Benchmarking of cable condition monitoring methods – lessons learned from a recent IAEA co-ordinated research programme

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Objectives of IAEA programme

- Identify practical condition monitoring methods for cable insulation & jacket materials of interest to NPPs
  - Methods that can trend degradation
  - Suitability for ageing assessment
- Assess the reproducibility of these methods
  - Benchmarking using different test laboratories
  - Identify ways to improve test methods
17 active participants from 13 different countries, plus several observers

6 different cables

- XLPE/CSPE (Rockbestos, USA)
- EPR/EVA (Eupen, Belgium)
- PEEK/XLPO (Habia, Sweden)
- SiR/SiR (Hew, Germany)
- XLPO/XLPO (Shanghai Special Cable, China)
- EPR/EPR (Changzhou Bayi Cable Co., China)
CM methods included in programme

- **Mechanical**
  - Elongation at break (EAB)
  - Indenter (IM)
  - Recovery time

- **Chemical/thermal**
  - Oxidation induction time (OIT)
  - Oxidation induction temperature (OITP)
  - Thermogravimetric analysis (TGA)
  - Fourier transform infrared spectroscopy (FTIR)

- **Electrical**
  - Dielectric loss (Tan delta)
  - Dielectric spectroscopy
  - Insulation resistance (IR)
  - Time domain reflectometry (TDR)
  - Frequency domain reflectometry (FDR)

- **Other**
  - Ultrasonic velocity
  - Density
Overall plan

- Each lab decided which materials and CM methods to test
- Labs prepared their own samples from whole cable
- Test method agreed at start of programme
  - Comparison of unaged data initially, method revised if necessary
- Labs did thermal ageing at agreed temperature
- Limited no. of radiation aged samples
- Data collated in standard format
Main concern – variability between labs

- Initial results on unaged material – update to test methods
- On aged materials, variability was considerable for some CM methods
- Important to understand reasons for variability
Variability between labs – EAB (1)

CSPE jacket (Rockbestos)

EAB (%) vs. Ageing time at 120°C (hr)

- AMS
- LABOR-SCK
- VEIKI
- VUJE
- NIST
Variability between labs – EAB (2)
Variability between labs – EAB (3)

EVA jacket (Eupen)

EAB (%) vs. Ageing time at 120 C (hr)

- AMS
- LABOR
- SECRI
- VEIKI
- VUJE
- CNEA
- NIST
- UJV
Cable types

- CSPE jacket – reasonably uniform thickness, easy to cut dumb-bell samples for EAB
- EVA jacket – non-uniform thickness, moulded around insulated wires
- EPR insulation on solid tinned Cu – very difficult to strip
Reasons for variability - EAB

- Test method – type of extensometer used
  - Optical extensometer
  - Clip-on extensometer
  - Cross-head movement

- Sample preparation – biggest source of variability
  - Dumb-bell samples – removal of surface irregularities, dual layers, wrap materials
  - Tubular samples – method used to extract wire from insulation
  - Difficult to prepare specimens from aged cable
Variability between labs – IM (1)
Variability between labs – IM (2)

XLPO Insulation (Shanghai)

Ageing Time at 135°C (hr)

IM (N/mm)

- AMS
- INSS (corrected)
- SECRI
- AECL
Variability between labs – IM (3)
Reasons for variability - IM

- Probe tip diameter (correction to standard)
- Sample temperature
- Force range used for analysis
- Clamping force
- Variation in sample thickness
Recovery time

- Only 1 lab testing this method
- Often shows larger change than for indenter e.g for this XLPO, IM changes by factor of 2 and recovery time by factor of 5
Variability between labs – OIT (1)
Variability between labs – OIT (2)

EPR insulation (Changzhou)

OIT at 240°C (min)

Ageing time at 135°C (hr)
Variability between labs – OITP
Reasons for variability – OIT/OITP

- **Must** use same set temperature throughout series of tests for OIT

- Sample preparation for both OIT and OITP
  - Particle size and packing
  - Selection of sampled material (colour, dual layers)
  - Analysis method – specified in IEC/IEEE standard but may need to be done manually
Variability between labs – FTIR

![Graph showing variability in FTIR peak ratios for XLPE insulation (Rockbestos) with ageing time at 135°C (hr).]

- FTIR Peak ratio
- Ageing time at 135°C (hr)
- XLPE insulation (Rockbestos)

Key:
- KHNP 1735:1351
- NEL 1732:2917
- NEL 1507:2917
- NEL 3400:2917
Reasons for variability – FTIR

- Main problem is determining which peaks to compare – often not known before ageing programme starts
Potentially useful CM methods

- These have only been tested by 1 or 2 labs so there is no data on variability between labs
- Methods showing trends with ageing (for at least some materials)
  - Ultrasonic velocity
  - Dielectric spectroscopy
  - Frequency domain reflectometry (FDR)
Ultrasonic velocity

Figure 314. Cross-plot of ultrasonic velocity vs. EAB for XLPO insulation (Shanghai)

Ageing time at 155°C (hr)
Dielectric spectroscopy

- Highlights the problem of electrical measurements on thermally aged materials – large step change in values as cable is dried
- For irradiation at constant temperature, trends are more visible
Frequency domain reflectometry

EPR insulation (Eupen)

Figure 238. Cross-plot of FDR vs. EAB for EPR insulation (Eupen)
Summary of practical usefulness of CM methods for materials tested

- Used a colour code to indicate practical usefulness of each CM method tested
- This is specific to actual materials tested

<table>
<thead>
<tr>
<th>Practical Usefulness</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Very useful</td>
<td>Good correlation with ageing. Low inter-lab variability</td>
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<tr>
<td>Useful</td>
<td>Reasonable correlation with ageing. Some inter-lab variability but consistent trends</td>
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<tr>
<td>Potentially useful</td>
<td>Moderate correlation with ageing. Large variability but shows potential for improvement. New method</td>
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<tr>
<td>Not useful</td>
<td>No correlation with ageing, or changes only when heavily aged</td>
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<td>No data/not applicable</td>
<td>No data or method not applicable to that material (e.g. electrical tests for jacket materials)</td>
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<tr>
<td>Potentially useful (limited)</td>
<td>Moderate correlation with radiation ageing only</td>
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</tbody>
</table>
Example – very useful
Example – potentially useful
Example – not useful
## Summary of practical usefulness of CM methods for materials tested

<table>
<thead>
<tr>
<th>CM method</th>
<th>EAB</th>
<th>IM</th>
<th>Recovery</th>
<th>OIT</th>
<th>OITP</th>
<th>TGA</th>
<th>Density</th>
<th>FTIR</th>
<th>Ultrasonic</th>
<th>Tan δ</th>
<th>Dielec. Spec.</th>
<th>IR</th>
<th>FDR</th>
<th>TDR</th>
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Lessons learned

- Three critical areas for practical use of CM methods in ageing assessment
  - Specification of test method
  - Sample preparation method
  - Data analysis
Specification of test method

- All aspects must be tightly defined and consistent throughout monitoring programme
  - Type of test equipment e.g. grips, extensometer for EAB
  - Test parameters e.g. OIT set temperature
  - Identify those parameters that are critical to reproducibility
  - Not all parameters are critical e.g. cross-head speed in EAB tests
  - Ensure enough measurements are made to reduce standard deviation of measurements
Sample preparation

- The most important factor in inter-lab variability
- For EAB need to define
  - Size of dumb-bells
  - Surface treatment
  - Removal of conductors from insulation
  - Use of end-tabs for tubular insulation
  - Type of grips
- For OIT/OITP/TGA
  - Selection of sample material e.g. dual layers
  - Method of size reduction and particle size
  - Packing of particles in test pan
Data analysis

- Check algorithms used in test equipment
  - May need to analyse manually e.g. to define baseline and threshold for OIT, OITP; force range used for IM
- In EAB, measurement of elongation relative to start of test
  - If using cross-head movement (not recommended) define gauge length to be used
- Define how mean and standard deviation are reported
  - Do you discard outliers?
Summary

- Toolbox of useful CM methods available
- Several potentially useful methods identified
- Suitable CM methods are material dependent
- Test methods must be very well defined
  - Including sample preparation and data analysis
  - Standards are being developed/revised for some CM methods
Summarised results are in IAEA-TECDOC-1825, can be downloaded from