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

Participants & materials

- 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

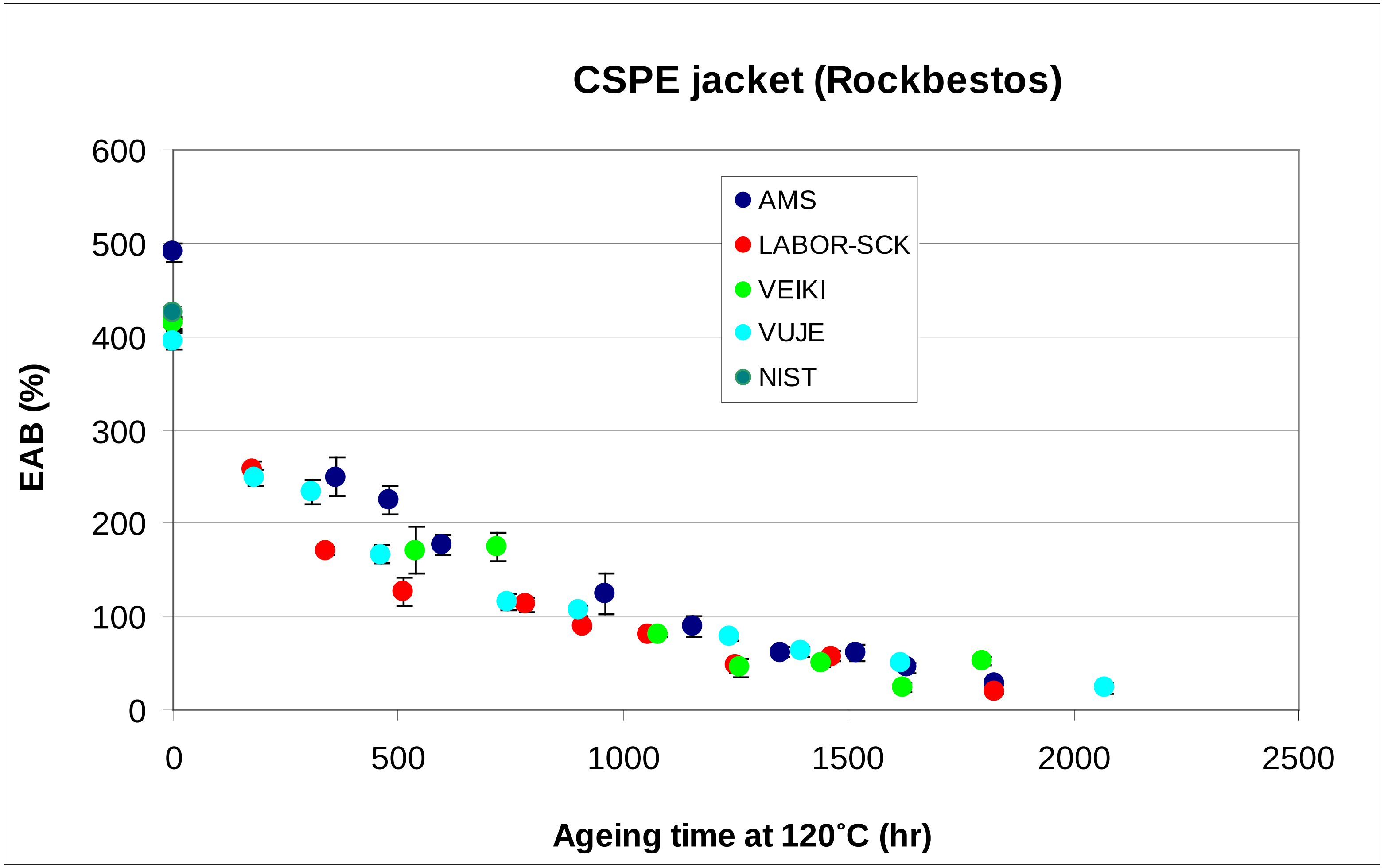
Overall plan

- 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

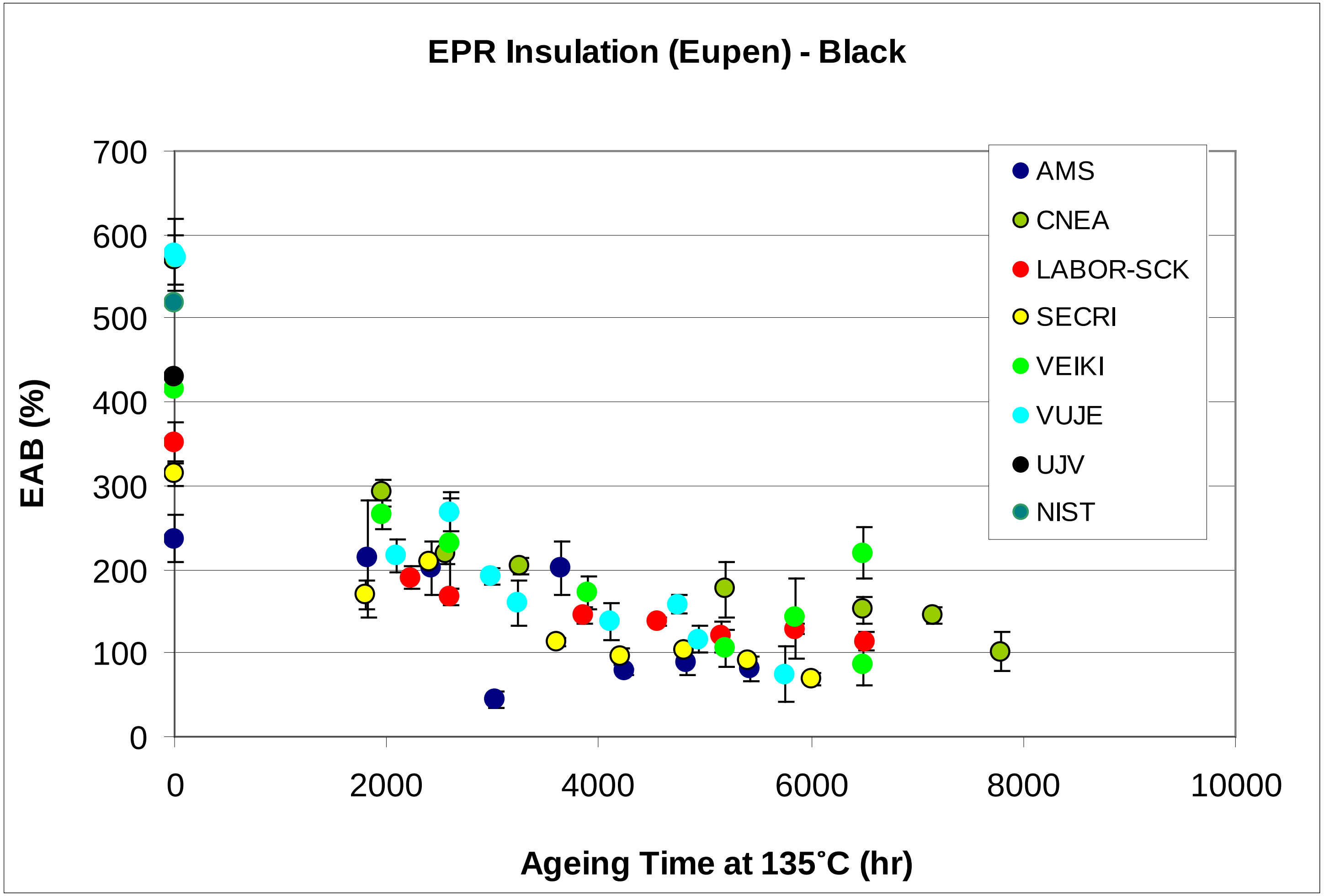
Main concern – variability between labs

- 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

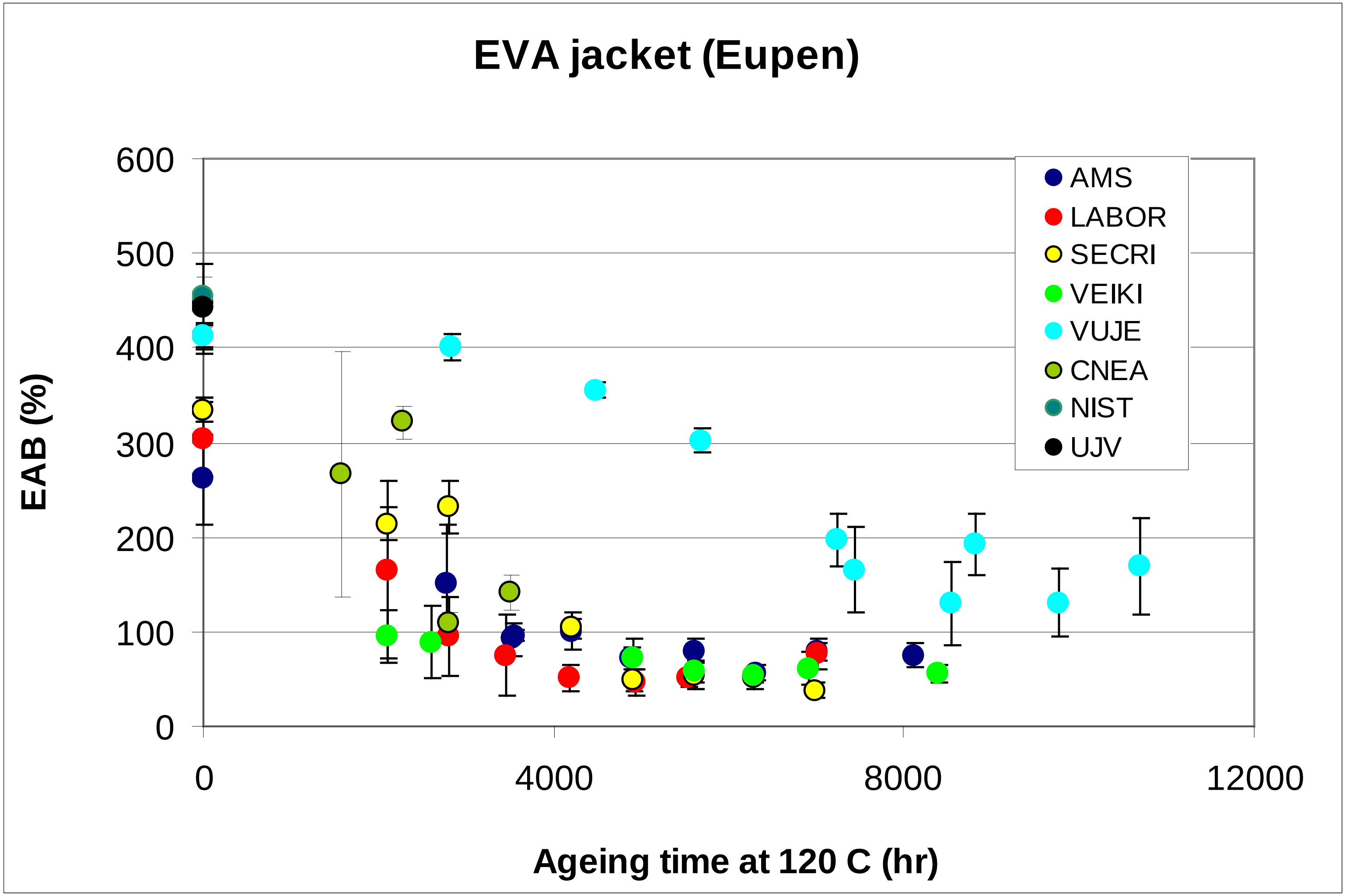
Variability between labs – EAB (1)



Variability between labs – EAB (2)



Variability between labs – EAB (3)



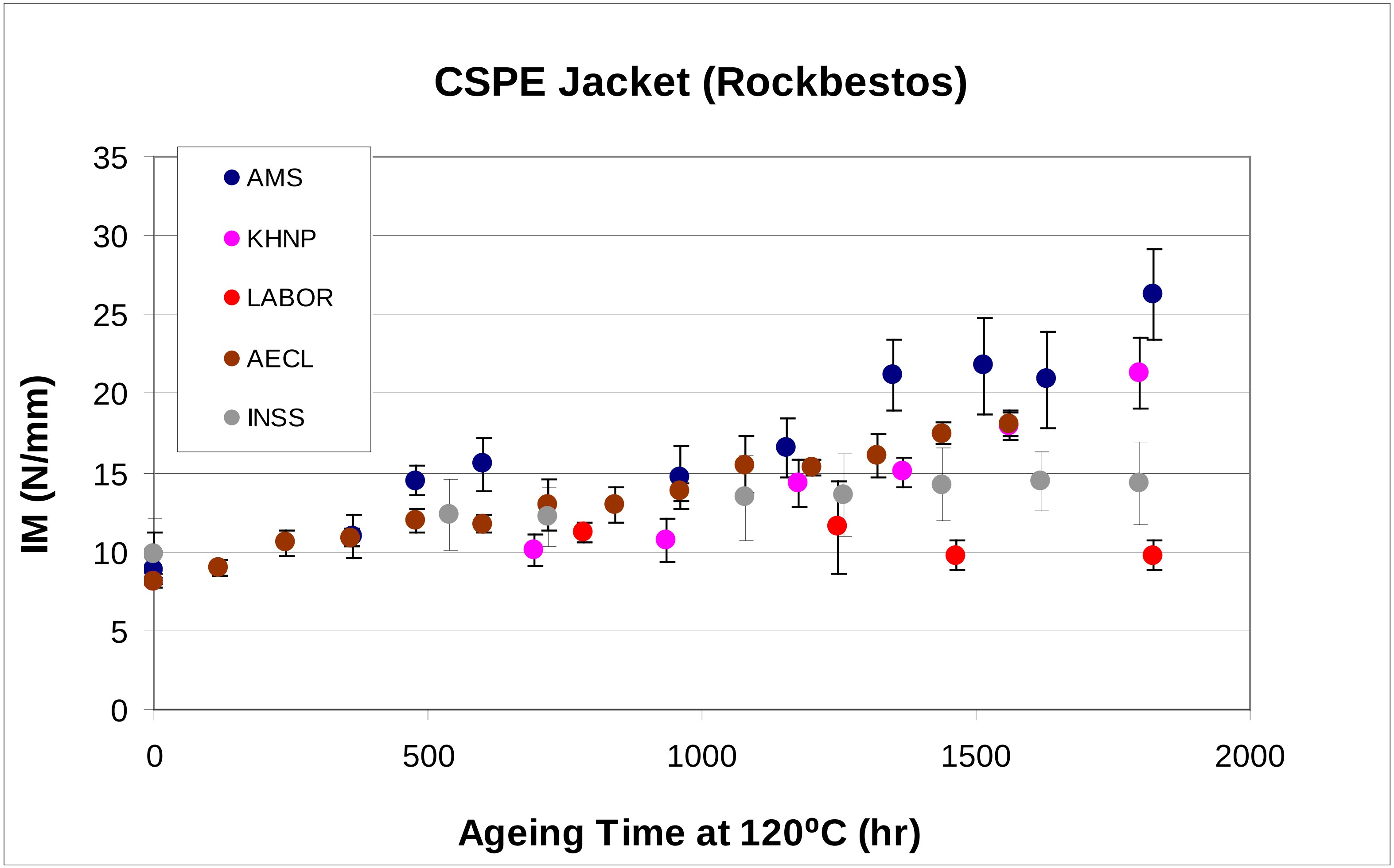
Cable types

- 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

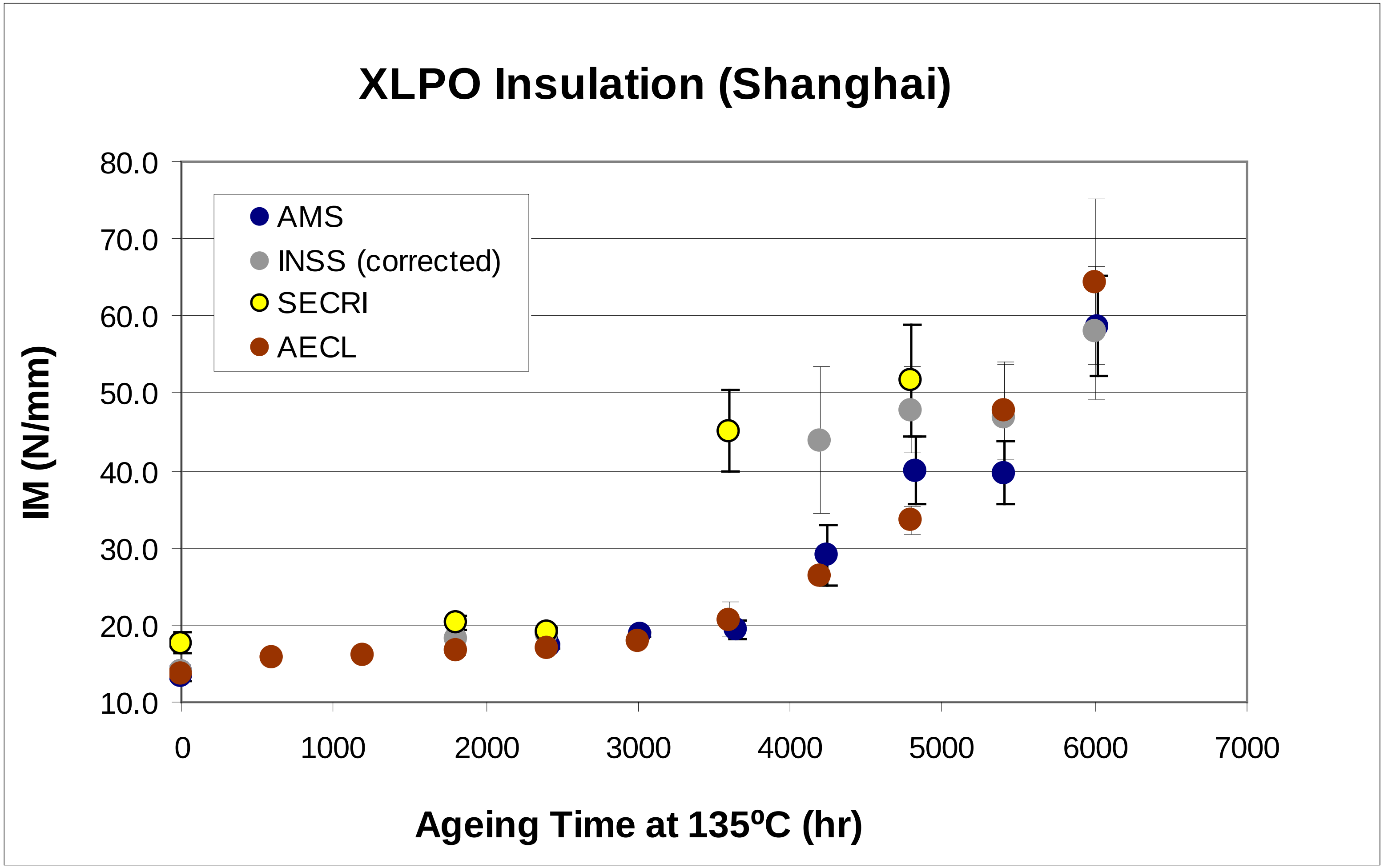
Reasons for variability - EAB

- 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

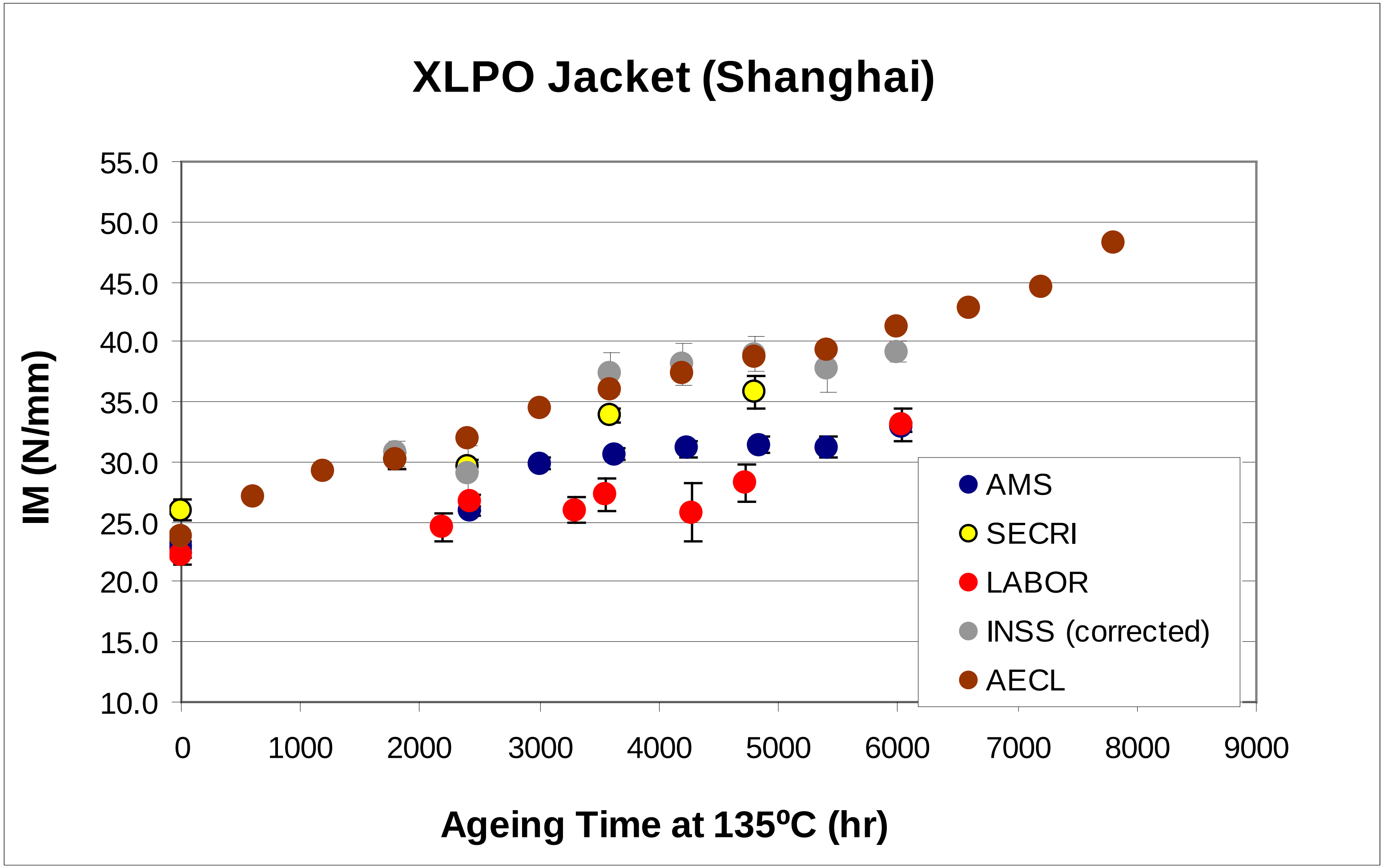
Variability between labs – IM (1)



Variability between labs – IM (2)



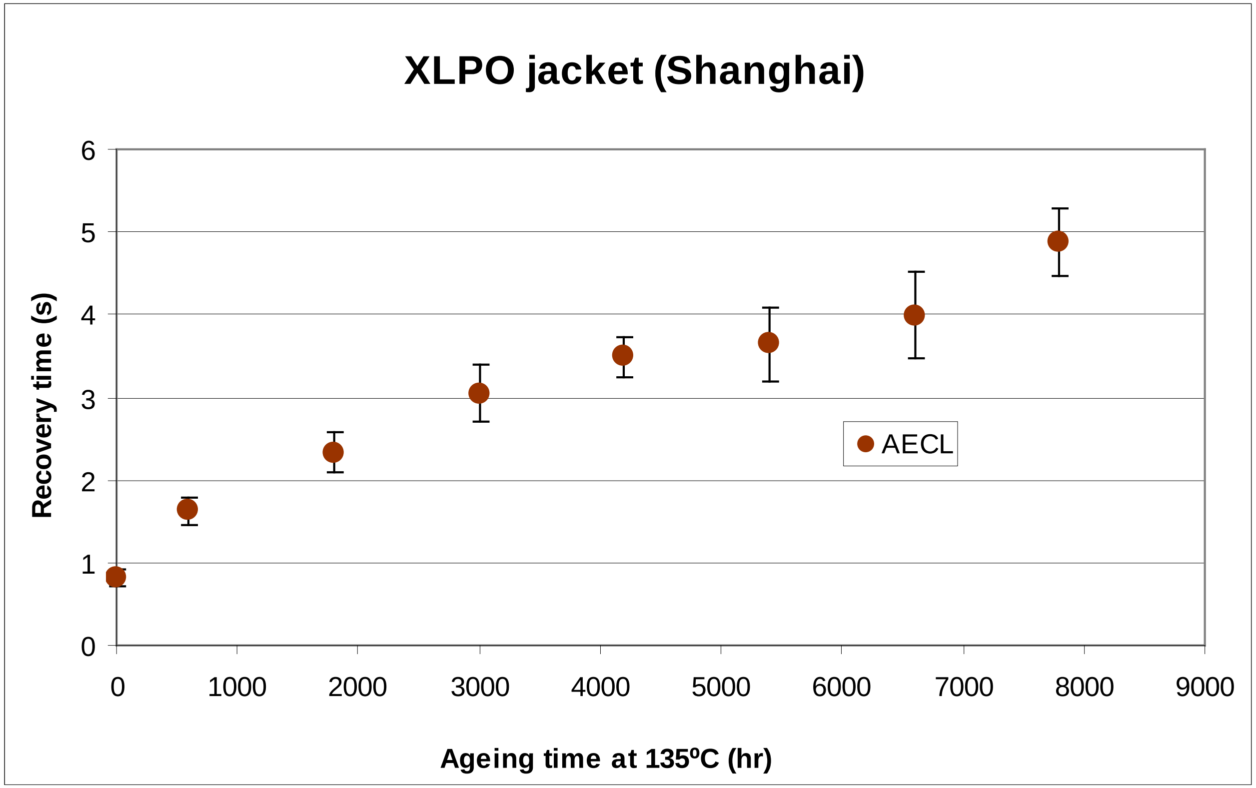
Variability between labs – IM (3)



Reasons for variability - IM

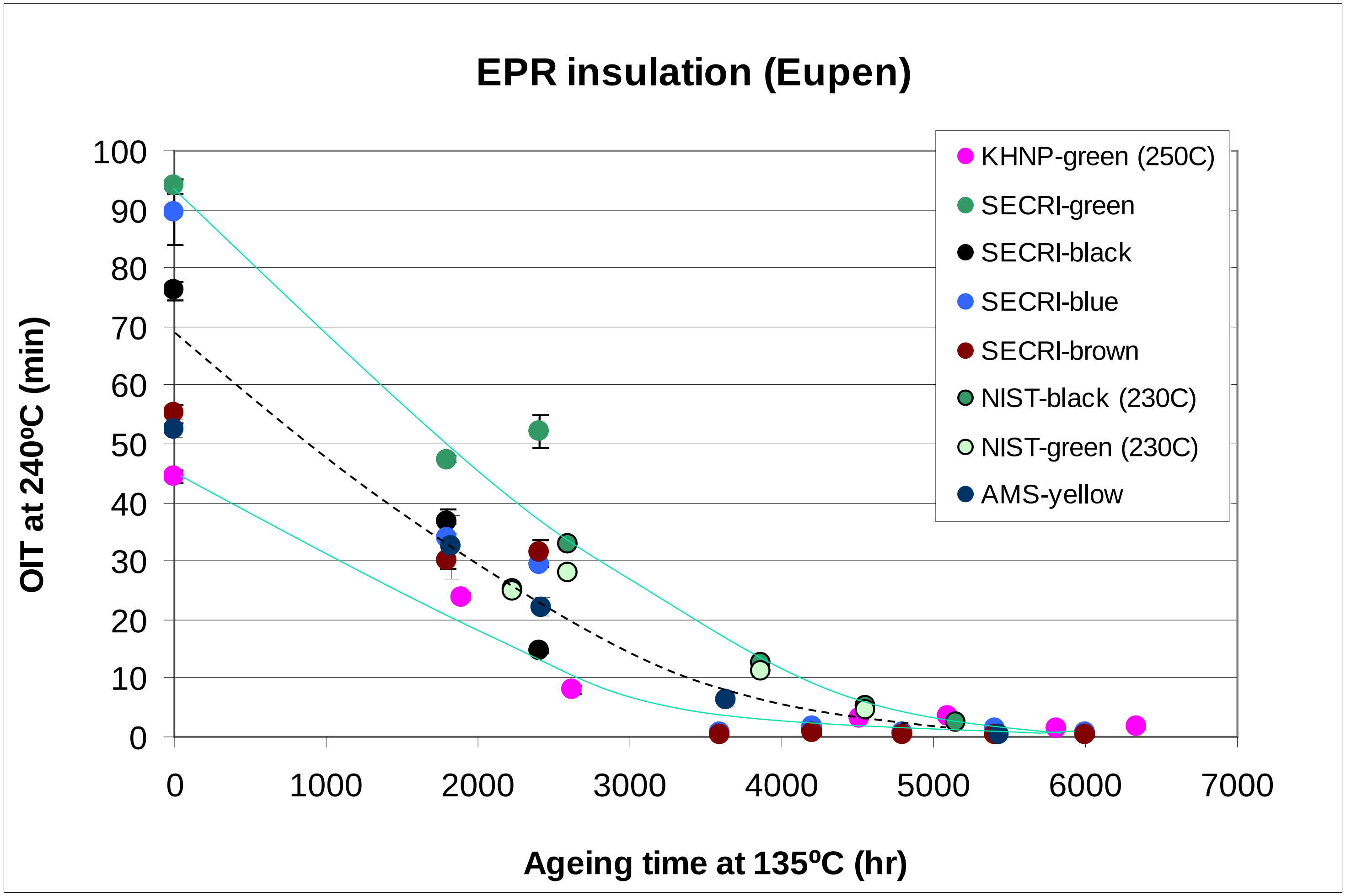
- Probe tip diameter (correction to standard)
- Sample temperature
- Force range used for analysis
- Clamping force
- Variation in sample thickness

Recovery time

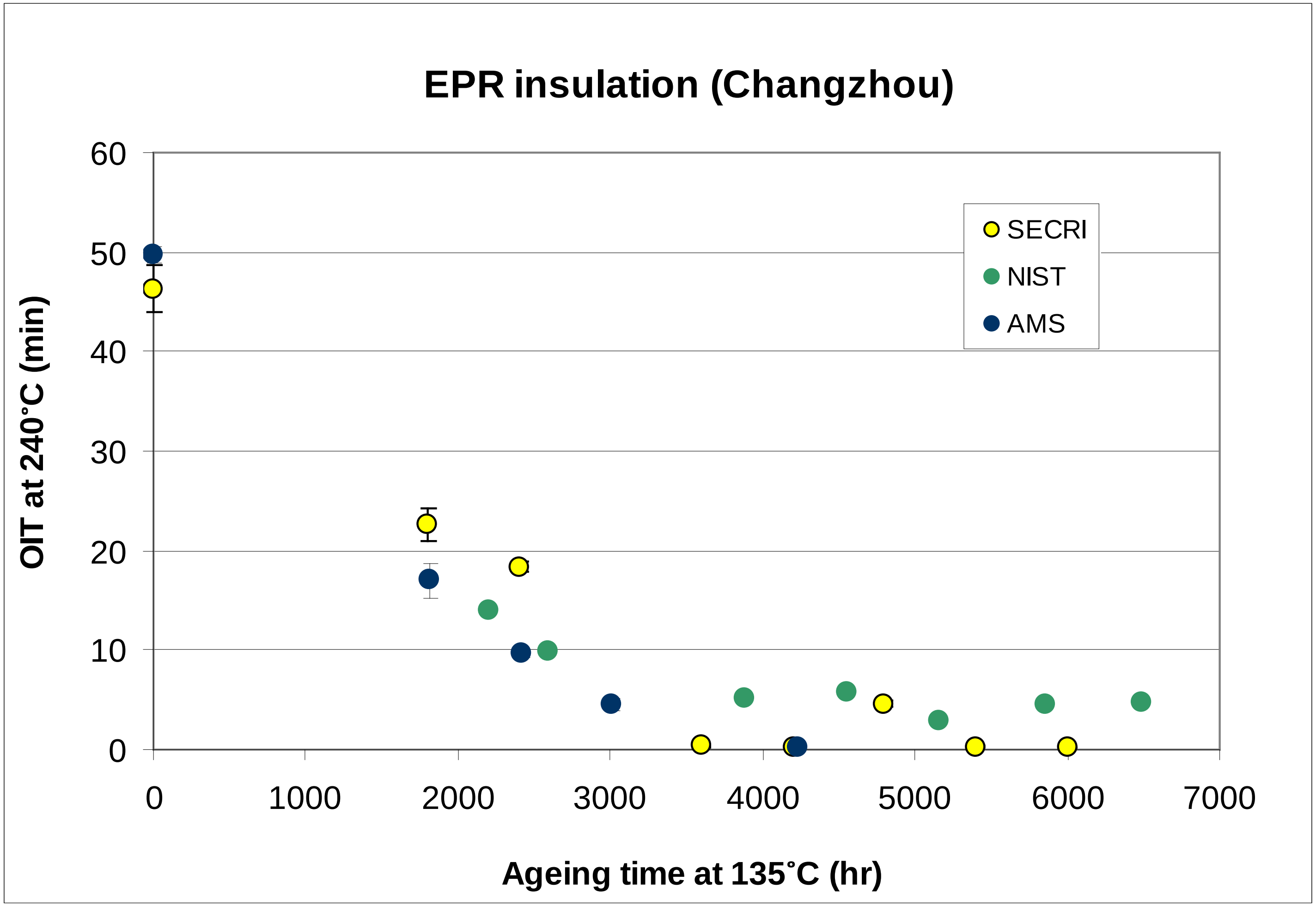


- Only 1 lab testing this method
- Often shows larger change than for indenter e.g for this XLPO, IM changes by factor of 2 and recovery time by factor of 5

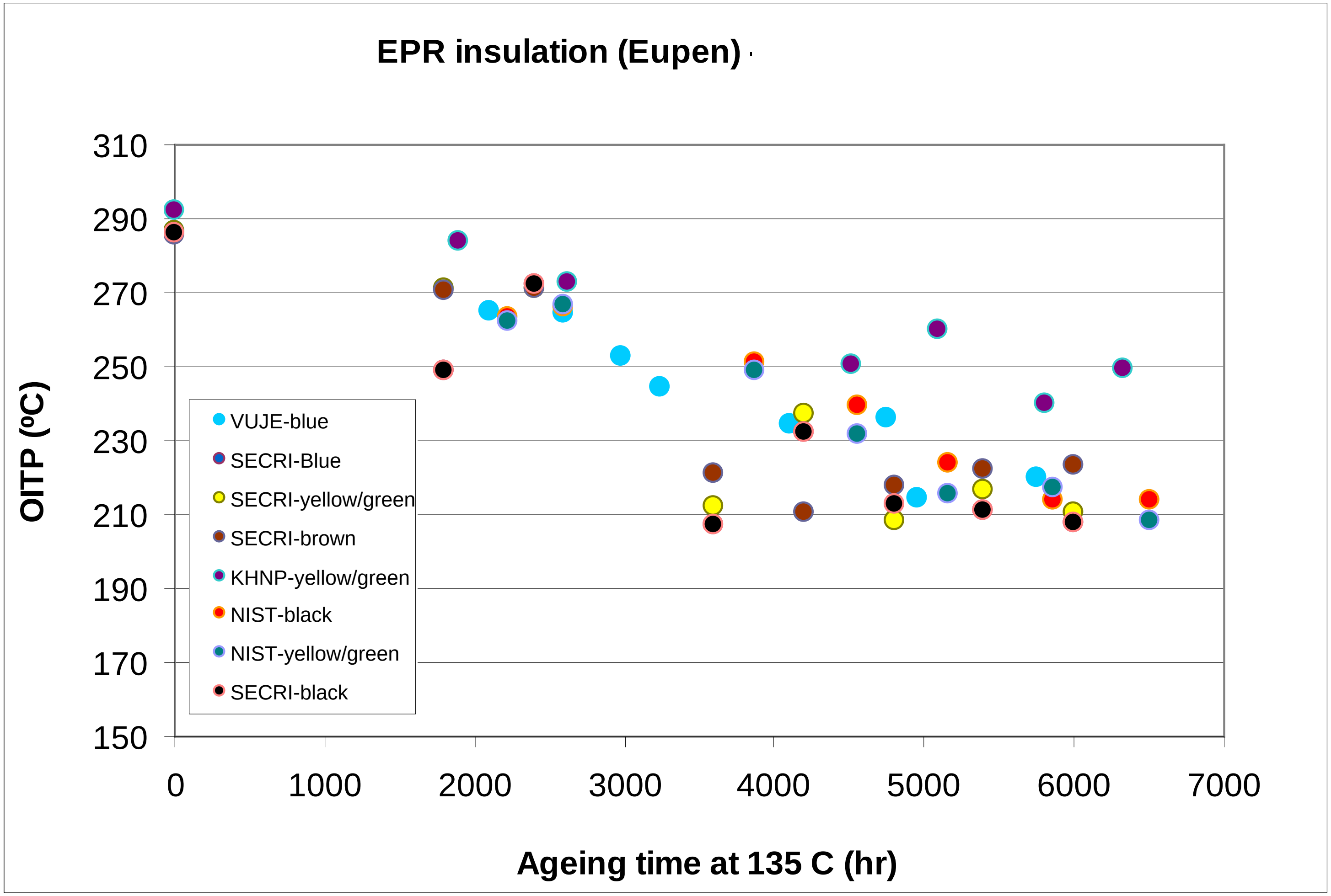
Variability between labs – OIT (1)



Variability between labs – OIT (2)



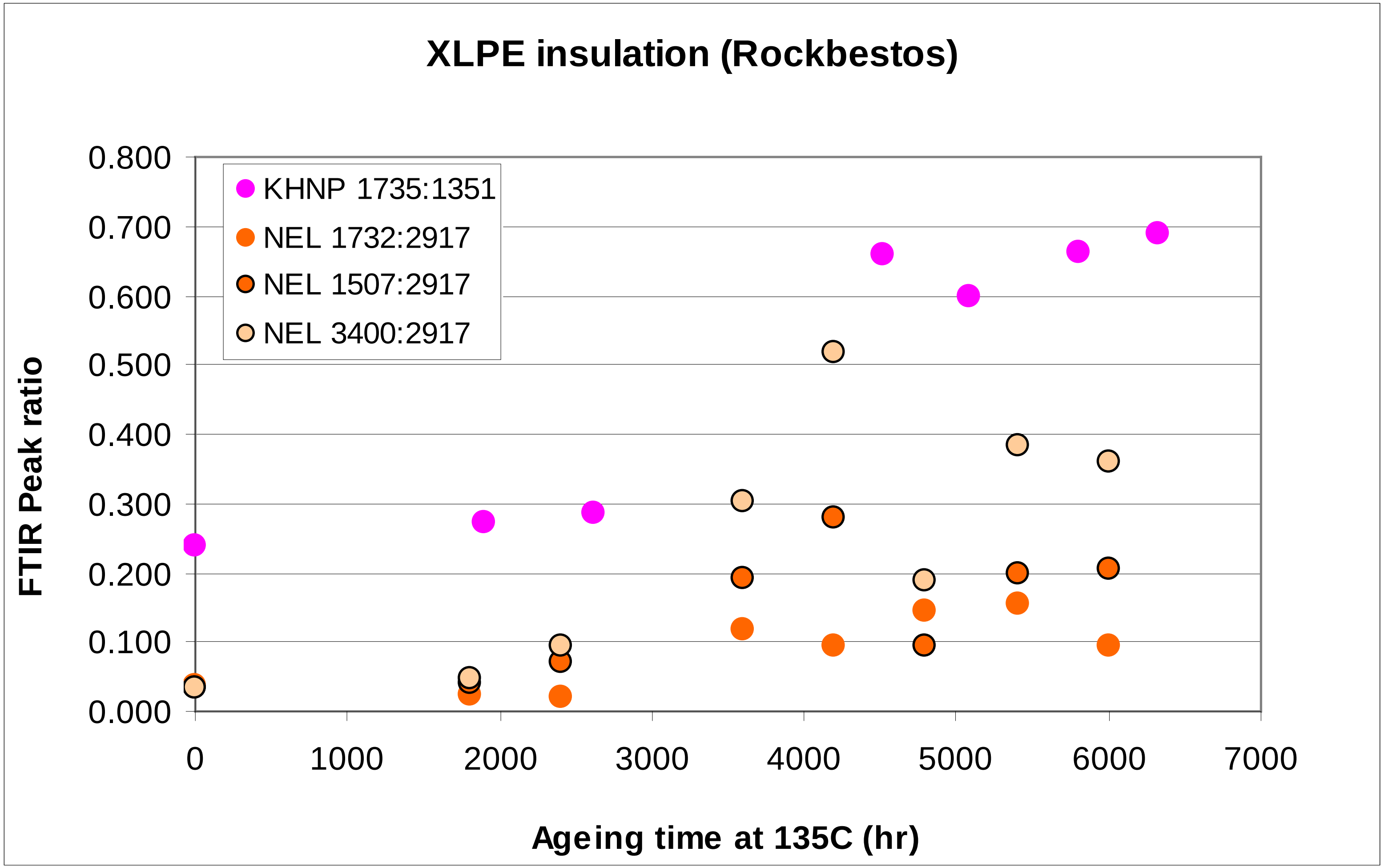
Variability between labs – OITP



Reasons for variability – OIT/OITP

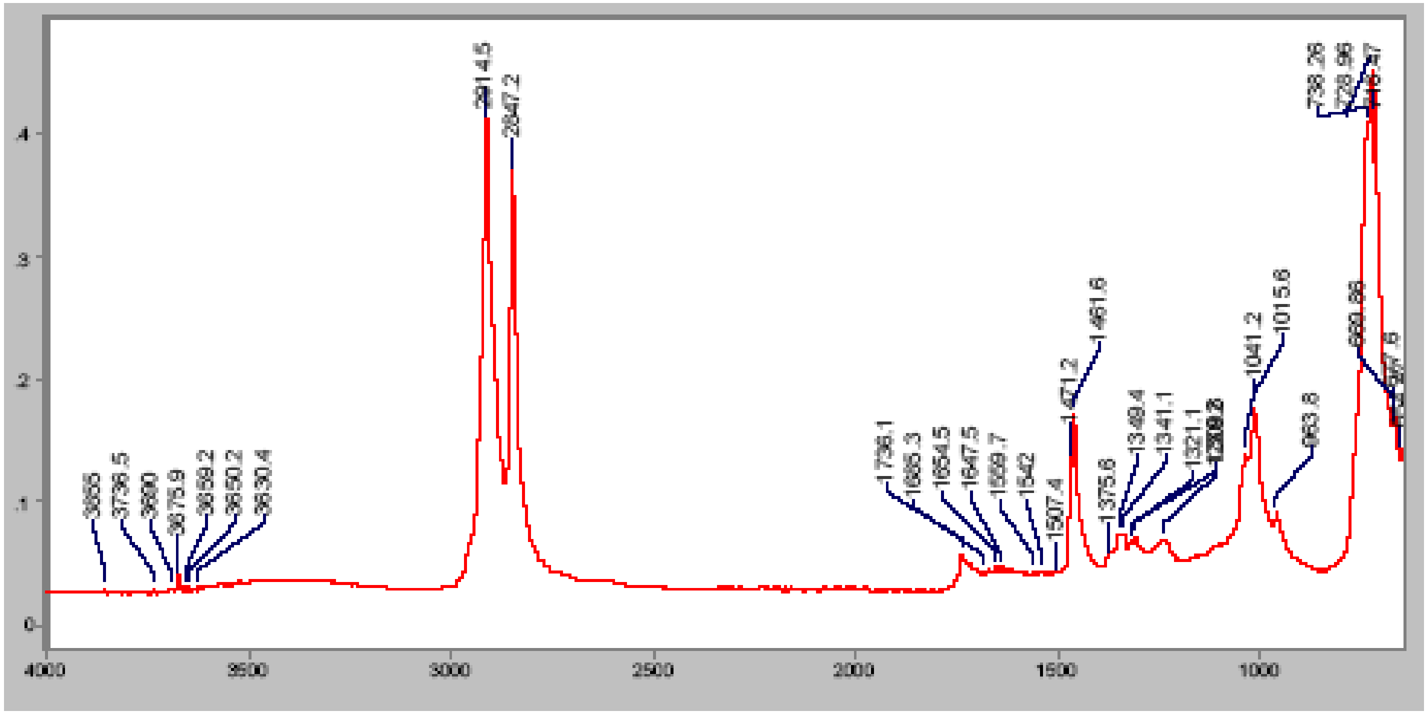
- Must use same set temperature throughout series of tests for OIT
- Sample preparation for both OIT and OITP
  - Particle size and packing
  - Selection of sampled material (colour, dual layers)
  - Analysis method – specified in IEC/IEEE standard but may need to be done manually

Variability between labs – FTIR



Reasons for variability – FTIR

XLPE insulation (Rockbestos)



- 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

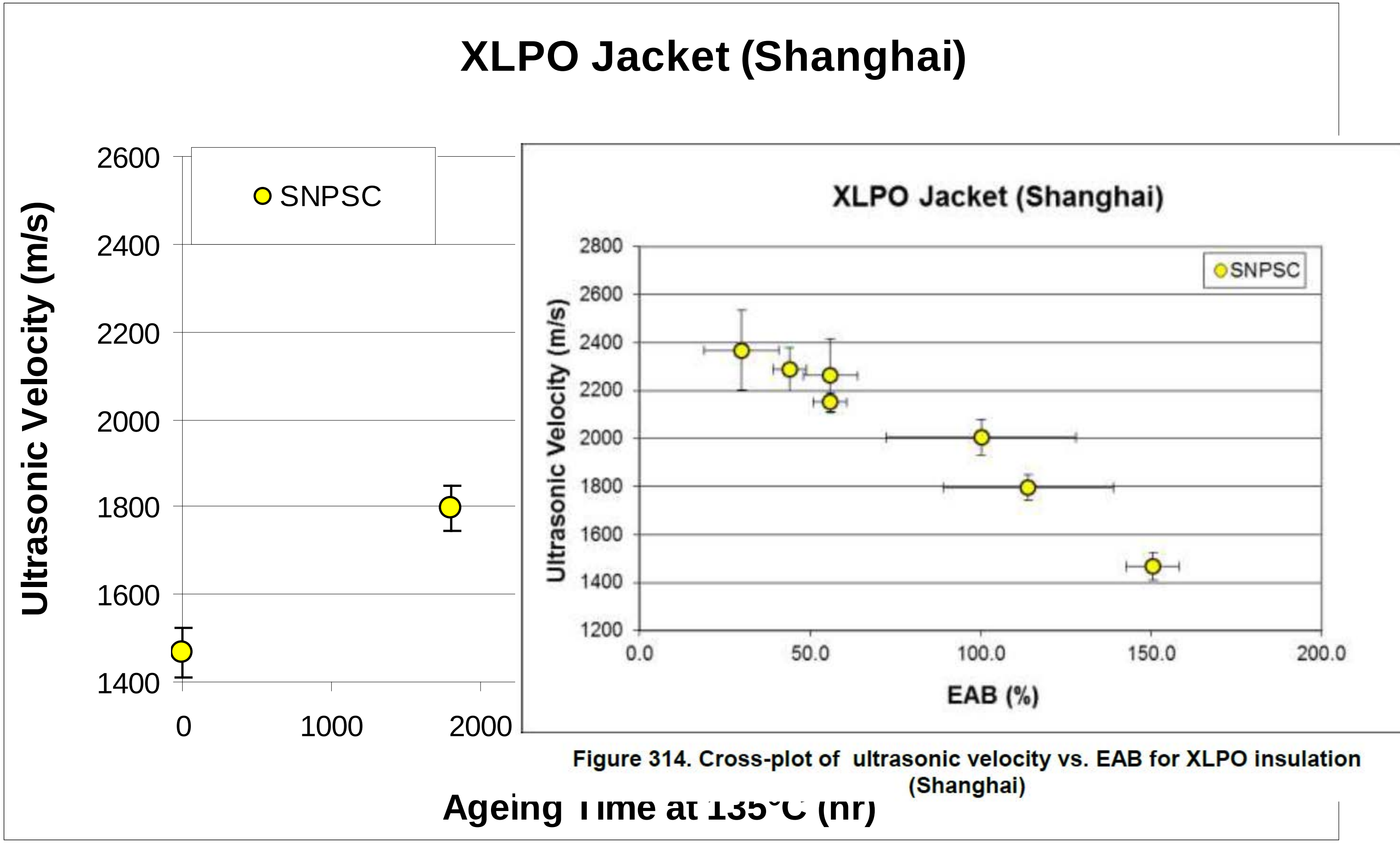


Figure 314. Cross-plot of ultrasonic velocity vs. EAB for XLPO insulation (Shanghai)

Dielectric spectroscopy

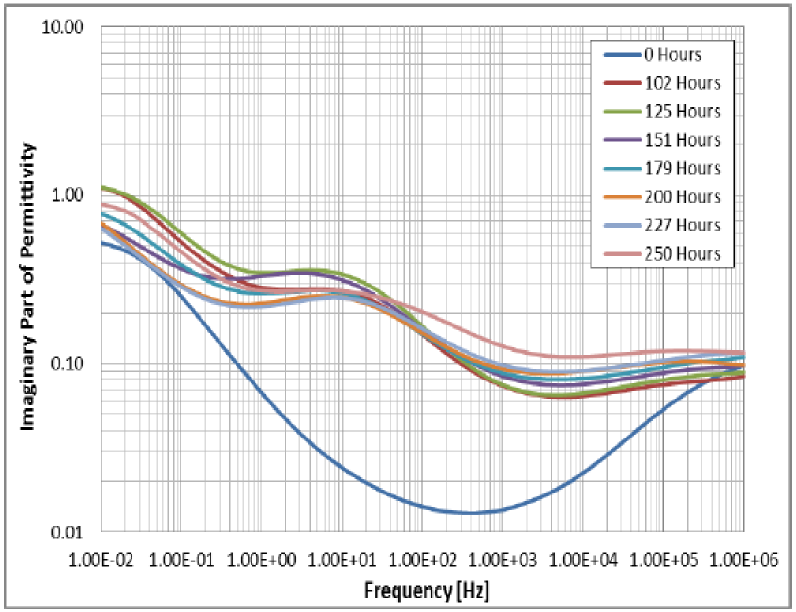


Figure 175. Imaginary Part of Permittivity vs Frequency of Rockbestos (XLPE/CSPE) cable after thermal ageing at 135°C.

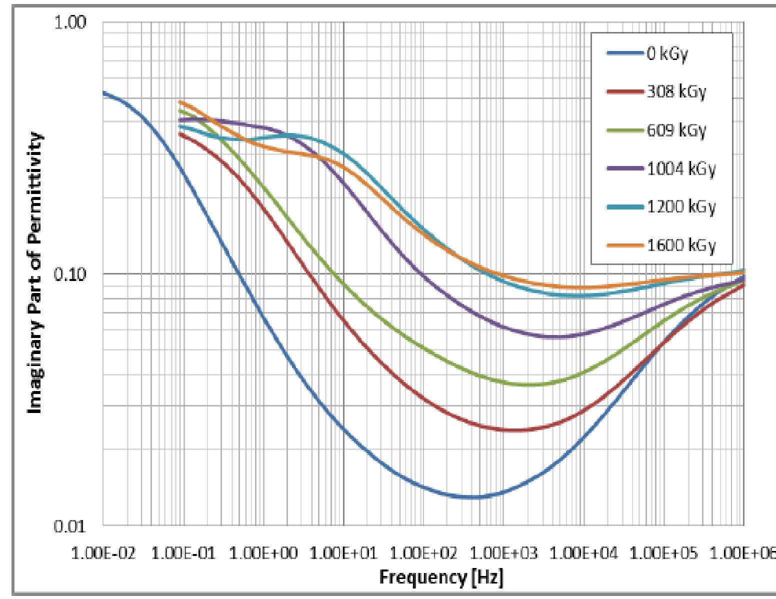


Figure 177. Imaginary Part of Permittivity vs Frequency of Rockbestos (XLPE/CSPE) cable after irradiation at room temperature (0.3 kGy/h)

- 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

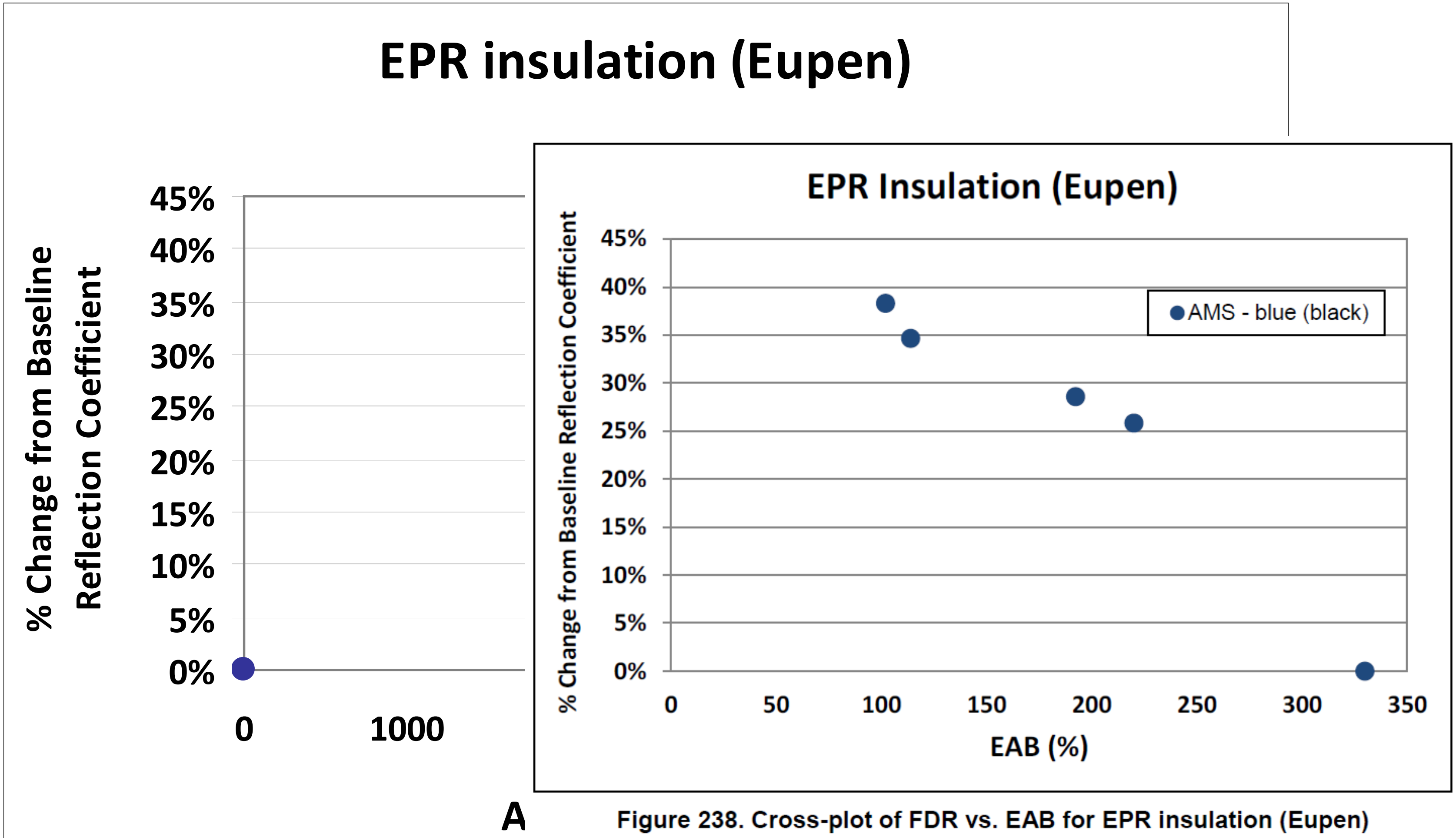


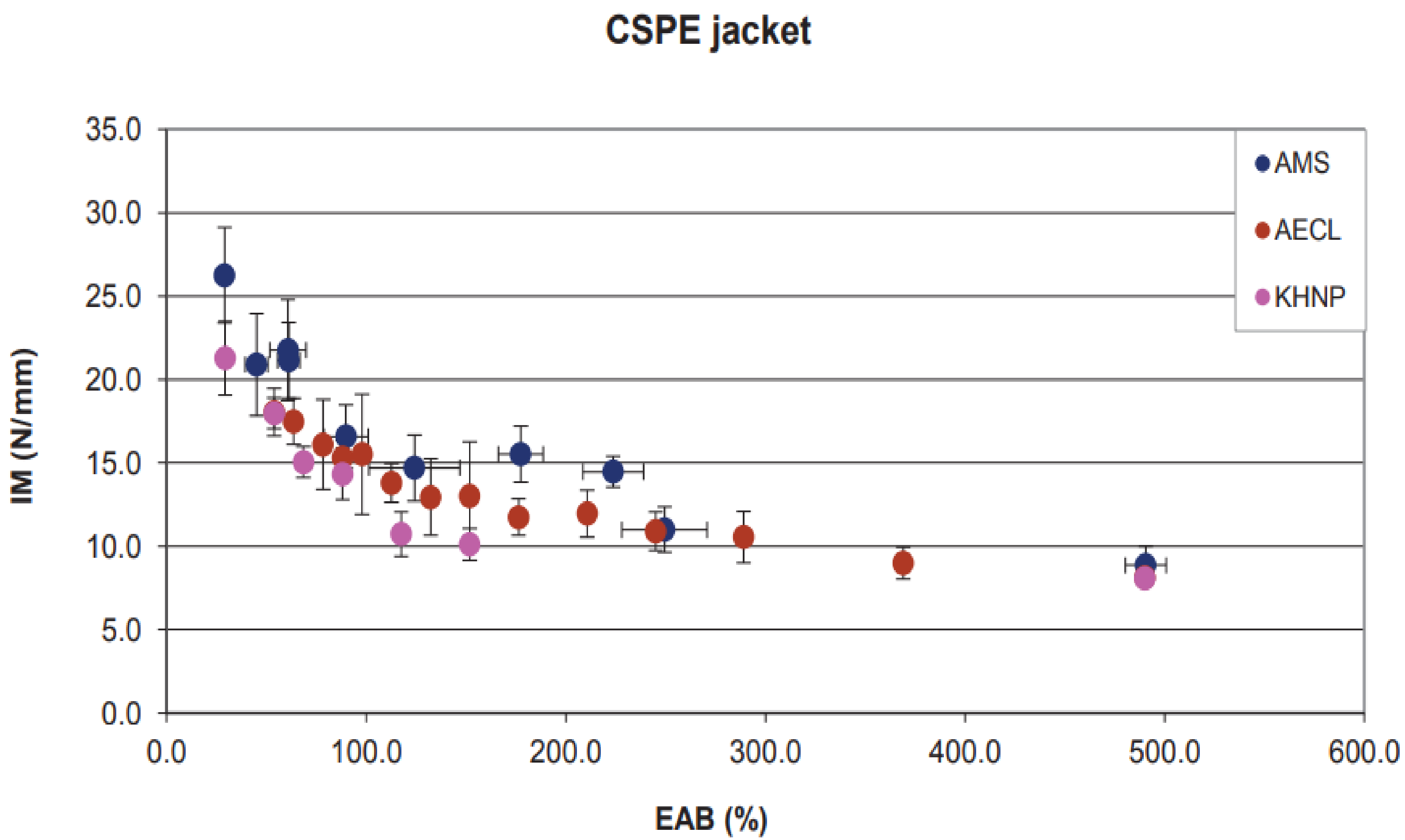
Figure 238. Cross-plot of FDR vs. EAB for EPR insulation (Eupen)

Summary of practical usefulness of CM methods for materials tested

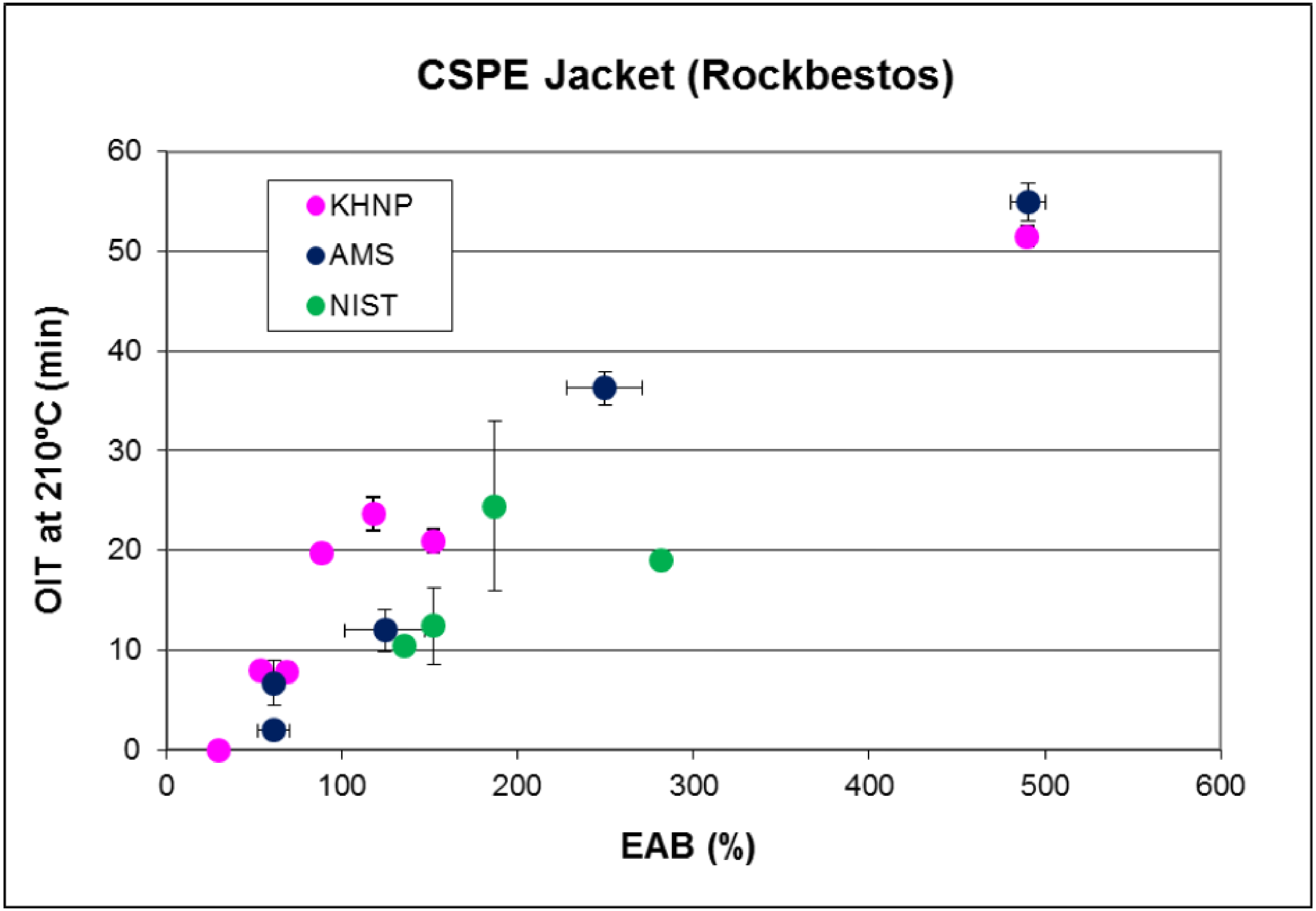
- Used a colour code to indicate practical usefulness of each CM method tested
- This is specific to actual materials tested

Very useful		Good correlation with ageing.Low inter-lab variability
Useful		Reasonable correlation with ageing. Some inter-lab variability but consistent trends
Potentially useful		Moderate correlation with ageing. Large variability but shows potential for improvement. New method
Not useful		No correlation with ageing, or changes only when heavily aged
No data/not applicable		No data or method not applicable to that material (e.g. electrical tests for jacket materials)
Potentially useful (limited)		Moderate correlation with radiation ageing only

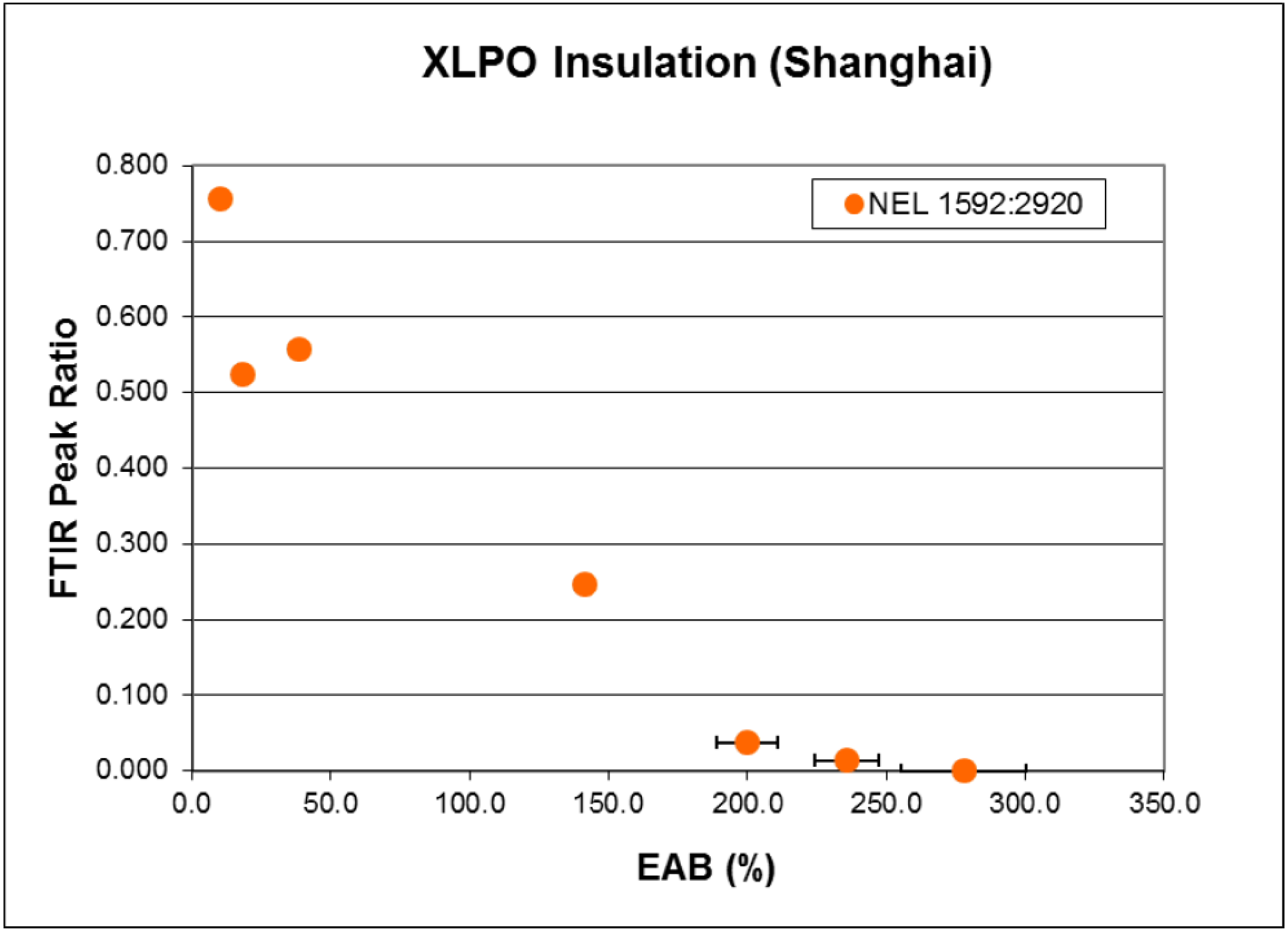
Example – very useful



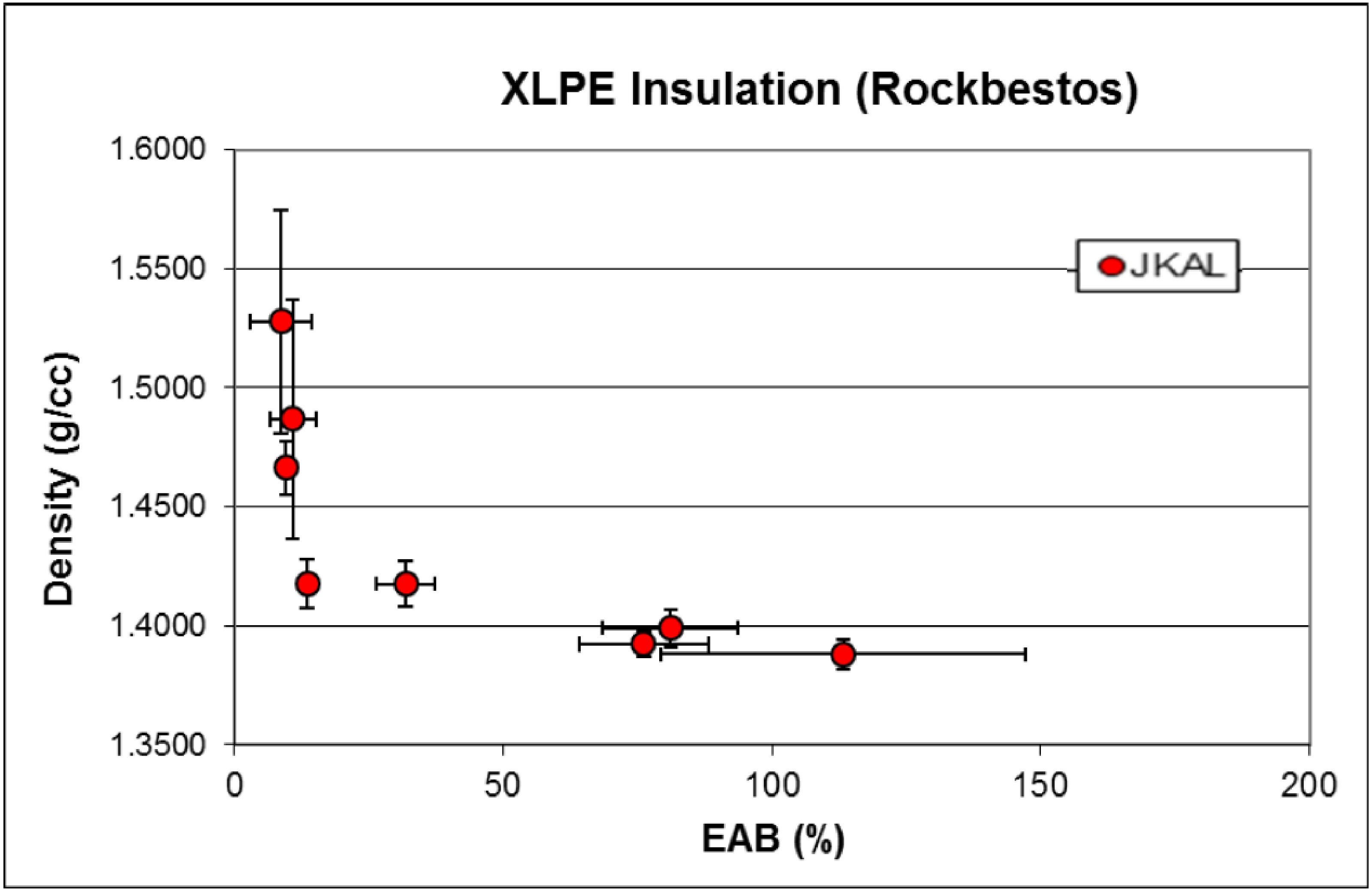
Example - useful



Example – potentially useful



Example – not useful



Summary of practical usefulness of CM methods for materials tested

	CM method	1 EAB	2 IM	3 Recovery	4 OIT	5 OITP	6 TGA	7 Density	8 FTIR	9 Ultrasonic	10 Tan δ	11 Dielec. Spec.	12 IR	13 FDR	14 TDR
1	PEEK (Habia)												*	*	*
2	XLPO (Habia)														
3	EPR (Eupen)														
4	EVA (Eupen)														
5	SiR – insul. (Hew)														
6	SiR – jacket (Hew)														
7	XLPE (Rockbestos)														
8	CSPE (Rockbestos)														
9	EPR – insul. (Changzhou)														
10	EPR – jacket (Changzhou)														
11	XLPO – insul. (Shanghai)														
12	XLPO – jacket (Shanghai)														

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 <u>throughout</u> 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?

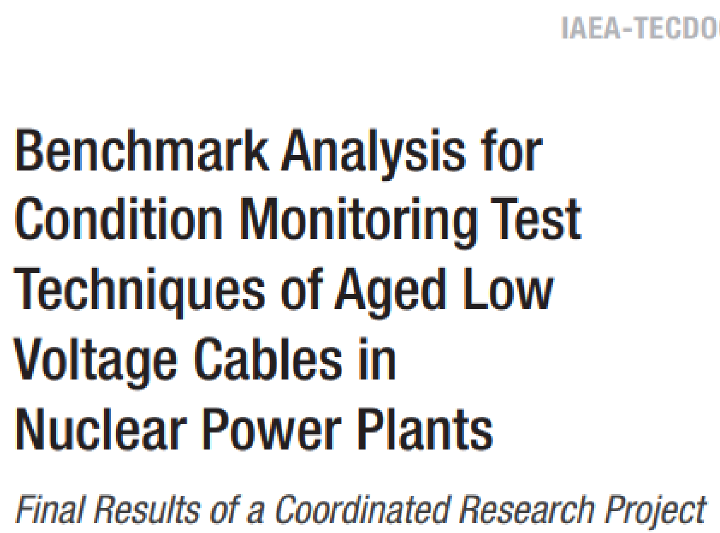
Summary

- 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

For more information

- Summarised results are in IAEA-TECDOC-1825, can be downloaded from

http://www-pub.iaea.org/books/IAEABooks/11164/Benchmark-Analysis-for-Condition-Monitoring-Test-Techniques-of-Aged-Low-Voltage-Cables-in-Nuclear-Power-Plants



IAEA-TECDOC-1825

Benchmark Analysis for Condition Monitoring Test Techniques of Aged Low Voltage Cables in Nuclear Power Plants

Final Results of a Coordinated Research Project