Condition monitoring of cables in NPPs – current status

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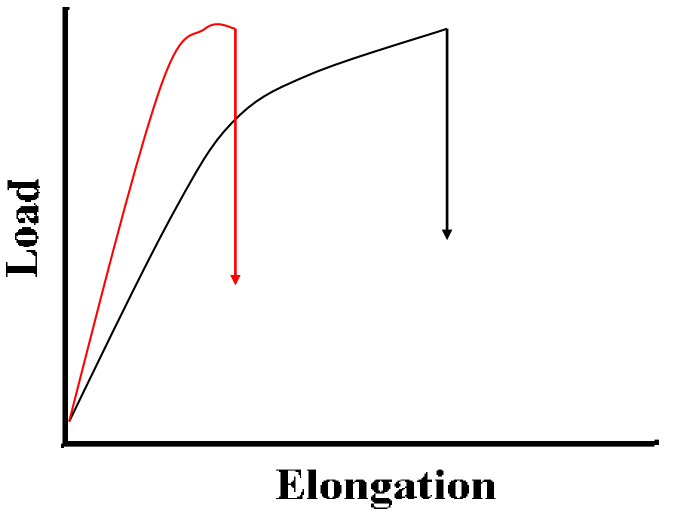
Ageing stressors in NPPs

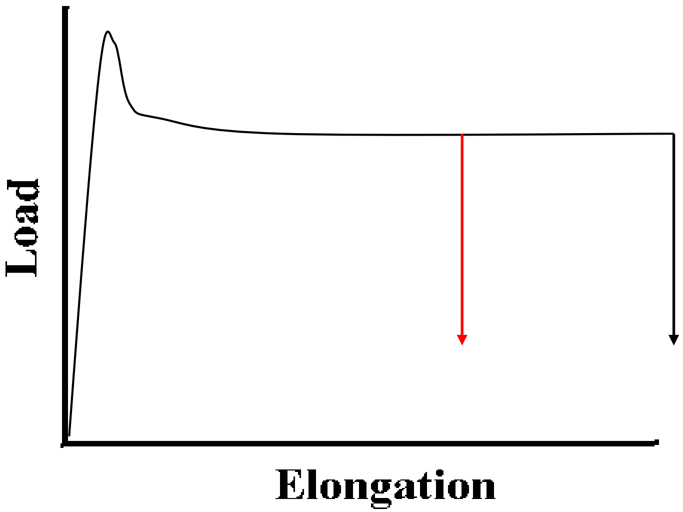
- For most cables, thermal ageing is prime stressor
- For a limited number of cables radiation is also an important stressor
- Secondary stressors –
  - Moisture
  - Vibration
  - Chemical contamination
  - Mechanical stress

Effects of degradation on bulk properties of polymers

- Tensile elongation decreases
- Tensile strength decreases (may show initial increase)
- Hardness increases (usually)
- Density increases
- Most electrical properties show little change until material is significantly degraded (with some exceptions)
- Dielectric properties can change significantly
- Changes in colour and surface texture often visible

Tensile tests - schematic





Condition monitoring (CM)

Objectives:

- Assessment of current state of degradation
  - Elongation at break often used for cables – 50% absolute is indicator of some remaining flexibility but not necessarily a good indicator of DBE survivability
- Prediction of remaining lifetime
  - Not straight forward, as rate of degradation is non-linear & dependent on several environmental stressors, but estimates can be made

Condition monitoring requirements

- Any CM method must
  - Be an indicator of functional integrity
  - Change significantly with ageing degradation
  - Be reproducible under different ageing conditions
- Ideally, a CM method should also
  - Be applicable to wide range of materials
  - Be usable in areas of limited access
- No current CM method satisfies all of these requirements
  - For cables, a number of useful methods have been evaluated and found to be potentially useful

CM methods for cables

- Many CM methods available, can be grouped as
  - Qualitative methods – can be applied to wide range of cables, giving broad indication of cable condition
  - Methods requiring sample removal or intrusion – mainly for sacrificial samples in cable deposits, or cables taken out of service
  - Methods not requiring sample removal – may be applicable to in-service cables or deposits
  - Electrical methods – applicable to in-service cables, but usually require disconnection of cable from end device

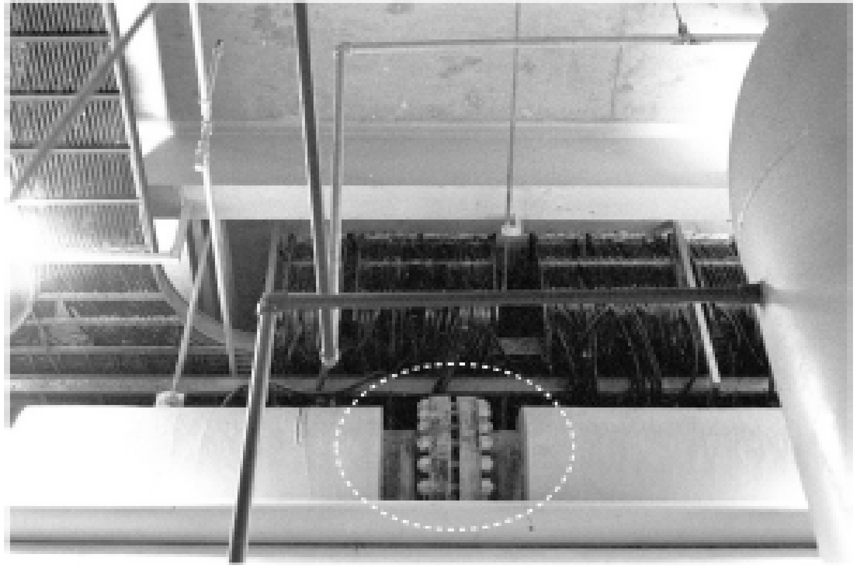
Most commonly used CM methods currently used in NPPs

- Visual & tactile inspection via walkdowns – qualitative, but valuable starting point
- Indenter – applicable to most cables but tests jacket only on accessible cables
- Oxidation induction methods (OIT/OITP) – usually on deposit samples but can be used on in-plant cables
- TDR/FDR methods – electrical methods becoming more widely used

Visual and tactile inspection

- Valuable method for evaluating condition using planned walkdowns
- Changes in colour, surface deposits, contamination, flexibility, hardness
- Localised damage, excessive bending, cracking
- Helps to identify where more sophisticated methods might be useful
- Identify locations likely to produce degradation (hot-spots)

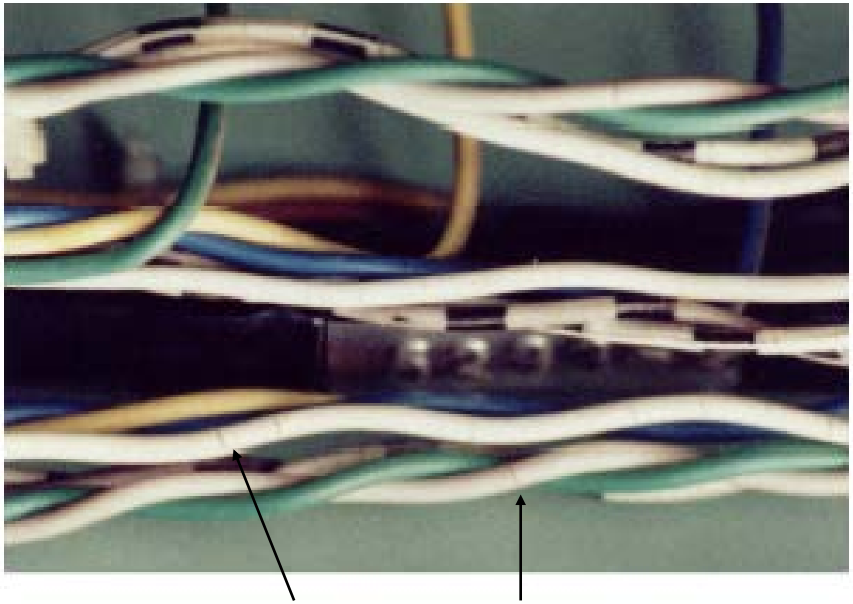
Some examples of potential problem areas identified in walkdowns (from EPRI report 1003663)



Missing thermal insulation

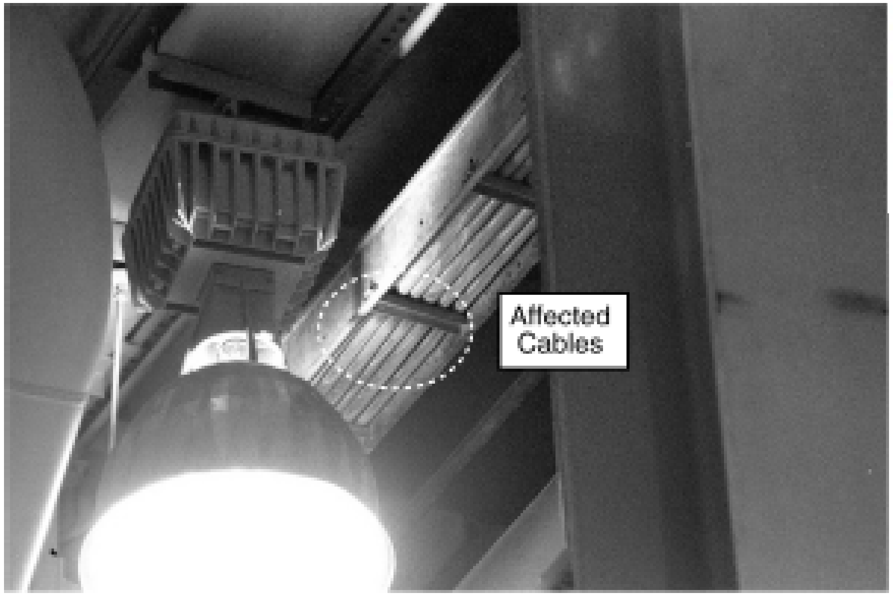
Displaced thermal insulation on valve operator

Some examples of potential problem areas identified in walkdowns (from EPRI report 1003663)



Cracking of PE wiring from fluorescent lights

Heat from high intensity lights



Oxidation induction methods

- Two types of test used – oxidation induction time (OIT) and oxidation induction temperature (OITP)
- Both use samples of approx. 10 mg, using standard laboratory equipment – differential scanning calorimeter
- OIT measures the time for onset of oxidation in oxygen at a constant temperature
- OITP measures the temperature of oxidation onset as temperature is increased at a constant rate (typically 10C/min)

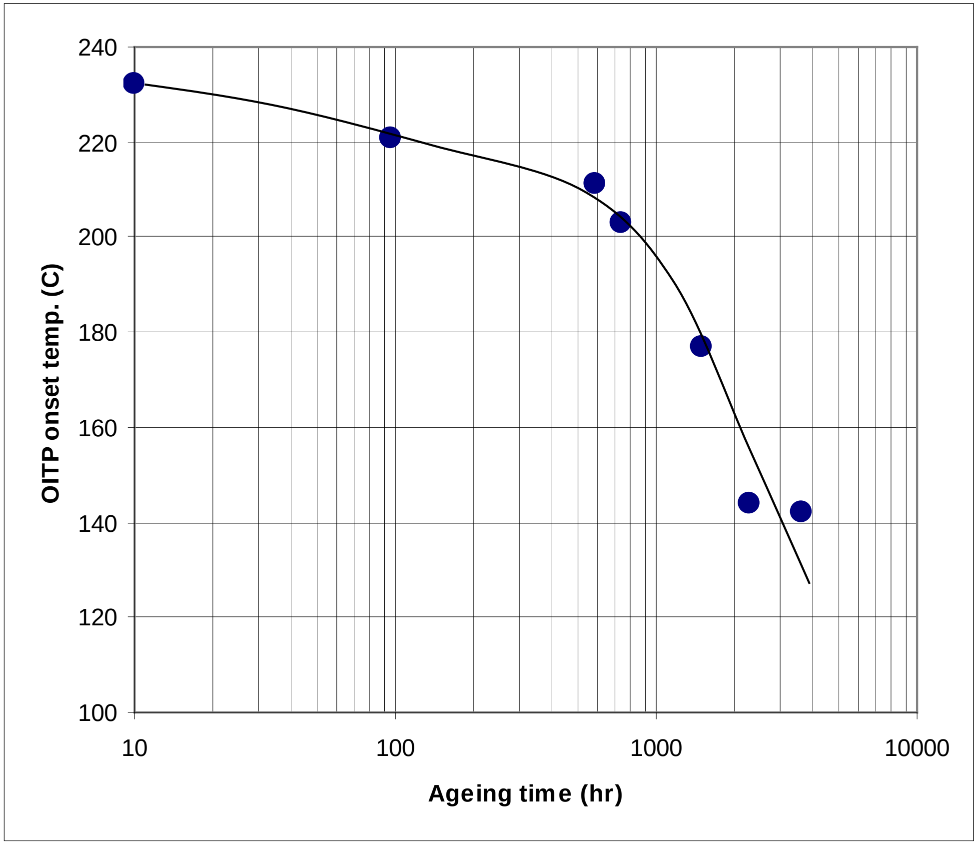
Micro-sampling methods

- These methods require only small samples (typically 10-20 mg of material)
- Some NPPs will allow sampling of operational cables, with approved repair methods
- Other NPPs may only allow sampling on deposit cables or cables taken out of service

Photos courtesy of UJV, Rez

Oxidation induction (OIT/OITP)

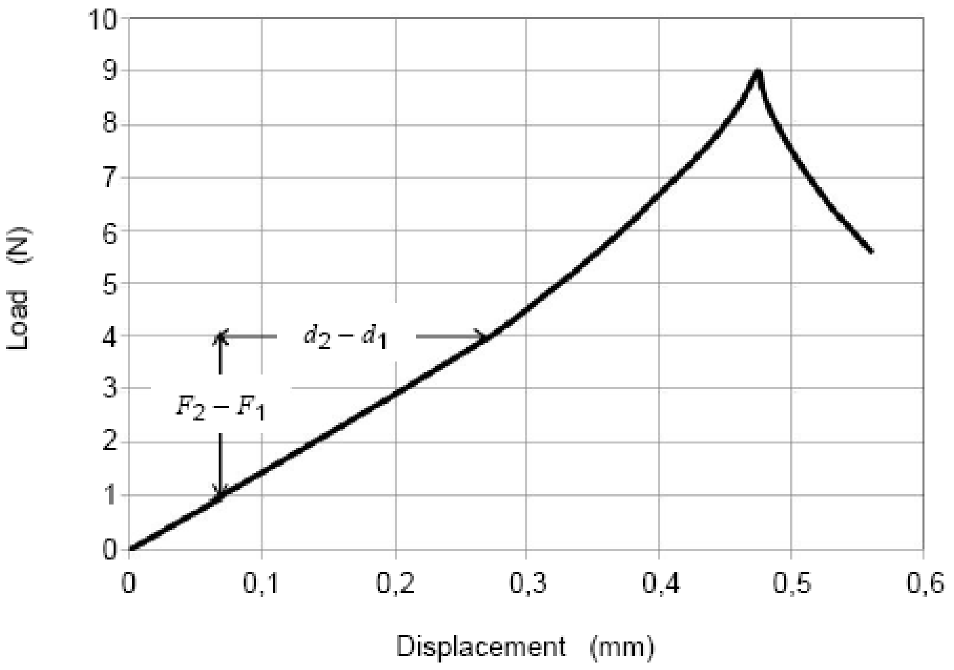
- OITP trends well with ageing in EPR and PE-based materials
- OIT trends well at early stages of ageing when other CM methods show little change – can provide early warning of degradation
- Both methods need to be correlated with changes in EAB for specific formulation tested



EPR cable insulation, aged at 200 Gy/hr at 25C

Indenter measurements

- Portable instrument that can be used in-plant
- Measures load exerted on a probe tip pressed into surface under controlled conditions
- Slope of load-displacement curve is a measure of the modulus of the material
- Considerable data available on correlation with ageing degradation



Indenter modulus – examples of correlation with EAB (from JNES-SS-0903)

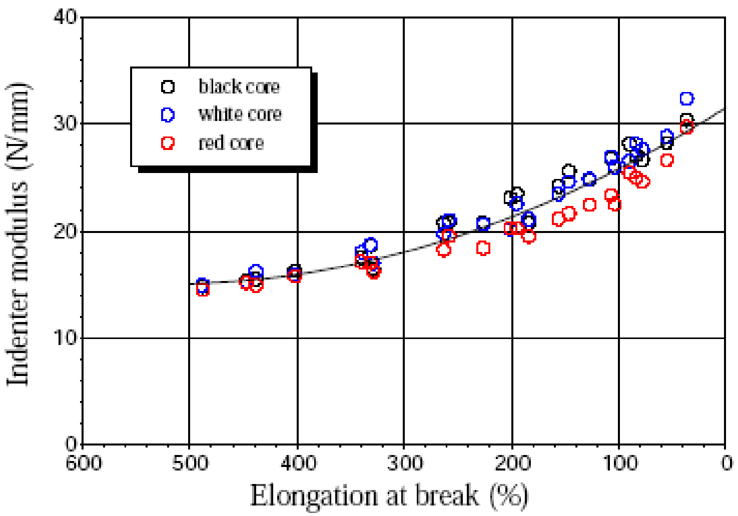


Fig. 3-6 The EPR insulator made by Company C
The Indenter: R^2=0.93

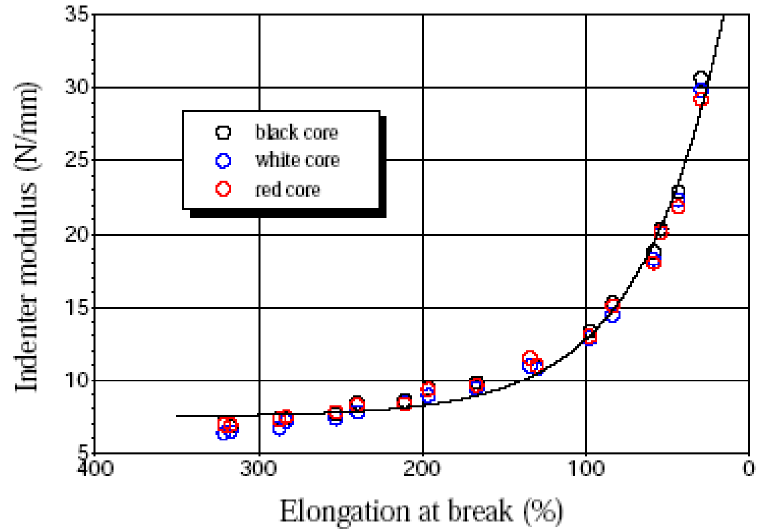


Fig. 3-21 The SIR insulator made by Company A
The indenter: R^2=0.99

- Indenter modulus values correlate well with elongation for most EPR materials
- For softer materials such as SiR, changes tend to be much larger
- Correlation is poor for harder materials such as XLPE and PEEK

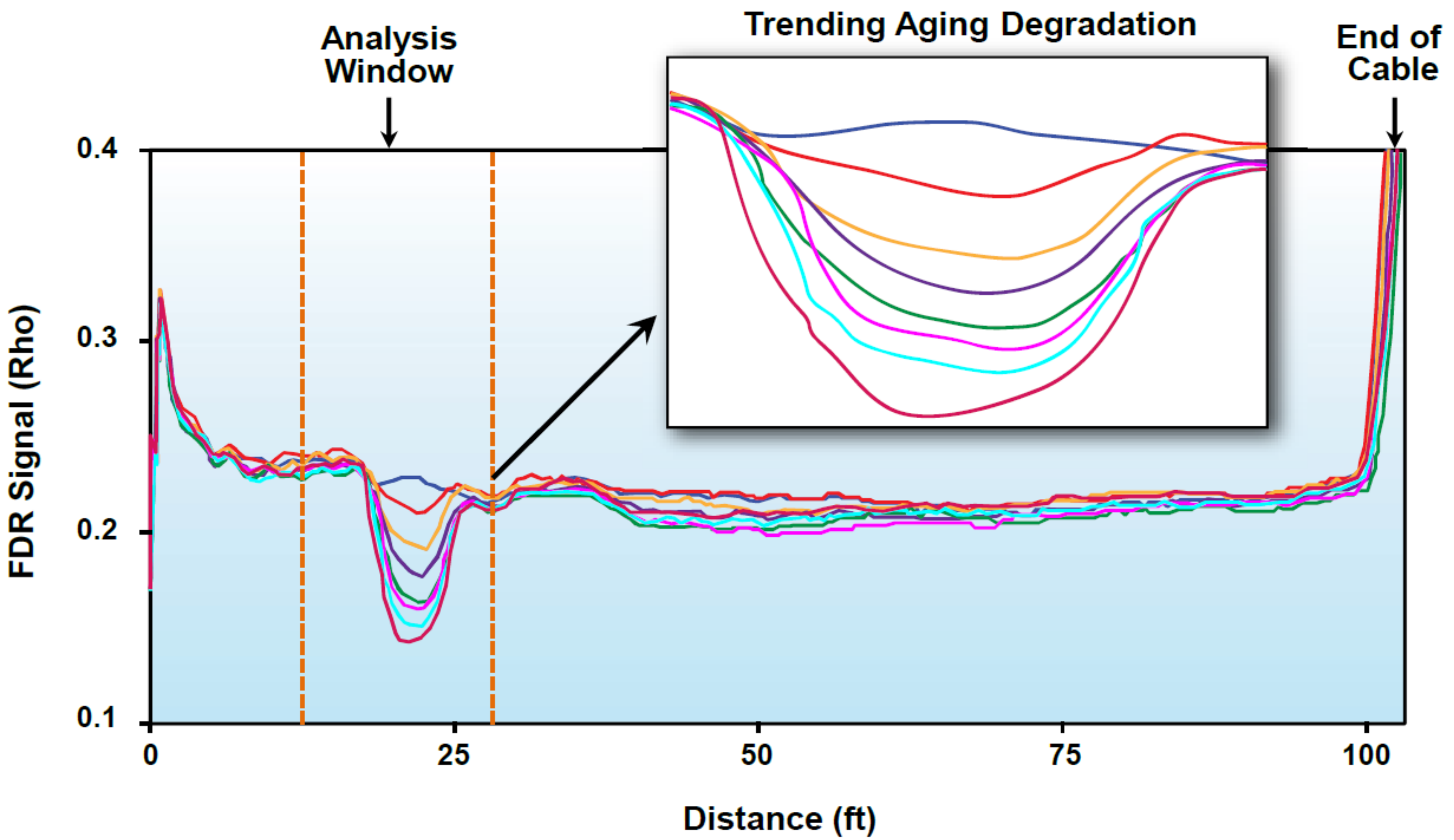
Indenter measurements

- Used in plant in several countries e.g. Canada, USA
- Limited to accessible cables so generally used on jacket materials
- Practical difficulties in access for measurements
- Useful applied to cable deposit samples
- Has been used to assess extent of damage in areas with localised ‘hot-spots’

Electrical methods (TDR/FDR)

- Can be used on in-service cables
- Combination of frequency domain reflectometry (FDR) and time domain reflectometry (TDR) is proving to be valuable
- Conventional electrical methods do not trend well with ageing but are useful for troubleshooting
  - LCR measurements
  - Insulation resistance

FDR measurements on a long cable with thermally degraded section



Example of use of electrical CM – Oyster Creek, USA

- BWR operating for 40 years
- Concern over degradation of specific I & C cables
- Initial plan
  - Mapping of cable routing
  - Extensive visual inspection
  - Contingency routing for replacement cables
- Would require extensive scaffolding and installation of multiple conduits/cable runs prior to outage
- Use of electrical CM could reduce amount of visual inspection required

Electrical CM at Oyster Creek

- Contractor provided data on correlation of EAB with in-situ electrical CM methods
- Enabled an estimate of cable condition from on site electrical tests –
  - TDR, IR and LCR to determine operational status
  - FDR to determine ageing degradation
- Correlation between FDR index and EAB determined in laboratory for each of cable types
- Estimated condition based on 50% EAB as end of life

Use of FDR to estimate cable condition – broad categories

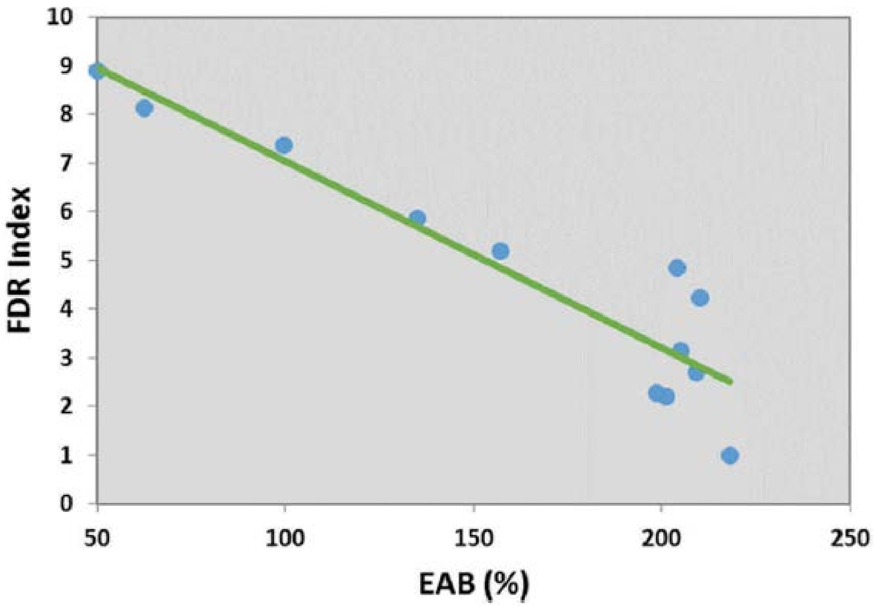


Fig. 14. Plot of EAB versus FDR index.

Comparison with values in benign environment area e.g. control room

Acceptance Criteria for Field Application

Category	Percent Aged	Comments
1	0 to 33	Little to no indication of age-related degradation.
2	33 to 66	Initial indication that age-related degradation has occurred.
3	66 to 99	Cable insulation has significant aging but is expected to function normally.
4	>99	Cable insulation is at or near its end-of-life condition as defined by 50% EAB.

Example of cable routing and corresponding FDR plot

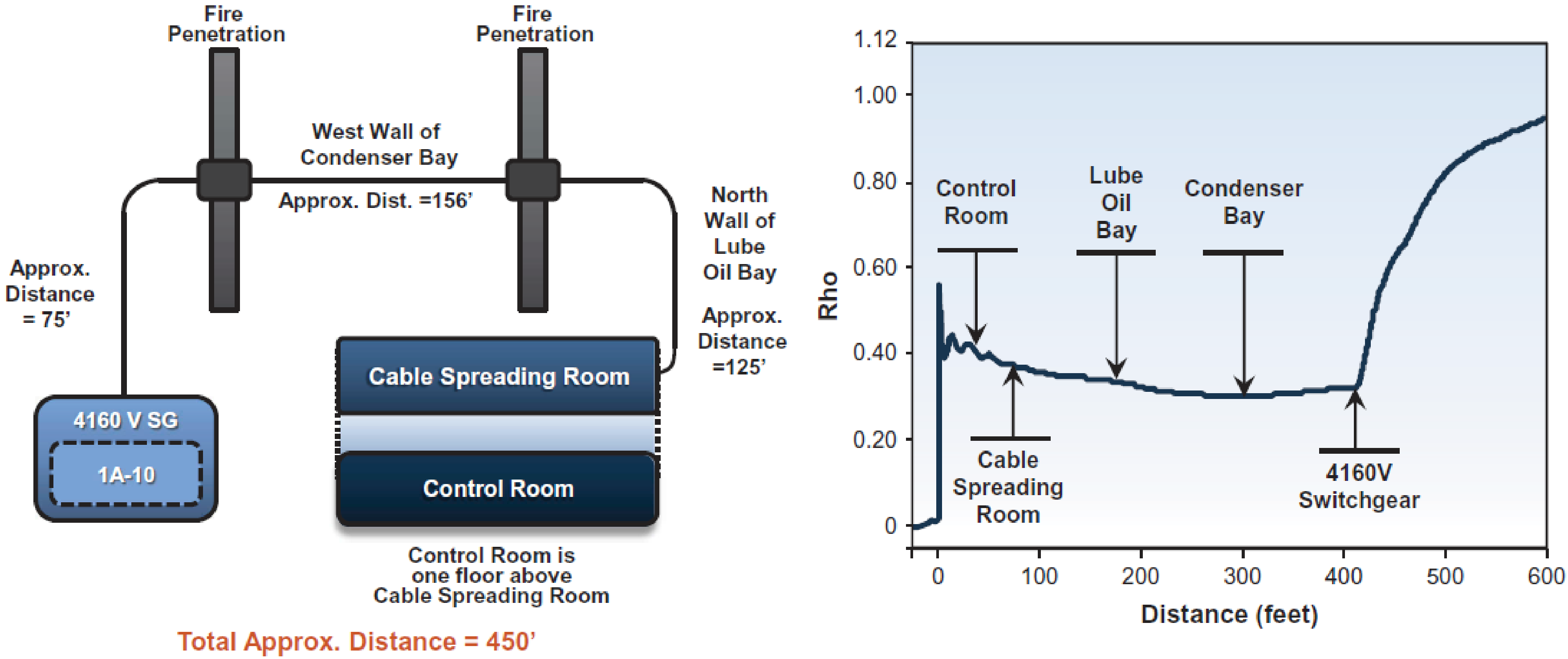
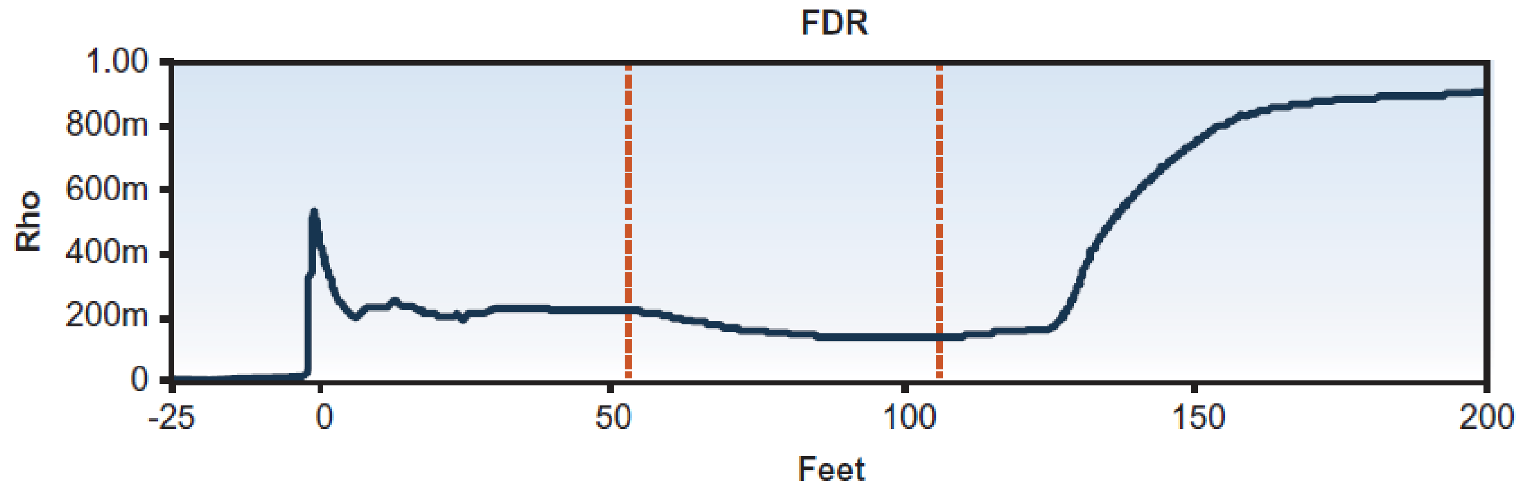
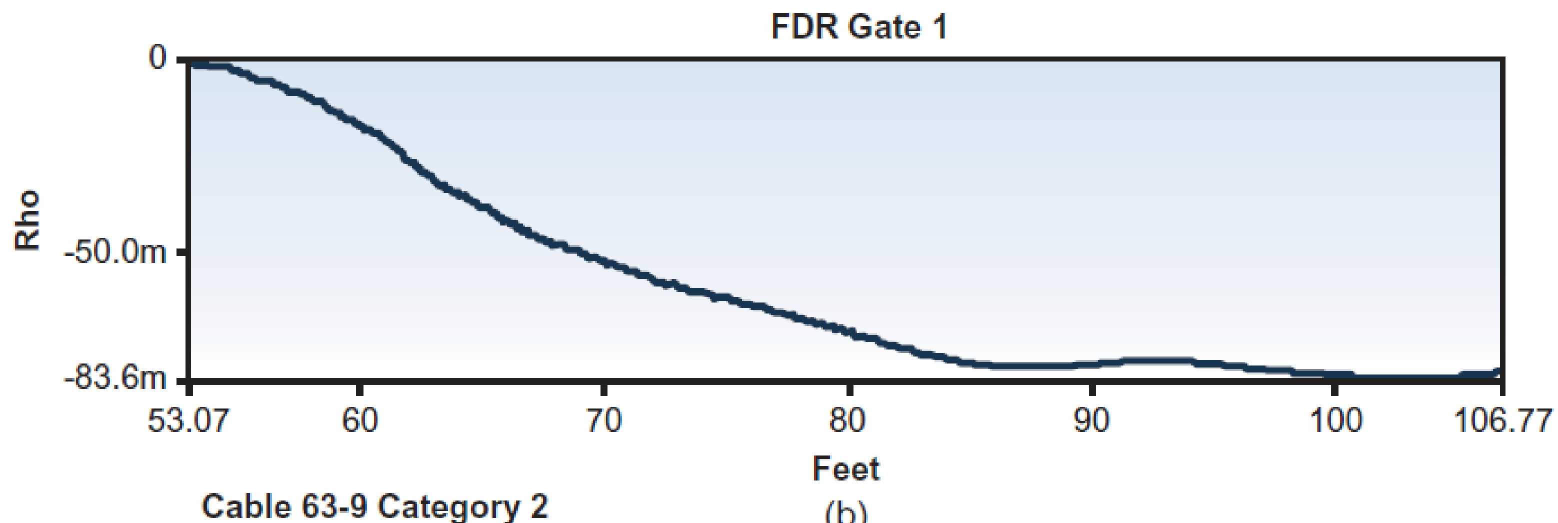


Fig. 15. Cable arrangement in the plant and corresponding FDR plot for the reactor feedwater pump 1B control cable.

FDR plot for turbine control cable with category 2 degradation (i.e. some degradation, still OK)



(a)



(b)

Advantages of electrical CM methods

- Example from Oyster Creek NPP, USA
- Significant cost savings
  - Scaffolding required for access reduced
  - Reduced contingency requirements
  - Time saving
  - Fewer cable replacements required
- Safety benefits
  - Reduced radiation exposure to personnel
  - Less scaffolding work
- Overall cost reduction of c. $3.7 million for outage

For more details of Oyster Creek example, see article below

NUCLEAR TECHNOLOGY · VOLUME 200 · 93–105 · NOVEMBER 2017

DOI: https://doi.org/10.1080/00295450.2017.1360716

Implementation of New Cable Condition–Monitoring Technology at Oyster Creek Nuclear Generating Station

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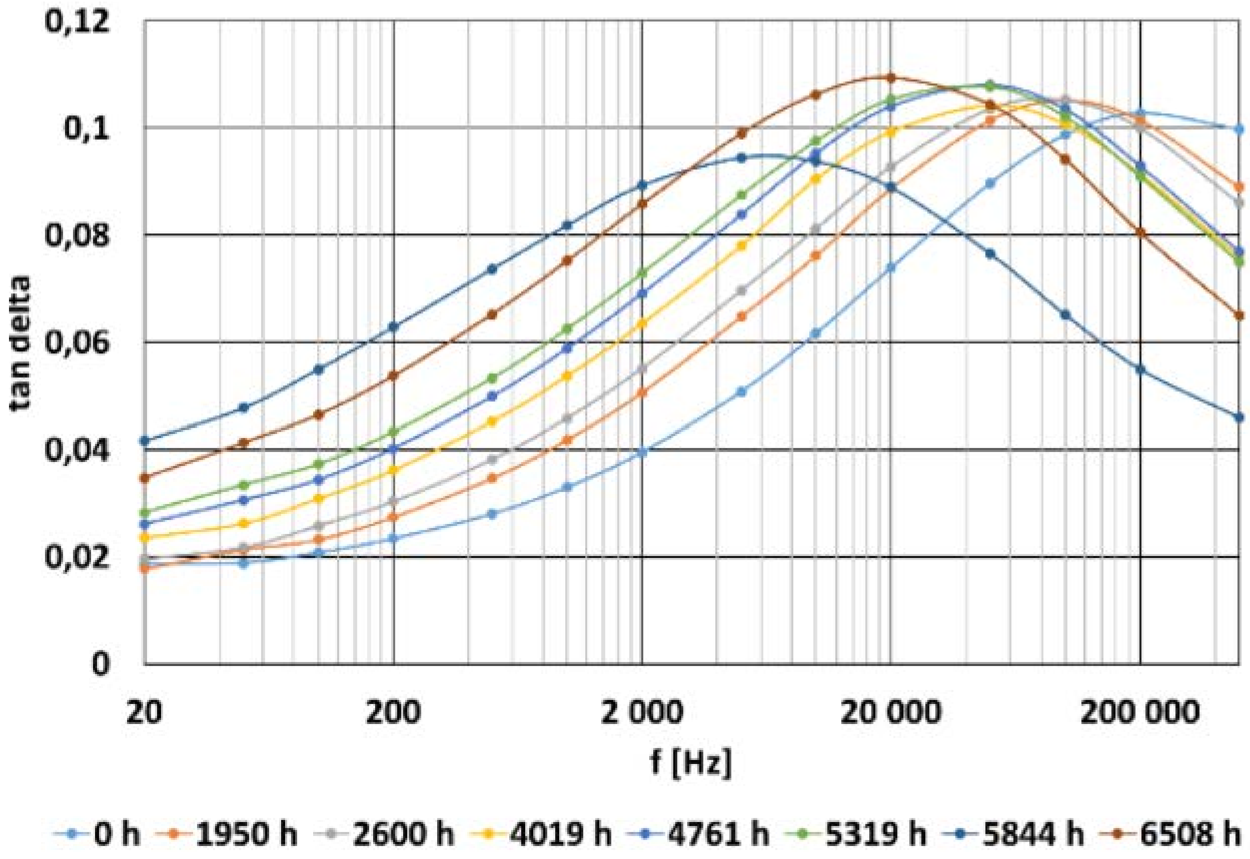
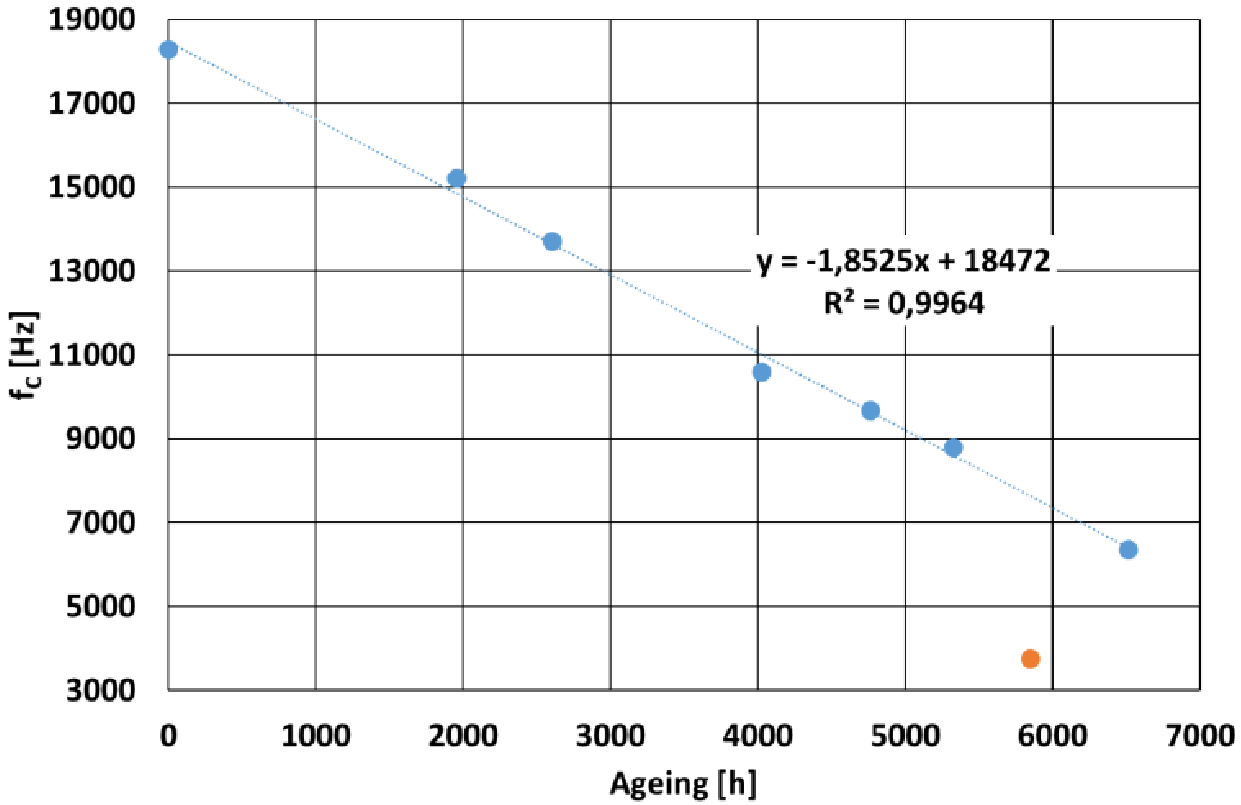
Other methods showing promise

- These are currently laboratory studies with limited NPP experience
  - Dielectric measurements – Tan D, permittivity, voltage response
  - Ultrasonic velocity
  - NMR

Tan D measurements on thermally aged EPR cable



Central frequency for Tan D correlates well with ageing



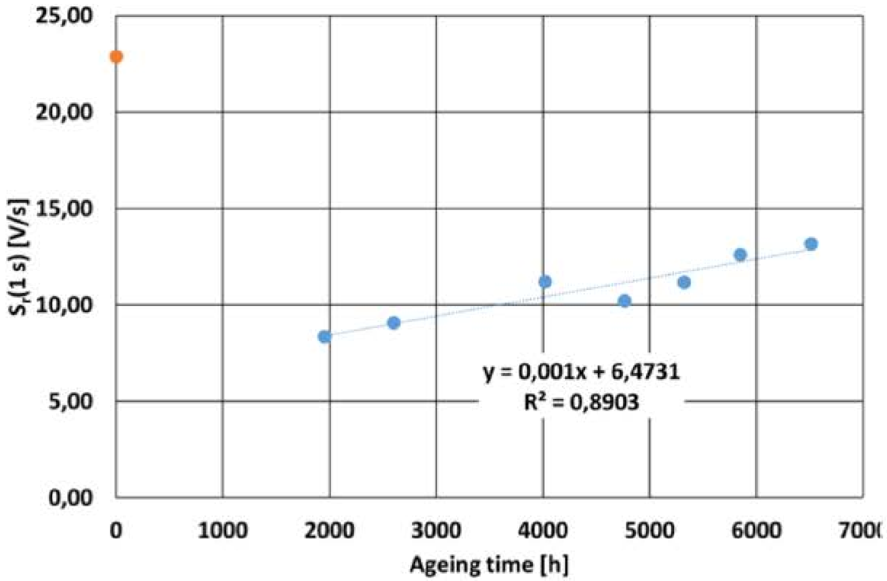
Potentially could be used in-situ in plant, non-destructive test but needs correlation with EAB for specific cable types

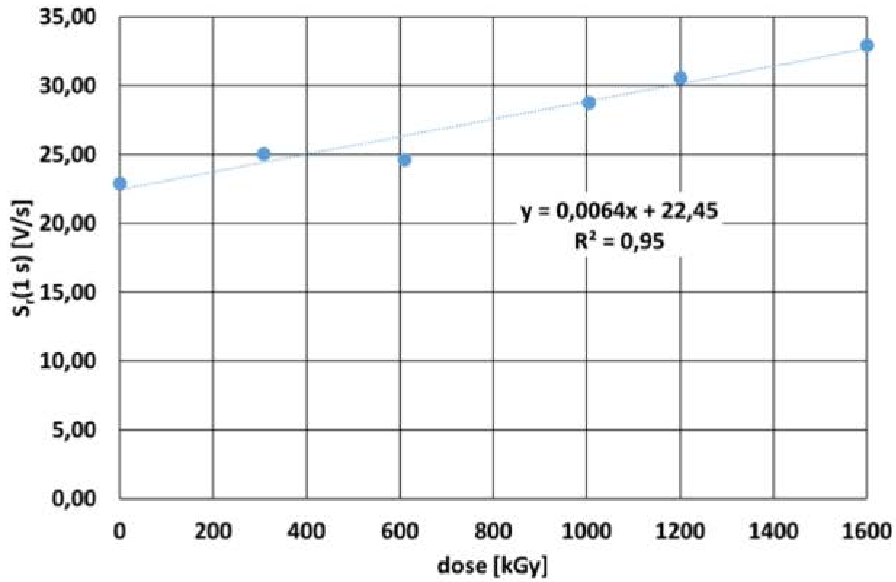
Extended voltage response (EVR)

- Shows some potential as a CM indicator
- Measurement of decay voltage and return voltages as different shorting times
- Slope of return voltage at 1 sec correlates quite well with both thermal and radiation ageing for EPR cable tested
- But anomalies with thermal ageing not yet fully explained
- Being evaluated in Paks NPP, Hungary

EVR tests on EPR cable

Anomaly with thermal data likely to be from drying of cable in accelerated ageing

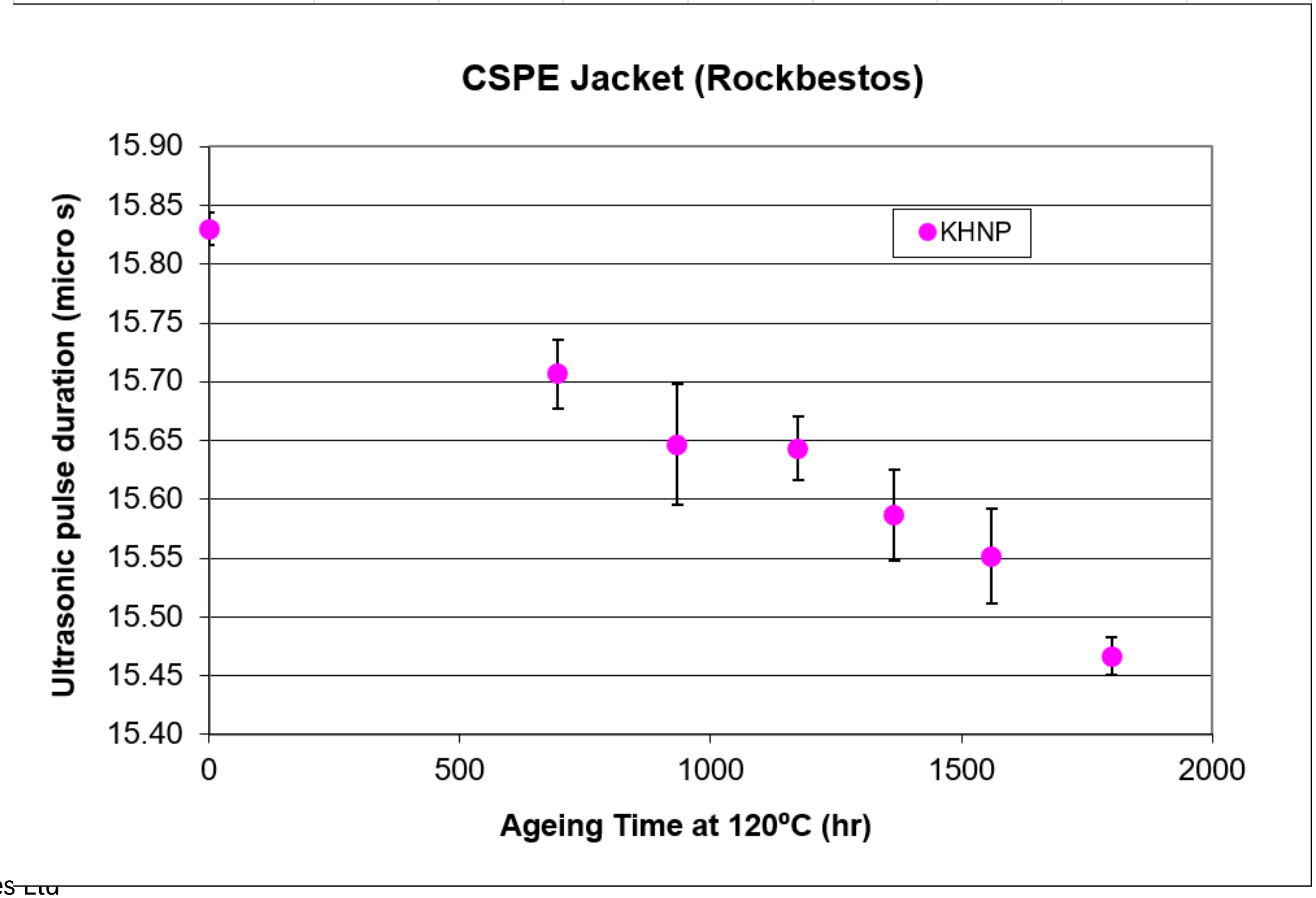




Z Á Tamus, B Deli, B Demkó, C Rusznyák, Y J Shin, Application of Derived Quantities from the Results of General Electrical Tests for Condition Monitoring of Nuclear Power Plant Instrumentation and Control Cables, FONTEVRAUD 9, Avignon, France, 2018

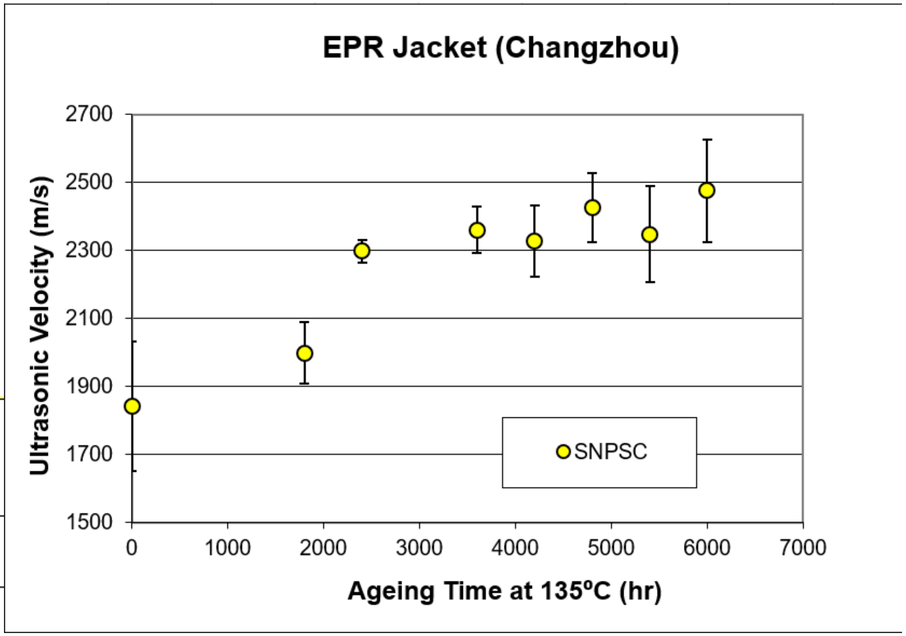
Ultrasonic velocity measurements

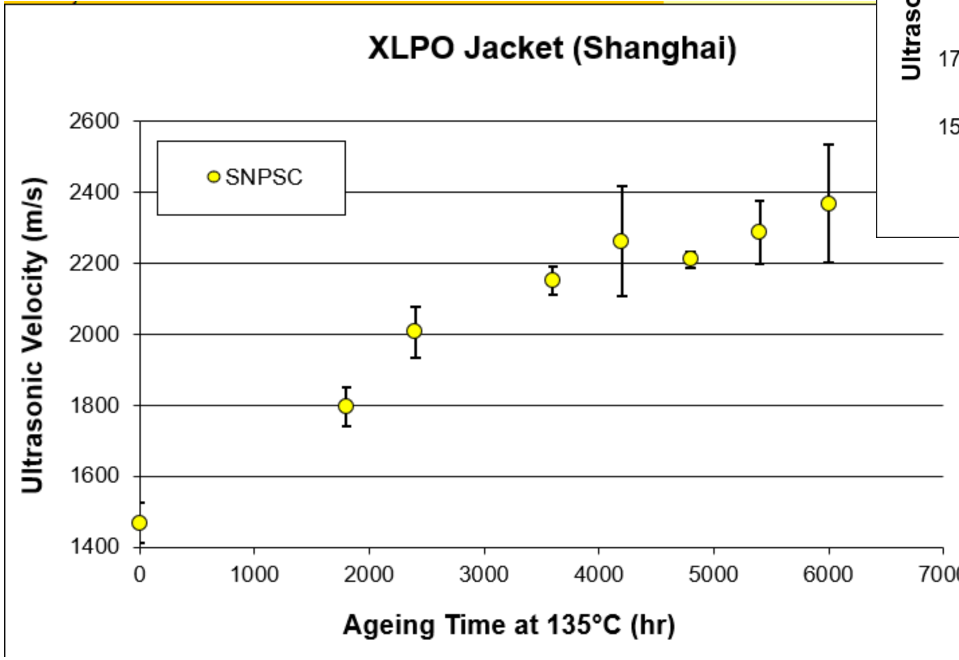
- Mainly applicable to jacket materials
- Likely to be sensitive to cable construction



Ultrasonic velocity - examples

Demonstrated for EPR, XLPO and CSPE jackets in laboratory tests, not yet in use in NPPs

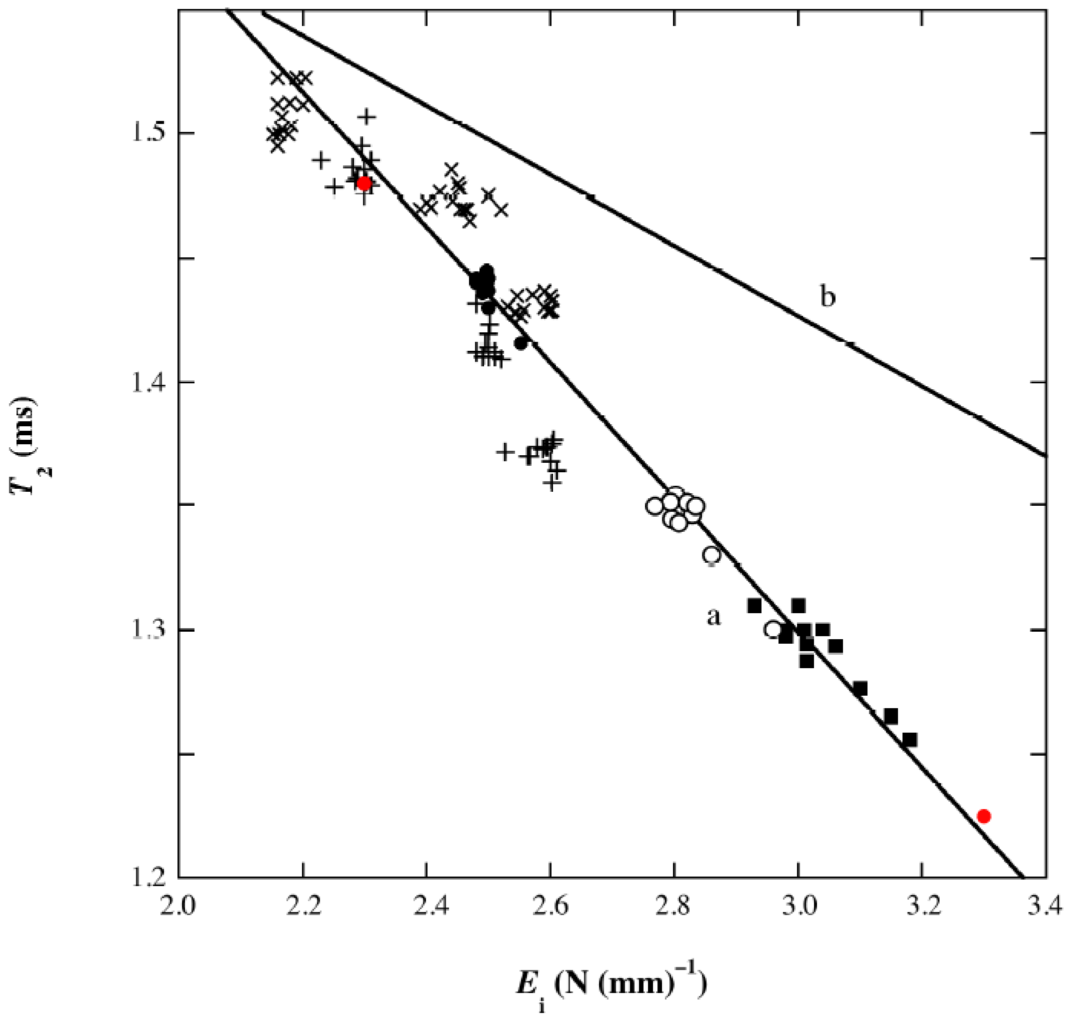




NMR measurements

- Potentially useful CM method using portable probe
- Shows good correlation with indenter measurements in EPDM seals
- Consistent for both accelerated ageing and long term in-plant ageing

NMR on EPDM seals



NMR measurements correlated with indenter modulus for various radiation ageing conditions, in air and low oxygen environments. Red circles are for samples from NPP aged for 21 years.

CM methods for cables - summary

- Wide range of CM methods available but there is no single technique suitable for every cable type
- Some techniques are well developed and are used in plant, with standards for some test methods (e.g. IEC 62582 series)
- Other techniques are still being evaluated in the laboratory
- Overall, there is a ‘tool-box’ of CM methods that can be applied – some to measure ageing degradation, some to locate faults or degraded areas

Lessons learned from recent IAEA condition monitoring programme

- Any method for condition monitoring must be very well specified including -
  - Sample preparation
  - Test environment and sample conditioning
  - Test method
  - Analysis method
- Acceptance criteria need to be specified, appropriate to CM method and cable usage
- Correlation with ageing is specific to a polymer formulation

Where do we go from here?

- Some suggestions –
  - Share experience of use of CM in-plant to develop best practice
  - Evaluate the practicality of newer methods for use in-plant
  - Would application of existing methods be cost-effective in your NPP?