to ageing, and ensuring their proper function throughout the whole lifetime of the plant holds significant importance, especially when lifetime extensions are considered.

This work focused on gathering experiences related to cable condition monitoring from plant personnel and identifying best practices. The topics of interest included the overall approach to setting up the condition monitoring, the applied condition monitoring methods and ageing data management. A common approach is to organize cable inspections systematically. Factors influencing the organization of inspections include the cable's safety relevance, location, environmental parameters, and its importance for maintaining uninterrupted normal operations. During the cable inspections, visual and tactile inspections are commonly used due to their simplicity. Regarding the other methods, the most practical outcome can be reached by combining global and local methods to ensure the most complete overall view of the cable condition. The collected cable ageing data is not necessarily used to provide exact predictions on the remaining lifetime, but rather to identify trends in material properties.

Keywords

Nuclear power plant, cables, condition monitoring, ageing management, user experience

Sammanfattning

Kärnkraftverk har olika system och komponenter som innehåller kablar som en del av signal- eller elöverföring. Dessa kablar utsätts för åldrande, och att säkerställa deras korrekta funktion under hela verkets livslängd är av stor betydelse, särskilt när livslängdsförlängningar övervägs.

Detta arbete fokuserade på att samla in erfarenheter relaterade till kablarnas tillståndsovervakning från personal på verket som arbetar med kablar och identifiera bästa praxis. De intressanta ämnena inkluderade den övergripande synen på att ställa in tillståndsovervakningen, de tillämpade metoderna för tillståndsovervakning och hantering av åldringsdata. En vanlig metod verkar vara att kablinspektionerna organiseras systematiskt. Faktorer som påverkar organiseringen av inspektionerna baseras på kabelns säkerhetsrelevans, plats, miljöparametrar och kabelns betydelse i förhållande till oavbrutna normala driftsförhållanden. Under kabelinspektionerna förlitar man sig vanligtvis på visuella och taktila inspektioner på grund av deras enkelhet. När det gäller de andra metoderna kan det mest praktiska resultatet nås genom att kombinera globala och lokala metoder för att säkerställa den mest fullständiga övergripande bilden av kabelns tillstånd. De insamlade uppgifterna om kabelns åldrande används inte nödvändigtvis för att ge exakta förutsägelser om den återstående livslängden, utan enbart de insamlade uppgifterna följs för att känna igen trender i materialegenskaperna.

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1 Introduction

Cables are an essential part of different instrumentation and electricity transfer systems in nuclear power plants (NPPs). One estimation of the total cable length in a single NPP is between 1000 and 2000 km [1, 2, 3]. There is a wide range of cable types of different voltages and materials which are all subjected to ageing [4, 5, 6]. Cable failures, including those at cable joints and terminations, can be significant from the perspective of nuclear safety or reliable electricity production. The proper function of the cable must be ensured, especially when they are part of a safety relevant system. There are also numerous cables that are part of non-safety critical systems but are required for maintaining normal operational conditions of the plant. Malfunction of these cables can lead to interruptions in electricity production and thus financial loss. The condition of cables is becoming more topical as the current nuclear fleet ages and lifetime extensions are considered.

An effective cable condition monitoring strategy is implemented to prevent failures in cables and their connection points, thereby ensuring the safe and cost-efficient operation of the nuclear power plant. As part of implementing the condition monitoring strategy, the scope and practises for assessing cable condition are defined. They are usually further detailed as a part of different types of cable ageing management programmes. The scope usually defines the cables to be included under regular monitoring and the monitoring frequency. The practises for assessing cable condition include the more detailed approaches and methods applied at the operative level. These actions provide information on the cable condition and surrounding environmental conditions (temperature, radiation, moisture, etc.) and define how the gathered ageing data is managed. As part of putting the condition monitoring strategy into action, the methods and scope for checking the cable's condition are defined. These usually take the form of different cable ageing programmes. The scope usually outlines which cables will be regularly monitored and how often the monitoring will take place. The practices for assessing cable condition involve more detailed methods used during actual operations. These actions help gather information about the cable's current state, the surrounding environmental conditions (such as temperature, radiation, and moisture), and how ageing data is managed.

The scope and practises of cable condition monitoring strategies can vary between NPP sites. Identifying good existing cable condition monitoring practises would help improve the overall ageing management of cables. This work aims to gather these well-established approaches, practices and methods by interviewing people working with cable condition monitoring in NPPs.

2 Interviews

The interviews were conducted with personnel from five different NPP sites in Europe. A total of 13 persons were interviewed. The interviews took place between March and April in 2025 and were carried out by the authors of this report. A set of questions related to planning cable condition monitoring, the methods used, and the management of ageing data formed the basis of the interviews:

- How do you decide which cables to inspect?
- Do you have a ranking system for cables based on their importance?
- How do you determine the frequency of inspections for each cable or group of cables?
- Does the location of a cable affect how it is inspected?
- What methods are used for monitoring the condition of cables?
- Can you briefly explain how each monitoring method works?
- Can you provide an example of an online monitoring procedure you have performed?
- How long have these methods been in use?
- What are the advantages and disadvantages of each monitoring method?
- What thresholds or acceptance criteria are used in different monitoring methods?
- How do the monitoring methods correlate with cable ageing?
- Do you store the measurement data and track its changes over time?
- Can you estimate the remaining lifespan of the inspected cables?
- How many cables typically fail the inspection?
- What are the most common causes of cable failures?
- What procedures are followed when a cable fails inspection?

The results from the interviews are summarized in this report.

3 Approaches for arranging cable ageing condition monitoring on site

This section summarizes how the cable ageing condition monitoring is organized at different NPP sites.

3.1 NPP SITE 1

The cables are inspected in a predetermined manner based on their location and safety relevance. Figure 1 summarizes the cable condition monitoring strategy of this site. Two separate condition monitoring programmes are in place. The first one is dedicated to the cables located inside the containment building and the second one covers cables outside the containment building with a safety classification. The cables located inside the containment are inspected based on their location. The containment area is divided into different sectors, and each sector is inspected during an outage. This results in an inspection frequency of five to six years.

Condition monitoring of cables outside the containment building was started a few years ago. The cables included in these inspections have a certain safety classification. Cables without a safety classification are excluded from this scope. The inspection frequency is the same as with the cables inside the containment building.

Cables excluded from the scope of the two condition monitoring programmes are spot-checked.

The cables located inside the containment building and safety classified cables are prioritized. The effect of the environment (high temperature, radiation and moisture) is acknowledged, and these so-called “hot spots” can be defined separately and taken under closer surveillance.

Furthermore, additional monitoring is performed parallel to the two aforementioned cable condition monitoring programmes. This additional monitoring is performed continuously along with other activities at different locations accessible during operation and it is applied on all types of cables and connector boxes. It can take place when a modification work is performed on a specific component by performing a simultaneous check of the nearby cables or when the installation inspections of equipment are performed.

Surveillance samples are cable segments placed at pre-determined locations and their properties are tested after a period of exposure to the service environment. The benefit of the surveillance samples is that destructive testing can be performed on them to obtain reliable data on the sample condition. Thus, they are useful for supporting the cable condition assessment. At this site, surveillance samples on the most common cable types have been placed at different pre-determined locations. The environmental conditions have an impact on the chosen location. The sampling frequency for surveillance samples is longer, e.g., 10 years, compared to the inspection frequency on in-service cables.

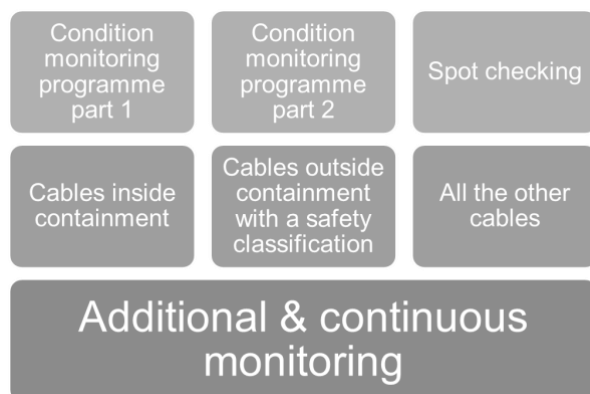


Figure 1. Summary of the condition monitoring at NPP site 1.

3.2 NPP SITE 2

The cables included in the ageing management programme were chosen based on an initial screening of systems and components. The criteria used during the screening process were based on cables' significance with respect to safe and economic operation. These cables were considered part of one of the following categories:

- Safety related components
- Non-safety related components that can affect safety (e.g., lighting, ventilation, etc.)
- Fire protection system
- Environmentally qualified components
- Station blackout component
- PTS (pressurized thermal shock) system
- ATWS (anticipated transient without scram)

Furthermore, additional walkdowns and assessments of environmental conditions were performed to identify adverse environments (high temperature, radiation, moisture, vibrations), so cables at these locations could also be included in the ageing monitoring programme. The following limit values have been used for determining the adverse environment:

- Temperature > 50 °C
- Radiation > 200 mSv/h
- Relative humidity 90-100%

The criticality of the cables has also been defined, to highlight their priority. There are four different classes (critical 1, critical 2, non-critical and run to failure). This classification also covers cables that do not have safety significance but are necessary for the normal operation of the plant. By using these two parallel systems, inspection frequencies of 18 months, three, six, or ten years can be defined. Cables submerged in water can be inspected more frequently than this. The inspection frequency of individual cables can be shortened if ageing is observed.

3.3 NPP SITE 3

The cables are inspected according to a strategic maintenance plan, which applies to all cables. It has been developed to establish processes and working methods aimed at preventing age-related cable issues. These methods are based on collective in-house experience and expertise in the field. The maintenance plan also consolidates cable-related maintenance activities for all reactors at the power plant.

The cables are divided into different categories based on their function and voltage rating. These categories include:

- High-voltage cables (> 36 kV)
- Medium-voltage cables (> 1 kV and ≤ 36 kV)
- Power cables (≤ 1 kV)
- Control and instrumentation cables
- Electronic cables
- Optical cables
- Internal cables

The frequency of cable inspections is determined through an ageing management program. This program follows international guidance [8] and includes both general and specific routines to prevent ageing-related problems.

How often a cable is inspected depends on the type of equipment it is connected to and how important that equipment is for safety and power supply. Cables that are more critical or exposed to harsher environments are inspected more frequently and with suitable methods for their type.

The location of a cable has a significant impact on how it is inspected. A systematic approach maps out areas with harsh conditions—such as high temperature, radiation, moisture, vibrations, or chemicals. Although most areas have stable conditions, some local "hot spots" can increase the risk of cable damage. These areas receive extra attention during inspections.

Each cable is registered in a database with information about its type, length, and installation location. There is also a room environment database that describes typical conditions in each part of the plant, such as temperature and humidity. If conditions are challenging, cables that can withstand these environments are selected, or inspections are conducted more frequently.

Mechanical damage, poor installation, or faulty connections can also cause problems. These risks are reduced by following design rules, and inspections sometimes include tools like thermal cameras to detect overheating.

In short, both how often and how a cable is inspected depend on its use and the surrounding environment. This ensures that inspections are carried out where they are most needed.

Cable surveillance samples at certain locations or dedicated areas allow cables to age naturally in a real and representative operational environment (in terms of temperature and radiation) so that elongation at break (EaB) and indenter measurements can later

be performed according to maintenance plans. Environmental parameters in the storage area for the surveillance samples are monitored annually and reported.

EaB tests help assess how the cables age under actual conditions, and results are compared to those from qualified cables to evaluate whether real ageing aligns with expected performance. Each type of surveillance sample cable has a dedicated section in a summary document outlining its history, pre-measurements, and ongoing tests. The surveillance samples are located inside the containment area of the reactors.

3.4 NPP SITE 4

The decision on which cables to inspect is based on their accessibility, function, and environmental conditions. All accessible cables are inspected, but those in challenging environments are prioritized. Cables that are not accessible, such as those installed in conduits, are not included in visual inspections but are inspected using other methods.

The cables are grouped based on their safety-related or operational function, depending on the equipment they serve. In addition to this, the cables are divided into six categories according to voltage level and function. There is no dedicated ranking system for individual cables; instead, their prioritization is determined by the criticality of the systems they are part of. For example, if a system requires annual inspections, the associated cables will follow the same inspection interval.

The frequency of inspections is determined by the environmental conditions (temperature, radiation, moisture, oil, etc.) and the importance of the cable. Cables in harsher environments, such as containment areas, are inspected annually, while those in less challenging environments, like turbine areas, are inspected every three years. If a more challenging environment is discovered, the inspection interval can be adjusted accordingly.

The location of a cable significantly affects how it is inspected. More accessible cables are more thoroughly inspected, both visually and tactilely. Specific instructions and tools, such as flashlights, are used during inspections, which are performed by maintenance personnel.

3.5 NPP SITE 5

The selection of cables to be inspected is not made systematically. Although there are ageing programs and instructions, they are not strictly followed. Cables in operation are not inspected systematically, and there are no specific plans for ranking or prioritizing cables for inspection. The primary reason for this lack of systematic inspection is that most of the cabling within the containment area was replaced about 10–15 years ago, and these cables are still relatively new. Outside the containment area, much of the old cabling remains, but these are considered lower priority due to their lower impact on reactor safety.

The frequency of inspections is not explicitly determined, as there is no systematic approach to cable inspection. However, it is understood that cables in harsher

environments, such as the containment area, would require more frequent inspections compared to those in less critical areas.

The location of a cable does affect how it is inspected. Cables in the turbine area, which are exposed to higher temperatures, may show more signs of ageing. Inspections are often carried out when maintenance teams are working on related projects and notice issues with the cables.

4 Cable condition monitoring methods

In this section, the cable condition monitoring methods that have been used on site are gathered and their advantages and disadvantages based on the user experience are presented. Furthermore, the maturity of each method's acceptance criteria is briefly discussed, again based on user experience. Their operational principles are described in more detail in [7].

4.1 VISUAL INSPECTION

Visual inspection is the most commonly used inspection method. It is described as easy, simple and inexpensive. Colour or other visual changes are usually easy to detect and are taken as rough indicators of ageing. Using visual inspection to predict the remaining lifetime of a cable is not considered feasible. Any observed changes of appearance can be followed up with tactile inspection to obtain a more complete assessment its condition. The use of a camera and photography can support visual inspection by providing more comprehensive documentation of the cable's condition.

- **Advantages:** Simple, cost-effective, and fast; useful for identifying surface defects and colour changes. Can be conducted online.
- **Disadvantages:** Cannot detect internal degradation; relies heavily on the inspector's experience. Limited to cables that are easily accessible.
- **Acceptance Criteria:** Any visible crack, deformation, or severe discolouration typically warrants further evaluation or replacement.

4.2 TACTILE INSPECTION

Another commonly and easily used testing method is tactile inspection the cable. This is conducted only when visual inspection indicates ageing. Tactile inspection is usually performed carefully just to determine whether the cable can withstand minor mechanical stress without breaking. It can provide useful information about the mechanical properties of the cable jacket. However, tactile inspection requires access to the cable, which limits the method's applicability.

- **Advantages:** Simple, cost-effective, and fast. Can complement visual inspection.
- **Disadvantages:** Provides only a simple indication whether the cable can withstand an unknown amount of stressing. May be potentially destructive.
- **Acceptance Criteria:** If the cable breaks or shows signs of degradation it is considered to have failed, although no well-defined acceptance criterion currently exists.

4.3 ELONGATION AT BREAK (EAB)

Tensile testing can be performed on surveillance samples or cables removed from service, and EaB is a single property that is known to correlate with cable ageing. Although it is a good ageing indicator, it requires a separate program based on surveillance samples. Limiting factors in such a program include the lack of representative reference data point and a limited number of samples, as the testing method is destructive.

- **Advantages:** Offers accurate insight into insulation brittleness and material ageing. Standardized and not very complicated to perform.
- **Disadvantages:** Destructive and cannot be applied to cables in service. Requires sample removal or a surveillance sample.
- **Acceptance Criteria:** An EAB value below 50% is commonly used as an acceptance criterion, indicating that the cable is nearing the end of its service life.

4.4 PARTIAL DISCHARGE (PD)

PD measurement is a standard method (e.g. IEC 60270), and it is most often performed by a third party. It is typically applied for larger cables.

- **Advantages:** Sensitive to weak spots in insulation. Enables continuous monitoring of developing faults; non-invasive.
- **Disadvantages:** May not reveal degradation uniformly across the cable; limited in assessing overall insulation health. Measurements can be easily disturbed by nearby activities and are technically challenging.
- **Acceptance Criteria:** PD activity above the threshold specified in international standards necessitates immediate analysis and possibly corrective measures.

4.5 INSULATION RESISTANCE

Insulation resistance measurement is also applied for larger cables. The method is standardized (e.g. IEC 60502-1). It is regarded as a simple measurement, but it can be sensitive to environmental effects, mostly moisture and temperature. It is possible to obtain rough indications of cable condition.

- **Advantages:** Widely available, easy to use, and interpretable in the field. Effective for detecting insulation faults.
- **Disadvantages:** May not detect subtle or localized ageing, only indicates whether the cable is completely degraded.
- **Acceptance Criteria:** Readings below 100 MΩ are typically seen as problematic and suggest moisture contamination or insulation failure.

4.6 DIRECT CURRENT (DC) RESISTANCE

DC resistance measurement assesses the conductivity of the conductor and any connecting points between two conductors. It is a relatively simple measurement.

- **Advantages:** This method has been useful especially in detecting degradation in junction points.
- **Disadvantages:** Provides only a pass/fail indication.
- **Acceptance Criteria:** An acceptance criterion of 1 Ohm has been applied by one of the sites.

4.7 INFRARED CAMERA

Infrared camera has been used to check hot spots and has been found useful for this purpose. It can be also used to detect faulty connections, since they tend to develop heat if there is additional resistance.

- **Advantages:** Fairly simple method to identify hot spots (in terms of temperature). Potentially viable method for detecting faulty connections.
- **Disadvantages:** Does not provide direct information on cable condition.
- **Acceptance Criteria:** Maximum allowed temperature can be set case-specifically when identifying hot spots. In the case of faulty connections, no well-defined acceptance criterion exists, but an experienced user can distinguish faulty connections.

4.8 REFLECTOMETRY METHODS

Reflectometry methods are based on sending a signal through the conductor and measuring the attenuation and reflection of the signal. The signal form differs between time and frequency domain methods. LIRA (line resonance analysis) is one form of reflectometry methods. It requires a baseline or reference measurement where the measurement data is compared to identify any signs of ageing. Other necessary information for high-quality measurement data includes cable material and length. It is considered a sensitive method and can provide false indications, e.g. tight bending of the cable can be detected with it. It is a good method for identifying variations in cable connections. LIRA provides a lot of data, and the data analysis requires expertise.

- **Advantages:** Effective at detecting early-stage thermal ageing; provides location-specific insights.
- **Disadvantages:** Requires specialized data interpretation and equipment. Cable type may impose limitations. Baseline data required.
- **Acceptance Criteria:** Any noticeable deviation in resonance or impedance values prompts further analysis or corrective action.

4.9 DIELECTRIC SPECTROSCOPY (DS)

Dielectric spectroscopy (DS) can be applied in two different manners. The first approach is standardized (e.g. IEEE 400.2) and uses a single frequency (usually referred to as tan delta measurement). It can provide information on the cable condition through the whole length of the cable. The overall experience with tan delta is good, but it is recommended to combine with other methods which are more sensitive towards local degradation (e.g. TDR, LIRA, PD).

The second approach applies a frequency range (e.g. 1 kHz to 1mHz) and can provide more detailed information on the ageing. Some testing has been performed with the broader frequency range and the method shows potential. However, it requires further development to be used at regular intervals in on site measurements.

- **Advantages:** Non-destructive and highly sensitive to dielectric ageing effects.
- **Disadvantages:** Requires precise instrumentation and expertise in data interpretation.
- **Acceptance Criteria:** A tan delta value exceeding 0.5 is generally interpreted as a sign of advancing degradation, prompting a closer inspection or retesting. In the case of broad frequency range DS, no definitive acceptance criterion has been set.

4.10 POLARIZATION CURRENT

Polarization current is similar to the method of insulation resistance, and it has been measured together with dielectric spectroscopy. The acceptance criterion is currently being developed.

- **Advantages:** Can detect thermal or water-related ageing.
- **Disadvantages:** Not much user experience yet.
- **Acceptance Criteria:** No proper acceptance criteria developed.

4.11 INDENTER MODULUS

The indenter modulus has been measured for several years at two of the interviewed sites and is considered to be reliable and useful. The usability is limited by accessibility, as the device needs to be clamped around the cable.

- **Advantages:** Non-destructive and gives a reliable indication on insulation ageing. Can be performed online.
- **Disadvantages:** Sensitive to temperature and material type; requires careful calibration. Not applicable to all types of cable materials.

- **Acceptance Criteria:** A doubling of the original indentation value generally signals the end of the cable's service life. If the original value is not available, a significant change in the indenter value can be applied.

4.12 OTHER PRACTICES

Other plant-specific practices, outside the scope of cable condition monitoring methods, that emerged during the interviews and could be useful at other sites as well:

- In the case of temperature monitoring at the locations at which the cables are, a specially designed temperature tape is used, which records the maximum temperature at the specific location.
- When cables are replaced with new ones, the removed cables can be used as surveillance samples.
- In the case of tensile testing, if no suitable reference cable (i.e. its properties and composition are comparable to a new cable) is available, a reference sample from cable storage can be used.
- Re-routing cables may be an option if adverse environmental effects can be avoided.
- Ageing related cable failures are less common than failures due to human action (e.g. damaging cables during maintenance work by accident).
- Communication with other plants and the sharing of practices have been considered helpful.
- Combining condition monitoring methods:
 - During maintenance shutdowns, several techniques are combined for a comprehensive condition assessment. For example: LIRA identifies "hot spots" in inaccessible areas, tan delta provides a broad view of dielectric ageing, EaB and indenter measurements are used to benchmark insulation flexibility and material integrity.
 - This multi-method strategy enhances confidence in the continued performance of safety-critical cables and aligns with the plant's ageing management plan.

The methods used at the different NPP sites, for which user experiences has been gathered, are presented in Table 1. Visual and tactile inspections, as along with insulation resistance and tan delta measurements, are the most commonly used methods. A significant amount of user experience has also been gathered on EaB, PD, insulation resistance, infrared cameras, reflectometry methods, and indenter modulus.

Table 1. Summary on the user experience of different condition monitoring methods at different NPP sites.

Method	Site 1	Site 2	Site 3	Site 4	Site 5

Visual inspection	x	x	x	x	x
Tactile inspection	x	x	x	x	x
EaB	x	x	x	x	
Partial discharge	x	x	x	x	
Insulation resistance	x	x	x	x	x
DC resistance	x				
Infrared camera		x	x	x	x
Reflectometry methods		x	x	x	
DS (tan delta)	x	x	x	x	x
DS (frequency scan)		x			
Polarization current		x			
Indenter modulus	x	x	x	x	

5 Ageing data management and application

This section summarizes practices related to ageing data management and how the collected data is applied as part of cable condition monitoring.

5.1 NPP SITE 1

Typical forms of deviations recorded in cable inspections are failed attachments causing dislocation of the cable, colour changes and mechanical damage (typically from personnel working with or next to cables). The inspection data is recorded in the measurement document and saved in a dedicated database. The acquired data can be used to evaluate the need for any additional actions. Faults are reported in the form of fault notifications and are responded with proposed actions, which include a description of fixing the fault. Furthermore, if any deviations are observed, additional monitoring can be implemented.

5.2 NPP SITE 2

Everything related to cable inspections is stored in work orders and no measures are performed without a work order. Dedicated ageing databases, which contain material ageing data (also from other sources than the specific NPP cables), are used in the estimation of the remaining lifetime. Corrective action programme takes place when a failed cable is found, which follows the subsequent principle of relocation, repair and removal.

5.3 NPP SITE 3

Measurement data from tools like LIRA are automatically stored and additionally backed up on secure servers to safeguard against data loss. These results are routinely compared with earlier records to identify trends and potential risks.

Trend analysis is central to cable monitoring. Baseline measurements are taken at cable installation, followed by periodic testing to track changes in insulation properties over time. This approach is applied across different voltage levels, with particular focus on critical areas such as reactor containment zones.

To estimate the remaining life of cables, both non-destructive and destructive testing methods are employed. Tan delta measurements can detect water treeing, while indenter testing assesses the elasticity of insulation. These results are correlated with EaB values, where values below 50% typically indicate end-of-life conditions.

Traditional techniques like tan delta and insulation resistance (Megger) testing have been used for several decades. In the past 20–30 years, more advanced methods such as LIRA, PD monitoring, and TDR have been progressively adopted. This shift is driven by the need for higher reliability and insights from international best practices in nuclear maintenance.

The common observations on this site show isolated cable faults, which in only a few cases have been due to ageing degradation. In most instances, the faults have been caused by mechanical damage or manufacturing defects, as well as installation errors, such as insufficiently tightened connections. An exception to this trend involves a specific type of cable, which have displayed clear signs of ageing due to inherent quality issues with this cable type.

When a cable shows signs of ageing or other changes, corrective actions are primarily undertaken through predictive maintenance. If these measures are insufficient, corrective (reactive) maintenance is applied. Since cable degradation is an irreversible process, the primary mitigation strategy is cable replacement.

The cable ageing management program is based on the principle that corrective measures should be guided by forecasts derived from repeated analyses or known material characteristics. Key degradation parameters are continuously monitored and analysed to predict the remaining service life of cables. This predictive approach enables planned and well-coordinated cable replacements, minimizing operational disruptions and ensuring long-term reliability of the plant's electrical systems.

5.4 NPP SITE 4

Measurement data is stored and tracked over time. Visual and tactile inspection data, including photos and notes, are saved in a database. Insulation resistance measurements are recorded in work orders. A project has been initiated to store high-voltage motor measurement data for historical tracking.

At the plant, diagnostic techniques are occasionally applied to estimate the remaining service life of power cables. While visual inspections can help identify early signs of degradation and inform maintenance decisions, more accurate assessments rely on diagnostic measurements. Techniques such as tan delta testing, PD measurements, and EAB tests provide quantitative data that correlate with the ageing of cable insulation materials. These methods enable more reliable predictions of remaining service life and support proactive maintenance planning.

The number of cables that fail to meet the qualitative acceptance criteria varies depending on the environment. In some areas, many cables may be flagged, while in others, very few issues are found. Common deviations from the acceptance criteria for cables include mechanical damage, discolouration, hardness, missing cable numbers, and improper installation angles. Environmental factors like heat and radiation also contribute to cable degradation. When a cable fails an inspection, the severity and importance of the cable are assessed. Immediate actions are taken for critical cables, involving maintenance, engineering, and operational departments. Less critical issues are documented and scheduled for future maintenance. All findings are recorded in a database for tracking and follow-up.

5.5 NPP SITE 5

Data from visual inspections and insulation resistance testing are recorded, but there is no systematic approach to tracking changes over time. The data is stored in maintenance records, but it is not always easily accessible for trend analysis.

Estimating the remaining lifespan of cables is not a common practice. Visual inspections may provide some indication of the condition, but more reliable estimates would require systematic measurements and analysis.

The number of cables that fail inspection varies, and no specific data is available on this. Failures are often detected during maintenance activities rather than through systematic inspections. The common causes of cable failures include mechanical damage, such as accidental damage from stepping on cable trays, and environmental factors like high temperatures causing the insulation to become brittle and crack.

When a cable fails an inspection, the issue is documented, and a plan for replacement or repair is developed. The urgency of the repair depends on the severity of the issue and the importance of the cable. Immediate actions are taken for critical cables, while less critical issues are scheduled for future maintenance. All findings are recorded in a database for tracking and follow-up.

6 Identified good practices

Based on the interviews, several good practices were identified. These practices are considered beneficial for improving cable condition monitoring at nuclear power plant sites.

- Systematic organization of cable inspections. A predetermined plan defining where and when cables are inspected can be based on variables such as location, environmental parameters, safety classification, or other factors relevant to maintaining normal operational conditions.
- Use of surveillance samples. Surveillance samples are beneficial as they can provide early warning signs of ageing. New samples can be prepared from the removed cables.
- Combining inspections with maintenance. A useful practice is to combine cable inspections with maintenance work performed on the equipment or system the cable is part of. This can also be applied to cables not included in an ageing management programme or under regular inspection.
- Visual and tactile inspections. These are widely used, easy to apply, and can provide preliminary indications of ageing.
- Standardized tan delta measurement. The tan delta method (IEEE 400.2) has proven reliable for EPR and XLPE medium-voltage cables.
- Use of indenter modulus. Indenter modulus has been found useful, especially for testing hot spots.
- Infrared camera. Infrared cameras are useful for detecting faulty connection points.
- Combining global and local methods. Combining global and local condition monitoring methods increases inspection efficiency. For example, tan delta can be used to assess the overall condition, and if signs of ageing are detected, local analysis can be performed using LIRA or another method.
- Temperature tape. A specially designed temperature tape can be used to record the maximum temperature at a specific location.
- Reference samples for tensile testing. If no suitable reference cable is available, a sample from cable storage can be used.
- Re-routing cables. Re-routing may be an option if adverse environmental effects can be avoided.
- Knowledge sharing. Communication with other plants and sharing user experiences have proven helpful.
- Use of external data. In addition to ageing data gathered at the plant, data from external databases can be used to calculate the remaining lifetime of cables.

7 Conclusions

NPP cable maintenance experts were interviewed regarding existing practices for cable condition monitoring. The interview topics focused on organizing the monitoring process, the methods used, and the management of collected ageing data.

The general aim of all plants is to carry out cable inspections in a predetermined and systematic manner. This enables efficient management of the inspections. The most important aspects to consider when selecting cables for inspection and determining their priority include:

- Safety relevance
- Location
- Environmental parameters (temperature, radiation, moisture, oil, etc.)
- Importance for maintaining normal operational conditions

If a cable is part of a safety-relevant system, its proper function is just as important as that of the entire system. Location is also important, as it allows for a straightforward division of inspection areas, for example by room. A common approach is to separate areas inside and outside the containment building. When environmental parameters for different locations are known, this information can be used to allocate inspections more efficiently. Including cables without direct safety relevance in the monitoring programme is often justified from an operational perspective, as it helps maintain stable system performance and prevents unplanned interruptions in electricity generation.

Eleven different condition monitoring methods were used at the NPP sites involved in this study. Among these, visual and tactile inspections, as well as tan delta and insulation resistance measurements, were the most commonly applied. The indentation method and LIRA were also considered practical and useful. All methods listed in this report provide information on specific properties, and it is possible to track how these properties evolve over time, helping to identify ageing-related trends or early warning signs. Several methods also have defined acceptance criteria (EaB, PD, insulation resistance, DC resistance, tan delta, indentation), which lowers the threshold for their implementation. If a more comprehensive view of cable ageing is desired, the use of these methods is recommended.

Good practices related to cable condition monitoring were identified and listed. One example is the combination of several methods to improve the assessment of cable condition, such as using both LIRA and tan delta. This highlights that no single method can provide a complete picture of cable condition.

There is a shared goal of systematic planning and documentation of cable condition monitoring activities. The recorded data is primarily used to track trends rather than to make precise predictions of the remaining service life. In general, obtaining information on cable condition and its properties over time was found to be useful, and there is interest in methods for predicting the remaining lifetime.

However, few such predictions have been made so far, and the collected ageing data is mostly used to monitor changes in cable materials. Calculating the remaining lifetime would be easier if more ageing data were available, for example from external databases. Given the large amount of data already collected, using it to estimate the remaining service life has the potential to significantly improve cable ageing management. This potential has not yet been fully realized at the NPPs.

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CABLE CONDITION MONITORING EXPERIENCES AT NUCLEAR POWER PLANTS

Nuclear power plant cables are subjected to ageing during their service life. Proper ageing management of cables is increasingly important as the plants age and lifetime extensions are considered. This work focused on identifying good practices currently existing at plants by interviewing experts working with nuclear power plant cables. The identified good practices can be shared among the plants to develop and improve currently existing cable condition monitoring programmes.

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