# Cable condition monitoring methods in nuclear power plants – A review

Konsta Sipilä

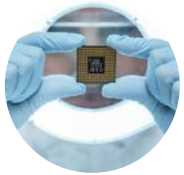
Polymers in Nuclear Applications 2024, 19-20th March 2024, Stockholm, Sweden

# VTT: Technical research centre of Finland Ltd

- Established in 1942
- Employees 2213
- Out of which a doctorate or a licentiate's degree 32%
- Steered by Ministry of Economic Affairs and Employment

## We create solutions in three business areas

Carbon neutral solutions



Digital technologies

Sustainable products and materials

**~150 persons working in nuclear safety research area**

# Objectives

1. Currently existing cable condition monitoring methods

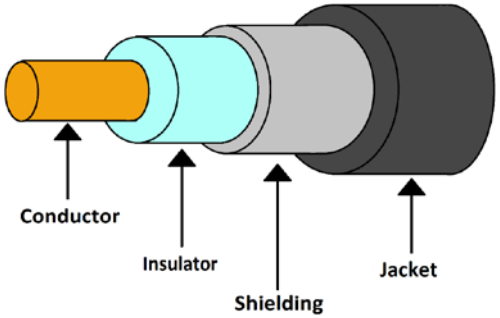
2. Assess their applicability for on-site cable inspections in nuclear power plants

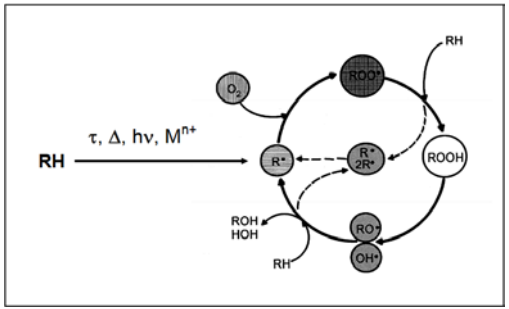
3. Gather existing knowledge and reports regarding cable condition monitoring methods being applied in nuclear power plants

4. List the most promising and advanced cable condition monitoring methods to be applied in nuclear power plants

# Cables in nuclear power plants

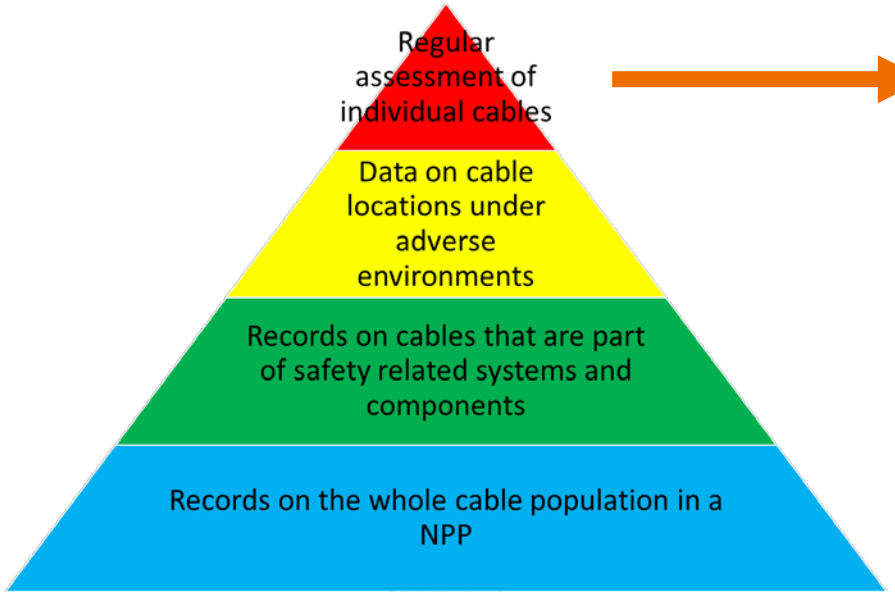
- Typical estimate 1000-2000 km per plant
  - Low (< 1kV), medium (1 – 45 kV) and high (> 45 kV) voltage cables
- Typical polymer types in cables
  - XLPE, CSPE, EPR, EVA, PEEK, XLPO, SiR, PVC
- Ageing (thermal & radiation)
  - Complex phenomenon
- Assess cable condition
  - Can they withstand the desgined and extended lifetime?




*Affolter S. Long-Term Behaviour of Thermoplastic Materials. 1999. NTB INTERSTAATLICHE HOCHSCHULE FÜR TECHNIK BUCHS.*

# Strategy behind effective cable condition monitoring strategy




Need for suitable cable condition monitoring methods

Review the current status of condition cable condition monitoring methods

# Cable condition monitoring methods

- Report lists 17 different non-destructive condition monitoring methods
  - Methods requiring minimal sample removal are considered non-destructive
  - The number can be greater or smaller depending on categorisation
- Distinguish global and local methods
  - *Global methods* are applied on a longer length to assess ageing or locate flaws (tan delta, dielectric spectroscopy, FDR/LIRA, insulation resistance, partial discharge, TDR, VLF withstand test)
  - *Local methods* are applied on one spot at time (DSC, density, gel fraction and solvent uptake, indenter modulus, infrared analysis, infrared thermography, NMR, TGA, terahertz method, ultrasonic technique)

# Global methods

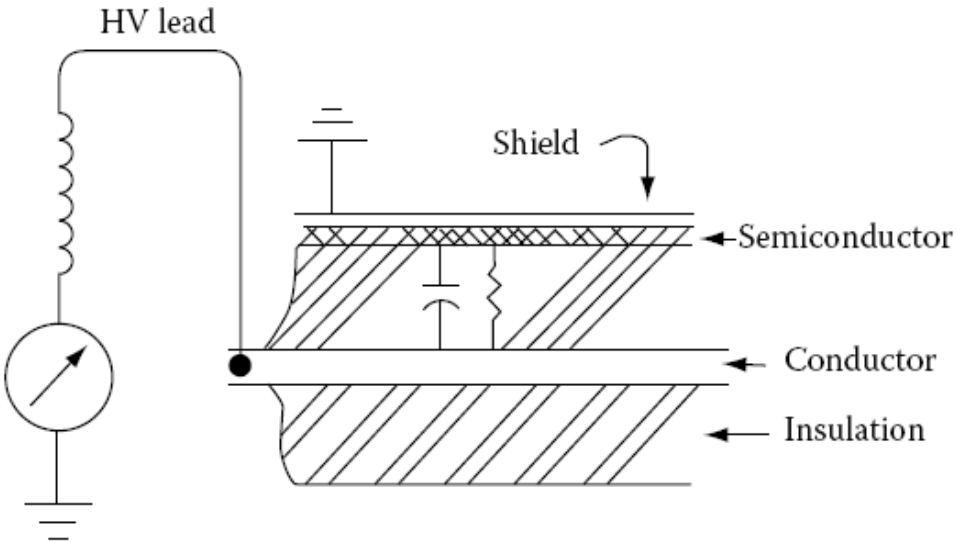
| Methods | Strengths | Weaknesses | Plant data |
|---|---|---|---|
| **Tan delta** | Sensitive towards water-related degradation, commercially available equipment and inspection services | Does not provide location for flaws, requires disconnecting | NPP user data available on various types of cables |
| **Dielectric spectroscopy** | Seems to be sensitive global cable condition assessment method, portable | Not very suitable for detecting localised ageing | Not available |
| **FDR/LIRA** | Can identify and locate faults on the whole cable length | Baseline measurements are usually required to monitor ageing, analysing data requires some expertise | FDR have been shown to be able detect ageing on thermally aged cables, LIRA has been applied on-site condition monitoring |
| **Insulation resistance measurement** | Simple method, does not require access to the whole cable | Not very accurate and sensitive to environmental effects, requires disconnecting | NPP user data available and according to it can detect the mostly degraded cables. |
| **Partial discharge** | Provides information on the fault location and severity, standardized procedures available | 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 |
| **TDR** | Been applied widely in other industries, portable | Requires baseline measurements, requires disconnecting, | Have been used in NPPs |
| **Very low frequency withstand test** | Well established method for detecting localized 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 |

# Global methods

| Methods | Strengths | Weaknesses | Plant data |
|---|---|---|---|
| **Tan delta** | Sensitive towards water-related degradation, commercially available equipment and inspection services | Does not provide location for flaws, requires disconnecting | NPP user data available on various types of cables |
| **Dielectric spectroscopy** | Seems to be sensitive global cable condition assessment method, portable | Not very suitable for detecting localised ageing | Not available |
| **FDR/LIRA** | Can identify and locate faults on the whole cable length | Baseline measurements are usually required to monitor ageing, analysing data requires some expertise | FDR have been shown to be able detect ageing on thermally aged cables, LIRA has been applied on-site condition monitoring |
| **Insulation resistance measurement** | Simple method, does not require access to the whole cable | Not very accurate and sensitive to environmental effects, requires disconnecting | NPP user data available and according to it can detect the mostly degraded cables. |
| **Partial discharge** | Provides information on the fault location and severity, standardized procedures available | 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 |
| **TDR** | Been applied widely in other industries, portable | Requires baseline measurements, requires disconnecting, | Have been used in NPPs |
| **Very low frequency withstand test** | Well established method for detecting localized 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 |

# Tan delta

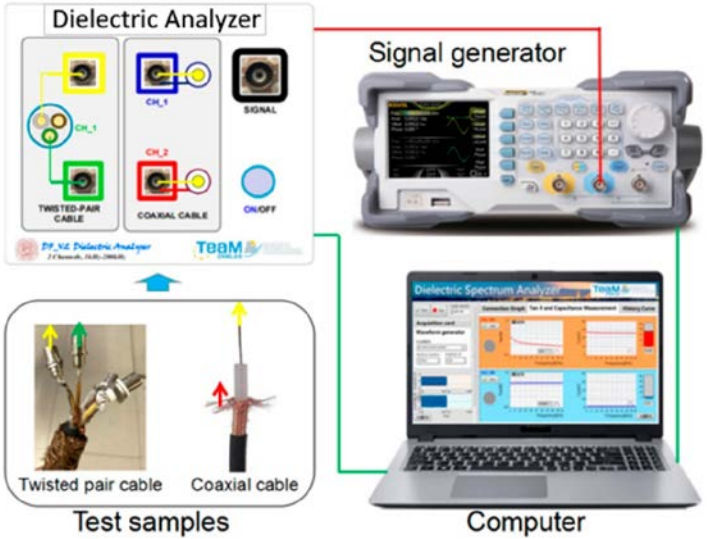
- Based on application of low frequency AC voltage over the conductor and external conductor (e.g. shielding) and measuring the current response → $tan\delta = \frac{I_R}{I_C}$
- Pros: well defined procedure, services commercially available, sensitive to water-related degradation, applied in NPP cables, EPRI and NRC approval
- Cons: does not provide locations for flaws, requires disconnecting




*Your Electrical Guide. 2024. Available: Tan Delta Testing of Cables - Your Electrical Guide*

# Dielectric spectroscopy

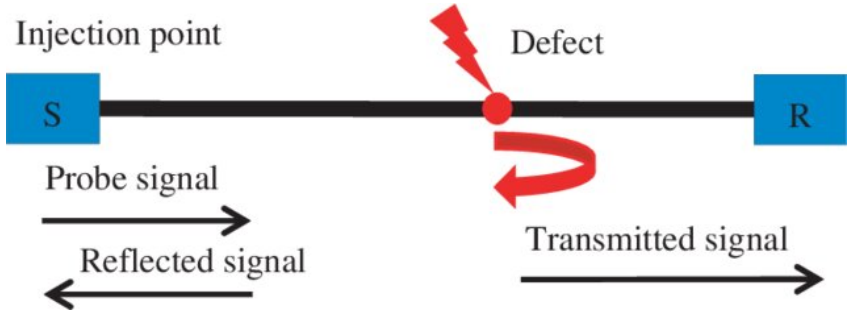
- Similar meauserement principle as in tan delta measurement, but the voltage is applied at a broad frequency range → possibly to assess the ageing with grater detail than Tan delta measurement
- Pros: convincing laboratory data for global characterization
- Cons: Not for local ageing, NPP trials?




*Suraci, S.V., Li, C., Fabiani, D. 2022. Dielectric Spectroscopy as a Condition Monitoring Technique for Low-Voltage Cables: Onsite Aging Assessment and Sensitivity Analyses. Energies 2022, 15, 1509.* https://doi.org/10.3390/en15041509

# Frequency domain reflectometry (FDR) / Line resonance analysis (LIRA)

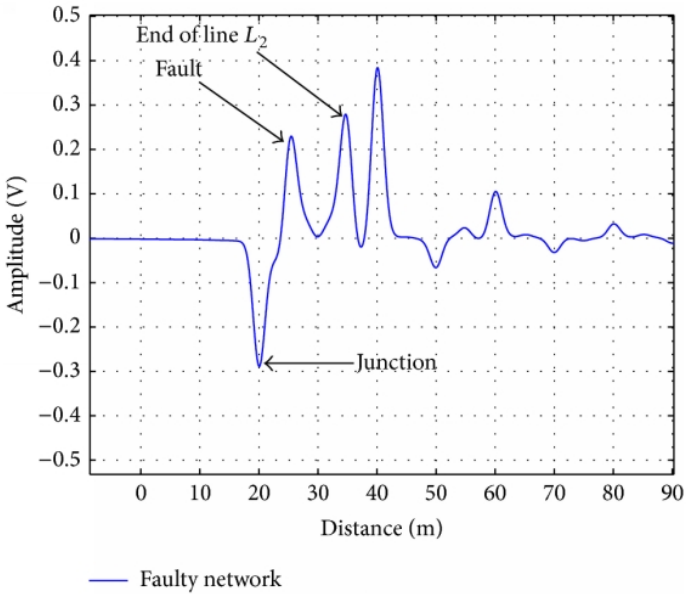
- Apply frequency signal sweeps and analyse the response → presence of defects affect on reflection
- LIRA – contains a special designend algoryth analysing the data
- Pros: Have been shown to be capable to assess cable ageing globally
- Cons: Baseline data required, disconnection required, data analysis requires expertise, reported experiences on-site




*Osman, O., Sallem, S., Sommervogel, L., Carrion, M., Bonnet, P., Paladian, F. 2020. Distributed Sensor Diagnosis in Twisted Pair Networks for Soft Fault Identification Using Reflectometry and Neural Network. Progress In Electromagnetics Research C, Vol. 100, 83-93, 2020 doi:10.2528/PIERC19122402*

# Time domain reflectometry

- Similar approach as in FDR, only the applied singal is low frequency pulse form
- Pros: experience from other industries, portable
- Cons: baseline data required, requires disconnecting




*Ben Hassen, W., Auzanneau, F., Incarbone, L., Pérès, F., Tchangani, A.P. Distributed Sensor Fusion for Wire Fault Location Using Sensor Clustering Strategy. International Journal of Distributed Sensor Networks. 2015;11(4). doi:10.1155/2015/538643*

# Local methods

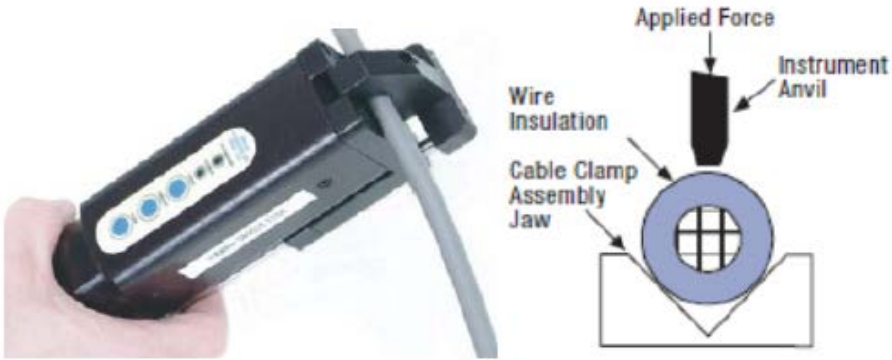
| Method | Strengths | Limitations | Data from plant conditions |
|---|---|---|---|
| **DSC** | Has been shown to be sensitive towards ageing in laboratory conditions, simple procedure | Requires microsampling, requires additional ageing data (e.g. EaB) for correlation, equipment not portable | NPP user data available on various types of cables but data not fully convincing |
| **Density** | Simple method, good correlation with ageing with CSPE, PE and silicon rubber, cheap. | Microsampling required, high scatter, sensitive to DLO. | No user data from NPPs was found. |
| **Gel fraction and solvent uptake** | Simple method, correlates to EaB with PE, CSPE and PCP. | Microsampling required, vacuum dryer (non-portable) required | No user data from NPPs was found. |
| **Indenter modulus** | Simple method, applies for broad range of materials | Limited accessibility to insulator, limited resolution to detect ageing with some polymers e.g. PEEK and XLPE | NPP user data available on various types of cables |
| **Infrared analysis** | Relatively simple method, available as portable version | Requires microsampling, analysis of black materials can be complicated, correct interpretation of measurement data requires expertise | Applied for real cables obtained from NPPs, it seems that the data analysis procedure needs to be unified for different polymer types. |
| **Infrared thermography** | 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** | Shown correlation with mechanical properties, portable | Portable sensor can currently measure only non-shielded cables | Cables obtained from NPPs tested. |
| **Thermogravimetric analysis** | Simple analysis, standardized method available | No direct correlation with ageing has been presented so far, more of a complementary analysis method | Have been used in few plants for cable condition analysis |
| **Terahertz method** | Can be sensitive towards detecting defects | Accessibility on insulator limited, cost, required expertise | No user data from NPPs was found. |
| **Ultrasonic technique** | Relatively simple analysis, portable equipment, fast measurement | Accessibility on insulator limited, some expertise required in data analysis | No user data from NPPs was found. |

# Local methods

| Method | Strengths | Limitations | Data from plant conditions |
|---|---|---|---|
| **DSC** | Has been shown to be sensitive towards ageing in laboratory conditions, simple procedure | Requires microsampling, requires additional ageing data (e.g. EaB) for correlation, equipment not portable | NPP user data available on various types of cables but data not fully convincing |
| **Density** | Simple method, good correlation with ageing with CSPE, PE and silicon rubber, cheap. | Microsampling required, high scatter, sensitive to DLO. | No user data from NPPs was found. |
| **Gel fraction and solvent uptake** | Simple method, correlates to EaB with PE, CSPE and PCP. | Microsampling required, vacuum dryer (non-portable) required | No user data from NPPs was found. |
| **Indenter modulus** | Simple method, applies for broad range of materials | Limited accessibility to insulator, limited resolution to detect ageing with some polymers e.g. PEEK and XLPE | NPP user data available on various types of cables |
| **Infrared analysis** | Relatively simple method, available as portable version | Requires microsampling, analysis of black materials can be complicated, correct interpretation of measurement data requires expertise | Applied for real cables obtained from NPPs, it seems that the data analysis procedure needs to be standardized for different polymer types. |
| **Infrared thermography** | 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** | Shown correlation with mechanical properties, portable | Portable sensor can currently measure only non-shielded cables | Cables obtained from NPPs tested. |
| **Thermogravimetric analysis** | Simple analysis, standardized method available | No direct correlation with ageing has been presented so far, more of a complementary analysis method | Have been used in few plants for cable condition analysis |
| **Terahertz method** | Can be sensitive towards detecting defects | Accessibility on insulator limited, cost, required expertise | No user data from NPPs was found. |
| **Ultrasonic technique** | Relatively simple analysis, portable equipment, fast measurement | Accessibility on insulator limited, some expertise required in data analysis | No user data from NPPs was found. |

# Indenter modulus

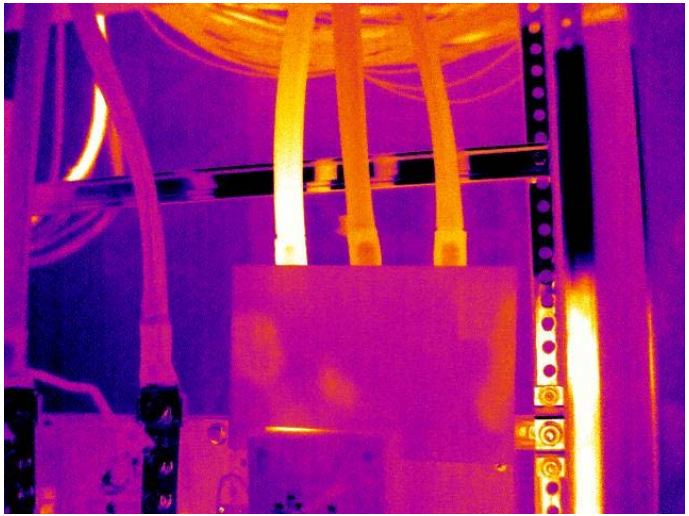
- Probe pressed is pressed into the material and penetration depth and force is measured
- Pros: Simple, test procedures exit, applied on-site, applies broad range of materials
- Cons: limited accessibility, limited usability on hard polymers (e.g. PEEK)




Pirc. 2016. Cable Aging Management Program Implementation in Krško NPP-NEK. Journal of Energy - Energija 65(1-2) pp. 50-62.

# Infrared thermography

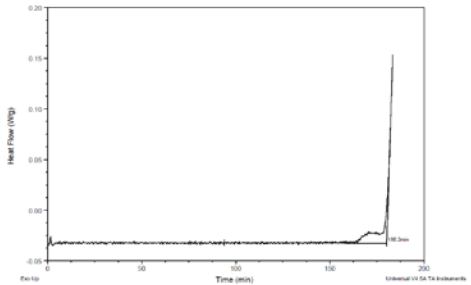
- Infrared thermography is based on measuring the wavelength of the electromagnetic radiation emitted by objects → identification of hot spots
- Pros: Simple, portable, commercially available, applied on-site
- Cons: No quantified data on cable condition



Thermal imaging Ltd. Electrical Thermographic Inspections - Ti Thermal Imaging LTD

# Differential scanning calorimetry DSC - OIT

- Oxidation induction time – measurement of time in isothermic conditions → assumed to correlate with antioxidant concentration
- Potentially a good early ageing indicator?
- Pros: a lot of laboratory data, simple and standardized procedure
- Cons: microsampling, not portable, inconclusive on-site data



# Current status of cable condition monitoring methods at NPPs

- Several broad reports assessing different methods published in the past 20 years (e.g. EPRI, PNNL, OECD NEA, NRC, IAEA)
  - EaB is the universal condition parameter and other methods are compared to it
  - There are no equivalent method, but indenter modulus and reflectometry are often referenced to be suitable for CM
  - The strategy should be merely to combine different methods (global and local) to obtain the best result

# Reported on-site experience 1/3

- LIRA tested at Ringhals in 2006
  - 4 PVC cables 142 m long 20+ years
  - No degradation observed
  - LIRA works on-site conditions
- Krsko NPP, Slovenia
  - Reports experiences from 6-year CM program (2016)
  - Hundreds of measurements/inspections by using six different methods
  - Data reported as pass/fail for MV and LV cables (not material specifically)
  - Most useful methods infrared camera, indenter, tan delta and LIRA

*Fantoni, P., Toman, G. 2008. Wire System Aging Assessment and Condition Monitoring Using Line Resonance Analysis (LIRA). Proceedings of the 16th International Conference on Nuclear Engineering. Volume 1: Plant Operations, Maintenance, Installations and Life Cycle; Component Reliability and Materials Issues; Advanced Applications of Nuclear Technology; Codes, Standards, Licensing and Regulatory Issues. Orlando, Florida, USA. May 11–15, 2008. pp. 177-186. ASME.* https://doi.org/10.1115/ICONE16-48523

*Pirc. 2016. Cable Aging Management Program Implementation in Krško NPP-NEK. Journal of Energy - Energija 65(1-2) pp. 50-62.*

# Reported on-site experience 2/3

- Oyster Creek NPP
  - 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
  - TDR, FDR, and impedance measurements
  - FDR measurement the cable condition was benchmarked against the cable locations under milder environment successfully
  - The authors had developed a classification table (4 conditions) → significant ageing was detected in some of the cables
  - Saved approximately 3.7 M$ in cost and reduced the time required for the inspections from 14 to four days

*Kiger, C. J. Sexton, C. D., Hashemian, H. M., O'Hagan, R. D., Dormann, L., Wasfy, W. 2017 Implementation of New Cable Condition–Monitoring Technology at Oyster Creek Nuclear Generating Station, Nuclear Technology, 200:2, 93-105, DOI: 10.1080/00295450.2017.1360716*

*Harmon, G., Toll, T., Sexton, C. 2020. Development And Implementation Of An In-Situ Cable Condition Monitoring Method For Nuclear Power Plants. 2020 Electrical Insulation Conference (EIC), Virtual Event, June 22 – July 03, 2020.*

# Reported on-site experience 3/3

- Water related degradation on cables obtained from NPP
  - PVC cables
  - IR method to detect moisture
  - TDR data set to back up
  - EaB, permittivity, OIT and colour changes indicated moisture ingression too
- Assessment of remaining useful lifetime for cables
  - Removal of real service cables for laboratory test (PVC, neoprene, XLPE, EPR, CSPE)
  - Artificial ageing
  - Periodical assessment of cable condition
  - Application of Arrhenius method to obtain remaining lifetime at lower temperatures
  - Will the cables endure the remaining service life

*Toll, Sexton, McConkey, Harmon. 2020. A Cable Condition Monitoring Strategy For Safe And Reliable Plant Operation. 2020 Electrical Insulation Conference (EIC), Virtual Event, June 22 – July 03, 2020.*

*Sexton, C., Toll, T., McConkey, B., Harmon, G. 2023. A Cable Condition Monitoring Strategy for Safe and Reliable Plant Operation, Nuclear Technology, 209:3, 437-447, DOI: 10.1080/00295450.2022.2072651*

# Conclusions

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 the 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. A feasible approach would be to combine methods that assess the cable condition globally and locally.

3) Global methods:
   - Reflectometry-based methods can be used to assess cable condition throughout their whole length even at locations hardly accessible by other methods. Promising in-service results.
   - Dielectric spectroscopy, an advanced version from tan delta measurement, which have been well demonstrated in laboratory conditions and is ready for on-site trials.
   - Other global methods can be considered for fault location, including water related degradation.

4) Local methods:
   - Infrared thermography can be used to boost visual inspections.
   - 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 on in-service cables should be assessed in more detail.

# Questions?

# Most promising CM methods in 2013

- Simmons, Pardini, Fifield, Tedeschi, Westman, Jones, Ramuhalli. 2013. Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Study FY13. Pacific Northwest National Laboratory. 66 pp.
- The most promising CM methods based on literature references