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

Final Results of a Coordinated Research Project

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BENCHMARK ANALYSIS FOR CONDITION MONITORING TEST TECHNIQUES OF AGED LOW VOLTAGE CABLES IN NUCLEAR POWER PLANTS

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FINAL RESULTS OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

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FOREWORD

In instrumentation and control systems, cable ageing and the need for condition monitoring is one of the most important aspects of plant life extension. Cables, especially their insulation and jacket material, are vulnerable to ageing degradation during normal operation, and unsafe operation can result from cable fires, moisture intrusion, a loss of functionality and noise interference in measuring process parameters.

The goal of this coordinated research project (CRP) on benchmark analysis for condition monitoring techniques of aged low voltage cables in nuclear power plants is to provide guidelines on how to monitor the performance of insulation and jacket materials of cables and to establish a programme for monitoring cable degradation. The group of experts for this CRP included 11 chief scientific investigators and 21 observers, representing 17 Member States.

The CRP established a benchmarking programme in which cable samples were donated by manufacturers, aged under thermal and radiation conditions, and tested before and after ageing by various organizations and according to different methods. The results of these tests were then compared to identify the proper condition monitoring techniques and to establish recommendations for improvements to these methods. In particular, 12 types of cable insulation or jacket material were tested, each using 14 different condition monitoring techniques.

Condition monitoring techniques yield usable and traceable results. Techniques such as elongation at break, indenter modulus, oxidation induction time and oxidation induction temperature were found to work reasonably well for degradation trending of all materials. However, other condition monitoring techniques, such as insulation resistance, were only partially successful on some cables and other methods like ultrasonic or Tan δ were either unsuccessful or failed to provide reliable information to qualify the method for degradation trending or ageing assessment of cables.

The electrical in situ tests did not show great promise for cable degradation trending or ageing assessment, although these methods are known to be very effective for finding and locating faults in cable insulation material. In particular, electrical methods such as insulation resistance and reflectometry techniques are known to be rather effective for locating insulation damage, hot spots or other faults in essentially all cable types. The advantage of electrical methods is that they can be used for in situ testing of installed cables while a nuclear power plant is operating.

This publication is an update of IAEA-TECDOC-1188 and of the information in IAEA Nuclear Energy Series No. NP-T-3.6, and it describes the fundamentals of cable performance and condition monitoring techniques. It identifies the condition monitoring techniques that show potential for further development and eventual implementation into a cable ageing management programme.

The IAEA wishes to thank the chief scientific investigators for their research and their contribution to the drafting and review of this publication. The IAEA officer responsible for this publication was K.S. Kang of the Division of Nuclear Power.

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1. INTRODUCTION

1.1.BACKGROUND

Condition monitoring (CM) of cable insulation material is an important aspect of nuclear power plant life management for long term operation. Cable insulation and jacket materials are vulnerable to ageing degradation during normal operation and means should therefore be established to ensure that cable ageing does not lead to unsafe operation. Furthermore, cable fires, moisture intrusion, loss of functionality, and sensitivity to noise/interference are examples of cable issues giving rise to current and future concerns about long term performance of cables in nuclear power plants. In fact, almost all organizations involved with the current and next generation of nuclear power plants have recognized the importance of cable qualification, CM and ageing management.

As a result, substantial research has been conducted by cable manufacturers, reactor vendors, laboratories, and standards organizations to understand the effects of ageing on cables and to establish effective and reliable means for cable qualification and CM. In particular, the Electric Power Research Institute (EPRI), the US Nuclear Regulatory Commission (NRC), National Institute of Standards and Technology (NIST), Sandia National Laboratory and Analysis and Measurement Services Corporation (AMS) in the USA, Halden Reactor Project (HRP) in Norway, the International Electrotechnical Commission (IEC), the International Atomic Energy Agency (IAEA), Atomic Energy of Canada Limited (AECL), Nuclear Research Institute of Czech Republic (UJV), Electricite de France (EdF), Institute for Electric Power Research of Hungary (VEIKI), and VUJE-Trnava of Slovakia, have spent substantial efforts to address cable qualification and ageing as well as cable CM. The IAEA initiated the development of TECDOC-1188 in the mid-1990s to address cable ageing and cable CM [1]. This publication was updated and published by the IAEA in 2012. The Nuclear Energy Series No. NP-T-3.6 contains the state of the art in cable qualification, CM and ageing management [2]. A number of international programmes are introduced in Appendix I.

The Institute of Electrical and Electronics Engineers (IEEE) and the IEC have developed standards which provide guidance on different methodologies for cable qualification and diagnostics. For example, IEEE has provided standards for qualification of equipment and cables such as IEEE 323 [3] and IEEE 383 [4] used for Class 1E safety functions. The IEC also has a general qualification standard IEC 60780 which is in the process of being harmonized with IEEE 323 in a dual log standard IEC/IEEE 323.

Any instrumentation and control (I&C) cable installed in a nuclear power plant for the purpose of supporting a safety function must be qualified to perform safely during normal service conditions and after a design basis accident (DBA) with consideration of in-service ageing.

In 2009, IEC published a standard (IEC 62465) [5] on management of ageing of electrical cabling systems. A method of cable testing is concerned primarily with applications of in situ methods to verify the integrity of cable conductors and connector material. Furthermore, IEC and IEEE have recently published a series of joint standards (IEC/IEEE 62582 dual logo) [6] which address specific test methods for cable CM. More specifically, the IEC 62465 standard is concerned with cable conductors and connectors while the IEC/IEEE 62582 series of standards address cable insulation and jacket material ageing and CM. A review of existing codes and standards from organizations including the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), the International Electrotechnical Commission (IEC), the Institute for Electrical and Electronics Engineers (IEEE), the International Organization for Standardization (ISO), and the Nuclear

Regulatory Commission (NRC) that are applicable to CM methods for cable testing is included in Appendix II.

The operating licenses at more than 250 nuclear power plants have been renewed beyond the original operational licensed timeframe of 40 years to 50–60 years using periodic safety review or licencing renewal application. In addition, the US. nuclear industry has recently announced that a subsequent licencing renewal application from 60 to 80 years is under consideration with the first US nuclear power plant planning to apply before 2020. With this development, cable ageing management will become more important to demonstrate adequate cable performance in normal operation and post-accident services.

1.2.SCOPE AND OBJECTIVES

This CRP identified CM methods versus cable insulation and jacket types for which these techniques can work for degradation monitoring and ageing assessment. Overall, 14 methods were examined for 12 different polymers of the types used for cable insulation or jacket material in nuclear power plants. These methods included in situ electrical tests such as insulation resistance (IR) measurements and reflectometry methods. The CM methods used on this CRP followed the IEC/IEEE 62582-3 standard, which contains methods for CM of organic and polymeric materials in I&C systems using tensile elongation techniques in the detail necessary to produce accurate and reproducible measurements. The primary target audiences are:

- Technical experts at nuclear utilities;
- Decision makers at regulatory authorities and utilities;
- Research and development organizations;
- Manufacturers and vendors.

1.3.CRP - ORGANIZATIONS PARTICIPATING IN BENCHMARKING

The 17 organizations listed in Table 1 representing laboratories, research facilities and universities participated in the CRP by performing a number of electrical, mechanical and chemical tests on several cable types during the benchmarking programme.

TABLE 1. ORGANIZATIONS PARTICIPATING IN BENCHMARKING

Organization	Country
CNEA	Argentina
Laborelec	Belgium
AECL	Canada
SNERDI with SECRI and SNPSC	China
UJV	Czech Republic
EDF	France
Budapest University	Hungary
VEIKI	Hungary
University of Bologna	Italy
NEL & INSS	Japan
Waseda University	Japan
Yonsei University	Korea, Republic of
KHNP	Korea, Republic of
VUJE	Slovakia
JKAL	UK
US NRC (NIST)	USA
AMS	USA

1.4.BENCHMARKING CABLES

The benchmarking exercise included representative samples of both material types that are in use in operating nuclear power plants and materials that may be used in a new nuclear power plant. The cable types and cable suppliers used for this CRP are shown in Table 2.

TABLE 2. BENCHMARKING CABLE TYPES AND MANUFACTURERS

Insulation/jacket	Manufacturer
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

CSPE - Chlorosulfonated polyethylene, EPR - Ethylene Propylene Rubber, EVA - Ethylene Vinyl Acetate, PEEK - Polyether Ether Ketone, SiR – Silicon Rubber, XLPE - Cross Linked Polyethylene, XLPO - Cross-Linked Polyolefin

2. FUNDAMENTALS OF CABLE SYSTEMS

Cable systems in nuclear power plants are degrading as they age and therefore require testing to ensure safe and efficient plant operation. Degraded cables suffer from embrittlement of cable insulation, which can cause a number of problems. During a loss of coolant accident (LOCA) for example, high pressure steam can easily penetrate small cracks in degraded cable insulation. This could lead to the failures of systems designed to keep the plant safe during such an event.

Additional cable system components such as connectors can also cause problems in ageing nuclear power plants. Ageing connectors can cause erratic signals, noise, measurement errors, spikes or other anomalies that can interfere with safe and efficient plant operation. This section aims to identify the fundamentals of cable systems and components.

2.1. CABLE TYPES

Cables in nuclear power plants can typically be grouped into the following functional types:

- Instrumentation and control cables (coaxial, triaxial, twisted, shielded);
- Low (less than 1 kV) and medium (less than 35 kV) voltage power cables;
- Specialty cables (such as articulating cables or those subjected to high levels of radiation);
- General service cables (ground cables, telephone cables, etc.).

The work performed during this CRP focuses on low voltage I&C cables, however the same principles and techniques may be applied to all cable types since the materials and degradation mechanisms are generally the same. Instrumentation cables normally carry low voltage and low current analogue or digital signals used by instruments. Resistance temperature detectors (RTDs), pressure transmitters and some thermocouple leads are normally composed of twisted pairs and are shielded. Radiation detection and neutron monitoring circuits often use coaxial or triaxial shielded configurations. Control cables for auxiliary components such as switches, valve operators, relays and contactors are typically low voltage type cables. These are often multi-conductor cables, and include shielding for application near high voltage systems. Low voltage power cables supply power to low voltage auxiliary devices such as motors, motor control centres, heaters and small transformers. These cables may be single conductor or multi-conductor and are usually unshielded. A cable typically consists of four to eight components. The main components of I&C or low voltage power cable are listed below and a typical cable construction is shown in FIG. 1.

2.1.1. Conductors

Copper, aluminium, nickel, gold and silver are good conductors of electricity and are commonly used in cables, with copper being the most common. Cable conductors are typically made of stranded wires for flexibility, or solid wires for strength.

2.1.2. Insulation

Cable conductors are typically insulated with a material that is highly resistive to the flow of electrical currents. Furthermore, cable insulation material should be resistant to water, chemicals, abrasion and heat. Insulation should also be a flame retardant in case of fire. There is a wide range of polymeric materials used for cable insulation. These include ethylene

propylene rubber (EPR) compounds, polyethylene compounds and elastomers. Specialty cables may use other insulation types, e.g. silicone rubber (SiR) or polyether ether ketone (PEEK).

2.1.3. Shielding

Shielding is used in cables to provide increased immunity to noise and electromagnetic/radiofrequency interferences (EMI/RFI). Cables can have foil shielding and/or braided shielding. Foil shields are typically a thin layer of aluminium bonded to a polyester film. A drain wire is sometimes used in conjunction with the foil shield to connect the shield to ground. Braided shields are usually made of copper or aluminium.

2.1.4. Jacket

A jacket is used to cover cables and to provide physical protection and mechanical strength. The jacket material for a cable is usually selected based on the environment in which the cable is to be used. Typically, cable jackets are made of similar materials to those used as cable insulation/dielectric but may also include chlorosulphonated polyethylene (CSPE) or ethylene vinyl acetate (EVA) based polymers.

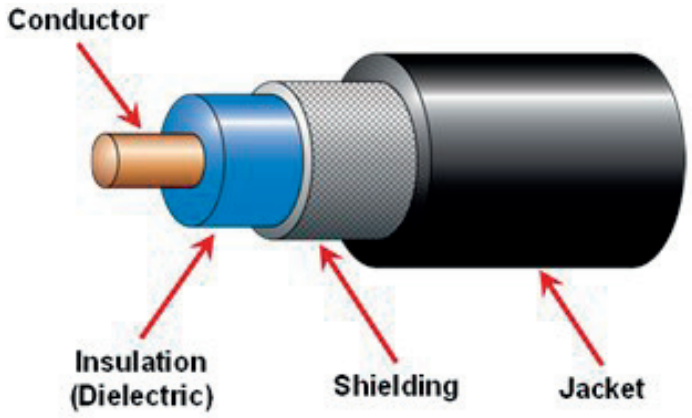


FIG. 1. Schematic of a typical cable (Reproduced with permission courtesy of AMS corporation).

In some cables, particularly control and low voltage power cables, there may be a jacketing layer over the insulation on the individual conductors, providing fire resistance. This is usually referred to as a conductor jacket or inner jacket. The term jacket normally refers to the outer layer of the cable. Other components that may be present in a cable include:

— Filler or bedding materials, which occupy the gaps between insulated conductors in multi-conductor or multicore cables and improve the mechanical stability of the cable;
— Tape wraps, which may provide additional electrical, mechanical, fire protection or identification of conductor grouping;
— Armouring layers, which are sometimes used for mechanical protection below the outer jacket.

2.2.CABLE STRESSORS

Exposure to radiation, heat, humidity, and vibration are the most common factors that contribute to cable ageing and degradation in nuclear power plants. Other environmental

factors including contact with chemicals (such as lubricants) and ohmic heating (caused by passage of electric current) may also affect the degradation process. Mechanical stressors such as bending and squeezing can hasten the degradation process. While cable degradation is typically associated with embrittlement of the jacket or insulation material, conductors can also be affected.

3. CABLE MONITORING TECHNIQUES

In recent years, cable ageing management has become more important for long term operation. Cables for nuclear power plant applications that affect safety are normally qualified using existing standards. The initial qualification activities are generally aimed at determining the accident survivability and reliability of the cables throughout the life of nuclear power plants; especially in post-accident conditions.

The nuclear power industry has recognized that there are limitations in existing cable qualification testing in the areas of pre-ageing and the use of models such as the Arrhenius law for assessing cable qualified life. As such, periodic cable testing in nuclear power plants is vital for troubleshooting and identifying problems such as signal anomalies. In addition, initial testing is needed to establish baseline measurements as a reference for predictive maintenance, and evaluating cable ageing.

A wide range of cable testing techniques has been developed for cable ageing management. Available cable testing techniques are able to test all parts of the cable (insulation, jacket, and conductor) as well as connections, penetrations, splices and terminations. In the broadest terms, there are four types of testing techniques (visual/tactile, electrical, mechanical, chemical) for cable ageing management and troubleshooting as shown in FIG. *2*.

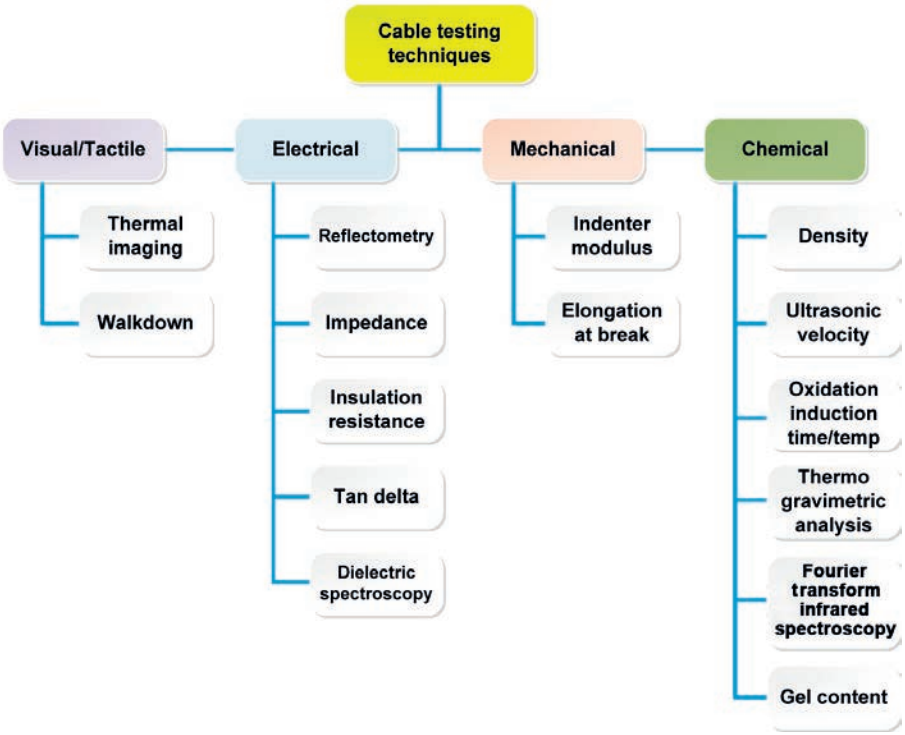


FIG. 2. Four types of testing techniques (Reproduced with permission courtesy of AMS corporation).

To guard against the adverse consequences of cable ageing and degradation, a cable ageing management programme should be included as part of the normal maintenance schedule in nuclear power plants. This is especially true for cables that serve safety related roles. In 2010, EPRI published guidelines to the nuclear industry on how to develop cable ageing management programmes for both low and medium voltage cables. These technical reports EPRI TR-1020804 (low voltage) [7] and EPRI TR-1020805 (medium voltage) [8] provide a method of determining the scope of a cable ageing programme, testing techniques and assessment criteria for ageing management. A number of testing techniques have been developed to measure the health of cables. Several of these tests are described in the following cable ageing management section.

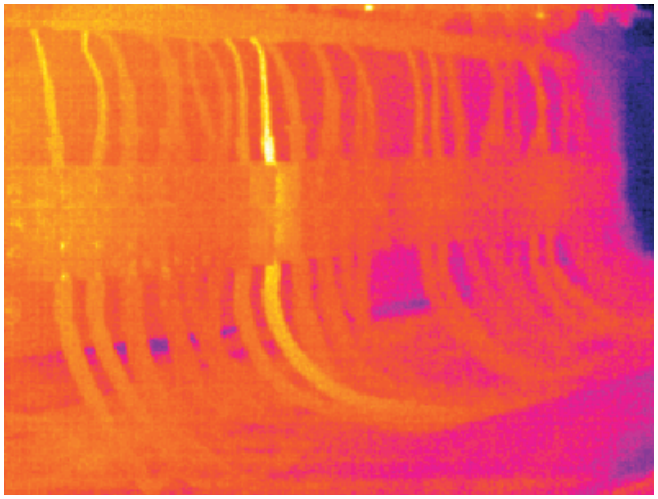
3.1.VISUAL/TACTILE TECHNIQUES

Visual/tactile testing methods are non-intrusive testing techniques for cable maintenance. The purpose of this physical inspection method is to identify cracks; discolouration; visible contamination of the cable surface; the presence of chemicals or oils; and other local damage such as swelling or deformation; to provide a qualitative assessment of the condition of a cable's jacket material. In addition, the environmental ambient conditions around the cable such as temperature, humidity, radiation or vibration should be monitored. Baseline information and experience is often crucial in detecting problems by visual and physical inspections.

Another visual testing method is infrared thermography, which identifies thermal hot spots in or around cables, connectors and other components of a wiring system. Cables are typically degraded from several sources, including proximity to a hot pipe, exposure to high radiation levels, or internal ohmic heating. Because both visual inspection and infrared thermography as shown in FIG. 3 can only be applied to cables that are accessible, they are

impractical in examining and inspecting cables that are in remote or hard-to-reach places including cable runs inside of conduit.

a) Tactile inspection of jacket cracking



b) *Thermograph of a control rod system*

FIG. 3. Examples of visual/tactile techniques of a) jacket cracking and b) thermograph of a control rod system (Reproduced with permission courtesy of AMS corporation).

3.2.ELECTRICAL TECHNIQUES

The following electrical test methods can provide a portion of the overall picture of a cable's health, as well as information for expediting any repairs that may be needed. If baseline data is available, then by comparison and interpretation, significant changes from the baseline indicating the effects of ageing may be identified. If such baseline data is not available, the characteristics of cables from similar installations may serve as a de-facto baseline. Each of the techniques is discussed in the following section.

3.2.1. Time–domain reflectometry

The time-domain reflectometry (TDR) test involves sending a voltage step with a fast rise time into a transmission line. Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity in the transmission line. The resulting

wave is captured in the time-domain and is a ratio of the incident signal and the reflected signal expressed in terms of reflection coefficient (Rho) [9].

The TDR technique has served the nuclear industry in testing instrumentation circuits, motors, heater coils and many other components to locate problems in the circuit in situ. FIG. 4 shows TDR results of a source range nuclear instrumentation (NI) detector used at a US nuclear power plant. In this example, a TDR test has identified a high impedance connection at the outboard penetration.

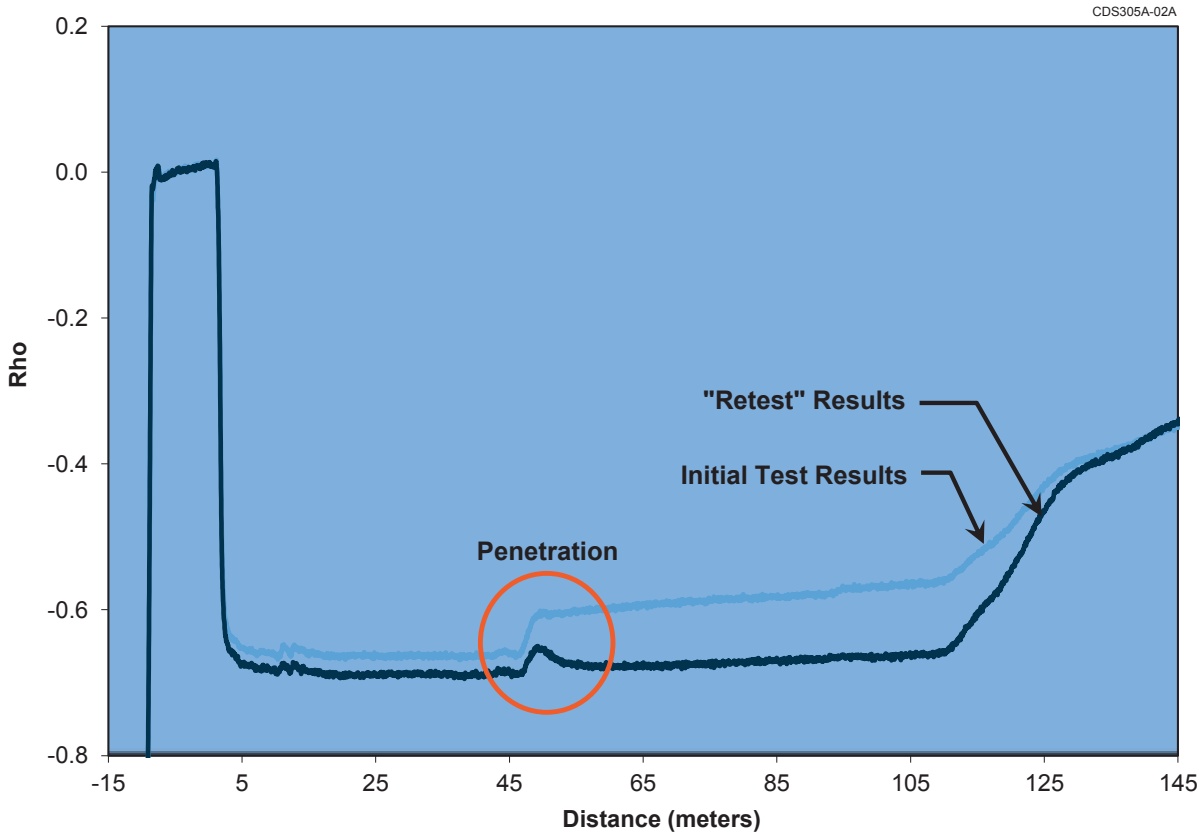


FIG. 4. TDR trace of NI circuit indicating a high impedance connection (initial test results) compared to TDR trace after the fault was repaired ('retest' results) (Reproduced with permission courtesy of AMS corporation).

3.2.2. Frequency domain reflectometry

Frequency domain reflectometry (FDR) is an electrical reflectometry technique similar to TDR, which identifies and locates faults in a cable system in situ. The FDR technique sends a swept frequency signal through the cable circuit and analyses the circuit impedance changes that are reflected. The reflected signals are measured in the frequency domain and then converted into the time-domain using an inverse fast Fourier transform to locate the impedance mismatches. The use of discrete frequencies makes it possible to identify and locate gross faults in cable insulation material as well as faults in connectors or conductors.

FIG. 5 shows the results of an FDR test of a typical nuclear power plant cable after accelerated thermal ageing was induced by heating the cable in a laboratory oven. The amplitude of the peaks in the FDR plot increase with thermal cable ageing where the cable is exposed to elevated temperatures, or hot spots. One can use the amplitude of the peaks or the

area under the peaks as an FDR index to characterize the severity of degradation or as a basis to determine the remaining useful life (RUL) of the cable [10–11].

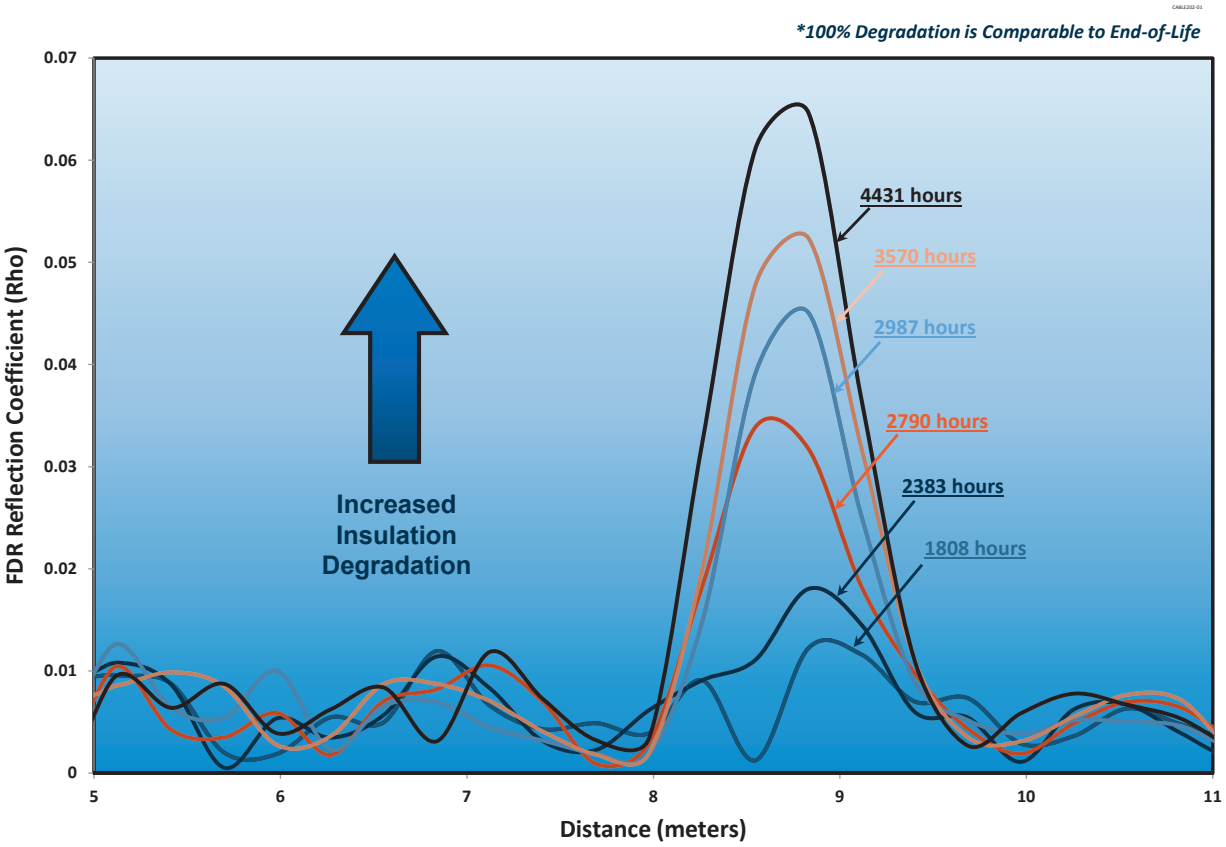


FIG. 5. Results of FDR testing of an EPR insulated cable after thermal ageing (Reproduced with permission courtesy of AMS corporation).

3.2.3. Alternating current impedance measurements

The alternating current (AC) impedance of an electrical circuit is measured to determine whether an electrical circuit is changing due to the degradation of the insulating materials, which influences capacitance or the degradation of the electrical wiring, which influences inductance. AC impedance is a combination of the inductance, capacitance and resistance (LCR) of the circuit, and must be defined at a given frequency. Impedance measurements are made to include the cable and the end device. The measurement is performed with a basic LCR meter that injects a current signal at various frequencies between pairs of conductors in the electrical circuit and measures the response of the circuit to the current. The response is defined as the impedance, and is composed of 2 parts: (1) the magnitude, (2) the phase angle between the injected current and resulting voltage produced by the current.

The magnitude of the impedance and the phase angle are measured at 100 Hz, 1 kHz, and 10 kHz. From this information, the resistance, inductance, and capacitance of the circuit can be determined, and with the LCR meter, these values can be displayed automatically.

AC impedance measurements for a particular electrical circuit are evaluated to determine if they are as expected for the type of circuit being tested. Imbalances, mismatches or unexpectedly high or low impedances between the cable leads would indicate problems due to cable degradation and ageing, faulty connections and splices or physical damage. Abnormal capacitance measurements are usually indicative of a breakdown in the insulation

dielectric properties of the cable. Abnormal inductive measurements may be due to changes in the inductive properties of the electrical end device, cable conductors or connections, or they may be due to changes in the capacitive properties of the circuit (direct current resistance, can then be used to evaluate whether the problem is due to the insulation properties or the inductive, wiring properties).

3.2.4. Insulation resistance measurement

The insulation resistance (IR) measurement is made to provide information about the insulation quality of cables, connectors and electrical end devices. The IR measurement is made by applying a voltage between a power lead and ground, and measuring the resulting leakage current. From the applied voltage and leakage current, the resistance can be found. The voltage is selected at a level that eliminates measurement noise while preventing stress to the insulation. In addition, the test current is limited to prevent inadvertent damage to the electrical system for the case where the IR is abnormally low. As the high voltage is applied, the leakage current through the insulating material is measured with respect to time to establish the cable insulation's quality and determine if there are any contaminants (moisture, grease, dirt, etc.) in the cable or connections. The data is typically analysed as a ratio of the IR value at two different times. These ratios are referred to as dielectric absorption ratio (DAR), polarization ratio (PR), and polarization index (PI), and are calculated using the following formulas:

$$DAR = \frac{IR\ @\ 60\ seconds}{IR\ @\ 30\ seconds} \quad (1)$$

$$PR = \frac{IR\ @\ 3\ minutes}{IR\ @\ 1\ minutes} \quad (2)$$

$$PI = \frac{IR\ @\ 10\ minutes}{IR\ @\ 1\ minutes} \quad (3)$$

Temperature and relative humidity may also cause minor changes in the IR value. These effects may need to be kept under control or compensated with a correction factor, but these changes may be minor compared to the basic quality of the insulating material.

As shown in data from a control rod drive mechanism (CRDM) cable installed in a nuclear power plant (NPP), during the first initial region the current flow is mainly influenced by capacitive charging. After the initial charging, leakage current through the insulation is the primary contributor shown in FIG. 6.

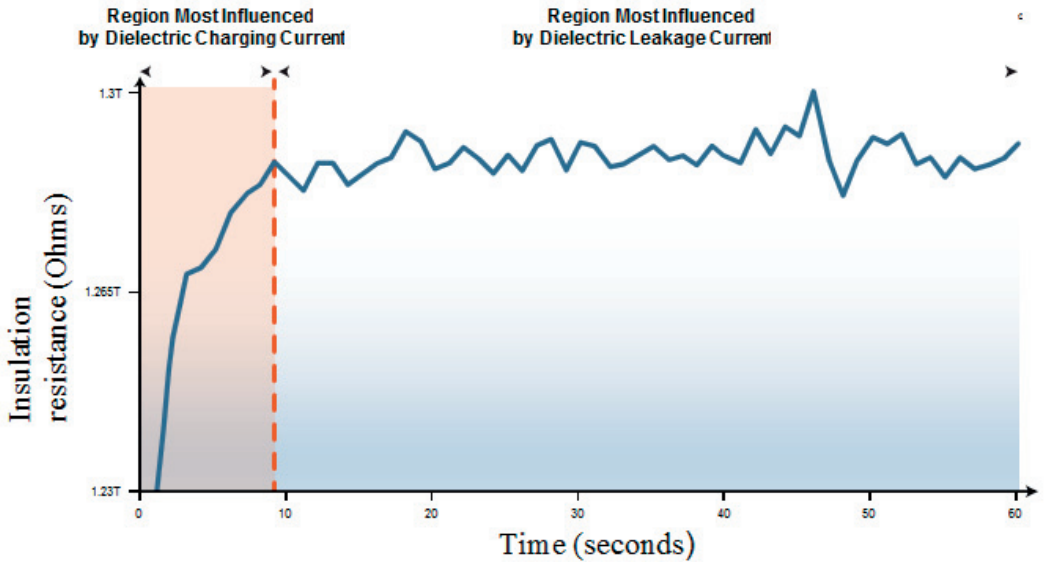


FIG. 6. Insulation resistance (IR) curve for a CRDM cable in NPP (Reproduced with permission courtesy of AMS corporation).

Note: Insulation resistance measurements are commonly used as a measure of the condition of cables during a simulated DBA, e.g. LOCA simulation. In this case, it is important to detect the lowest IR value during the DBA. For IR measurements during simulated DBA, it is therefore important to use methods that can follow the short term IR variation during time varying thermal/pressure conditions.

3.2.5. Tan delta

Tan delta (TD) or dissipation factor tests the integrity of the cable insulation by measuring the tangent angle between the resistive current and the capacitive current with an AC voltage applied. Impurities increase the resistive current in the insulation which causes the current and voltage angle to shift from the nominal 90-degree angle. Test methods include using a fixed frequency such as 60 Hz and stepping the AC voltage up to 1.2 times greater than the rated cable voltage or applying a low voltage with a varied frequency range up to 20 kHz. TD values can vary significantly as a function of frequency.

3.2.6. Dielectric Spectroscopy

Dielectric Spectroscopy is an electrical measurement of the dielectric properties of a cable material as a function of frequency. The test is based on the interaction of an electrical field with the electric dipole moment and charges of the cable material, also known as permittivity. This permittivity test is performed by first applying an input voltage to the first conductor of a cable while measuring the signal from the second conductor. A second measurement is made from the second conductor while connected to an electromagnetic shield. For cables with more than two conductors, the second conductor and the remaining conductors are shorted together for testing.

For the evaluation of the real part of permittivity, the software of the dielectric analyser requires a reference capacitance, C_0. Its value is equal to the capacitance of a parallel plate capacitor:

$$C_0 = \varepsilon_0 \frac{A}{s},$$

where A and s are the sample's area and thickness, respectively. For cable testing, it is necessary to calculate an equivalent reference capacitance.

3.3.MECHANICAL TECHNIQUES

Tensile testing and indenter cable testing techniques are described in this section. These techniques are useful in CM and trending the effective ageing of a cable's polymeric insulation and jacket material. These tests are commonly used on cables that are typically installed in a NPP; the indenter tests can be performed in situ while the plant is operational, whereas tensile testing requires removal of samples for testing.

3.3.1. Elongation at break

Currently, the nuclear industry relies on the tensile testing parameter elongation at break (EAB) to measure the degree of ageing degradation of a cable's jacket or insulation material. EAB is measured using a specimen of the cable's polymer material pulled in tension using a tensile test machine until the sample breaks. This test provides a quantifiable measure of the degradation of mechanical properties of the cable insulation/jacket materials and is often used as the benchmark against which other techniques are evaluated. One obvious limitation of the EAB test for monitoring the health of in-service cables is the requirement that sacrificial samples must be removed and taken to a laboratory for testing. Removal of a test sample from a cable usually follows cable replacement or splicing as part of a root-cause analysis. Alternatively, samples can be taken from a cable deposit specifically set up for testing.

3.3.2. Indenter modulus

The indenter polymer ageing monitor (IPAM) system is a portable, handheld, non-destructive test system that uses an instrumented anvil to indent the surface of a polymeric cable, and measures changes in hardness of the cable's jacket and insulation material. The indenter modulus is calculated from the force vs. deformation relationship of a probe that is pressed into a polymer material at a constant velocity (FIG. 7). Specific recommended parameters for indenter modulus measurements are published in IEC/IEEE 62582-2 [12]. The indenter modulus measurement is often correlated with EAB data to provide an assessment of a cable's present condition as well as its RUL as shown by the laboratory data example in FIG. 8.

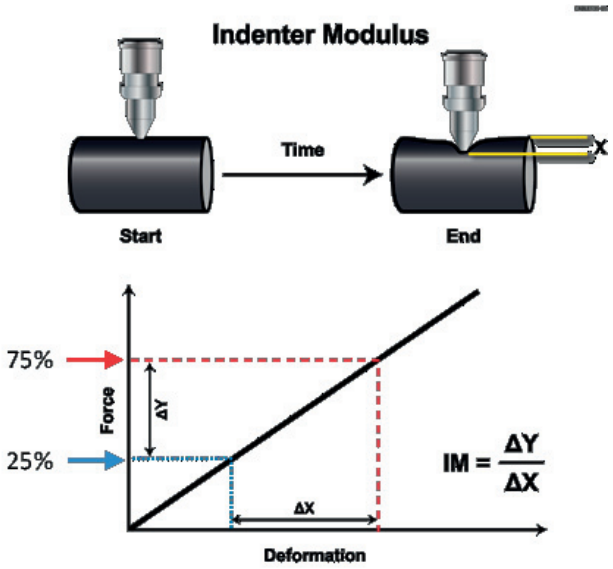


FIG. 7. Conceptual diagram showing the principle of the indenter modulus measurement (Reproduced with permission courtesy of AMS corporation).

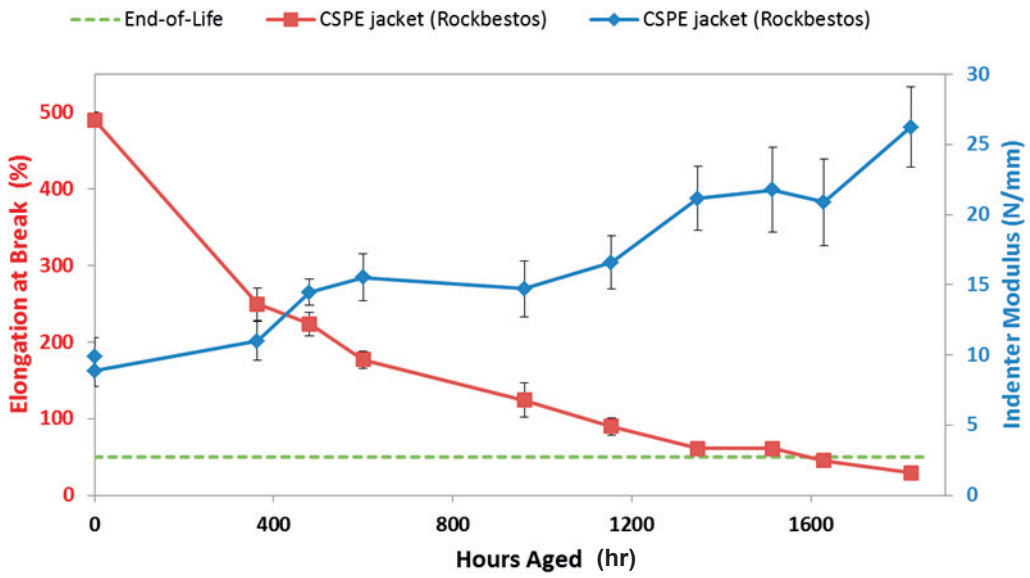


FIG. 8. Indenter modulus correlated with EAB using 50% EAB end of life designator (Reproduced with permission courtesy of AMS corporation).

3.3.3. Recovery time

The recovery time of a cable polymer can also be measured using an indenter system. The indenter probe is first pressed into the insulation or jacket material to a fixed depth and time. The probe is then retracted a pre-determined distance and the polymer material is allowed to expand back to its original uncompressed state. The recovery time is the time it takes to recover the deformation from the start of probe retraction to the reappearance of a force as the specimen comes into contact with the probe. The test procedure is shown schematically in FIG. 9. Both indenter modulus and recovery time can be obtained from the same test.

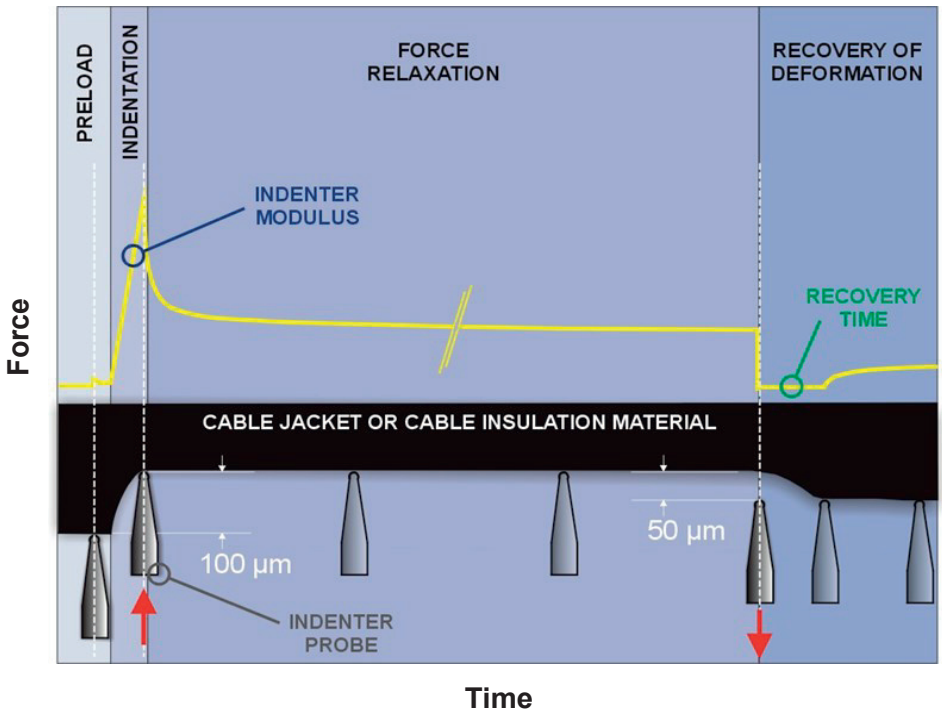


FIG. 9. Measurement procedure for recovery time (Reproduced with permission courtesy of AECL).

Recovery time measurements can be more sensitive to ageing degradation than indenter modulus measurements for some materials and can also trend with ageing for some materials where indenter modulus values do not change significantly with ageing, for example some semi-crystalline polymers such as XLPE/O. An example showing the increased sensitivity of recovery time compared with indenter modulus is shown in FIG. 10 for a CSPE jacket material.

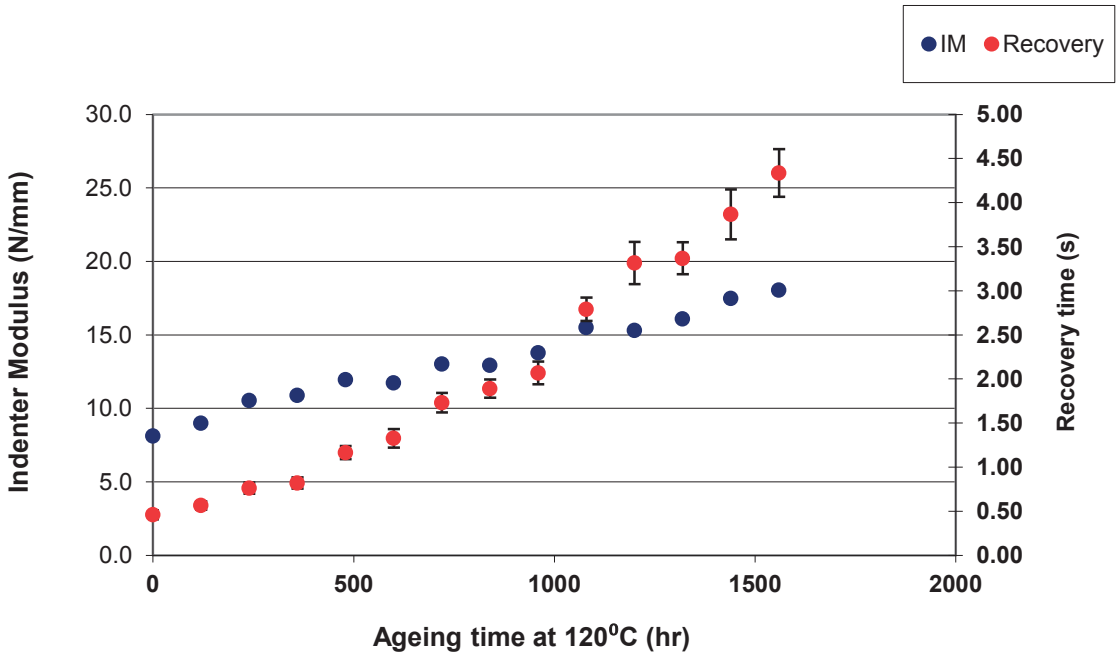


FIG. 10. Comparison of recovery time and indenter modulus measurements on CSPE (Rockbestos) jacket.

3.4.CHEMICAL TECHNIQUES

Differential scanning calorimetry (DSC), density measurements, Fourier transform infrared (FTIR) spectroscopy, thermogravimetric analysis (TGA), gel content testing and ultrasonic velocity techniques are described in this section. These techniques provide valuable information about the thermal and chemical properties of cable polymers, which can be used in CM and trending the degradation and ageing characteristics of a cable's polymeric insulation and jacket materials. A combination of these tests is commonly performed in polymer testing laboratories and is quite useful when determining the RUL of a cable.

3.4.1. Differential scanning calorimetry

One of the most common causes of chemical ageing (e.g. polymer chain degradation) is oxidation, which makes oxidation stability an important criterion for polymeric materials. The oxidation stability of a material can be determined via oxidation induction time (OIT)/ oxidation induction temperature (OITP) measurements by means of a DSC.

DSC is a thermo-analytical technique used to study the thermal transitions a polymer undergoes when subjected to a specified temperature profile. The heating characteristics of the sample are measured and compared to a reference material, and both the sample and reference material are measured at the same time and temperature during testing. Throughout the experiment, both the sample and reference are maintained at near the same temperature.

OIT and OITP are laboratory techniques that measure the loss of antioxidants in a polymer as it degrades. OIT is a measurement of the time at which oxidation of a specimen material occurs when exposed to a constant temperature and OITP is a measurement of the temperature at which oxidation initiates. When conducting OITP measurements, the temperature is increased at a specified rate with abundant oxygen supplied to the sample. The

onset of oxidation is usually considered to occur when the specimen has been depleted of antioxidants. The OIT curve for polyethylene (PE) is shown in FIG. 11.

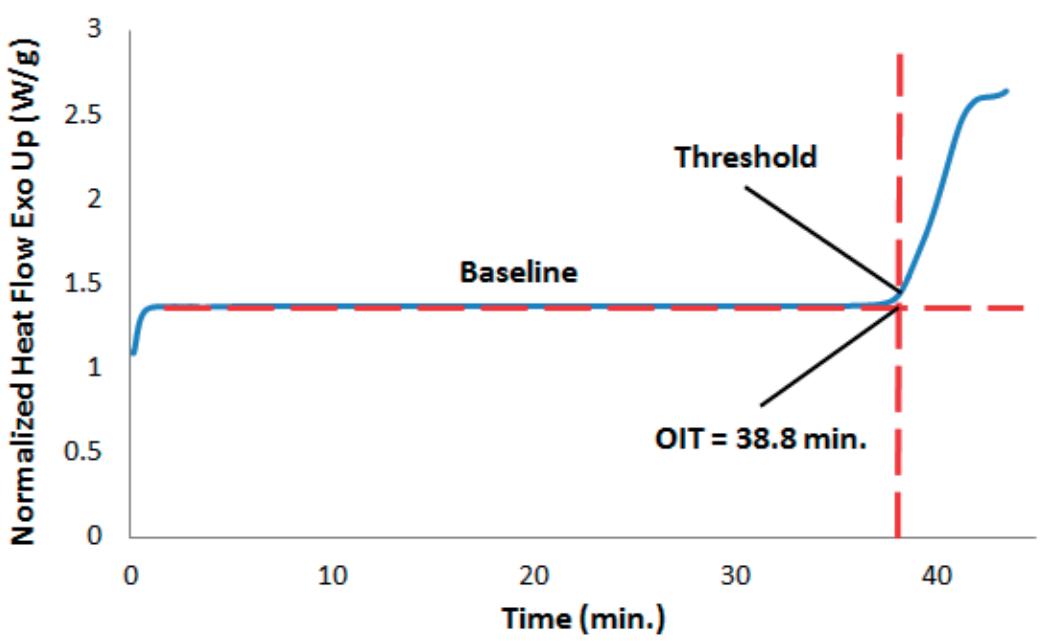


FIG. 11. OIT measurement of PE (215 °C) (Reproduced with permission courtesy of AMS corporation).

In addition to OIT and OITP, DSC is widely used to characterize a variety of polymer thermo-physical properties including:

- Melting and glass transition temperatures;
- Heat of melting;
- Percent crystallinity;
- Crystallization;
- Presence of recycles/regrinds;
- Plasticizers;
- Polymer blends (presence, composition and compatibility).

Many of these properties change as the polymer degrades and thus, may be used to understand and monitor the polymer's ageing characteristics. The DSC curve for polyether ether ketone (PEEK) is shown in FIG. 12, showing the glass transition temperature at 146°C, recrystallization at 177°C and melting of the crystallites at 338°C.

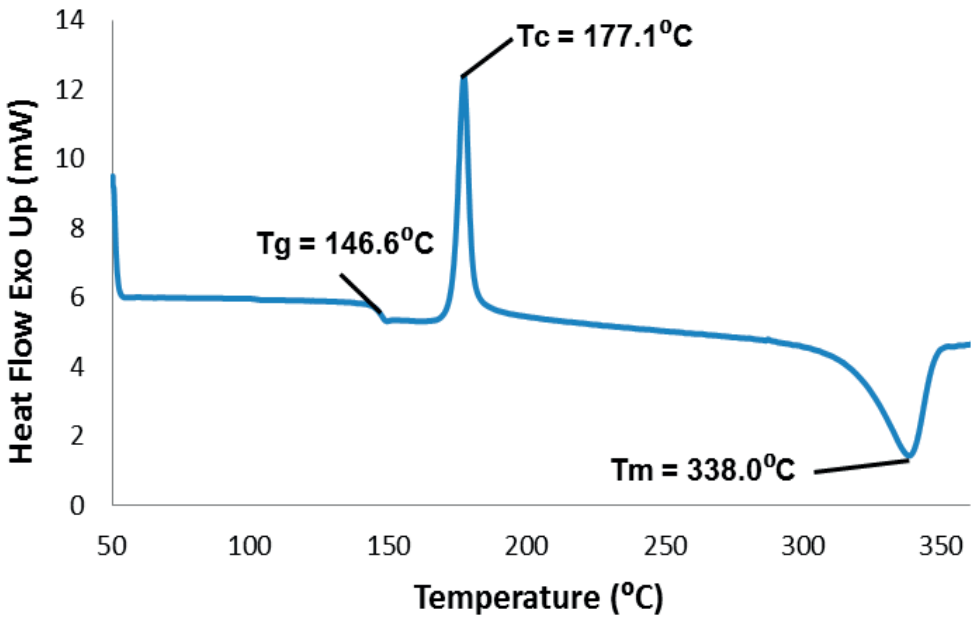


FIG. 12. DSC Curve showing transition temperatures of PEEK (Reproduced with permission courtesy of AMS corporation).

3.4.2. Density

Measuring the density of cable polymer material can be performed using multiple methods. One method is to measure the weight of a specimen in both air and a liquid, preferably distilled water, deionized water or alcohol. The density of the specimen can be calculated from these weight measurements. Another method of determining density is placing the specimen into a calibrated liquid column and deriving density from a known calibration curve once equilibrium has been reached. Density measurements are considered a useful CM technique because the values correlate with EAB for some of the polymers used in cables.

3.4.3. Fourier transform infrared spectroscopy

A technique used in materials analysis for over 70 years, FTIR spectroscopy is perhaps the most powerful tool for identifying types of chemical bonds (functional groups). This technique is based on infrared radiation passed through a sample, such as a cutting from cable insulation. In the test, a sample both absorbs and transmits parts of the infrared spectrum. The wavelength of light absorbed is characteristic of the chemical bond. An annotated FTIR spectrum for the Habia XLPO jacket is shown in FIG. 13.

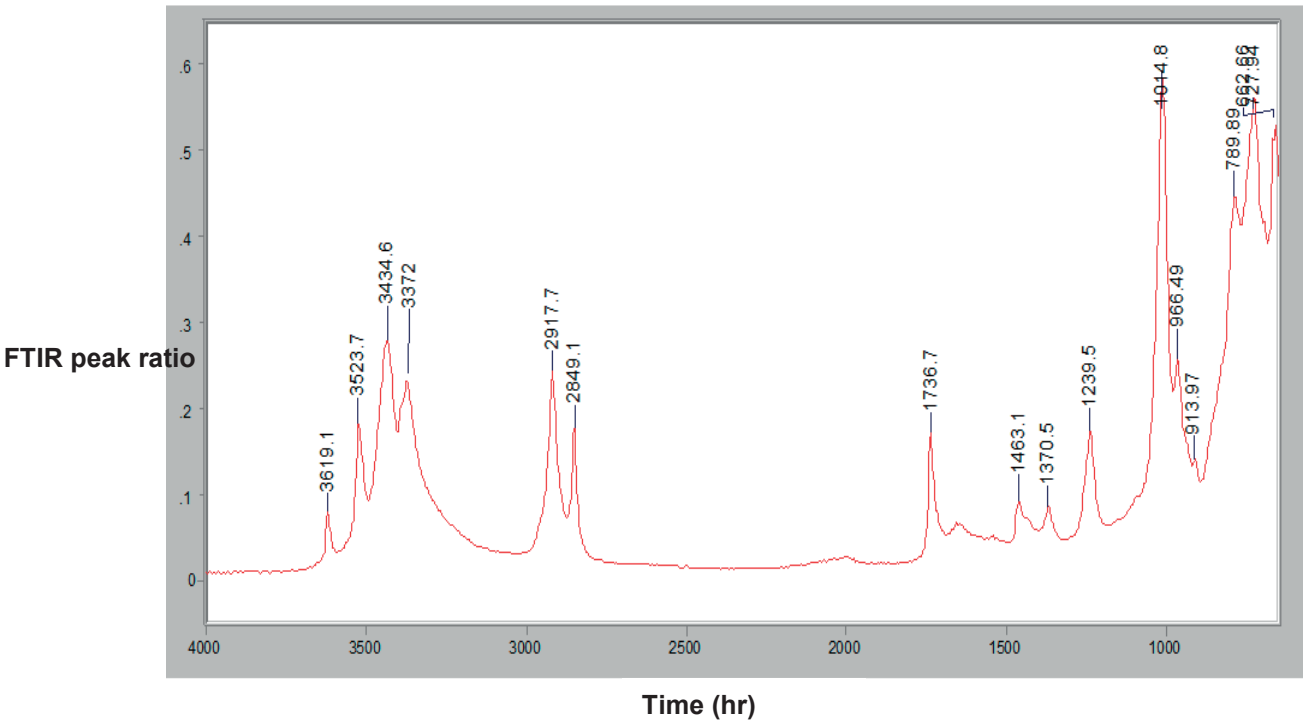


FIG. 13. Attenuated FTIR spectrum for the Habia XLPO jacket (Reproduced with permission courtesy of Korea Hydro Nuclear Power Company).

FTIR spectra of pure compounds are generally so unique that they are like a molecular 'fingerprint'. As a result, this spectral signature can be used to quantify physical changes to the insulation during the ageing process, such as molecular quality, consistency and the amount of components present in a sample. Many of the polymers used in cables are heavily filled and contain several additives, which makes interpretation of changes in FTIR spectra more difficult.

3.4.4. Thermogravimetric analysis

Thermogravimetric analysis (TGA) is one of a number of thermal analysis techniques used to characterize a wide variety of polymers. It provides complimentary and supplementary characterization information to the most commonly used thermal technique, DSC. TGA measures the amount and rate of change in the mass of a sample as a function of temperature or time in a controlled atmosphere. The measurements are used primarily to determine the thermal and/or oxidative stabilities of materials as well as their compositional properties. This test is particularly useful for some cable materials because the weight loss can be linked to cable insulation embrittlement from loss of volatile organic compounds and oxidation. The TGA curve for the Rockbestos XLPE insulation is shown in FIG. 14.

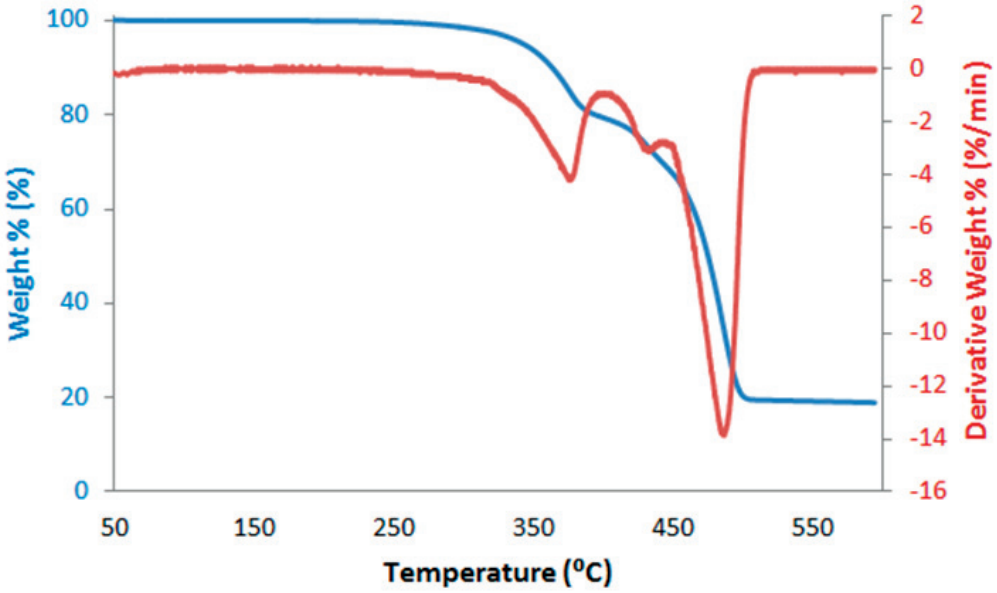


FIG. 14. TGA curve showing decomposition characteristics of the Rockbestos XLPE insulation (Reproduced with permission courtesy of AMS corporation).

As shown above, a thermogravimetric analyser can be used to map the degradation temperatures and rates for cable jacket and insulation samples. In addition to evaluating polymer degradation characteristics, TGA is particularly useful for the following types of measurements:

— Compositional analysis of multi-component materials or blends;
— Thermal stabilities;
— Oxidative stabilities;
— Estimation of product lifetimes;
— Effects of reactive atmospheres on materials;
— Filler content of materials;
— Moisture and volatiles content.

3.4.5. Gel content/solvent uptake factor

The degree of cross-linking of polymers is often characterized by gel content and solvent uptake factor. Both parameters are derived from calculation of the same experimental test. The test consists of refluxing a known weight of polymer sample (w_0) in an appropriated solvent until saturation is reached. Then the swollen sample is weighed (w_s) to determine the mass of the adsorbed solvent. Finally, the solvent is removed from the sample by holding it in a vacuum oven until a final and constant weight is achieved (w_f). The gel content is defined as the ratio between w_f and w_0 while solvent uptake factor is defined as the ratio between w_s and w_0.

This technique is very useful when cross-linking is the main ageing mechanism present in a polymeric material, normally when high radiation dose is present during cable working life. For its application as a CM technique, the gel content evolution during ageing should be related to another traceable degradation property, such as the EAB measurement that provides an acceptance criterion for end-of-life.

3.4.6. Ultrasonic velocity

The ultrasonic velocity test involves transmitting a series of pulses along the surface of a cable to measure the transit time of the signal versus the separation of two attached test probes. The time between the transmitter and receiver probes is a function of the elastic modulus and polymer density of the cable material. Changes in ultrasonic velocity may be an indicator for ageing degradation of the cable. The probes are coupled to the jacket using machine oil or grease. TABLE 3 compares all of the above cable monitoring techniques and provides features of each test for applicable materials.

TABLE 3. COMPARISON OF VARIOUS CABLE MONITORING TECHNIQUES

No	Technique	Monitoring Type	Description	Destructive / Intrusive	Features	Remarks / Applicable Materials
1	Walk downs	Visual and Tactile	Identifying cables that should be considered for more detailed testing by using appropriate manipulating and observation.	No/ No	Easier operation and low cost method applicable to all material with immediate information.	Need to be carried out by skilled technicians. /All materials.
2	Thermal Imaging/ Thermograph	Visual and Tactile	A measurement used during walk downs for identifying environmental hot spots and unanticipated operating conditions.	No/ No	The best supplements to plant walk downs to check out cable degradation due to a localized hotspot or unanticipated operating condition and to provide a 'snapshot' of the plant at intervals (e.g. every 10 years) through the plant life.	The technique has significant limitations for use as a diagnostic tool due to hot spots inside ducts and conduits not being visible. It also cannot locate hotspots that only occur during full power operation of the plant. / All materials.
3	Elongation at Break (EAB)	Mechanical	The benchmark property of the cable by tensile testing.	Yes/ Yes	Although this method is impractical to be used as a routine CM method, it generates the optimum data for cable condition assessment and is particularly useful where cable samples have been placed in a sample deposit, specifically for CM.	50% absolute EAB is normally defined the end of life condition based on a conservative estimate of aged cable to survive DBA condition. / All materials.
4	Indenter Modulus (IM)	Mechanical	A measurement of the force exerted by a probe pressed to the surface of the cable material. The IM is a parameter associated with the specific compressive stiffness of the tested material calculated by the depth of penetration of the probe against the force exerted on the probe.	No/ Mainly No	Only provides information on the condition at the locations tested. Could be used on operational cables.	A probe with known dimensions is driven into the surface of a sample at a carefully controlled speed. / PVC, CSPE, EPR, EPDM.

TABLE 3. COMPARISON OF VARIOUS CABLE MONITORING TECHNIQUES (cont.)

No	Technique	Monitoring Type	Description	Destructive/ Intrusive	Features	Remarks / Applicable Materials
5	Recovery Time	Mechanical	A measurement of the time to recover a set deformation resulting from prior indentation, which is made during the post-indentation phase, following a force relaxation phase, and upon retraction of the indenter probe.	No/ Mainly No	The recovery time measurement has a higher sensitivity and stronger correlation with elongation than that of the IM for some materials.	A parameter that has recently proven very useful to assess the degradation of cables. / All materials, except EPR.
6	Frequency domain reflectometry (FDR)	Electrical	A non-destructive cable testing technique based on transmission line theory by using a swept frequency signal to transmit through an electrical cable circuit and analyses the circuit impedance changes that are reflected. These reflected signals are measured in the frequency domain and then converted into the time-domain using an inverse Fourier transform.	No/ Disconnection Needed	The reflected signal can travel through miles of cable with less attenuation than the traditional TDR signal. This technique provides diagnostic information about the cable insulation material.	The behaviour of a transmission line, as a part of electric circuit, depends on its length in comparison with the wavelength of the electrical signal travelling into it. / All materials.
7	Time-domain reflectometry (TDR)	Electrical	A technique based on transmission line theory just as FDR while involving sending a DC pulsed signal through a cable circuit and measuring its reflection to identify the location of any impedance change in the cable and the end device (load).	No/ Disconnection Needed	The technique provides diagnostic information about the cable conductor and any connector or connection in the circuit, and to a lesser extent, the cable insulation material.	It can also provide diagnostics about a device at the end of the cable, such as an RTD or thermocouple. The test depends largely on comparisons with a baseline TDR. / All materials.
8	Inductance, capacitance and resistance (LCR)	Electrical	Impedance measurements including Inductance (L), Capacitance (C), and Resistance (R) are made using an LCR instrument at specific frequencies to verify the characteristics of the cable conductor, insulating material and the end device.	No/ Disconnection Needed	The measurement for detecting imbalances, mismatches or unexpectedly high or low impedances between the cable leads due to cable degradation and ageing, faulty connections and splices or physical damage.	Measurement results are evaluated to determine if they are as expected for the type of circuit being tested. / All materials.

TABLE 3. COMPARISON OF VARIOUS CABLE MONITORING TECHNIQUES (cont.)

No	Technique	Monitoring Type	Description	Destructive/ Intrusive	Features	Remarks / Applicable Materials
9	Insulation resistance (IR)	Electrical	Measurements are made using an IR instrument at specific voltages to validate the cable insulating material characteristics.	No/ Disconnection needed	The measurement for detecting expected IR change due to a cable ages either through oxidation, moisture intrusion or other environmental effects.	Typically, a voltage lower than the maximum rated voltage of the cable is applied to an inner conductor or the cable shield (if the cable has one) and a ground plane in contact with the cable. Furthermore, the current in the cable is limited to avoid cable damage. / All materials.
10	Tan Delta	Electrical	Monitoring integrity of the cable insulation by measuring the tangent (loss) angle between the resistive current and the capacitive current with an AC voltage applied.	No/ Disconnection needed	The measurement for detecting resistance current increase due to changes in the insulation.	Methods include using a fixed frequency such as 60 Hz and stepping the AC voltage up to 1.2 times the rated cable voltage or applying a low voltage with a varied frequency range up to 500 kHz. / All materials.
11	Dielectric Spectroscopy	Electrical	Monitoring the integrity of the cable insulation by measuring the electrical permittivity of the polymer material.	No	The measurement for detecting permittivity changes due to changes in the insulation.	The method is useful for identifying permittivity changes along a cable's insulation, which change over time due to ageing of the material./All materials.
12	Density	Chemical	The measurement of density in small samples of polymer by Archimedes approach (measure the weight of a specimen in both air and a liquid of lower density than the specimen under test) or by using a density gradient column (placing the specimen into a calibrated liquid column and deriving density from a known calibration curve once equilibrium has been reached).	No/ Micro-sampling required	The measurements results are known to correlate with EAB for some materials.	The higher the level of ageing, the greater the concentration of oxidation products and the higher the density. / XLPE, other thermoplastics and some elastomers EPR.
13	Ultrasonic Velocity (UV)	Chemical	The measurement of change of velocity of sonic propagation in cable material due to the elastic modulus and density can change during ageing of cable materials.	No/ No	This technique measures properties of the cable jacket over a small volume between the transducer probes. The technique is still under development.	The measurements obtained can be strongly dependent on the cable construction and the specific formulation of the jacket material. Extensive baseline data may be required. / PVC, PE, EPR.

TABLE 3. COMPARISON OF VARIOUS CABLE MONITORING TECHNIQUES (cont.)

No	Technique	Monitoring Type	Description	Destructive/ Intrusive	Features	Remarks / Applicable Materials
14	Oxidative Induction Time (OIT) and oxidation Induction Temperature (OITP)	Chemical	Measures the loss of antioxidants in a polymer as it degrades. OIT measures the time at which oxidation occurs when exposed to a constant temperature. OITP measures the temperature at which oxidation occurs when temperature is increased at a specified rate with oxygen applied to the sample.	No/ Micro-sampling required	The method has been standardized for use in CM and has been shown to correlate well with degradation of certain polymers (e.g. OIT for polyethylene and EPRs and also CSPE and PCP). OITP does not correlate well with CSPE degradation.	Degradation products from halogenated materials can damage expensive calorimeter cells, and continued multiple testing on this kind material is impractical, unless specific non-corrodible cells are used. /EPR, PE, XLPE, PVC.
15	Thermogravimetric Analysis (TGA)	Chemical	Measures changes in weight relative to changes in temperature.	No/ Micro-sampling required	Sample preparation is similar to OIT/OITP testing. Usually carried out on samples that evolve corrosive degradation products as the sample chambers are chemically far more robust than those used in DSC.	The reference temperature is determined by 1 of 2 methods: temperature at which 5% mass loss occurs or the temperature corresponding to the point at which the maximum rate of weight loss occurs. /PVC. No correlation observed for other polymers.
16	Fourier Transform Infrared (FTIR) Spectroscopy/ Near infrared reflectance (NIR)	Chemical	Measures the absorption characteristics of the chemical bonds within the material. The measurement of FTIR is based on infrared radiation passed through a sample, such as a cutting from cable insulation. NIR is measured by a portable near infrared spectrometer, in which the infrared analysis is carried out in reflectance mode.	No / No for NIR (FTIR requires micro-sampling)	The spectral signature, that a sample both absorbs and transmits parts of the spectrum, is used to quantify physical changes to the insulation during the ageing process, such as molecular quality, consistency and the amount of components present in a sample.	The measurement is not applicable to polymers that contain heavily absorbents materials such as carbon black, e.g. CSPE and PCP/FTIR: PVC, XLPE, EPR, PE NIR: EPR, PE.
17	Gel content	Chemical	Gel content is determined by extracting soluble phase with solvent from a small sample and weighing the final dry sample. Gel content is defined as the ratio between the weight of not soluble phase and total weight	No/ Micro-sampling required	In polymers where cross-linking is the main ageing mechanism instead of chain scission an increase of content of insoluble phase (gel) is expected. The gel content should be correlated with EAB or other techniques that can provide an acceptance criterion.	If the initial gel content is higher than 90% it may not be sensitive enough to correlate it with mechanical properties. It can be used in polymers such as SiR, EPR

4. BASELINE RESULTS OF BENCHMARKING

The benchmarking programme provides important comparison results of current and new cable conditioning monitoring tests on a variety of NPP cables. Cable manufacturers that supported this CRP donated the test cables and distributed the appropriate samples to the participating testing and ageing organizations. The initial baseline testing of unaged cable samples has been shared and reviewed to align testing techniques and reduce measurement variances among the participants. The detailed baseline results are described in country reports in Appendix III and procedures for CM techniques are described in Appendix IV.

4.1.BENCHMARKING TESTS

A wide range of CM methods has been included in the programme. These include some established methods such as EAB, where there are considerable data and experience available, as well as more recently developed methods where data are limited. The methods included are as follows:

— Mechanical/thermal/chemical:

- Elongation at break;
- Indenter modulus;
- Recovery time;
- Oxidation induction time;
- Oxidation induction temperature;
- Thermogravimetric analysis;
- Density;
- Fourier transform infrared spectroscopy;
- Ultrasonic velocity.

— Electrical:

- Tan Delta (Dielectric loss);
- Dielectric spectroscopy;
- Insulation Resistance
- Time-domain reflectometry;
- Frequency domain reflectometry.

A number of different specimens were prepared from the cable samples. The sample preparation method used depended on the CM method being applied:

— Samples for electrical tests and ultrasonic velocity were aged as whole cable samples;
— Indenter and recovery time samples used whole cables for measurements on the outer jacket material. For measurements on the insulation materials, insulated cores stripped from whole cables were aged separately;
— Samples for all other chemical tests used jacket and insulation material stripped from whole cable before ageing;
— Elongation test specimens were prepared before ageing.

Recommendations as to how specimens should be aged (example ageing chamber shown in FIG. 15) are given in ageing procedures for benchmarking tests in Appendix V.

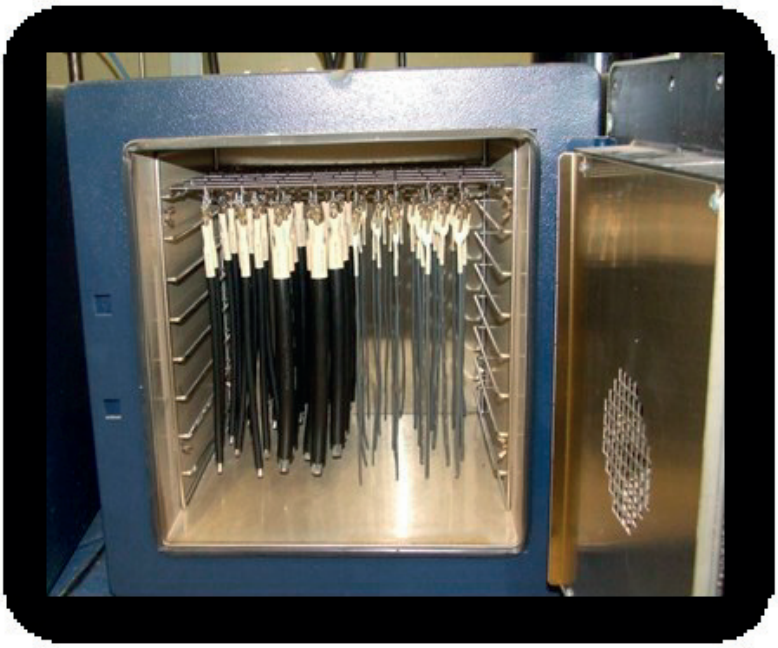


FIG. 15. Ageing chamber with mechanical test samples (Reproduced with permission courtesy of AECL).

4.2.BENCHMARKING GOALS

- To test techniques that might be able to locate hot spots (thermal ageing) along a cable. These techniques are primarily electrical test methods;
- To test techniques which have the potential to track ageing degradation (thermal and radiation conditions). These techniques are primarily mechanical/chemical test methods;
- Identify the critical test parameters for each of the techniques so that suitable test standards can be developed in the future.

4.3.KEY RESULTS FROM THE BASELINE TESTS

Baseline tests on unaged material for each of the CM methods were made by the participating laboratories. For some of the methods, there were up to 8 laboratories involved (e.g. for elongation measurements), whereas for other methods only 2 or 3 laboratories did measurements. The following sections describe the sample baseline results for each test method and discuss test improvements based on the initial unaged cable sample tests.

4.3.1. Elongation at break

The standard for this CM method is IEC/IEEE 62582-3 [13]. All participating laboratories that carried out these tests should have used this standard. Tests on jacket materials were made using dumbbell specimens cut from the jacket using a suitable cutting die. When possible, these samples were made using a die manufactured to one of the International Organization for Standardization (ISO) 37 dimensions, and if this was not available, then dies manufactured to national standards were used. Insulation materials used tubular specimens prepared from individual insulated wires from which the conductor had been removed. The exception was the Rockbestos insulation which used dumbbell samples.

Initial results from the baseline tests on unaged cable materials showed considerable variability in the values obtained for EAB between the participating laboratories. FIG. 16 and FIG. 17 show the raw data reported by each of the laboratories for the Eupen cable (EPR insulation and EVA jacket) as an example.

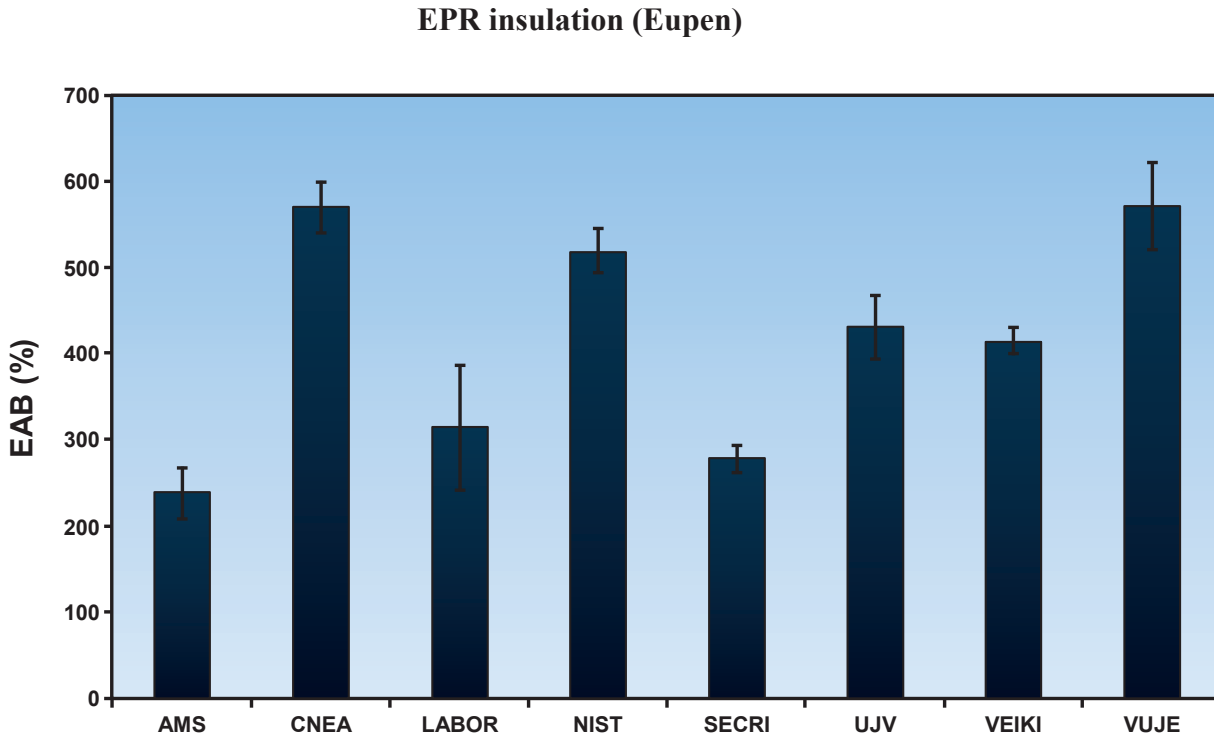


FIG. 16. Elongation data for Eupen EPR insulation (error bars are ± one standard deviation).

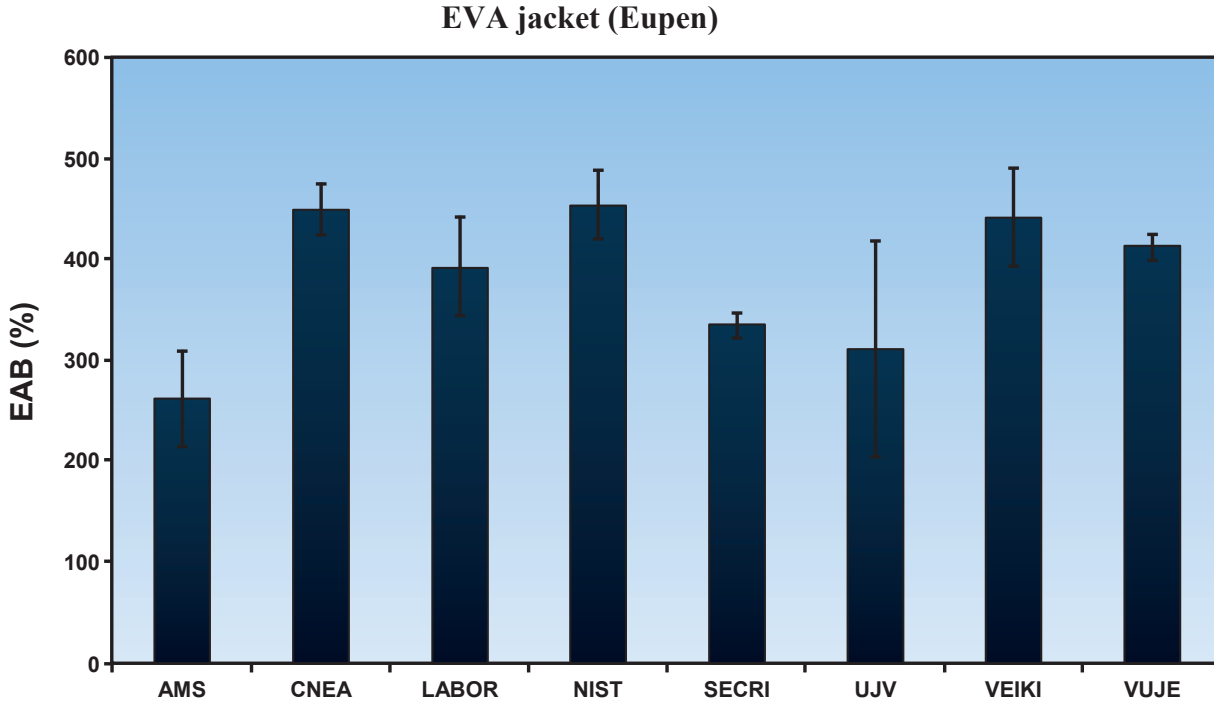


FIG. 17. Elongation data for Eupen EVA jacket (error bars are ± one standard deviation).

In some cases, the raw data can be adjusted to correct for known errors and to remove outlier data points. If this is done, the variability is not quite as marked. An example is shown in FIG. 18 for the CSPE jacket (Rockbestos). In general, five specimens were tested and averaged, but where one or two samples were very significantly different, this could reduce to three values averaged.

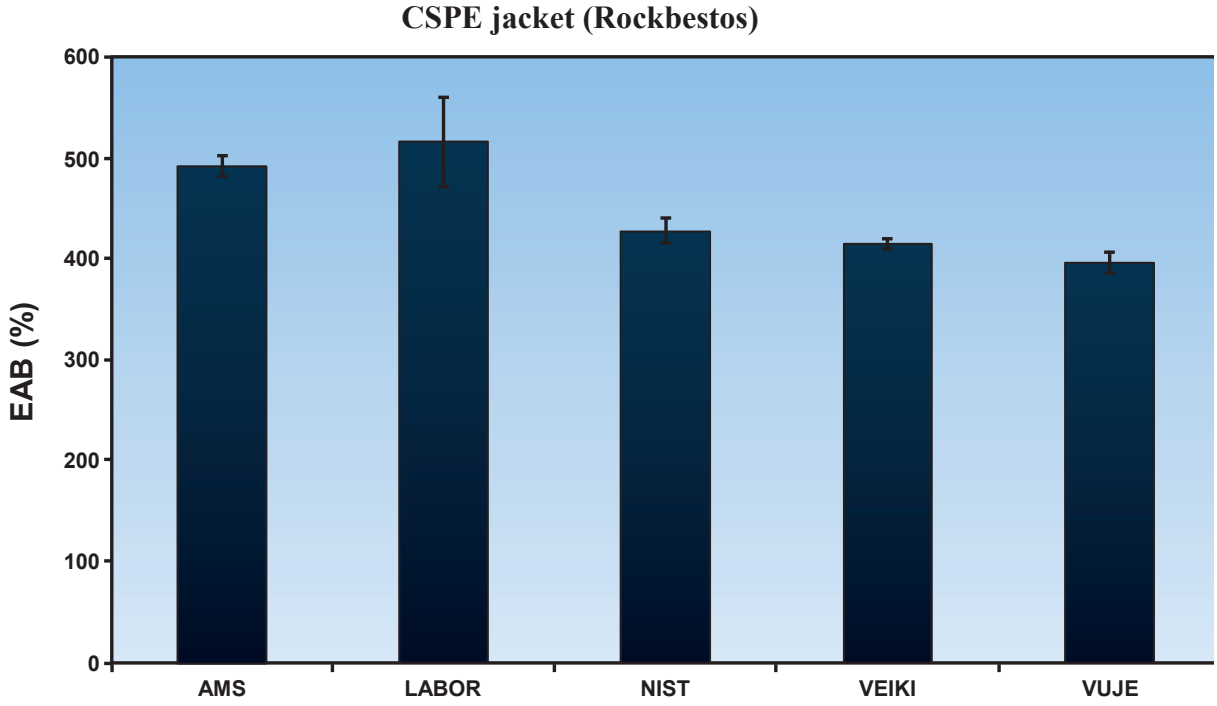


FIG. 18. Adjusted data for CSPE jacket (Rockbestos).

Because of the number of factors that could affect the variability, it was difficult to identify the specific causes of differences between the laboratories. To eliminate some of the variables and highlight the real areas of concern more standardized specimens were used, as an adjunct to the benchmarking programme. These samples have only been tested in the unaged condition as part of baseline tests:

- One material (XLPO jacket material) was prepared by Habia cable in the form of flat strips approximately 2 mm thick, from which specimens could be prepared;
- Dumbbell specimens were prepared by Habia from this strip material with a single size of cutting die (ISO 37 type 2). Batches of dumbbell specimens were sent to each of the laboratories for testing using their own test procedures;
- In addition, samples of the strip material were also sent to these same laboratories to enable them to cut their own specimens using the same size as in their own test procedure (often smaller dumbbell sizes, e.g. ISO type 37);
- Comparison of the 2 sets of data for each laboratory indicated the differences introduced by using different specimen sizes;
- Comparison of data between the laboratories highlighted the effect of different grip types and the use of extensometers.

The results of these additional tests shown in FIG. 19 have helped to identify the critical parameters for elongation measurements and the reasons for laboratories variability.

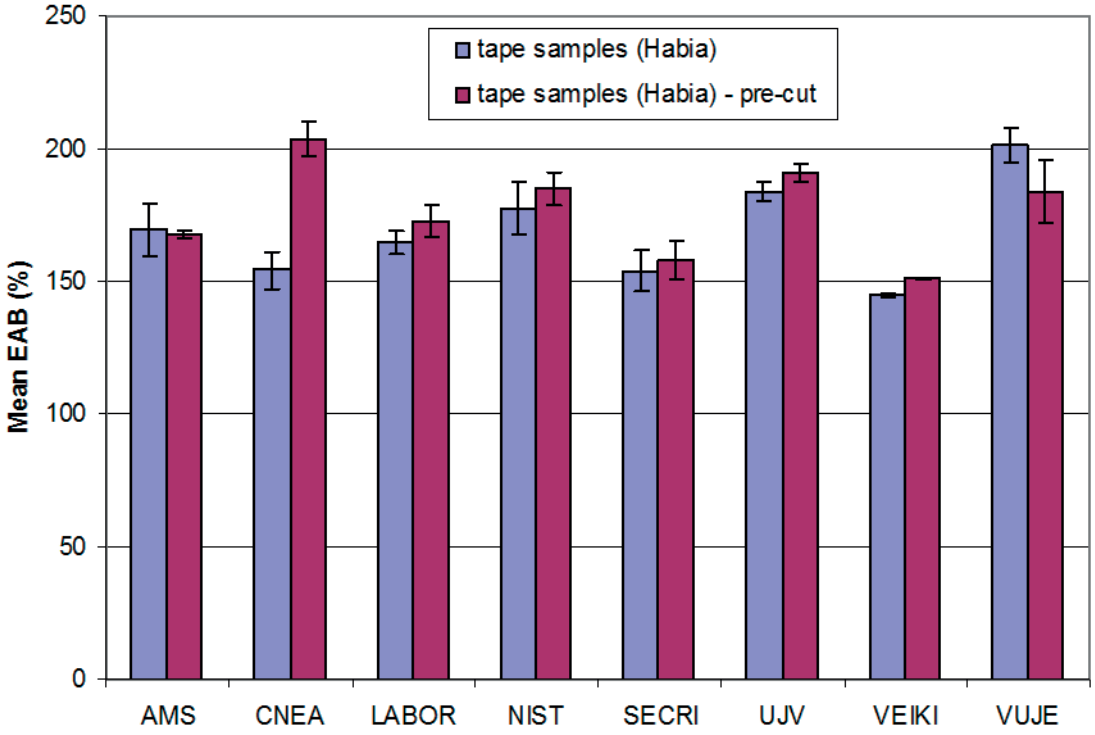


FIG. 19. EAB results for additional baseline tests on tape samples.

Only CNEA and AMS did not use extensometers. EAB values based on cross-head movement can be considerably different to those based on extensometer measurements. It was recommended that extensometers are used for all future EAB tests. The type of extensometer used does not appear to be significant – both contact and non-contact extensometers give similar results on these unaged samples.

Preparation of samples by the individual laboratories and the use of different size specimens do not introduce any significant difference in the values obtained by the individual laboratory. Note that these have all been prepared from tape samples, so the variability between as-cut and buffed/sliced specimens has been eliminated and standard deviation values are smaller than seen in samples cut from cables. Although the values for the two types of samples are very similar within the same lab, there is still significant variability between laboratories for all that used extensometers. This was partly due to the temperature at which tests were carried out. FIG. 20 shows the observed variation of measured EAB values with test temperature for both the pre-cut Habia samples and those prepared by the individual laboratories, illustrating that the test temperature can have a significant effect on the EAB values measured.

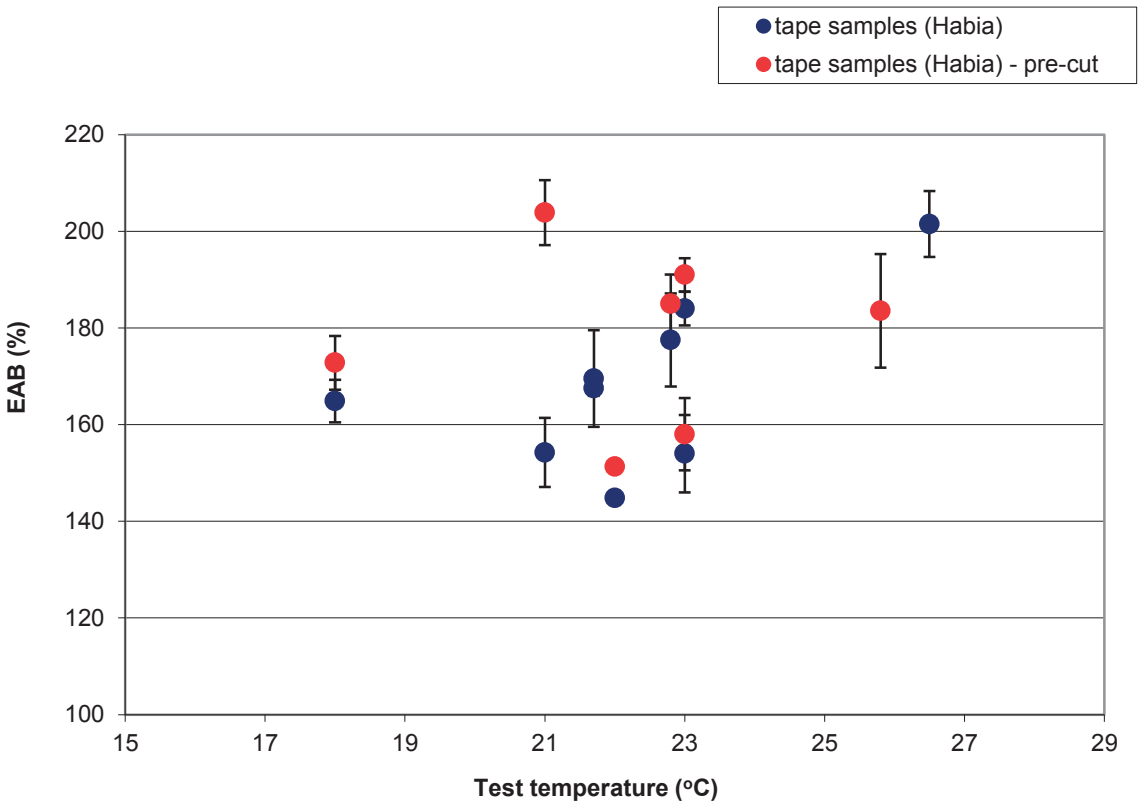


FIG. 20. Temperature variation of EAB for the Habia tape samples (each data point is for a different lab).

4.3.1.1.Testing technique improvements

Based on the results of the baseline study, considerable differences are observed between dumbbell specimens tested as-cut and those where irregularities or layers on the inner surface have been removed by buffing or slicing. As-cut specimens show significantly lower values of EAB and much higher scatter within a batch.

The type of grip used in the tensile testing machine may also affect the values obtained and can have a significant effect on the scatter of data within a test batch. Grip types used in the tests included pneumatic, mechanical with manual tightening, mechanical with self-tightening, rubber faced types and S-grips (for tubular samples). The grip type appears to have less effect on the values obtained than the other variables identified.

The use of contact extensometers appears to have an effect on the values obtained, which tend to be lower than those tested without an extensometer. If available, optical extensometers are preferred. It is important that the correct value is used for the effective gauge length of the specimen. For dumbbell samples, the nominal gauge length is dependent on the die used (e.g. ISO 37 type 3 is 10 mm nominal) but the straight section of the specimen is longer (e.g. 16 mm for type 3). If an extensometer is not used, it is important to specify what length is used as the initial sample length.

The cross-head speed used for the tests does not appear to be a significant factor in variability between laboratories. Regarding the deviation of the test results in tubular samples, conductor removal was identified as a critical step in sample preparation. The data derived from the samples where the copper conductors were not possible to remove without cutting

along the length of the samples, seemed to be extremely variable and strongly dependent on the sample preparation instead of actual cable mechanical properties.

4.3.2. Indenter modulus

The standard for this CM method is IEC/IEEE 62582-2. All participating laboratories carrying out these tests should have used this standard. Measurements of Indenter Modulus (IM) on the jacket materials used sections of whole cable approximately 250 mm long, aged as whole cable. For measurements on the insulation materials, insulated cores were stripped from a cable sample and aged separately.

The first important conclusion from the benchmarking baseline results is that most of the partners used a different indenter tip than the one specified in the current IEC standard. This explains mainly why there was an important difference between some of the results. It was realized from these baseline tests that there was an error in the probe tip dimensions specified in the current standard, which should have been the same dimensions as those used in the IPAM indenter. This error is being rectified in the IEC standard. For most of the measurements performed with the IPAM device, the reproducibility was considered to be good. However, it has been pointed out that, for soft materials, the results were closer even if the shape of the tip was different (FIG. 21). The other test parameters were generally close to those prescribed in the IEC standard. For example, the test temperature as well as the test speed was within the specified limits.

In FIG. 21, the solid bars are for tests made with the 0.56 mm tip diameter and the hatched bars are for tests made with 0.79 mm tip diameter.

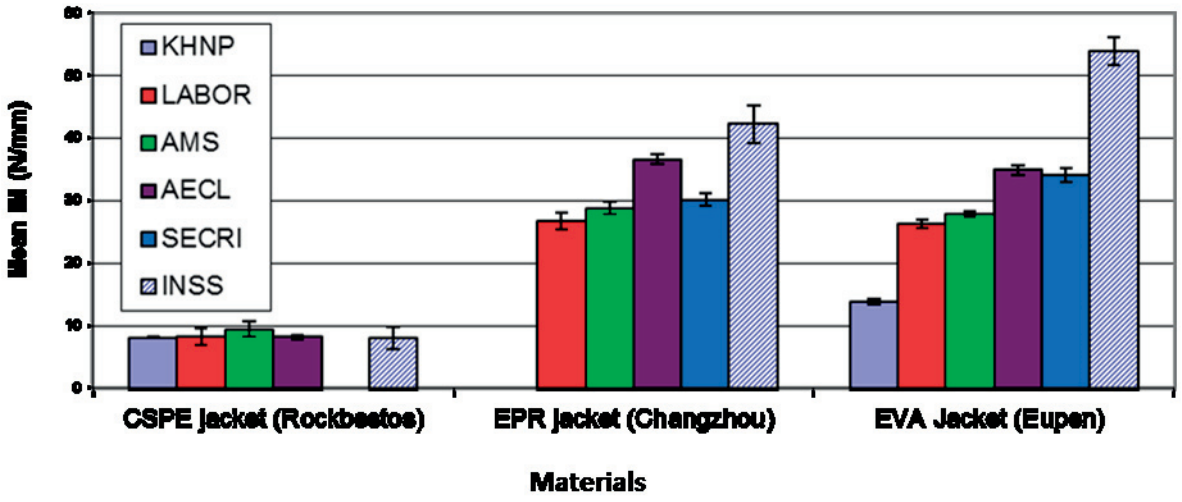


FIG. 21. Indenter data on as-received samples for jackets.

Four different types of indenters were used for testing the cables in the project. The different configurations can induce variability in the measured results. Several possible sources of deviation were identified in the hardware:

— Probe tip dimensions - the choice of the indenter tip is of particular importance because the recorded force (and the derived modulus) is directly derived from it. It is thus necessary for the comparison between laboratories that the partners use the standard truncated cone tip described in the corrected IEC/IEEE 62582-2 standard (0.56 mm diameter, 35° angle) for further measurements. For the one lab that used a

larger tip diameter, additional measurements were made to correlate the IM values determined from the two different tip dimensions;
- Driving mechanism - the diversity of driving mechanisms was identified as being a likely source of variability of the results. However, it was decided to keep the devices as is because such a modification cannot be done easily (or at all) for some devices;
- Clamping system - another important factor identified by the members of the study group is the influence of the clamping force. This can modify the response of the cable to the indentation. As explained in the IEC standard, this force has to be low to avoid interfering too much with the measurements. However, it was agreed that, if the force can be precisely controlled, a higher clamping force can be used in order to secure the position of the indenter system on the cable during on-site testing;
- The penetration depth at which 'full contact' of the probe tip is achieved can also be an important parameter in evaluation of the IM and has to be further investigated, particularly for small diameter wires/cables.

4.3.2.1.Testing technique improvements

- The participants agreed to use the corrected IEC indenter tip dimensions for future measurements;
- As prescribed in the IEC standard, the highest and lowest value of IM was ignored for the calculation of the mean value and the standard deviation;
- Also, in order to enable future comparisons in different ranges of force or depth, the raw data of force against penetration from 1 N to 10 N were saved in spreadsheets. This will enable the partners to evaluate whether or not it is better to work with a fixed force range or a fixed displacement;
- The influence of the clamping force on the measured value was not evaluated under this programme;
- Besides these elements, the decision was also taken to evaluate the influence of a deformation based modulus between 50 and 150 micrometres and a force based modulus from1 N to 4 N.

4.3.3. Recovery time

The recovery time of a cable polymer can also be measured using an indenter system. The indenter probe is first pressed into the insulation or jacket material to a fixed depth and time. The probe is then retracted a pre-determined distance and the polymer material is allowed to expand back to its original uncompressed state. The recovery time is the time it takes to recover the deformation from the start of probe retraction to the reappearance of a force as the specimen comes into contact with the probe. As only one lab used recovery time measurements, laboratories variability could not be evaluated at this stage. Recovery time could not be measured for the SiR jacket and insulation materials.

4.3.4. Differential scanning calorimetry

The standard for this CM method is IEC/IEEE 62582-4 [14]. All participating laboratories carrying out these tests should have used this standard. These two CM methods use standard thermal analysis equipment (DSC) to measure the onset of oxidation in micro-samples exposed to oxygen. Examples of the variability observed in measurements made by different laboratories on unaged samples are shown in FIG. 22 (OIT) and FIG. 23 (OITP).

For the OIT tests, there are significant differences in the values obtained between the laboratories. For a few cases, different temperatures were used but even when the test temperature used is the same there are still large differences. OITP values also show significant variations between laboratories. The main cause of these variations is believed to be the sample preparation methods used by each lab.

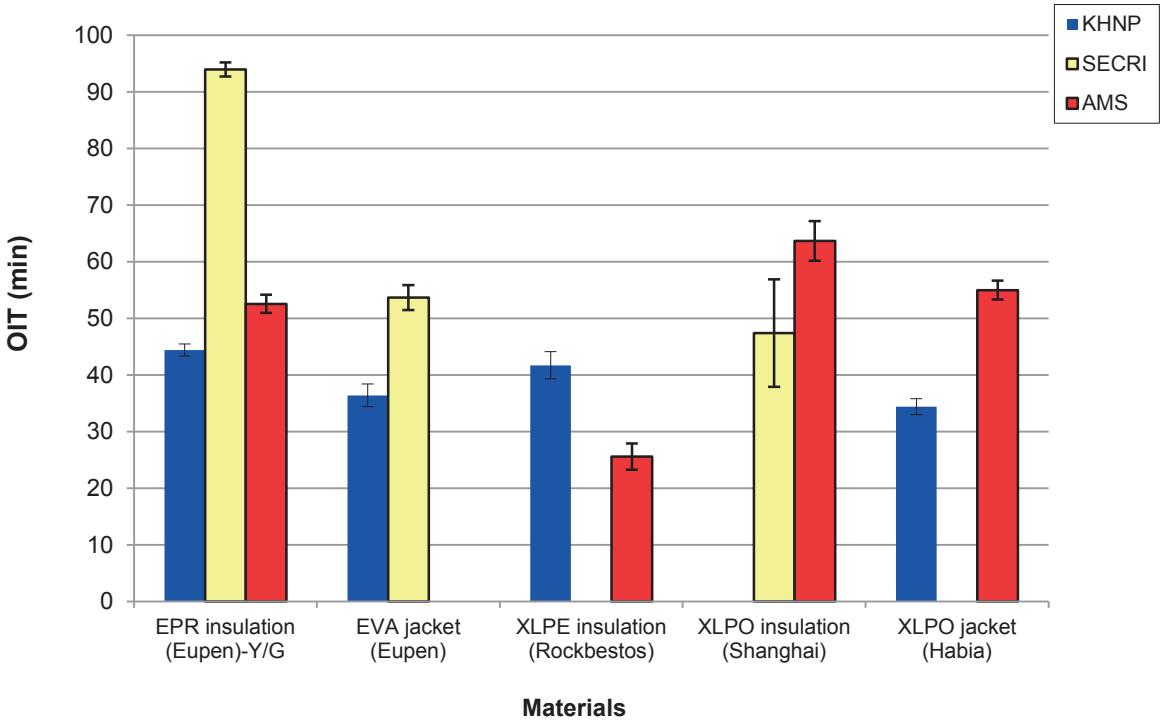


FIG. 22. Example of variability of OIT data for unaged samples.

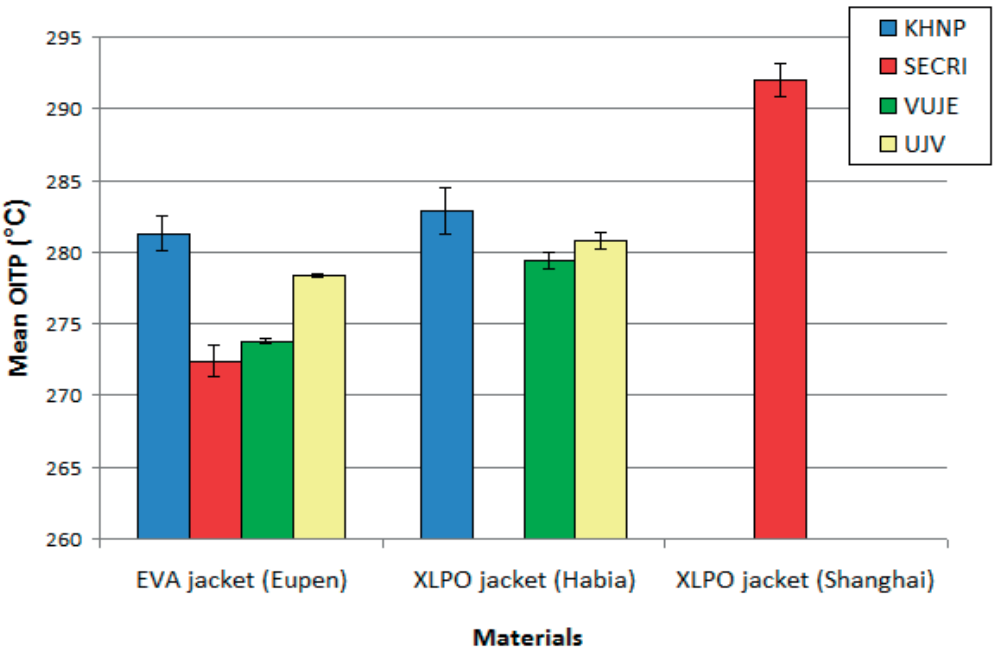


FIG. 23. Example of variability of OITP data for unaged samples for jackets.

4.3.4.1.Testing technique improvements

For all of the methods based on thermal analysis, specimen preparation is very important in getting reproducible results. The current test procedure does not specify this in sufficient detail and needs to be updated. Chopped or ground samples need to be sieved at 2 sizes to remove both larger and smaller particles. The degree of contact of the specimen with the test pan can be critical. If possible the chopped specimen should form a single layer in the test pan and the pan should be open or have a mesh lid. For modern instrumentation, a 5 mg specimen is sufficient but with older instrumentation that is not as sensitive, 10 mg may be necessary as specified in IEC/IEEE 62582-4.

For OIT tests, the main source of variability is the set temperature used to determine the oxidation time. It is important that this is the same for each laboratory. The set temperature will vary for different materials, but the value used should be specified in the test procedure and maintained throughout the series of tests on aged samples.

For both OIT and OITP methods, the threshold used should be as specified in IEC/IEEE 62582-4. For some instruments, the software may not allow for this and the end point may need to be determined manually.

4.3.5. Thermogravimetric analysis

This CM method uses standard thermal analysis equipment to measure the weight loss of a micro-sample during heating in nitrogen. Examples of the laboratories variability of TGA 5% weight loss measurements on unaged samples are shown in FIG. 24. There are significant differences between the laboratories, most likely due to differences in the sample preparation methods used by each lab.

4.3.5.1.Testing technique improvements

For the TGA method, it was not known whether the 5% weight loss temperature or the temperature at maximum rate of weight loss would be more likely to track ageing degradation for the different materials. The flow rate of nitrogen can have an effect on the values obtained, but this effect is quite small in the baseline tests. As with OIT and OITP tests, improvements to the sample preparation method would need to be made for this technique to be used.

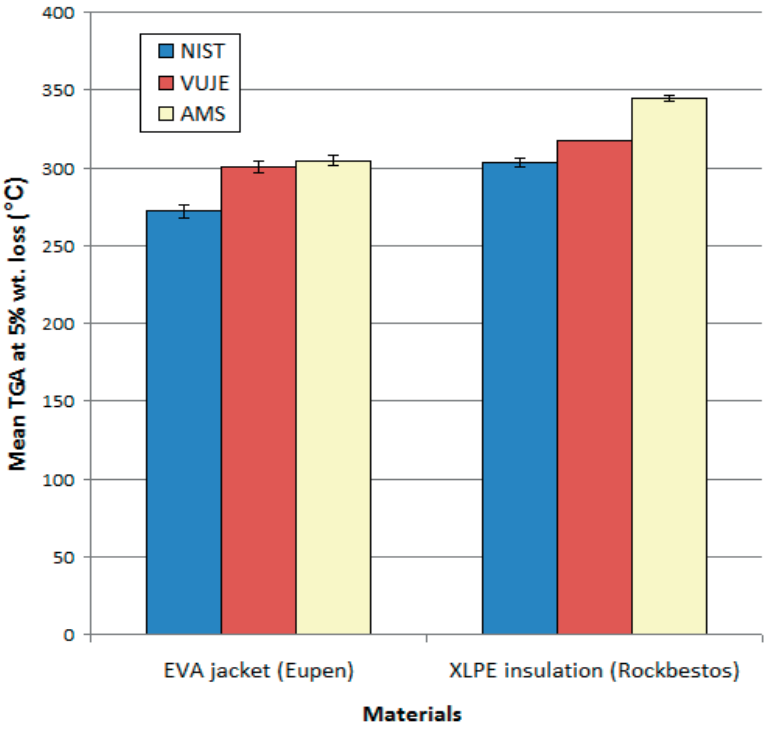


FIG. 24. Example of variability of TGA data for unaged samples.

4.3.6. Density

4.3.6.1.Baseline key results

Example data of baseline density measurements are shown in FIG. 25. Data from two of the participating laboratories demonstrate that it is possible to measure density with sufficiently small standard deviation as to make the technique viable as a monitoring tool.

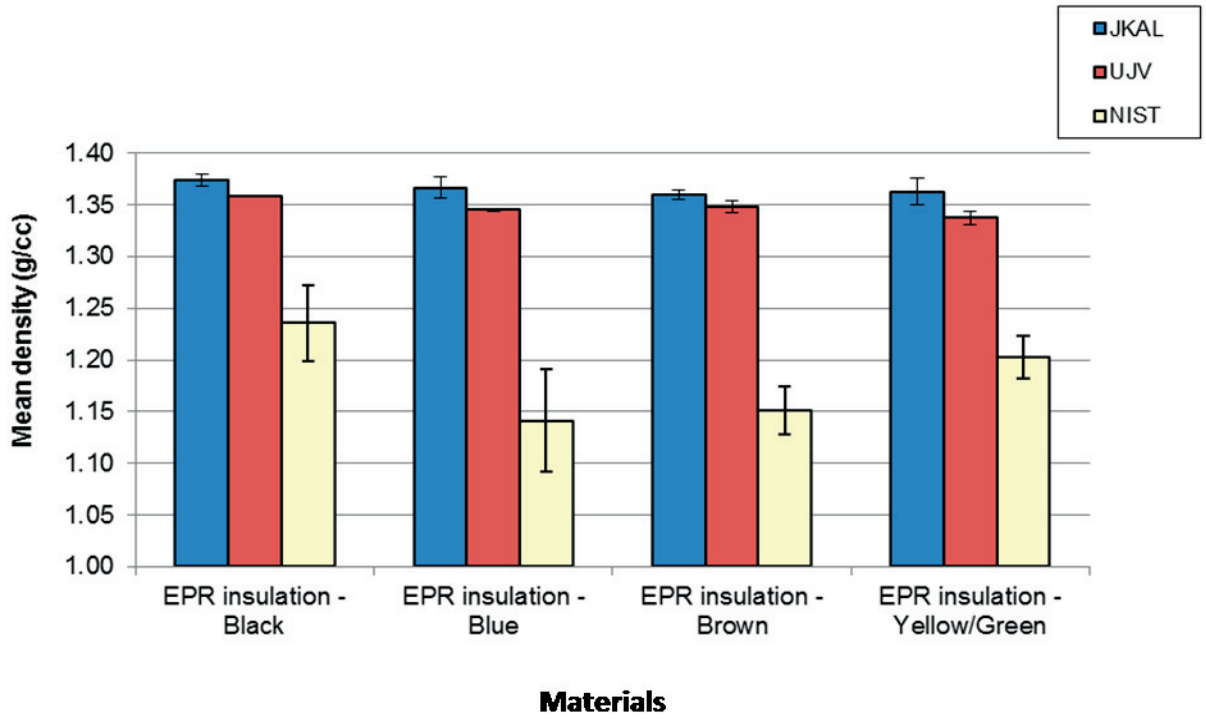


FIG. 25. Variability of density measurements (Example is for different coloured EPR insulations, Eupen).

4.3.6.2.Testing technique improvements

Significant variations between laboratories have been observed in the baseline tests. At present, the CRP test procedure is not sufficiently well-defined and needs to be updated. The test temperature and test liquid should be specified in the procedure.

The presence of air bubbles on the surface of the specimen is the main source of variability. It is therefore essential to ensure that air bubbles are excluded from the sample. This is usually done by using a wetting agent (e.g. isopropanol) on the sample, but care must be taken to ensure that carry-over of the wetting agent to the test liquid does not affect the density of the test liquid. The test procedure was updated to emphasize this.

4.3.7. Fourier transform infrared

4.3.7.1.Test procedure and sample preparation

Fourier Transform IR measurements can be used to determine the level of oxidation in a range of polymeric materials by measuring the height (or area) of the absorption related to oxidative species e.g. the –C=O carbonyl group. The ratio of the height (or area) of the carbonyl absorption near 1720 cm^{-1} and the –C–H absorption near 1370 cm^{-1} is the oxidation index. The specific peaks that best monitor ageing in the cable materials being tested cannot be specified initially, but were determined on the basis of all of the ageing data obtained.

4.3.7.2.Baseline key results

An example of the FTIR spectrum for an unaged XLPE insulation (Rockbestos) sample is shown in FIG. 26 indicating the level of complexity usually seen in such data.

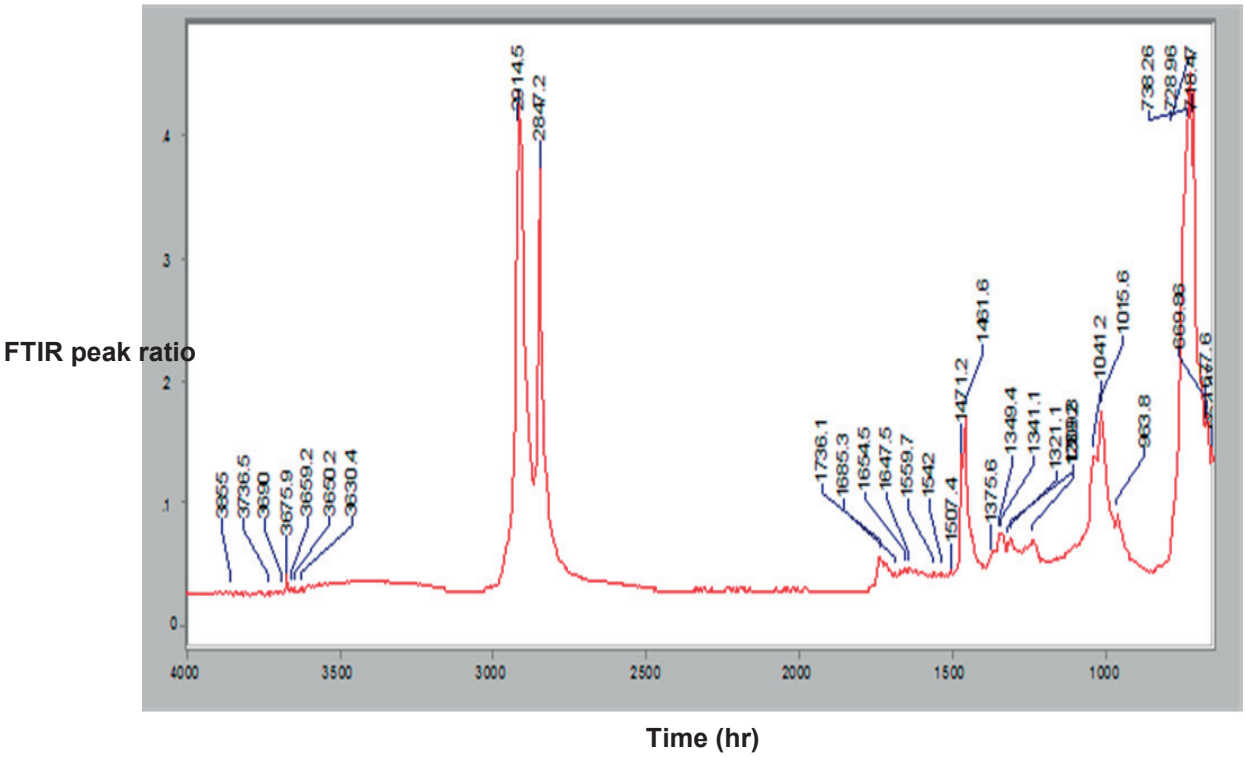


FIG. 26. Example of an FTIR spectrum for XLPE insulation (Rockbestos).

4.3.7.3.Testing technique improvements

FTIR spectra are complex and it is necessary to use an internal peak that does not change with ageing to normalize the data, together with baseline correction of the spectra. The peaks that will track ageing are not always known, and will be material dependent. Each laboratory has made its own choice of the peaks to report, so there was no direct comparison possible between laboratories. Future development of the technique would need to specify the peaks to be tracked and the method used to obtain a ratio between the tracked peak and the internal reference peak. Some laboratories used peak height, others used peak area.

4.3.8. Ultrasonic velocity

Ultrasonic velocity measurements are made by attaching two probes to the outer surface of the cable, one probe emits the signal and the second probe receives the signal. The ultrasonic transmission time between the probes will be a function of the probe separation and the ultrasonic velocity within the jacket material. The probes are coupled to the jacket using improved coupling gel agents or grease.

4.3.8.1.Baseline key results

Ultrasonic velocity data on unaged samples are shown in FIG. 27.

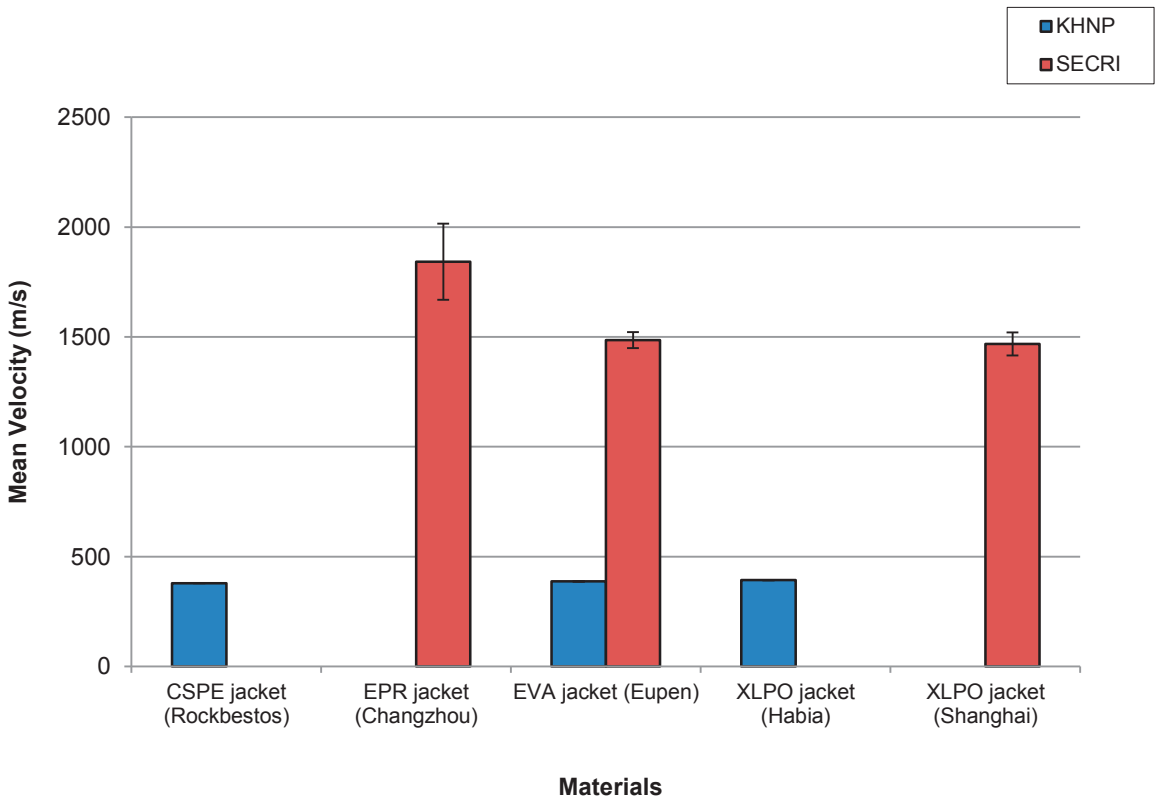


FIG. 27. Ultrasonic velocity for as-received samples.

4.3.8.2.Testing technique improvements

Two laboratories provided baseline data for ultrasonic velocity measurements. Of these two laboratories, only one material (EVA jacket material from Eupen) was tested and reported by both. Mean velocity measurements varied greatly between the two measurement techniques which included different probe coupling agents (grease vs. oil), signal frequencies (1 MHz vs. 2 MHz) and probe separation distances (5 mm vs. 6 mm). The testing techniques and set-up variances need to be evaluated for their impact on the baseline and aged cable test results.

4.3.9. Tan delta

4.3.9.1.Baseline key results

Tan δ test method (b) frequency dependent example data on an unaged PEEK insulation cable sample is shown in FIG. 28.

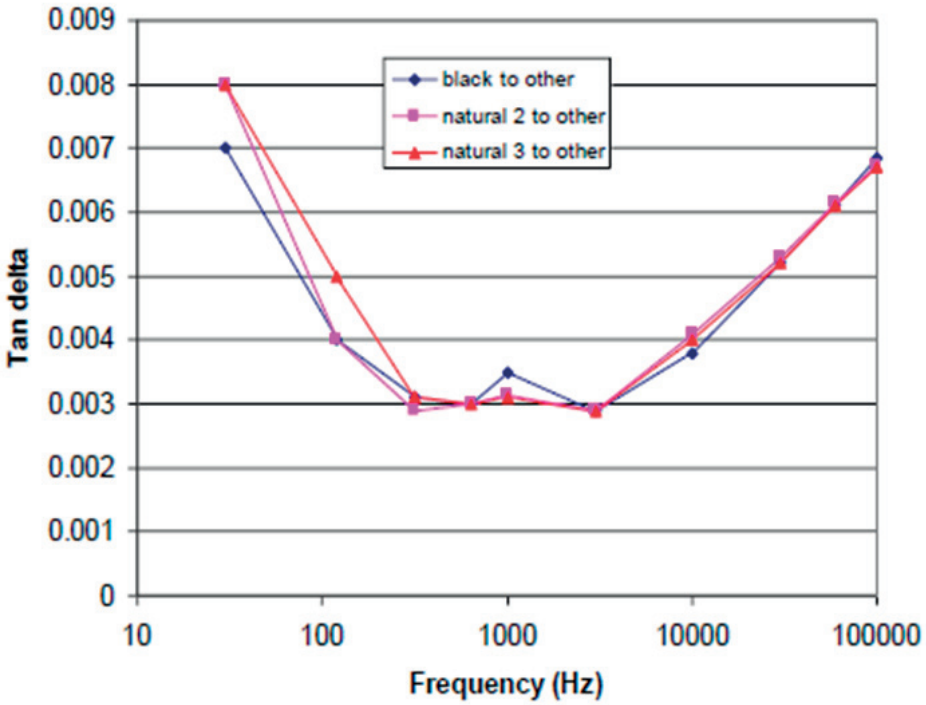


FIG. 28. Tan δ Data on unaged PEEK cable with sweep frequency 30 Hz – 105 Hz provided by VEIKI-VNL.

4.3.9.2.Testing technique improvements

- Method (a) - measurements at power frequency as function of voltage. Measurement at different temperatures is suggested, but in situ application is questionable;
- Method (b) - measurements at fixed voltage as function of frequency. Specify frequency range.

It is recommended that tan delta is measured over as wide a frequency range as reasonable (e.g. 20 Hz to 500 kHz), because the important frequency ranges from the point of view of ageing are not known in advance. However, in situ application of higher frequencies (e.g. 1 MHz or above) is questionable due to the wave propagation phenomenon. To access lower frequencies, longer samples (> 1 m) would be required.

4.3.10. Dielectric spectroscopy

4.3.10.1. Baseline key results

The dielectric properties of the example material are evaluated over a wide range of frequencies and measured at the amount of permittivity for the insulation material. Dielectric spectroscopy example data on unaged Habia PEEK insulation samples are shown in FIG. 29.

The voltage is supplied to insulation n.1; the signal is measured from insulations. Note that in unshielded cables shown in FIG. 29, significant shifts in the frequency response can be seen on repeat scans.

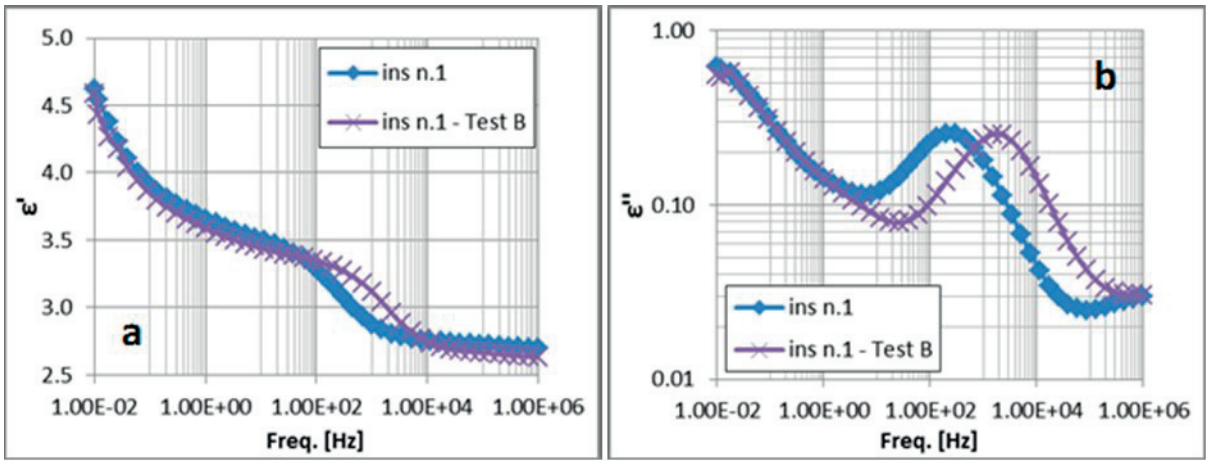


FIG. 29. University of Bologna results of dielectric spectroscopy performed on PEEK/XLPO (Habia) cable: (a) real part of permittivity. (b) imaginary part of permittivity. Frequency range 10^{-2} Hz – 10^{6} Hz.

4.3.10.2. Testing technique improvements

The results shown in this report highlight the limits of dielectric spectroscopy when applied to unshielded cables such as those provided for the project. The effect of stray capacitances on the repeatability of the measurement is clearly evident. Stray capacitances seem to alter significantly the frequency of the polarization peaks as well as the shape of the real part of permittivity vs. frequency.

In order to limit the influence of stray capacitance, future testing should include electromagnetic shielding. The idea is to surround the outer jacket with a wire mesh, which will be grounded during the test. In addition, dielectric spectroscopy should be repeated at 50°C. It has already been observed (ageing diagnostics and prognostics of low-voltage I&C cables (ADVANCE) project), in fact, that at this temperature the quality of the results is enhanced, probably because the insulating material becomes softer and the contact between conductor and insulation is improved. Moreover, at higher test temperatures the mobility of polymer chains also increases.

4.3.11. Insulation resistance

4.3.11.1. Baseline key results

Measurements of IR were made by applying a 500 Volt DC voltage between conductors for 10 minutes to obtain the PI number. A plot of IR versus time for seven samples of unaged Shanghai XLPO cable is shown in FIG. 30.

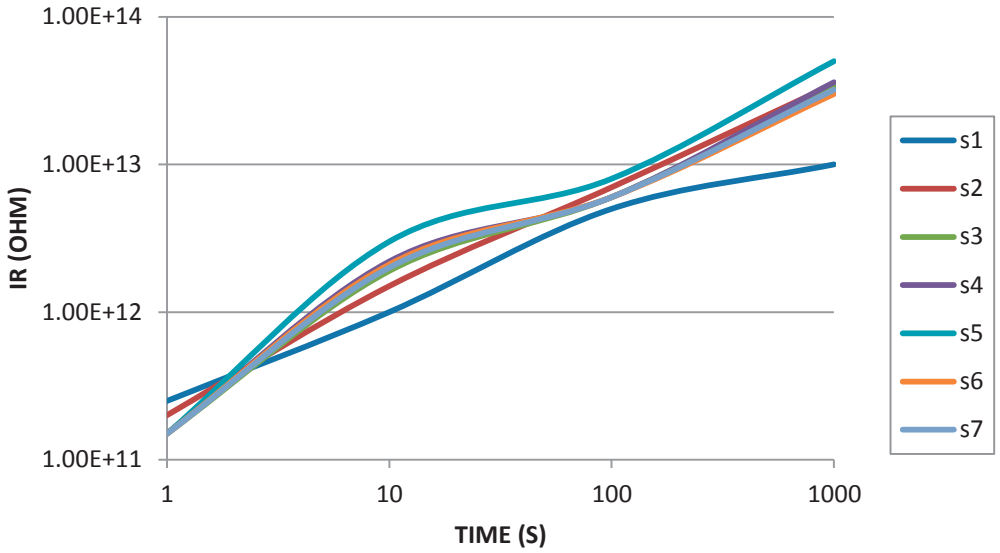


FIG. 30. Insulation Resistance Test Results for Seven Unaged Shanghai XLPO Cable Samples (reproduced with permission of Budapest University).

4.3.11.2. Testing technique improvements

Several issues were raised:

— DC voltage: different laboratories have measured the IR at different voltages (500 and 600 V). The difference between measurements at the two voltages is not large but it is recommended that participants use a standardized 500 V test voltage to minimize the variation of results;
— Define testing procedure for multicore cables: each laboratory has used different testing arrangement for the measurement of multicore cables. Some laboratories measure between two cores, while other laboratories energize a selected core while all other cores are grounded. The results of the two methods are not comparable. The second method provides lesser variation of results due to the lesser sensitivity to the mechanical and electromagnetic factors. The test procedure should be updated to recommend this;
— After the measurement of a selected core the slow dielectric polarization processes remain activated in the insulating material. The activated polarization processes have an effect on the results of other cores. To reduce the effect of slow polarization processes, it is recommended to short circuit the cable for a duration of at least three times the energizing time (e.g. for a 10 min measurement time, short circuit for 30 min);
— Specification of sampling rate required: the IR versus time curve provides more information about the dielectric processes of insulation. It is recommended to record the IR-time function with a suggested sampling time of 1 second. Moreover, the curve of IR may be changed by ageing and the shape of the IR-time curve is independent of the cable length. The time functions of IR show that the dielectric polarization processes having high time constant play important role in shape of IR-time curves, therefore adding Voltage Response measurement is suggested to investigate slow polarization processes;
— Cleaning exposed insulation - during sample preparation, the core insulation may be contaminated. This contamination can increase the leakage current on the outer

surface of the core insulation. For short samples, this can result in a high deviation of measurements. It is recommended that the outer surface of core insulation be cleaned using ethanol;

— Measure IR/unit length - different laboratories have carried out the IR measurement on different cable lengths. It is recommended that the results be normalized, expressed as Ω x m.

4.3.12. Reflectometry methods

4.3.12.1. Baseline key results

Time domain reflectometry data on an unaged 20-meter sample of Changzhou cable is shown in FIG. 31. A cable of 7 meters in length was connected to test. The nominal impedance of the Changzhou cable was calculated from the unit less reflection coefficient (Rho) value as 96.2 Ω.

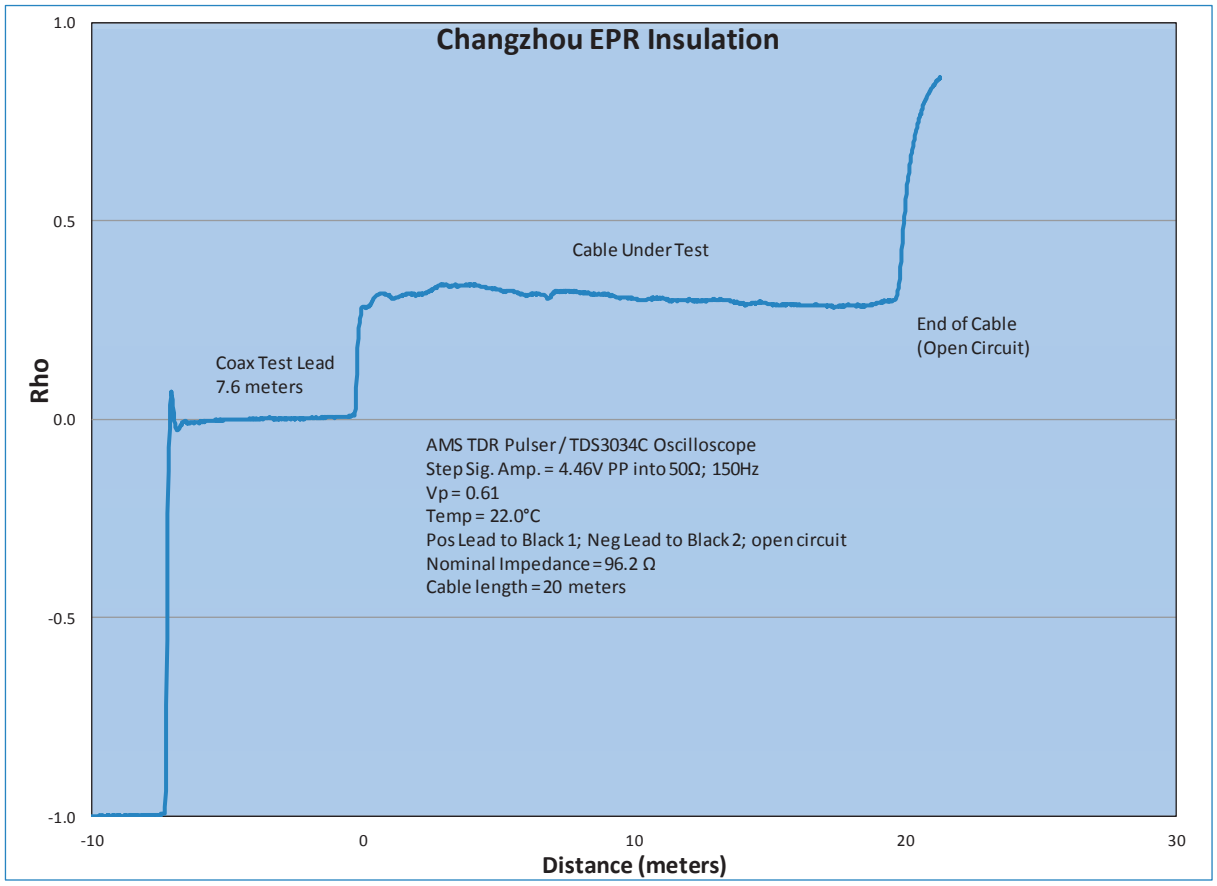


FIG. 31. TDR example data on unaged Changzhou EPR cable (reproduced with permission of AMS corporation).

4.3.12.2. Testing technique improvements

Time domain reflectometry (TDR): In order to share experimental data for reflectometry methods, numerical data from reflectometry should be provided together with a graphic file that shows waveforms. The report should include equipment details with

specification. Moreover, due to the nature of reflectometry techniques, it is necessary to utilize a test lead that connects the cable sample under test and the equipment.

Frequency domain reflectometry (FDR): In case of FDR reporting, it should also include magnitude and phase together. The same experimental conditions can be applied for all the types of reflectometry techniques. However, the reporting format may slightly vary depending on the techniques.

5. AGED CABLE RESULTS OF BENCHMARKING

Preliminary analysis of the test data received show that, for some of the CM techniques, good correlation is observed with ageing time and there is consistency in measurements between the different laboratories carrying out the tests. The level of correlation with ageing time and the degree of variability between the different laboratories is dependent on the material being tested and the CM techniques being used.

For some combinations of material and CM techniques, there can be a large degree of variability between laboratories, even though there is good correlation with ageing time. The reasons for discrepancies in values between the different laboratories have been assessed. For some CM techniques, there is no significant trend with ageing observed for particular materials.

The benchmarking results are summarized by CM techniques and by material, identifying those CM techniques that proved to be most suitable for each material. Note that these conclusions apply to the specific cable material that was tested and may not be applicable to other cable materials of similar generic type.

EAB is usually regarded as a prime indicator of degradation in polymers. Other CM techniques can be assessed by comparing the changes observed on ageing relative to the changes in EAB. Since EAB is a direct indication of ageing degradation, cross-plots of the CM parameter against EAB are a useful indicator of the usefulness of other techniques for ageing assessment. For the limited amount of test data on radiation aged samples, EAB data is not available so cross-plots against IM have been used instead. The detailed aged test results are described in country reports in Appendix III.

5.1.ELONGATION AT BREAK

Most of the variability between laboratories observed in the benchmarking test programme was associated with sample preparation. For the insulation materials, there were considerable difficulties in preparing tubular samples by removing the conductor with the exception of the Rockbestos cable where dumbbell samples could be cut from the insulation. Bonding of the insulation to the conductor was a significant problem for all of the other cables, which prevented the insulation from being removed from the conductor using normal cable strippers. For most of the insulation materials, the conductor was stripped out after slitting of the insulation along its length. During tensile testing of this type of sample, failure at stress raisers introduced during the slitting process would be expected. This would account for the some of the large standard deviations observed, e.g. for the PEEK insulation (FIG. 32). Some laboratories took the approach of stretching the conductor in an effort to remove it by releasing the bond with the insulation material resulting in a tubular specimen.

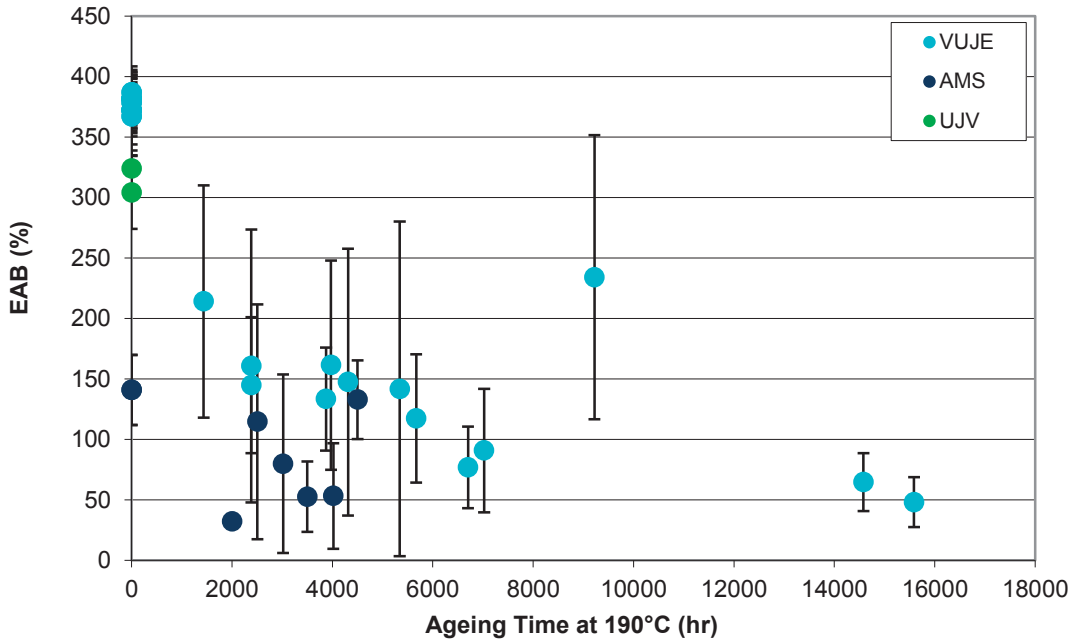


FIG. 32. EAB data for PEEK insulation.

The second source of variability between laboratories arose from the method of analysis used by those laboratories that did not use extensometers. Initial length for dumbbell samples was taken as the cross-head separation in some cases or the gauge length of the dumbbell sample (the straight section of the sample) in others.

A third source of variability is the type of extensometer used to measure elongation. Although this appears to have little effect on the EAB value for unaged material, it can affect the values measured on aged material. In particular, clip-on extensometers appear to significantly reduce the EAB values measured on aged samples.

A fourth potential source of variability is the variation in clamping systems used by each lab. Grip types included pneumatic, self-tightening, and manual/mechanical grips. There was not enough information in the data to isolate the relative effects of the different types of grips.

For the jacket materials, most laboratories prepared dumbbell samples with the full jacket thickness with no attempt to remove thickness variations arising from moulding of the jacket around the wire insulation. VUJE from Czech Republic prepared dumbbell samples using a slicing technique with the inner and outer surfaces removed to give a uniform thickness sample. CNEA from Argentina removed thickness variations by sanding. The slicing technique used by VUJE seems to have a major effect on the EAB values for this Eupen EVA jacket polymer (FIG. 33), tending to higher values of EAB under all test conditions. This is not unexpected as the presence of thickness variations will give rise to stress raisers that would initiate failure particularly in heavily aged samples. For the Rockbestos CSPE jacket material, which was not heavily ridged on the inner surface, the EAB data between laboratories was much more consistent (FIG. 34).

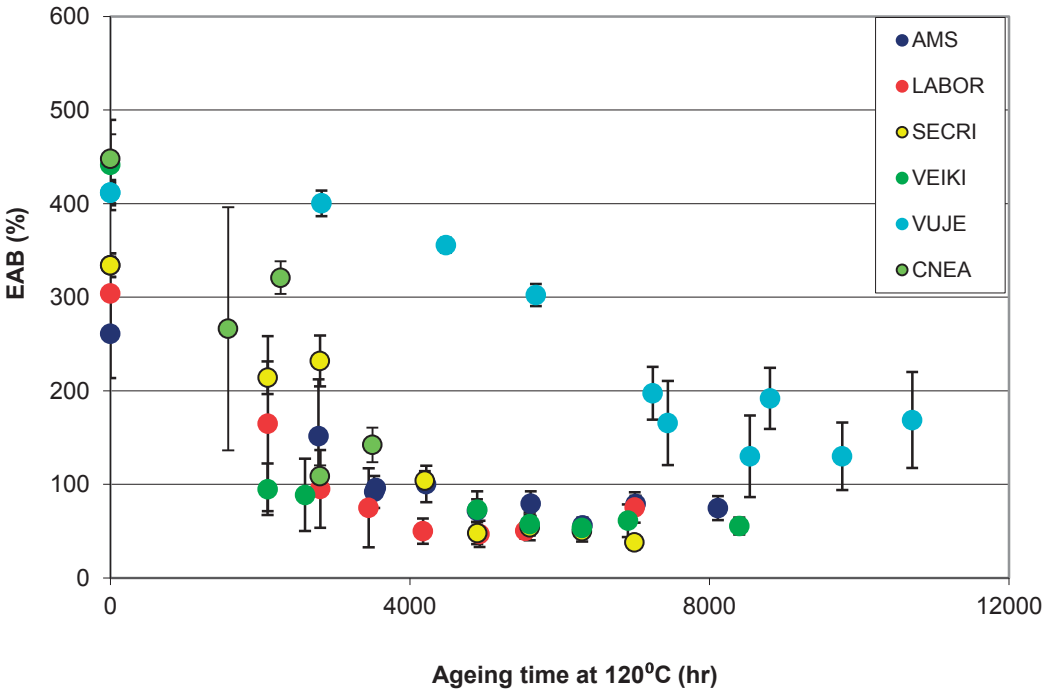


FIG. 33. EAB data for thermally aged EVA jacket (Eupen).

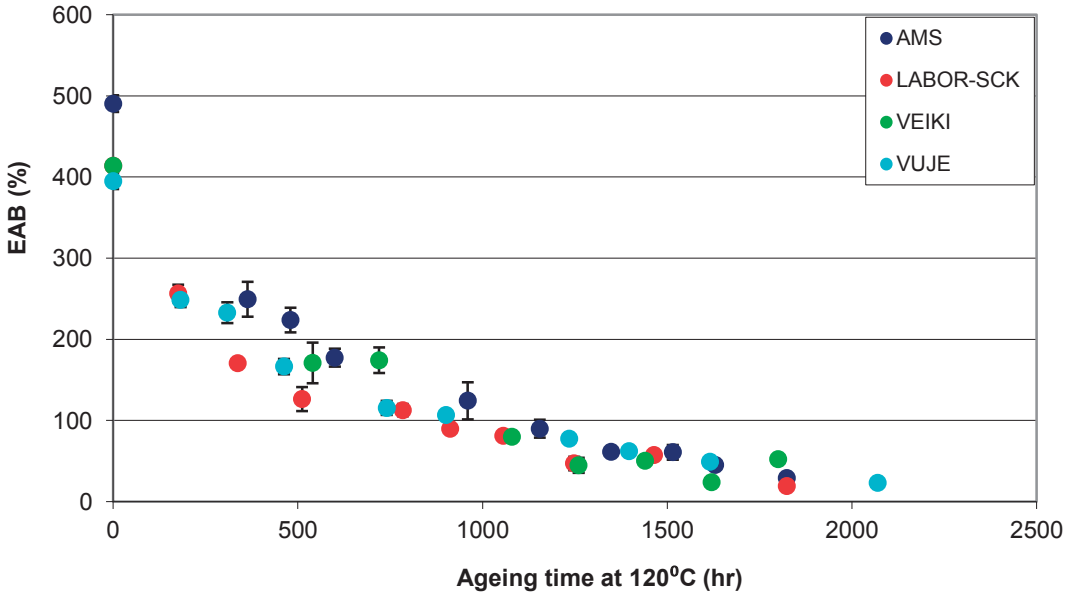


FIG. 34. EAB data for thermally aged CSPE jacket (Rockbestos).

An additional source of variation for some of the jacket materials was the presence of an inner wrap material partially bonded to the jacket, e.g. for the Shanghai cable, this was a fibreglass braid. Where possible, this braid was removed before testing but as the material aged it became more difficult to remove and remnants were likely to still be attached to the test samples. The variations in thickness and the presence of wrap layers bonded to the jacket has given rise to large standard deviations in the EAB measurements, particularly for heavily aged samples.

5.2.INDENTER MODULUS

5.2.1. Effect of probe tip dimensions on measured IM values

Institute of Nuclear Safety System (INSS) used an indenter probe tip with different dimensions to those used by all of the other laboratories. In the INSS indenter, the probe tip diameter was 0.79 mm (cf. 0.56 mm for other laboratories) and the tip angle was 70º (cf. 35º for other laboratories). As part of the CRP programme, a series of samples were supplied by INSS from the JNES test programme JNES-SS-0903 (the final report of the project on assessment of cable ageing for NPPs [15]), covering a wide range of indenter values, from 5 to 50 N/mm. These were tested independently by Iowa State University using an IPAM 4 indenter supplied by AMS. The correlation curve between INSS indenter measurements and IPAM 4 measurements is shown in FIG. 35.

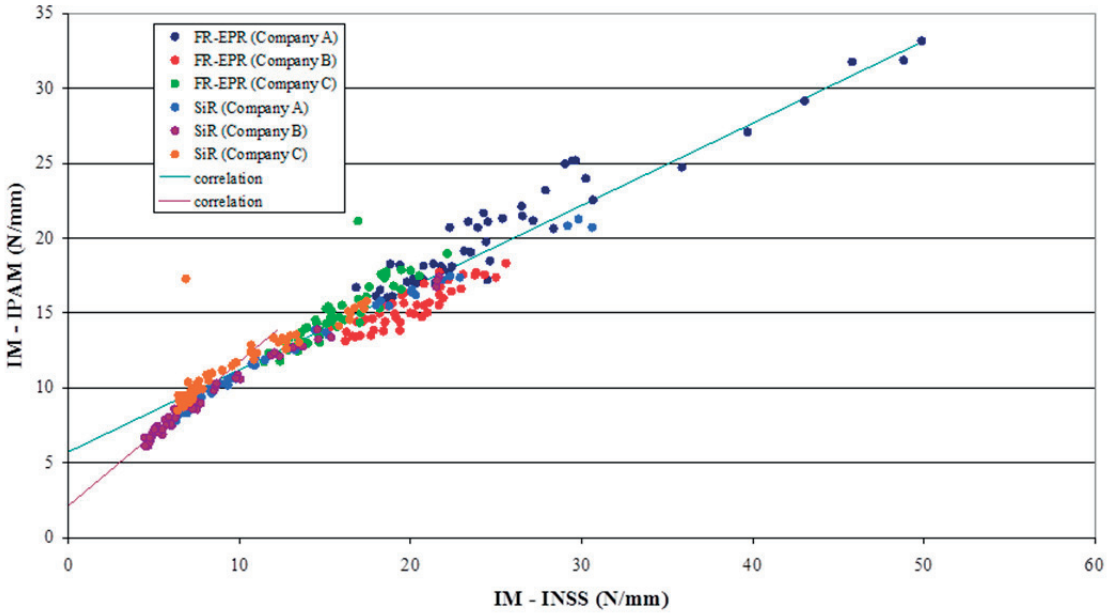


FIG. 35. Correlation curve for indenter measurements using the INSS indenter, compared with the IPAM 4 indenter.

5.2.2. Laboratories variability of IM data

Based on IM data collected from several different laboratories, it has been observed that harder materials (e.g. PEEK, XLPO) tend to show little to no trending of IM data versus ageing time at elevated temperature. However, some materials demonstrate definitive trending (e.g. SiR, CSPE, EPR). Data at long ageing times tend to have larger standard deviations.

Once corrections have been made for variation in probe tip dimensions, the other main sources of variability between laboratories are likely to be the force range used for measuring IM, the test temperature and clamping forces. Most participants used 1 to 4 N force ranges for analysis but some laboratories used a slightly different range.

For most polymers used as cable materials, the measured IM values will vary as a function of temperature. For the range of test temperatures used in this programme (17ºC to 26ºC) some variation would be expected. For example, for an EPR insulation material tested in an earlier CRP, the observed temperature variation of IM is shown in FIG. 36. The sensitivity of IM measurements to test temperature will be specific to the material being tested.

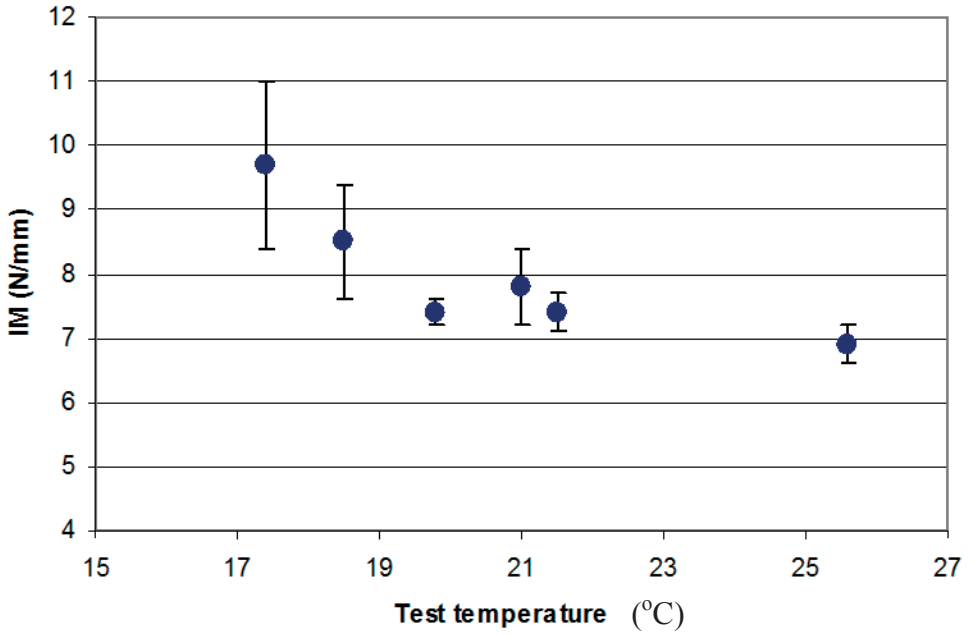


FIG. 36. Temperature variation of IM for EPR insulation.

The other likely source of variation between laboratories is the level of clamping force used when attaching the indenter to the cable sample. For the instrument type used by most of the participants, this clamping force is not controlled or measured but is dependent on the operator. For heavily aged samples, in particular, clamping force issues increase the standard deviation of the data.

Most of the cable samples used in the CRP have a variance in thickness around the circumference of the material. Therefore, testing needs to be averaged around the entire circumference of the cable for best results as stated in IEC/IEEE 62582-2.

5.2.3. Comparison of force range and depth range for IM values

An important point has been raised by AECL regarding the force range used for analysis of the IM. In the standard IEC/IEEE 62582-2, the force range is specified as 1 to 4 N. However, it has been pointed out that the lower limit of 1 N may be insufficient for full contact with the probe tip area specified in the standard and may be one reason why there is non-linearity in the force/displacement curves. This would be particularly important for the harder materials, such as PEEK and XLPO, and for small diameter insulation materials.

With ageing and hardening, the IM would be measured in a lower depth range for the 1 to 4 N force ranges. Therefore, one may not compare like with like if the depth range corresponding to 1 to 4 N has reduced.

Some examples of the IM values obtained using force range versus depth age are shown in FIG. 37 for EPR jacket (Changzhou) and FIG. 38 for CSPE jacket (Rockbestos). Both depth and force ranges show similar trends.

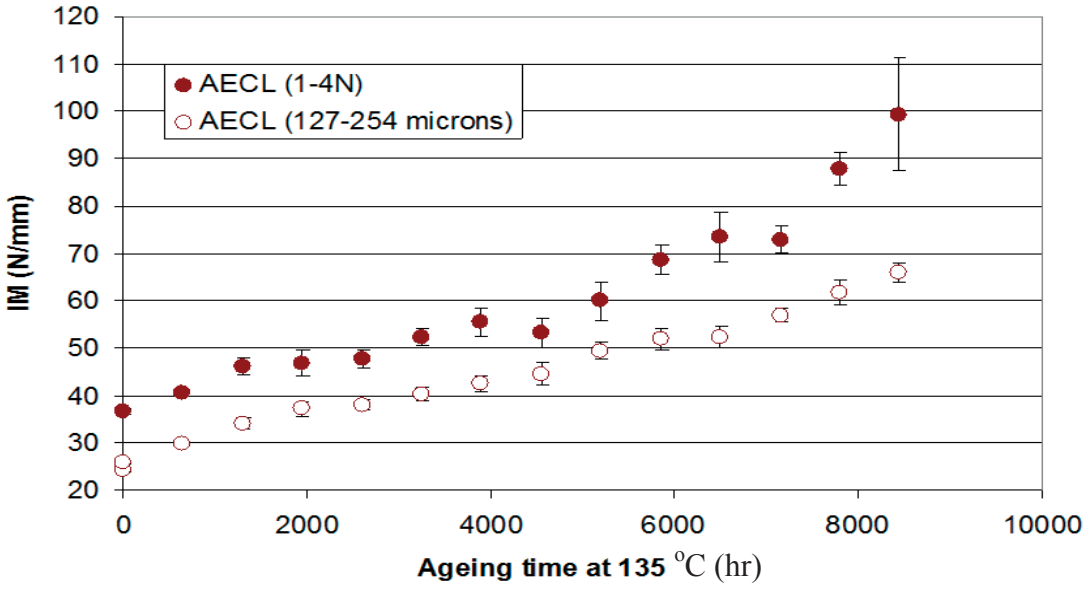


FIG. 37. Comparison of IM values for thermal ageing using 1-4 N force range and 127-254 micron depth range for the EPR jacket (Changzhou).

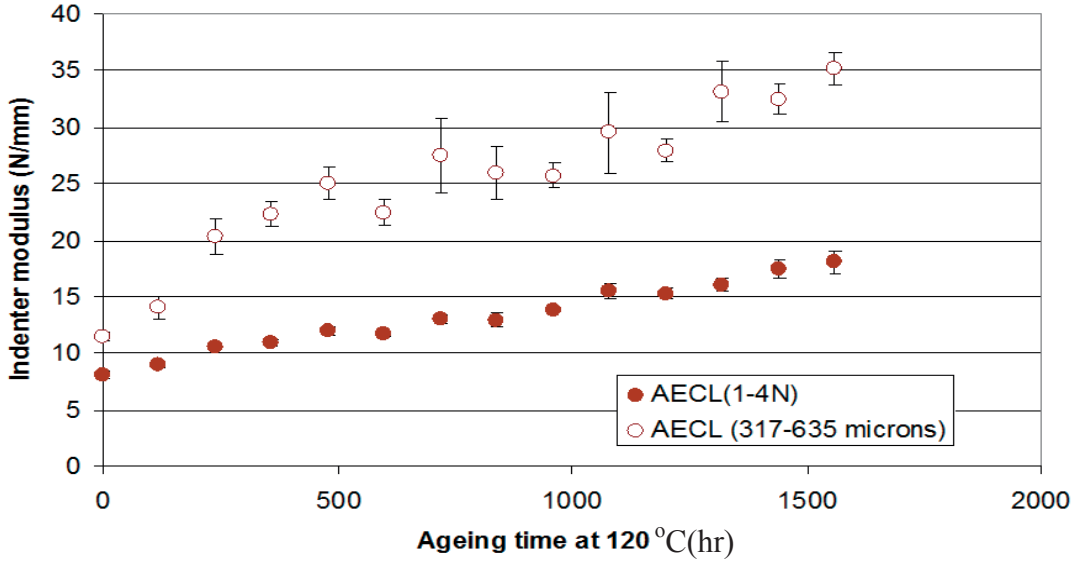


FIG. 38. Comparison of IM values for thermal ageing using 1-4 N force range and 317-635 micron depth range for the CSPE jacket (Rockbestos).

5.3.RECOVERY TIME

Only one lab is currently carrying out recovery time measurements at present, so there was no opportunity to assess laboratories variability in this programme. The recovery time method has proved to be particularly useful for those material types where indenter measurements are not useful, e.g. XLPO materials (FIG. 39).

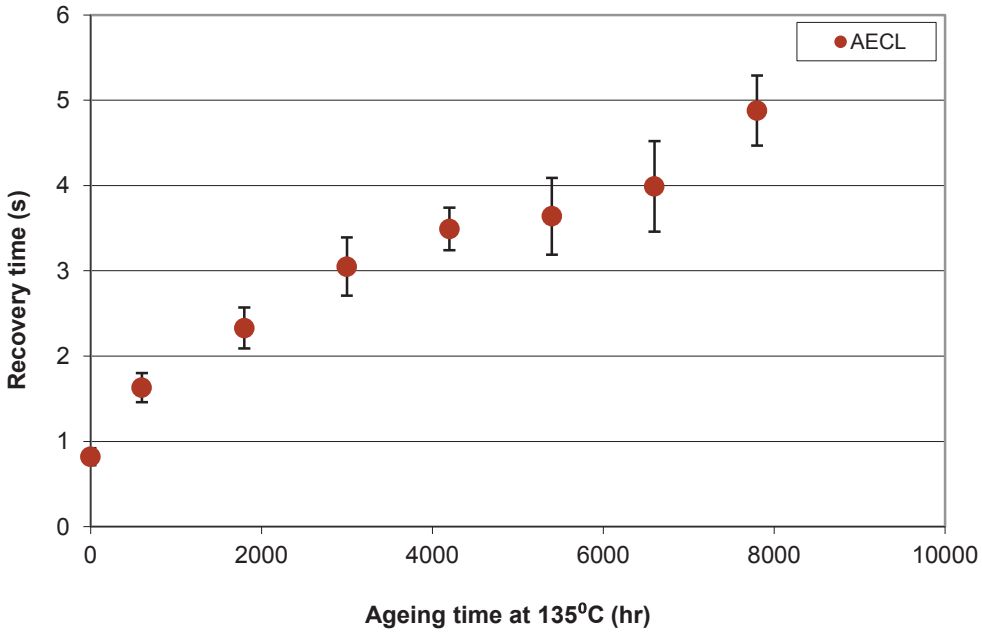


FIG. 39. Recovery data for thermally aged XLPO jacket(Shanghai).

5.4.OXIDATION INDUCTION TIME

The variations in the OIT data reported by each lab are attributed to differences in test temperatures, sample preparation and data analysis techniques. For XLPO and XLPE materials, differences in the testing temperature used by each lab resulted in discrepancies in the OIT data with the OIT values obtained at lower temperatures being longer than the ones obtained at higher temperatures. Despite these differences, the OIT values reported by each lab showed consistent trends for each of these materials.

In contrast, the Eupen EVA data shown in FIG. 40 was one example where the OIT data sets collected by each lab did not compare in terms of magnitude and trending characteristics. The discrepancies in OIT data for this polymer may have been caused by differences in the sample preparation and data analysis methods used by each lab. Overall, the OIT data reported by each lab shows consistent trending for most of the polymer types during the early portion of the ageing process, and, therefore, OIT testing is a useful method for monitoring the early stages of degradation, particularly for the XLPE and XLPO based materials.

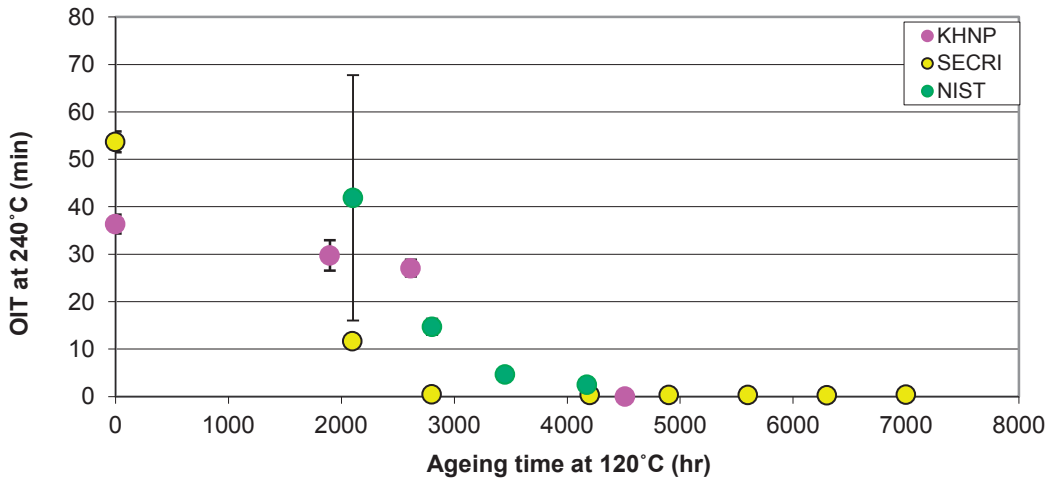


FIG. 40. OIT data for thermally aged EVA jacket(Eupen)

5.5.OXIDATION INDUCTION TEMPERATURE

The variations in the OITP data reported by each lab are likely to be due to differences in sample preparation techniques. The size of the chopped material, their degree of contact with the sample pan and the selection of material for sampling will all make a difference to the values obtained. For the Eupen EVA jacket shown in FIG. 41, the differences in the sample preparation methods used by each lab resulted in discrepancies in the OITP data. Where there are dual layer structures (e.g. the Changzhou EPR jacket) or the presence of braid layers on the inner surface (e.g. Shanghai XLPO jacket), these may also have caused variations in the sample compositions used by each lab, which may explain the discrepancies in the OITP data. Overall, the OITP data reported by each lab shows consistent trending for most of the polymer types throughout the ageing process, and, therefore, OITP testing may be a useful method for monitoring degradation.

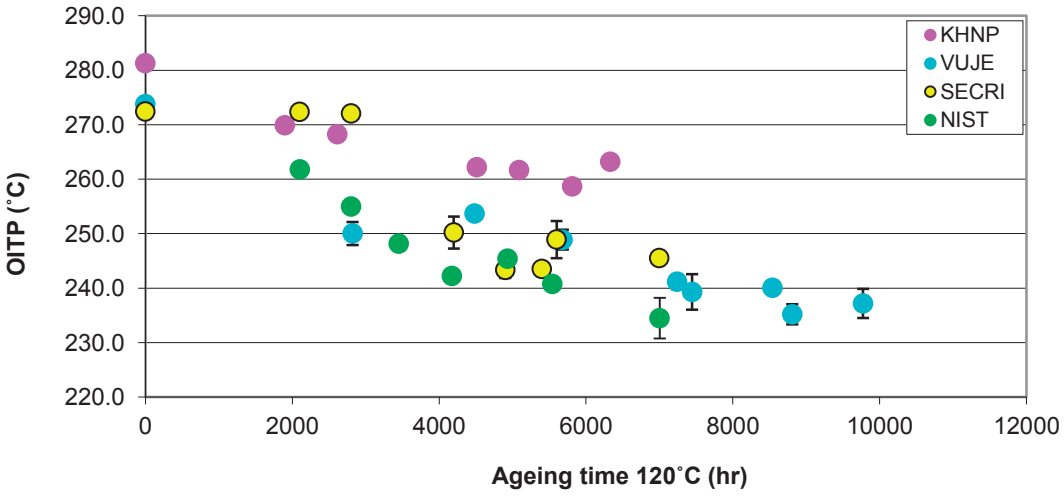


FIG. 41. OITP data for thermally aged Eupen EVA jacket.

In general, the OIT and OITP techniques are usually complementary, OIT tracking the early stages of degradation and OITP the later stages.

5.6.THERMOGRAVIMETRIC ANALYSIS

The variations in the TGA data reported by each lab are likely to be due to differences in sample preparation techniques and sample composition. Where more than one lab has carried out TGA tests (e.g. for Rockbestos XLPE), the differences in the sample preparation methods used by each lab may have caused discrepancies in the reported TGA 5% and max weight loss data. Overall, the TGA data reported by each lab shows little to no trending for most of the polymer types during the ageing process, and, therefore, TGA testing is not a useful method for monitoring degradation of most of these materials. For the few materials that do show a trend, the changes are large enough to be potentially useful.

5.7.DENSITY

Only one lab carried out density measurements on aged samples, but several laboratories measured the unaged material. Provided that care is taken to eliminate air bubbles on the sample surface and to minimize carryover of the wetting agent into the measuring liquid, consistent results are achievable with either the density bottle method or the Archimedes principle method. It is necessary to correct for the temperature variation of the density of water if using the density bottle method, or if using the Archimedes principle method without a controlled temperature water bath.

Overall, density changes are measurable but in most cases the changes are not large compared with the standard deviation of the measurements and therefore density is generally not practical as a CM method.

5.8.FOURIER TRANSFORM INFRARED SPECTROSCOPY

Only two laboratories carried out FTIR measurements in this programme, and each used different peaks to track changes so there is no direct comparison possible between laboratories. However, the general trends appear to be similar where both laboratories have tested the same material.

At present, the FTIR technique is at the potentially useful stage. Trends are observable with ageing but the test method needs to be refined to make it a practical technique for CM.

5.9.ULTRASONIC VELOCITY

For these tests, the two laboratories participating tested different materials (with one exception) and used different reporting parameters, so there is no direct comparison possible between laboratories. However, the same general trend has been seen in both laboratories.

This is another technique that shows considerable promise as a CM method but needs further refinement to become practically useful.

5.10. TAN DELTA

Measurements of Tan Delta or dielectric loss are made on samples aged as whole cable. A minimum length of 1 m was used. There are no consistent comparisons of Tan Delta data between the two participating laboratories but the general trend of the Eupen EPR is similar for both laboratories as shown in FIG. 42. The Changzhou EPR samples shown in FIG. 43 indicate the most consistent trend line for the thermally aged conditions, but were only from one lab. A further analysis of all frequencies may provide evidence of comparable results.

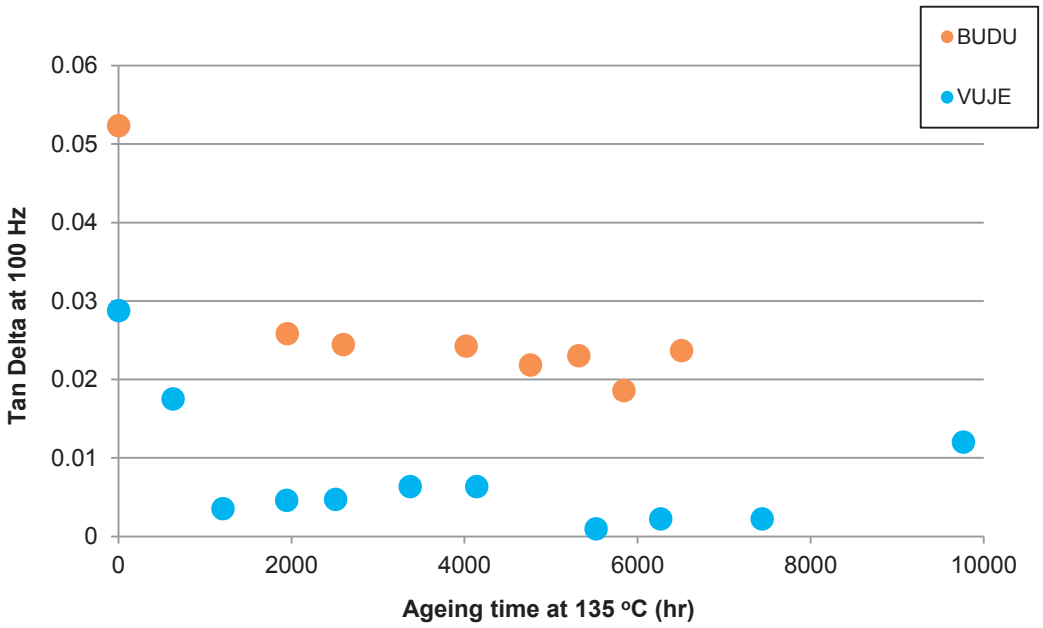


FIG. 42. Tan δ data for thermally aged EPR insulation (Eupen) black/all.

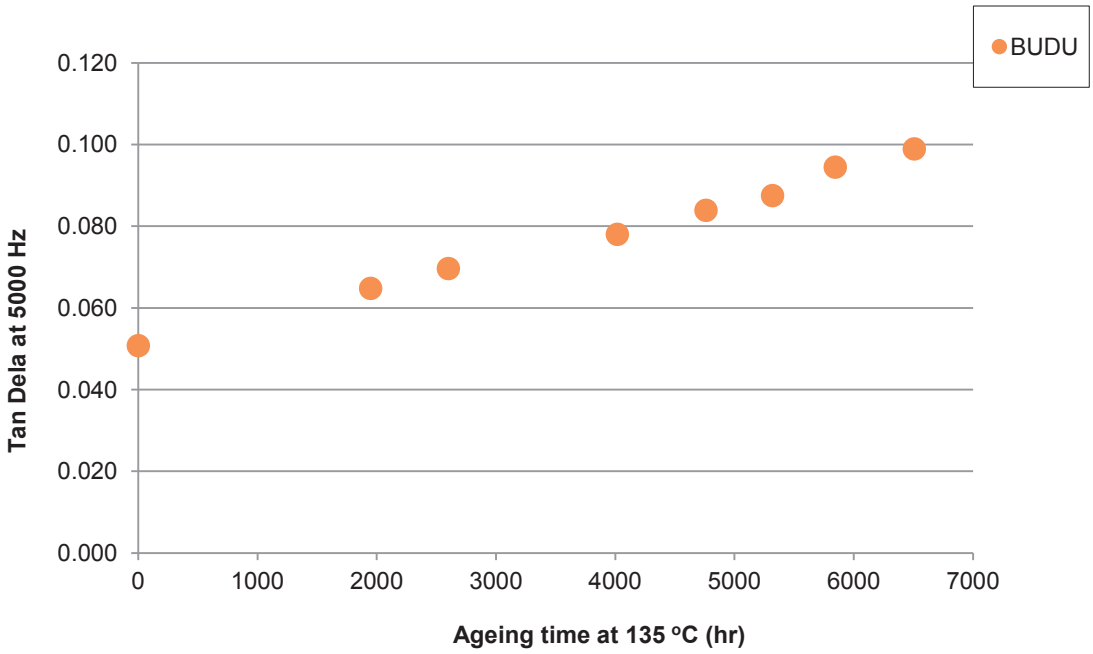


FIG. 43. Tan δ data for thermally aged EPR insulation (Changzhou).

5.11. DIELECTRIC SPECTROSCOPY

The dielectric spectroscopy testing technique which is a measure of the cable material's permittivity was performed by one laboratory only. Also for this test, the Habia cable was aged at a high temperature of 190°C which did not allow for testing beyond the initial unaged condition. Permittivity changes were more consistent for the radiation aged samples than for the thermal aged ones. The EPR insulated cables indicated the more consistent results as shown in FIG. 44 and FIG. 45 but not consistent enough for trending.

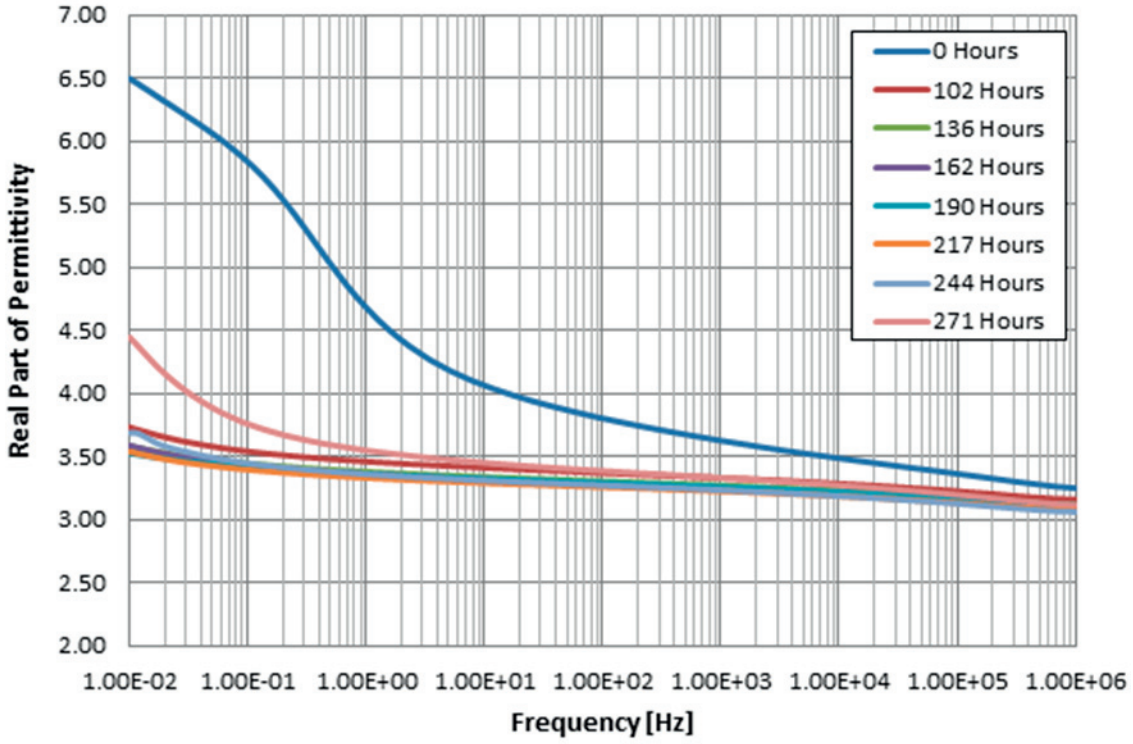


FIG. 44. Real part of permittivity vs frequency of Eupen (EPR/EVA) cable after thermal ageing at 135°C.

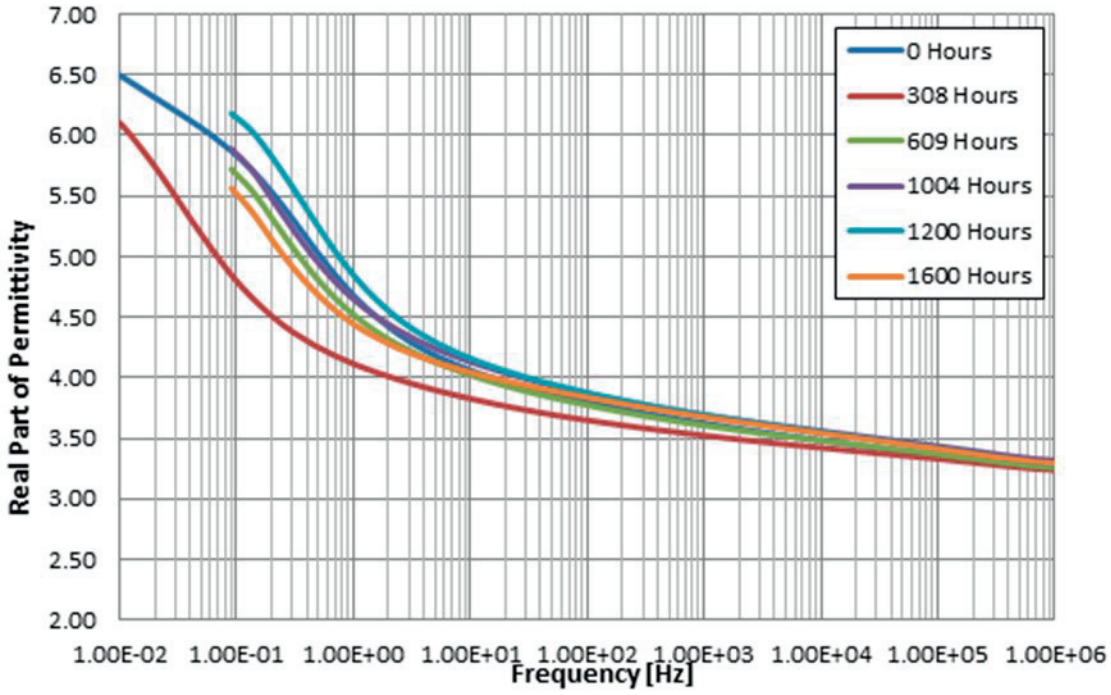


FIG. 45. Real part of permittivity vs frequency of Eupen (EPR/EVA) cable after irradiation at room temperature (0.3 kGy/h).

5.12. REFLECTOMETRY

For reflectometry testing, a ‘hot spot’ of 1 meter or less in length was induced on a portion of the cable. The test cable was removed periodically from the ageing oven and tested at thermally aged conditions that corresponded to the mechanical and chemical test samples.

The TDR testing did not detect or trend with the thermally induced hot spots located along the length of the cable. Only the Habia PEEK cable thermally aged at 190°C showed any change with TDR. The high temperature applied to the PEEK material caused permanent insulation damage and a maximum TDR change at the first ageing condition. Further testing for this material would need to be aged at a lower temperature to allow for moderate degradation. The TDR technique is not a good CM method for trending insulation ageing.

The FDR technique test results for the Habia PEEK cable identified the same ageing temperature issue by measuring a maximum degradation peak at the first ageing condition. However, the FDR technique did provide better test results than TDR on several cable types. Both the Eupen EPR (FIG. 46) and the Hew SiR (ageing time at 190°C (hr), FIG. 47) cable samples trended an increase in insulation degradation for all the ageing conditions. Also, the Changzhou EPR cable sample indicated a moderate amount of degradation. The degradation trend line begins later than the traditional EAB data. This reflectometry technique can be used as a lagging degradation indicator for several of the most common cable types.

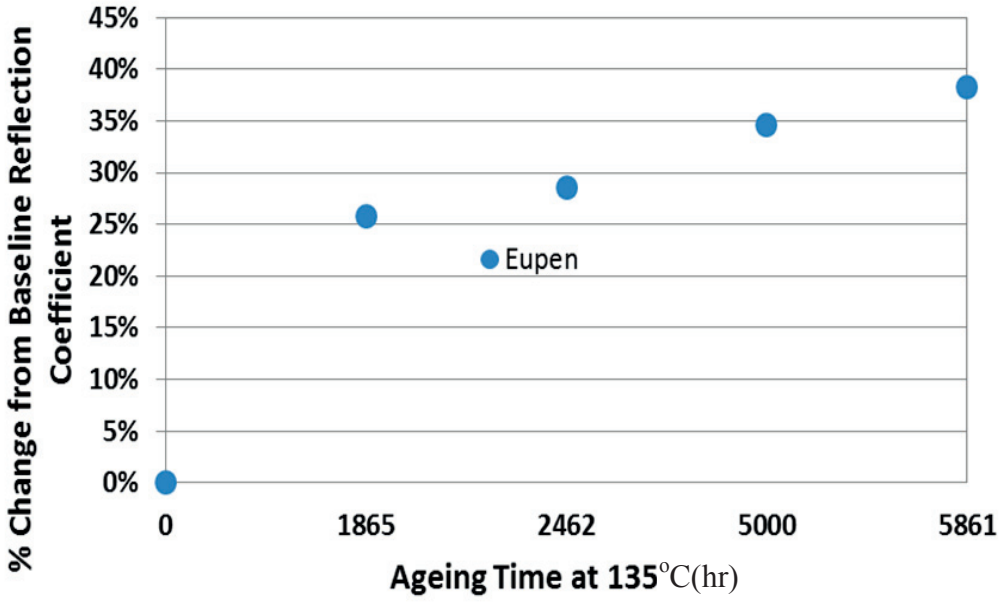


FIG. 46. FDR data for thermally aged Eupen insulation (EPR)

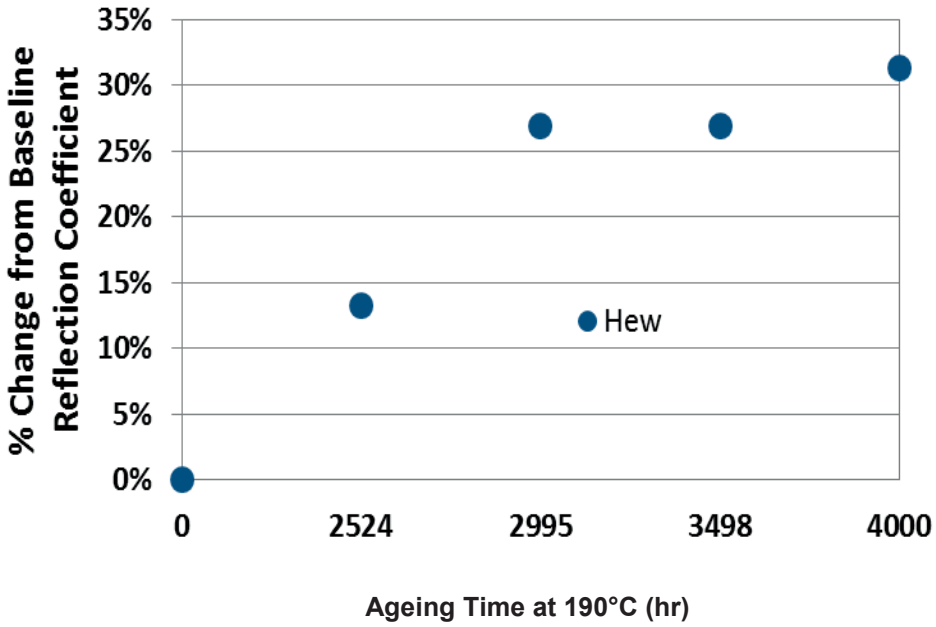


FIG. 47. FDR data for thermally aged Hew insulation (SiR).

5.13. INSULATION RESISTANCE

Each participating lab used different cable lengths for their IR study. The different lengths were used to calculate a compensated IR value at the 1 minute measurement for comparison among the participating laboratories. There were no insulation material types that indicated a reasonable trend for this CM technique. This measurement of the integrity of the cable insulation does not consistently follow increased insulation damage caused by thermal or radiation ageing.

5.14. IMPEDANCE: CAPACITANCE

The impedance data results were a total capacitance measurement of the cable sample aged as a whole. There were no insulation material types that indicated a reasonable trend for this CM technique. This measurement of the capacitance does not consistently follow increased insulation damage caused by thermal ageing.

5.15. BENCHMARKING TEST

5.15.1. PEEK insulation: Habia

EAB data for thermally aged PEEK insulation shows some trending with ageing time but is victim to large standard deviations that undermine the trending results. The average standard deviation for the data from VUJE (as displayed by the vertical error bars in FIG. 32) is 28.2%. A similar trend is seen for the unpigmented PEEK insulation, with an average standard deviation of 29.3%. These large standard deviations arise partly from the sample preparation method used and partly from the change in morphology observed after thermal ageing.

Cross-plots of IM, TGA 5% weight loss, TGA max rate of weight loss and density versus EAB all show no usable trend.

Reflectometry results did not indicate any trending for the Habia PEEK insulated cable. A localized hot spot was induced in several locations along the length of a 20 meter cable sample and thermally aged at 190°C. This high temperature immediately caused permanent damage to the XLPO jacket as well as the PEEK insulation. Both TDR and FDR traces indicated a maximum peak that did not change after the initial measurement at the hot spot locations.

5.15.2. XLPO Habia jacket

EAB measurements on this XLPO jacket material show a strong downward trend with thermal ageing time (FIG. 48), although there are significant differences between laboratories in terms of the absolute values measured. Cross-plots of IM vs. EAB show no useful trend for this material. Recovery time, however, does trend well with EAB, increasing as the EAB value decreases (FIG. 49).

OIT values show a useful trend with EAB for the early stages of ageing and would be useful as an early warning CM method. OITP shows a useful trend over the full range of EAB (FIG. 50). Neither of the TGA parameters shows any useful trend with EAB.

Density shows a slight trend with EAB for thermal ageing but it is not large enough to be useful. FTIR and ultrasonic velocity measurements show no usable trend with EAB.

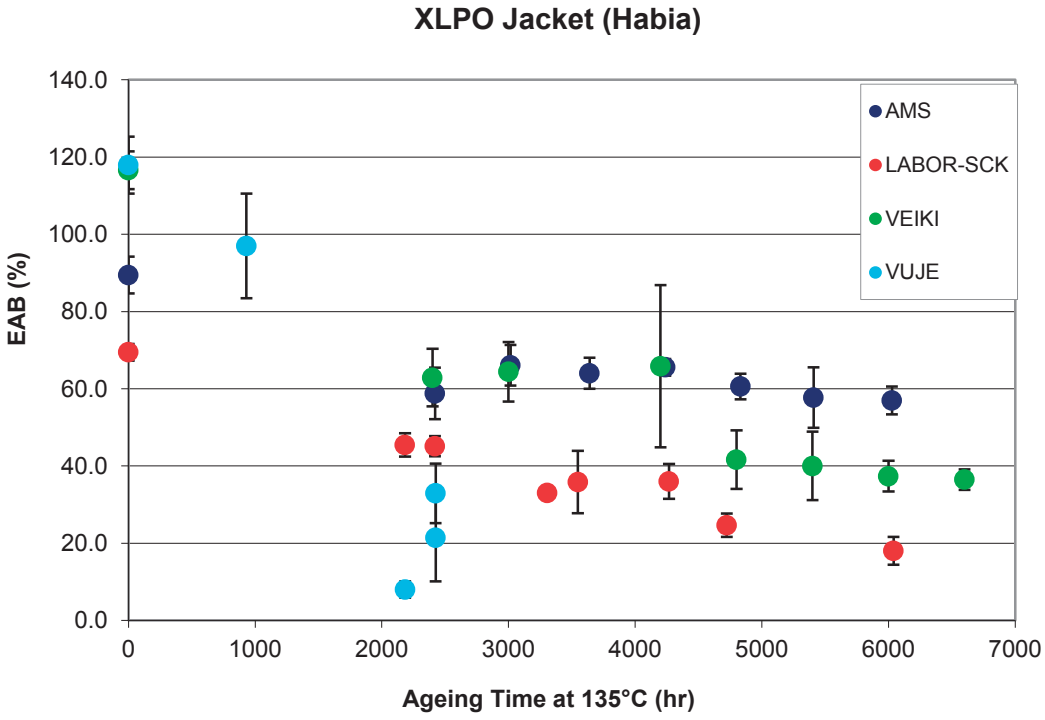


FIG. 48. EAB data for thermal ageing of XLPO jacket (Habia).

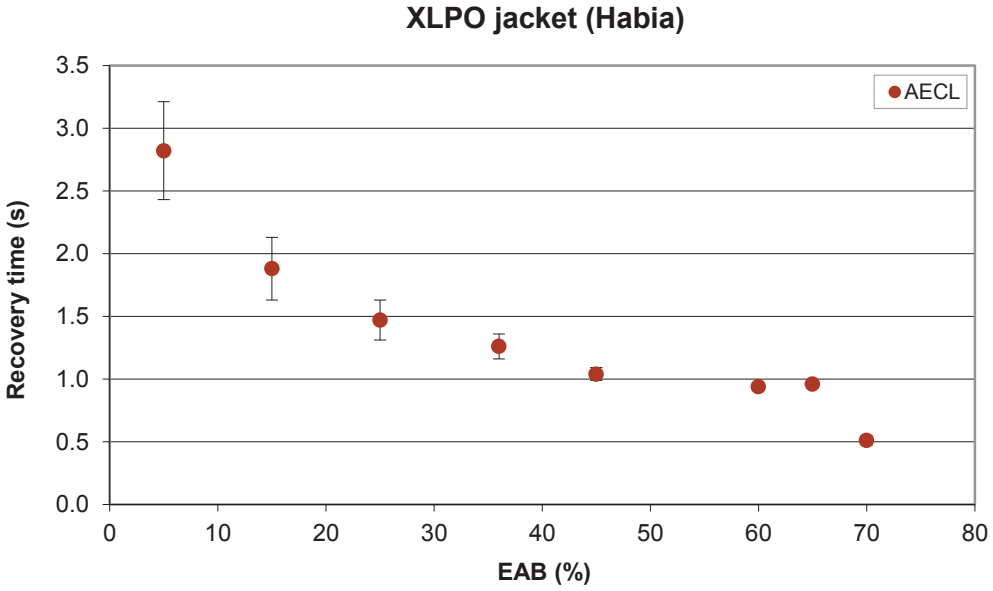


FIG. 49. Cross-plot of recovery time vs. EAB for XLPO jacket (Habia).

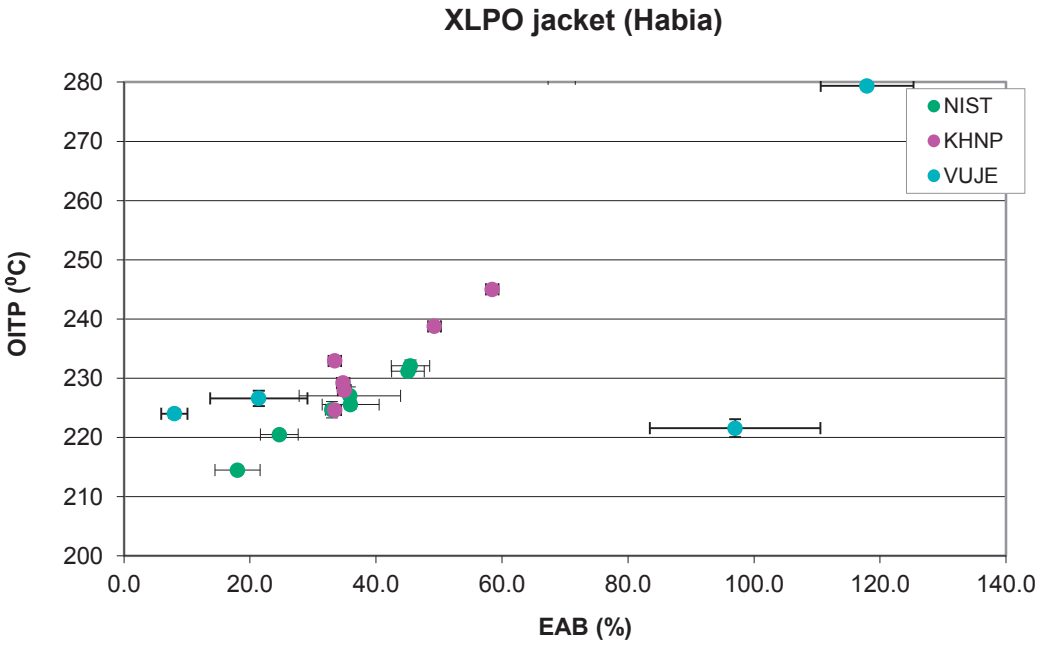


FIG. 50. Cross-plot of OITP vs. EAB for XLPO jacket (Habia).

5.15.3. EPR Eupen insulation

EAB values for EPR insulation (black colour) show a strong decrease with thermal ageing time (FIG. 51). Similar trends are seen for the other colours tested.

Cross-plots of IM vs. EAB are shown in FIG. 52, for one of the laboratories. During the early stages of the ageing process (EAB > 150%), the IM data follows a slight upward trend with decreasing % EAB. The average increase in the IM data over this range is only 28%, but,

since the average standard deviation of the data is 3.9%, this increase in IM is measurable. Below the 150% EAB point, the IM data shows a significant upward trend with decreasing % EAB, increasing by an average of 61% over this range, which indicates that IM testing, would be more useful for assessing the later stages of degradation for this polymer.

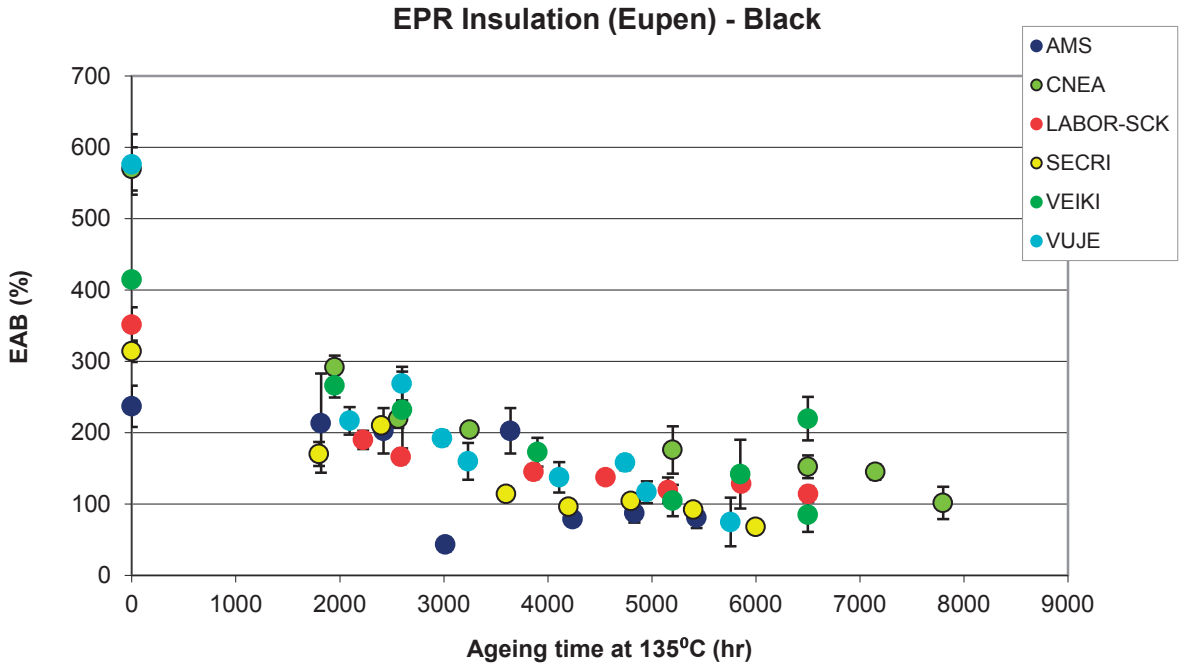


FIG. 51. EAB data for thermal ageing of EPR insulation (Eupen) – black colour.

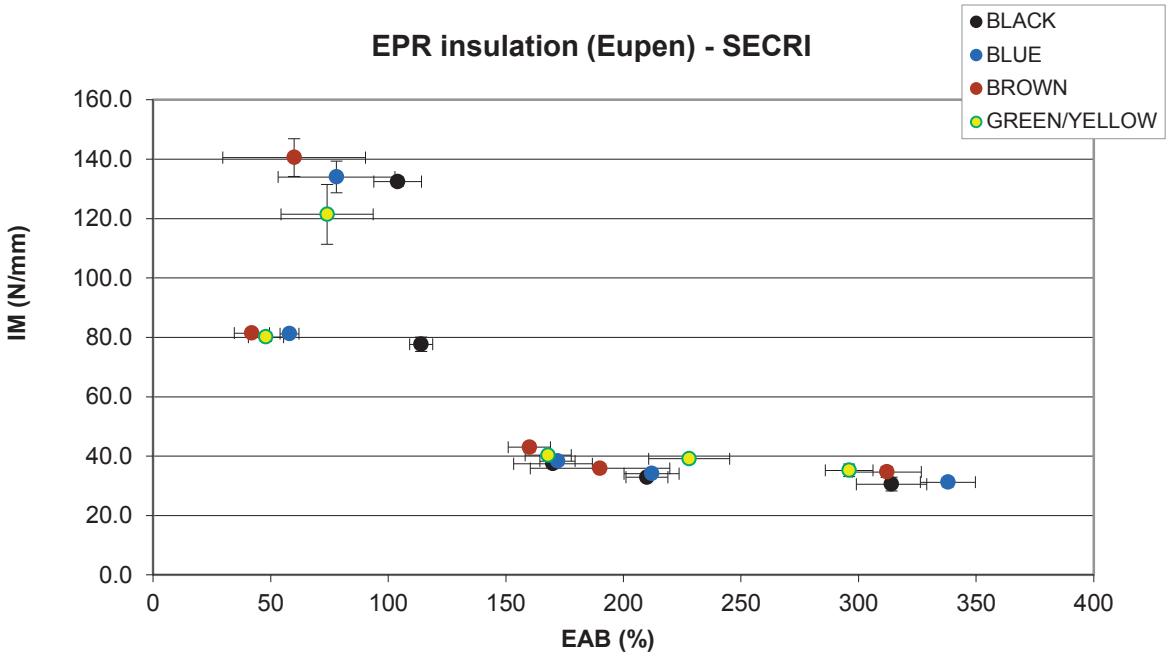


FIG. 52. Cross-plot of IM vs. EAB for EPR insulation (Eupen) – Shanghai Electric Cable Research Institute (SECRI) data.

Cross-plots of OIT vs. EAB show that OIT testing is quite useful for assessing the early stages of degradation for this polymer. During the early stages of the ageing process (EAB >150%), the OIT values reported by each lab decreased by an average of 56%. Since the average standard deviation of each data point is only 1.04%, this large change in OIT can be useful for monitoring early onset degradation for this material. Below 150% EAB, the OIT values reported by each lab rapidly approach 0 minutes.

Cross-plots of OITP vs. EAB (FIG. 53) show that OITP measurements can be used to monitor the degradation of this material during the later stages of the ageing process. The OITP data reported by each lab shows a gradual decrease with increased EAB %. Above 200% EAB, the OITPs is decreased by an average 8.0%, which indicates that OITP measurements can be somewhat useful for assessing the early portion of the degradation process. However, since the OITPs is decreased on average by 21.0% below the 200% EAB mark; this test technique would be more useful for examining the later stages of the ageing process for this polymer. The OIT and OITP tests are complementary for this EPR material.

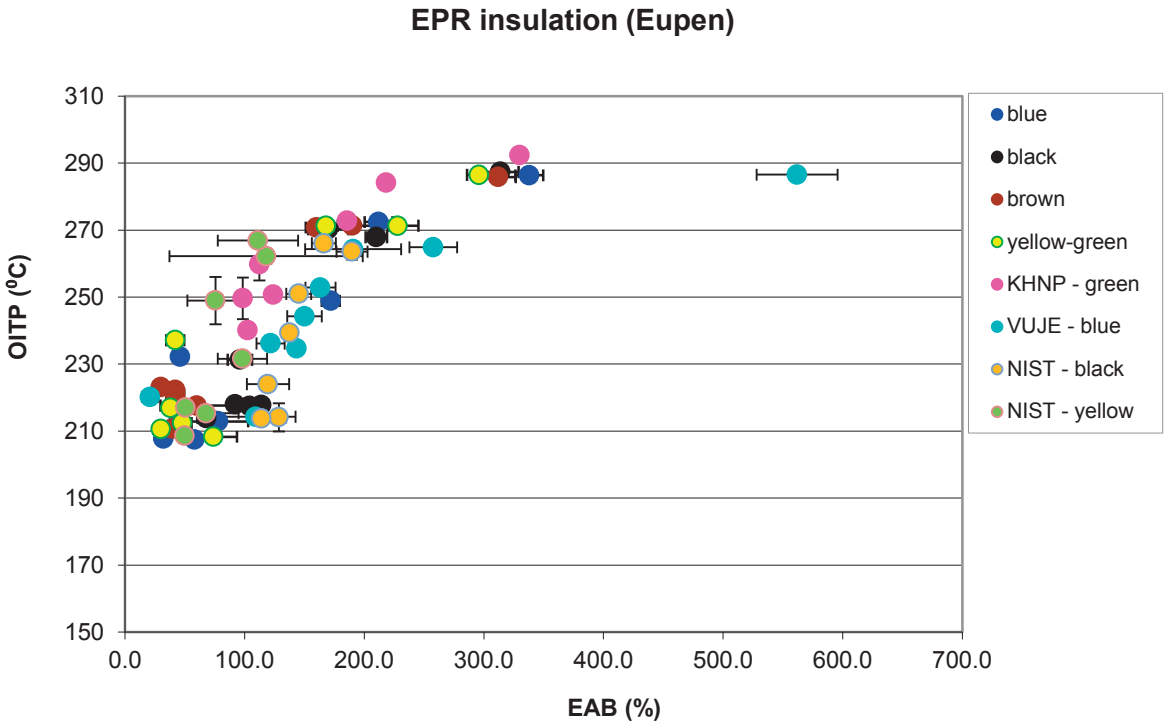


FIG. 53. Cross-plot of OITP vs. EAB for EPR insulation (Eupen).

The cross-plot of density vs. EAB shows no usable trend for this EPR material and therefore density is not useful for tracking degradation for this polymer.

Cross-plots of FTIR data indicate that FTIR may be useful for assessing the later stages of the degradation process for this material. Though the data is rather scattered, an obvious upward trend does appear in the FTIR results with decreasing EAB%.

Reflectometry results indicated trending for the Eupen insulated cable. A localized hot spot was induced in several locations along the length of a 20-meter cable sample and thermally aged at 135°C. Subsequent measurements of the hot spot showed increased degradation for each FDR measurements. The FDR trend consistently shows a per cent increase from baseline throughout the ageing process. TDR did not indicate any noticeable trend.

5.15.4. EVA Eupen jacket

The EAB results for thermally aged EVA jacket are shown in FIG. 33, showing a large decrease with ageing time. Cross-plots of IM vs. EAB are shown in FIG. 54. Though the data sets show discrepancies in the IM results reported by each lab, each IM data set follows a similar upward trend with decreasing EAB%. Over the 250% to 50% EAB range, the IM data increases by an average of 60%, which, since the standard deviation is < 8%, indicates that this technique is quite useful for tracking the ageing process of this polymer.

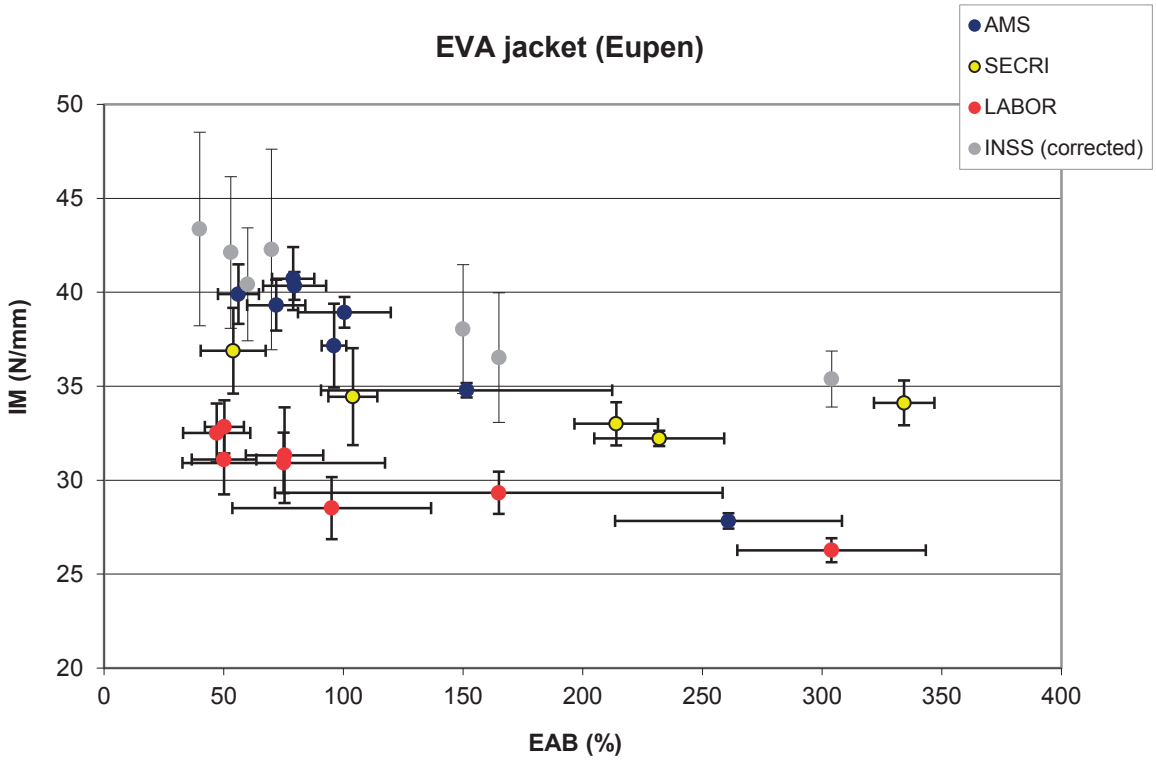


FIG. 54. Cross-plot of IM vs. EAB for EVA jacket (Eupen).

The cross-plot of recovery time vs. EAB shows that recovery time measurements are not very useful in tracking degradation for this polymer. The recovery time undergoes a large decrease during the earliest portion of the ageing process but shows no significant trend afterwards.

The cross-plots of OIT vs. EAB indicate that OIT testing is quite useful for assessing the early stages of degradation for this polymer. During the early stages of the ageing process (EAB > 150%), the OIT values dropped from 55 minutes to 0 minutes. This large change in OIT values can be useful for monitoring the early stages of degradation for this material.

Cross-plots of OITP vs. EAB indicate that OITP can be used to monitor the degradation of this material during the later stages of the ageing process. Though the data sets show differences in the OITP results reported by each lab, each OITP data set follows a downward trend with decreasing EAB % as shown in FIG. 55. Above 200% EAB, the OITPs decrease very little, which indicates that OITP measurements are not useful for assessing the early portion of the degradation process. However, since the OITPs decrease on average by 7.0% below the 200% EAB mark (standard deviation is on average 1.2%), this test technique would be more useful for examining the later stages of the ageing process for this polymer. For this EVA jacket material, OITP and OIT are complementary tests, OIT being more useful for assessing early degradation and OITP more useful for the later stages of degradation.

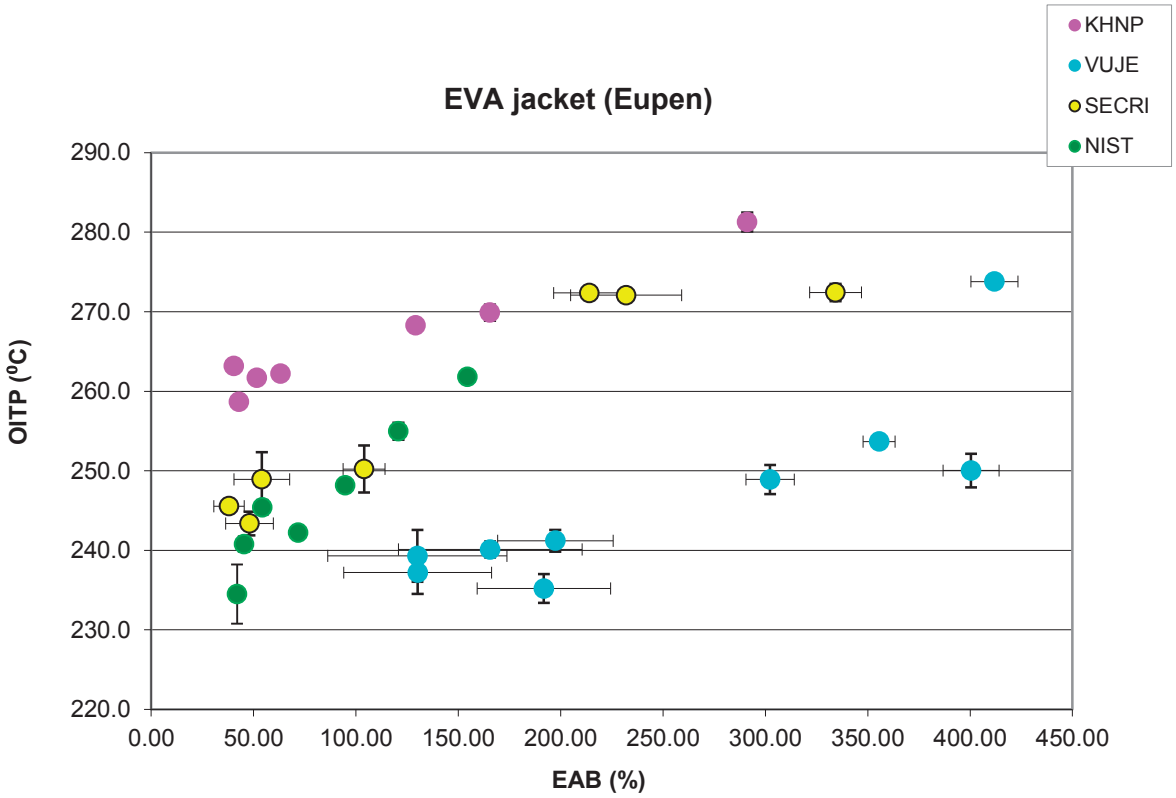


FIG. 55. Cross-plot of OITP vs. EAB for EVA jacket (Eupen).

Cross-plots of density and the TGA parameters vs. EAB show no usable trends during the ageing process for this material, and, therefore, cannot be used to assess degradation. However, there is some indication that density may trend for radiation ageing.

Cross-plots of FTIR ratios show an upward trend in the peak ratios with decreased EAB %, but the data reported by each lab are very scattered. To make an accurate determination of how this technique can be used to track the degradation of this material, more data must be collected and the technique must be refined.

The cross-plots of ultrasonic velocity results (FIG. 56) indicate that ultrasonic velocity testing has the potential to be very useful for assessing degradation throughout the ageing process for this polymer. The pulse duration data reported by Korea Hydro & Nuclear Power Company follows a gradual decrease with decreasing EAB %, but unfortunately the average decrease (3.0%) matches the standard deviation of each data point, which indicates that this method of reporting ultrasonic data may not be useful for degradation assessment. However, the ultrasonic velocity data reported by State Nuclear Power Plant Service Company (SNPSC) shows a substantial increase (50% over the 100% – 350% EAB range) with decreasing EAB %. Since the standard deviation of each data point is less than 10.0%, this test technique has the potential to be quite useful for ageing assessment and tracking of this material, but needs refinement to reduce the degree of scatter in the data.

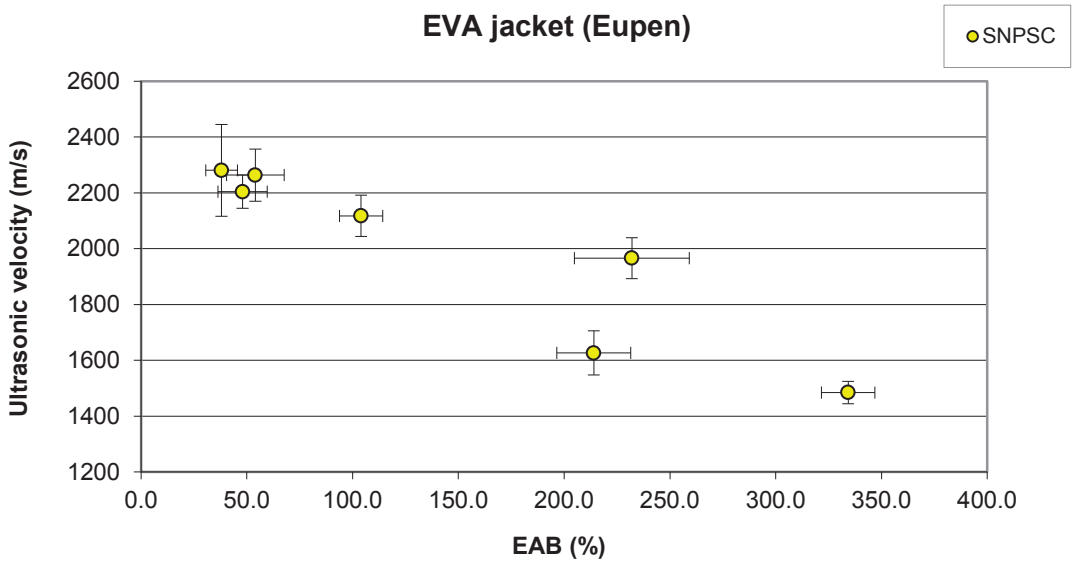


FIG. 56. Cross-plot of ultrasonic velocity vs. EAB for EVA jacket (Eupen).

5.15.5. SiR Hew insulation

For this cable type, there was only a limited amount of material available, so the number of test methods used in the benchmarking programme was very limited. The EAB data for thermally aged SiR insulation exhibits good trending behaviour. Despite the limited number of data points, the IM data cross-plotted against EAB (FIG. 57) exhibits good trending behaviour. The average standard deviation of the IM data is 5.2% and the average standard deviation of the EAB data is 16.1%.

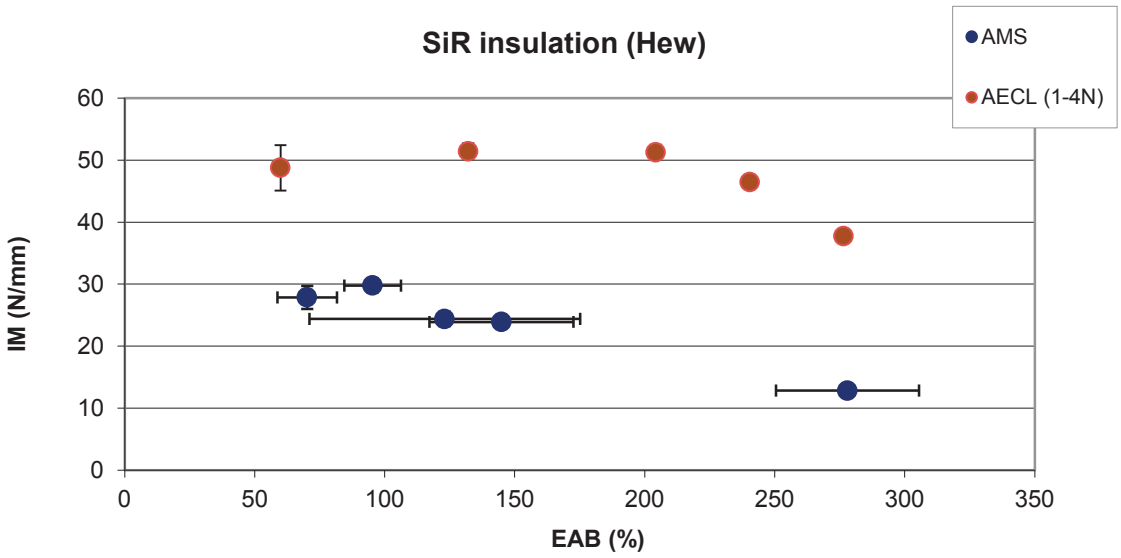


FIG. 57. Cross-plot of IM vs. EAB for SiR insulation (Hew).

Reflectometry results indicated trending for the Hew SiR insulated cable. A localized hot spot was induced in several locations along the length of a 20 meter cable sample and thermally aged at 190°C. Subsequent measurements of the hot spot showed increased degradation for each FDR measurements. The FDR trend did reveal a plateau in degradation

for two consecutive ageing times but then continued to increase from baseline for the remaining ageing process. TDR did not indicate any noticeable trend.

5.15.6. SiR Hew jacket

EAB % shows very good trending over ageing time with very small error bars. Cross-plots of IM vs. EAB show a consistent trend, increasing with decreasing EAB values (FIG. 58). No other CM methods were assessed for this material.

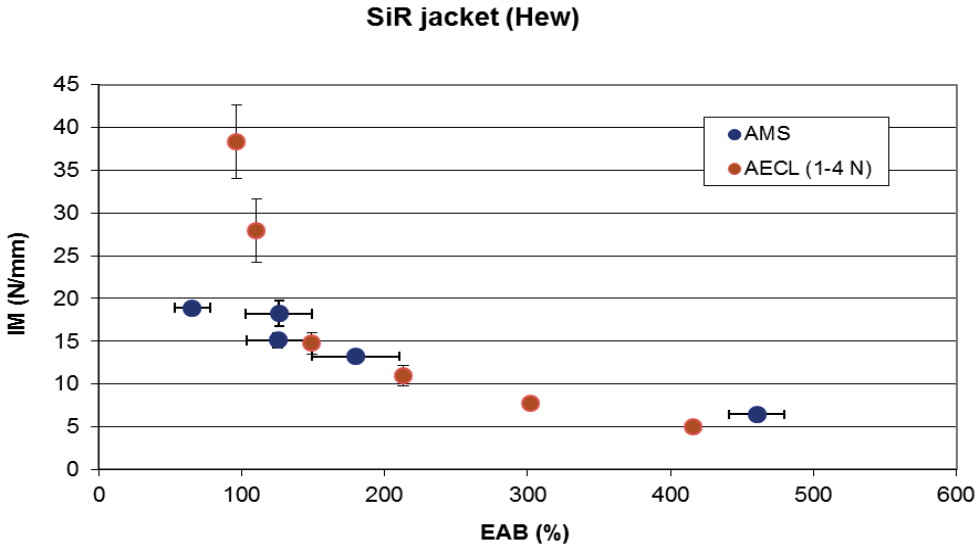


FIG. 58. Cross-plot of IM vs. EAB for SiR jacket (Hew).

5.15.7. XLPE Rockbestos insulation

The EAB data for the XLPE insulation material is shown in FIG. 59. Significant differences between laboratories are seen for EAB measurements on this material, for both initial values and after thermal ageing. The IM data does not provide any useful trending for this XLPE material.

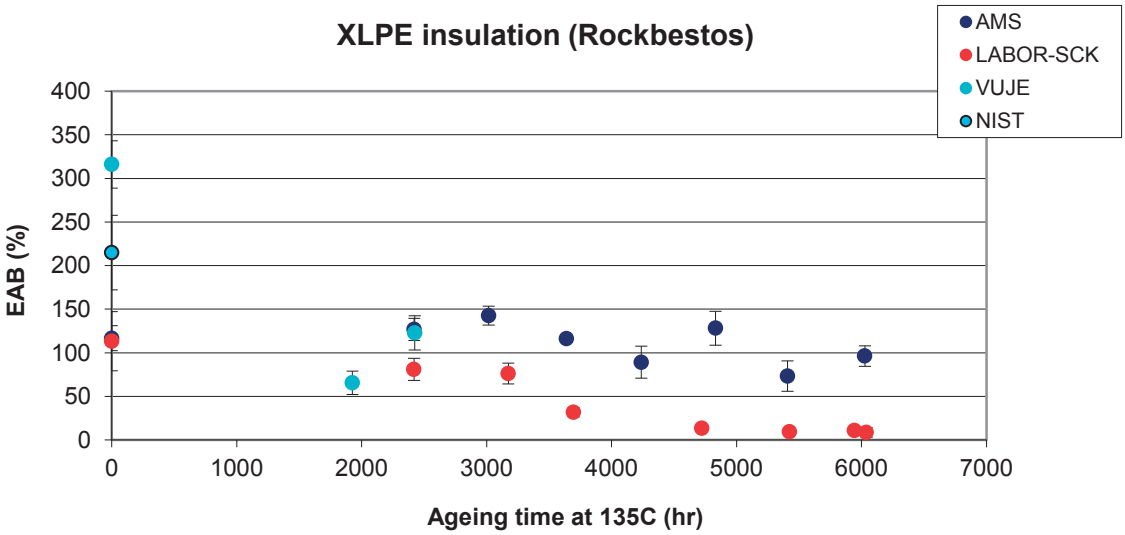


FIG. 59. EAB data for XLPE insulation (Rockbestos).

The OIT cross-plot in FIG. 60 indicates good trending of degradation from the initial EAB value of 200% to the 100% absolute value. As the material degrades below the EAB value of 100%, the OIT measurements reach zero and are no longer useful as an indicator. However, the method is useful for assessing the early stages of degradation.

The OITP cross-plot indicates some change, but the data is somewhat scattered for trending degradation on this material. The decrease in temperature is less than 10% for a reduction in EAB to 100%.

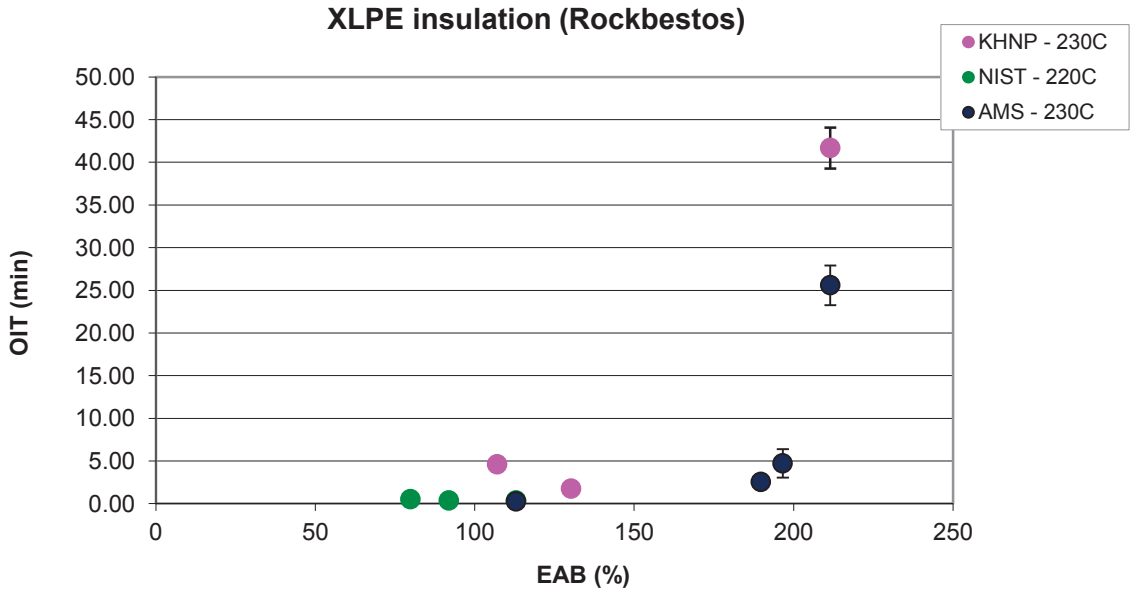


FIG. 60. Cross-plot of OIT vs. EAB for XLPE insulation (Rockbestos).

TGA measurements for both 5% weight loss and maximum weight loss did not indicate any trend as compared to EAB. This CM technique is not useful for the XLPE material.

Density measurements for this material show a strong trend line starting at the initial EAB value of 115%. However, since large changes are only observed for heavily degraded material (EAB < 25%), density measurements are not a practical CM method for this material.

The FTIR CM technique indicates a general increase with decreasing EAB, but is too scattered to provide a usable trend. This technique has potential if the method of testing is improved.

No reflectometry testing could be completed on this Rockbestos XLPE insulation due to the construction of the cable which contained only one conductor and no shield for signal reflections.

5.15.8. CSPE Rockbestos jacket

The EAB data for the CSPE jacket material is compared in FIG. 34. IM and recovery time cross-plots with EAB indicate that both these CM techniques provide measurable changes for early stages of degradation with an IM increase of approximately 50% at EAB value of 100% absolute shown in FIG. 61. The degradation trend line shown in FIG. 62 for recovery time has a larger increase of 4 times greater than the original value at the EAB value of 100%.

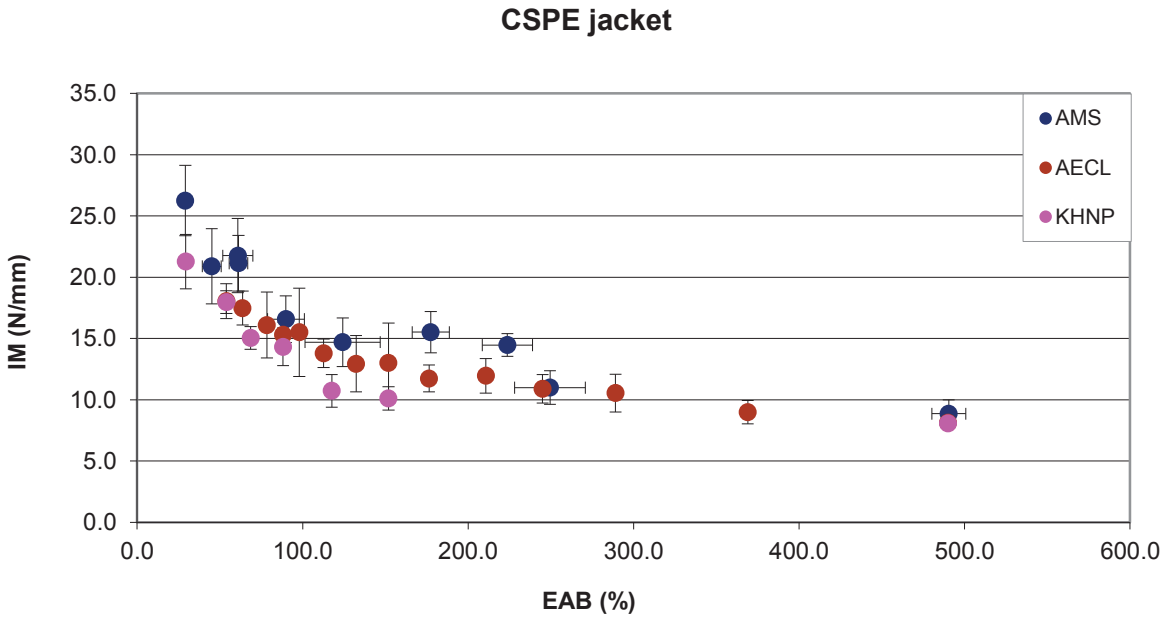


FIG. 61. Cross-plot of IM vs. EAB for CSPE jacket (Rockbestos).

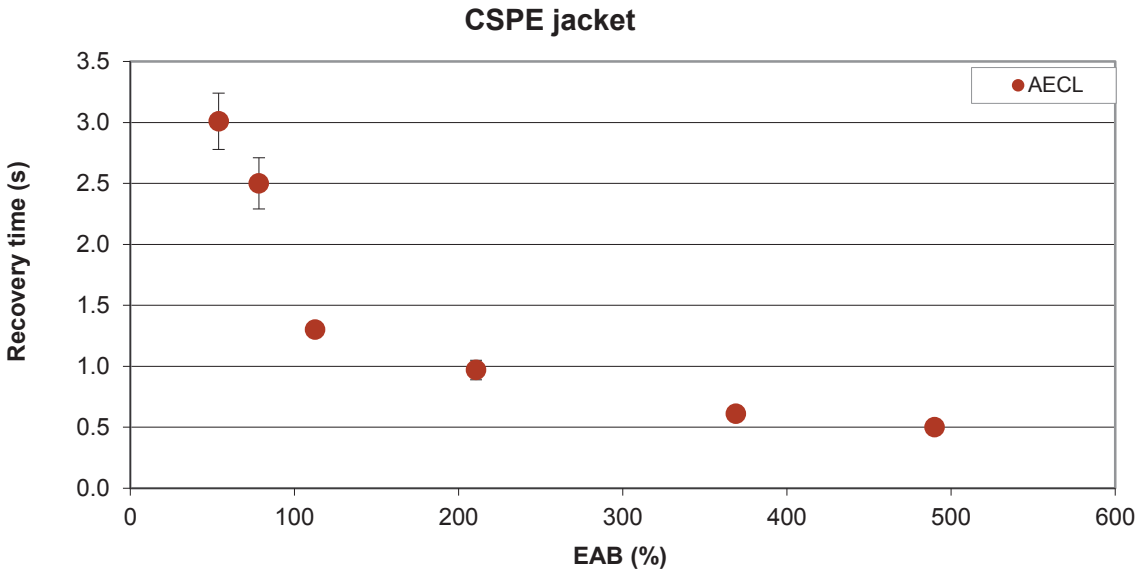


FIG. 62. Cross-plot of recovery time vs. EAB for CSPE jacket (Rockbestos).

The OIT cross-plot in FIG. 63 indicates good trending of degradation from the initial EAB value of 500% to the 100% absolute value. As the material degrades below the EAB value of 100%, the OIT measurements are not as useful.

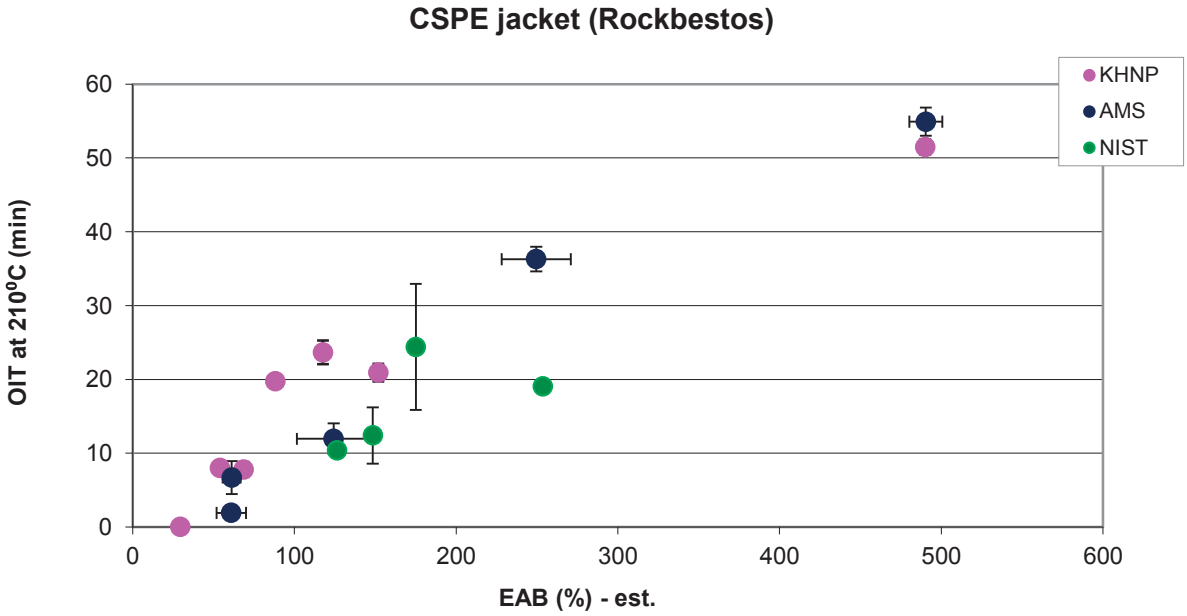


FIG. 63. Cross-plot of OIT vs. EAB for CSPE jacket (Rockbestos).

The OITP cross-plot indicates some change, but is not significant to be useful for trending degradation on this material. The decrease in temperature is about 20ºC for a decrease in the absolute EAB to 100%. Standard deviation for OITP measurements for this material is typically < 1ºC, so the method is potentially useful.

TGA measurements for both 5% weight loss and maximum weight loss do not indicate any change with decreasing EAB %. This CM technique is not useful for the CSPE material.

Density measurements for this material (FIG. 64) do indicate a good trend line starting at the initial EAB value of 400% with an increase of 5% in density which is a significant change relative to the standard deviation of the measurements for trending degradation.

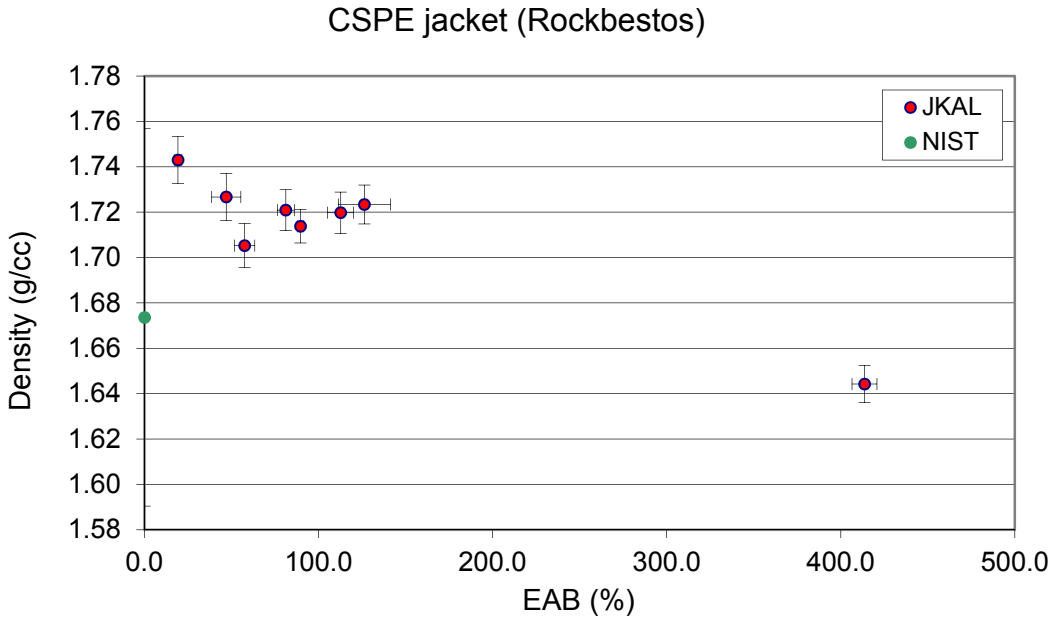


FIG. 64. Cross-plot of density vs. EAB for CSPE jacket (Rockbestos).

The ultrasonic velocity cross-plot for this material is also a good indicator of degradation with an early trend of decreasing pulse duration to the 100% absolute value of EAB (FIG. 65).

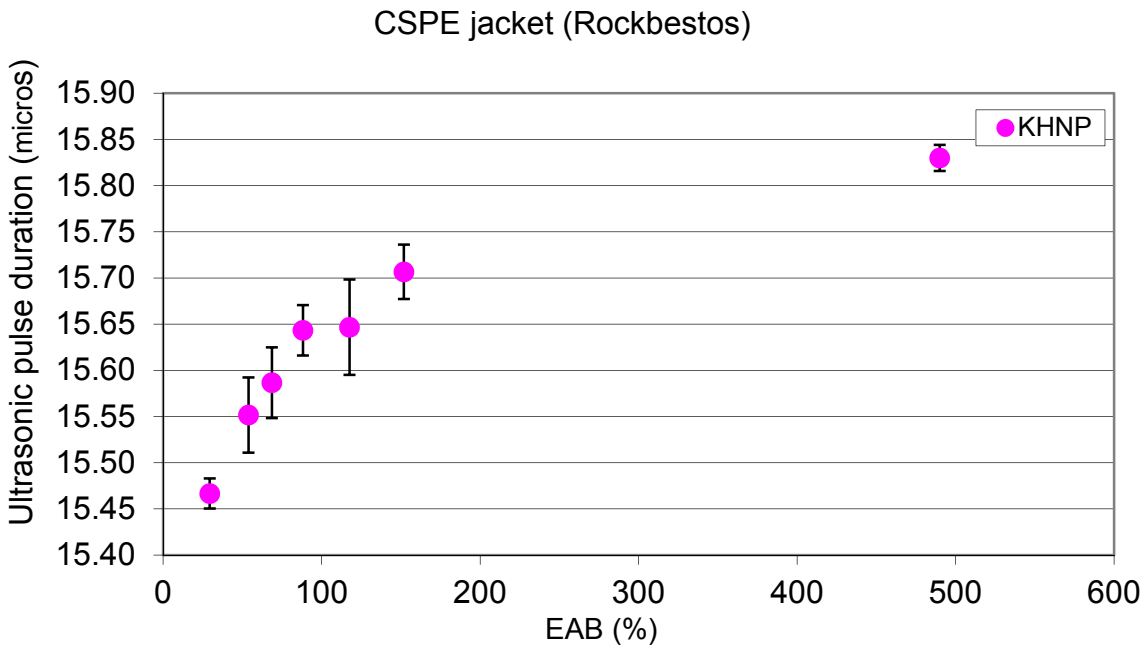


FIG. 65. Cross-plot of ultrasonic velocity vs. EAB for CSPE jacket (Rockbestos).

The FTIR CM technique does indicate a degradation pattern but is too scattered to provide a usable trend. This technique has potential if the method of testing is improved.

5.15.9. EPR Changzhou Bayi insulation

The EAB data for EPR insulation shows a strong trend, with consistent decrease with ageing time (FIG. 66).

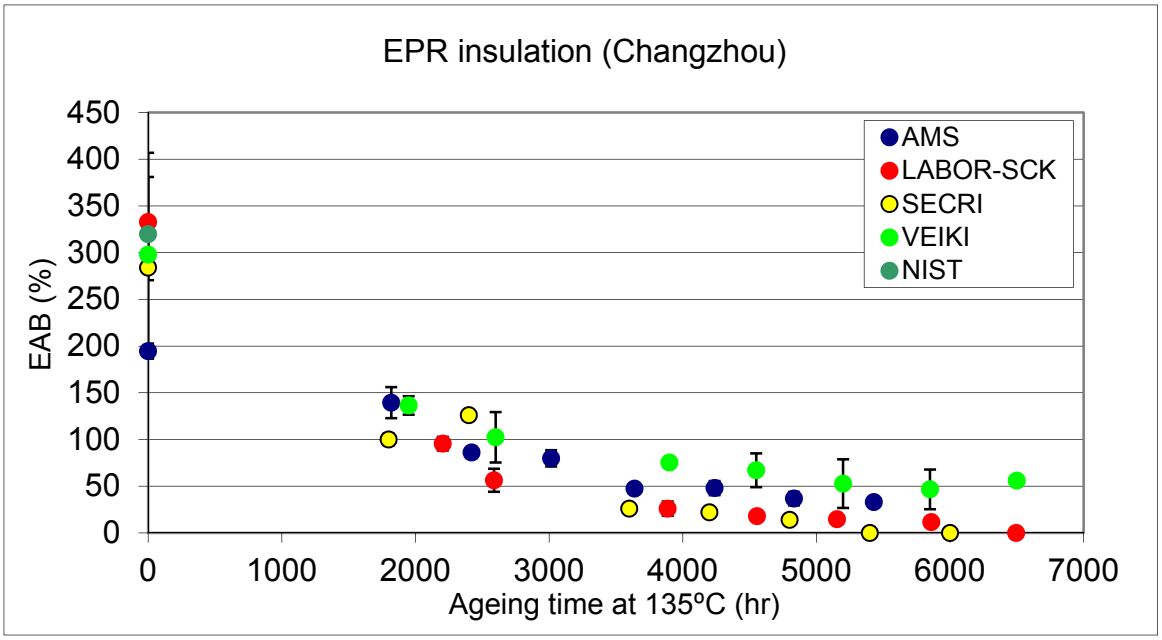


FIG. 66. EAB data for EPR insulation (Changzhou).

Cross-plots of IM vs. EAB show a marked trend with IM values increasing as the EAB decreases (FIG. 67). The largest changes are seen for EAB values < 100%, but for the early stages of degradation changes in IM values are measureable.

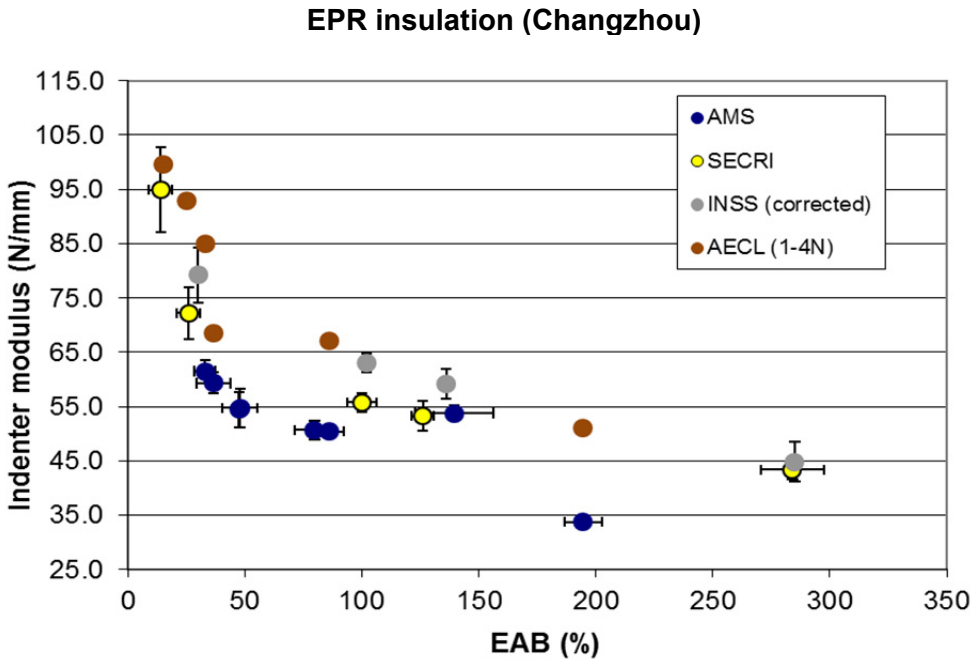


FIG. 67. Cross-plot of IM vs. EAB for EPR insulation (Changzhou).

The OIT data show a strong correlation with EAB for each of the laboratories, although there are differences in the absolute values measured (FIG. 68). OITP data also show a strong correlation with EAB, with large decreases in OITP values relative to their standard deviation (FIG. 69).

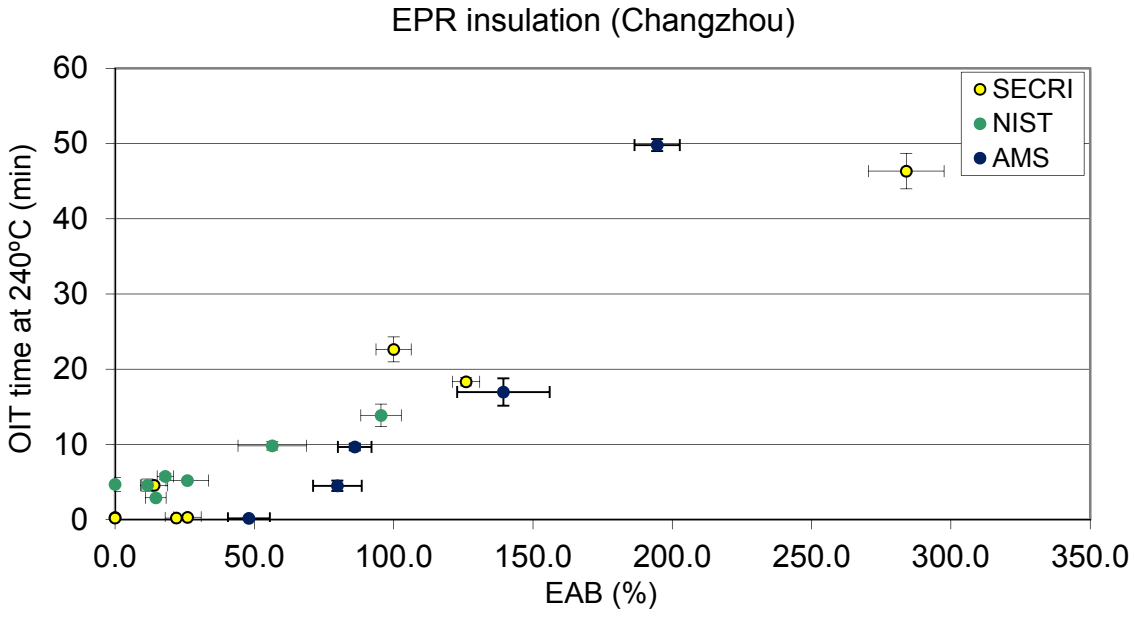


FIG. 68. Cross-plot of OIT vs. EAB for EPR insulation (Changzhou).

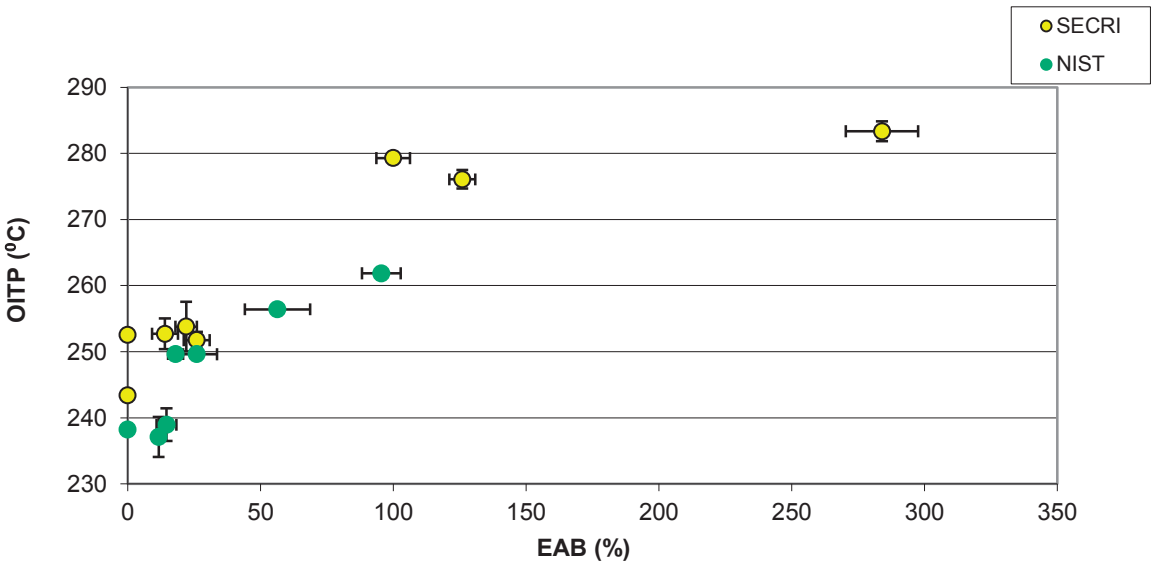


FIG. 69. Cross-plot of OITP vs. EAB for EPR insulation (Changzhou).

Neither of the TGA parameters show any correlation with changes in EAB; therefore, this method is not useful as a CM technique for this material.

Density values show a strong correlation with EAB values (FIG. 70), but the changes are not large relative to their standard deviation, so may not be practical as a CM technique for this material.

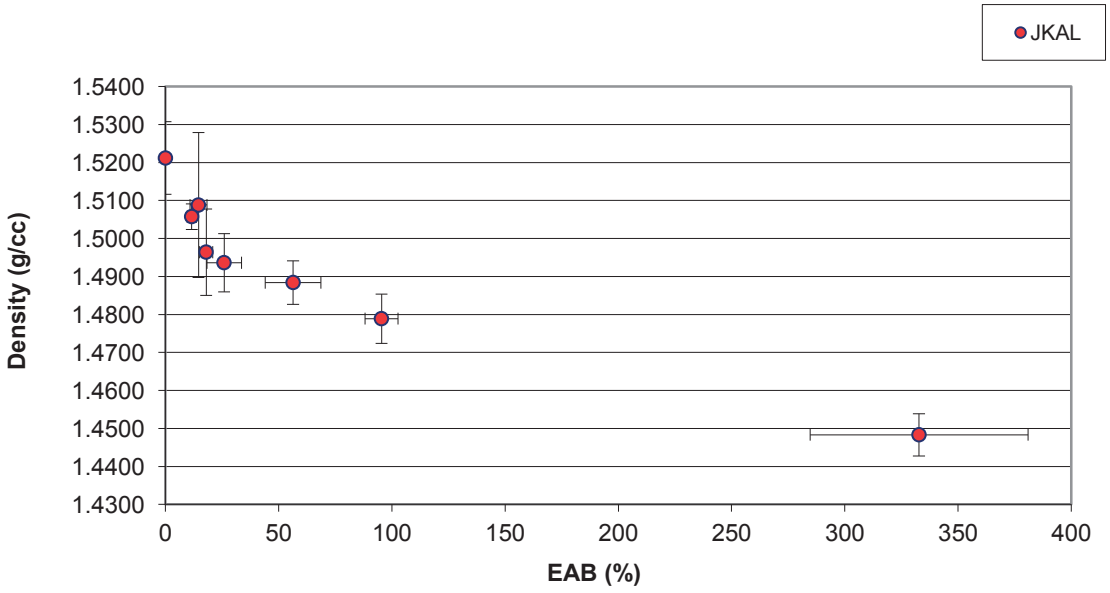


FIG. 70. Cross-plot of density vs. EAB for EPR insulation (Changzhou).

FTIR measurements show some correlation with changes in EAB, but the data are rather scattered and more data and an improvement in the test method is required before this can be used as a practical CM technique.

Reflectometry results indicated a very moderate trend for the Changzhou EPR insulated cable. A localized hot spot was induced in several locations along the length of a 20 meter

cable sample and thermal aged at 135°C. The FDR data was inconsistent but indicated some insulation degradation at the hot spot location. TDR traces did not indicate a clear trend.

5.15.10. EPR Changzhou Bayi jacket

The EAB values for the EPR jacket material are shown in FIG. 71.

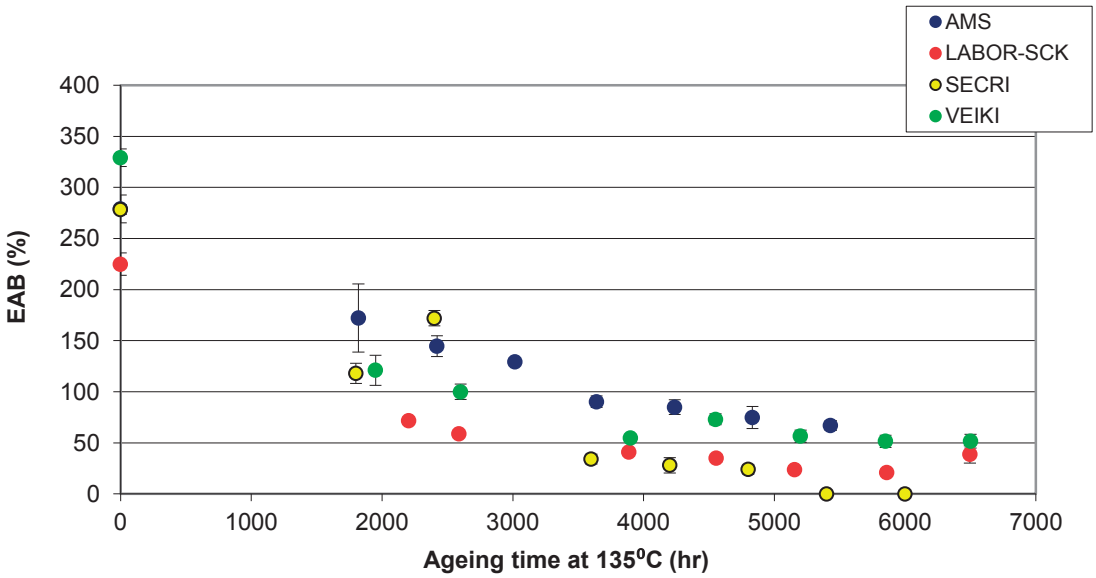


FIG. 71. EAB data for EPR jacket (Changzhou).

IM values show a strong increasing trend as EAB decreases (FIG. 72). For a decrease to 100% EAB the IM increases by 35%, compared with a standard deviation typically of 5-6%. Although the absolute values are different for each lab, all show the same general trend.

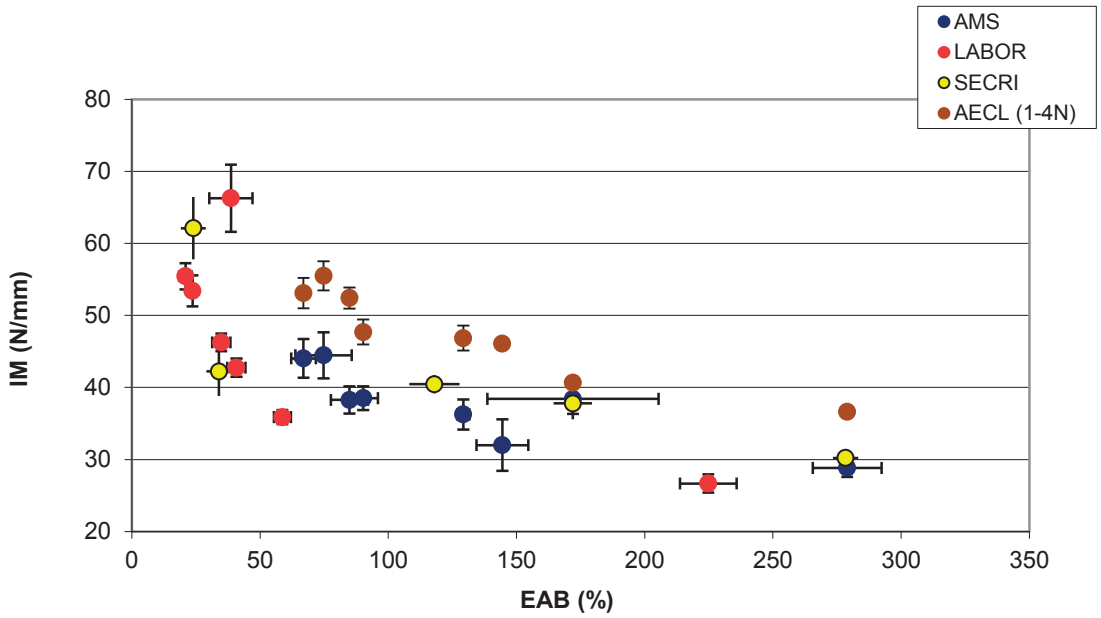


FIG. 72. Cross-plot of IM vs. EAB for EPR jacket (Changzhou).

Recovery time measurements show a small decrease with decreasing EAB until < 100% EAB, where the recovery time increases dramatically. This type of behaviour shows that recovery time would not be a useful CM method for this particular material.

OIT measurements show a decrease from 60 minutes down to zero at EAB < 50% so OIT measurements are a practical indicator for CM over the whole EAB range. Standard deviations for OIT measurements are typically 5% for this material. OITP measurements show a large decrease as EAB decreases, reducing by 30˚C for EAB of 50%. Standard deviations for these measurements are typically 1˚C for this material, so this is a practical CM method.

Density measurements show an increase with decreasing EAB values (FIG. 73), increasing by 4% for EAB of 50%. Standard deviations for these measurements are typically 0.4%, so although the changes are small they are measurable. Cross-plots against IM also show a strong correlation for both thermal and radiation aged EPR jacket shown in FIG. 74.

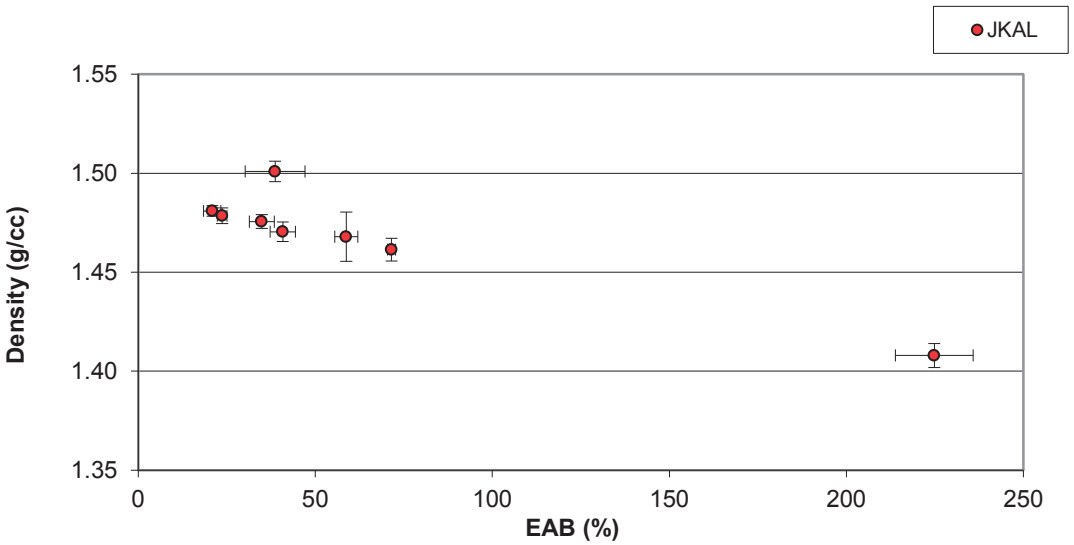


FIG. 73. Cross-plot of density vs. EAB for EPR jacket (Changzhou).

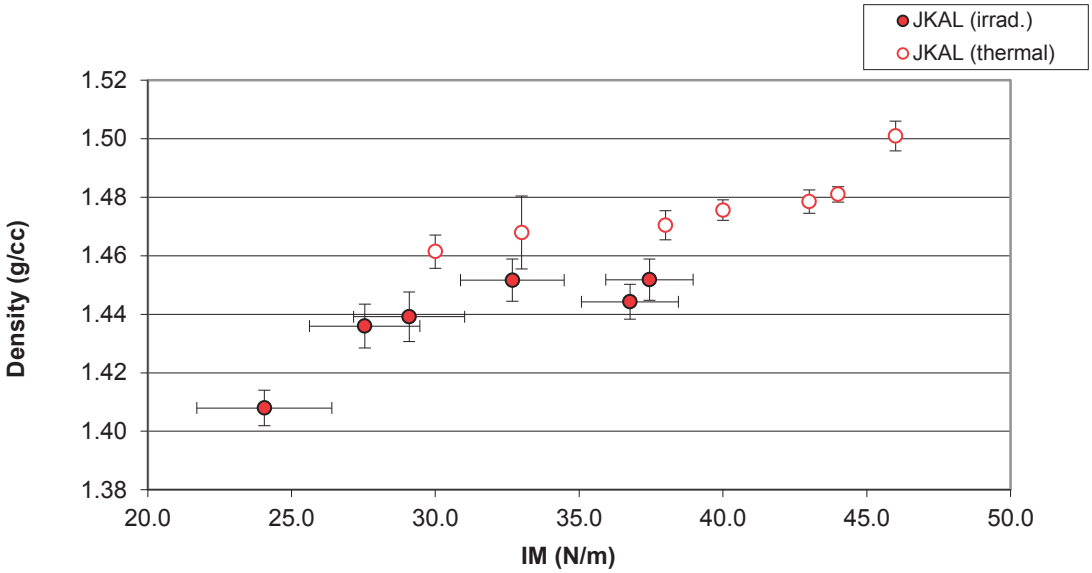


FIG. 74. Cross-plot of density vs. IM for EPR jacket (Changzhou Bayi).

FTIR peak ratios show very scattered data with some possible indication of a trend with EAB. At present this is not suitable as a CM method for this material.

Ultrasonic velocity measurements show some trends with EAB but the data is rather scattered. The method shows some potential, but more data are required before it could be a useful CM method.

5.15.11. XLPO Shanghai insulation

EAB values for XLPO insulation are shown in FIG. 75. There are differences between the data from different laboratories but the general trend is similar.

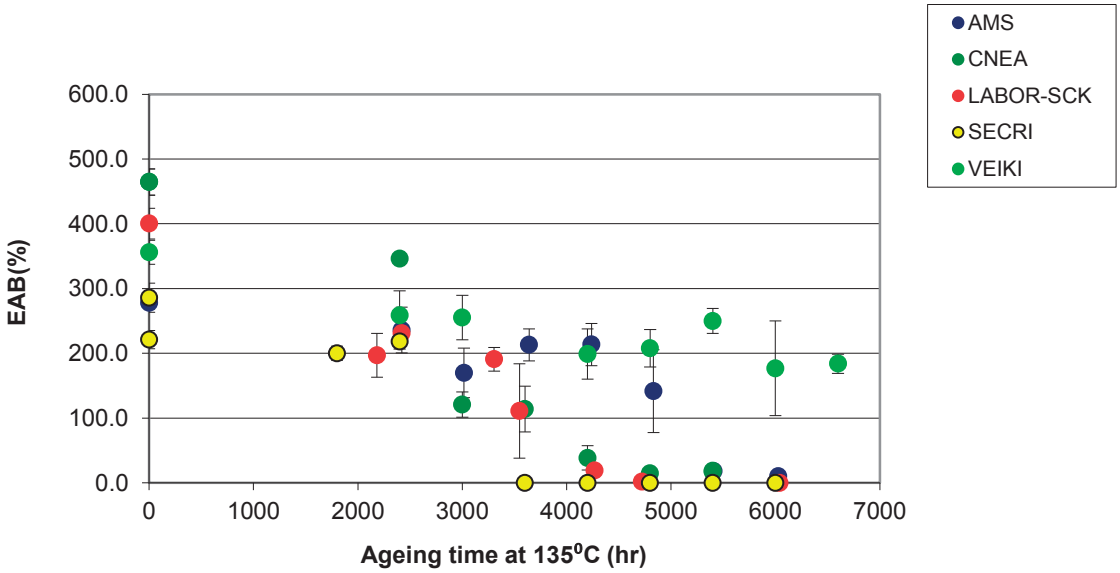


FIG. 75. EAB data for XLPO insulation (Shanghai).

IM measurements show a strong trend, increasing as the EAB decreases (FIG. 76). When the data for INSS are corrected for the different probe tip diameter used, a consistent

data set is obtained, with the IM doubling in value for a decrease in EAB to 100% absolute. Standard deviations for IM measurements are typically 4% in this region.

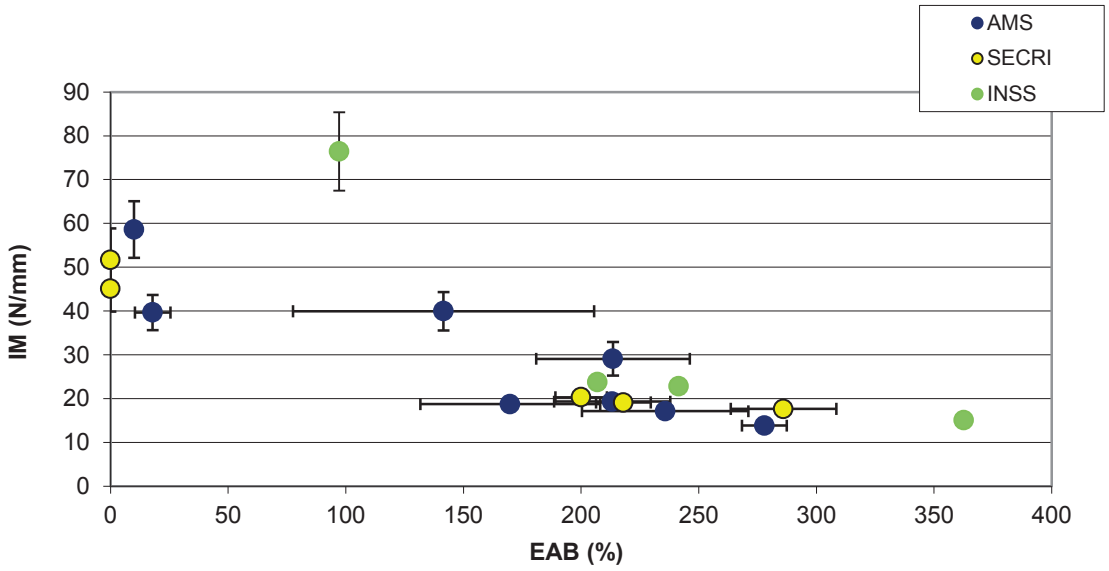


FIG. 76. Cross-plot of IM vs. EAB for XLPO insulation (Shanghai).

OIT measurements show a large decrease from 64 minutes down to zero for EAB of around 150% and so OIT measurements are a useful indicator of the early stages of degradation (FIG. 77). OITP measurements show a similar trend decreasing by 45˚C for EAB down to 150%, but little change is apparent for lower EAB values (FIG. 78). Standard deviation for OITP measurements is typically < 2˚C so these are easily measurable changes. This is a region where the IM does not change very much, so the OIT and OITP measurements usefully complement indenter measurements. Note that the initial value of OIT and the EAB value at which OIT reduces to zero will be dependent on the test temperature used.

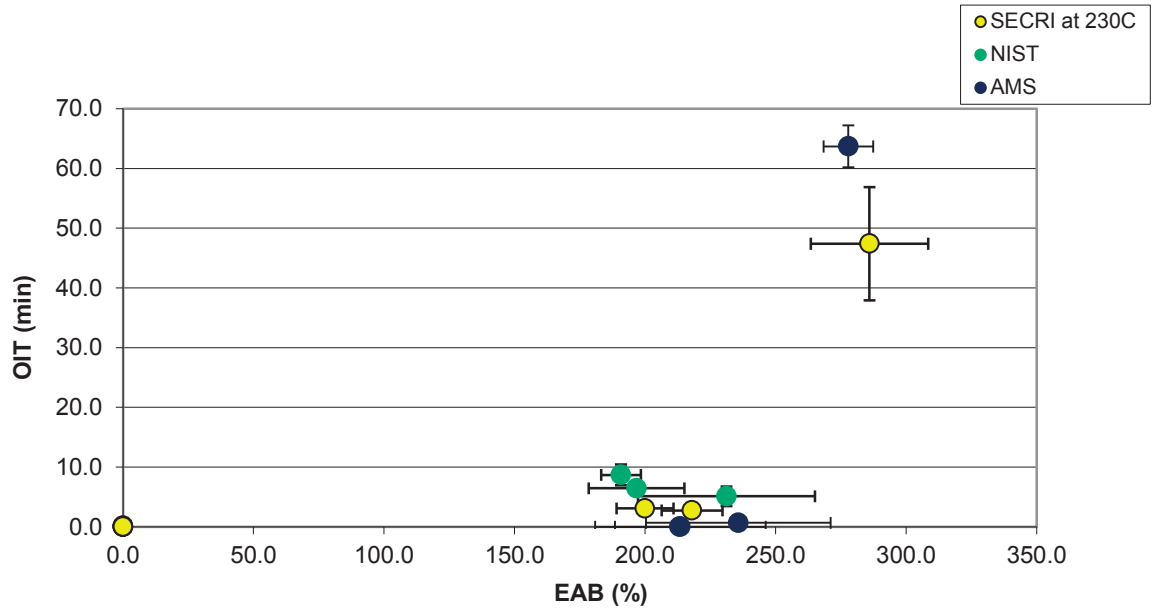


FIG. 77. Cross-plot of OIT vs. EAB for XLPO insulation (Shanghai).

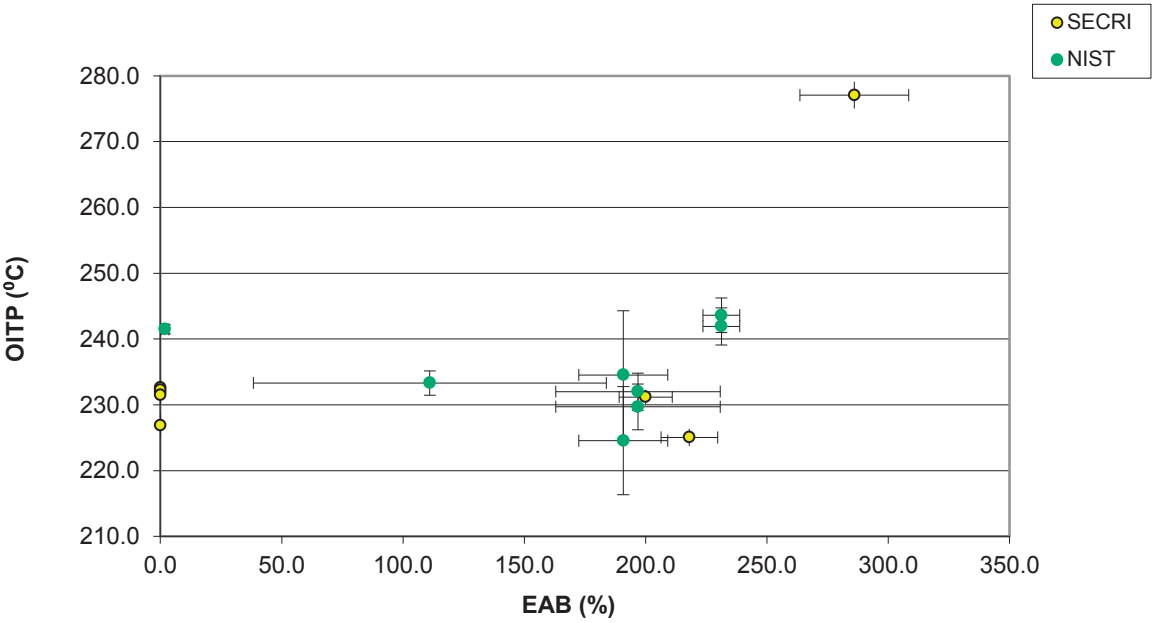


FIG. 78. Cross-plot of OITP vs. EAB for XLPO insulation (Shanghai).

TGA measurements for both 5% weight loss and maximum weight loss do not indicate any change with decreasing EAB %. This CM technique is not useful for this XLPO insulation material.

Density increases steadily with decreasing EAB but the changes are relatively small. The maximum density change is approximately 6% compared with a standard deviation of 0.6% typically seen, so the changes are measurable but not really practical in terms of a CM method for this material.

Measurements of FTIR peak ratios show some promise as a CM method but the data available for this material was very limited with more than half of the data points corresponding to heavily degraded material with effectively 0% EAB.

Reflectometry results did not indicate any trending for the Shanghai XLPO insulated cable. A localized hot spot was induced in several locations along the length of a 20-meter cable sample and thermal aged at 135°C. Neither TDR nor FDR traces indicated a clear trend. The FDR and TDR data traces did not show any significant changes from the baseline to the final aged measurement point.

5.15.12. XLPO Shanghai jacket

EAB values are shown in FIG. 79 for the XLPO jacket material. Although there are differences in the absolute values measured by different laboratories, the general trend is similar.

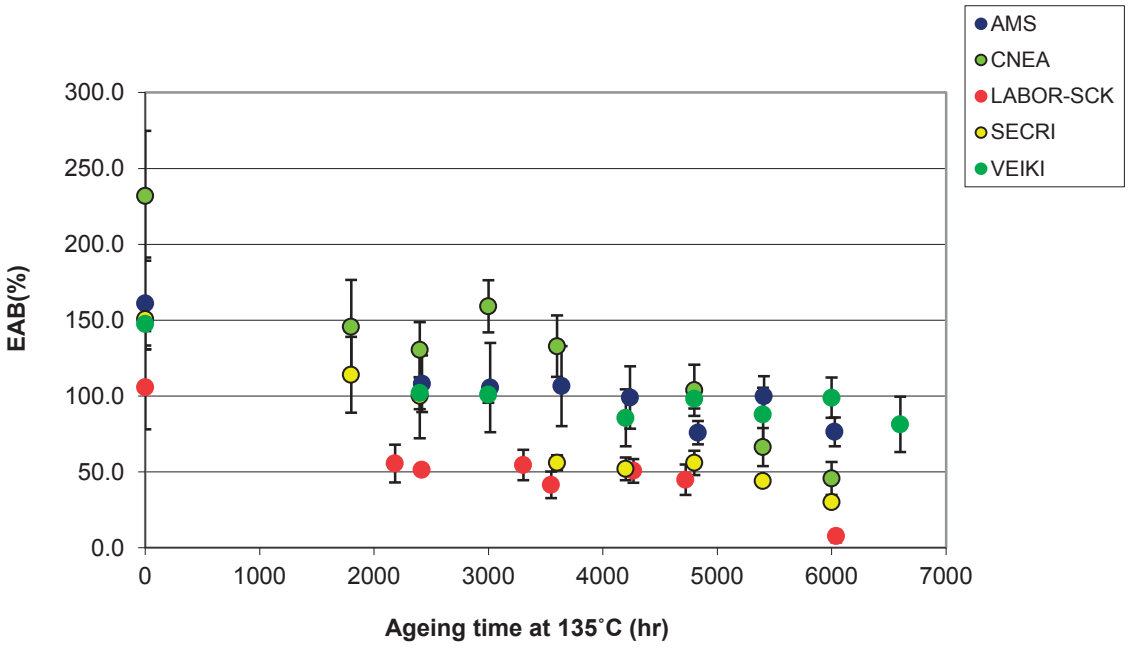


FIG. 79. EAB values for XLPO jacket (Shanghai).

Indenter measurements show a strong trend with IM values increasing as the EAB values decrease (FIG. 80). When the INSS data is corrected for probe tip diameter, these data also lie on the same trend line as the AMS and the SECRI data. The LABOR data shows a similar trend but off-set, since the EAB measurements from this lab are consistently lower than the others. Indenter values increase by approx. 40% from unaged material down to 100% EAB, compared with a standard deviation typically of 2% for these measurements.

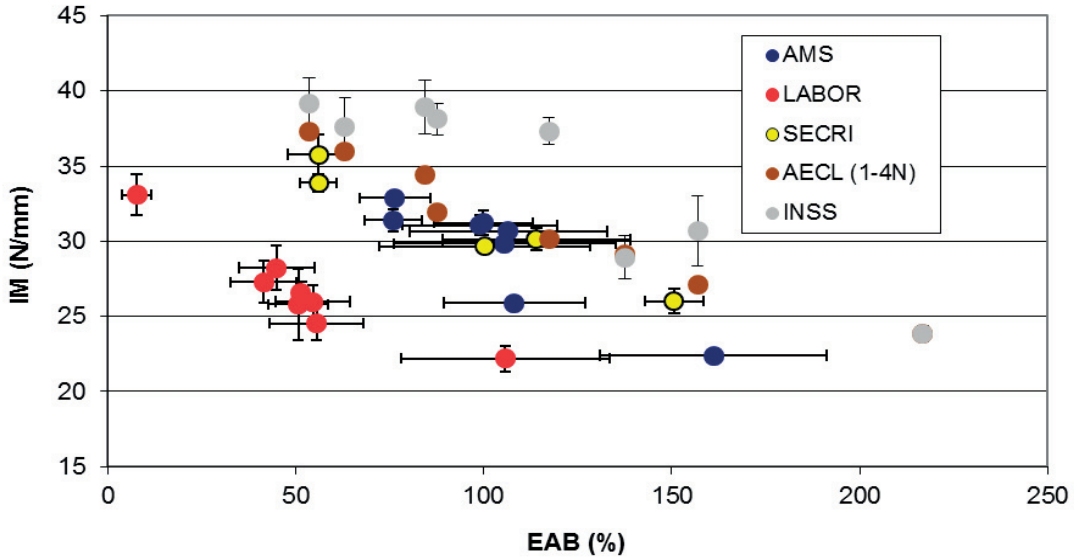


FIG. 80. Cross-plot of IM vs. EAB for XLPO insulation (Shanghai).

Recovery time measurements show a large increase with decreasing EAB, increasing by a factor of 5 for a reduction in EAB to 100% (FIG. 81). Standard deviation for these measurements is typically 5-7%. These changes are much larger than the IM changes that are observed over the same range.

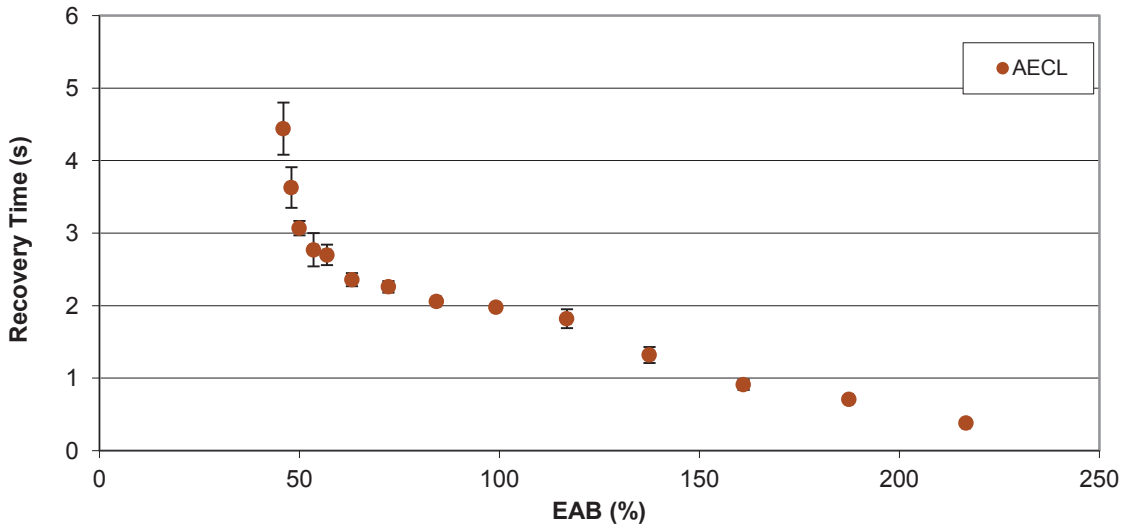


FIG. 81. Cross-plot of recovery time vs. EAB for XLPO insulation (Shanghai).

OIT measurements decrease from 60 minutes for unaged material down to zero at 50-100% EAB. This makes OIT a useful indicator of the early stages of degradation in this material.

OITP measurements show a large decrease over the full range of EAB values, decreasing by 25˚C for a decrease in EAB to 100% and by 50˚C for EAB of 50%. Standard deviation for these measurements is typically 1 - 2˚C.

Density increases as the EAB decreases but the changes are not large compared with the standard deviation of the measurements. Increases of 3% are observed for a decrease in EAB to 50%, compared with standard deviation of typically 0.5 - 0.7%. These changes are measurable but are too small to be a practical CM method. Cross-plots of density vs. IM for both thermal and radiation aged XLPO show some correlation.

FTIR peak ratios show some indication of a trend but the data are too scattered to be a useful method at present.

Measurements of ultrasonic velocity show a large increase as the EAB decreases (FIG. 82). The velocity increases by 150% for a decrease in EAB to 50%, compared with standard deviations for the velocity measurements of 4% typically.

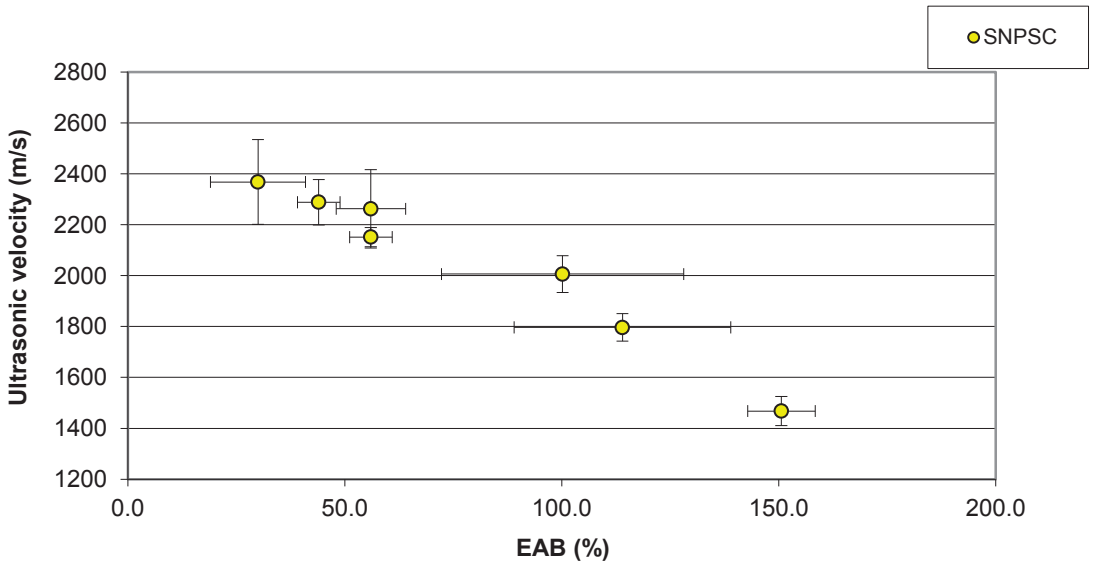


FIG. 82. Cross-plot of ultrasonic velocity vs. EAB for XLPO insulation (Shanghai).

5.16. PRACTICAL APPLICABILITY OF CM TECHNIQUES

The practical applicability of each of the CM techniques is summarized in Section 2. The key to the colour coding in the table is shown below, based on the observed correlation with ageing, variability of the data and laboratories variability. The electrical tests such as IR and TDR that are not useful for ageing assessments are known to be very effective for finding and locating cable insulation faults, damage and hot spots. Tables 4 and 5 are concerned with degradation trending and ageing assessment of cable insulation material.

TABLE 4. COLOUR CODE KEY

Very Useful		Good correlation with ageing. Low laboratories variability.
Useful		Reasonable correlation with ageing. Some laboratories variability but consistent trends.
Potentially Useful		Moderate correlation with ageing. Large variability but method shows potential for improvement.
Not Useful		No correlation with ageing.
No Data or Not Applicable		No data available on this programme or test method not applicable for that material (e.g. electrical test for jacket polymers).
Potentially Useful (Limited)		Moderate correlation with radiation ageing only.

TABLE 5. PRACTICAL USEFULNESS OF CM METHODS FOR EACH OF THE BENCHMARKED CABLE MATERIALS

	CM method	1 EAB	2 IM	3 Recovery	4 OIT	5 OITP	6 TGA	7 Density	8 FTIR	9 Ultrasonic	10 Tan delta	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)														

*The Habia cable was thermally aged at 190°C which caused permanent maximum insulation degradation at the first aged condition. No trending was possible for the electrical cable samples.

6. IMPROVEMENT OF CURRENT TESTING TECHNIQUES FROM CABLE RESEARCH

The use of CM methods for ageing assessment is limited in many cases due to the variability of results. If the variability of a measurement is higher than the change of the measured value with ageing, the reliability of CM test is questionable. The most useful improvement is to decrease the standard deviation of measurements.

Deviation is caused by:

— Material inhomogeneity;
— Equipment;
— Testing procedure such as samples preparation, testing condition, human factors, etc.

For in situ monitoring methods, the measurement must be robust i.e. the dependence on environmental factors such as temperature, humidity, electromagnetic noise etc. are understood.

6.1.ELECTRICAL TESTS

6.1.1. Tan delta

The length of the cable sample used for Tan δ measurements will limit the range of frequencies that can be applied in the test. A minimum length of sample should be specified in the test method. It is recommended that Tan Delta is measured over as wide a frequency range as reasonable (e.g. 20 Hz to 500 kHz), because the important frequency ranges from the point of view of ageing are not known in advance.

6.1.2. Dielectric spectroscopy

The results shown in this report highlight the limitations of dielectric spectroscopy when applied to unshielded cables such as those provided for the project. The effect of stray capacitances on the repeatability of the measurement is clearly evident. Stray capacitances seem to alter significantly the frequency of the polarization peaks as well as the shape of the real part of permittivity vs. frequency.

In order to limit the influence of stray capacitance, future testing should include electromagnetic shielding. The idea is to surround the outer jacket with a wire mesh, which will be grounded during the test. In addition, dielectric spectroscopy should be repeated at 50°C. It has already been observed (Ageing diagnostics and prognostics of low-voltage I&C cables (ADVANCE) project), in fact, that at this temperature the quality of the results is enhanced, probably because the insulating material becomes softer and the contact between conductor and insulation is improved. Moreover, at higher test temperatures also the mobility of polymer chains increases. However, the use of elevated temperatures would limit the practical application of the technique for in situ testing, although it could be appropriate for laboratory studies or for tests on sacrificial cable samples.

6.1.3. Insulation resistance and impedance

Each laboratory has used different testing arrangements for the measurement of multicore cables. Some laboratories measure between two cores, while other laboratories energize a selected core while all other cores are grounded. The results of the two methods are not comparable. The second method provides lesser variation of results due to the lesser

sensitivity to the mechanical and electromagnetic factors. The test procedure should be updated to recommend this. To reduce the effect of slow polarization processes it is recommended to short circuit the cable for duration of at least three times the energizing time. (e.g. for a 10 min measurement time, short circuit for 30 min).

6.1.4. Reflectometry

The reflectometry CM technique has multiple methods for applying and measuring the reflected signal that can be better aligned for more consistent results. The TDR technique uses two very different test types (step or impulse signal) and the results can be displayed in time or distance. The FDR technique uses a wide variety of frequency spans and signal amplitudes based on the test equipment. Also, conversion of the raw data itself varies to locate and quantify the insulation degradation. These test parameters must be aligned or compensated to compare test results more effectively.

Sample preparation including the length and location of the induced hot spot has a direct impact on test results. Also the method for determining the amount of degradation (maximum peak, area under the peak, etc.) from baseline needs to be aligned with participating laboratories.

6.2.MECHANICAL TESTS

6.2.1. Elongation at break

There are a several improvements to the elongation testing method that could produce better results. Using an extensometer would help to yield more reproducible baseline results. It can be seen that the baseline data point for certain materials varies up to 200% between laboratories in certain cases and consistency in agreement between lab's data is not present.

Specimen preparation was one of the main sources of variability in these tests. Considerable differences are observed between dumbbell specimens tested as-cut and those where irregularities or layers on the inner surface have been removed by buffing or slicing. As-cut specimens show significantly lower values of EAB and much higher scatter within a batch. For tubular insulation samples, conductor removal was identified as a critical step in sample preparation. The data derived from the samples where the copper conductors were not possible to remove without cutting along the length of the samples, seemed to be extremely variable and strongly dependent of the sample preparation instead of actual cable mechanical properties.

The type of grip used in the tensile testing machine may also affect the values obtained and can have a significant effect on the scatter of data within a test batch. Grip types used in the tests included pneumatic, mechanical with manual tightening, mechanical with self-tightening, rubber faced types and S-grips (for tubular samples). The grip type appears to have less effect on the values obtained than the other variables identified.

The use of contact extensometers appears to have an effect on the values obtained, which tend to be lower than those tested without an extensometer, particularly for aged samples. If available, optical extensometers are preferred.

It is important that the correct value is used for the effective gauge length of the specimen. For dumbbell samples, the nominal gauge length is dependent on the die used (e.g. ISO37 type 3 is 10 mm nominal) but the straight section of the specimen is longer (e.g. 16 mm for type 3). If an extensometer is not used, it is important to specify what length is used as the initial sample length e^0.

The cross-head speed used for the tests does not appear to be a significant factor in variability between laboratories. This test programme used batches of 5 samples for EAB measurements, but a larger number would help to reduce the variability observed.

6.2.2. Indenter modulus

The IM data is affected by probe tip diameter, sample clamping force and the test temperature among others. The standard for this CM method is IEC/IEEE 62582-2. The test probe should be a truncated cone with a cone angle of 17.5° and a circular tip diameter of 0.56 mm. The value of the IM data measured is dependent on the tip shape and dimensions. Therefore, it is important to note any differences in test equipment (and perform corrections if necessary) when comparing IM data sets.

Discrepancies between data sets that exhibit similar trending but differ in IM magnitude is likely caused by dissimilar sample clamping forces. For example, it has been demonstrated that a greater sample clamping force will skew IM results higher than expected. Sample clamping force should be as uniform and repeatable as reasonably possible to ensure comparable data. Indenter instruments with controlled clamping forces would help eliminate a significant operator-dependent factor in the variability of IM data.

The IEC/IEEE 62582-2 standard specifies a force range of from 1 N to 4 N for determination of the IM value. This may not be the optimum range for all materials but this range is used as it represents the most linear part of the force-displacement curve for most materials and has been shown to be correlated with ageing under a wide range of conditions. For measurements made under a long term ageing management programme, it is important that the range used is standardized. Although a percentage range of the maximum force applied might give a wider span of data, there is the risk that data is not directly comparable if different maximum forces are used.

The use of a depth range instead of a force range for determination of the IM value has been investigated. It would ensure that the same region of the material is being sampled during ageing but there is the risk that the force required to reach specific depths may be too high in heavily aged cables, resulting in the potential for localized cracking. Also, it would be difficult to standardize on a depth range that would be applicable to all types of cable material. For these reasons, a force range is still the recommended way to measure IM.

6.3.CHEMICAL TESTS

6.3.1. Oxidation induction time and oxidation induction temperature

To improve both the OIT and the OITP test methods, the sample preparation, loading and analysis procedures should be modified. These modifications should include altering the test procedure to establish a uniform sample preparation method for the OIT samples (e.g. as in ASTM standards). Under the current test procedure, 10 mg. samples are required to perform the OIT tests. This sample mass is not needed for modern instrumentation, and should be changed to 5 mg. In addition, the initial weight of the sample should be accurate to the nearest 0.1 mg.

Currently, the sample preparation method listed in the test procedure states that the sample should be chopped into pieces with maximum dimensions of 1 mm. In addition, it is recommended that the chopped sample be screened with a mesh to ensure all particle sizes are no greater than 0.85 mm. While this procedure does help with maintaining sample uniformity, the use of a sample preparation method that ensures a high degree of particle uniformity (e.g. ball milling) could help reduce variability in the data.

In addition to sample preparation procedures, improvements to the sample loading procedure would improve the OIT test method. This includes tightly packing the sample into the sample pan to make a single layer of material. The reproducibility of the OIT measurements may be affected by how much of the sample is making contact with bottom of the sample pan, and, thus, evaluating the effects of sample packing is a critical next step for making improvements to the OIT test method.

The various software packages used to perform the OIT analysis use different algorithms to calculate OITs. To reduce variability between data sets reported by different laboratories, the OIT analysis procedure specified in IEC/IEEE 62582-2 should be implemented.

6.3.2. Thermogravimetric analysis

Improvements to the TGA test method primarily include modifications to the sample preparation and loading procedures, and the sample weight, as described for OIT and OITP tests.

6.3.3. Density

Density data must be collected using an analytical balance with a resolution of at least ±1 mg. The specimen should be > 0.25 g to achieve reproducible results. If the sample has been thermally aged, it shall be allowed to equilibrate with the surrounding laboratory conditions for at least 24 hours before testing. Due to the relatively small specimen size, care must be taken when handling and conducting measurements. Forceps should be used to eliminate contact with skin oils or other contaminants that may compromise the integrity of the density measurements. Fresh distilled (or deionized) water shall be used for each test performed with the sample submerged in water. Changes in density can be sensitive to the purity of the water used for testing and shall be maintained as pure as possible. The main source of error, when performing density measurements in water, is the presence of air bubbles on the surface of the specimen. If air bubbles are widely apparent, it is recommended that surface-active materials be added in trace amounts (1 part in 10 000) to increase the fluid to surface contact area. Addition of any detergents or alcohols must not introduce swelling or leaching on the material and care should be taken to minimize water contamination.

Two methods of density measurement may be used: the first involves the use of a density bottle (a 25 ml density bottle is suitable) and the second involves a balance pan straddle that suspends the specimen in the fluid (Archimedes principle). For either method, it is necessary to correct for any temperature variation of the density of the water.

6.3.4. Fourier transform infrared spectroscopy

To improve the FTIR test method, a single test procedure for analysis should be developed considering the highest peak. Currently, the highest peak to monitor for each material during the ageing process is not established. As a result, various laboratories monitored different peaks during the course of this research endeavour. Establishing the peak frequencies and the method of calculating the ratios of the peaks used to monitor degradation for each polymer type would help reduce the variability of the data reported by each lab.

6.3.5. Ultrasonic velocity

Improvements to the ultrasonic velocity technique primarily include establishing and implementing the most effective probe coupling agents (oils compared to grease), signal frequency and probe separation to yield reproducible results. The testing techniques and set-

up variances could be evaluated for their impact on baseline and aged cable samples. Standardization of a testing procedure for this technique could help data be more reproducible.

7. SUMMARY AND CONCLUSIONS

Seventeen organizations participated in the CRP providing cable samples, laboratory ageing of the cable samples, and CM of the cable samples. Most CM techniques were performed by at least two organizations covering most of the jacket and insulation materials donated by cable manufacturers. In particular, 12 individual polymer materials were tested using 14 different CM techniques. The participating organizations performed sample preparation, ageing or CM testing following written procedures. All organizations were periodically discussed to ensure comparable and useful tests results and find the main reasons to the different results. Improvements to the CM test techniques and sample preparations were summarized after the completion of baseline testing and upon completion of the ageing programme.

The conclusions of the data analysis provide insight into which CM techniques yield usable results. Some techniques indicate a trend in the early stages of degradation such as the OIT and OITP. For most materials, the OIT values reached the end of trending in the first 2000 hours of accelerated ageing. However, the OITP test continued to trend throughout the ageing process on the EPR and EVA polymer materials. Other chemical CM techniques such as TGA did not provide useful trending of degradation for any of the tested materials. Other chemical CM techniques (e.g. density, ultrasonic velocity and FTIR) indicated promising results for early degradation detection or some trending capability for specific materials.

CM techniques of organic and polymeric materials in I&C systems were applied in accordance with the IEC/IEEE 62582 standard. Traditional mechanical CM techniques, tensile testing and IM, provided useful trending data for most of the polymer material tested. The exception for IM being the very hard material PEEK and the XLPE/O materials that have initially very high IM values, which do not increase significantly during the ageing process. Of the electrical CM techniques applied to the insulation materials, only the dielectric spectroscopy and FDR tests indicated useful degradation trending. Dielectric spectroscopy showed better results for the irradiated samples than for the thermally aged samples. FDR signature peaks increased with insulation degradation for all the thermal ageing conditions for the EPR and the SiR materials. As for fault finding as opposed to condition monitoring/ageing assessment, electrical tests such as IR and reflectometry are proven to work on essentially all insulation materials used in nuclear power plant cables. These electrical tests can be applied in situ as cables remain installed in an operating plant and thereby locate damage, faults and hot spots on the insulation material along a cable.

This report outlines the major conclusions of the CRP such as:

- The benchmarking tests reported herein provided information on the usefulness of a range of CM techniques and their applicability to different cable materials;
- A toolbox of CM techniques was identified and validated in this CRP for use as part of a cable ageing management programme;
- The usability of each CM techniques is specific to the cable material tested, but usually the same CM techniques can be used for the same generic polymer type;
- The causes of variability of test data between laboratories have been identified in many cases and suggestions made as to improvements to the CM test procedures that would reduce this variability;

This CRP focused on cable ageing assessment through CM techniques. However, electrical in situ methods such as IR and reflectometry tests should be considered as proven methods for locating faults, damage and hot spots along a cable.

APPENDIX I. INTERNATIONAL RESEARCH AND DEVELOPMENT

A number of international programmes are under way related to NPP cables. These are reviewed here.

I.1. ADVANCE: AGEING DIAGNOSTICS AND PROGNOSTICS OF LOW VOLTAGE I&C CABLES

I.1.1. Objective

The overall objective of the project is to adapt, optimize and assess electrical CM techniques for nuclear cables that would allow utilities to assess in situ the current cable degradation condition and, together with the establishment of appropriate acceptance criteria, to verify its qualified state over its entire length and to estimate its residual lifetime.

I.1.2. Process

ADVANCE is a 3-year collaborative project launched in the framework of the EURATOM programme. It ended in December 2013 and involves 11 European partners (operators, universities, laboratories, cable manufacturer). It consists in studying with accelerated ageing tests a representative selection of cables already installed in European NPPs in order to evaluate the ability of electrical CM techniques to detect local and global cable ageing.

Tests are supported by a study of the impact of cable polymers ageing on the electrical properties. It provides help to interpret the results of the electrical measurements, to extend the validity of the results to other similar cables.

I.1.3. Outcome

Six safety related cables (low voltage power, I&C) representative from those currently employed in European NPPs have been selected studied and tested in the project. The project provided a large amount of test results on various cable designs and in various conditions of ageing. The test results were compared and correlated to those obtained with more conventional CM techniques for validation and residual life estimation. Cable samples and test results were stored and are available for further studies.

Investigations carried out on short samples (aged in severe conditions) have shown that dielectric spectroscopy is the most promising electrical CM technique among those investigated. For the selected cables the imaginary part of permittivity at high frequency could be used as ageing indicator. Nevertheless, further study is necessary to know at what extend this indictor is applicable and to know the limit values of electrical parameters in the view to estimate time to replacement of cables used in NPPs.

Measurements on long samples with promising electrical CM techniques have been compared to those with more traditional CM techniques. Long sample cables were probably not enough aged during accelerated ageing process defined in the project, so it was difficult to detect a global ageing with new electrical CM techniques. It is considered at the moment more adapted to focus TDR/FDR techniques on the study of local defect evolution rather than global ageing.

To conclude, further developments are required to improve measurement techniques and analysis.

I.2. CADAK: OECD/NEA CABLE AGEING DATA AND KNOWLEDGE PROJECT

I.2.1. Objective

This is a continuation of SCAP Project (stress corrosion cracking and cable ageing). The SCAP database contains the following information: cable technical data, the environment, technical standards being applied in the qualification of cables and inspection methods being used, CM techniques applied. The database will be an up to date encyclopaedic source to monitor and predict the performance of numerous unique applications of cables.

I.2.2. Process

13 countries (Belgium, Canada, Czech Republic, France, Germany, Japan, Norway, Slovenia, Sweden, Ukraine, and the United States of America) are participating to continue to update the database. The focus is to evaluate CM techniques to monitor and predict the performance of every unique application of cables. Countries will continue to provide research activities and reports to keep the knowledge base up to date. Additional participation is welcome (please contact the OECD/NEA).

I.2.3. Expected outcome

At the end of the project, a commendable practices report will be published, to include accumulated knowledge in the area of equipment qualification (EQ) and CM. Such documents will help regulators and operators to enhance ageing management. Staff plans on writing several sections of the report.

I.3. MATERIALS AGEING INSTITUTE

I.3.1. Objective

By 2020, one third of the world's nuclear fleet will be 40 or more years old. In 2030, this figure will increase to 80%. The objective of the MAI is to bring together scientific skills and research facilities to address ageing of materials used in electric power plants, and particularly in NPPs. Non-metallic materials used in cables are part of these studies.

I.3.2. Process

The MAI is an international utility-oriented research centre co-financed by EDF (F, founder member), EPRI (USA), KANSAI/INSS (J), CGN/SNPI (CN), Rosenergoatom (RU), TEPCO (J), MHI (J), CRIEPI (J), CEA (F) and Areva (F). It is a collaborative effort. The research programme is decided yearly by the funding members.

I.3.3. Expected outcome

It is expected that sharing research, scientific information, experimental results, modelling results will significantly contribute to the understanding of the ageing processes taking place in materials and in particular in polymers used in NPP cables. As a consequence, this research can be used to anticipate the ageing and to increase the durability of NPP equipment. One of the core missions of the MAI is education and training. Courses on materials ageing are being developed and offered to graduate and postgraduate students as

well as to working engineers in the nuclear industry. In addition, seminars and workshops are organized by the MAI to promote discussions and knowledge sharing on technical subjects.

I.4. USA - ARGENTINA COLLABORATION

I.4.1. Objective

Bi-national Energy Working Group (BEWG) is a collaboration agreement between US DOE and Secretary of Energy of Argentina to investigate several areas of improvement in the energy field, nuclear energy being one of the main areas of interest.

I.4.2. Process

As members of BEWG, Sandia National Laboratory from the US and CNEA from Argentina have started collaboration on the development of CM techniques in SiR cables used in Argentinean NPP. EAB and gel content/solvent uptake was tested. Based on test data, gel content/solvent uptake has shown to be an effective CM technique for SiR.

I.4.3. Expected outcome

It is expected that this cooperation work will establish a set of CM techniques applicable for SiR. It is expected to carry out an assessment of these techniques in samples that were in-service in NPPs.

I.5. OTHER RESEARCH

Table 6 is a summary of what other countries are doing in this area.

TABLE 6. CABLE AGEING RESEARCH BY COUNTRY

Country	Specific research activity on cable ageing
Belgium	– IM – Investigation of TDR/FDR/LIRA – Investigation of OFDR
Canada	– Recovery time indenter
China	– IQ qualification AP 1000
Czech Republic	– OIT round robin test – Influence of pigments on ageing
France	– Modelling of material ageing (kinetic model, mechanical model) – Reflectometry
Republic of Korea	– JTFDR
Slovakia	– Optimization of silane cross-linking process – Periodic measurement of cables in operation (EDAC system)
USA	– Submerged cable degradation (NRC, EPRI) – Assessment of CM methods under simultaneous radiation + thermal ageing (NIST, SANDIA) – Development of an in situ technique for assessing the age of cable insulation (AMS), R&D performed with grant from US. Department of Energy under the SBIR programme – Development of an on-line cable monitoring system for detecting intermittent faults (AMS)
USA – Iowa State University	– In situ techniques for cabling ageing assessments

APPENDIX II. REVIEW OF EXISTING CODES AND STANDARDS

II.1. REVIEW OF EXISTING CODES AND STANDARDS

A wide range of standards exists, related to methods for CM. Although most of them are not specifically designed for use in management of ageing of cables in NPPs, some of them are still useful for this purpose.

The usefulness of standards for CM as a tool for management of ageing of cables in NPP depends on fulfilling certain criteria. The condition indicator must have a consistent trend following the ageing of the material on which it is applied. A very important prerequisite for applicability of a CM standard to the management of ageing is that it specifies the CM methods in sufficient detail to enhance the accuracy and repeatability of the measurements.

The table below includes examples of standards related to the CM techniques used in this project. The degree to which the standards included in the table are sufficient in details of the procedures to ascertain reproducibility and applicability to management of ageing in NPPs varies. The IEC/IEEE standards in Table 7 are especially designed to fulfil the criteria above for use in management of ageing of components (including cables) in NPPs.

TABLE 7. CODES AND STANDARDS RELATED TO CABLE TESTING

Codes/Standards	Title of codes/standards	Publication year	CM methods
ANSI/ICEA T-24-380	Standard for Partial Discharge Test Procedure	2007	partial discharges
ANSI/ICEA T-27-581/NEMA WC 53	Standard Test Methods for Extruded Dielectric Power, Control, Instrumentation and Portable Cables for Test	2008	dielectric and mechanical
ANSI/SCTE 03	Test Method for Coaxial Cable Structural Return Loss	2008	structural return loss (SRL)
ASTM D150	Test methods for AC loss characteristics and permittivity (dielectric constant) of solid electrical insulation (equivalent to IEC 60250)	2011	dissipation factor and dielectric constant
ASTM D257	Standard Test Methods for DC Resistance or Conductance of Insulating Materials	2007	dielectric
ASTM D2765	Standard Test Methods for Determination of Gel Content and Swell Ratio of Cross-linked Ethylene Plastics	2011	gel content and swell
ASTM D3850	Standard test methods. Rapid thermal degradation of solid electrical insulating materials by thermogravimetric method (TGA)	2012	TGA
ASTM D3895	Standard test method for OIT of polyolefins by DSC	2007	OIT by means of DSC
ASTM D412-06 a	Test Methods for Vulcanized Rubber and Thermoplastic Elastomers –Tension	2013	tensile properties
ASTM D638	Standard test methods for tensile properties of plastics (Equivalent to ISO 527-1)	2010	tensile strength and elongation at break
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics		

Codes/Standards	Title of codes/standards	Publication year	CM methods
ASTM D7567	Standard Test Method for Determining Gel Content in Cross-linked Ethylene Plastics Using Pressurized Liquid Extraction	2009	gel content
ASTM D792	Test methods for density and specific gravity (relative density) of plastics by displacement	2008	changes of density
ASTM F2778	Standard Test Method for Measurement of Per cent Crystallinity of Polyetheretherketone (PEEK) Polymers by Means of Specular Reflectance Fourier Transform Infrared Spectroscopy (R-FTIR)	2009	FTIR
EN 3475-303	Aerospace series - Cables, electrical, aircraft use - Test methods - Part 303: Insulation resistance	2002	insulation resistance
IEC 60060-1	High voltage test techniques - Part 1: General definitions and test requirements	2010	dielectric
IEC 60270	High voltage test techniques – Partial discharge measurements	2000	partial discharge
IEC 60345	Method of test for electrical resistance and resistivity of insulating materials at elevated temperatures	1971	insulation resistance and volume resistivity of materials up to at least 800 degC
IEC 60544-5	Electrical insulating materials – Determination of the effects of ionizing radiation – Part 5: Procedures for assessment of ageing in-service	2011	General, incl. OIT/OITP, Elongation at break, IM, etc.
IEC 60780	Nuclear power plants – Electrical equipment of the safety system – Qualification	1998	general
IEC 60811-512	Electric and optical fibre cables - Test methods for non-metallic materials – Part 512: Mechanical tests – Methods specific to polyethylene and polypropylene compounds – Tensile strength and elongation at break after conditioning at elevated temperature	2012	tensile strength and elongation at break
IEC 61156-1 ed3.1 Consol. with am1	Multicore and symmetrical pair/quad cables for digital communications – Part 1: Generic specification	2007	dielectric and mechanical
IEC 61196-1-102	Coaxial communication cables – Part 1-102: Electrical test methods – Test for insulation resistance of cable dielectric	2005	insulation resistance
IEC 61557-2	Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 2: Insulation resistance	2007	insulation resistance
IEC 61746-1	Calibration of optical time-domain reflectometers (OTDR) - Part 1: OTDR for single mode fibres	2009	OTDR

Codes/Standards	Title of codes/standards	Publication year	CM methods
IEC 61746-2	Calibration of optical time-domain reflectometers (OTDR) – Part 2: OTDR for multimode fibres	2011	OTDR
IEC 62465	Nuclear power plants - Instrumentation and control important to safety - Management of ageing of electrical cabling systems	2009	
IEC/TR 60465	Nuclear power plants – Instrumentation and control important to safety – Management of ageing of electrical cabling systems	2010	electric and dielectric, elongation at break. (includes a detailed description of TDR)
IEC/IEEE 62582-2	Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment CM methods Part 2: Indenter modulus	2011	IM
IEC/IEEE 62582-3	Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment CM methods Part 3: Elongation at break	2012	elongation at break
IEC/IEEE 62582-4	Nuclear Power Plants – Instrumentation and control important to safety – Electrical equipment CM methods Part 4: Oxidation induction techniques	2011	OIT and OITP
IEC/TS 61244-3	Long term radiation ageing in polymers – Part 3: Procedures for in-service monitoring of low voltage cable materials	2005	Broad range of methods
IEEE 383	IEEE Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations	2003	general
IEEE 323	IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations	2003	Application of CM
ISO 10640:2011	Plastics – Methodology for assessing polymer photoageing by FTIR and UV/visible spectroscopy	2011	FTIR
ISO 11357-6	Plastics – Differential scanning calorimetry (DSC) – Part 6: Determination of oxidation induction time (isothermal OIT) and oxidation induction temperature (dynamic OIT)	2008	OIT and OITP by means of DSC
ISO 2951	Rubber, vulcanized or thermoplastic -- Determination of insulation resistance	2012	insulation resistance
ISO 604	Plastics – Determination of compressive properties	2002	compressive modulus
MIL-STD-1344	Test Methods for Electrical Connectors	1977	Tension, dielectric
SFLC STANDARD SPECIFICATION 3014	Shipboard electrical cable test	2009	conductor resistance (Ω/m) and insulation resistance (Ω-m)

Codes/Standards	Title of codes/standards	Publication year	CM methods
NUREG/CR-7000/BNL-NUREG90318	Essential Elements of an Electric Cable CM Programme	2010	very broad range of methods
NUREG//CR-6869, BNL-NUREG-73676	A Reliability Physics Model for Ageing of Cable Insulation Materials	2005	elongation at break
Reg. Guide 1.211	Qualification of Safety Related Cables and Field Splices for Nuclear Power Plants	2009	Application of CM
UL 2556	Wire and Cable Test Methods	2005	Tension, dielectric
FED-STD-228	Cable and wire, insulated; methods of testing	1967. Draft 228 A 2009	tension, dielectric, voltage withstand
IPC/WHMA A-620B	Requirements and Acceptance for Cable and Wire Harness Assemblies	2012	Tension, dielectric

APPENDIX III. COUNTRY REPORTS

III.1. CANADA

AECL has focused so far on thermal ageing and irradiation of jacket and insulation samples and on indenter modulus testing (IM and recovery time) using the AECL portable polymer tester (PPT).

Thermal ageing of all cable samples is completed. The irradiation work is still on-going. This work is performed at low dose rate in a small volume gamma cell. The scope of the irradiation work includes providing samples to our Asian partners. Two rounds of irradiated samples have gone through the shipping cycle from Canada to the Republic of Korea, China, and Japan and back to Canada for further irradiation. The third irradiation cycle just started at AECL in March 2014.

At AECL, indenter modulus testing is now complete for all available jacket samples. Both IM and recovery time were generated for all requested thermal ageing levels and for some of the irradiated samples. The results were provided to S. Burnay in early 2014 October and were presented at our 3rd CRP meeting in Shanghai. PPT results for the remaining jacket samples (irradiated) and for insulation samples were generated at AECL and testing completed in the spring of 2015.

III.1.1. Test characteristics

For the baseline indenter modulus tests, AECL had initially used an indenter probe as per design specified in the CRP test requirements (IEC/IEEE Standard probe). As per outcome of the 2nd CRP Meeting discussions in Knoxville, AECL agreed to modify the indenter probe used in the PPT to match the design of the IPAM indenter probe (which is different from the current IEC/IEEE standard design soon to be revised). This change in specifications was made because the IPAM-style probe was used by many CRP partners and had been extensively used in the past. AECL proceeded with redesign and manufacture of the probe in late 2013. Baseline IM data was generated again using the IPAM-style probe and, as expected, was found to better match results of the other IPAM probe users. All PPT indenter moduli data (IM and recovery time) performed for cable jacket samples in 2014 was generated using the IPAM-style probe.

AECL provided to date several types of IM results for the baseline samples: one series with the IEC/IEEE indenter probe and with indenter moduli derived for a pre-defined indentation depth, one series with the IEC/IEEE indenter probe and with indenter moduli derived for a variety of pre-defined force ranges, including the 1 – 4 N range specified in the CRP test requirements, one series with the IPAM-style indenter probe and with indenter moduli derived for a pre-defined indentation depth, and one series with the IPAM-style indenter probe and with indenter moduli derived for the 1 – 4 N range specified in the CRP test requirements.

AECL provided two types of the IM results for the aged samples: one series with the IPAM-style indenter probe and with indenter moduli derived for a pre-defined indentation depth range, and one series with the IPAM-style indenter probe and with indenter moduli derived for the 1–4 N range specified in the CRP test requirements. The pre-defined indentation range was always chosen to be 50 to 100% of the max indentation depth. The max indentation depth was chosen to ensure that a maximum force of at least 4 N would be reached for the unaged sample.

Recovery time was measured following a force relaxation phase of 1 min and a probe retraction phase. Recovery time is measured when the material contact following probe retraction. The probe retraction rate is changed from one material to the other in order to

optimize the sensitivity of recovery time to cable degradation. For the tested jacket materials, the chosen probe retraction rates varied from 60% of the maximum indentation depth (for the Habia XLPO jacket) to 80% (for the Rockbestos jacket).

III.1.2. Recommendations for improved IM measurement test protocol

In 2014, AECL dedicated some effort to better understand the implications of using a pre-defined depth range as opposed to a pre-defined force range for IM measurements. During the indentation phase, relationship between force and probe displacement (i.e. indentation depth) can be linear, as for Case #1 of the Shanghai XLPO shown in FIG. 83, or non-linear, as for Case #2 of the Rockbestos CSPE jacket shown in FIG. 84.

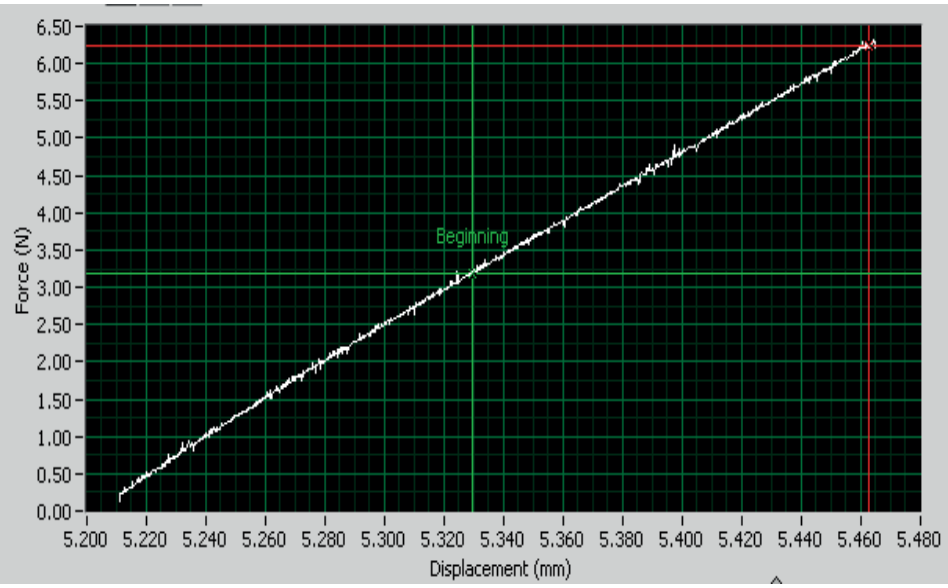


FIG. 83. Force-displacement curve for indentation of unaged Shanghai XLPO jacket.

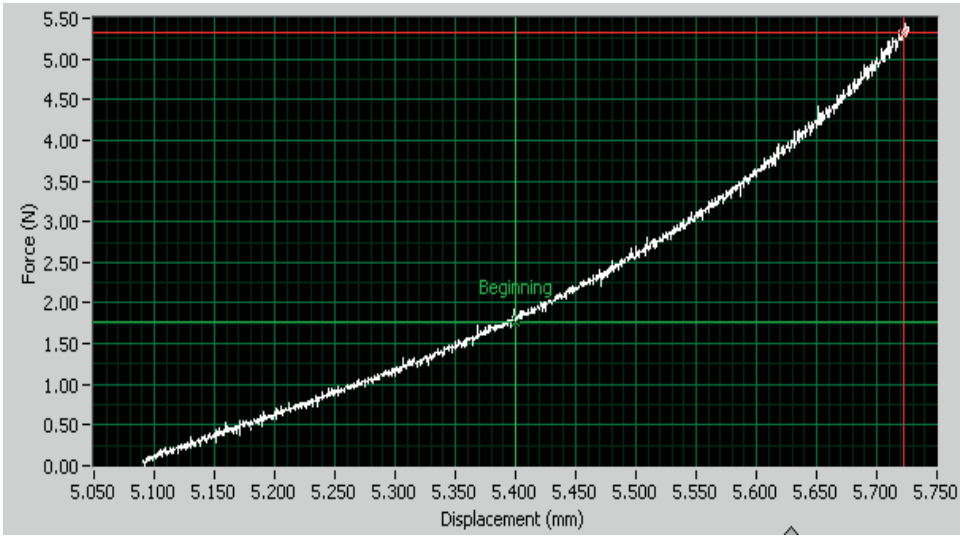


FIG. 84. Force-displacement curve for indentation of unaged Rockbestos CSPE Jacket.

For materials displaying relatively good linear behaviour in the ranges of forces or indentation depths considered for a typical cable indentation test (Case #1), there are no implications of measuring IM whether it is done based on depth ranges or based on force

ranges. However, for Case #2, IM can vary significantly based on the depth range where it is measured. When performing a series of tests for a variety of aged samples, measuring IM using a pre-defined force ranges of for example 1–4 N, will likely lead to measuring closer and closer to the cable sample surface as ageing increases, with the risk of underestimating or overestimating degradation depending on curve inflexion. This issue is clearly illustrated in FIG. 85 and FIG. 86, where the results of using both measurement methods are shown for an unaged and a 1560h thermally aged Rockbestos CSPE jacket sample. In FIG. 85, both measurement ranges overlap and the IM results are fairly similar. In FIG. 86, for the aged sample, the modulus is measured much closer to the sample surface when using the 1–4 N range and the IM measured there (18 N/mm) does not match the IM of 35 N/mm measured in the pre-defined depth range of 317–635 microns (12.5 –25 mils).

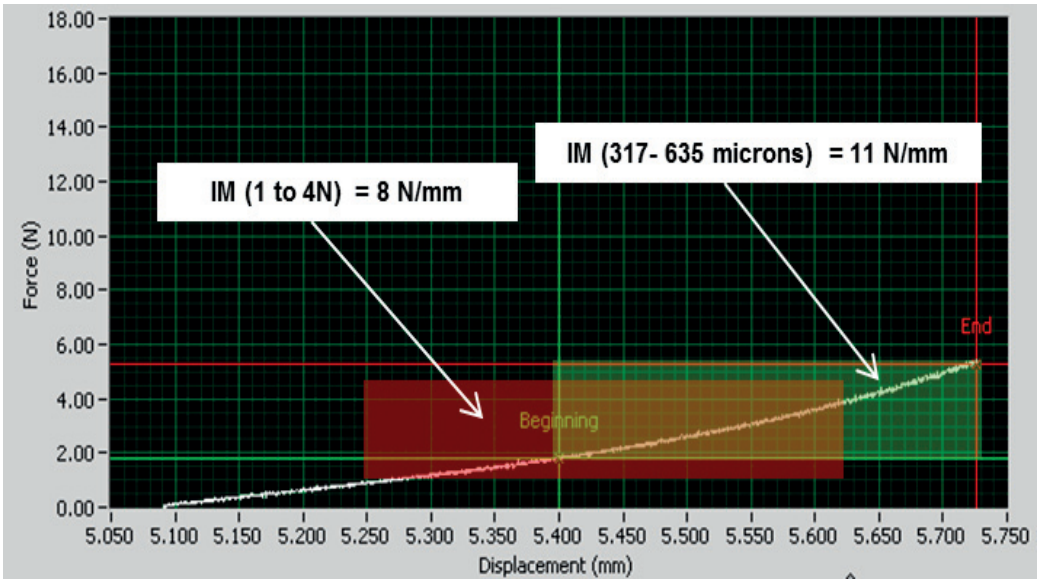


FIG. 85. Unaged Rockbestos CSPE jacket.

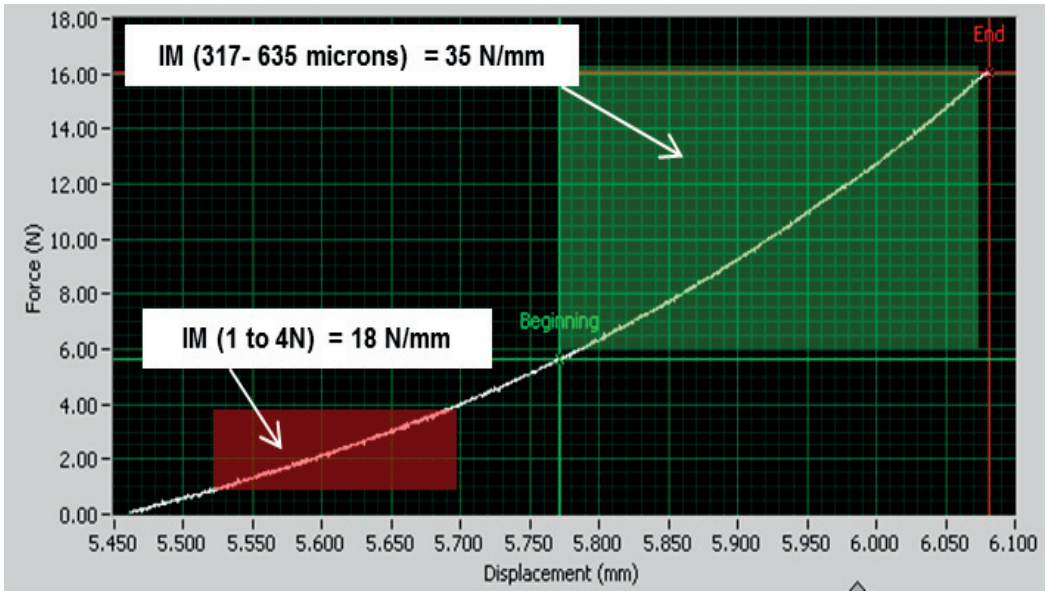


FIG. 86. 1560h thermally aged Rockbestos CSPE jacket.

III.1.3. Test results

The IM and recovery time results are shown in FIG. 87–FIG. 91 for the following jacket materials: Rockbestos CSPE, Changzhou EPR, Eupen EVA, Habia XLPO and Shanghai XLPO. IM measured for a force range of 1–4 N is shown in red, IM measured for a pre-defined depth range is shown in green, and recovery time is shown in black. The Y-scale have been kept identical for all materials in order to more easily compare the respective sensitivities to degradation of a given condition indicator for the various tested material. The typical standard deviation for measured indenter moduli was between 3% and 10% of the mean. The typical standard deviation for measured recovery times was between 5% and 10% of the mean.

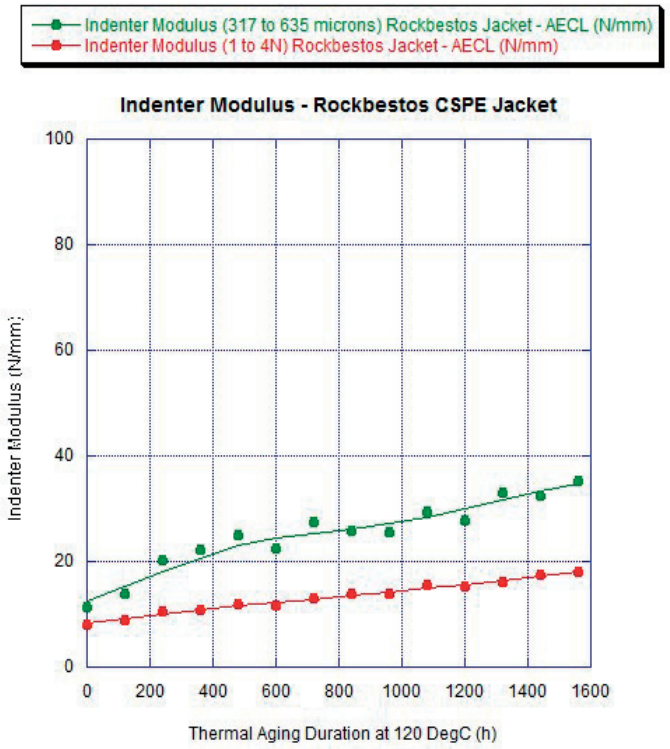
For the Rockbestos jacket (FIG. 87), the IM increased by a factor of approximately three between the unaged and most severely aged sample. The increase in IM was much less pronounced if using the 1–4 N force range for measurement higher and therefore degradation would tend to be underestimated in this case. The recovery time increased by approximately a factor of nine between the unaged and most severely aged sample.

For the Changzhou EPR jacket (FIG. 88), the IM increased by a factor of approximately three between the unaged and most severely aged sample when using a constant depth range for measurement. If using the 1–4 N range, the increase was higher and therefore degradation would tend to be overestimated in this case. The recovery time decreased slightly at first (probably as a result of early material transformations due to the high temperature ageing process). It then increased steadily for thermal ageing durations between 2500–6000h and then sharply after 6000h at 135˚C.

For the Eupen EVA jacket (FIG. 89), apart from a slight increase at the start of the ageing process, there was no significant change in IM with increasing thermal ageing time. The recovery time decreased sharply right at the start of the ageing process (probably as a result of significant material transformations due to the high temperature ageing process). It then remained flat and started increasing only when past 6000 hours of thermal ageing at 135˚C.

For the Habia XLPO jacket (Fig. 90), there was a slight increase in IM at the start of the ageing process and then no significant change. The recovery time increased significantly (a factor of five between the unaged and most severely aged samples). Three distinct stages of increase were noted: one at the start (probably as a result of early material transformations due to the high temperature ageing process), one after 2500h at 135˚C, and one after 5500h at 135˚C.

For the Shanghai XLPO jacket (FIG. 91), indenter moduli measured between 1 and 4 N and measured between 127 and 254 microns (5 to 10 mils) were similar for all tested samples because for this material, the force-depth relationship was linear. The IM increased by approximately a factor of two between the unaged and the most severely aged sample. The recovery time increased by approximately a factor of nine between the unaged and most severely aged sample. The recovery time increase was sharper after 6000h of thermal ageing at 135˚C.



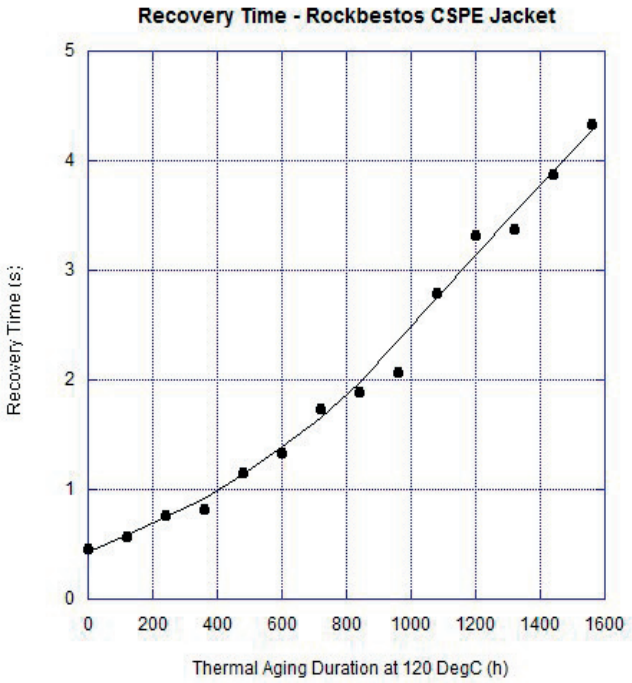
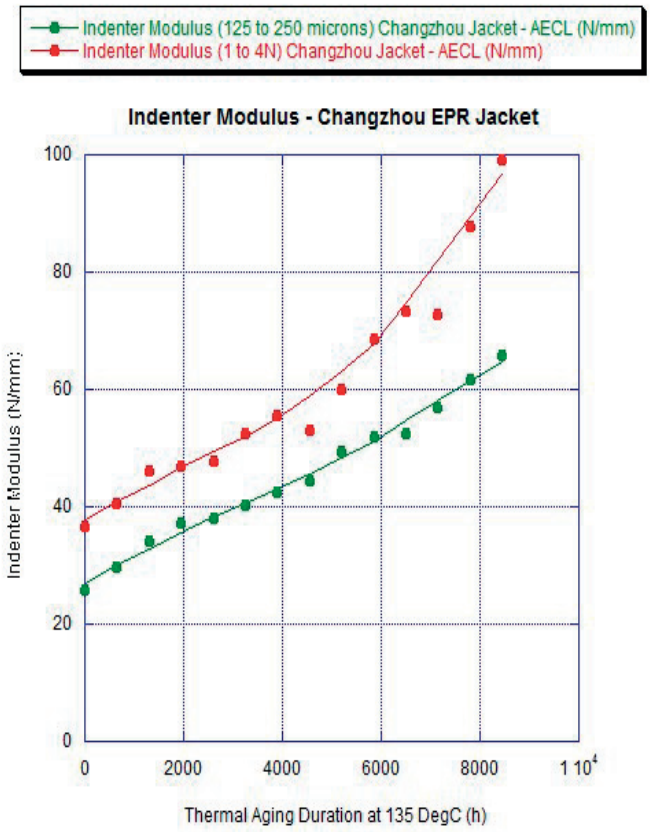


FIG. 87. IM and recovery time results for unaged and thermally aged Rockbestos CSPE jacket samples.



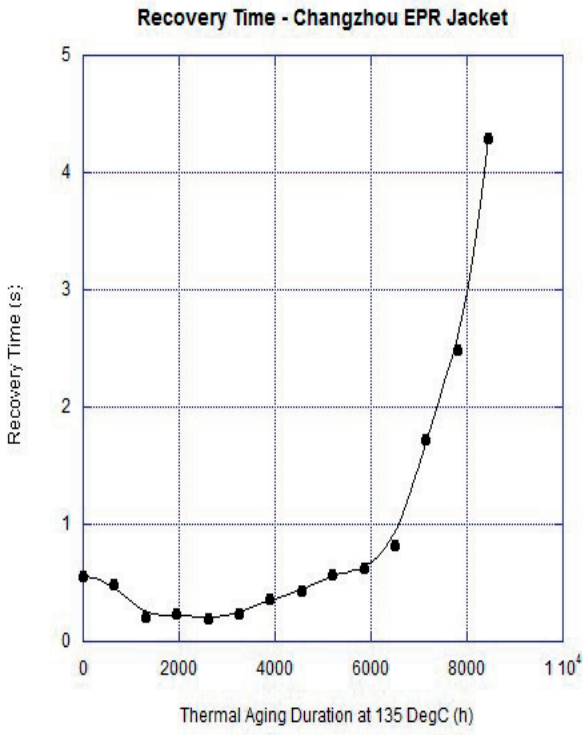
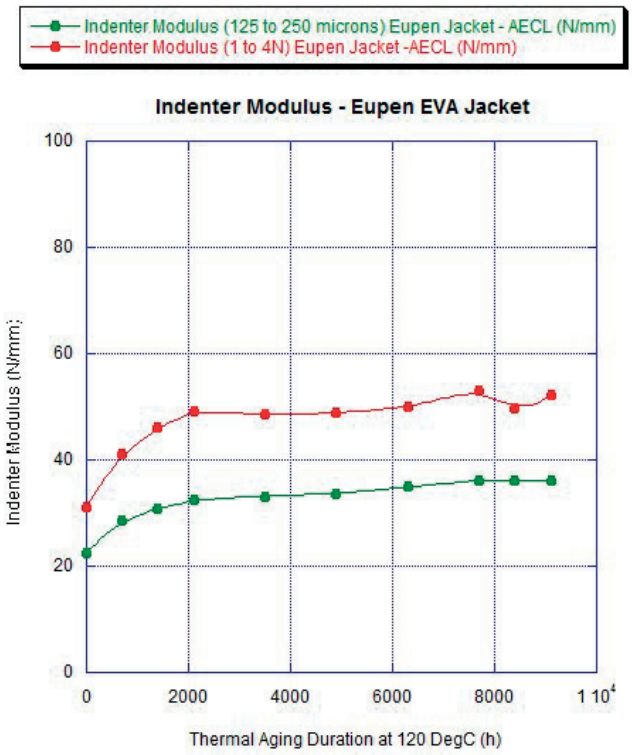


FIG. 88. IM and recovery time results for unaged and thermally aged Changzhou EPR jacket samples.



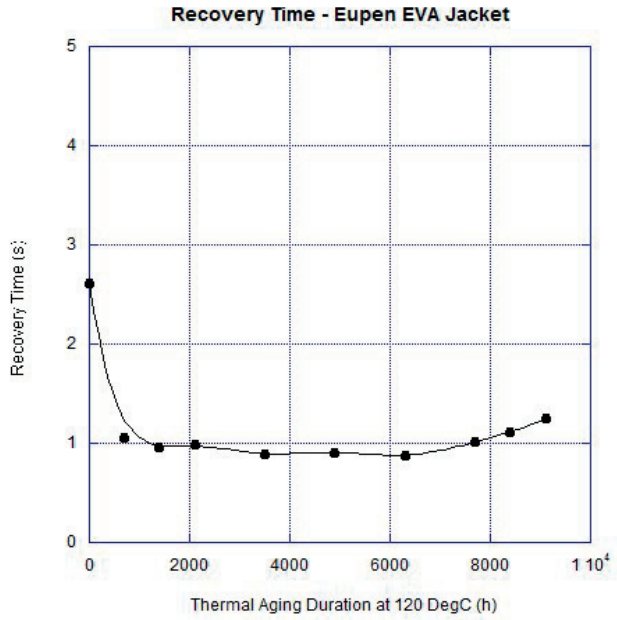
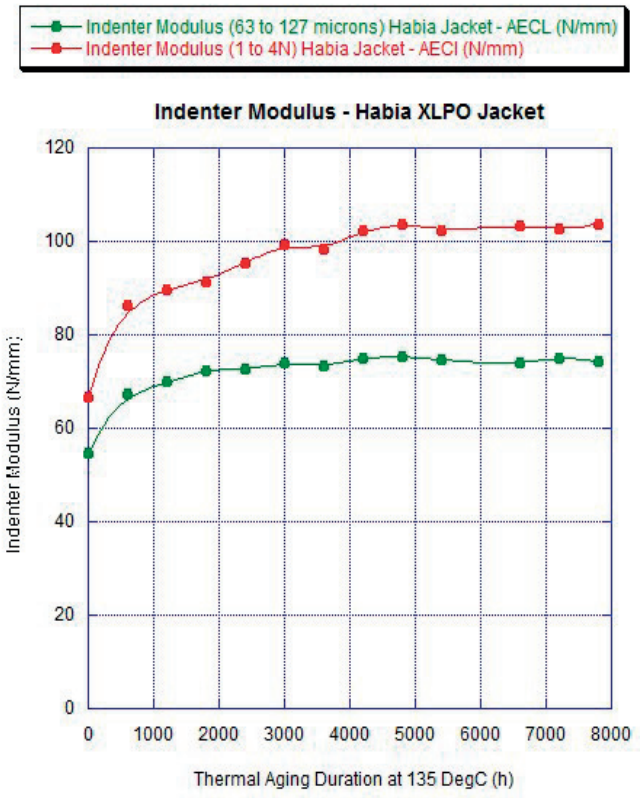


FIG. 89. IM and recovery time results for unaged and thermally aged Eupen EVA jacket samples.



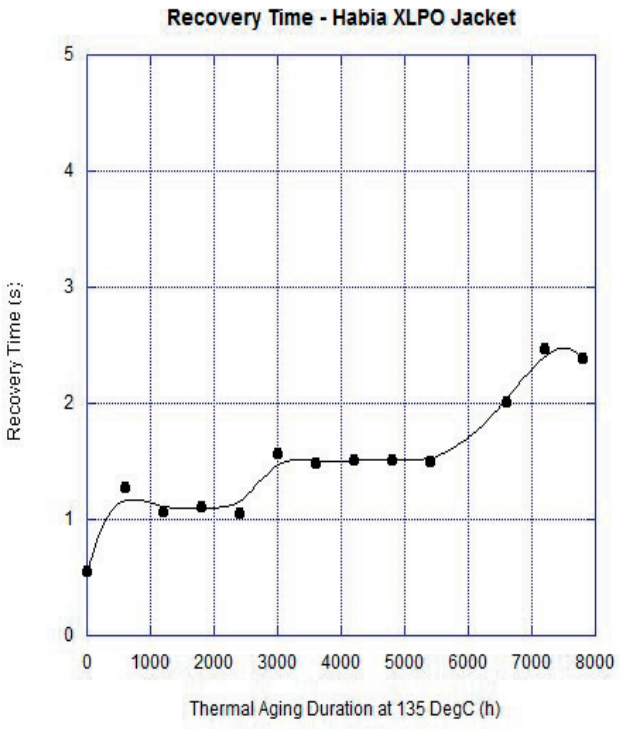


FIG. 90. IM and recovery time results for unaged and thermally aged Habia XLPO jacket samples.

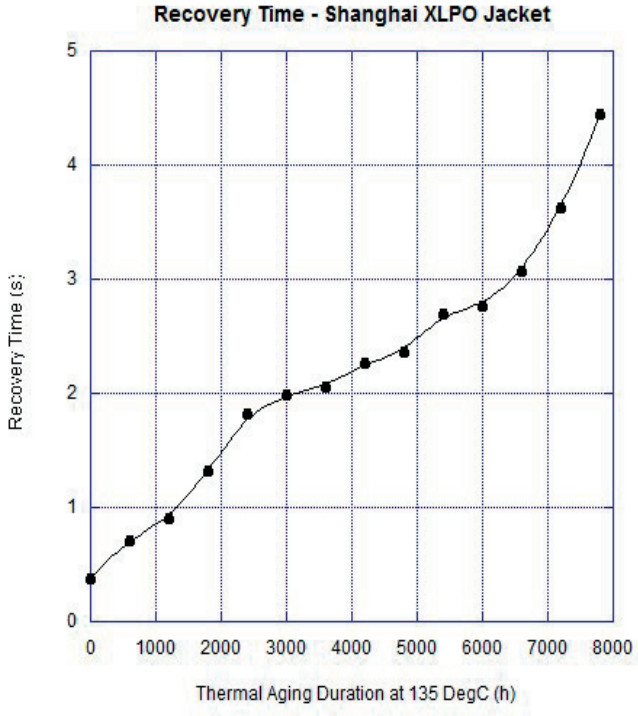


FIG. 91. IM and recovery time results for unaged and thermally aged Shanghai XLPO jacket samples.

III.1.4. Conclusions

AECL has been focused on thermal ageing and irradiation of cable samples as well as IM and recovery time testing. The main effort so far was dedicated to testing jacket samples. The main conclusions for the work performed to date are as follows:

— It is essential to compare indentation results for tests performed with identical indenter probes. As agreed after the 2nd CRP meeting, AECL changed from an IEC/IEEE standard indenter probe to an IPAM-style indenter probe. Following this change, AECL's IM results were in good agreement with IPAM user results;
— Using a defined force range (i.e., 1 to 4 N) to derive IM can have a significant impact on reliability of condition assessment. It is recommended to use a defined depth range for IM measurements rather than a defined force range;
— Recovery time showed high sensitivity to degradation for most jacket materials tested to date. The analysis of recovery time results also helped detect that material transformations are likely occurring very early in the ageing process for some of the materials exposed to relatively high ageing temperatures.

AECL will focus next on completing the cable sample irradiation programme and generating indenter modulus and recovery time for the irradiated cable jacket samples and for the thermally aged and the irradiated cable insulation samples.

III.2. ARGENTINA

III.2.1. Test methods

Thermal ageing and tensile tests (EAB) were carried out by CNEA. CNEA received samples for thermal ageing according to standardized procedures provided by the CRP organizer. Later, EAB tests were carried out at different ageing times in order to study the degradation evolution of cables insulation material. Tensile tests were performed also on irradiated samples provided by UJV.

III.2.2. Tested cables

CNEA performed thermal ageing on 3 types of cables and tensile test on 4 different kinds of cables. Details of these tests are summarized in Table 8.

TABLE 8. TEST SUMMARY - CABLE TYPE AND TEST CONDITIONS

Cable name	Material	Ageing temperature	Dose (kGy)	Type of sample
Eupen	Insulation (EPR)	135°C	1422	Tubular
	Jacket (EVA)	120°C	-	ISO type4
Hew	Insulation (SiR)	190°C	-	Tubular
	Jacket (SiR)	190°C	-	ISO type4
Shanghai	Insulation (XLPO)	135°C	1422	Tubular
	Jacket (XLPO)	135°C	-	ISO type4
Habia	Insulation (PEEK)	-	1422	Tubular

III.2.3. Test results

The thermal ageing behaviour of Eupen, Hew and Shanghai cables are presented in FIG. 92-FIG. 94. Eupen insulation samples were difficult to prepare due to the fact that the insulation material was extremely attached to metal conductor. The black colour insulation material was the only one that could be removed without any additional procedures. For the rest of the colours it was necessary to cut along the length in order to remove the conductor. These additional preparation procedures produced an additional variation in samples that gave rise to large data dispersion.

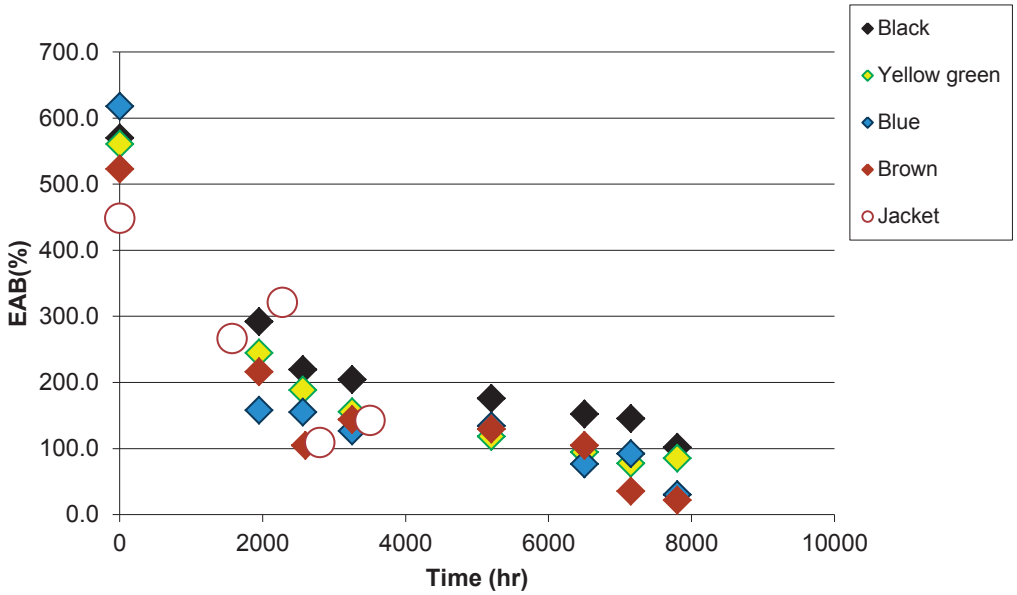


FIG. 92. EAB vs time for Eupen insulation and jacket materials.

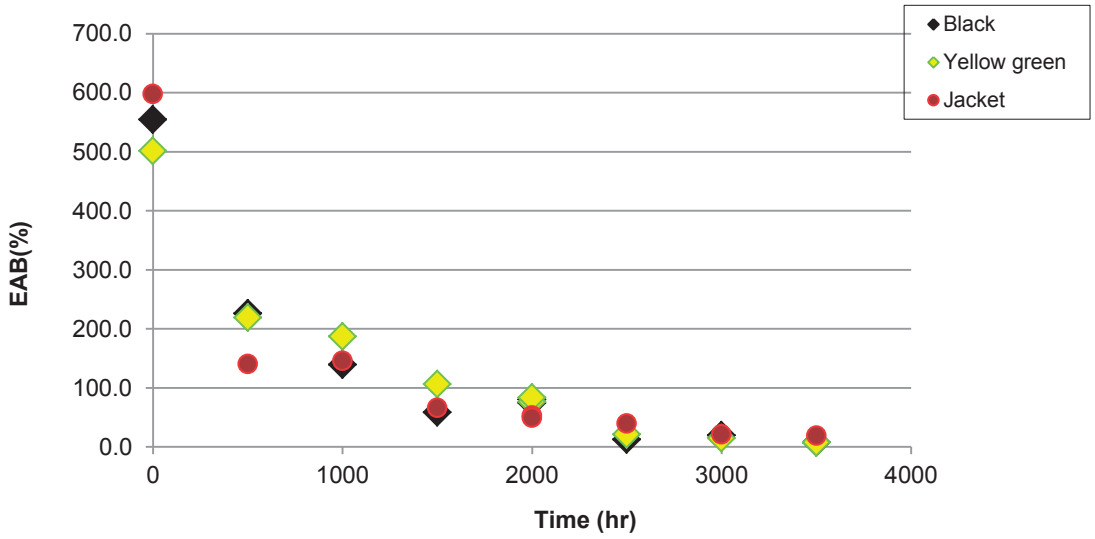


FIG. 93. EAB vs time for Hew insulation and jacket materials.

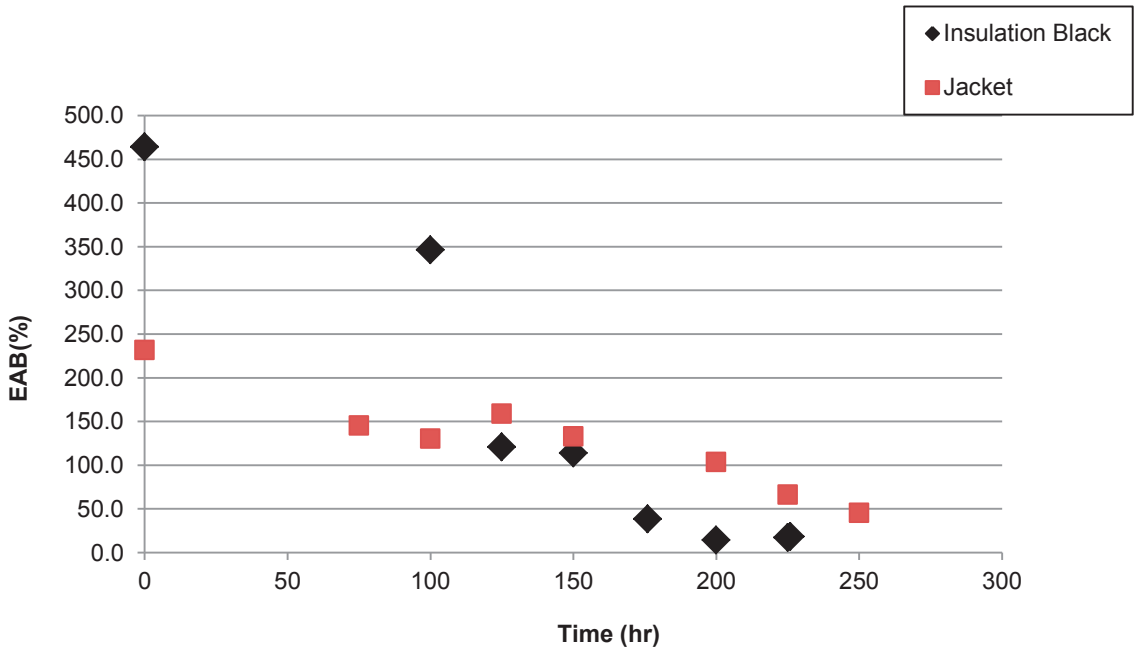


FIG. 94. EAB vs time for Shanghai insulation and jacket material.

The results of the tests performed on irradiated samples are summarized in Table 9. As can be seen it was not possible to perform tensile tests in some cases because the material embrittlement made it impossible to remove the conductor without causing serious damage to the insulation. In the case of Habia insulation the problem was not the embrittlement of the material but the insulation-conductor attachment.

TABLE 9. TEST RESULTS FOR IRRADIATED SAMPLES

Cable name	Material	Dose (kGy)	EAB (%)	Comment
Eupen	Insulation Black	1422	124.9	
	Insulation Yellow green	1422	-	Not possible to prepare samples because of material embrittlement
	Insulation Blue	1422	93.8	
	Insulation brown	1422	105.5	
Shanghai	Insulation black (XLPO)	1422	-	Not possible to prepare samples because of material embrittlement
Habia	Insulation (PEEK)	1422	-	Not possible to prepare samples because of insulation-conductor attachment

III.2.4. Opinion

EAB seems to be good parameter for indicating cable condition, is reproducible and shows good trending with thermal ageing for all the insulation materials. In the case of EVA/EUPEN there was a big data dispersion and difference between laboratories because of the sample preparation process. This process is essential for cable ageing management during a NPP's lifetime. In this context where CM techniques should be performed though many years a detailed samples preparation procedure and methodology are critical.

There is no perfect CM method which is applicable for all material. The suggestion is to use more than one method in order to assess cable ageing and/or cable failure.

III.3. BELGIUM

III.3.1. Overview

The ageing evaluation of cable samples was mainly focused on mechanical properties i.e. indenter modulus and tensile testing. Because of a lack of irradiation facilities, only thermal ageing was performed on the following cable types: Changzhou, Shanghai, Eupen, Rockbestos and Habia. The thermal ageing and tensile testing were executed in collaboration with the Belgian Research Centre for Nuclear Energy (SCK.CEN) and many samples were also provided to our British partner for density measurements.

III.3.2. Sample preparation and thermal ageing

Insulation and jacket materials were aged separately. No full cable piece was included in the ageing programme. Ventilated ovens were used and periodic checks of the remaining elongation property were performed. Based on the results, the sample extraction time was adjusted.

Some insulation materials were extremely difficult to separate from the conductors. This was mainly true for the Eupen and Habia cables. In order to produce test samples, insulated wires were heated up to soften the polymer and the insulation was slit along the length of the sample. The slitting process led to tiny defects on the edge of the cut. This had an important influence on EAB values afterwards. Table 10 shows the extraction intervals for all samples.

TABLE 10. EXTRACTION INTERVALS FOR THERMAL AGEING STUDY

Cable type	T(°C)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Changzhou I	135	0	2205	2588	3888	4556	5155	5860	6495		
Changzhou J	135	0	2205	2588	3888	4556	5155	5860	6495		
Shanghai I	135	0	2183	2419	3305	3548	4267	4723	6040		
Shanghai J	135	0	2183	2419	3305	3548	4267	4723	6040		
Eupen I	135	0	2225.2	2588	3864	4556	5155	5860	6504		
Eupen J	120	0	2103	2803	3450	4175	4932	5544	7004		
Rockbestos I	135	0	2419	3173.5	3696	4723	5424	5945	6040		
Rockbestos J	120	0	176	337.5	511.5	784	912	1056	1248	1464	1824
Habia J	135	0	2183	2419	3305	3548	4267	4723	6040		

III.3.3. Tensile test

A Tinius Olsen tensile test system was used in combination with a clip on extensometer. Elongation at break results given in FIG. 95 - FIG. 103 show the ability of the tensile testing technique to monitor the mechanical degradation of the polymer constituting of the insulation

and jacket. However, some unexpected increases of the EAB values are reported (FIG. 95, FIG. 97 and FIG. 101) in the middle of the ageing process. This behaviour, coupled with results dispersion can disqualify the technique for the ageing monitoring of some polymers, especially if this behaviour is expected to occur in the 50% remaining elongation region (criterion usually used as end of life). Indeed, results produced by an ideal CM technique should have a strictly monotonic evolution with respect to the ageing time.

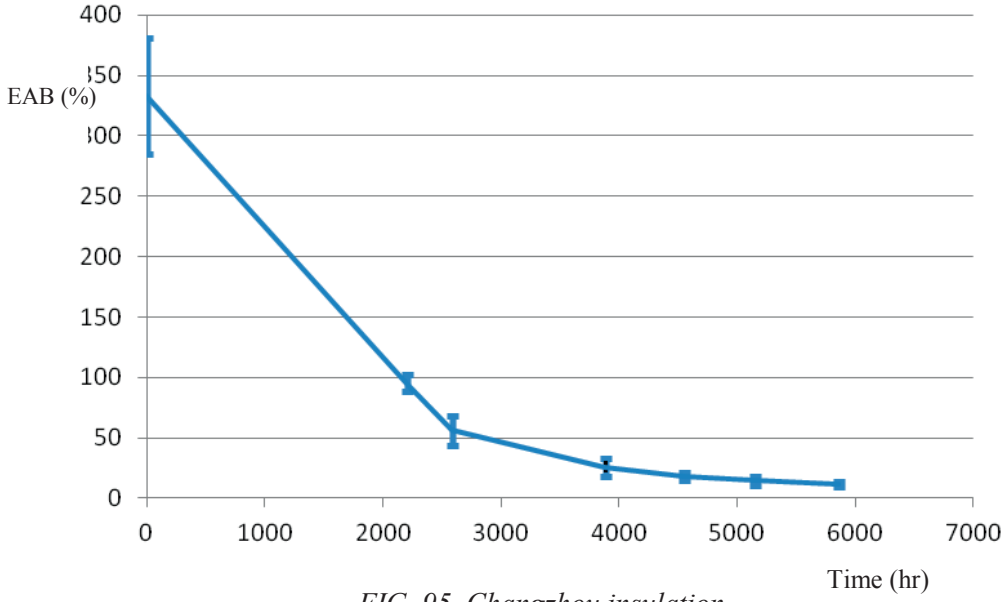


FIG. 95. Changzhou insulation.

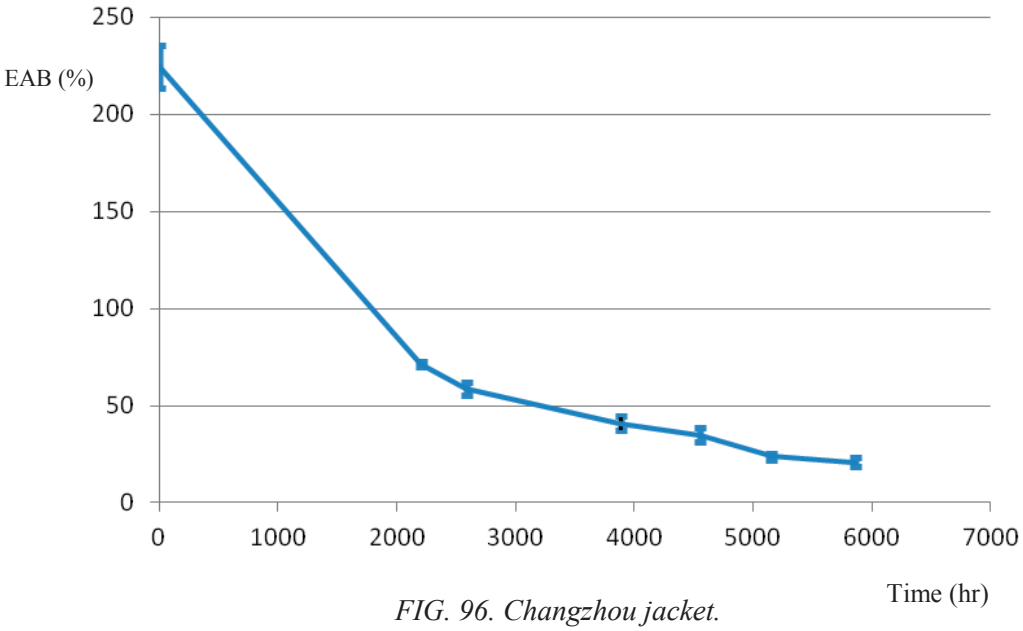


FIG. 96. Changzhou jacket.

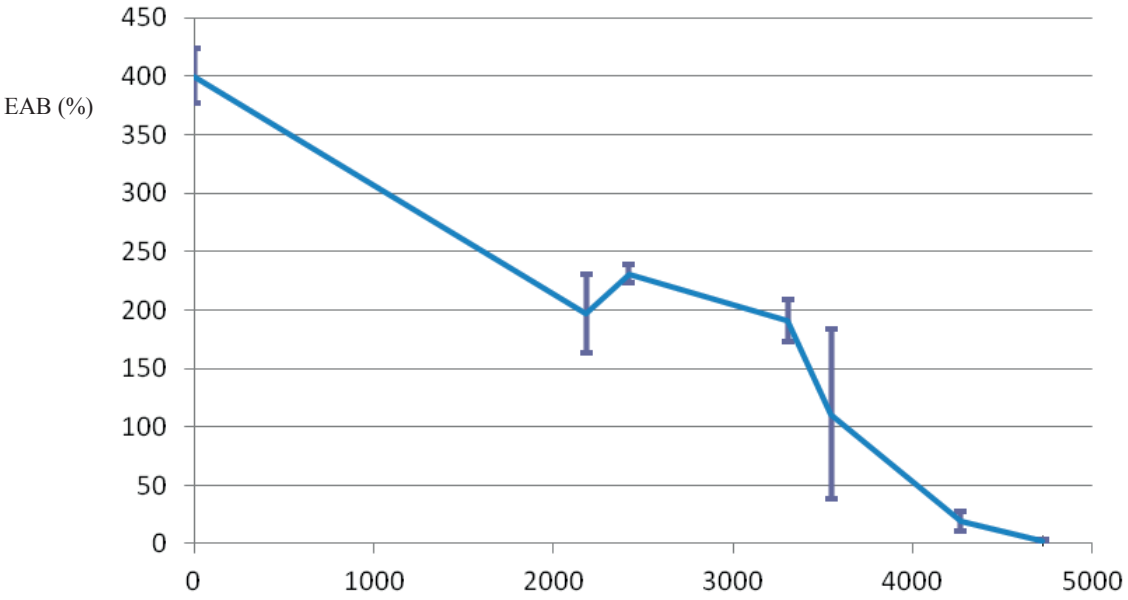


FIG. 97. Shanghai insulation.

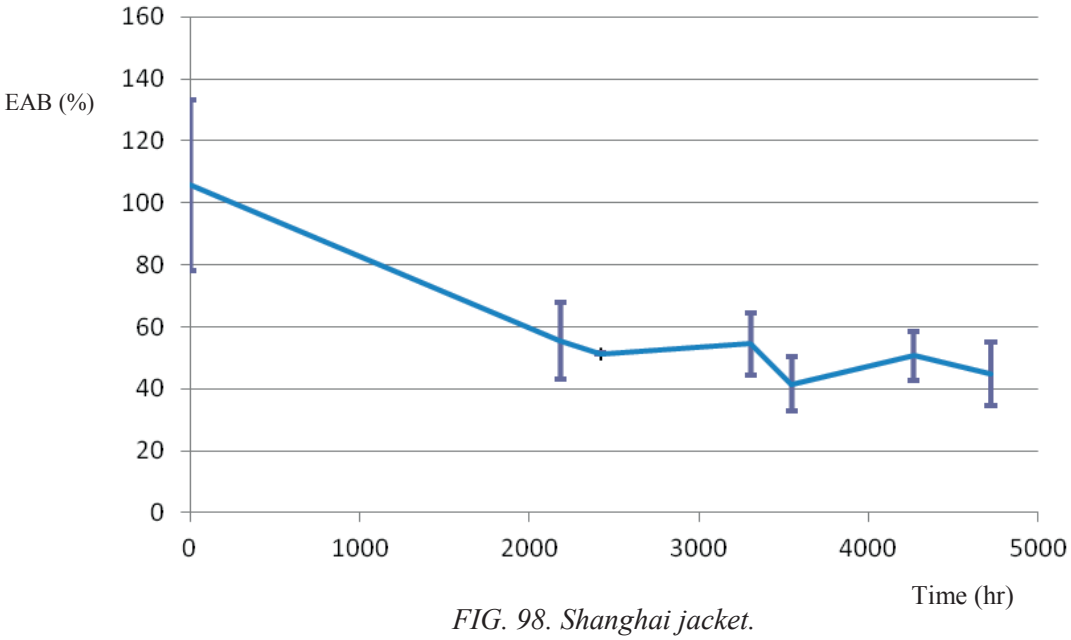


FIG. 98. Shanghai jacket.

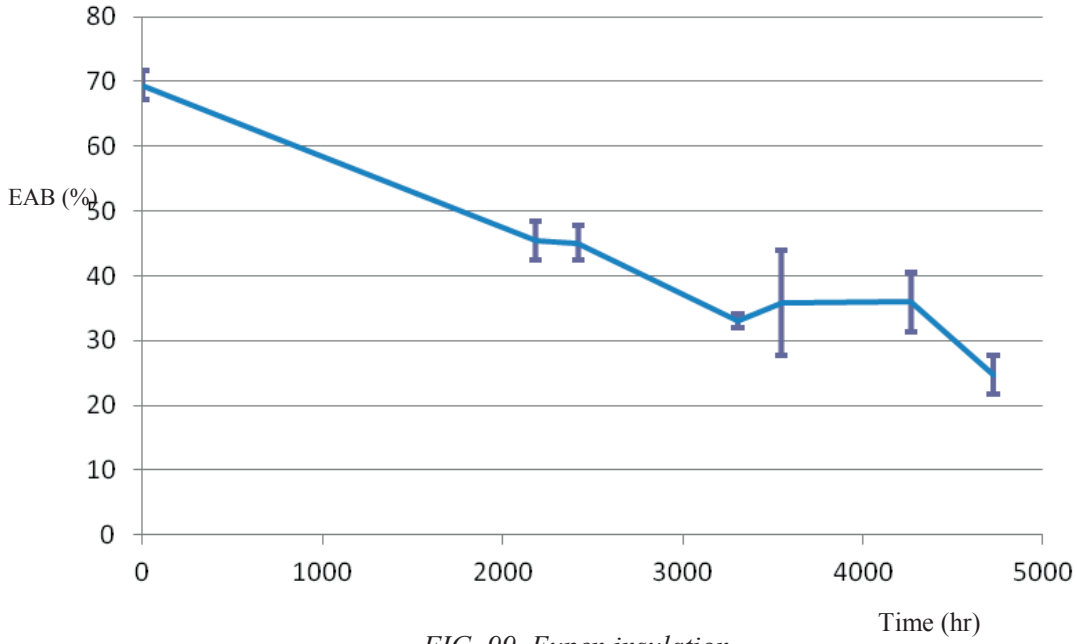


FIG. 99. Eupen insulation.

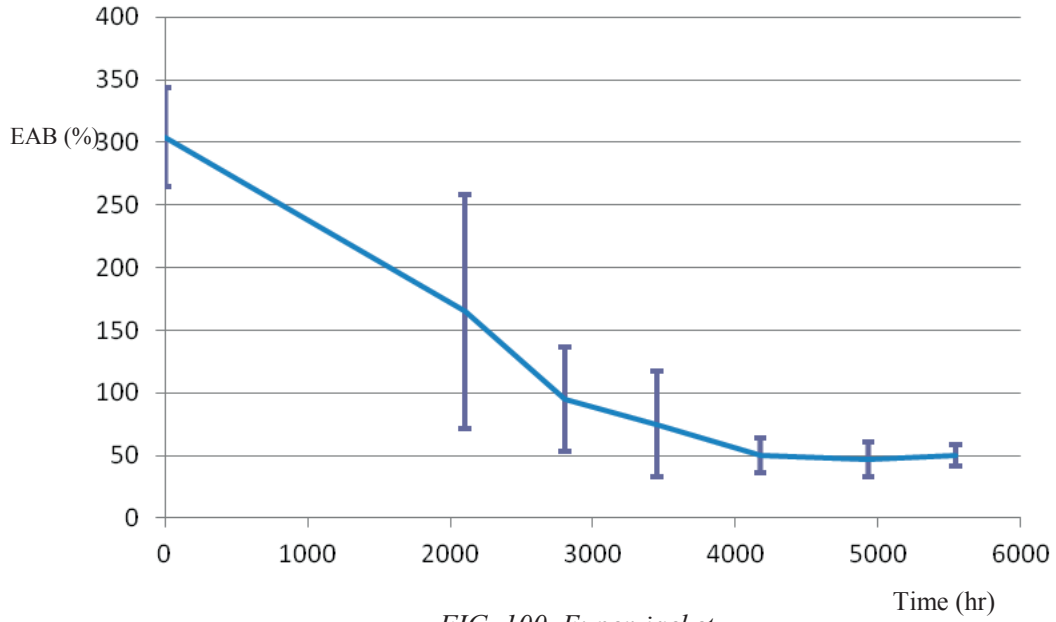


FIG. 100. Eupen jacket.

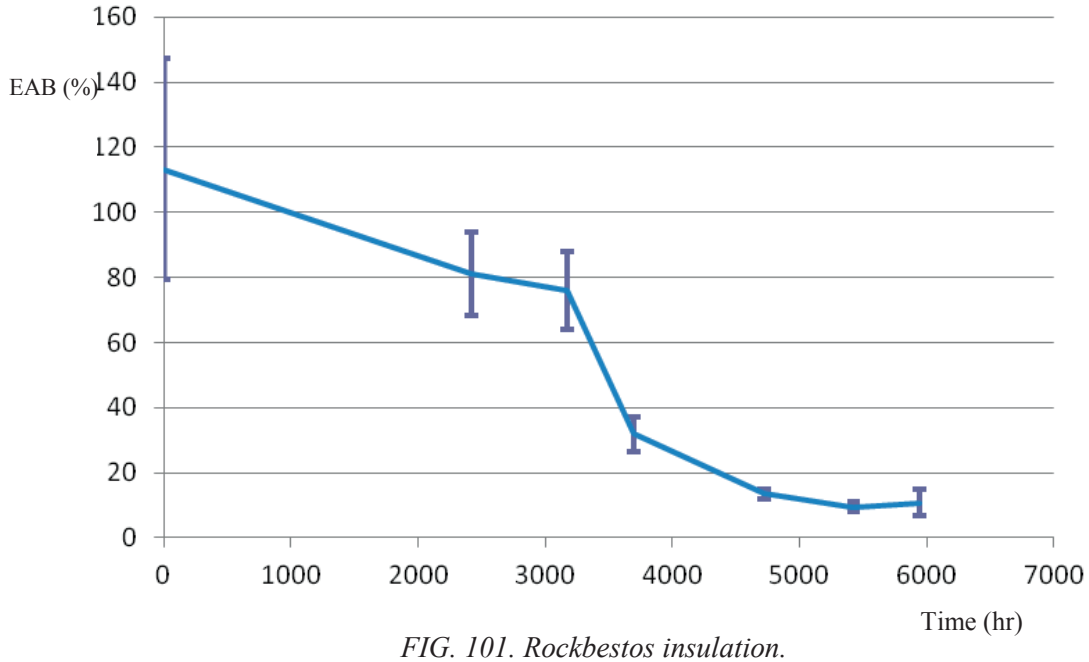


FIG. 101. Rockbestos insulation.

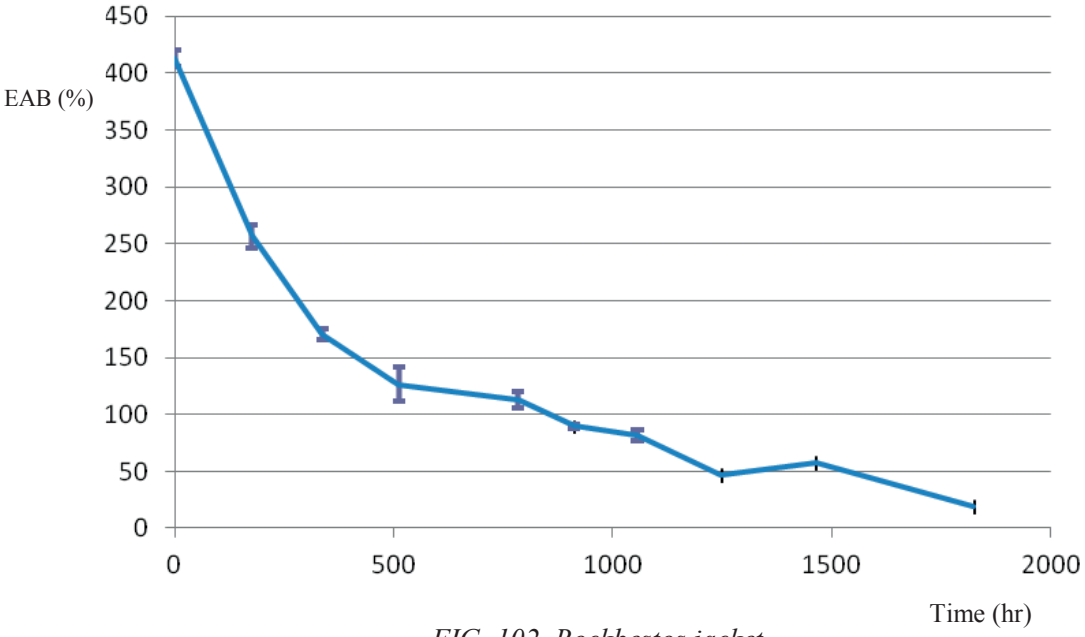


FIG. 102. Rockbestos jacket.

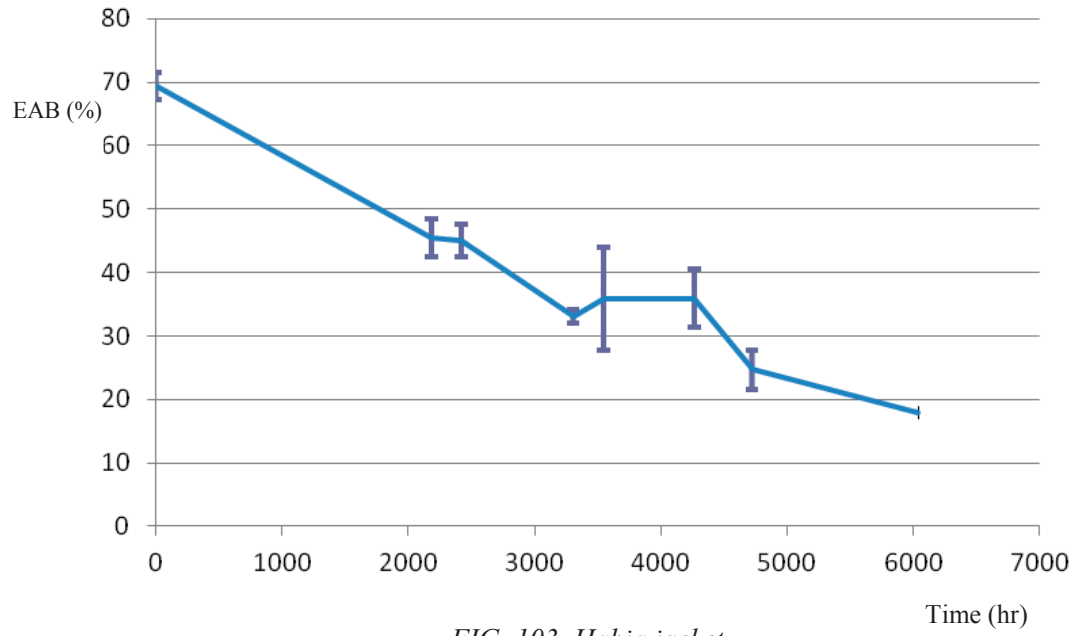


FIG. 103. Habia jacket.

III.3.4. Indenter modules test

The IPAM 3 device produced by Analog Interfaces was used for indenter modulus measurements. Cable jackets were tested using pre-cut dumbbells. No measurement was performed on the insulation. A data reprocessing was thereafter performed with Matlab in order to refine raw results. IM given in FIG. 104 -

FIG. 107 were computed between 1 N–4 N. 10-12 measurements were performed each time and outliers identified with a curve based analysis were removed.

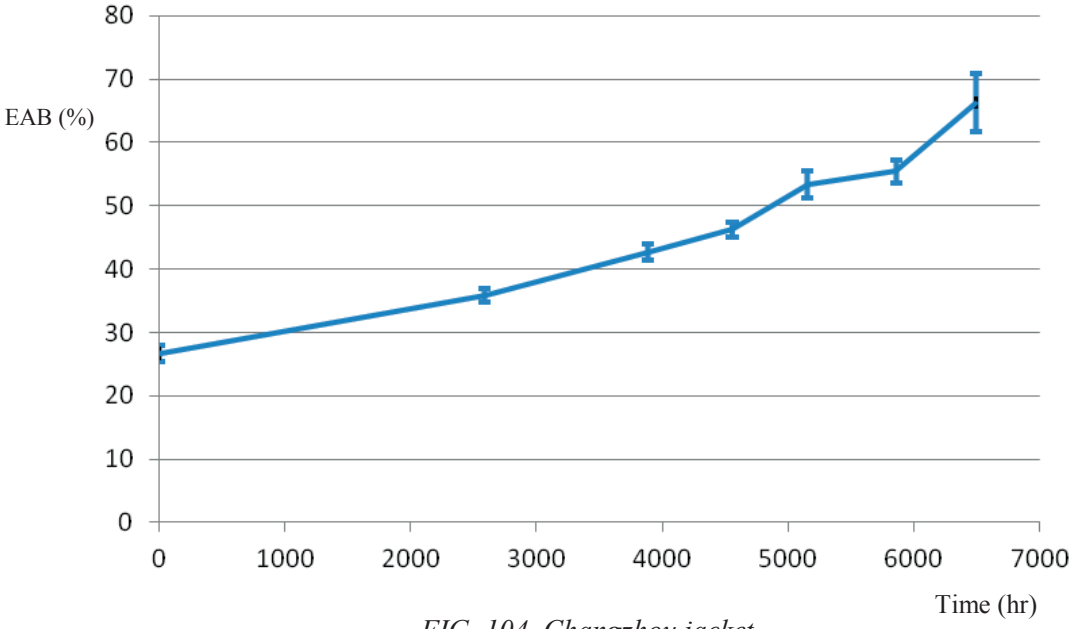


FIG. 104. Changzhou jacket.

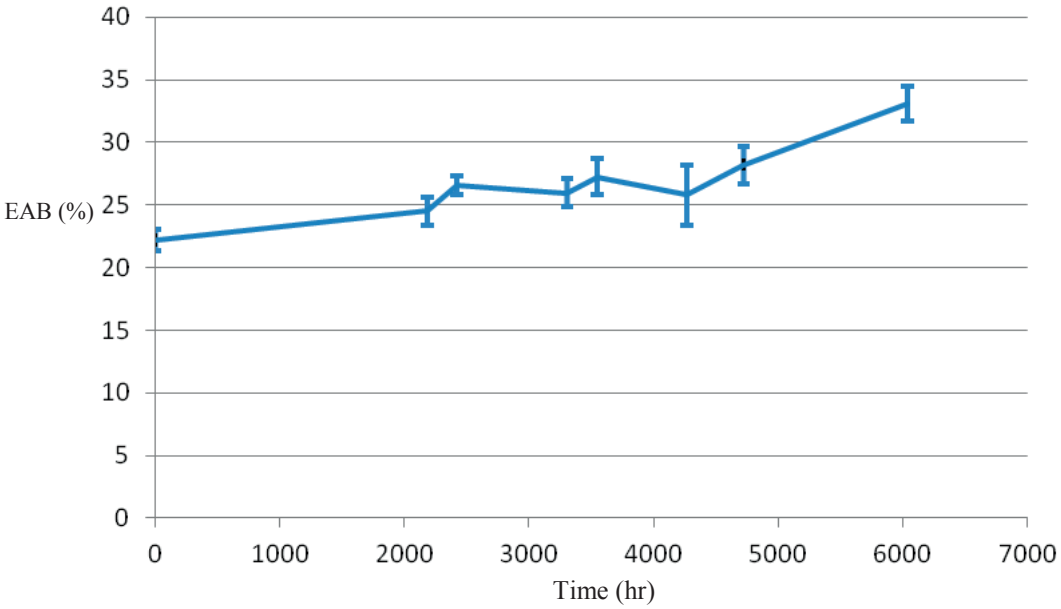


FIG. 105. Shanghai jacket.

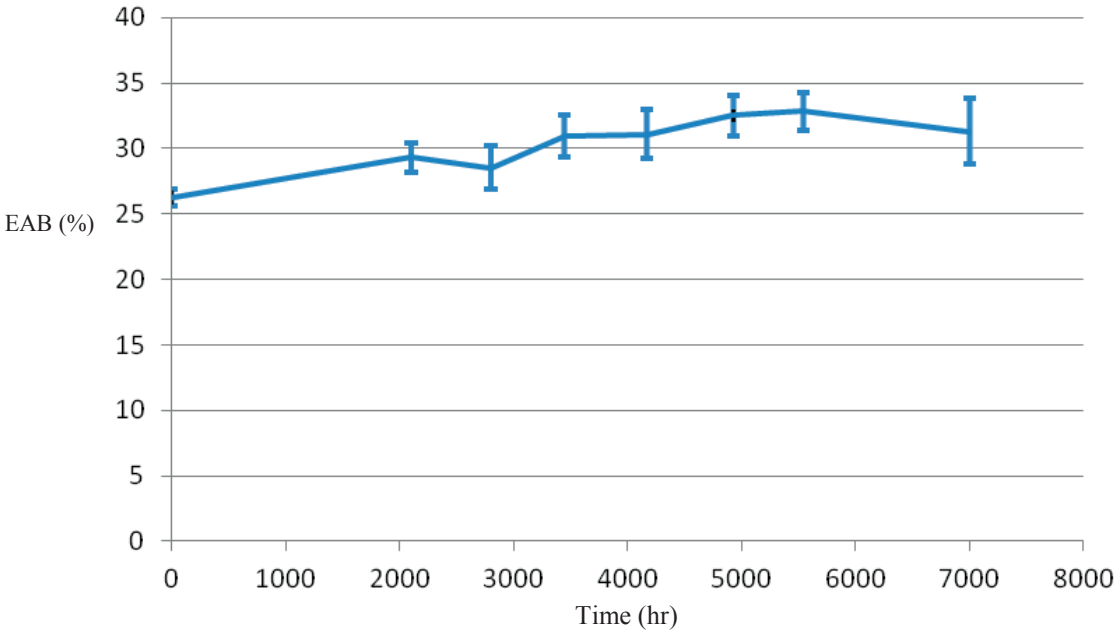


FIG. 106. Eupen jacket.

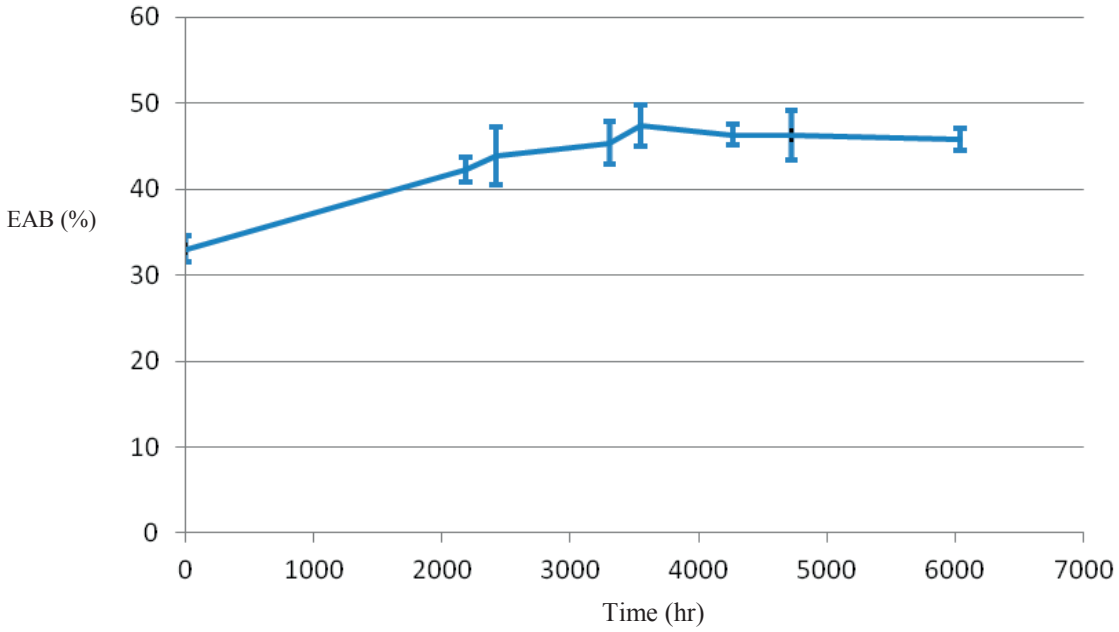


FIG. 107. Habia jacket.

As for the EAB values, the indenter modulus method shows some ability to follow up mechanical properties evolution with respect to ageing time. Spreading of measures remains an important concern, especially when the IM does not vary much.

As stated above, Matlab was used for retreating data. As can be seen in FIG. 108, the starting point of the curves is not always at the origin. This phenomenon hinders the identification of outliers because the 'strange' behaviour of the curves can be hidden by the superposition of the curves. FIG. 109 shows the reprocessing result. The first curve on the left was disqualified because of its too steep slope. Further investigation showed that the material thickness was too thin at the measurement point. This case highlights the importance of looking at the curves when performing indentation measurements.

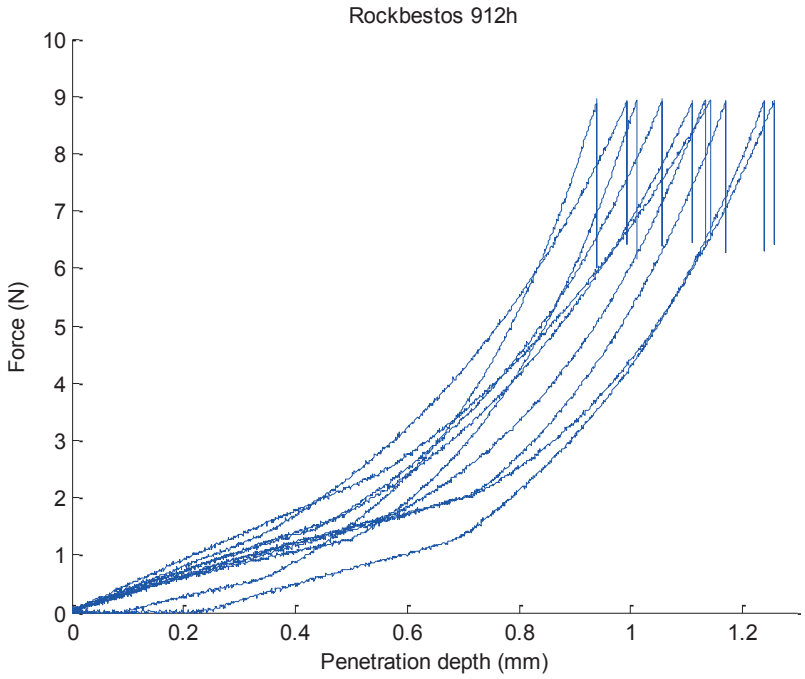


FIG. 108. Rockbestos jacket 912h without reprocessing.

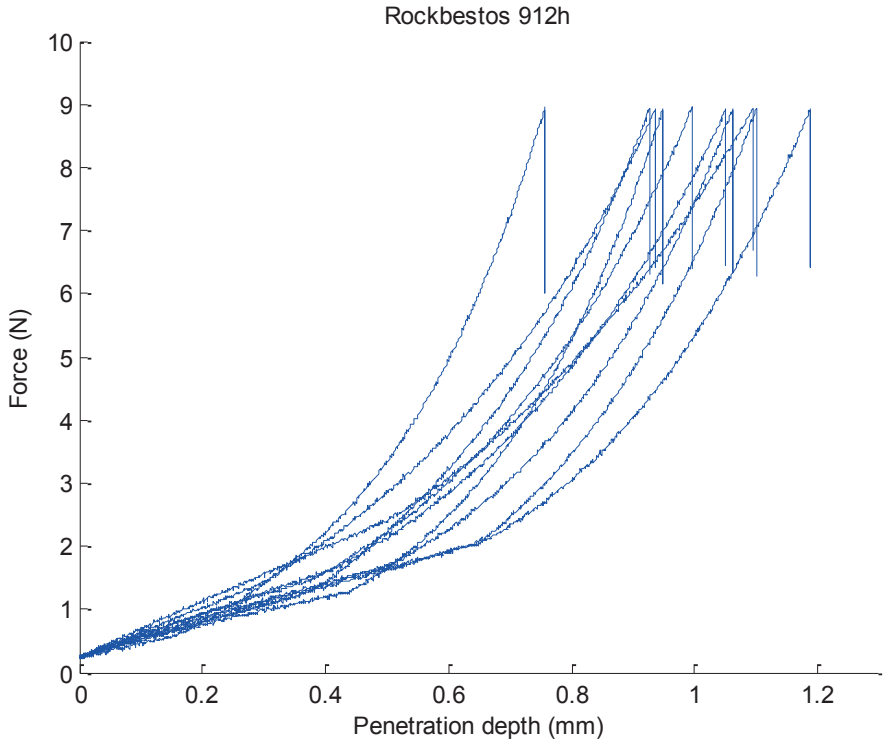


FIG. 109. Rockbestos jacket 912h with reprocessing.

III.3.5. Overall summary of Laborelec data results

The work performed by Laborelec was dedicated to the mechanical assessment of cable jackets material. The effect of thermal ageing was studied but no irradiation was performed. Material properties measured with tensile and indenter modulus tests showed an evolution

with the ageing time. However, this evolution was not always strictly monotonic. Important improvements are needed for both techniques in order to reduce result spreading.

III.3.6. Recommendations

Laborelec proposes to improve existing standards with following elements:

— Indenter modulus:

- Use a depth range instead of a force range for modulus calculation. Indeed, 4 N can be too high for soft materials. The ageing and related hardening of the material can induce a variation of the measured depth. The depth imposed should take into account edge effect as well as indentation-thickness consideration;
- Give guidelines for a quality control based on analysis of the curves;

— Tensile testing:

- Give more freedom for test speed determination. Elastomer can have very high EAB values which imposes very long testing time. This can also lead to non-realistic values if the polymer is not cross-linked (flow of the material). Imposing a maximum test time of 3 minutes should be considered;
- Improve the preparation of test samples is very important. Indeed, many results were impacted negatively by defects, especially for the insulation. Giving a stripping procedure is welcome;
- Accept the 50% remaining EAB as generic acceptance criterion for this technique. This criterion is widely justified in many publications, including some of IAEA.

III.4. CHINA

III.4.1. Test methods

Led and guided by SNERDI (Shanghai Nuclear Engineering Research and Design Institute), SECRI and SNPSC performed cable CM tests of 5 methods suggested by IAEA in the CRP, which are EAB, indenter modulus, OIT, OITP and ultrasonic velocity tests. EAB, indenter modulus, OIT and OITP were performed at SECRI while ultrasonic velocity was performed at SNPSC. All tests were conducted on both jacket and insulation except that ultrasonic velocity tests were conducted only on jacket due to the test equipment's capacity (small size insulation cannot be tested).

III.4.2. Test cables

Three types of cables are included in SNERDI's testing scope, which are Changzhou Bayi Cable (EPR/EPR), Shanghai Special Cable (XLPO/XLPO) and Eupen Cable (EPR/EVA).

III.4.3. Ageing test

Thermal ageing tests are performed at SECRI. 50 mm long insulation tubular specimens and 75 mm long jacket dumbbell specimens (ISO type II) with a gauge length of 20 mm were prepared for EAB tests. 300 mm long completed cables and 300 mm long insulated conductors taken from the completed cables were prepared for indenter tests. The same completed cable specimens used for indenter tests were also used for ultrasonic velocity tests.

Small specimens for both OIT and OITP were taken from tubular, dumbbell, completed cable or insulated conductor specimens.

According to the ageing procedure of the CRP, samples should be thermally aged to 7 different conditions to reach the 50 - 100% absolute elongation. Therefore, all above test specimens include 7 ageing conditions (S1 ~ S7) plus S0 for the unaged condition. However, during the long time thermal ageing, significant ageing degradation were witnessed at S2 (0.8 of the expected end point time) for Bayi, Shanghai and Eupen cables and all ageing ovens were stopped. After evaluating the condition of samples and for the purpose of obtaining sufficient sample data at different ageing phases, the rest ageing programme was resumed.

In addition to the above thermal ageing of SNERDI's cope, specimens from Nuclear Engineering Nuclear (NEL), Japan were also thermally aged at SECRI, which includes Rockbestos (XLPE/CSPE), Habia (PEEK/XLPO), Eupen (EPR/EVA), Bayi (EPR/EPR) and Shanghai (XLPO/XLPO) completed cable and insulated conductor specimens. Besides the same cable types of SNERDI's scope, Rockbestos and Habia cable specimens were also aged to the scheduled S7 condition.

Table 11 shows ageing durations and temperatures for all test specimens.

TABLE 11. AGEING DURATIONS AND TEMPERATURES

Specimen		Temp. (℃)	Ageing Time (hour)						
			S1	S2	S3	S4	S5	S6	S7
Bayi	Jacket	135	2400	4800	6000	1800	4200	5400	3600
	Insulation	135	2400	4800	6000	1800	4200	5400	3600
Shanghai	Jacket	135	2400	4800	6000	1800	4200	5400	3600
	Insulation	135	2400	4800	6000	1800	4200	5400	3600
Eupen	Insulation	135	2400	4800	6000	1800	4200	5400	3600
	Jacket	120	2800	5600	7000	2100	4900	6300	4200
RSCC	Insulation	135	2400	4800	6000	1800	4200	5400	3600
	Jacket	120	480	960	1200	600	8400	1080	1320
Habia	Insulation	190	2400	4800	6000	1800	4200	5400	3600
	Jacket	135	2400	4800	6000	1800	4200	5400	3600

III.4.4. CM test results

III.4.4.1. Elongation at break

Initially, EAB tests were performed by using electronic tensile machine with extensometer, however, after comparing S0 test results with other participants, the measured values were found significantly smaller than those from others. Further comparisons were done by SECRI and the conclusion was that the machine's grip tends to become loose when testing. After further assessment, S0 insulation specimens were re-prepared and re-tested using another manual tensile machine without extensometer, however, the tested value looks

closer to other participants' test results. Therefore, all the rest of aged specimens were tested using the manual machine:

— All samples from S0 through S7 are aged as specified. However, due to significant degradation, EAB of samples at the last several phases of the ageing programme cannot be tested. The tested results seem reversed for S1 and S4. A possible reason could be that uneven distribution of temperature in the ageing oven and therefore specimens are aged with different temperatures;
— Test results are predictable in general.

III.4.4.2. Indenter modulus

Indenter modulus tests for both insulated conductor and completed cable were performed using IPAM4 from AMS. The indenter modulus tests were performed 9 times per specimen according to the test procedure of the CRP. The maximum force is 9 N. Diameter of probe tip was 0.56 mm, and force range used for calculation is in range of 1.25 ~ 3.75 N:

— All Bayi, Shanghai and Eupen cables showed increasing trend with ageing time;
— Jacketed specimens of Eupen cable showed a little scattered data;
— All test results are predictable in general.

III.4.4.3. Oxidation induction time

OIT (oxidation induction time) tests were performed for each aged and unaged test specimens using MettlerToledo DSC1. Tests were conducted following the test procedure of the CRP. Test temperature for insulation and jacket of Eupen and Bayi was 240ºC, while that for Shanghai's specimen temperature for insulation and jacket was 230ºC and 250ºC respectively:

— Since the Shanghai cable insulation specimens for several ageing conditions, lost elongation, OITs were measured as 0;
— All test results are very predictable.

III.4.4.4. Oxidation induction temperature

OITP (oxidation induction temperature) tests were performed for each aged and unaged test specimens using Mettler Toledo DSC1. Tests were conducted following the test procedure of the CRP. Test temperature ramp rate was 10ºC/min. Oxygen flow rate was 60 ml/min:

— It seems that OITP is a more reliable and time saving method comparing with OIT;
— All test results are very predictable.

III.4.4.5. Ultrasonic velocity

Ultrasonic velocity tests were performed for each aged and unaged jacketed specimens using ultrasonic velocity machine developed by SNPSC.

Tests were performed 6 times for each specimen:

— All tests on Bayi, Shanghai and Eupen jacketed cable have predictable results. However, deviations of test results are larger than expected.

III.4.4.6. Summary and opinion

Test results of Bayi, Shanghai and Eupen cables have similar behaviour as shown in Table 12. But it does not mean that these CM tests are suitable for testing of all types of cable materials. It is considered that the materials used for Bayi, Shanghai and Eupen have similarities between each other which mostly with EPR compounds. Other materials such as PEEK, CSPE, PVC, etc., were not tested. However, the above tested materials are most commonly used in NPPs in China.

Accuracy of age conditioning is very important for benchmarking of CM tests. Different ageing conditions will bring varied test results which brings difficulty of comparing and trending.

OITP is considered a better CM method than OIT not only for the test results but also the time saving aspect. However, both OIT and OITP, by micro-sampling, seems not so good or representative as expected while testing double layer insulation specimens or specimens in case of uneven distributed compounds along the length of a cable.

TABLE 12. SUMMARY OF TEST RESULTS

Specimen		Method				
		EAB	Indenter Modulus	OIT	OITP	Ultrasonic velocity
Bayi	Jacket (EPR)	O	Δ	O	O	Δ
	Insulation (EPR)	O	Δ	O	O	-
Shanghai	Jacket (XLPO)	O	X	Δ	Δ	Δ
	Insulation (XLPO)	O	Δ	X	X	-
Eupen	Jacket (EVA)	O	Δ	O	O	Δ
	Insulation (EPR)	O	Δ	O	O	-
Trends:	O : good	Δ : fair		X : bad		- : not measured

Regarding indenter modulus testing, different test parameters, such as force, speed and tip cross-section and angle may cause variations in test results. Also, the procedure of operating the machine by different people may cause test variations. Therefore, it is suggested that a uniform detailed test standard is developed for the test.

In general, due to different test results and accuracies between different test methods, several methods should be used in combination to develop an overall CM model.

III.5. CZECH REPUBLIC

III.5.1. Radiation ageing of samples for the CRP

Table 13 shows the results of radiation ageing of samples.

TABLE 13. RADIATION AGEING OF SAMPLES FOR THE CRP

UJV No.	Cable	Length	Irradiation dose (MGy) Plan
2013/69	Habia XLPE/PEEK	0.50 m, 5 pcs	0.4 / 0.8 / 1.2 / 1.6 / 2.0
2013/59	Eupen EPR/EVA	0.35 m, 5 pcs	0.3 / 0.6 / 1.0 / 1.2 / 1.6
2013/60	Changzhou EPR/EPR	0.35 m, 5 pcs	0.3 / 0.6 / 1.0 / 1.2 / 1.6
2013/61	Rockbestos XLPO/CSPE	0.35 m, 5 pcs	0.3 / 0.6 / 1.0 / 1.2 / 1.6
2013/62	Shanghai XLPO/XLPO	0.35 m, 5 pcs	0.3 / 0.6 / 1.0 / 1.2 / 1.6
2013/64	Shanghai XLPO/XLPO	1 pcs 20 m	2
2013/65	Changzhou EPR/EPR	1pcs 20 m	1.6
2012/99	Habia XLPE/PEEK	1 pcs 4.3 m	2
2012/98	Habia XLPE/PEEK	0.50 m, 3 pcs	2
2013/01	Eupen EPR/EVA	1pcs 4.3 m	2

III.6. FRANCE

TDR and FDR measurements — Hot spot detection and evolution with ageing on Habia cable (peek insulation) shown in Table 14.

TABLE 14. TDR AND FDR MEASUREMENTS

Cable type		Expected progress on ageing	Expected progress on testing
Habia	PEEK insulation*	TDF/FDR new + 100 hours × 10	All step (1000 hours) completed
	XLPO jacket	'Not tested directly'	'Not tested directly'

* Total ageing 1000 hours at 190°C (hot spot)

III.6.1. Cable data

- LV cable Habia (Sweden), peek insulation, XLPO sheath, 20 meters;
- HFFR (halogen free flame retardant), low smoke generation;
- The total cable length is about 20 m.

III.6.1.1. Cables

About 50 mm of sheath were removed and 10 mm of insulation were removed. Then cable ends were equipped with terminations for measurement.

III.6.1.2. Measuring equipment

- Measuring equipment: Agilent E5071C ENA (Network Analyser), 9 kHz – 6.5GHz with module TDR;
- The network analyser has been calibrated prior to each measurement;

— FDR and TDR measurements have been made with the same equipment (network analyser) and using the same connections. Connection of the cable to network analyser was short (about 5 cm).

III.6.1.3. Measurement procedure

— Measurements were performed from March 2014 to August 2014;
— A small part of the cable was put in a heating chamber (hot spot) and aged from new to 1000h (100h steps). The cable outside of the heating chamber was coiled;
— Each sequence of measurement includes 3 TDR or FDR measurements between cores number 1 and 2; cores number 1 and 3; cores number 2 and 3.

III.6.2. CM test results and conclusions

The hot spot is slightly visible (only a very small change is observed) after the first ageing period (100h). The colour of the sheath changed, but no mechanical damage has been observed before removing the sample from the heating chamber. At the end of the test, the part of the jacket located in the heating chamber was very brittle.

A slight progressive change of propagation velocity is observed.

The hot spot observed is probably due to the ageing of the jacket that participates as a part of the propagation media. For further studies with this type of cables, it is suggested to simulate the hot spot with a less severe constraint (lower temperature).

III.7. JAPAN

III.7.1. Test methods

Waseda University performed FDR test, NEL performed FTIR test and INSS performed indenter test. NRA (former JNES) did not perform any test but provided aged cable samples together with indenter modulus and EAB results from their previous project.

III.7.2. Test cables

Five types of cable were tested. Changzhou Bayi (EPR/EPR), Eupen (EPR/EVA), Rockbestos (XLPE/CSPE) and Habia (PEEK/XLPO) was tested with FTIR and indenter modulus. Shanghai Special (XLPO/XLPO) was tested with FDR, FTIR and indenter modulus.

III.7.3. Ageing test

SNERDI/SECRI from China had provided the thermal ageing specimens for indenter modulus and FTIR test. AECL had provided the radiation samples. Heated portion for FDR test was made by a ribbon heater.

III.7.4. CM test results

III.7.4.1. Indenter modulus

INSS performed indenter modulus tests for each insulation and jacket sample. The equipment used for the test was developed by INSS. The probe tip diameter is 0.79 mm.

The measured value trend with ageing time for EPR, XLPO and CSPE. But shows little or no trend for EVA, XLPE and PEEK.

III.7.4.2. FTIR

NEL performed FTIR tests for each insulation and jacket sample. The equipment is a portable machine which is available on the market.

The peaks which show trend with ageing time are different for all material and manufacturer. Some peaks showed good trend, but no trending peak was found for most jacket sample and PEEK insulation.

III.7.4.3. FDR

Waseda University performed FDR for Shanghai special cable. The result showed that FDR can detect the heated portion and locate it. The differential spectra showed clear trend with heating temperature.

III.7.4.4. Summary

No single perfect CM method which is applicable for all material is available yet. But all three methods showed very good performance for some material. It may be practical to use more than one method, which shows different property of the material and complement with each other, for the same sample. Table 15 shows the summary of test results.

TABLE 15. SUMMARY OF TEST RESULTS

Cable type		Indenter Modulus		FTIR		FDR
		thermal	radiation	thermal	radiation	
Changzhou Bayi	Insulation (EPR)	✓	✓	✓	✓	
	Jacket (EPR)	✓	✓	×	×	
Shanghai Special	Insulation (XLPO)	✓	?	✓	✓	✓
	Jacket (XLPO)	✓	?	×	✓	
Eupen	Insulation (EPR)	✓	✓	✓	×	
	Jacket (EVA)	?	?	✓	✓	
Rockbestos	Insulation (XLPE)	×	?	✓	✓	
	Jacket (CSPE)	✓	✓	×	×	
Habia	Insulation (PEEK)	×	×	×	×	
	Jacket (XLPO)	✓	✓	?	✓	

✓ : trend with ageing ×: does not trend with ageing **?**: need more data to determine

III.8. KOREA, REPUBLIC OF

III.8.1. Test methods

Central Research Institute of Korea Hydro & Nuclear Power Company performed cable CM tests with 6 methods suggested by IAEA. The methods are indenter modulus test, ultrasonic velocity test, OITP, OIT, TGA and FTIR test. Indenter modulus test and ultrasonic velocity test were performed only for the jackets due to the test equipment capacity (small insulation cannot be tested), and other tests were performed for both jacket and insulation.

III.8.2. Test cables

We received 3 types of cable from IAEA. Cables are Eupen (EPR/EVA), Habia (Peek/XLPO), and Rockbestos (XLPE/CSPE) cable.

III.8.3. Ageing test

For ageing of indenter and ultrasonic velocity test specimens, 7 cable specimens which were 27 cm long per cable type were prepared. For ageing of other test specimens, 7 stripped cable specimens per cable type were also prepared. Table 16 is the ageing durations and temperatures according to each cable type. Specimen S7 was not tested due to ageing time error. During the ageing, 135℃ ageing oven was stopped for 4 days (middle of November) due to the electrical trouble. 4 days of ageing time was extended for compensation.

TABLE 16. AGEING DURATIONS AND TEMPERATURES

Specimen		Temp. (℃)	Ageing Time(hour)					
			S1	S2	S3	S4	S5	S6
Eupen	Insulation	135	2615.5	5089	6332	1898	4513	5811
	Jacket	120	2615.5	5089	6332	1898	4513	5811
RSCC	Insulation	135	2615.5	5089	6332	1898	4513	5811
	Jacket	120	696	1365.5	1800	933.5	1175	1560
Habia	Insulation	190	2615.5	5089	6332	1898	4513	5811
	Jacket	135	2615.5	5089	6332	1898	4513	5811

III.8.4. CM test results

III.8.4.1. Indenter modulus

We performed indenter tests for each aged cable jacket using a portable cable indenter developed by Korea Hydro & Nuclear Power Company (see FIG. 110 - FIG. 112). The indenter tests were performed 9 times per specimen. The diameter of the probe tip was 0.56 mm, and modulus value was calculated in the range of 1 N to 4 N:

— Eupen and RSCC cables showed increasing trend according to ageing time;
— Habia cable showed scattered data. It did not show any ageing trend.

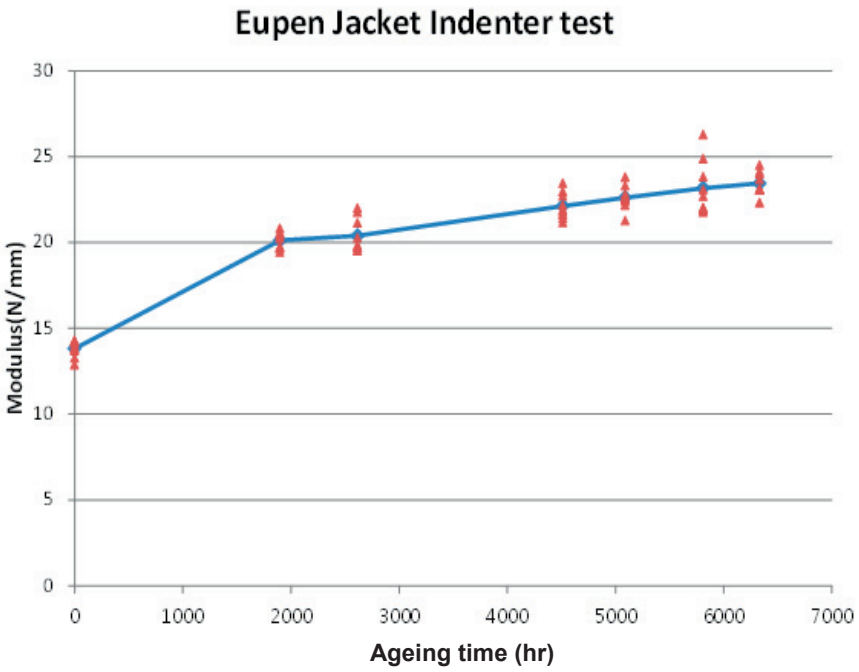


FIG. 110. Eupen jacket indenter test results

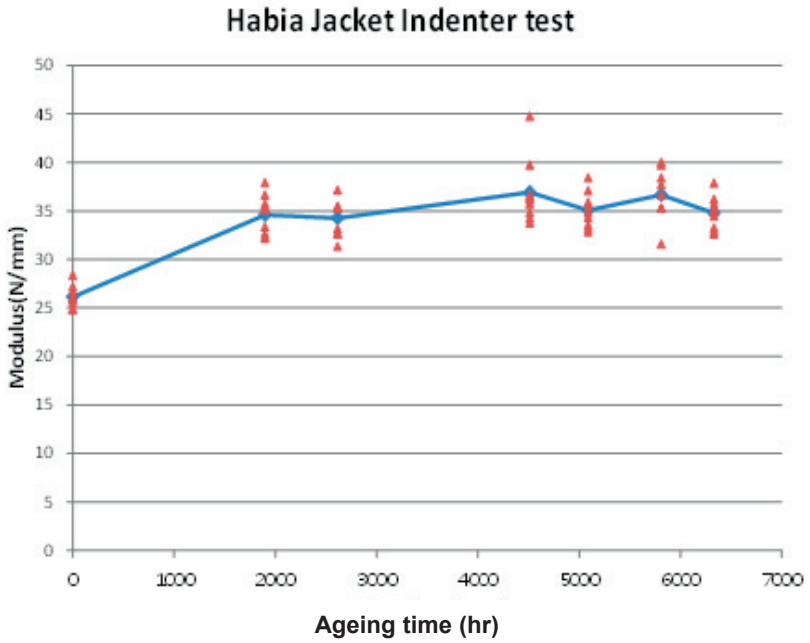


FIG. 111. Habia jacket indenter test results

FIG. 112. RSCC jacket indenter test results.

III.8.4.2. Ultrasonic velocity

We performed ultrasonic velocity tests for each aged cable jacket using a Mitsubishi UA-23 machine. Tests were performed 5 times per specimen:

- RSCC cable showed that duration time of ultrasonic decreased according to ageing time;
- Eupen and Habia cable showed scattered data. It did not show any ageing trend.

III.8.4.3. Oxidation induction temperature

All the stripped cable specimens for chemical CM methods (OITP/OIT, TGA) were milled to powder using a freezer mill. We performed OITP tests for each aged cable jacket and insulation using a PerkinElmer Diamond DSC machine. Tests were performed 3 times per specimen:

- Eupen cable showed a decreasing trend of OITP according to ageing time;
- RSCC cable showed a decreasing trend of OITP according to ageing time. During this test, it was found that the OITP of a long time aged cable couldn't be calculated because the oxidant was disappeared. RSCC insulation specimens, aged less than 4513 hours, showed two oxidation reactions. RSCC specimens, aged more than 4513 hours, showed one oxidation reaction. RSCC jacket showed similar problems;
- Habia cable showed decreasing trend of OITP according to ageing time. It was found that oxidation reaction of the insulation wasn't detected until temperature reached 400℃. We stopped temperature increasing for the consideration of the machine safety.

III.8.4.4. OIT

We performed OIT tests for each aged cable jacket and insulation using a PerkinElmer Diamond DSC machine. Tests were performed 3 times per specimen:

— Eupen cable showed a decreasing trend of OIT according to ageing time both for insulation and jacket. OIT of the jacket aged more than 4513 hours couldn't be calculated because oxidation reaction of these specimens occurred immediately after changing to oxygen gas;
— RSCC cable showed a decreasing trend of OIT according to ageing time for both the insulation and jacket. Like OITP, OIT could not be calculated for long time ageing cable;
— Habia cable showed a decreasing trend of OIT according to ageing time. The OIT test of insulation wasn't performed.

III.8.4.5. TGA

We performed TGA tests for each aged cable jacket and insulation using a TA instruments Q5000IR machine of TA. Tests were performed 3 times per specimen. We could not find any ageing trend at 5% weight loss and max rate of weight loss.

III.8.4.6. FTIR

We performed FTIR tests for each aged cable jacket and insulation using a Smith Travel IR machine. We measured the height of near 1720 cm^{-1} and 1370 cm^{-1} frequency at each frequency domain graph:

— Eupen cable didn't show any trend. It was found that peak ratio of jacket increased according to ageing time;
— RSCC cable insulation showed increasing trend of peak ratio according to ageing time. RSCC jacket didn't show any trend;
— Habia cable showed decreasing trend of peak ratio according to ageing time. It was an unexpected result because other cables showed an increasing trend. In the frequency domain graph of the insulation, no peak was detected near 1720 cm^{-1} and 1370 cm^{-1} frequency.

III.8.4.7. Summary

It was found that each CM test method was material dependent. An omnipotent CM test method did not exist. A simple determination guide of CM method for each cable material should be provided.

For most plant cable ageing management programmes, detection of insulation defects is more important than detection of ageing trend. A cable often has a defect on its insulation during manufacturing, transportation, storing and installation, which may cause a severe cable fault during operation. An insulation defect is not easy to detect because the insulation is hidden under the cable jacket. There is no way to detect insulation defects during receipt inspection. The TDR/FDR method is expected to develop further to solve cable receipt inspection problems in the plant. Table 17 shows the summary of test results.

TABLE 17. SUMMARY OF TEST RESULTS

Method	Specimen	Indenter	Ultrasonic velocity	FTIR	OITP	OIT	TGA

Eupen	Insulation (EPR)			X	O	O	X
	Jacket (EVA)	O	X	O	O	Δ	X
Habia	Insulation (PEEK)			X	X	X	X
	Jacket (XLPO)	X	X	O	O	O	X
RSCC	Insulation (XLPE)			O	Δ	Δ	X
	Jacket (CSPE)	O	O	X	Δ	Δ	X
Trends:	O : good		Δ : shown a little		X : not shown		

III.9. SLOVAKIA

III.9.1. Test methods

The following tests were carried out by VUJE:

— Thermal ageing;
— Tensile test – EAB;
— OITP test;
— TGA test;
— Electrical tests (IR, Tan Delta (b), TDR).

These tests were made on prepared samples of jackets and insulation materials (EAB, OITP, TGA) – as-received and then after thermal ageing. Electrical parameters were measured on whole cables – as-received and after thermal ageing.

III.9.2. Test cables

Table 18 shows the test cables type and CM methods.

TABLE 18. TEST CABLES

Insulation/Jacket	Manufacturer	Cable Type — CM test types
XLPE/CSPE	Rockbestos, USA	Firewall III-J, P62-3902 (1/0 AWG) – *tensile test - EAB, thermal analysis (OITP, TGA)* Type PXJ, mark WDE-52 – electrical test (IR)
EPR/EVA	Eupen, Belgium	NU-EHXHX-J 4x4 - *tensile test (EAB), thermal analysis (OITP, TGA),* electrical test (IR, Tan D)
PEEK/XLPO	Habia, Sweden	700042403 (19 core, AWG14) – *tensile test (EAB), thermal analysis (OITP, TGA)* 700042402 (3 core, AWG14) – electrical test (IR)

III.9.3. Ageing test

For ageing, the indicator for end of thermal ageing was EAB. After the cable insulation samples reached 50% EAB, thermal ageing was stopped. After the EAB tests — the same samples were used for thermal tests and in the same time interval (+/-) the electrical parameters were measured on whole cables. The progress of the thermal ageing programme is shown in Table 19.

TABLE 19. PROGRESS OF THERMAL AGEING

Material/Cable	Thermal ageing	Note
XLPO/HABIA	2425hr/135C	Finished
XLPE/Rockbestos	2425hr/135C	Finished
CSPE/Rockbestos	1616hr/135C	Finished
EPR/EUPEN black ins EPR/EUPEN blue ins EPR/EUPEN yg ins	5756hr/135C	Finished
EVA/EUPEN	9774hr/120C	Finished
PEEK/HABIA transp ins	15587hr/190C	Finished
PEEK/HABIA black ins	15587hr/190C	

III.9.4. CM test results

EAB seems to be a good parameter for indicating cable condition, in general this method is reproducible and has good trending with thermal ageing for most of the materials, but more samples have to be tested to get better results (mean values). Table 20 shows the EAB test results.

TABLE 20. ELONGATION AT BREAK

Material/cable	EAB [%]				Thermal ageing	Note
	initial	end	Difference			
			Value	(%)		
XLPO/HABIA	118	21	-97	-82	2425hr / 135°C	short TA time; lack of data
XLPE/Rockbestos	316	123	-193	-61	2425hr / 135°C	short TA time; lack of data
CSPE/Rockbestos	396	49	-347	-87.6	1616hr / 135°C	good trending
EPR/EUPEN black ins	576	75	-501	-87	5756hr /135°C	'burned' end of samples – last measurement is strongly distorted, good trending
EPR/EUPEN blue ins	567	30	-538	-95		
EPR/EUPEN yg ins	562	107	-455	-81		
EVA/EUPEN	412	130	-282	-68.4	9774hr / 120°C	50% EaB not reached after 9800hr/120°C, good trending
PEEK/HABIA transp ins	372	185	-187	-50	8382hr /190°C	large difference between the individual samples – but in global good trending
PEEK/HABIA black ins	377	234	-143	-38	9220hr /190°C	

The largest difference between other laboratories was for EVA/EUPEN because the samples were flattened according to ISO37. The sample preparation process is the main source of deviations between EAB tests by other laboratories.

OITP tests are strongly dependent on the type of material. For EPR/EUPEN there is a strong correlation between EAB and OITP. For EVA/EUPEN the correlation with EAB is questionable. Table 21 shows OITP results; Tables 22 and 23 show the test results for the TGA tests.

TABLE 21. OITP TEST

Material/Cable	OITP [°C]				Thermal ageing	Note
	initial	end	Difference Value	(%)		
XLPO/ HABIA	279.4	226.6	-52.8	-19	2425hr/135 °C	sharp descent (930hr), then no change
XLPE/Rockbestos	262.4	213.7	-48.7	-19	2425hr/135 °C	descent (1926hr – first msrmnt), then no change
EPR/EUPEN	286.5	220.2	-66.3	-23	5756hr/135 °C	linear descent; the same trend of change as EAB; blue ins; good trending
EVA/EUPEN	273.8	237.2	-36.6	-13	9774hr/120 °C	linear descent; 'good' trending

TABLE 22. TGA TEST (5% MASS LOSS TEMPERATURE)

Material/Cable	TGA 5% mass loss [°C]				Thermal ageing	Note
	initial	end	Difference Value	(%)		
XLPO/HABIA	302.4	307.8	+5.4	+1.8	2425hr / 135°C	almost no change; useless
XLPE/Rockbestos	322.5	330.3	+7,8	+2,4	2425hr / 135°C	almost no change; useless
EPR/EUPEN	329.6	345.5	+15.8	+4.8	5756hr / 135°C	minimum increase, applicability questionable; black ins
EVA/EUPEN	309.8	319.2	+9,4	+3.0	5684hr / 120°C	minimum increase, applicability questionable
PEEK/HABIA	571.9	570.2	-1.8	-0,3	6702hr / 190°C	no change; useless

TABLE 23. TGA TEST (MAXIMUM RATE OF MASS LOSS TEMPERATURE)

Material/Cable	TGA max mass loss rate [°C]				Thermal ageing	Note
	initial	end	Difference			
			Value	(%)		
XLPO/HABIA	469.9	472.2	+2,8	+0.6	2425hr / 135°C	no change; useless
XLPE/Rockbestos	478.2	476.8	-1.4	-0,3	2425hr / 135°C	no change; useless
EPR/EUPEN	470.1	467.9	-2,2	-0.5	5756hr / 135°C	no change; useless; black ins
EVA/EUPEN	469.7	470.9	+1.2	+0,3	5684hr / 120°C	no change; useless
PEEK/HABIA	587.7	587.7	0.0	0.0	6702hr / 190°C	no change; useless

TGA tests seems to be absolutely useless for these types of materials, there is no change during the thermal ageing.

III.9.5. Electrical tests

The insulation resistance (IR) is strongly dependent on more parameters which cause strong deviations (environment, temperature, humidity, and operator). It is hard to eliminate this influence. Tan Delta increased with thermal ageing as was expected. A better measurement set-up (shielding, faraday cage etc.) may decrease the deviations, making this measurement method potentially useful as a cable condition indicator. Tables 24 and 25 show the electric test results.

TABLE 24. ELECTRICAL TESTS (SPECIFIC IR)

Cable	Configuration	Specific IR [GΩ.km]				Thermal ageing	Note	Material
		initial	end	Difference				
				Value	(%)			
HABIA	black (1) /all	24	281	+257	+1105	9636hr / 190°C	increasing trend results depend on measurement condition (operator, humidity...)	PEEK ins/ XLPO jack
	transp (2) /all	20	137	+117	+580			
	transp (3) /all	22	169	+147	+670			
EUPEN	black /all	6,3	3,7	-2.6	-41	9768hr / 135°C	no trending results depend on measurement condition (operator, humidity...)	EPR ins/ EVA jack
	brown /all	12.2	6,6	-5.6	-46			
	yg /all	6,6	6.1	-0.5	-7,6			
	blue /all	7.1	6.2	-1.0	-13.8			
Rock	conductor/water	6.4	1.1	-5.3	-83	1850hr / 135°C	decreasing trend; results depend on measurement condition (operator, humidity...)	XLPE ins/ CSPE jack

TABLE 25. ELECTRICAL TESTS (TAN DELTA)

Cable	Configuration	Tan D at 100 Hz [-]				Thermal ageing	Note	Material
		initial	end	Difference				
				Value	(%)			
HABIA	black (1) /all	4,85E-03	1,85E-02	+0.0137	+281	9636hr / 190°C	good trending (increasing with TA)	PEEK ins / XLPO jack
	transp (2) / all	1,75E-03	2,01E-02	+0.0183	+1046			
	transp (3) / all	1,74E-03	1,60E-02	+0.0142	+817			
EUPEN	black /all	2,88E-02	1,20E-02	-0.0168	-58	9768hr / 135°C	initial decrease, then return to original values trending questionable	EPR ins / EVA jack
	brown /all	3,59E-02	1,77E-02	-0.0182	-51			
	yg /all	3,03E-02	8,18E-02	-0.0222	-73			
	blue /all	2,39E-02	6,89E-03	-0.0171	-71			
Rock	conductor / water	1,74E-03	1,69E-02	+0.0152	+874	1850hr / 135°C	increasing trend	XLPE ins / CSPE jack

III.10. UNITED KINGDOM

III.10.1. Introduction

Density measurements are potentially a useful method for cable CM. The measurements do not require expensive equipment and an accuracy of < 1% can be achieved. For comparison, changes in density in aged cable samples can be up to 40%. However, to get this level of accuracy, the test procedure must be rigorously followed. For some materials, significant changes in density are only observed in heavily degraded samples.

Density measurements have been carried out on all of the cable materials in the benchmarking programme, but data on thermally aged cables have not yet been completed for the PEEK insulation and the SiR insulation and jacket materials. Irradiated samples have not yet been measured.

III.10.2. Test method

The test method utilizes a density bottle with distilled water as the immersion liquid and isopropanol as the wetting agent. It is very important that the temperature of the immersion liquid is known to 0.1°C to correct for both the temperature dependence of the density of water and for its thermal expansion. Differences between test laboratories observed in baseline tests are likely to be from differences in the test method used. To get reproducible results it is also necessary to use a sample size of > 0.2 g (see FIG. 113).

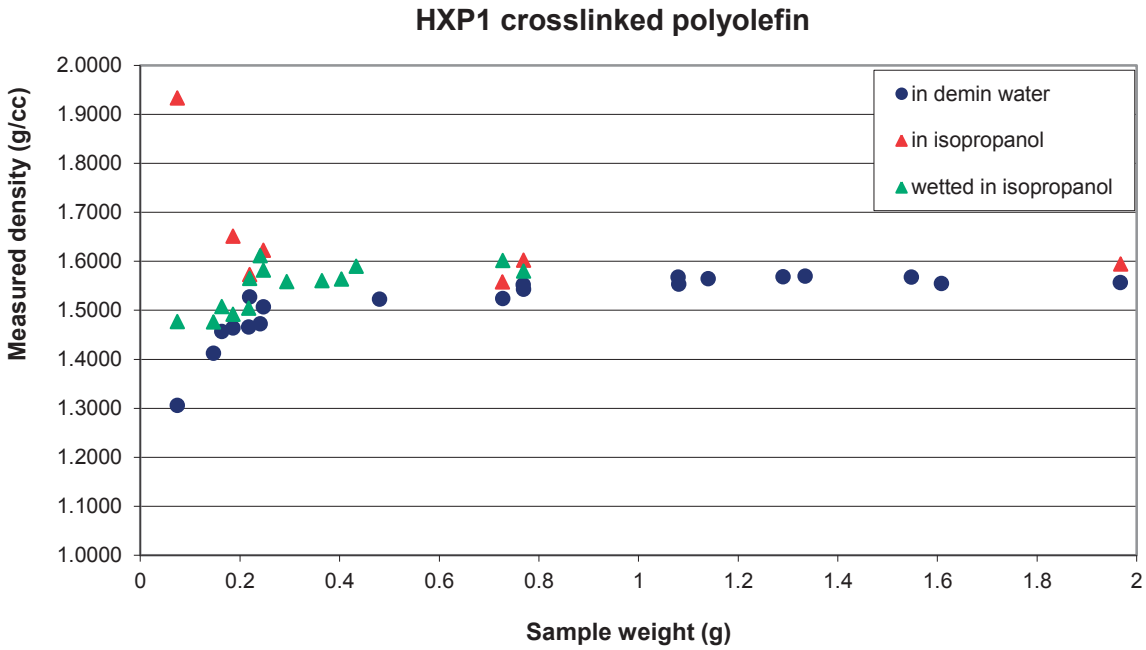


FIG. 113. Effect of sample size on density measurements.

Density measurements were carried out by 3 laboratories on the unaged material. Consistent results were obtained for 2 of the laboratories, even though they used different test methods (UJV used Archimedes principle method, JKAL used density bottle method). The 3rd lab used Archimedes principle but did not use distilled water as the immersion liquid and had much larger variability than the other 2 laboratories.

III.10.2.1. Test results on aged cables

For some of the materials tested, measureable changes in density are observed that correlate well with changes in EAB on the same material. An example for EPR insulation (Changzhou Bayi) is shown in FIG. 114 and FIG. 115. In other materials, although large density changes are observed, the changes only occur in heavily aged material, as shown in FIG. 116 and FIG. 117 for XLPO insulation (Rockbestos). Not all materials show significant density changes, even in heavily degraded samples. An example is shown in FIG. 118 and FIG. 119 for EVA jacket material (Eupen).

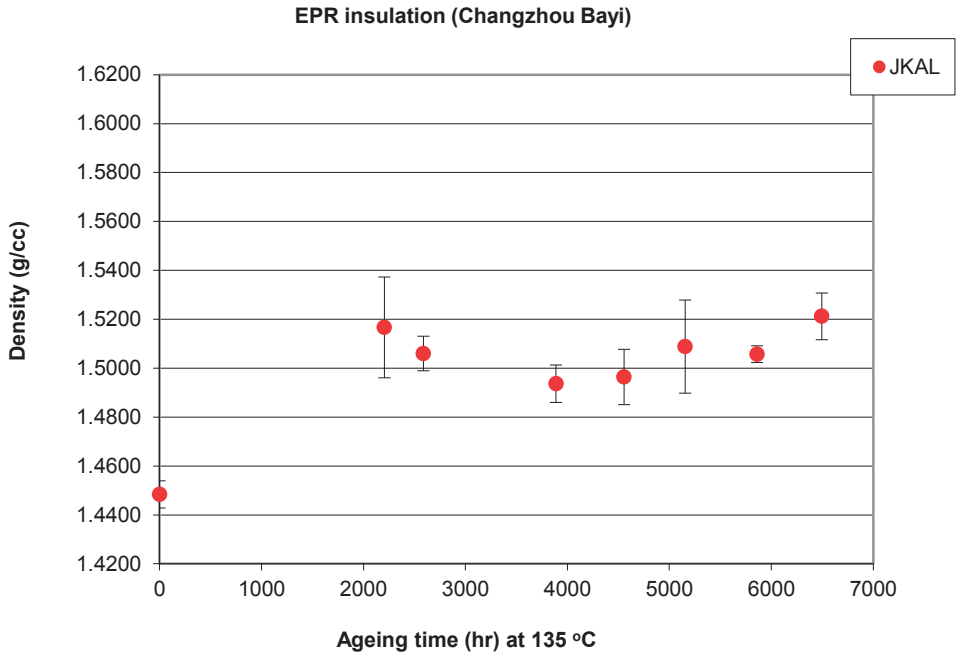


FIG. 114. Density changes in aged EPR insulation (Ageing time)

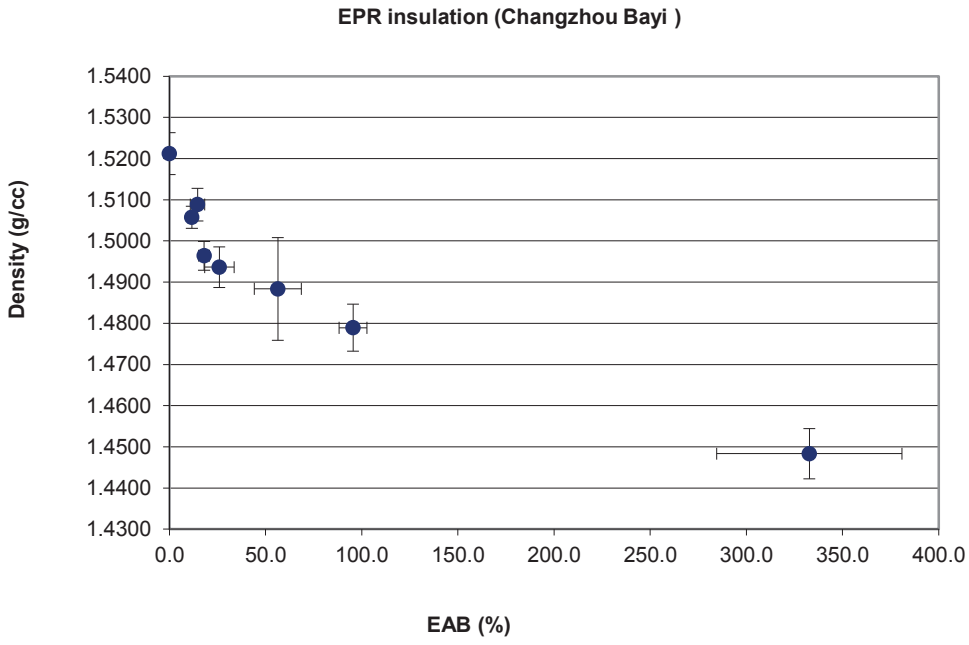


FIG. 115. Density changes in aged EPR insulation (EAB).

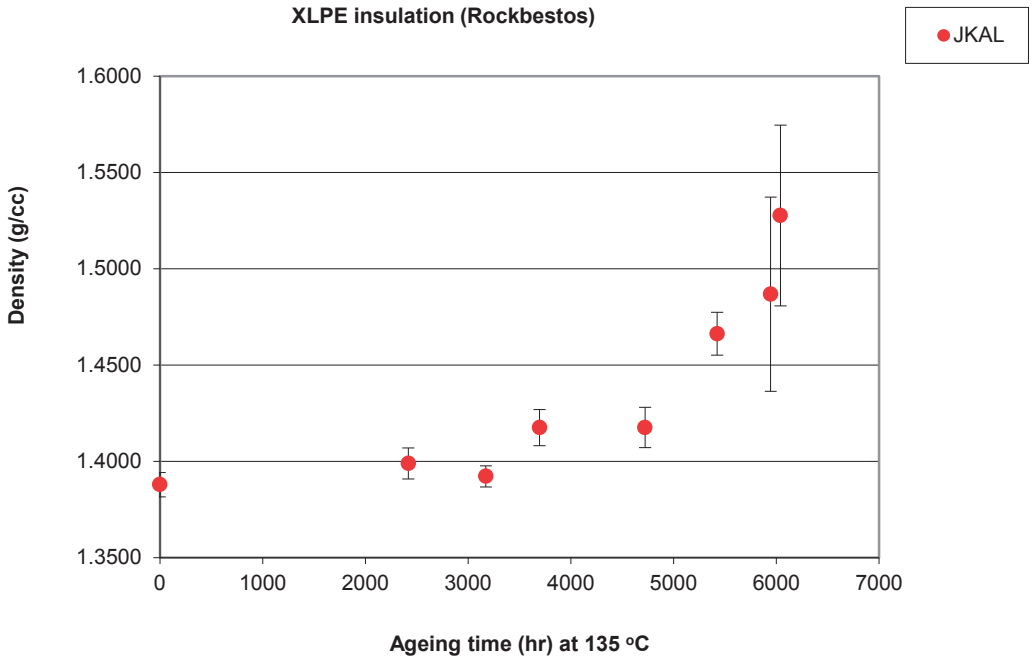


FIG. 116. Density changes in XLPO insulation (Ageing time).

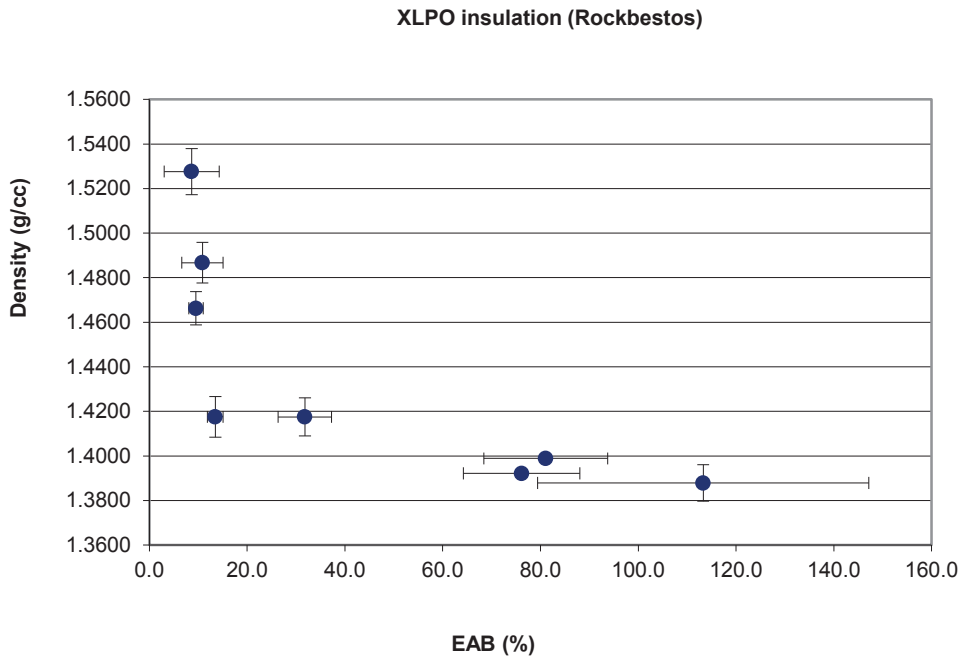


FIG. 117. Density changes in XLPO insulation (EAB).

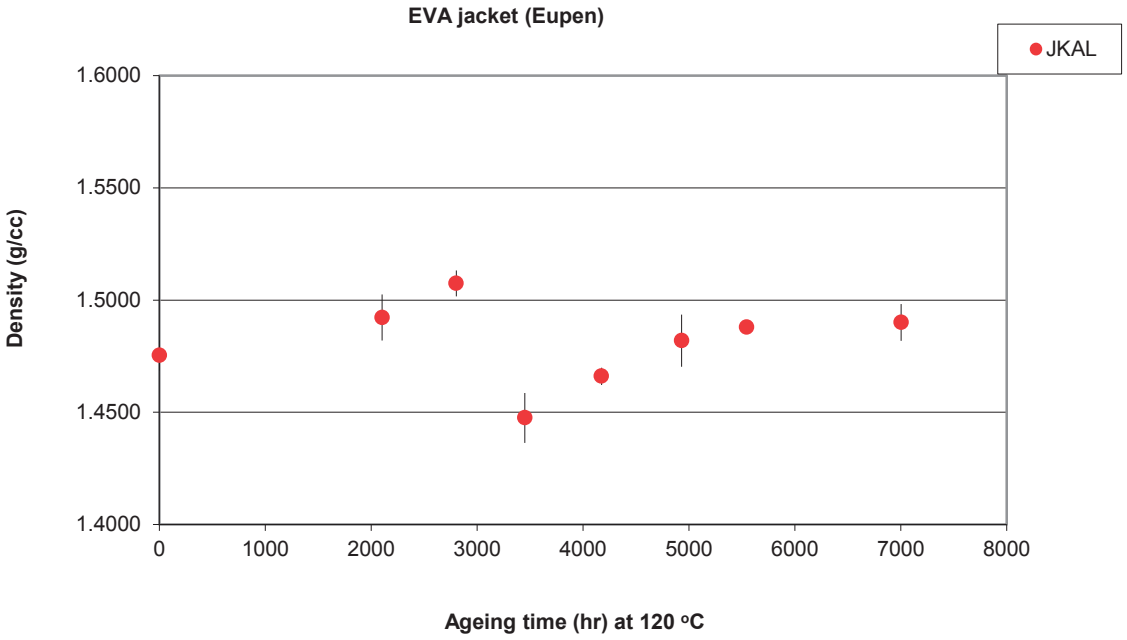


FIG. 118. Density changes in EVA jacket (Ageing time).

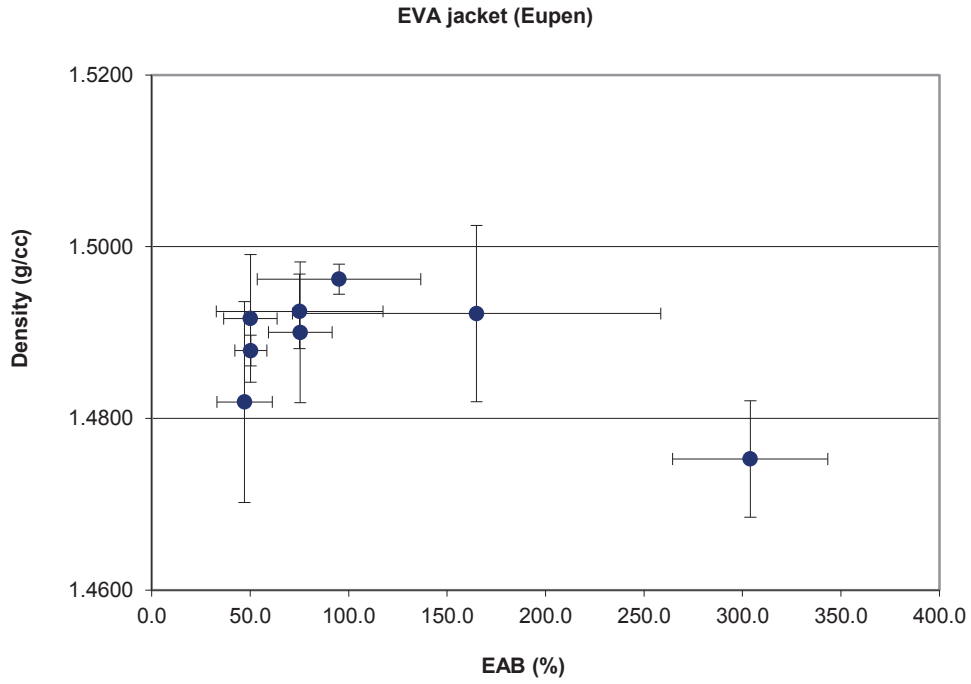


FIG. 119. Density changes in EVA jacket (EAB).

The potential for density as a CM tool is summarized in Table 26.

TABLE 26. DENSITY AS A CM TOOL

Cable	Insulation	Jacket
EPR/EPR (Changzhou Bayi)	Potentially useful, changes by 20 % for EAB=100%	Potentially useful, changes by 28% for EAB=100%
XLPO/XLPO (Shanghai Cable)	Possibly useful, but density changes are small	Possibly useful, but density changes are small
EPR/EVA (Eupen)	Density changes are insignificant, not useful	Density changes are insignificant, not useful
XLPO/CSPE (Rockbestos)	Not useful, changes only significant for EAB <50%	Potentially useful, changes by 40 % for EAB=100%
PEEK/XLPO (Habia)	[not tested yet]	Potentially useful, changes by 12 % for EAB decreasing from 80 to 40%

III.10.3. Recommendations for test method improvements

To get the accuracy required for the use of density as a CM method, it is essential that a rigorously controlled test method is used. For the density bottle method, the liquid temperature needs to be known to 0.1°C during the measurement to correct for the temperature dependence of density of water and to allow for thermal expansion of the liquid in the density bottle during handling. Carryover of the wetting agent into the immersion liquid must be minimized. This is particularly important for the density bottle method but also must be considered for the Archimedes principle method.

III.11. USA NIST

III.11.1. Test methods

NIST, on behalf of the US NRC performed baseline measurements on the series of IAEA cables. Baseline tests included the OIT and OITP (via DSC), TGA, density, EAB, indention, and molecular spectroscopy (FTIR and Raman). Sue Burnay requested that NIST complete OIT and OITP measurements on thermally aged samples. Sue sent the thermally aged samples to NIST in batches and NIST is still completing all the measurements.

III.11.2. Test cables

Table 27 outlines the samples and times of ageing. These samples were analysed for OIT and OITP.

TABLE 27. AGEING TIMES OF SAMPLES

Sample	Polymer	Ageing temperature (°C)	Ageing Time (hours)						
RO-J	CSPE	120	511.5	784	912	1056	1248	1646	1824.5
RO-I	XLPE	135	2419	3173.5	3696	4723	5424	5945	6040
SH-J	XLPO	135	2183	2419	3305	3548	4267	4723	6040
SH-I	XLPO	135	2183	2419	3305	3548	4267	4723	6040
HA-J	XLPO	135	2183	2419	3305	3548	4267	4723	6040
CB-J	EPR	135	2205	2588	3888	4556	5155	5860	6495
CB-I	EPR	135	2205	2588	3888	4556	5155	5860	6495
EU-J	EVA	120	2103	2803	3450	4175	4932	5544	7004
EU-I C1	EPR	135	2225	2588	3864	4556	5155	5860	6504
EU-I C2	EPR	135	2225	2588	3864	4556	5155	5860	6504
EU-I C3	EPR	135	2225	2588	3864	4556	5155	5860	6504
EU-I C4	EPR	135	2225	2588	3864	4556	5155	5860	6504

III.11.3. Measurement procedures

OIT and OITP measurements were carried out on a TA Q2000 DSC using indium reference and an empty cell baseline. For OIT, a flow of 50 ml/min was used for both oxygen and nitrogen. Cell temperature ranged from 210°C to 240°C depending on the polymer type. For OITP, the ramp 10°C /min and the oxygen flow was 50 ml/min. A sample mass of 5 mg was used for all tests. Procedures outlined in the baseline measurements report were followed for replicates and data treatment. A 0.3 threshold was used.

III.11.4. CM test results

Results to date for OIT are shown in FIG. 120. The figure shows that for most polymer resins, the value of OIT decreases with increasing thermal ageing. The extent of decrease varies significantly among resins. The RO-J material, CSPE, shows a significant and linear decrease such that the OIT value falls by a factor of 3 after 1400 hours ageing. The CB-J material also showed a decrease in OIT with increasing thermal ageing, but the slope was not as great. Although a decreasing trend is something that desired, this extreme decrease could overestimate a measure of degradation. As with any CM method, one must assess whether the degradation mechanism represented in the measurement embodies the degradation mechanism observed in operational ageing condition. The OIT measurement was developed to measure the change in concentration of anti-oxidant additives found in polymer systems. It appears that this measure is not a good degradation mechanism to follow for operational aged cables.

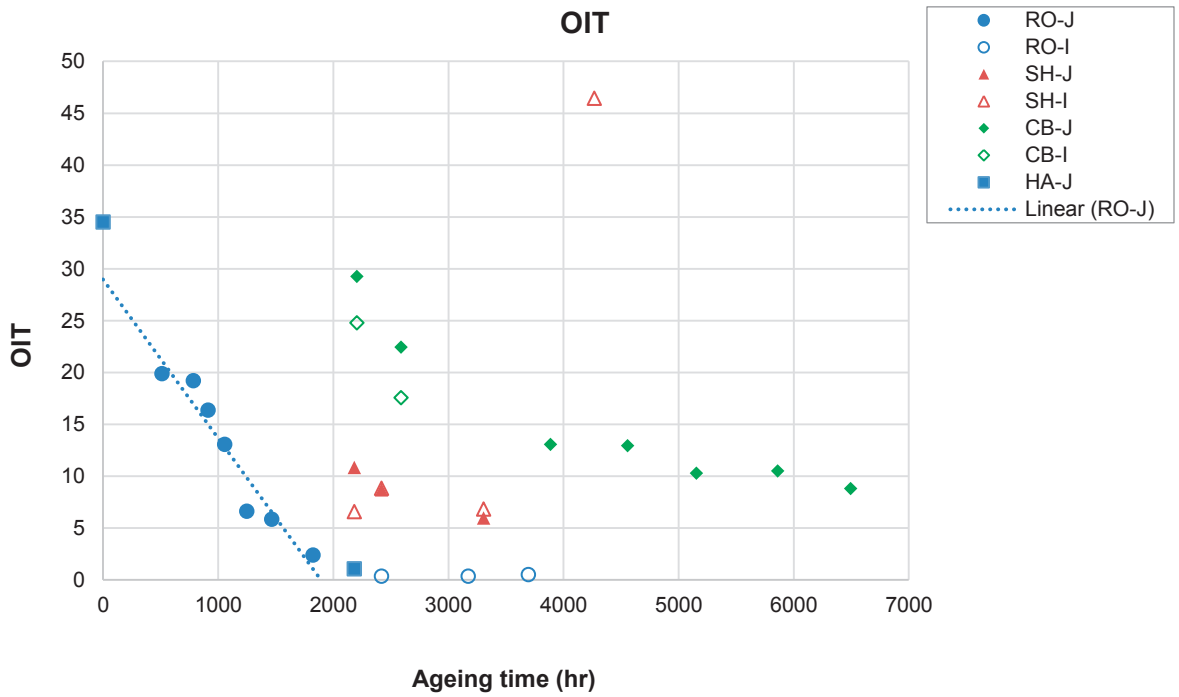


FIG. 120. OIT results for a series of thermally aged cable insulation and jackets.

The results to date for OITP measurements are found in FIG. 121. The figure shows a variety of trends that vary with polymer resin. Most of the samples do not show a significant change with ageing compared to OIT. The polymers found in CB-J and HA-J show a decreasing OITP with increasing thermal ageing. This decreasing trend is not as significant as observed for OIT. More data is needed to complete the trends found for the other samples.

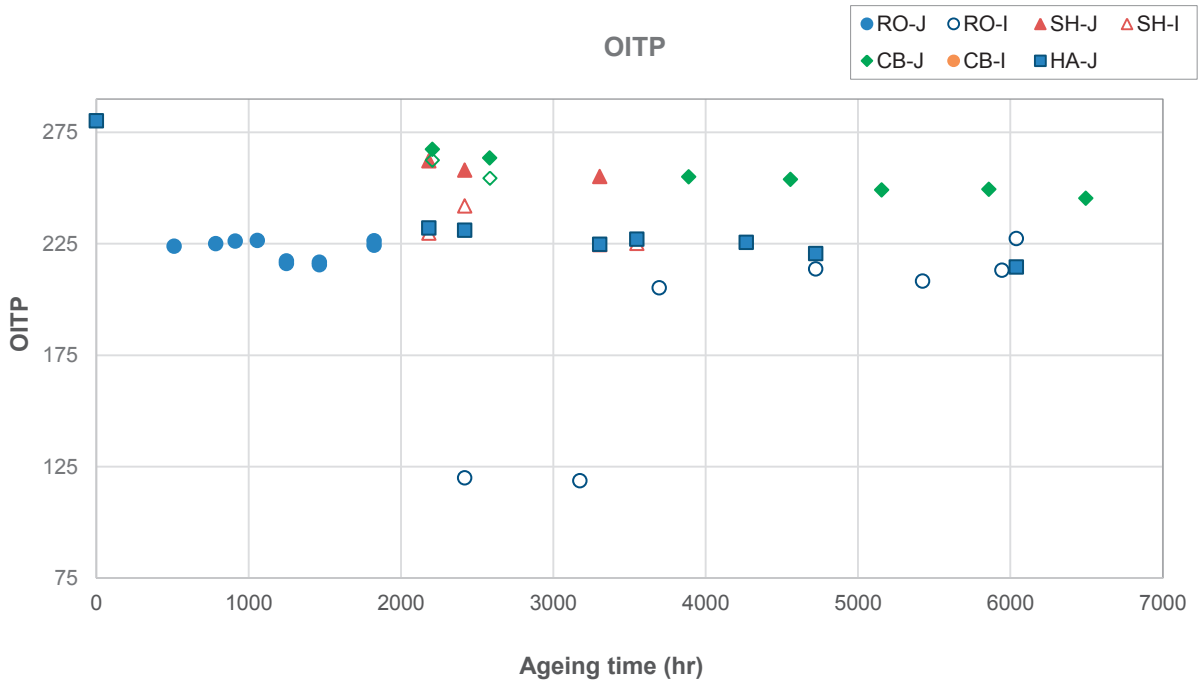


FIG. 121. OITP results for a series of thermally aged cable insulation and jackets.

III.11.5. Summary of results

The methods of OIT and OITP appear to show changes with thermal ageing. The extent of change depends on the polymer resin. For any CM method, one must assess whether the degradation mechanism represented in the CM measurement embodies the degradation mechanism observed in operational ageing condition.

III.11.6. Recommendations

A mass of 5 mg for sample analysis results in less deviation of results for both OIT and OITP.

III.12. USA AMS

III.12.1. Overview

A total of 11 cable samples were received to perform the benchmarking testing. Five larger diameter cables (Habia, Rockbestos, Shanghai, Changzhou, Hew) were used for mechanical and chemical tests (Table 28). Four smaller diameter cables (Habia, Rockbestos, Shanghai, Changzhou) were used for only electrical testing. Note that the Rockbestos cable was constructed of one conductor with no shield and therefore could not be used for electrical testing. One cable (Eupen) was used for mechanical, chemical and electrical tests and counted as one large diameter cable and one small diameter cable for a total of 11 cable samples (6 type a/5 type b).

TABLE 28. CABLE SAMPLES

Manufacturer	Insulation/ Jacket	Mechanical Samples	Electrical Samples
Habia Cable, Sweden	PEEK / XPLO	Type A (15 mm)	Type B (10 mm)
Rockbestos, USA	XLPE / CSPE	Type A (15 mm)	Type B (10 mm)
Changzhou Bayi Cable Co., China	EPR / EPR	Type A (15 mm)	Type B (10 mm)
Shanghai Special Cable, China	XLPO / XLPO	Type A (15 mm)	Type B (10 mm)
Hew, Germany	SiR / SiR	Type A (15 mm)	Type B (10 mm)
Eupen, Belgium	EPR / EVA	Type A (16 mm)	Type A (16 mm)

Samples for each test technique were prepared in advance for all baseline and thermal ageing testing. The number of samples prepared for each cable type allowed for seven thermal ageing times for each polymer. The samples were divided into two sets with the second set added to the ovens at a later date to provide flexibility in the total amount of ageing time for best results.

III.12.1.1. IM test

The indenter model IPAM4M was used to obtain IM measurements on the six type a cables. The indenter uses a probe velocity of 5.08 mm/min and a maximum force of 8.89 N. The force range of 1– 4 N was used to determine the average IM value. Each of the six cables was tested by recording indenter measurements of 3 locations around the circumference of the

cable. This procedure was repeated for 3 different locations along the cable length. The tested locations were centre, left 50 mm from centre, and right 50 mm from centre. The total procedure was repeated to obtain 9 measurements for repeatability. The high and low value of each measurement set was removed from the average:

— Sample size 225 mm (Jacket and Insulation);
— 9 Test points with high/low removed;
— Probe tip 0.56 mm Diameter (17.5° Angle);
— Probe speed 5.08 mm/minute;
— Data reported from force range 1 – 4 N.

FIG. 122 and FIG. 123 show IM test results for SiR jacket and XLPE insulation respectively.

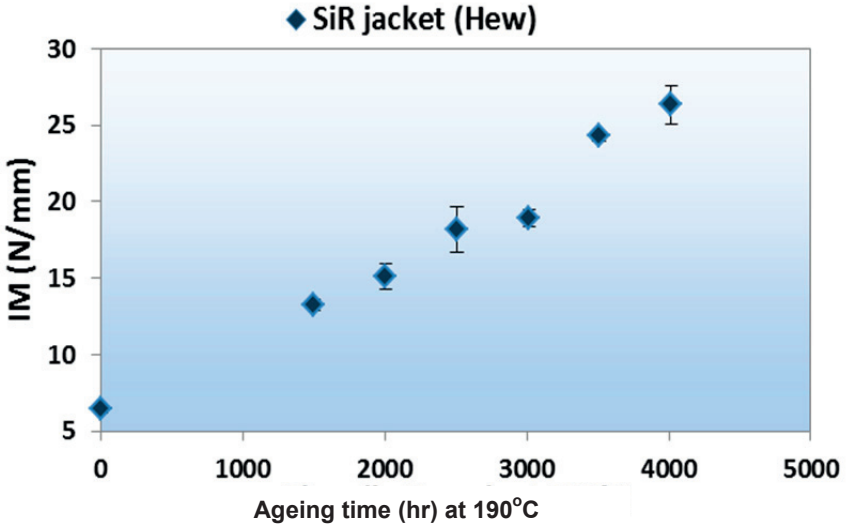


FIG. 122. SiR jacket IM test.

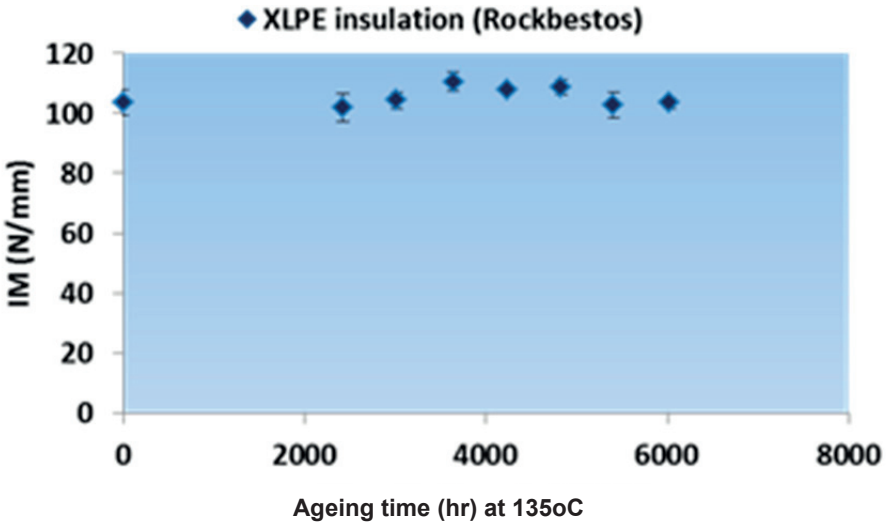


FIG. 123. XLPE insulation IM test.

III.12.2. Thermal ageing conclusions for indenter testing

Most polymers trended with increasing IM values from baseline. XLPO samples indicated a modest change from baseline while XLPE and PEEK samples did not indicate a degradation trend from baseline.

III.12.3. Elongation at break test

The Oakland tensile test machine 1500 was used to obtain EAB measurements on the six types of cable. Samples were prepared and tested using the IEC/IEEE 62582-2 standard with dumbbells and insulation tubes of 50 mm in length. The cross-head speed was 10 mm/min for dumbbells and 40 mm/min for the insulation tubes. Some dumbbells contained filler material (tape, threading) or as molded ribs. This material was removed if possible. Some insulation tubes had the insulation bonded to the conductor which required slitting lengthwise to remove the copper wire. Table 29, FIG. 124 and FIG. 125 show the test specification and EAB test results for CSPE jacket (Rockbestos) and PEEK insulation (Habia).

TABLE 29. TEST SPECIFICATION OF EAB

JACKET DUMBBELLS	INSULATION TUBES
– Size ISO 37 Type 3	– Speed 40 mm/minute
– Speed 10 mm/minute	– Gauge Length 30 mm
– Gauge Length 30 mm	– No Extensometer
– No Extensometer	– Habia PEEK and Eupen EPR
– XLPE Tested as Dumbbells	– Samples Slit Lengthwise

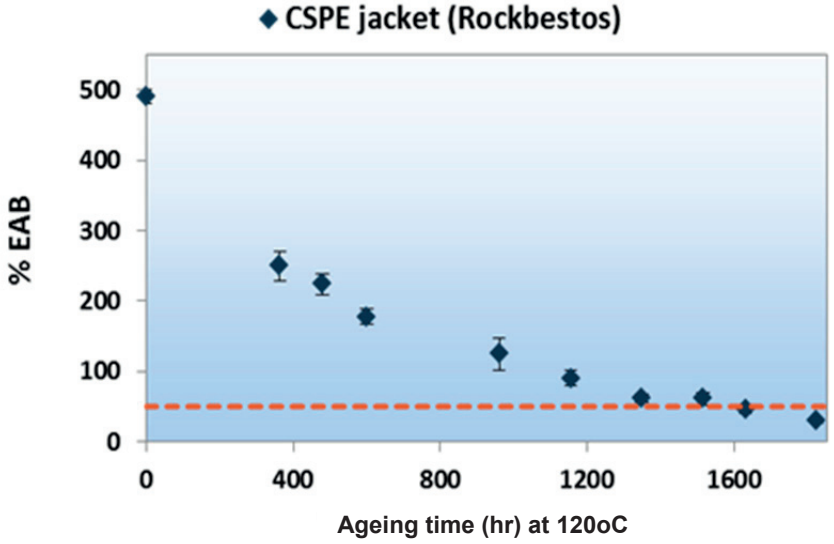


FIG. 124. CSPE jacket EAB test.

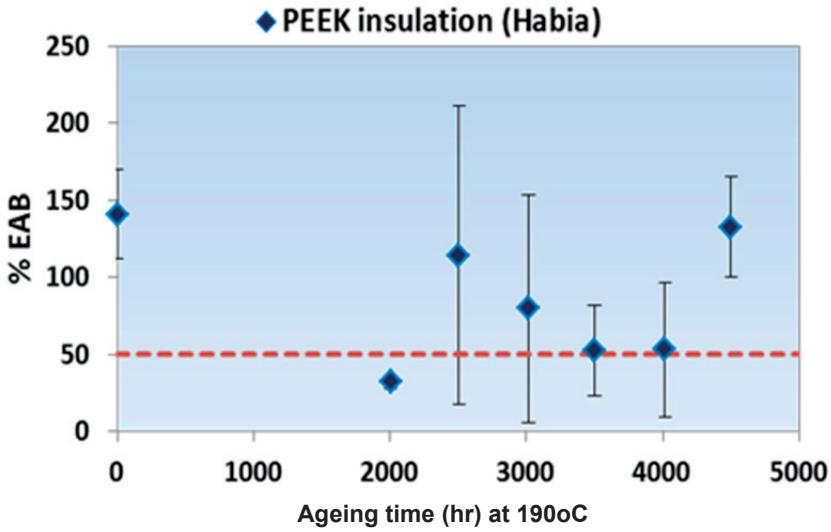


FIG. 125. PEEK insulation EAB test.

III.12.4. Thermal ageing conclusions for EAB testing

Most polymers trended with deceasing EAB values from baseline. XLPO samples indicated a modest change from baseline while XLPE and PEEK samples did not indicate a degradation trend from baseline.

III.12.5. Thermogravimetric analysis and oxidation induction time tests

The Perkin Elmer TGA 7 and DSC 7 machines were used to perform mass loss and OIT measurements on the insulation and jacket materials that were evaluated as part of this project. Samples were prepared as through thickness slices of the insulation or jacket polymers. Each specimen was in the range of 10 mg ± 2 mg in weight. The samples were chopped into pieces with maximum dimensions of 1 mm. TGA and OIT test specification and results show on Table 30 and FIG. 126 - FIG. 128 for EPR insulation.

TABLE 30. SPECIFICATION OF TGA AND OIT

TGA	OIT
– Temperature Ramp Rate 10 °C/minute – Nitrogen Flow Rate 50 ml/minute – Sample Weight 10 mg +/- 2 mg – Measured 5% Mass Loss and Maximum Rate of Mass Loss	– Test Temperature 210 °C – 240 °C – Oxygen Flow Rate 50 ml/minute – Nitrogen Flow Rate 50 ml/minute – Sample Weight 10 mg+/- 2 mg – Measured Induction Time

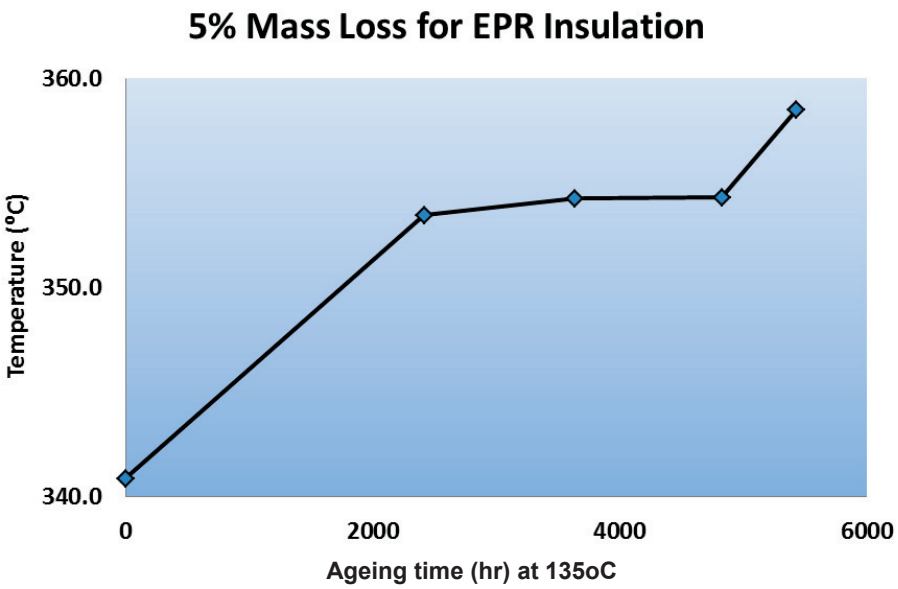


FIG. 126. Thermogravimetric analysis in case of 5% mass loss.

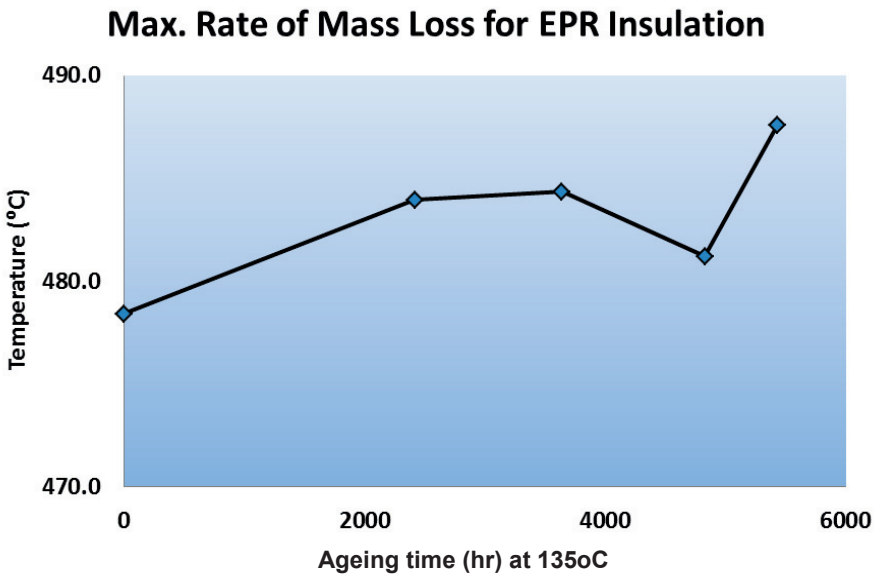


FIG. 127. Thermogravimetric analysis in case of max rate mass loss.

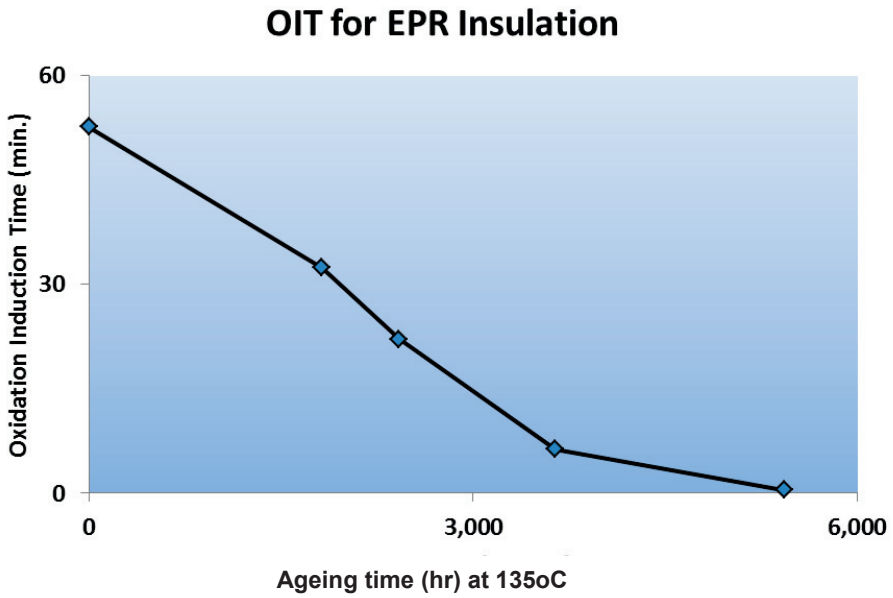


FIG. 128. Thermogravimetric analysis in case of oxidation induction time tests.

III.12.6. Thermal ageing conclusions for TGA and OIT testing

No polymers showed a trend with degradation for the 5% mass loss and maximum rate of mass loss temperatures that were evaluated during TGA testing. The OIT test indicated a trend for decreasing induction time for most materials tested. Based on these results, TGA testing is not a useful cable CM technique while OIT testing is quite useful for evaluating the early stages of degradation for many cable polymers.

III.12.7. General electrical tests

Testing was conducted on 1-meter whole cable samples. All type b cable samples were tested with the exception of the Rockbestos single conductor cable. For the IR, capacitance (C), Inductance (L) and Dissipation Factor (DF) testing, the CHAR-2010 system was used, which contains an oscilloscope, LCR meter and high resistance meter (HP4339B). The IR test was completed by applying a 500 v dc constant voltage for 10 minutes while taking measurements for each minute. Additional general electrical measurements were performed in the 20-meter cable samples primarily used for reflectometry tests. Measurements were normalized for 1-meter unit length for comparison to other participating laboratories. Table 31 shows the test specification and requirement.

TABLE 31. SPECIFICATION OF ELECTRICAL TEST

Insulation Resistance	Impedance
– Test Voltage 500 V DC	– Total Capacitance with Open Leads
– Values in G Ω	– DF with Open Leads
– Data Points Every 1 Minute	– Total Inductance with Shorted Leads
– PI is 10 Min / 1 Min	– Test Voltage 2 V AC
– Data Collected from Across 2 Conductors	– Test Frequencies: 100, 1k, 10 kHz
	– Data Collected from Across 2 Conductors

III.12.8. Thermal ageing conclusions for general electrical testing

No polymer types indicated a clear degradation trend from baseline. Polymer EPR capacitance DF data did indicate an increase at the final thermal ageing point but similar results not shown for other impedance values.

III.12.9. Reflectometry tests — Time-domain reflectometry and frequency domain

TDR testing was conducted on all the type b cable samples with the exception of the Rockbestos single conductor cable. A TDR pulser developed by AMS with a rise time of approximately 700ns and an oscilloscope TDS 3034C with a 300 MHz bandwidth and 2.5 GS/s sampling rate was used for the testing. The TDR pulser frequency measured at 146.8 Hz with amplitude of 4.46 V peak to peak.

TDR was performed with a TDRpulser and oscilloscope. The TDR pulser was connected to the oscilloscope with a BNC T-Connector and two male-to-male adapters connected to the CRP cable with a 25-foot yellow coax test lead. The 25 ft. coax test lead was then connected from one end of the BNC T-Connector to the CRP cable under test via a BNC binding post.

FDR testing was conducted on all the type b cable samples with the exception of the Rockbestos single conductor cable. The FDR test used a National Instruments PXIe-5632 vector network analyser with a frequency span of 300 KHz to 8.5 GHz. Only port 1 was used with an AMS' developed LabVIEW application. Port 1 was connected through a SMA 10.5 inch RG-316 coax cable to the CRP cable via a BNC binding post. Table 32 shows the specification of TDR and FDR.

TABLE 32. SPECIFICATION OF TDR AND FDR

TDR	FDR
– Performed on 20 meter samples only – Three 0.6 meter hot spots – Located at 6 (20 ft), 10 (33 ft), 14 (46 ft) Meters – Test voltage less than 5 V AC – TDR step signal at 150 Hz – Test lead influence compensated for TDR	– Performed on 20 meter samples only – Three 0.6 meter hot spots – Located at 6 (20 ft), 10 (33 ft), 14 (46 ft) Meters – Test voltage less than 5 V AC – FDR sine waves at frequencies: 100 MHz to 1 GHz – Test lead less than 25 centimetres for FDR

III.12.10. Thermal ageing conclusions for TDR and FDR

The EPR and SiR polymers indicated a clear degradation trend from baseline measurements at the third induced hot spot for the FDR test (FIG. 129). However, none of the cable types indicated a trend for the TDR measurements. The Habia cable was thermally aged at 190°C which permanently damaged the insulation at the first aged condition which did not allow for trending. The XLPO insulation polymer did not degrade significantly at the hot spot location.

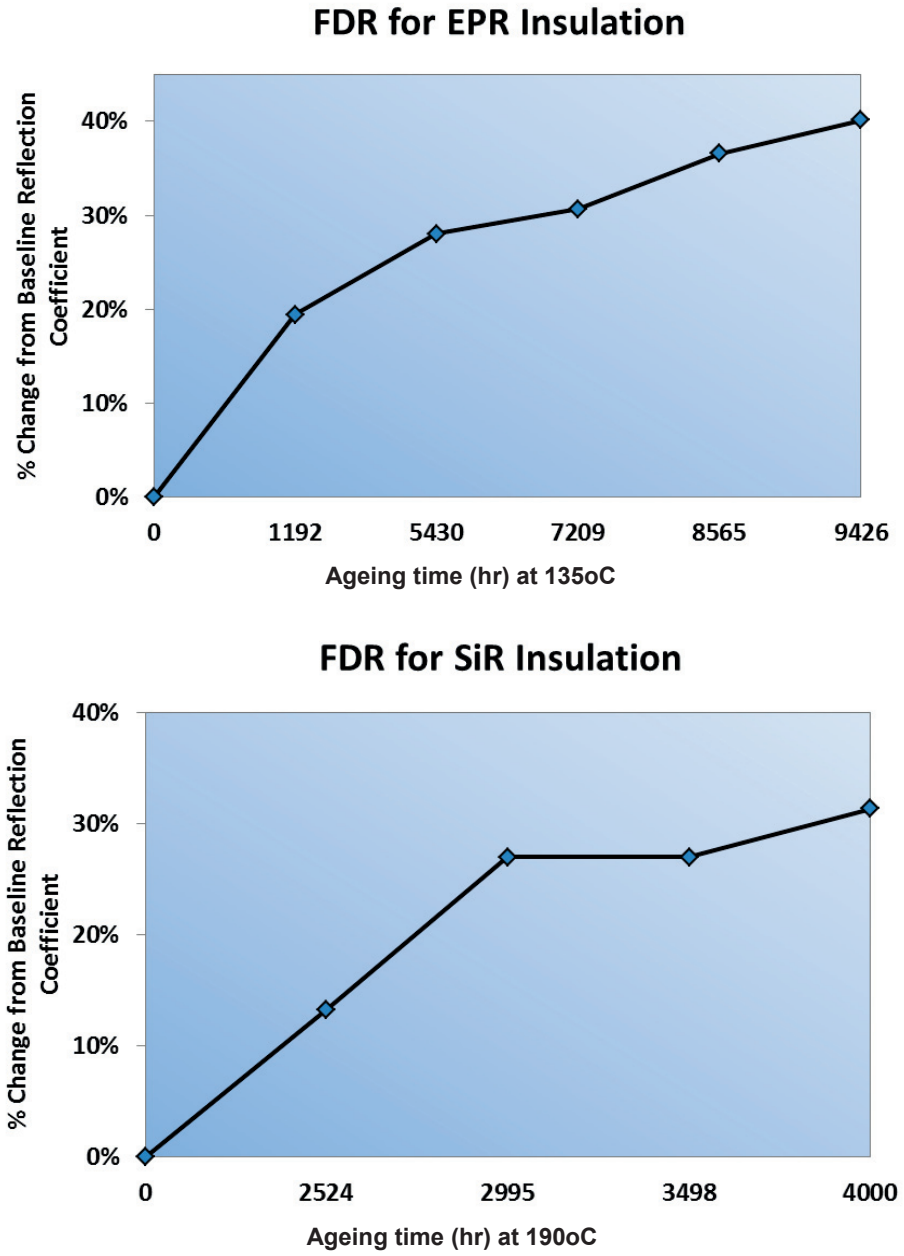


FIG. 129. Thermal ageing conclusions for TDR and FDR a) 135^{o}C, b) 190^{o}C.

III.12.11. Overall summary of data results

Table 33 shows the overall summary of data results. The detailed analysis results are:

— Mechanical EAB and IM test results correlated very well with thermal ageing except for materials XLPE, PEEK and XLPO;
— Chemical OIT tests indicated a clear change for most insulation materials during the thermal ageing programme;
— IR and Impedance test results did not correlate with thermal ageing of any insulation material;

— Frequency domain reflectometry tests proved to detect ageing degradation in SiR and EPR. More thermal ageing time is required for the XLPO insulation material. The PEEK insulated cable would require thermal ageing at a lower temperature.

TABLE 33. OVERALL SUMMARY OF DATA RESULTS

Which tests trend with each polymer type?

Manufacturer	Component	Material	EAB	IM	TGA	OIT	IR	C	DF	TDR	RDF
Shanghai	Jacket	XLPO	✓	✓	-	✓✓	-	-	-	-	-
Shanghai	Insulation	XLPO	✓	✓	☒	✓✓	☒	☒	☒	☒	☒
Changzhou	Jacket	EPR	✓✓	✓✓	-	-	-	-	-	-	-
Changzhou	Insulation	EPR	✓✓	✓✓	☒	✓✓	☒	✓	✓	☒	✓
Hew	Jacket	SiR	✓✓	✓✓	-	-	-	-	-	-	-
Hew	Insulation	SiR	✓✓	✓✓	-	-	☒	☒	☒	☒	✓✓
Eupen	Jacket	EVA	✓✓	✓✓	-	-	-	-	-	-	-
Eupen	Insulation	EPR	✓✓	✓✓	☒	✓✓	☒	☒	☒	☒	✓✓
Habia	Jacket	XLPO	✓	✓	-	-	-	-	-	-	-
Habia	Insulation	PEEK	☒	☒	☒	✓✓	☒	☒	☒	-	-
Rockbestos	Jacket	CSPE	✓✓	✓✓	-	✓✓	-	-	-	-	-
Rockbestos	Insulation	XLPE	☒	☒	☒	✓✓	-	-	-	-	-

✓✓ Trending ✓ Moderate Trending ☒ No Trending

APPENDIX IV. TEST PROCEDURES FOR BENCHMARKING OF CM TECHNIQUES

IV.1. INTRODUCTION

The programme of benchmarking tests will form part of the IAEA CRP on cable ageing starting in 2012. The test programme will cover some of the cable CM methods that are currently in use or are being investigated for future use in NPP.

The benchmarking exercise has the following main aims:

- To test techniques that might be able to locate 'hot spots' (both thermal and radiation) along a cable, where there is localized degradation. These techniques are primarily electrical methods of test;
- To test techniques that have the potential to track ageing degradation under thermal, radiation and combined radiation/thermal conditions. These techniques are primarily mechanical or chemical methods of test;
- To identify the critical test parameters for each of the techniques so that suitable test standards can be developed in the future.

This report covers the procedures for the CM methods included in the programme.

IV.1.1. Cable samples

Two sizes of cable sample will be used for most of the cable types in the benchmarking tests. One with a minimum diameter of 15 mm will be used for the preparation of samples for all of the mechanical/chemical CM methods. The second type (with a diameter of <10 mm) will be used for all of the electrical tests:

- Samples for electrical tests and ultrasonic velocity will be aged as whole cable samples;
- Indenter and recovery time samples will use whole cable for measurements on the outer jacket material. For measurements on the insulation materials, insulated cores stripped from whole cable will be aged separately;
- Samples for all other chemical tests will use jacket and insulation material stripped from whole cable before ageing;
- Elongation test specimens will be prepared before ageing.

IV.2. CM TEST PROCEDURES

For some of the CM methods included in the benchmarking programme, standards are available. Where such standards are not available, it will be important that the test parameters used are recorded and are preferably the same for each test laboratory.

All of the CM test methods will need to report the same header information as shown below. In addition, required data that is specific to the individual CM method is shown in Table 34.

TABLE 34. CM TEST METHODS

Test no.	This is the test no. used within the test laboratory (nn – see below)
Test lab	e.g. AMS, USA
Cable type	e.g. PEEK insulation (Habia)
Colour	e.g. natural, black lettering
Ageing conditions:	
Temperature (ºC)	
Total dose (Gy)	
Dose rate (Gy/hr)	
Ageing time (hr)	
Ageing lab (if different)	

Examples of the sort of information required are shown in the tables in each of the individual CM methods.

Data supplied in these formats will make it easier to compile the data into the final database of results. Within the database, each result can then be identified by a unique code of the following format:

A-B-C-D-nn

Where:

— A is the material ID;
— B is the CM method ID;
— C is the ageing condition ID;
— D is the test lab ID;
— nn is the test no. within each laboratory.

Suggested reporting formats for the additional data required for each of the test methods are given in each section.

The number of measurements required for each method is given in the following sections. It is recommended that this number is doubled for the baseline tests on unaged material.

IV.2.1. Elongation at break

The standard for this CM method is IEC/IEEE 62582-3. All participating laboratories that will be carrying out these tests should be using this standard.

IV.2.1.1. Sample preparation

Tests on jacket materials should be made using dumbbell specimens cut from the jacket using a suitable cutting die. If possible, use a die to one of the ISO 37 dimensions — if this is not available, then dies to national standards may be used. Insulation materials will use tubular specimens prepared from individual insulated wires from which the conductor has been removed.

For tubular specimens, end tabs or soft inserts are needed to prevent breakage in the grips of the tensile testing machine. For specimens with outside diameters of < 4 mm, end tabs should be fitted and for larger diameter tubular specimens, soft inserts should be used.

To prepare tubular specimens for testing, cut the specimen to a length of 50 mm. For tubular specimens < 4 mm in diameter, cut two end tabs 8 mm in length and slide them over the ends of the specimen, leaving 2 mm of the specimen protruding above the end tab. For larger diameter tubular specimens, cut two inserts 10 mm in length and insert into the ends of the tubular specimen. Place the specimen in the test machine and tighten the grips leaving a central gauge length of 30 mm.

Note: The end tabs and/or inserts need to be of polymeric material of similar modulus to the material being tested. For example, a rubber or plastic sleeve material can be used for the end tabs and a length of insulation could be used for inserts. The combination of end tabs and/or inserts are used to avoid excessive stress in the sample at the clamping position. This emulates the use of dumbbell specimens, where stress is concentrated in the gauge length during the test.

IV.2.1.2. Test parameters

The testing speed that should be used for each specimen type is as Table 35.

TABLE 35. TESTING SPEED FOR SPECIMEN TYPE

Specimen type	Testing speed ($mm \cdot min^{-1}$)
Dumbbell specimens – 20 or 25 mm gauge length (e.g. ISO type 1, 1 A or 2)	20
Dumbbell specimens – 12.5 mm gauge length (e.g. ISO type 3)	10
Tubular specimens – 50 mm overall length	50

Note : Type 1 in the table above is equivalent to ASTM D-412-C.

If an extensometer is used to measure elongation, this should be a non-contact type (e.g. optical type). Otherwise use the grip separation to measure elongation.

Elongation at break values should be reported as a percentage of the initial value:

$$EAB\% = (E_b – E_0)/E_0 \times 100 \quad (4)$$

Where:

— E_0 is the initial grip separation (or distance between extensometer marks);
— E_b is the separation between grips (or marks) at specimen breakage.

IV.2.1.3. Reporting format

Please attach sample image of typical load-extension curves plus the following data (Table 36).

TABLE 36. REPORTING FORMAT OF TYPICAL LOAD EXTENSION

Test machine (model)	e.g. Instron model 1100
Calibration method	
Extensometer type	e.g. none / optical / clip-on
Lab temperature during test (ºC)	
Cross-head separation (mm) **	
Cross-head speed (mm/min)	
Specimen type & size	e.g. ISO type 3, 12.5 mm gauge length
Elongation at break (%)	
Test 1 Test 2 Test 3 Test 4 Test 5 (min. 5 specimens, 10 for as-received)	
Mean elongation (%)	
Standard deviation	
Comments	Highlight any anomalies in the test series, e.g. specimen 2 broke in the grips.

** or marker separation (if using an optical extensometer)

IV.2.2. Indenter modulus

The standard for this CM method is IEC/IEEE 62582-2. All participating laboratories that will be carrying out these tests should be using this standard.

IV.2.2.1. Sample preparation

Measurements of IM on the jacket materials will use sections of whole cable approximately 250 mm long, aged as whole cable. For measurements on the insulation materials, insulated cores should be stripped from a cable sample and aged separately.

IV.2.2.2. Test parameters

The value of IM measured will be dependent on the shape and dimensions of the probe tip used in the test instrument. IEC/IEEE 62582-2 specifies the probe dimensions shown in FIG. 130. If a different probe is used, details of the dimensions must be given in the test report.

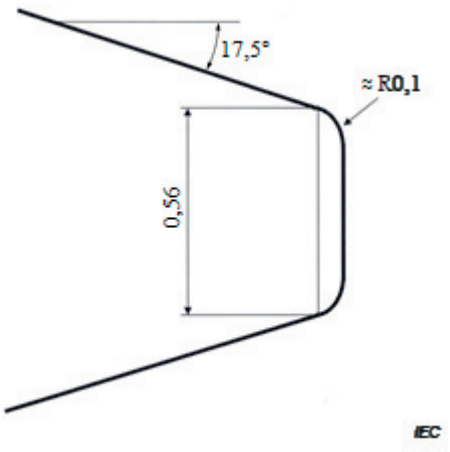


FIG. 130. Indenter (Dimensions in millimeters).

The probe velocity should be 5.1 ± 0.1 mm/min and a maximum force of 10 N should be set for all materials except SiR. For these softer materials, a maximum force of 5 N would be more appropriate. If this probe velocity is not possible on the instrument being used, select the nearest value to this velocity and ensure that it is included in the report.

Measurements of IM should be made at 3 locations around the circumference of whole cable samples, at each of 3 locations along the cable. For measurements made on insulated wires stripped from whole cable, 9 locations along the length of the wire should be made. IEC/IEEE 62582-2 specifies that indenter measurements should not be made within 100 mm of the end of the cable sample. However, if the sample being tested is only 250 mm long (as in this programme) this can be reduced to not less than 50 mm from the ends.

IM is calculated from the slope of the force-displacement curve, expressed in N/mm (FIG. 131). The IM should be determined by using the values F_1 = 1 N and F_2 = 4 N, see below:

$$IM = (F_2 - F_1)/(d_2-d_1) \quad (5)$$

Where:

— F_i is the corresponding force value at displacement d_i.

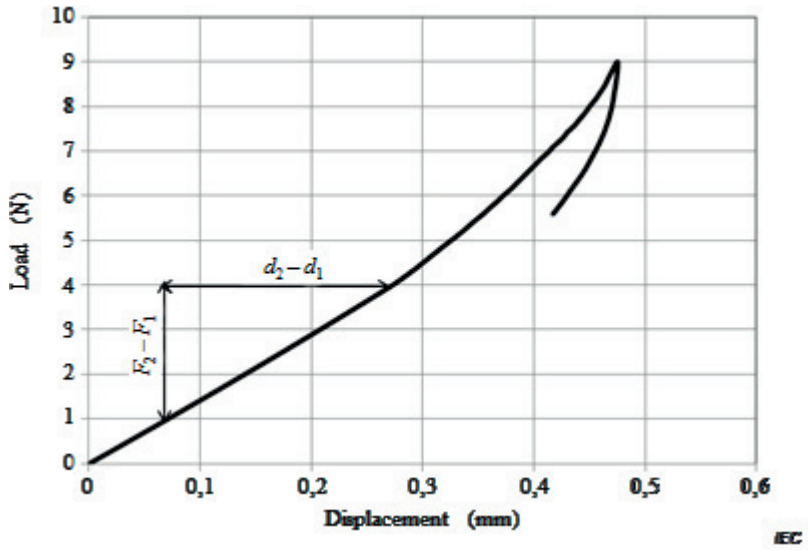


FIG. 131. Calculation of IM.

Since IM values can be dependent on temperature, measurements should be made at a laboratory temperature of 20ºC. If a different temperature is used, this should be recorded in the test report.

Note: Any indenter sample which has been aged at elevated temperature needs to be allowed to equilibrate with atmospheric humidity for a minimum of 24 hours before any measurements are made.

IV.2.2.3. Reporting format

Attach sample image of typical force-deflection curves together with the following Table 37.

TABLE 37. REPORTING FORMAT OF TYPICAL FORCE-DEFLECTION CURVES

Test machine	e.g. Ogden
Calibration method	
Lab temperature during test (ºC)	
Probe speed (mm/min)	e.g. 5 mm/min
Max. force (N)	e.g. 10 N
Force range used for calculations (N)	e.g. 1 – 4 N
Specimen type	e.g. whole cable / insulated wire
IM (N/mm) IM1 IM2 IM3 IM4 IM5 IM6 IM7 IM8 IM9	
Mean IM (N/mm)	
Standard deviation	
Comments	Highlight any anomalies in the test series e.g. test 5 over thin part of jacket

IV.2.3. Recovery time

Recovery time measurements are a variation of the indenter method, where the time required for the material to recover from a set indentation is made.

IV.2.3.1. Sample preparation

The same as used for indenter measurements.

IV.2.3.2. Test parameters

The test sequence for generating recovery time results is shown in the schematics below. The indenter probe is driven towards the sample until the sample surface is found. Once it is located at the surface, the probe is preloaded against the cable sample via a small 0.5 mils displacement into the material. The preload phase is followed by a typical 5 mils

indentation phase during which force and displacement are recorded to derive the specific compressive stiffness. At the end of the indentation phase, the probe is kept in its indented position and the force is allowed to relax for one minute. Following the relaxation phase, the probe is very quickly retracted by a set percentage of the initial indentation depth. The time to recover the deformation is calculated from the start of probe retraction to the reappearance of a force as the sample comes into contact with the indenter probe.

The percentage of retraction is changed according to the type of material tested. For example, retraction rates of 60 and 90% are typically used for PVC and XLPE, respectively. When testing new materials, the retraction rates are adjusted to maximize the sensitivity to degradation. Usually the rates are chosen to obtain recovery time on unaged samples in the order of 0.2 to 1 second.

The probe size used is as per the IEC/IEEE 62582-2 standard. However, for harder materials, a smaller diameter probe may be used to ensure that a local indentation mark is indeed generated prior to measuring recovery times.

Results are generated both at the prescribed IEC/IEEE 62582-2 standard temperature of 20ºC and at a reference temperature of 35ºC. Any sample which has been aged at elevated temperature needs to be allowed to equilibrate with atmospheric humidity for a minimum of 24 hours before any measurements are made. Any measurement at a reference temperature should be taken only once the cable sample has fully equilibrated at that temperature.

IV.2.3.3. Reporting format

Use Table 38 for reporting format of typical force-deflection curves.

TABLE 38. REPORTING FORMAT OF FORCE-DEFLECTION CURVES

Test machine (model)	
Calibration method	
Lab temperature during test (ºC)	
Probe speed (mm/min)	
Max. indentation depth (mm)	
Probe retraction rate	As % of initial indentation
Probe tip diameter (mm)	
Specimen type	e.g. whole cable / insulated wire
Recovery time (sec) T1 T2 T3 T4 T5 T6 T7 T8 T9	
Mean (sec)	
Standard deviation	
Comments	Highlight any anomalies in the test series

IV.2.4. Oxidation induction time/temperature

The standard for this CM method is IEC/IEEE 62582-4. All participating laboratories that will be carrying out these tests should be using this standard.

These two CM methods use standard thermal analysis equipment (differential scanning calorimeter) to measure the onset of oxidation in micro-samples exposed to oxygen.

IV.2.4.1. Sample preparation

Samples should be taken as a through thickness slice of the insulation or jacket material being tested. Each sample for OIT or OITP measurement should be in the range 10 mg ± 2 mg in weight. Each sample should be chopped into pieces with maximum dimensions of 1 mm. It is recommended that the chopped sample should be screened with a mesh to provide a particle size not greater than 0,85 mm as consistent sample preparation is important to enable reproducible oxidation of the sample during measurement. The chopped sample should be placed into a sample pan appropriate to the instrument being used. The sample pans should be of aluminium and be open or have lids with holes or mesh to allow free access for oxygen during the measurement.

A minimum of three samples should be measured. If the results of measurements on three samples have a standard deviation > 10% of the mean value for OIT or > 3% of the mean value for OITP, an additional two samples should be measured.

IV.2.4.2. Test parameters

Oxidation induction time measurements: The reproducibility of OIT measurements is dependent on using a standardized thermal history. The sample is heated in a nitrogen gas flow at a rate of temperature rise of 50°C min^{-1} until 10°C below the set temperature. The ramp rate is then reduced to 5°C.min^{-1} to reach the set temperature. The sample is then held for 2 min at the set temperature in nitrogen after which the atmosphere in the instrument is switched to oxygen. The flow rate for oxygen during OIT tests should be 50 - 100 ml.min^{-1}.

The flow rate for nitrogen during the initial phase of OIT tests is not critical but it is recommended that a similar flow rate be used. The oxidation exotherm is detected by a rapid increase in heat flow. The time from switching the atmosphere to oxygen until the sample starts oxidizing is the OIT. This is determined from the intersection with the oxidation exotherm of a line at a threshold of 0.1 W/g above the baseline, as shown schematically below (FIG. 132).

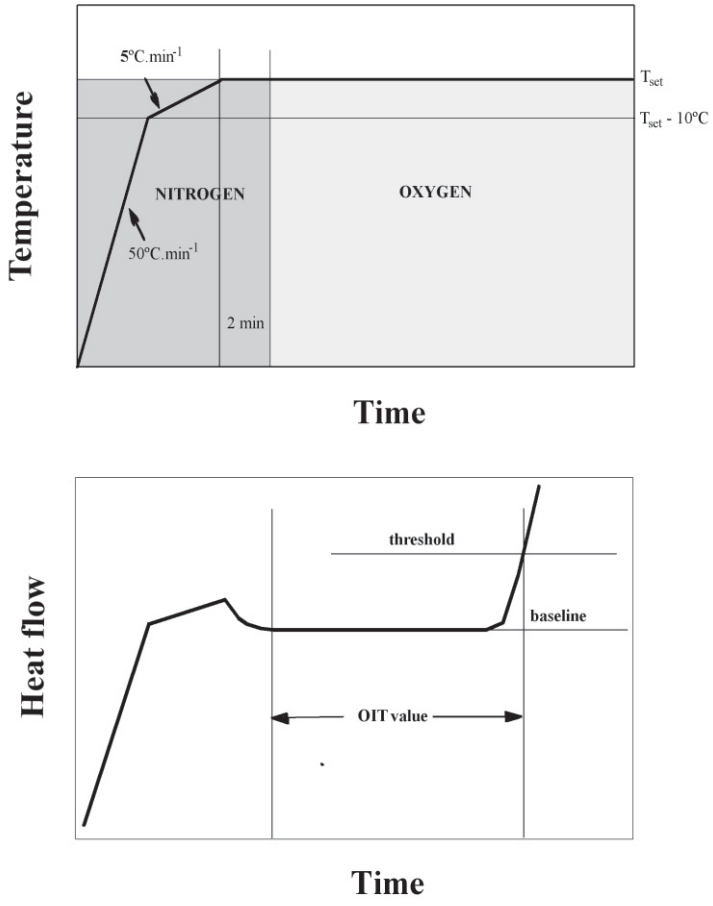


FIG. 132. Oxidation induction time measurements.

The recommended set temperature for OIT measurements is 210°C, provided that the oxidation induction time for unaged material is at least 30 min. If the OI time is less than 30 min for unaged material, then the set temperature should be reduced in 10°C increments until the OIT is > 30 min. If the OI time is > 90 min for unaged material, then the set temperature should be increased in 10°C increments until the OI time is < 90 min. Once the set temperature has been selected for a specific material, the same set temperature must be used for all subsequent measurements on that material.

Oxidation induction temperature measurements: OITP measurements are carried out using a constant temperature ramp rate in a gas flow of oxygen. The oxidation exotherm is detected by a rapid increase in heat flow. The flow rate for oxygen during OITP measurements should be 50 - 100 ml.min^{-1}. The temperature ramp rate should be 10ºC.min^{-1} from the start temperature until the oxidation onset is observed. When carrying out consecutive measurements, the starting temperature shall be < 50ºC.

The onset temperature (OITP value) is defined by the intersection of the oxidation exotherm with a threshold value of 0.5 W/g above the baseline, as shown below (FIG. 133).

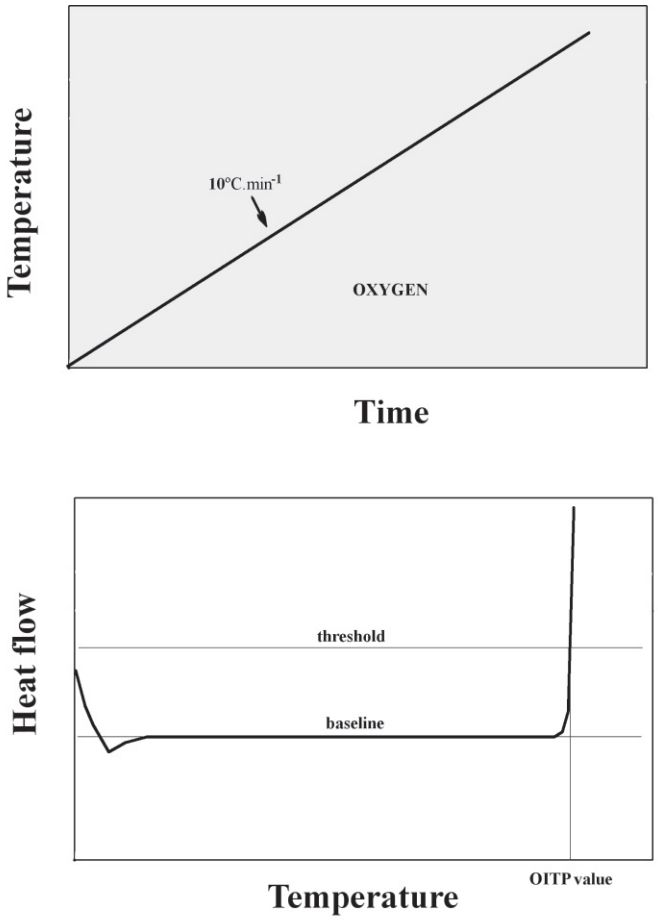


FIG. 133. Oxidation induction temperature measurements.

Note: Heat flows during OITP measurements are considerably higher than in OIT measurements. The selection of a higher threshold value than that used for OIT measurements enables a more consistent value to be obtained for the onset.

IV.2.4.3. Reporting format

Oxidation induction time: attach sample image of typical heat flow versus time curves plus the following information. Use Table 39 for reporting format of OIT.

TABLE 39. REPORTING FORMAT OF OIT

Test Instrument (Model)	e.g. DuPont 2110	
Calibration method		
Test temperature(ºC)	e.g. 210ºC	
Oxygen flow rate (ml/min)		
Nitrogen flow rate (ml/min)		
	Sample weight (mg)	OI time (min)
OIT1		
OIT2		
OIT3		
OIT4		
OIT5		
Mean OIT (min)		
Standard deviation		
Comments	Highlight any anomalies in the test series	

Oxidation induction temperature (OITP): attach sample image of typical heat flow versus temperature curves plus the following information.

IV.2.5. Thermogravimetric analysis

This CM method uses standard thermal analysis equipment to measure the weight loss of a micro-sample during heating in nitrogen.

IV.2.5.1. Sample preparation

Samples should be taken as a through thickness slice of the insulation or jacket material being tested. Each sample for TGA measurement should be in the range 10 mg ± 2 mg in weight. The sample should be chopped into pieces with maximum dimensions of 1 mm. It is recommended that the chopped sample should be screened with a mesh to provide a particle size not greater than 0.85 mm as consistent sample preparation is important to enable reproducible weight loss of the sample during measurement. The chopped sample should be placed into a sample pan appropriate to the instrument being used. The sample pans should be of aluminum and be open or have lids with holes or mesh.

A minimum of three samples should be measured. If the results of measurements on three samples have a standard deviation > 10% of the mean value, an additional two samples should be measured.

IV.2.5.2. Test parameters

Each TGA sample should be heated in flowing nitrogen at a temperature ramp rate of 10ºC/min. The flow rate is not critical but a rate of 50 – 100 ml/min is recommended. When carrying out consecutive measurements, the starting temperature shall be < 50ºC.

The temperature at maximum rate of weight loss and the temperature at 5% weight loss should be reported.

IV.2.5.3. Reporting format

Please attach sample image of typical weight loss versus temperature curves plus the following information. Use Table 40 for reporting format of TGA.

TABLE 40. REPORTING FORMAT OF TGA

Test instrument (model)	e.g. DuPont 2110		
Calibration method			
Temperature ramp rate (ºC/min)	e.g. 10		
Nitrogen flow rate (ml/min)			
	Sample weight (mg)	5% wt. loss temp. (ºC)	Temp. at max. loss rate (ºC)
TGA1			
TGA2			
TGA3			
TGA4			
TGA5			
Mean TGA (ºC)			
Standard deviation			
Comments	Highlight any anomalies in the test series		

IV.2.6. Density

Density measurements are made by weighing the specimen in air and in distilled (or de-ionized water) using an analytical balance capable of weighing to 1 mg or better. Either of two methods may be used – method A: using a density bottle; or method B: using a balance pan straddle and suspending the specimen in air, then in water.

IV.2.6.1. Sample preparation

The specimen size should be > 0.25 g per measurement to get reproducible results. Each specimen may be a single piece if using method B on jacket materials. For insulation materials in the form of tubes, the specimen should be split longitudinally to expose the inner surface. For method A, the specimens will need to be cut up to dimensions suitable for the size of density bottle used. A 25 ml density bottle is acceptable for this method.

IV.2.6.2. Test parameters

All samples that have been thermally aged should be allowed to equilibrate with standard laboratory conditions for at least 24 hours before testing.

The main source of error in density measurements arises from the presence of air bubbles on the surface of the specimen. In order to minimize air bubbles on the test specimen, it is permissible either to add a trace (say 1 part in 10 000) of surface-active material such as a detergent to the distilled water or to dip the test specimen momentarily into a suitable liquid (such as an alcohol), miscible with water and having a negligible swelling or leaching action on the material. If the latter method is adopted, precautions shall be taken to minimize the carry-over of alcohol.

For method A, the density ρ is calculated from:

$$\rho = m_1 / (m_1 - m_2) \quad (6)$$

Where:

— m_1 is the mass in air and m_2 is the mass in water.

For method B, the density ρ is calculated from:

$$\rho = (m_2 - m_1) / (m_4 - m_3 + m_2 - m_1) \quad (7)$$

Where:

— m_1 is the mass of the density bottle;
— m_2 is the mass of the density bottle + test specimen;
— m_3 is the mass of the bottle + test piece + water;
— m_4 is the mass of the density bottle filled with water.

IV.2.6.3. Reporting format

Use Table 41 for reporting format of density.

TABLE 41. REPORTING FORMAT OF DENSITY

Balance (model)	e.g. Adam PW124	
Calibration method		
Test method	e.g. density bottle	
Immersion liquid	e.g. de-ionized water	
	Sample weight (g)	Density (g/cm^3)
D1		
D2		
D3		
D4		
D5		
Mean density (g/cm^3)		
Standard deviation		
Comments	Highlight any anomalies in the test series	

IV.2.7. Fourier transform infrared spectroscopy

FTIR measurements can be used to determine the level of oxidation in a range of polymeric materials by measuring the height (or area) of the absorption related to the –C=O carbonyl group. The ratio of the height (or area) of the carbonyl absorption near 1720 cm^{-1} and the –C-H absorption near 1370 cm^{-1} is the oxidation index. Materials containing carbon black are difficult to measure because of the high absorption observed across the IR frequency range.

Near IR (NIR) covers the range 12,900 to 4000 cm^{-1}. The peaks are very broad, but can be useful for some systems.

IV.2.7.1. Sample preparation

FTIR can be used in two different modes – in transmission or by attenuated total reflectance (ATR). In transmission mode, thin slices of material (typically 200 μm thick) are required. In ATR mode the specimen is pressed against an ATR crystal and no special sample preparation is required, other than cutting the sample into a small enough piece to suit the crystal.

IV.2.7.2. Test parameters

FTIR instruments should be calibrated over the range 1200 – 2000 cm^{-1} and measurements made under an inert dry gas flow, e.g. nitrogen. Typically, 50 scans across this range would be averaged to provide the specimen spectrum for analysis, scanned at a resolution of at least 4 cm^{-1}.

IV.2.7.3. Reporting format

Please attach sample image of typical spectrum plus the following information. Use Table 42 for reporting format of test parameters.

TABLE 42. REPORTING FORMAT OF TEST PARAMETERS

Instrument (model)	
Frequency range (cm^{-1})	
Resolution (cm^{-1})	
No. of scans averaged	
1st peak (cm^{-1})	e.g. –C=O at 1720 cm^{-1}
2nd peak (cm^{-1})	e.g. –CH at 1320 cm^{-1}
Peak height or area	
Oxidation index (ratio of 1st/2nd peaks)	
Comments	Highlight any anomalies in the test series

IV.2.8. Ultrasonic velocity

Ultrasonic velocity measurements are made by attaching two probes to the outer surface of the cable, one probe emits the signal and the second probe receives the signal. The ultrasonic transmission time between the probes will be a function of the probe separation and the ultrasonic velocity within the jacket material. The probes are coupled to the jacket using machine oil or grease.

IV.2.8.1. Sample preparation

Measurements will be made on jacket materials using samples aged as whole cable. The samples should have a length of approximately 250 mm.

IV.2.8.2. Test parameters

Measurements should be taken at 3 positions around the circumference of the cable and duplicate measurements made at each position.

IV.2.8.3. Reporting format

Use Table 43 for reporting format of Ultrasonic velocity test results.

TABLE 43. REPORTING FORMAT OF TEST RESULTS

Test instrument (model)	
Frequency	
Probe separation	
Coupling agent	e.g. machine oil
Velocity (m/s) V1 V2 V3 V4 V5 V6	
Mean velocity (m/s)	
Standard deviation	
Comments	Highlight any anomalies in the test series

IV.2.9. Time domain reflectometry

The TDR test involves sending a voltage step with a fast rise time into a transmission line. Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity in the transmission line. The resulting wave is captured in the time-domain and is a ratio of the incident signal and the reflected signal expressed in terms of Reflection Coefficient (Rho) or ρ. The speed that the incident and reflected signals travel in the transmission line is known as the velocity of propagation (V_P) which has a magnitude that is a percentage of the speed of light (V_s) in a vacuum (V_s = 0.3 meters / nanosecond) and is determined by the relative permittivity or dielectric constant of the media's insulating material. Distance to an impedance change can be determined by multiplying the V_P of the transmission line by half the time it takes for the incident wave to travel to the impedance change and get reflected back to the generator:

$$Rho = \frac{V_{reflected}}{V_{incident}} \quad (8)$$

$$Distance = \frac{V_p T}{2} \quad (9)$$

Where:

— T = transit time from generator to impedance change and back to generator.

IV.2.9.1. Sample preparation

TDR measurements should be made on whole cable samples with minimum length of 20 meters. The cable should be laid out flat rather than coiled while performing tests. Remove approximately 50 mm length of jacket material and expose approximately 12 mm of the conductor from any insulation material. Ensure a low resistance connection between test equipment connection and cable sample.

IV.2.9.2. Test parameters

Measurements should be made between each pair combination of the individual insulated conductors and to shield if part of the cable construction.

Determine velocity of propagation (V_p) of each cable type by measuring cable length then adjust V_p so that cable length shown on TDR plots match measured length. For example, a 20-meter cable distance and a measured transit time of 300 nanoseconds would require a V_p of 0.444 V_s. A new V_p should be measured for data taken at each ageing interval.

$$V_P = \frac{2*Distance}{T} = \frac{2*20m}{\left(\frac{0.3m}{ns}\right)*300ns} = 0.444\ V_s \qquad (10)$$

Test Equipment Specifications:

— Equipment Rho minimum resolution = 5mρ;
— Equipment bandwidth minimum = 100 MHz;
— TDR pulse rise time (10% - 90%) minimum = 1 nanosecond.

IV.2.9.3. Reporting format

Please document the amplitude of TDR signal (e.g. 3 V_p into 50Ω) and whether the TDR signal is a pulse or step signal. A Pulse signal is a single short burst of a sine wave. A step signal is a continuous square wave. (e.g. step at 150 Hz, 50% duty cycle). Please attach TDR plot of the cable sample test and include the following information on the plot (Table 44).

TABLE 44. TEST PARAMETERS OF TDR

Test instrument (model)	e.g. AMS CHAR 2012
Velocity of propagation	e.g. 0.444 V_s
Cable temperature	e.g. 25°C
Connection	e.g. Pos Lead to white, Neg Lead to black; open circuit

Both the amplitude value for the cable sample nominal impedance and the amplitude value at any degradation should be indicated on the plot. Test measurements of cable samples should be made at ambient environmental conditions.

IV.2.10. Frequency domain reflectometry

The FDR technique sends an incident wave of varying frequencies into a transmission line. Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity in the transmission line. These reflected waves are measured in the frequency domain from differences in magnitude and phase to the original incident wave. Sample preparation

FDR measurements should be made on whole cable samples with minimum length of 20 meters. The cable should be laid out flat rather than coiled while performing tests. Remove approximately 50 mm length of jacket material and expose approximately 12 mm of the conductor from any insulation material. Ensure a low resistance connection between test equipment connection and cable sample.

IV.2.10.1. Test parameters

Measurements should be made between each pair combination of the individual insulated conductors and to shield if part of the cable construction.

Determine V_P of each cable type by measuring cable length then adjust V_p so that cable length shown on FDR plots match measured length. For example, a 20-meter cable distance and a measured transit time of 300 nanoseconds would require a V_p of 0.444. A new V_p should be measured for data taken at each ageing interval (formula 10).

Test equipment specifications:

— Dynamic measurement specifications;
— Noise floor of dynamic range > 100 db;
— Measurement resolution 6 dB above the noise floor;
— Span ($F_{stop} - F_{start}$) = 90 MHz minimum;
— Distance resolution ($\Delta T * V_p$) = 1 meter maximum; $\Delta T = \frac{1}{2*SPAN}$

IV.2.10.2. Reporting format

Document the amplitude of FDR signal (e.g. 5 dBm or 1.125 V PP into 50Ω) and FDR plot of the cable sample test and Table 45 will be used for plot.

TABLE 45. TEST PARAMETERS OF TDR

Test instrument (model)	e.g. AMS CHAR 2012
Frequency span	e.g. 10 MHz – 100 MHz
Velocity of propagation	e.g. $0.444V_s$
Cable temperature	e.g. 25°C
Connection	e.g. Positive lead to white, Negative lead to black; open circuit

Both the amplitude value for the cable sample nominal impedance and the amplitude value at any degradation should be indicated on the plot. Test measurements of cable samples should be made at ambient environmental conditions.

IV.2.11. Dielectric loss measurements: Tan Delta

Dielectric loss measurements are made by applying an AC voltage of varying frequency and measuring the current response. The phase angle between the voltage and current response is used to calculate the loss factor (Tan δ).

IV.2.11.1. Sample preparation

Measurements of dielectric loss are made on samples aged as whole cable. A short length of jacket should be removed from each end and the conductors of individual wires exposed before ageing. A minimum length of 1 m is required.

IV.2.11.2. Test parameters

There are two approaches to dielectric loss measurements – (a) measuring the voltage dependence of the dielectric loss at a fixed frequency and (b) measuring the frequency dependence of the dielectric loss at a single voltage:

— Method (a) usually uses a frequency of 50 or 60 Hz and tests the cable at test voltages of 0.5, 0.75, 1.0 and 1.2 times the rated voltage of the cable – this is similar to the approach used for medium voltage cables;
— Method (b) typically uses an applied voltage of 5V and a frequency range of 20 Hz to 20 kHz - this is more appropriate for I&C cables.

Measurements should be made between individual insulated wires in a multi-conductor cable, or between shield and individual wires if a shield is present in the cable construction. The individual wires are usually in a parallel configuration, i.e. the wires are open circuit.

Note that any sample which is aged at elevated temperature needs to be allowed to equilibrate with atmospheric humidity before any measurements are made, as the measurements can be very sensitive to the moisture content of the cable.

IV.2.11.3. Reporting format

Use Table 46 for reporting format of dielectric loss measurements.

TABLE 46. REPORTING FORMAT OF TAN DELTA (I)

Test instrument (model)	e.g. ESI 2110 Video Bridge	
Frequency (Hz)	e.g. 50 Hz	
Applied voltage range (V)	e.g. 300 V – 720 V	
Connection	e.g. black to red, open circuit	
	Voltage (V)	Tan δ
TD1		
TD2		
TD3		
TD4		
TD5		
Comments	Highlight any anomalies in the test series	

Use Table 47 for sample image of typical loss versus frequency spectrum if more than 10 frequencies are measured.

TABLE 47. REPORTING FORMAT OF TAN DELTA (II)

Test instrument (model)	e.g. ESI 2110 Video Bridge	
Frequency range	e.g. 20 Hz – 20 kHz	
Applied voltage (V)	e.g. 5V	
Connection	e.g. black to red, open circuit	
	Frequency (Hz)	Tan δ
TD1		
TD2		
TD3		
TD4		
TD5		
TD6		
TD7		
TD8		
TD9		
TD10		
Etc.		
Comments	Highlight any anomalies in the test series	

IV.2.12. Insulation resistance

Measurements of insulation resistance are made by applying a DC voltage, typically 500 V, between conductors and ground for 10 minutes. The resistance is measured at intervals during this time period, usually every minute. The polarization index is defined as being the ratio of the insulation resistance at 10 min divided by the value at 1 min.

Note that any sample which is aged at elevated temperature needs to be allowed to equilibrate with atmospheric humidity before any measurements are made, as the measurements may be sensitive to the moisture content of the cable.

IV.2.12.1. Reporting format

Use Table 48 for reporting format of IR.

TABLE 48. REPORTING FORMAT OF IR

Test instrument (model)		
Applied voltage (V)	e.g. 500V	
Connection	e.g. black to red + ground	
	Time (min)	IR (ohm)
R1		
R2		
R3		
R4		
R5		
R6		
R7		
Comments	Highlight any anomalies in the test series	

APPENDIX V. AGEING PROCEDURES FOR BENCHMARKING TESTS

V.1. INTRODUCTION

The programme of benchmarking tests will form part of the IAEA CRP on cable ageing starting in 2012. The test programme will cover some of the cable CM methods that are currently in use or are being investigated for future use in NPP.

The benchmarking exercise has the following main aims:

— To test techniques that might be able to locate 'hot spots' (both thermal and radiation) along a cable, where there is localized degradation. These techniques are primarily electrical methods of test;
— To test techniques that have the potential to track ageing degradation under thermal, radiation and combined radiation/thermal conditions. These techniques are primarily mechanical or chemical methods of test;
— To identify the critical test parameters for each of the techniques so that suitable test standards can be developed in the future.

This publication covers the ageing procedures to be used in the programme.

V.2. SCOPE OF THE PROGRAMME

V.2.1. Materials

The cable materials to be tested in the programme represent a range of materials that are either in use in current NPPs or are likely to be used in new NPPs, from manufacturers worldwide. The cable materials that will be included in the programme are shown in Table 49.

TABLE 49. MATERIALS IN THE PROGRAMME

Insulation/jacket	Manufacturer
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

*The insulation materials of these cables are dual layers with inner layer for dielectric properties and outer layer for flame retardancy.

V.2.2. CM methods

A wide range of CM methods will be included in the programme. These include some established methods (such as EAB) where there are considerable data and experience available, as well as more recently developed methods where data are limited. The methods that will be included are as follows:

— Mechanical /chemical:

- Elongation at break;
- Indenter modulus;
- Recovery time;
- OIT/OITP & TGA;
- FTIR & NIR;
- Density;
- Ultrasonic velocity;

— Electrical:

- TDR and FDR based methods (including JTFDR & LIRA);
- Tan Delta;
- General electrical tests;
- Broadband impedance.

V.2.3. Ageing

V.2.3.1. Tracking ageing degradation

The programme will subject cable samples to a range of ageing conditions. Since the aim of the programme is to identify which CM methods correlate well with ageing degradation, it is important that samples are aged to a level where significant degradation has occurred. The ageing does not aim to simulate specific ageing conditions in NPPs. However, the range of degradation levels should cover the types of ageing seen in normal operation and in 'hot spot' areas.

The following ageing conditions are suggested:

— Thermal: 7 ageing conditions representing a range from lightly aged to significantly degraded. The ageing temperature and time should be calculated using the activation energy for the specific material being tested;
— Radiation: 5 ageing conditions representing a range from lightly aged to significantly degraded. Ageing should be carried out at near ambient temperature (< 30ºC) at a low dose rate;
— Combined thermal/radiation: 2 ageing conditions at a single dose rate at an elevated temperature.

Including ageing under thermal, radiation and combined thermal/radiation ageing will help to determine whether the CM method being tested can consistently track degradation under any of the conditions that may occur in a NPP.

V.2.3.2. Location of 'hot spots'

For the part of the programme assessing the ability of CM methods to locate 'hot spots', long cable samples will be required containing several localized areas of degradation. This would include both thermal and radiation aged areas:

— Thermal degradation (well defined localized degradation) — 3 segments representing 3 levels of degradation, ranging from lightly degraded to significantly degraded;

— Radiation aged area created by running a long cable into a radiation cell close to the sources (more diffuse localized degradation).

The long sample used for these tests should be set up to represent the type of environment that would be typical in an NPP, i.e. with bends, clamps, and connections.

V.3. AGEING PROCEDURES

V.3.1. General requirements

In any accelerated ageing programme, the aim is to simulate in the short term the ageing degradation that would occur in the long term in a NPP. One of the concerns is the effect of diffusion-limited oxidation (DLO) in accelerated testing. When DLO effects are present, the degradation of the surface of the material may be significantly different to that through the thickness of the material. DLO can occur in both thermal and radiation ageing if the temperatures or radiation dose rates used are too high.

The CM methods that are being assessed will be sampling the properties of different parts of the cable. For example, FTIR would be measuring the surface of the material; the indenter would be testing the properties of perhaps the top mm of material whereas density measurements will be an average of the properties of the full thickness. It is therefore important to try to minimize the effects of DLO in the accelerated ageing process.

The timescale of the thermal ageing should be up to 12 months to produce significant degradation. The temperature at which ageing is carried out and the timescale of the ageing will be determined by the activation energy, using the Arrhenius relationship and should be the minimum temperature to keep within this timescale. Values of the activation energy will be required for the specific cable materials to be tested.

For samples aged as whole cable, the activation energy to be used will depend on the test method that is being assessed. For indenter and recovery time measurements, the jacket value should be used. However, measurements on insulated cores aged separately should use the value for the insulation. For all of the electrical test samples, the activation energy to be used should be that for the insulation.

The dose rate used for radiation ageing should be about 500 Gy/hr to produce significant ageing in a timescale of up to 12 months. The temperature of the irradiation cell will be determined by the facilities available but should be < 30ºC. Samples being irradiated will need to have good access to air.

For samples exposed to combined thermal/radiation ageing, similar dose rates to those used in ambient radiation ageing should be used. The suggested temperature for combined ageing is 50ºC and good air access to the samples is necessary.

V.3.2. Thermal ageing conditions

The activation energies for the materials included in the benchmarking programme are shown in Table 50.

TABLE 50. ACTIVATION ENERGIES FOR MATERIALS IN THE PROGRAMME

Cable manufacturer	Ea (eV) – insulation	Ea (eV) – jacket
PEEK/XLPO (Habia Cable) *	1.2	1.1
EPR/EVA (Eupen) *	1.21	1.35
SiR/SiR (Hew) *	0.863	1.45
XLPE/CSPE (Rockbestos) **	1.35	1.11
EPR/EPR (Changzhou Bayi Cable) *	1.261	1.256
XLPO/XLPO (Shanghai Cable) *	1.25	1.25

* data from manufacturer

** data from NEPO report

In selecting a temperature for carrying out the thermal ageing, the lowest temperature possible is preferred but there is a practical limitation on the length of time available for the ageing. For the benchmarking exercise to be completed within the timescale of the CRP, a maximum ageing time of about 12 months is required. The temperature selected needs to ensure that significant degradation occurs in the sample at this maximum time.

Ageing temperatures of 120ºC or 135ºC would be appropriate for most of the cable samples in the programme, but these temperatures will be insufficient for the SiR based materials and PEEK. The suggested ageing temperatures and estimated time to reach 50-100% elongation are shown in Table 51. Note these times are rough estimates based on experience with these types of polymeric cable materials and information from the cable manufacturers. The actual ageing times required for the specific materials being tested may be different.

TABLE 51. THERMAL AGEING CONDITIONS

Material	Ageing temp. (ºC)	Time to reach 50-100% EAB (hr)
CSPE	120	~ 1800
EVA	120	~ 7000
EPR	135	~ 6500
XLPE/XLPO	135	~ 6000
SiR	190	~ 5000
PEEK *	190	~ 6000

*Note that elongation values for unaged PEEK are normally much less than for other polymers, so this time corresponds to a reduction to approximately 50% of initial elongation, not absolute elongation.

V.3.3. Radiation ageing conditions

To reduce the effects of DLO, as low a dose rate as possible should be used for the radiation ageing of cable samples. A maximum dose rate of 500 Gy/hr is suggested as being a practical compromise. An estimate has been made of the approximate dose required to reach

50–100% elongation for each of the materials being tested. The required ageing time to reach this dose is shown in Table 52. Note that these doses are rough estimates based on experience with these types of polymeric cable materials. The actual ageing times required for the specific materials being tested may be different.

TABLE 52. RADIATION AGEING CONDITIONS

Material	Dose to 50–100% EAB (MGy)	Time to reach this dose at 500 Gy/hr (Hr)
CSPE	0.4	800
EPR	1.2	2400
EVA	1.0	2000
SiR	0.8	1600
XLPE/XLPO	2.0	4000
PEEK	>2.0 *	> 4000

*Note that elongation values for unaged PEEK are normally much less than for other polymers, so this dose corresponds to a reduction to approximately 50% of initial elongation, not absolute elongation.

V.3.4. Ageing conditions for each of CM methods

As mentioned in Section 3.1, the ageing conditions to be used will also be dependent on the CM method that is being tested. Table 53 indicates whether ageing conditions for the jacket or insulation should be used for each method.

TABLE 53. AGEING CONDITIONS FOR EACH METHOD

CM method	Material tested	Sample type	Use ageing conditions for
Elongation	Jacket	Dumbbell	Jacket
	Insulation	Tube (stripped wire)	Insulation
Indenter, recovery time	Jacket	Whole cable	Jacket
	Insulation	Insulated wire	Insulation
Ultrasonic velocity	Jacket	Whole cable	Jacket
OIT, OITP, TGA, FTIR, density	Jacket	Stripped sample	Jacket
	Insulation	Stripped sample	Insulation
Electrical tests (TDR, FDR, LIRA, Tan δ, impedance)	Insulation	Whole cable	Insulation

V.3.5. Ageing times — general considerations

For most of the material types being tested, the shape of the degradation versus time curve is not known. Selection of the ageing times will be quite critical if significant

degradation is to be achieved. The suggested approach is shown in the following sections for thermal and radiation ageing.

V.3.6. Ageing times — thermal

For the thermal ageing part of the programme, 7 different ageing times were used to find thermal effects at the set temperature (Table 54). To allow for some flexibility in the ageing times used, the scheme shown below is suggested, where tm is the estimated time for the material to reach 50-100% elongation at the test temperature.

TABLE 54. THERMAL AGEING TIMES

Thermal ageing														
	t=0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	tm
Sample															
S1					0.4										
S2									0.8						
S3											1				
S4						0.3		0.5							
S5										0.7					
S6												0.9			
S7									0.6					1.1	

Three samples (S1–S3) are put in the ageing oven at time t=0 and the remaining 4 samples (S4–S7) are put in at t=0.2 tm. The first sample (S1) is removed at t=0.4 tm. It should show some degradation but not a significant amount (say > 70% of initial value).

If S1 shows significant degradation, then pull out S4 and test at t=0.3 tm and shorten S5–S7 times.

Assuming S1 shows > 70% initial, then if S4 shows significant degradation (< 50% initial) at t=0.5 tm, then shorten S7 to t=0.6 tm.

S2 should show significant degradation at t=0.8 tm. If not, then leave S5-S7 in longer than specified.

These ageing conditions are for those CM methods that are destructive or only use small samples. For non-destructive tests (e.g. indenter, Tan δ –method b) it will be possible to use a single sample that is removed at intervals for testing and then replaced in the ageing oven. The same time intervals as shown above should be used to enable correlation with the other CM methods (additional measurements at intermediate intervals can also be carried out if practical).

V.3.7. Ageing times — radiation

For the radiation ageing part of the programme, 5 different ageing times were used at the set dose rate (Table 55). There is less opportunity for adjusting the timescales here, so the scheme shown below should be used, where Dm is the estimated dose required to reach 50–100% elongation.

TABLE 55. RADIATION AGEING TIMES

Radiation ageing											
	t=0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	Dm
S1			0.2									
S2					0.4							
S3							0.6					
S4									0.8			
S5											1	

These ageing conditions are for those CM methods that are destructive or only use small samples. For non-destructive tests (e.g. indenter, Tan δ –method b) it will be possible to use a single sample that is removed at intervals for testing and then replaced in the radiation cell. The same time intervals as shown above should be used to enable correlation with the other CM methods (additional measurements at intermediate intervals can also be carried out if practical).

V.3.8. Ageing times — combined thermal/radiation ageing

Only 2 samples will be available for these tests at 50ºC and 500 Gy/hr. It is suggested that ageing times equivalent to 0.3 Dm and 0.6 Dm are used.

V.3.9. Ageing conditions for long cable samples

The long cable samples that will be used for electrical tests aimed at locating ‘hot spot’ areas will need to include segments that have been aged. The suggestion is to incorporate 3 segments thermally aged to the equivalent of 0.2 tm, 0.4 tm and 0.6 tm. These segments would each contain a single well defined aged area of the cable.

In addition, a radiation aged segment with a more diffuse aged area, formed by running a cable section close to a radiation source would also be useful. This would help to identify whether the electrical methods can pick up a more gradual change in ageing.

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ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
AMS	Analysis and Measurement Services Corporation
CNEA	Comisión Nacional de Energía Atomica
CRDM	Control Rod Drive Mechanism
CRP	Coordinated Research Project
CSPE	Chlorosulphonated Polyethylene
DAR	Dielectric Absorption Ratio
DBA	Design Basis Accident
DSC	Differential Scanning Calorimetry
EAB	Elongation at Break
EdF	Electricite de France
EMI	Electromagnetic Frequency Interferences
EPR	Ethylene Propylene Rubber
EQ	Equipment Qualification
EVA	Ethylene Vinyl Acetate
FDR	Frequency Domain Reflectometry
FTIR	Fourier Transform Infrared
HRP	Halden Reactor Project
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	Indenter Modulus
INSS	Institute of Nuclear Safety System
IPAM	Indenter Polymer Ageing Monitor
IR	Insulation Resistance
ISU	Iowa State University
KHNP	Korea Hydro & Nuclear Power Company
JKAL	John Knott Associates Limited
LCR	Inductance, Capacitance and Resistance
LDPE	Low Density Polyethylene

NI	Nuclear Instrumentation
NIST	National Institute of Standards and Technology
NEL	Nuclear Engineering Limited
NPPs	Nuclear Power Plants
NRC	Nuclear Regulatory Commission
OIT	Oxidation Induction Time
OITP	Oxidation Induction Temperature
PDMS	Polydimethylsilozane
PE	Polyethylene
PEEK	Polyether Ether Ketone
PI	Polarization Index
PR	Polarization Ratio
RFI	Radiofrequency Interferences
Rho	Reflection Coefficient
RTDs	Resistance Temperature Detectors
RUL	Remaining Useful Life
SECRI	Shanghai Electric Cable Research Institute
SiR	Silicone Rubber
SNERDI	Shanghai Nuclear Engineering Research and Design Institute
SNSPC	State Nuclear Power Plant Service Company
TD	Tan Delta
TDR	Time-Domain reflectometry
TGA	Thermogravimetric Analysis
UJV	Nuclear Research Institute of Czech Republic
VEIKI	Institute for Electric Power Research of Hungary
VP	Velocity of Propagation
Vs	Speed of Light

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