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Wire System Ageing Assessment and Condition Monitoring (WASCO)

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Abstract

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical.
In this report 3 techniques for cable global ageing assessment were tested and evaluated. The EAB technique is a destructive, local technique that is often used as a reference for other methods. The indenter is a local, in-situ mechanical technique that is currently quite often used in NPPs. LIRA is an electrical method, full line, in-situ. LIRA correlated quite well with EAB and both tend to flatten when the ageing time reaches 40 years. The only cable type that was difficult to assess for all the 3 methods was the medium type in air environment. These tests considered only thermal ageing, up to 50 years and should be completed by considering also gamma irradiation ageing.

Key words

Condition monitoring, cable aging, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA, positron

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Contents

1 Introduction

The interest of safety aspects of wire systems aging (especially those wire systems used for control and instrumentation) is increasing worldwide because of their impact on several industrial fields, like power generation, transportation and defense. Although the environment conditions and degradation mechanisms of installed cables can be different from target to target, the negative consequences of wire failures, both from a safety and performance standpoint, are so important that almost all the countries in the industrialized world have some research project in progress in this area.
In the nuclear field, where cables are normally qualified before installation for an expected life of 40 years, there are a number of issues that are not completely solved today. These issues include:

- The effect of the particular adverse environment conditions (high radiation, humidity and temperature), especially during and after a Design Basis Accident (DBA).
- Extending the plant life after 40 years involves the requirement to assess and qualify the cable conditions for a longer time.
- Many cables condition monitoring techniques do exist today, but none of them is considered accurate and reliable enough for all the cable materials in use and conditions. In addition to that, only few of them are non-destructive techniques and are applicable in situ.
- Accelerated aging techniques, for qualification purposes under DBA conditions, are often not conservative and should be complemented with reliable condition monitoring methods.

An important issue is the assessment of the condition of installed cables that have been exposed for a long time (more than 30 years) to relative high temperature and gamma radiation (the condition of cables inside the reactor containment). Several techniques have been proposed to monitor and identify cables that are close to the end of their qualified life. The purpose of this work was to evaluate 3 well known techniques and finding the correlation among them. These techniques are the Elongation-At-Break (EAB), the Indenter and the Line Resonance Analysis (LIRA). The first one is the reference technique, for which a limit of 50% absolute was set by several international standards. The Indenter is a local technique that has got good results, mainly with EPR insulated cables. LIRA is an emerging technique based on the evaluation of electrical properties and their trends with the aging conditions.

The cable tested are low-voltage, EPDM insulated cables produced by the Swedish Lipalon. The reason for this choice is that this type of cables is widely in use in all the Swedish nuclear power plants. Samples 5m long of 3 Lipalon cable types were globally aged artificially for different times and their condition was analyzed using the 3 methods mentioned above. This report describes the findings and results if this analysis.

2 Material

The materials used in this study are unexposed Lipalon cables that have been stored in a cold and dark place at Ringhals. Three different types of unexposed cables have been aged and studied by mechanical and electrical testing. The jacketing of Lipalon cables is based on chlorosulfonated polyethylene (Hypalon) and the core insulation has a thin outer layer of Hypalon and a thicker inner layer of EPDM rubber [2]. The diameters of the cables were between 11 to 16 mm. In Table 1 the cables are presented with their codes.

Table 1. The different Lipalon cables.

Code	Start condition	Denoted
FSAR-TG 3x1+S	Unexposed	Medium
FSFR 7x1	Unexposed	Large
FSSR 3x1	Unexposed	Small

3 Oven ageing

The unexposed cables were cut into 5.4 m long objects and winded onto aluminum cylinders. The diameters of the cylinders were calculated from the least bending radius (> 8 times the cable diameter) allowed for the cables. These cylinders with the winded cables were aged in ULE-600 ventilated ovens (Memmert, Germany) at a temperature of 140 °C in two different environments: air and nitrogen. To be able to verify that the LIRA method works even for long cables, which is the case in real life, two long objects 20 respectively 30 m of the small cable were aged at two different ageing times in air at 140 °C.

3.1 Air ageing

Cable objects from the three different types, small, medium and large, were aged in air directly in the ovens. Each cable type were aged at 10 different ageing times in 140 °C.

3.2 Nitrogen ageing

Cable objects from the small cable were aged in glass chambers specially made to fit the small aluminum cylinders. Chambers that were large enough to fit the aluminum cylinders with the larger cables, type medium and large, were constructed from ventilation cylinders. The samples were flushed with nitrogen for 24 hours at room temperature before oven ageing. The nitrogen flow was 20 ml/min during both the preflush and the ageing. Each cable type were aged at 10 different ageing times in 140 °C.

4 Experimental analysis

After ageing, 0.4 m long cable samples were removed from the long objects and used for the mechanical testing. The remaining 5 m objects, still winded on the aluminum cylinders, were tested at IFE for the electrical performances.

4.1 Indenter modulus measurements

The surface hardness of the jacketing and of the core insulation was monitored by micro-indentation (Ogden Indenter Polymer Aging Monitor, IND-IM-1) 22±2 °C and 40% RH. A sharp indenter was pressed against the surface at constant velocity and the force was recorded as a function of penetration depth. The slope gives the indenter modulus with the unit N mm^{-1}. Sixteen measurements were taken in a screw-like orientation along the cable samples.

4.2 Tensile testing

The jackets of the cables were punched to get dumbbell shaped specimens (length of narrow part = 16 mm; width = 4 mm according to ISO 27-3). The specimens were tested in an Instron 5566 tensile testing machine at an elongation rate of 30 mm min^{-1} and at 23 ± 2 °C and 50% RH. The strain was monitored using an Instron video extensiometer. Samples from the core insulation were tested as cylindrical specimens with the conductor removed at an elongation rate at 30 mm min^{-1}. Three specimens (both jacket and core) from each cable sample were tested.

4.3 Swelling measurements

Specimens from both jacket and core were placed in tetrahydrofuran, THF, for 48 h and then dried for 48 h. The weights of the specimens were recorded at the beginning (w_i), directly after they were removed from the solvent (w_s) and finally after being dried (w_d). The soluble percentage ($100(w_i-w_d)/w_d$) and the solvent uptake factor (w_s/w_d) were then calculated.

4.4 Infrared spectroscopy (IR)

Thin slices were cut from the cross section of both jacket and core. Reflection spectra were obtained using a Perkin-Elmer Spectrum 2000 FT-IR spectrometer (PerkinElmer Inc., USA) equipped with an attenuated total reflection (ATR) device. The spectra were taken between 4000 cm^{-1} and 600 cm^{-1} and an average of 16 scans were recorded.

5 Electrical analysis, LIRA

The Line Resonance Analysis (LIRA) method, initially developed by the Halden Reactor Project in the years 2003-2005 [5] and then further develeped by Wirescan AS, is based on transmission line theory. A transmission line is the part of an electrical circuit providing a link between a generator and a load. The behavior of a transmission line depends on its length in comparison with the wavelength λ of the electric signal traveling into it. The wavelength is defined as:

$$\lambda = {}^{v}\!/_{f} \tag{1}$$

where v is the speed of the electric signal in the wire (also called the *phase velocity*) and f the frequency of the signal.

When the transmission line length is much lower than the wavelength, as it happens when the cable is short and the signal frequency is low, the line has no influence on the circuit behavior and the circuit impedance (Z_{in}), as seen from the generator side, is equal to the load impedance at any time.

However, if the line length and/or the signal frequency are high enough, so that $L \geq \lambda$, the line characteristics take an important role and the circuit impedance seen from the generator does not match the load, except for some very particular cases.

The voltage V and the current I along the cable are governed by the following differential equations, known as the *telephonists equations*:

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V \tag{2}$$

$$\frac{d^2I}{dz^2} = (R + j\omega L)(G + j\omega C)I \tag{3}$$

where R is the conductor resistance, L is the inductance, C the capacitance and G the insulation conductivity, all relative to a unit of cable length.

These four parameters completely characterize the behavior of a cable when a high frequency signal is passing through it. In transmission line theory, the line behavior is normally studied as a function of two complex parameters. The first is the *propagation function*

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{4}$$

often written as

$$\gamma = \alpha + j\beta \tag{5}$$

where the real part α is the line *attenuation constant* and the imaginary part β is the *propagation constant*, which is also related to the phase velocity and wavelength through:

$$\beta = \frac{2\pi}{\lambda} = \frac{\omega}{v} \tag{6}$$

The second parameter is the *characteristic impedance*

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{7}$$

Using (4) and (7) and solving the differential equations (2) and (3), the line impedance for a cable at distance *d* from the end is:

$$Z_d = \frac{V(d)}{I(d)} = Z_0 \frac{1 + \Gamma_d}{1 - \Gamma_d} \tag{8}$$

Where Γ_d is the *Generalized Reflection Coefficient*

$$\Gamma_d = \Gamma_L e^{-2\gamma d} \tag{9}$$

and Γ_L is the *Load Reflection Coefficient*

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{10}$$

In (10) Z_L is the impedance of the load connected at the cable end.

From eqs, (8), (9) and (10), it is easy to see that when the load matches the characteristic impedance, $\Gamma_L = \Gamma_d = 0$ and then $Z_d = Z_0 = Z_L$ for any length and frequency. In all the other cases, the line impedance is governed by eq. (8), which has the shape of Figure 1.

LIRA includes a proprietary algorithm to evaluate an accurate line impedance spectrum from noise measurements. Figure 1 shows the estimated impedance for a PVC instrument cable 100m long, in the 0-10 MHz range.

Line impedance estimation is the basis for local and global degradation assessment. Tests performed with LIRA show that thermal degradation of the cable insulation and mechanical damage on the jacket and/or the insulation do have an impact on C and at a lesser degree on *L*. Direct measurement of *C* (and *L*) would not be effective because the required sensitivity has the same magnitude of the achievable accuracy, due to the environment noise normally present in installed cables (especially for unshielded twisted pair cables. Some results were achieved with coaxial cables [4]). LIRA monitors *C* and *L* variations through its impact on the complex line impedance, taking advantage of the strong amplification factor on some properties of the phase and amplitude of the impedance figure.

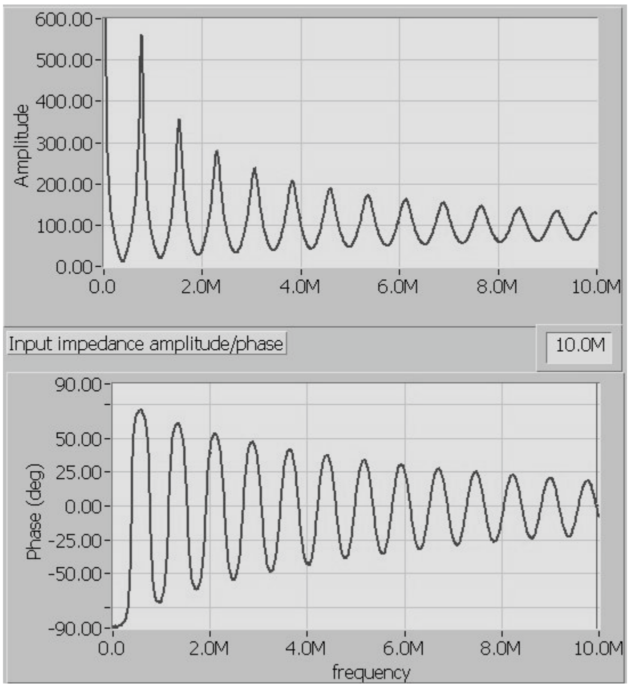

Figure 1 Impedance spectrum of an unmatched transmission line.

One of these possible monitoring techniques is the so called zero-crossing phase monitoring method [5], which can be used to monitor and assess cable global degradation. This method tries to correlate the impedance phase shift from zero (a resonance condition) to the insulation degradation. Although LIRA implements also this technique, it has the following drawbacks:

- Resonance values (and the corresponding zero-crossing conditions) not only depend on the cable electric parameters, but also on the cable length and the reactive component of the connected load. In other words, this technique needs a reference for each tested cable (not just each cable type), from which a zero-crossing deviation can be monitored. This method is effective for continuous real-time monitoring of cable state (for example in aerospace applications), but not for diagnosing degradation in old installed cables.
- It is difficult to discriminate between cable faults (degradation) and load faults (changes in load reactance).

For these reasons, LIRA implements proprietary algorithms for an accurate estimation of the local degradation severity and position (DNORM) and the global cable condition (CBAC2).

5.1 Global Condition Assessment

Several tests [1, 3, 4, 6, 7, and 8] have shown that global degradation in a cable insulation results in changes in the dielectric capacitance and cable inductance, at some degree. These changes affect the cable attenuation, which can be expressed as:

$$\alpha(dB/km) = Kf^{a}\sqrt{\frac{C}{L}} \tag{11}$$

Where *K* is constant for a particular cable type and geometry and depends on the DC resistance, *f* is the signal frequency and the exponent *a* takes into account the skin effect and ranges between 0.5 and 1. Figure 2 shows an example of LIRA calculated cable attenuation as a function of frequency.

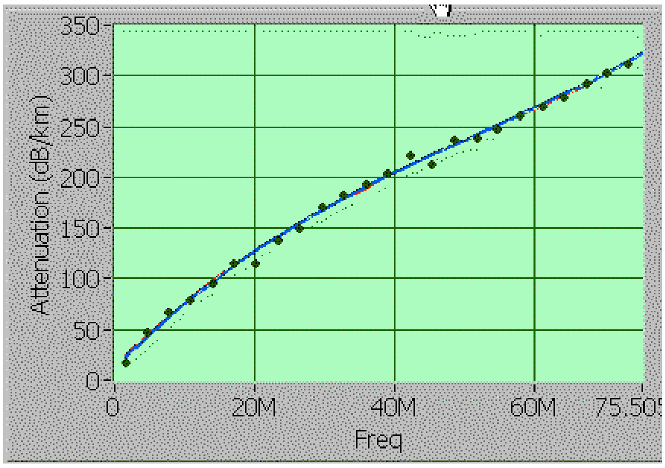

Figure 2 Cable attenuation (estimated by LIRA)

Eq. (11) shows that frequency acts as a gain factor in the relation between α and C/L and for this reason LIRA uses high frequency attenuation values as the basis for a global condition indicator. High frequency attenuation is estimated by LIRA through a proprietary method called 3rd-harmonic analysis [8].

However, the use of an attenuation figure as it is would not be enough for condition assessment, because of its dependence on the ratio *C/L*. Degradation affects *C* and *L* in a complex way and the shape of its ratio might be non monotonic through the entire cable life. For this reason, LIRA implements a method, sketched in Figure 3, where the contributions from *C* and *L* are isolated, resulting in an indicator sensitive only to *C* (CBAC2) and another indicator sensitive only to *L* (CBAL). Since it has been demonstrated that degradation affects *C* at a higher degree than *L* [7-9], CBAC2 is used as a global condition indicator. Note that no attempt is done to estimate directly *C* or *L*: CBAC2 is calculated through the estimation (using frequency analysis) of:

1. The high frequency attenuation (3rd harmonic analysis)
2. The cable characteristic impedance Z0
3. The signal phase velocity VR

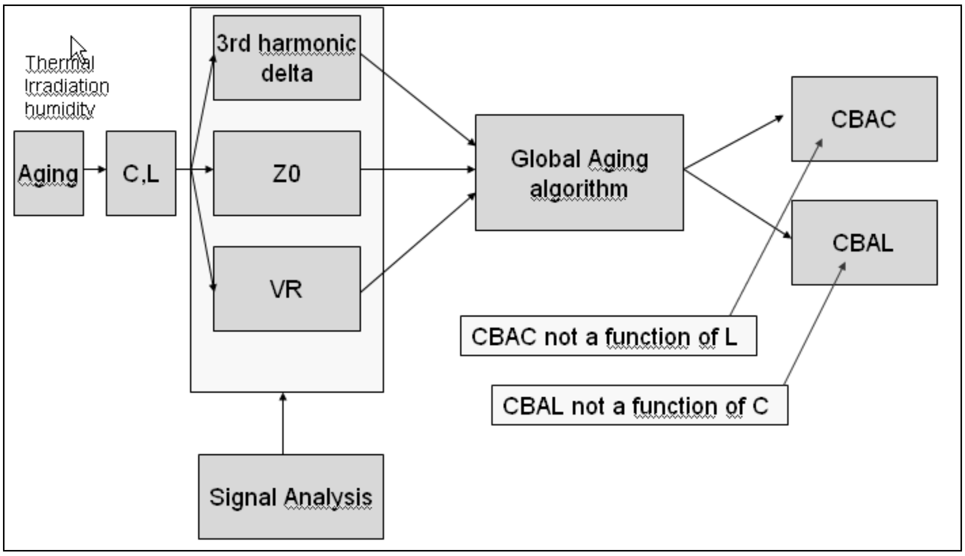

Figure 3 Global condition indicator algorithm

6 Results and discussion

The results from the mechanical and electrical testing will first be presented separately and then correlated to give a full picture of the ageing mechanisms.

6.1 Air as ageing environment – material analysis

Previous studies on Lipalon cables have shown air to be a more degrading environment than nitrogen (2).

6.1.1 Indenter modulus

Figures 4a-b displays the results from the measurements made on the small cable and Figures 5a-b and 6a-b are the results from the medium and large cable, respectively. Figures 4a, 5a and 6a are the results from the jacketing and 4b, 5b and 6b are from the core insulation. The jacketing from the small cable has an initial value of 4.5 (±0.2) N mm^{-1} and reaches a value of 16 (±1.1) N mm^{-1}after 135 h at 140°C. The core insulation from the small cable starts at 4.7 (±0.4) N mm^{-1} and increases with ageing time. After 135 h the indenter modulus reaches a mean value of 11 (±2.5) N mm^{-1}.

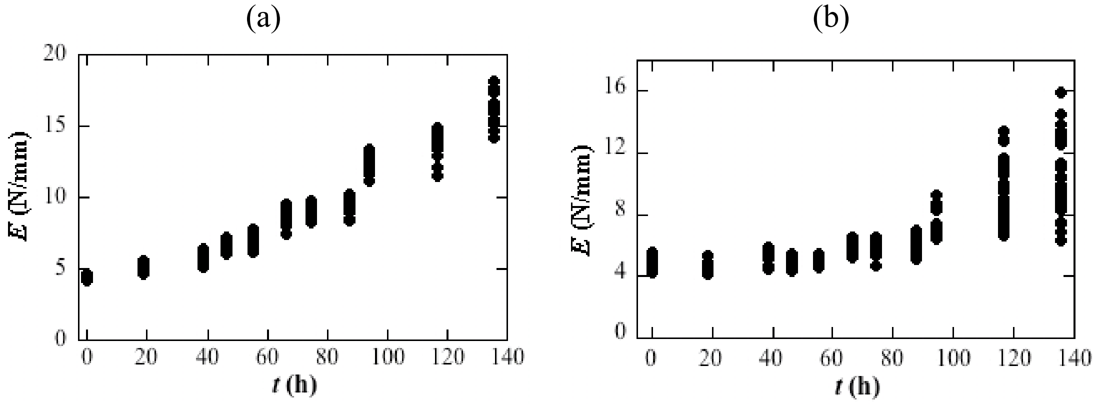

Figure 4. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the small cable aged in air.

The indenter modulus measured on jacketing from the medium cable (Figure 5a) has an initial value of 6.2 (±0.7) N mm^{-1}. The modulus increases with ageing time and after 135.5 h the value is 16 (±1.1) N mm^{-1}. The core insulation from the same cable (Figure 5b) increases from 6.3 (±0.8) N mm^{-1} to 8.5 (±0.7) N mm^{-1} after 135.5 h of ageing.

(a) (b)

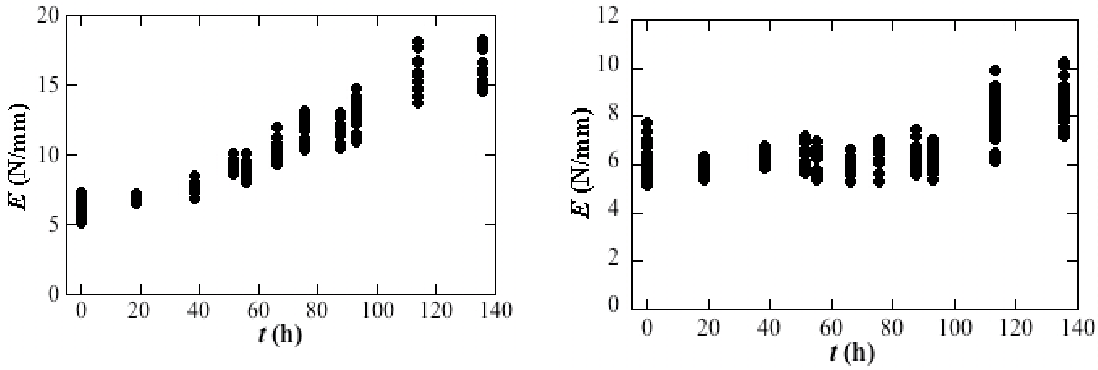

Figure 5. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the medium cable aged in air.

Figure 6a displays the results from the jacketing of the large cable with a starting value of 5.3 (±0.4) N mm^{-1}. The modulus reaches a value of 15 (±1.8) N mm^{-1} after 135.5 h in air at 140°C. The core insulation (Figure 6b) starts with a modulus of 6.2 (±0.6) N mm^{-1} and reaches a value of 9.3 (±1.1) N mm^{-1} after 135.5 h.

(a) (b)

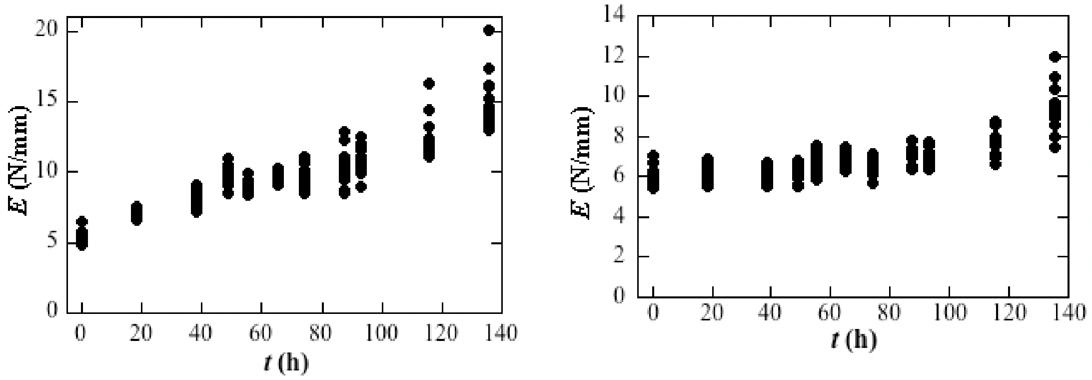

Figure 6. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the large cable aged in air.

The jacketing of all three cables increases their modulus with ageing time in the same manner, as seen in Figure 7a. The jacketing of the medium cable has slightly higher values for all the ageing times including the starting value. The initial indenter modulus for the core insulation from all the cables is spreading more in the data compared to the aged samples. This gives a small decrease of the modulus in the beginning of the curves. This is more pronounced for the medium cable but can also be seen for the small and large cable. After approximately 40 h for the small cable and 50 to 60 h for the medium and large cable the modulus reaches a small peak and then slightly decreases again until 90 h of ageing. At this point the values steadily increases with ageing time for all the three cables. After 90 h the spreading of the data increases a lot for the small cable compared to the others. The modulus also reaches higher values. This is probably due to the fact that the geometry of the small cable differs from the two others. The small cable does not have the shielding and the rubber material separating the jacketing from the core insulation as the medium and large cable have. This makes the core insulation for the small cable less protected. The curve shapes differ a lot between the jacketing and the core insulation as seen in Figures 7a and 7b. The reason is that the material of the two insulations differs. The jacketing is based on Hypalon and the core insulation has a thin outer layer of Hypalon and a thicker inner layer of EPDM rubber.

(a) (b)

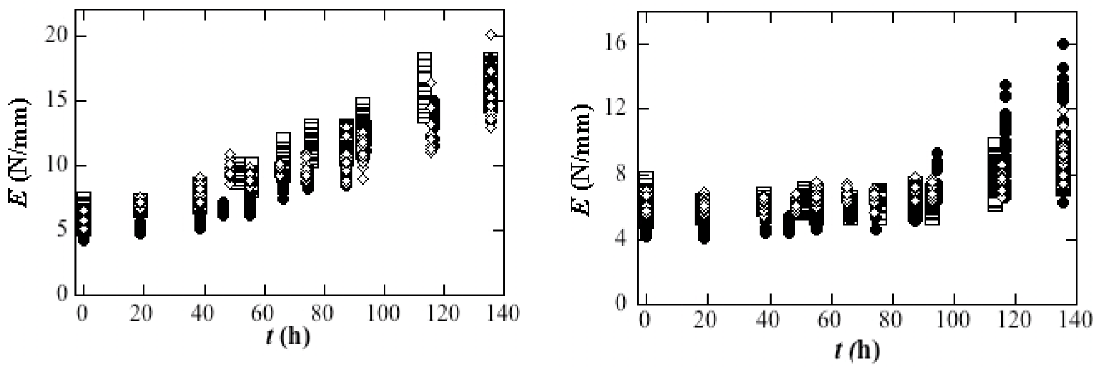

Figure 7. The indenter modulus as a function of ageing time for the jacketing (a) and core insulation (b) for small cable (●), medium cable (□) and large cable (◇).

6.1.2 Tensile testing

The tensile strain and stress for the small, medium and large cable aged in air are displayed in Figure 8-10. The strain for the jacketing taken from the small cable (Figure 5a) has an initial value of 427 %, which increases for the first 20 h. The value then decreases to 79 % after 135.5 h of ageing. The tensile stress (Figure 8b) follows the same pattern starting with a value of 9.8 MPa and a small initial increase, followed by a decrease ending up with a mean value of 6.8 MPa after 135.5h.

(a) (b)

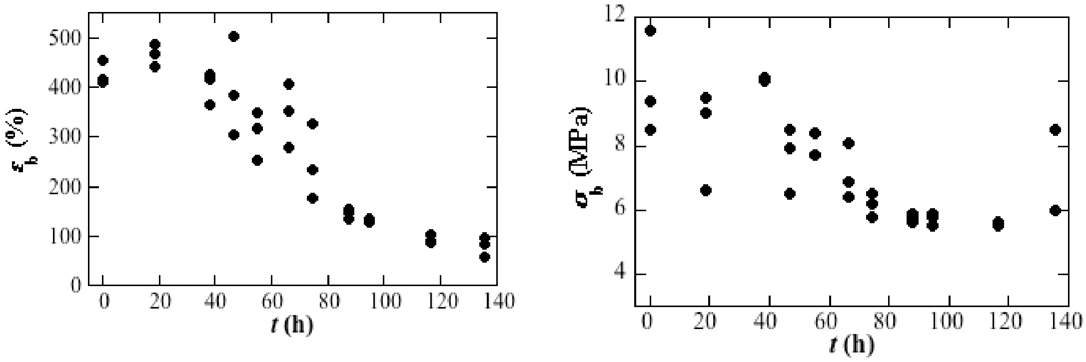

Figure 8. Tensile strain (a) and tensile stress (b) as functions of ageing times for jacketing from small cable aged in air.

The result from the tensile testing on the core insulation (Figure 9a) gives a starting value of 709 % for the strain. The strain then decreases before it almost flattens out after 100 h and reaches a value of 134 % after 135.5 h. The stress (Figur 9b) has a starting value of 6.7 MPa and a final value of 2.6 MPa.

(a) (b)

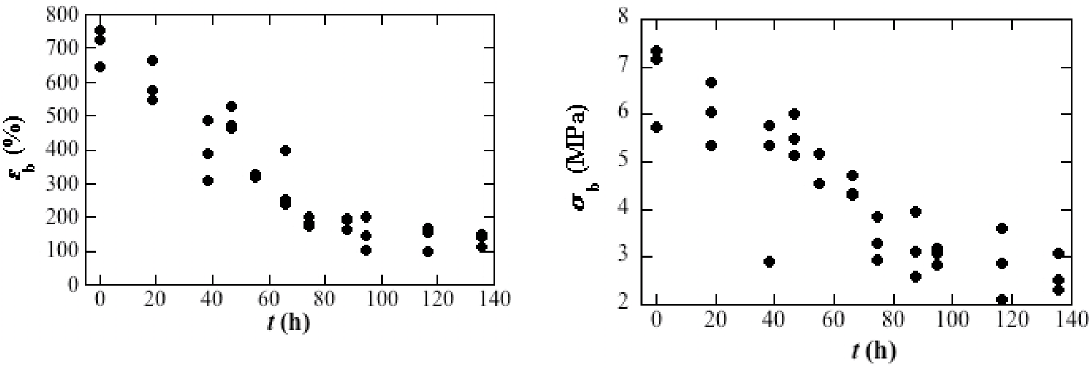

Figure 9. Tensile strain (a) and tensile stress (b) as functions of ageing times for core insulation from small cable aged in air.

The results from the medium cable can be viewed in Figure 10 and 11. The strain for the jacketing has a lower starting value, 172 %, compared to the initial value measured on the jacketing from the small cable, 427 %. Nevertheless, the curve shapes of the strain as a function of ageing time are almost the same: an initial increase with a following decrease reaching a value of 98 % after 135.5 h. The values of the tensile stress (Figure 10b) start at 5.3 MPa and follows by a sharp increase with ageing time. The decrease is not so pronounced as for the small cable so the final value is 5.9 MPa, which is even higher than the starting value.

(a) (b)

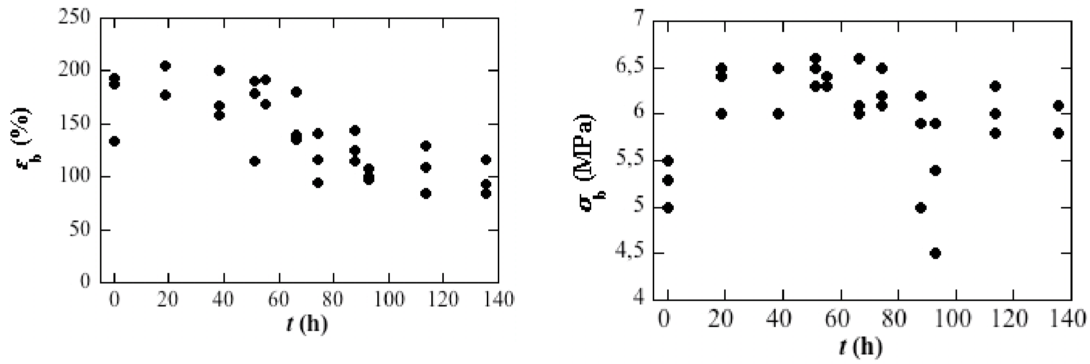

Figure 10. Tensile strain (a) and tensile stress (b) as functions of ageing times for jacketing from medium cable aged in air.

The strain for the core insulation (Figure 11) starts at 540 % and has a small initial increase with ageing time. The values are almost constant until 110 h where the strain starts to decrease. After 135.5 h the value is 249 %. The stress (Figure 11b) has the same type of plateau with a starting value of 9.8 MPa. The decrease starts at around 110 h and has a final value of 5.9 MPa.

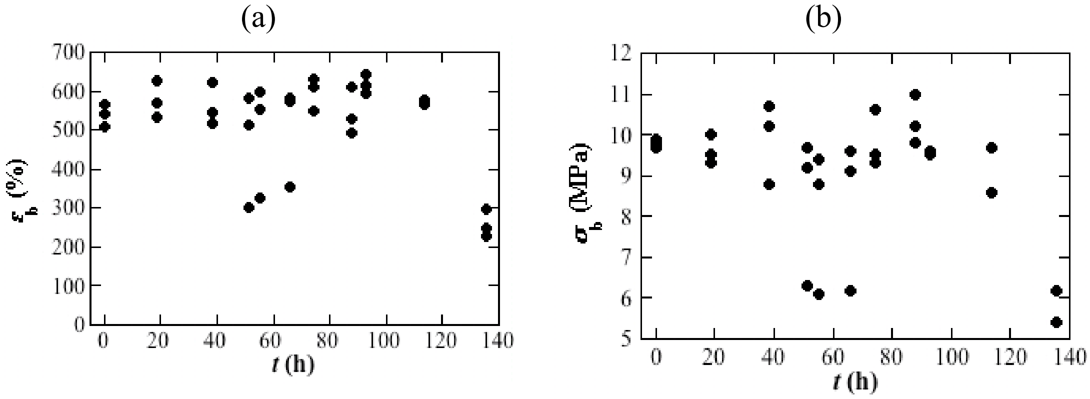

Figure 11. Tensile strain (a) and tensile stress (b) as functions of ageing times for core insulation from medium cable aged in air.

The jacketing from the large cable has an initial strain value of 93 %, the lowest initial value of all the three cables, Figure 12a. The small initial increase with ageing time seen for the two others can also be seen for the large cable. This increase is followed by a decrease and the value after 135.5 h is 73 %. The strain for the jacketing has an initial value of 6.5 MPa and an end value of 5 MPa after 135.5 h.

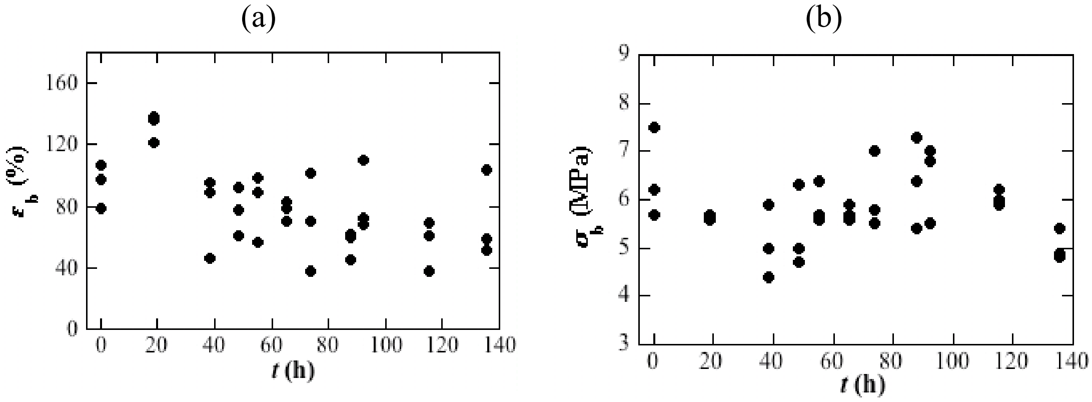

Figure 12. Tensile strain (a) and tensile stress (b) as functions of ageing time for jacketing from large cable aged in air.

The strain measured on the core insulation, Figure 13a, has a starting value of 513 %. The shape of the curve, tensile strain as a function of ageing time, shows a peak between 50 and 60 h and then a decrease down to a value of 154% after 135.5 h. The stress as a function of ageing time shows the same tendencies as the strain: a pronounced peak after 50 to 60 h of ageing. The initial value is 7.9 MPa and the value after 135.5 h of aging is 4.4 MPa.

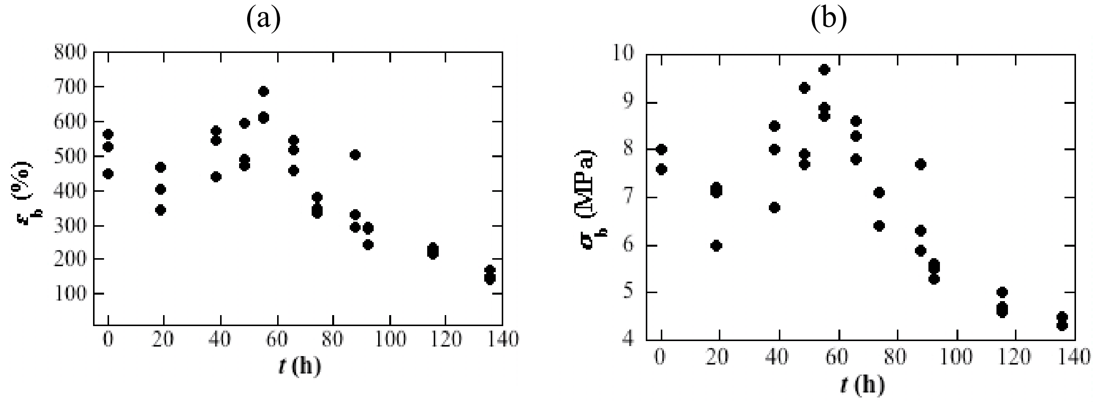

Figure 13. Tensile strain (a) and tensile stress (b) as functions of ageing times for core insulation from large cable aged in air.

6.1.3 Swelling measurements

Swelling measurements were performed on samples from reference cable and from samples aged in air at a temperature of 140°C for 66 and 136 h. Figure 14 a and b displays the soluble percentage and solvent uptake factor, respectively, for a reference specimen and specimens aged in air as functions of ageing time. The soluble percentage (Fig.14 a) indicates the different materials, Hypalon for the jacketing and Hypalon/EPDM for the core insulation. The jacketing continuous to crosslink or gets a tighter network, which results in a decrease in the solubility. The core insulation, on the other hand gets an increases in the solubility with ageing time. The ability to take up solvent, SUF, seems to be relatively stable (Fig.14 b). This concludes that the probable cause for the decrease in solubility of the jacketing is a result of a tighter network rather than a higher degree of crosslinking.

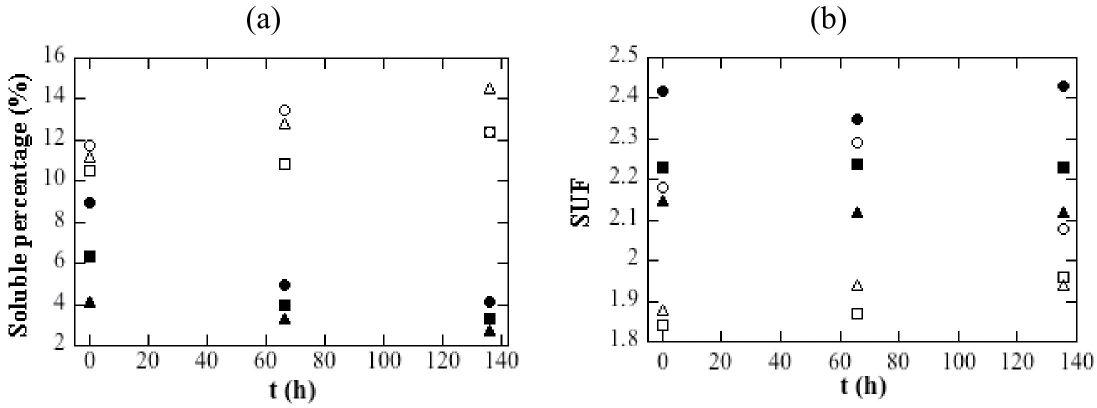

Figure 14. Soluble percentage (a) and solvent uptake factor (SUF) in (b) as functions of ageing time for small jacketing (●) and core insulation (○), medium jacketing (■) and core insulation (□) and large jacketing (▲) and core insulation (△)

6.1.4 Correlation between results from indentation and tensile testing

To see the correlation between the results from the mechanical testing, the indenter modulus as a function of tensile strain for the three types of core insulation aged in air is plotted in Figure 15. All of the three correlations follow the same curve type: when the tensile strain increases the value of the indenter modulus decreases.

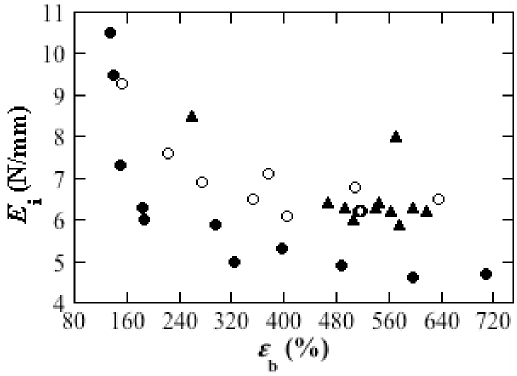

Figure 15. Indenter modulus, E_i, as a function of tensile strain, e_b, for the core insulation of the small (●), *medium* (▲) *and large* (○) *cables.*

6.2 Air as ageing environment – electrical analysis

The cable samples were tested with LIRA at the IFE Laboratory in Halden, in the period May-August 2009. The short length of the samples (all about 5m long), resulted in an additional challenge for LIRA, because the sensitivity to electrical parasitic effects and to the real cable length was significantly increased.

The sample were connected to LIRA at one side, leaving the far end open. The next sections report the findings and results, in terms of the LIRA global ageing indicator CBAC2, for the three cable types (Small, Medium and Large), both in air and nitrogen environment,

6.2.1 Small Type

The small type is a 3 conductors cable, measured with LIRA in the 3 possible pair combinations.

Table 2 shows the main electrical parameters, as estimated by LIRA on the reference (unaged) sample.

Table 2 Reference Electrical Parameters at 15 MHz – Small Type

Char Imp (Ω)	93
Phase Velocity Ratio	0.5472
Inductance (µH/m)	0.56
Capacitance (pF/m)	64.8
CBAC2	1204

Above about 1 MHz, these parameters are almost constant with frequency, as shown in Figure 16 and Figure 17. The cable attenuation increases with about the square root of the applied frequency, as shown in Figure 18.

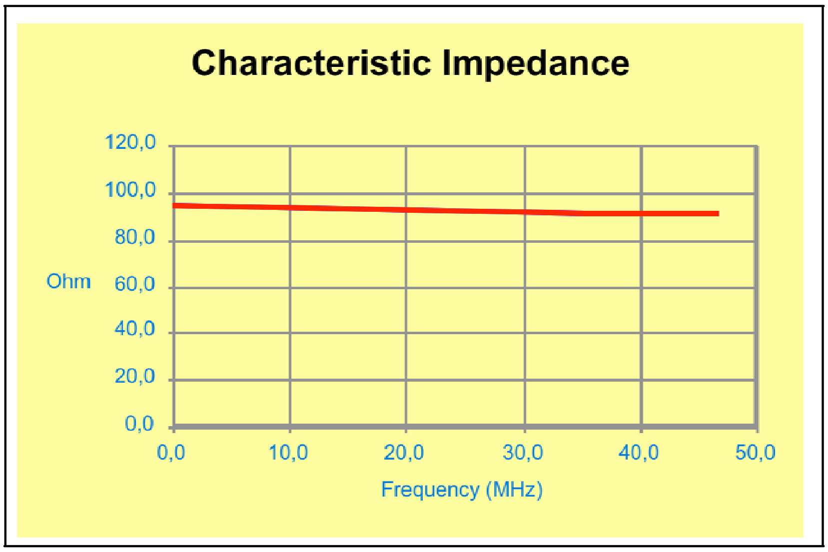

Figure 16 Char. Imp spectrum, small type

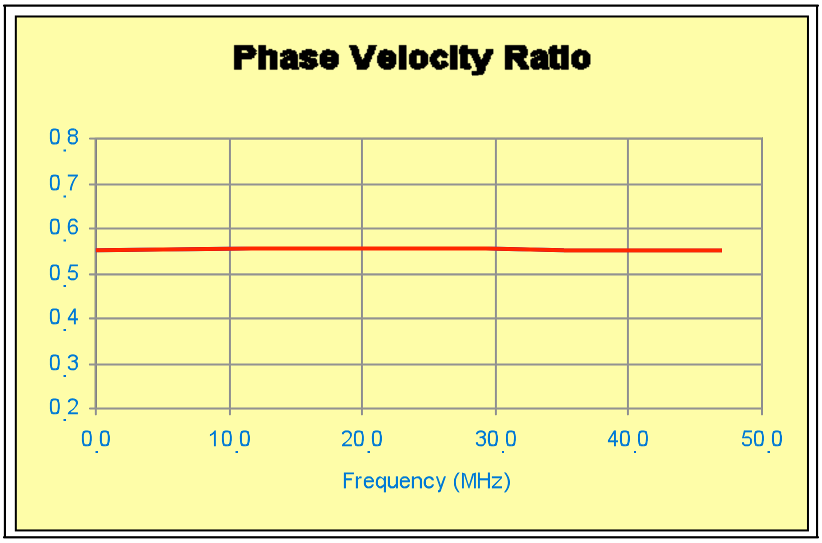

Figure 17 Phase Velocity spectrum, small type

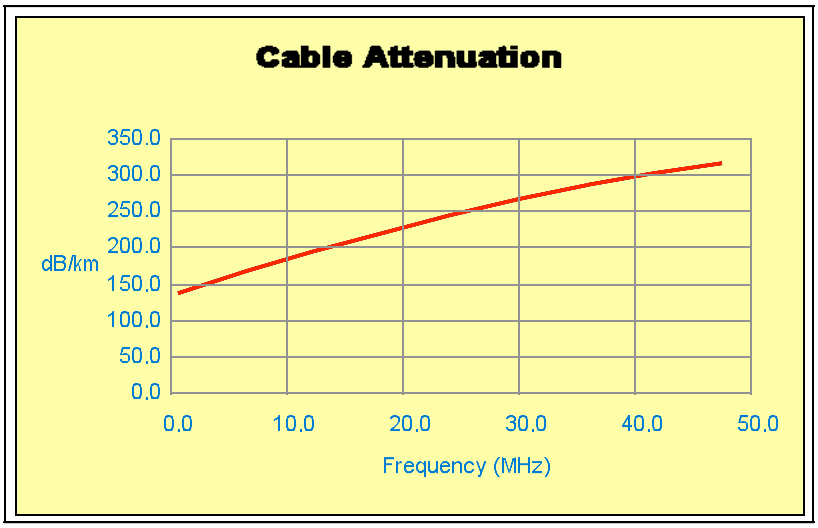

Figure 18 Attenuation spectrum, small type

Three measurements for each ageing condition have been performed, to estimate the LIRA CBAC2 global ageing indicator. Each measurement was performed using different wire pairs. The results are shown in Figure 19. Note that the scattering among the 3 measurements at each time point are not a consequence of noise or measurement errors, but a real difference in electrical parameters in different wires.

CBAC2 is expressed as a percentile of the average initial value, which is 1204 for the small type (see Table 2) and it decreases as the ageing time increases.

The yellow stars in Figure 19 displays the results from the two long cables, 20 m and 30 m. This verifies that the cable length is not a sensitive parameter for the CBAC2 estimation, which means that CBAC2 is not a function of cable length.

It is interesting to see that the cable condition improves initially, with the indicator topping at about 110% after the first 10-15 hours heating time (at 140 C). This behavior is also visible in the EAB measurement on the jacket, but not on the insulation. This effect has been reported in previous experiments on Hypalon insulated cables and in this case it could be a combined effect of the thin Hypalon layer on top of the EPDM insulation.

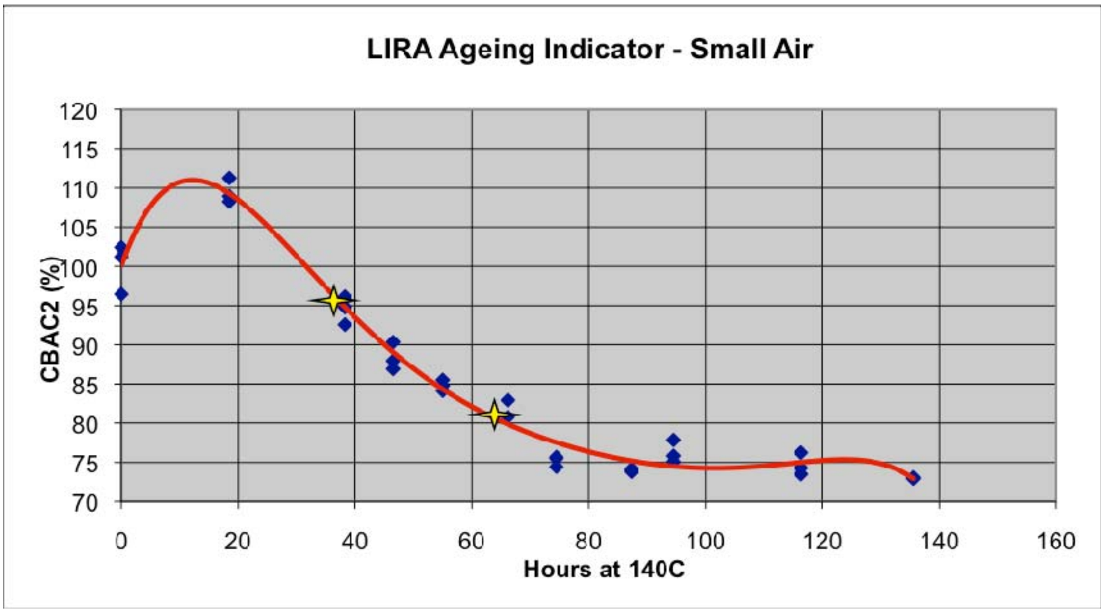

Figure 19 CBAC2 vs. ageing time, small type, air

6.2.2 Medium Type

The reference electrical parameters, estimated by LIRA, for the medium type are shown in Table 3.

Table 3 Reference Electrical Parameters at 15 MHz – Medium Type

Char Imp (Ω)	83
Phase Velocity Ratio	0.5220
Inductance (μH/m	0.52
Capacitance (pF/m)	77
CBAC2	1037

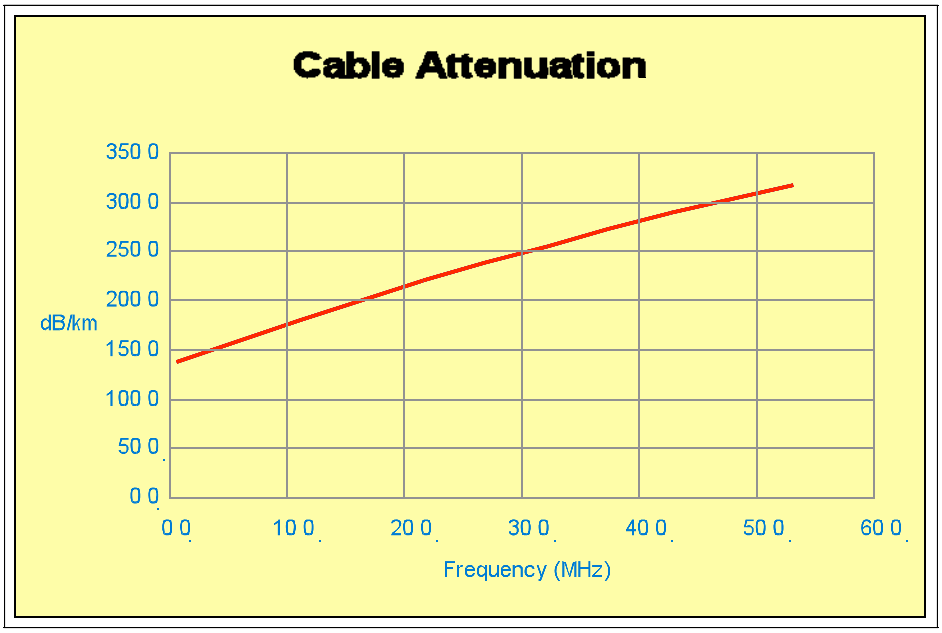

Figure 19b Attenuation spectrum, medium type

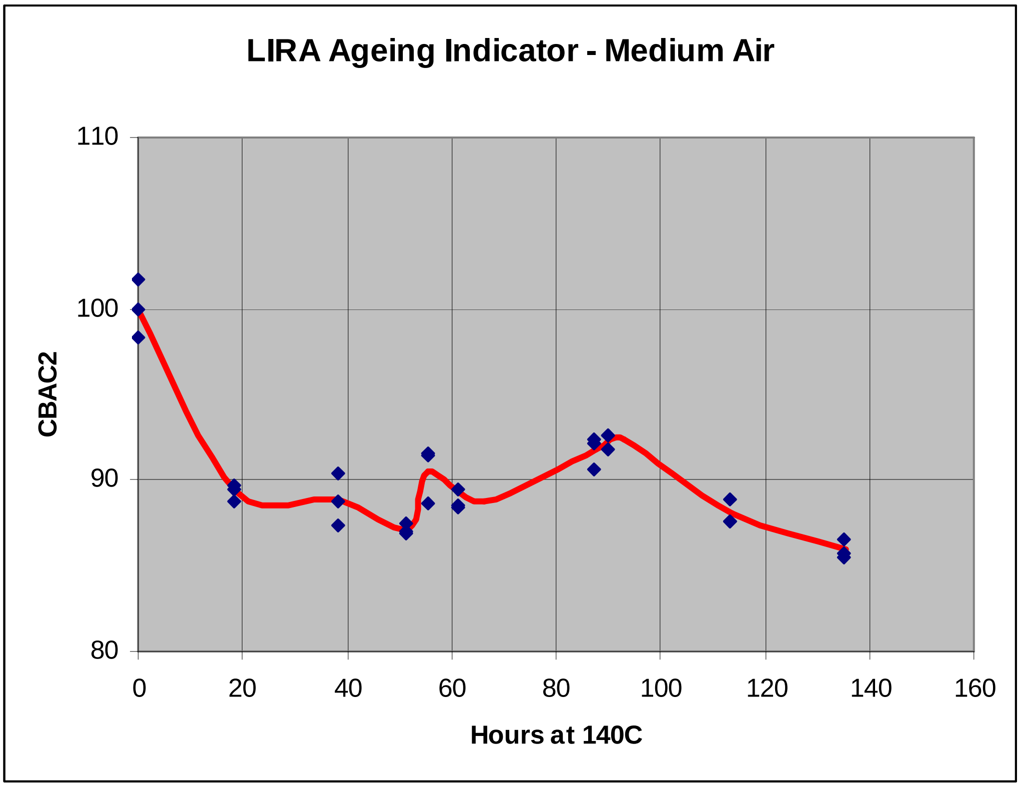

Figure 20 CBAC2 vs. ageing time, medium type, air

The CBAC2 estimation as a function of ageing time is displayed in Figure 20, where a flat region between 20 and 110 hours is visible, as for the EAB and Indenter measurements for the insulation. In LIRA there is an initial 10% drop of the ageing indicator, not reported with the EAB and Indenter measurements, and a final drop at very high ageing values (about 60 years of natural ageing time).

It seems that the medium type insulation has very little sensitivity to thermal ageing in air, both mechanically and electrical. The Hypalon sensitivity (the jacket) shows higher correlation to ageing, as it results from the jacketing EAB and Indenter measurements (the jacket condition has very little influence on the LIRA measurements). Jacket measurements can be used as a leading indicator of ageing degradation, although a real degradation assessment should reflect the insulation condition.

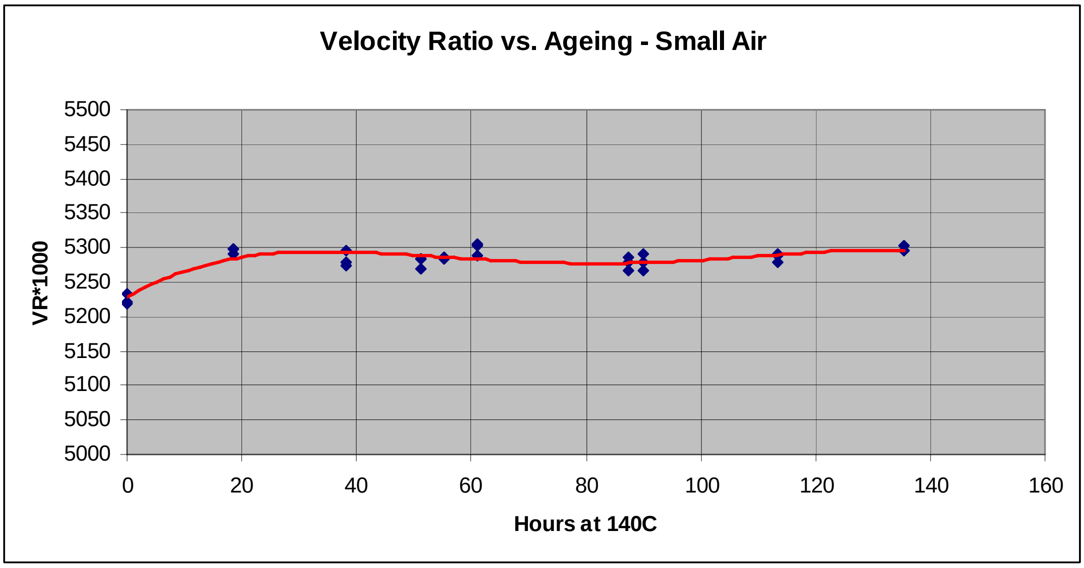

Figure 21 Velocity Ratio as a function of ageing time, medium air

Figure 21 shows the sensitivity of the estimated VR to ageing, for the medium type. The fact that it is almost constant with ageing, at an average value of 0.5275, is very important, because the VR value is a critical parameter for LIRA in those cases where the cable length is not accurately known (cable length can be estimated from the known value of VR).

6.2.3 Large Type

The large type reference electrical parameters are shown in Table 4.

Note the larger capacitance value and the low inductance and characteristic values, compared with the two other cable types. This is a consequence of the particular setup for this measurement, where LIRA was connected to the central wire and the return line were the surrounding wires in parallel.

Table 4 Reference Electrical Parameters at 15 MHz – Large Type

Char Imp (Ω)	49
Phase Velocity Ratio	0.5431
Inductance (μH/m	0.27
Capacitance (pF/m)	113
CBAC2	795

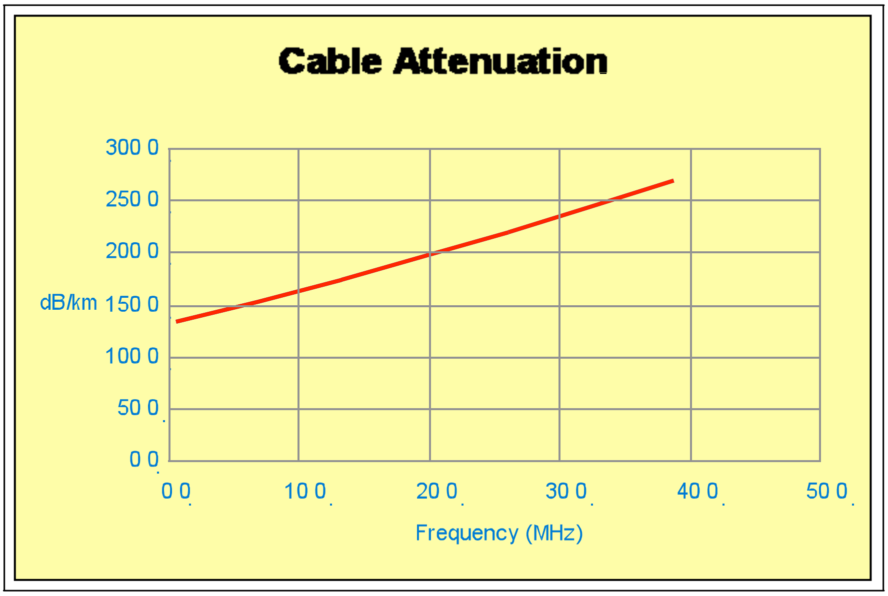

Figure 22 Attenuation spectrum, large type

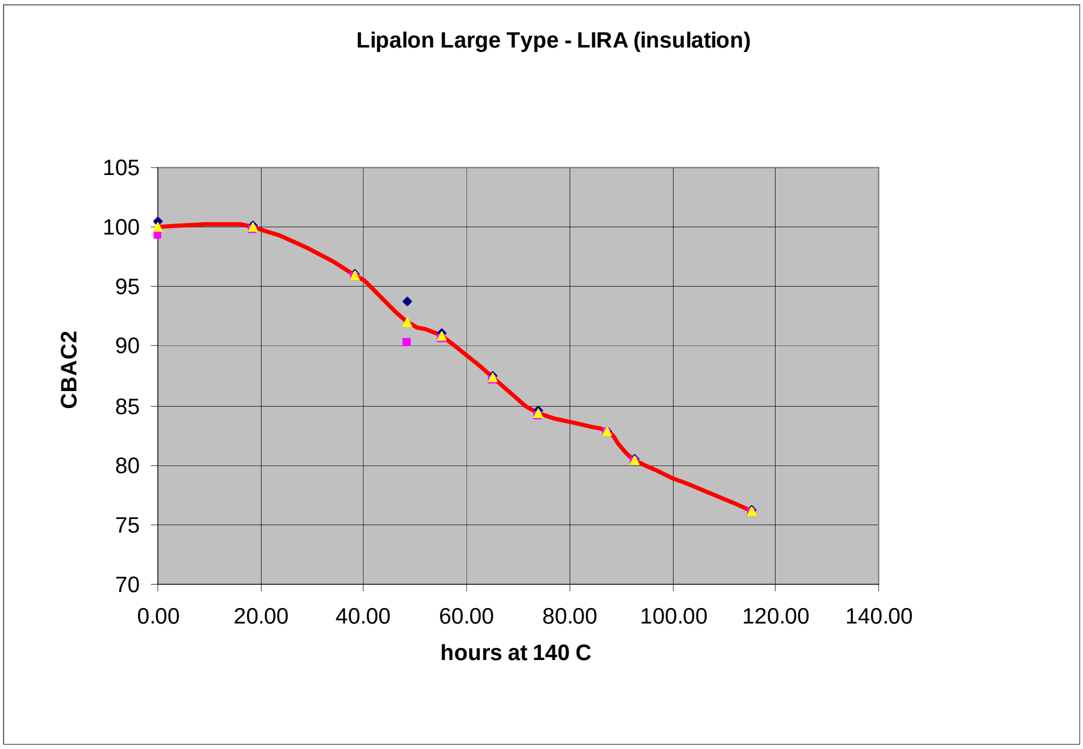

Figure 23 CBAC2 vs. ageing time, large type, air

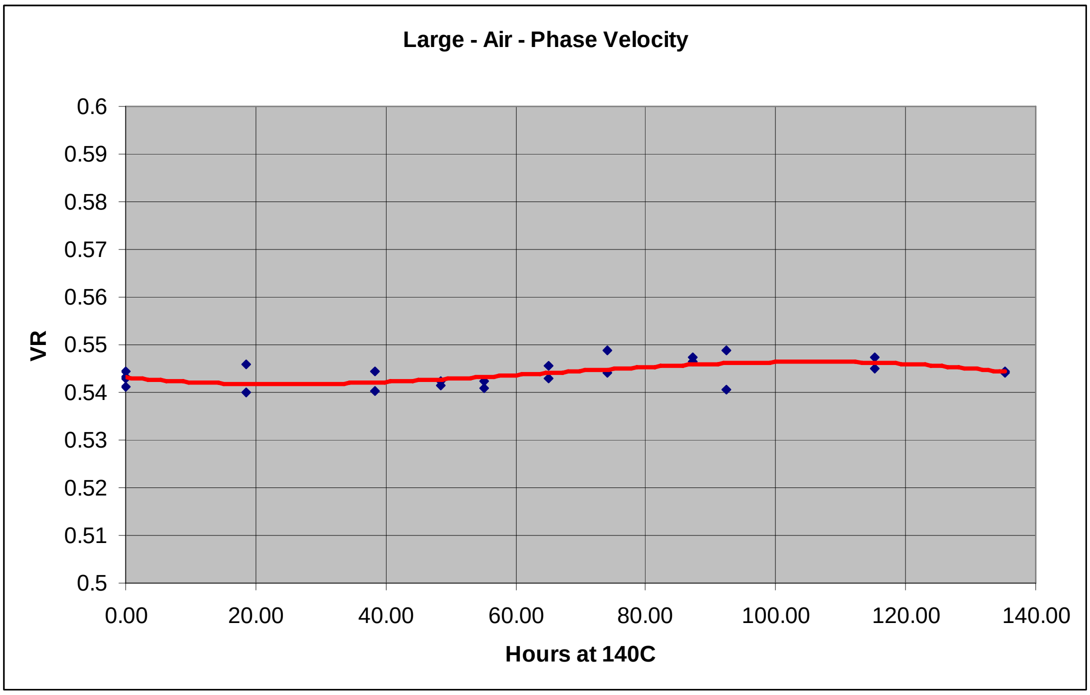

Figure 24 Velocity Ratio as a function of ageing time, medium air

Figure 23 shows the result of the CBAC2 estimation as a function of ageing time, where a nice linear trend, after the first 20 hours, is visible.

Also in this case the VR parameter is quite insensitive to ageing, Figure 24.

6.3 Nitrogen as ageing environment – material analysis

6.3.1 Indenter modulus

The indenter modulus for the small, medium and large cables aged in nitrogen at 140° are displayed in Figure 25-27. The modulus for the small jacketing starts at a mean value of 4.5 (±0.2) N/mm and increases with ageing time to a value of 16 (±1.2) N/mm after 503 h (Fig. 25a). The core insulation has an initial value of 4.7 (±0.4) and an end value of 11 (±1.0) after 503 h (Fig. 25b).

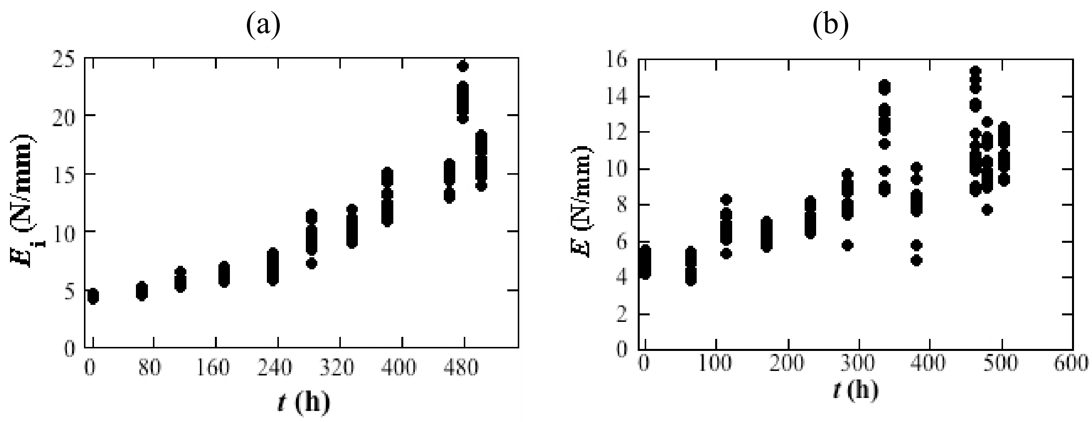

Figure 25. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the small cable aged in nitrogen at 140°C.

The medium cable has a starting value of 6.2 (±0.73) N/mm and ending at 25 (±2.0) for the jacketing. The indenter values taken after 380 h of ageing are very high as seen in Figure 26a. This is probably due to unwanted oxygen that entered the chamber. The amount of unwanted oxygen seem to be relatively low and consumed in the jacketing since it does not seem to reach the core insulation (Fig. 26b). The core insulation has an initial value of 6.3 (±0.8) N/mm and after 567 h the value has reached 11 (±1.7) N/mm. The quantity of the medium cable available at Ringhals were less than the other two, so therefore the data points are a few less for the nitrogen ageing.

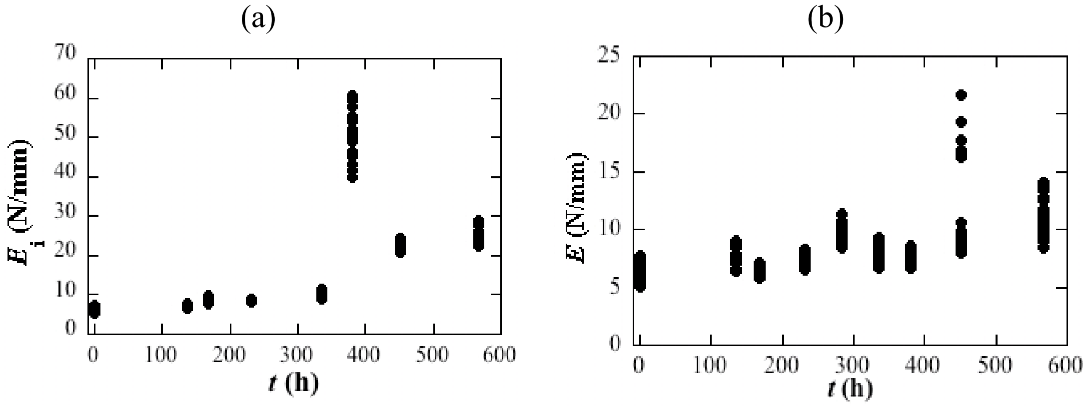

Figure 26. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the medium cable aged in nitrogen at 140°C.

The jacketing of the large cable starts with an initial value of 5.3 (±0.4) N/mm and reaches 15 (±0.8) N/mm after 456 h of ageing (Fig. 27a). The core insulation starts at 6.2 (±0.6) N/mm and reaches a value of 10.3 (±1.6) N/mm after 456 h in 140°C (Fig 27b).

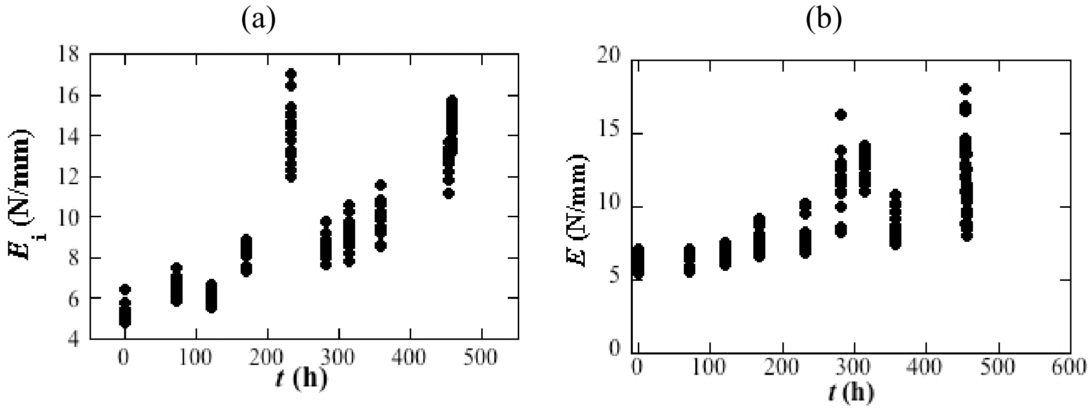

Figure 27. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the large cable aged in nitrogen at 140°C.

The indenter modulus data for the jacketing and the core insulation follow the same trends for the three different cables as seen in Figure 28. The spreading of the data points is more pronounced for the core insulation compared to the jacketing.

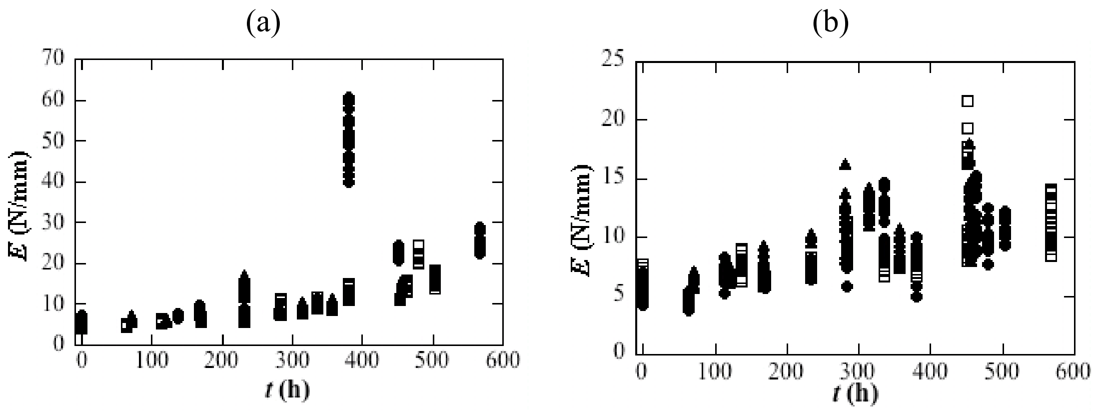

Figure 28. The indenter modulus as a function of ageing time for the jacketing (a) and the core insulation (b) for the small, medium and large cable aged in nitrogen at 140°C.

6.3.2 Extrapolation of data

In Figure 29 the indenter modulus data taken at 140°C in air and nitrogen are extrapolated to service temperatures at 50°C according to Arrhenius equation. The activation energies used are taken from Sandelin and Geddes previous study on the long-term performance of Hypalon and Lipalon cables [2]. As seen, air is a much more degrading environment compared to nitrogen for the surface of the cables.

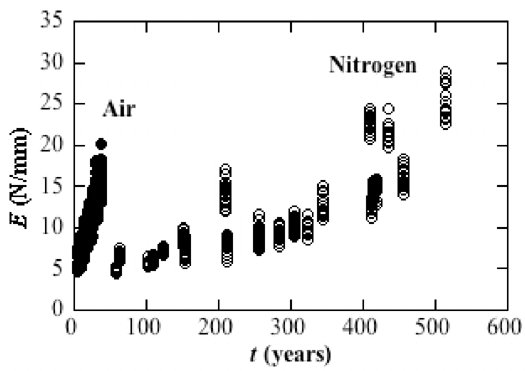

Figure 29. The data taken at 140°C are extrapolated to service temperatures at 50°C for all the three different cable samples aged in air and nitrogen.

6.3.3 Tensile testing

The tensile strain and stress for the core insulation of the three cables are displayed in Figure 30a-b. The data is very consistent and the decrease in both stress and strain follows the same trend for all the cables accept for the initial part of the large cable. The data implies an improvement of the material the first 70 hours. The starting values of the strain, 709 %, 540% and 525%, for the small, medium and large cable decreased to 116%, 113% and 87%.

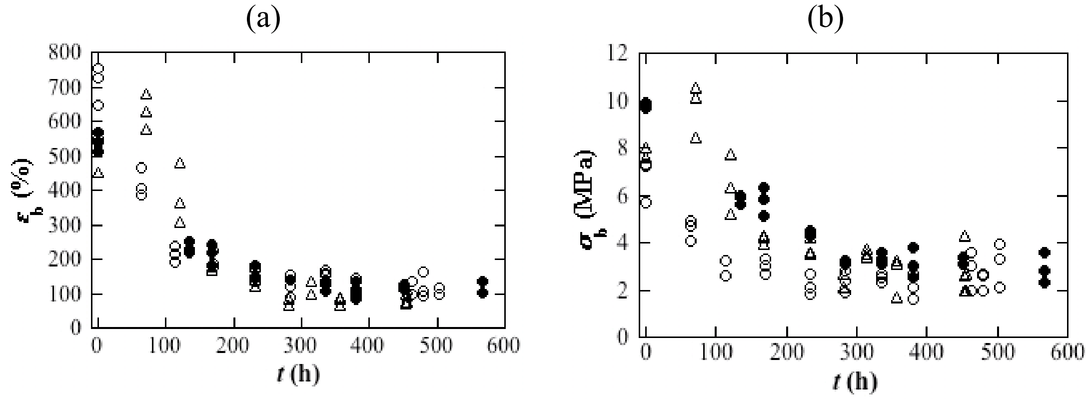

Figure 30. The tensile strain (a) and stress (b) as functions of ageing time for the jacketing the core insulation for the small (○), *medium* (●) *and large* (△) *cable aged in nitrogen at 140°C.*

6.3.4 Correlation between results from indentation and tensile testing

The correlation between the indenter modulus and the tensile strain at break are shown in Figure 31. The spread in data is a little less pronounced for this correlation when the samples are aged in nitrogen compared to air.

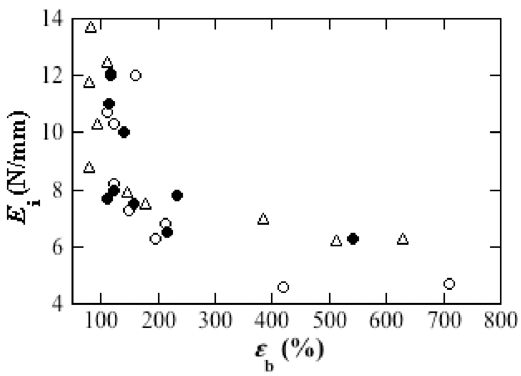

Figure 31. Indenter modulus, E_i, as a function of tensile strain, e_b, for the core insulation of the small (●), *medium* (▲) *and large* (○) *cables aged in nitrogen.*

In Figure 32 the correlation between indenter modulus and tensile strain at break for both air and nitrogen are plotted in the same graph. As seen in the figure, the ageing environment seems to affect the different properties.

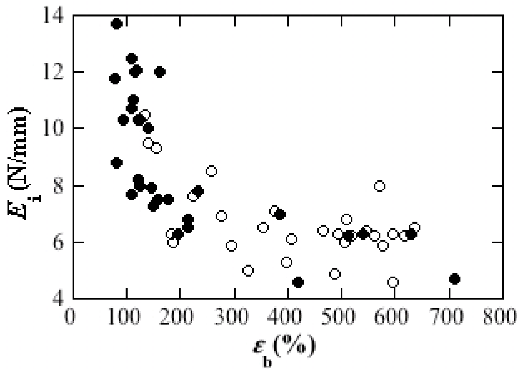

Figure 32. Indenter modulus, E_i, as a function of tensile strain, e_b, for the core insulation of all the cable samples aged in air (○) *and in nitrogen* (●).

6.4 Nitrogen as ageing environment – electrical analysis

Samples of the same type and length were tested after accelerated ageing in nitrogen environment, a typical condition existing in BWR containment.

The results of the LIRA measurements for the three cable types are shown in Figure 33, Figure 34 and Figure 35.

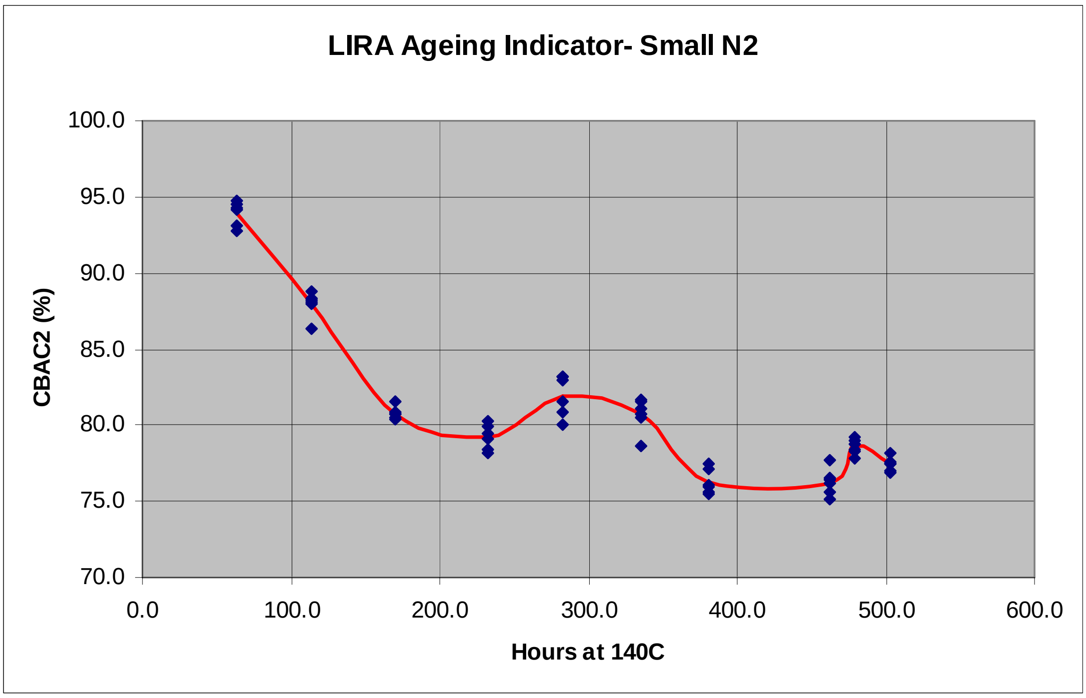

Figure 33 CBAC2 vs. ageing time, small type, N2

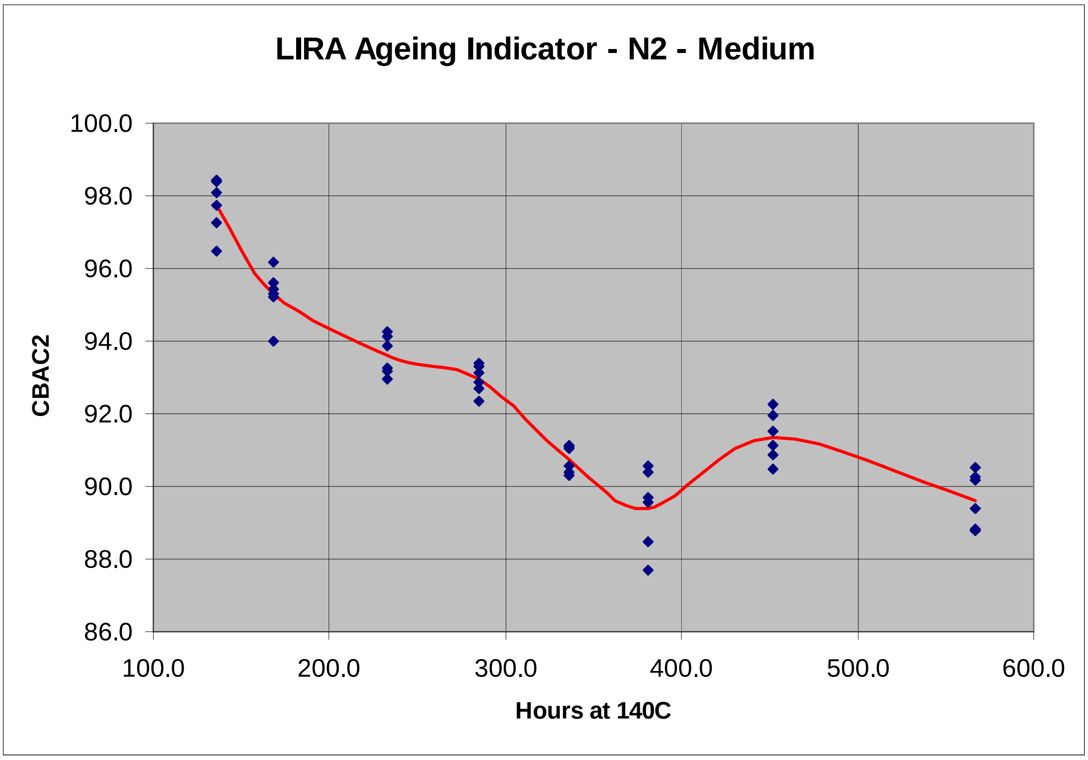

Figure 34 CBAC2 vs. ageing time, medium type, N2

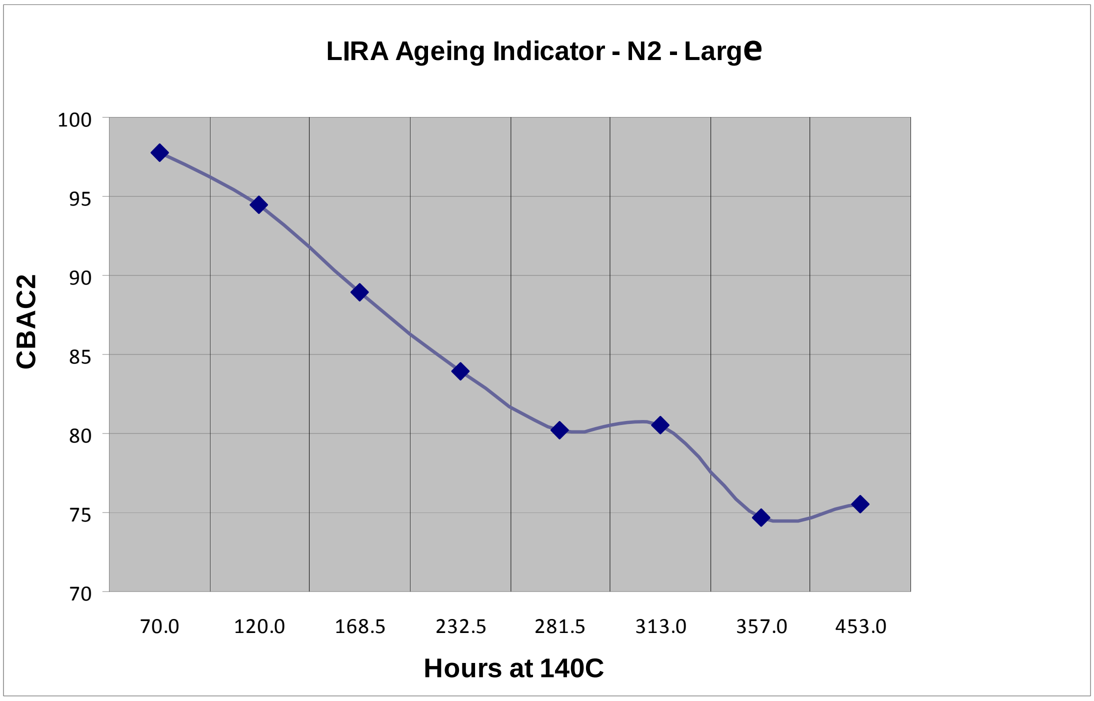

Figure 35 CBAC2 vs. ageing time, large type, N2

All the 3 three types tend to flatten out at very high ageing condition, same effect as for the mechanical tests. The small pull up at around 300 hours in the small type, 450 hours in the middle type and 310 hours in the large, has a similar behaviour in the EAB test and the reason could be air intrusion in the oven during the heating process.

6.5 Infrared spectroscopy

Figure 36 displays the results from the infrared spectroscopy of the small cable taken on samples aged in both air and nitrogen.

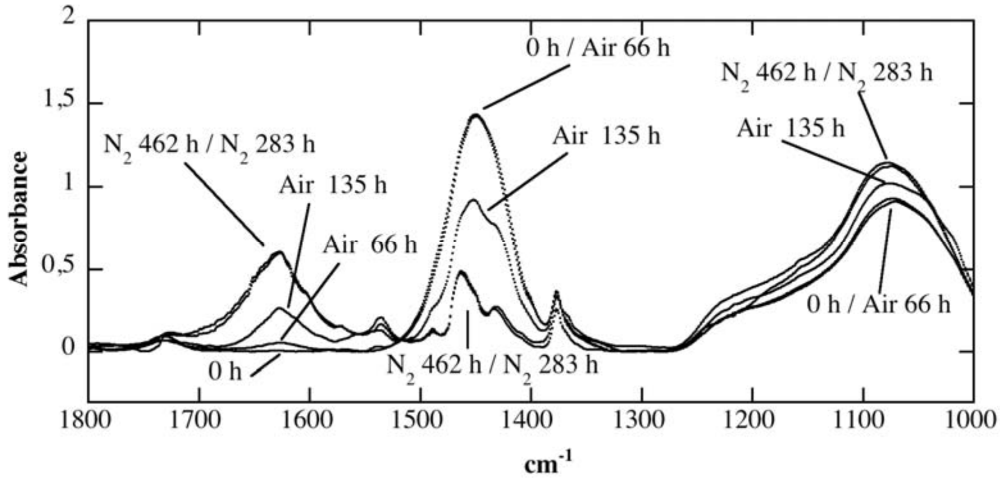

Figure 36. Spectra taken on samples aged in both air and nitrogen for the small cable.

Figure 37 displays the results from the infrared spectroscopy of the medium cable taken on samples aged in both air and nitrogen.

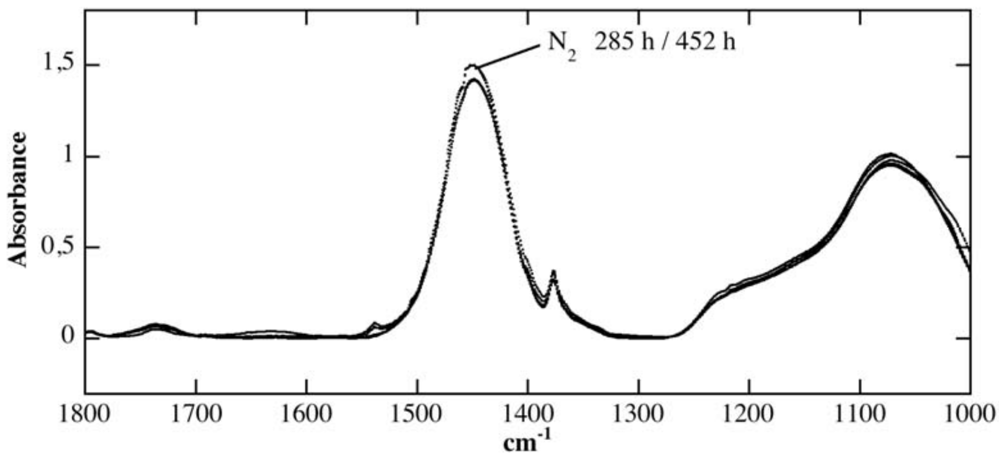

Figure 37. Spectra taken on samples aged in both air and nitrogen for the medium cable.

Figure 38 displays the results from the infrared spectroscopy of the large cable taken on samples aged in both air and nitrogen.

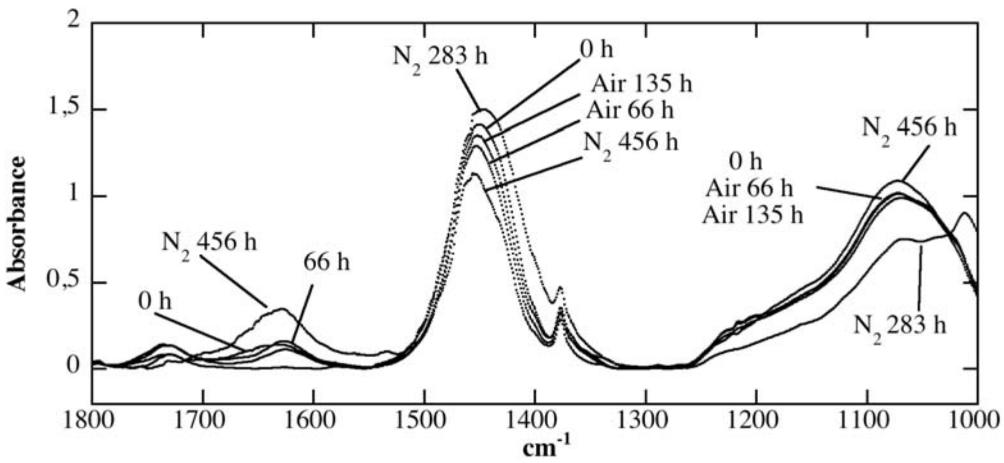

Figure 38. Spectra taken on samples aged in both air and nitrogen for the medium cable.

6.6 Correlation between electrical and mechanical data

The figures in this section show how the LIRA indicator CBAC2 correlates with the EAB and the indenter indicators.

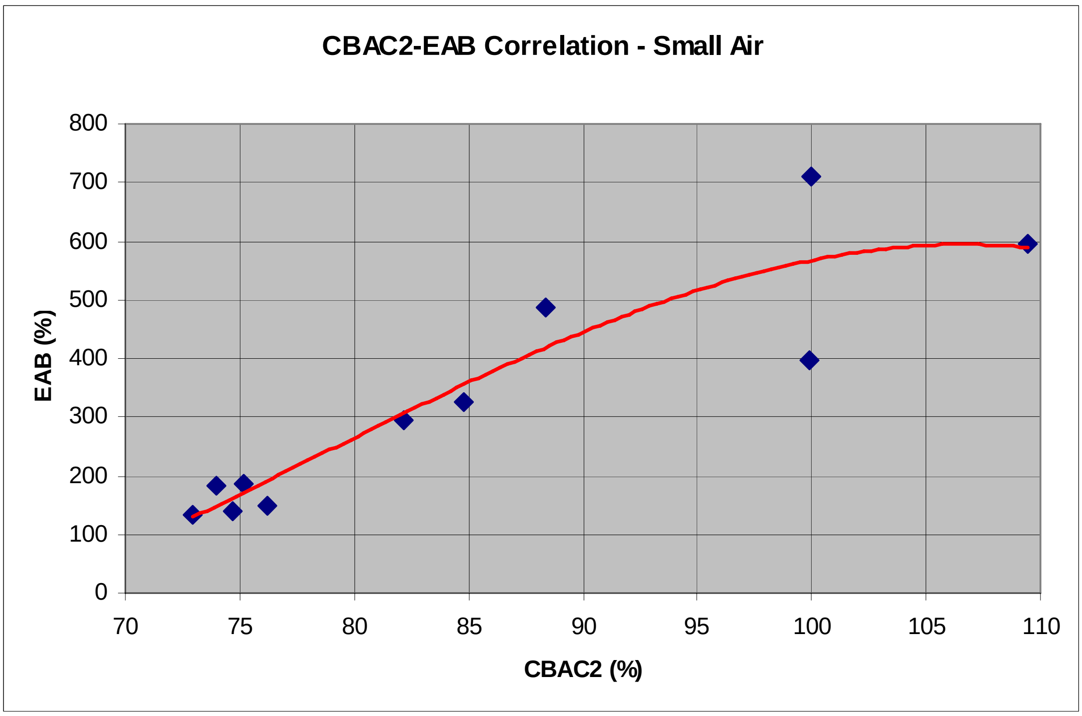

Figure 39 CBAC2/EAB correlation for the small type, air environment

For the small type in air environment **(**Figure 39 and Figure 40), CBAC2 correlates well with EAB, especially at high ageing times. The large deviation on the right part of the graph (low ageing time) is due to the improvement effect of CBAC2 that was not found with the EAB test (this could be a difference between electrical and mechanical behaviour at low ageing conditions).

The indenter correlates reasonably well, although the indenter appears quite flat at low ageing conditions (high CBAC2 values).

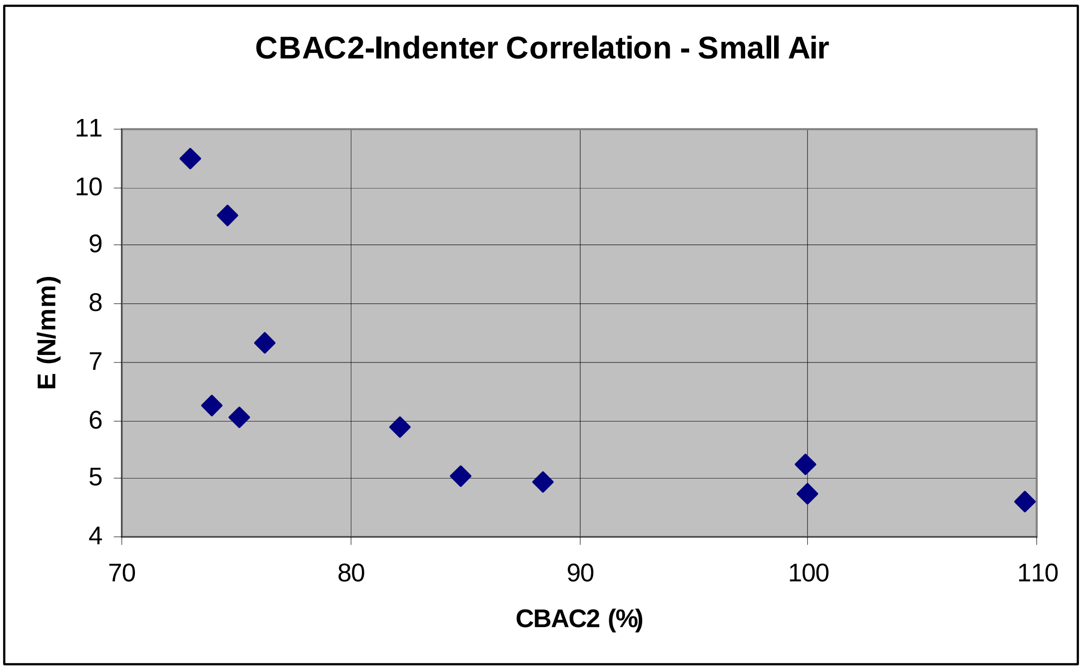

Figure 40 CBAC2/Indenter correlation for the small type, air environment

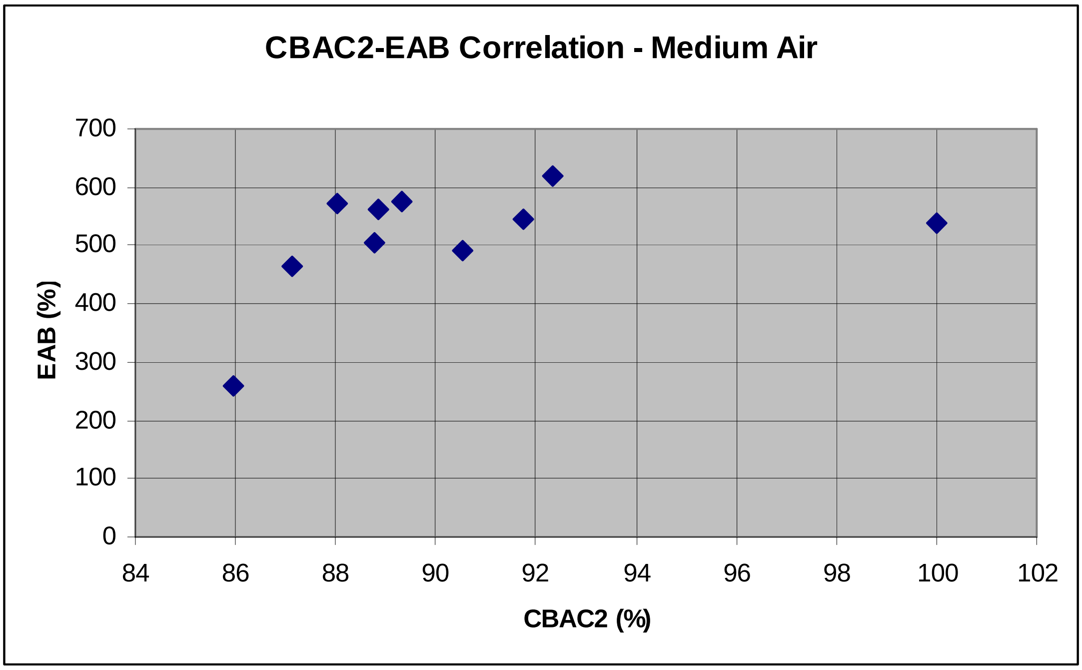

Figure 41 CBAC2/EAB correlation for the medium type, air environment

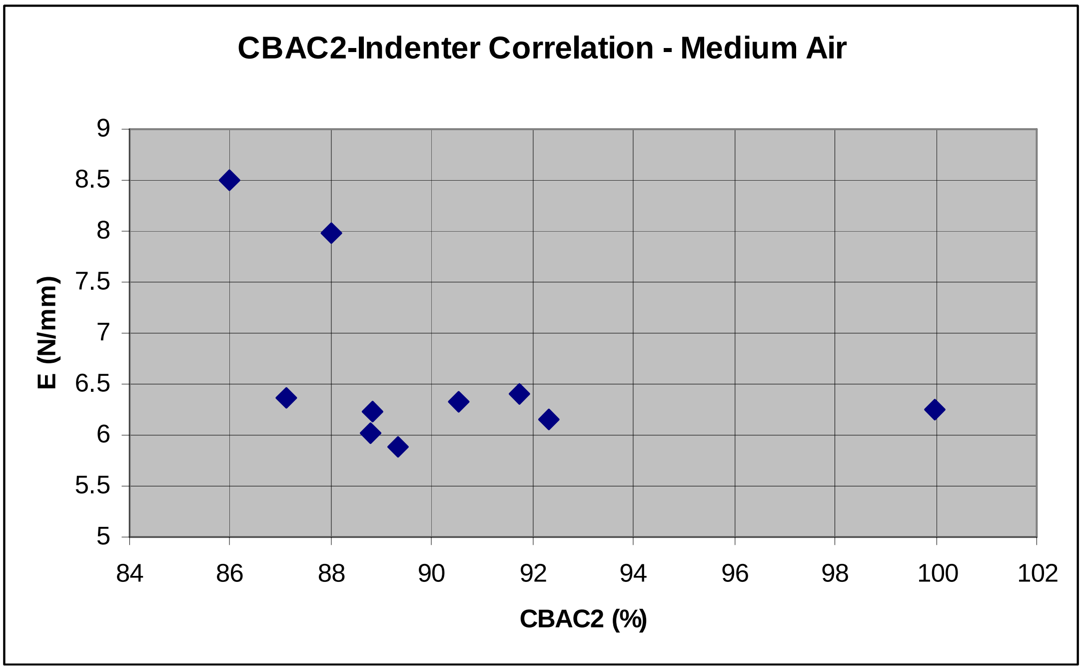

Figure 42 CBAC2/Indenter correlation for the mediuml type, air environment

The correlation for the medium type reflects the relative insensitivity of all methods in a large portion of the ageing period (Figure 41 and Figure 42).

However, for high ageing time conditions (low CBAC2 value), there is a substantial agreement among the 3 methods.

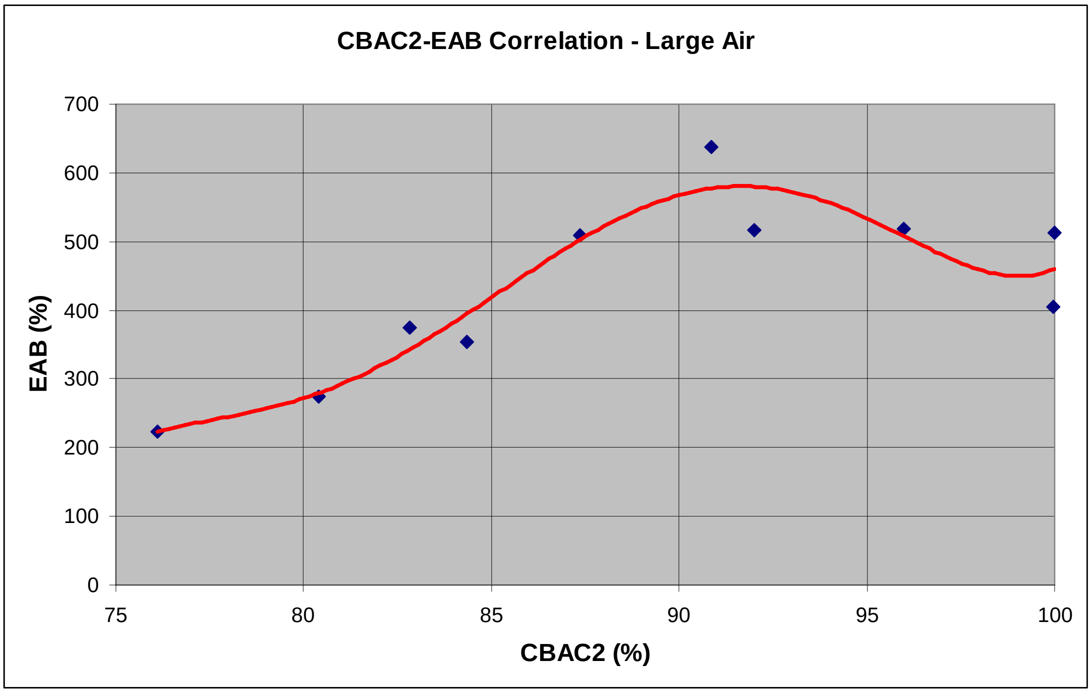

Figure 43 CBAC2/EAB correlation for the large type, air environment

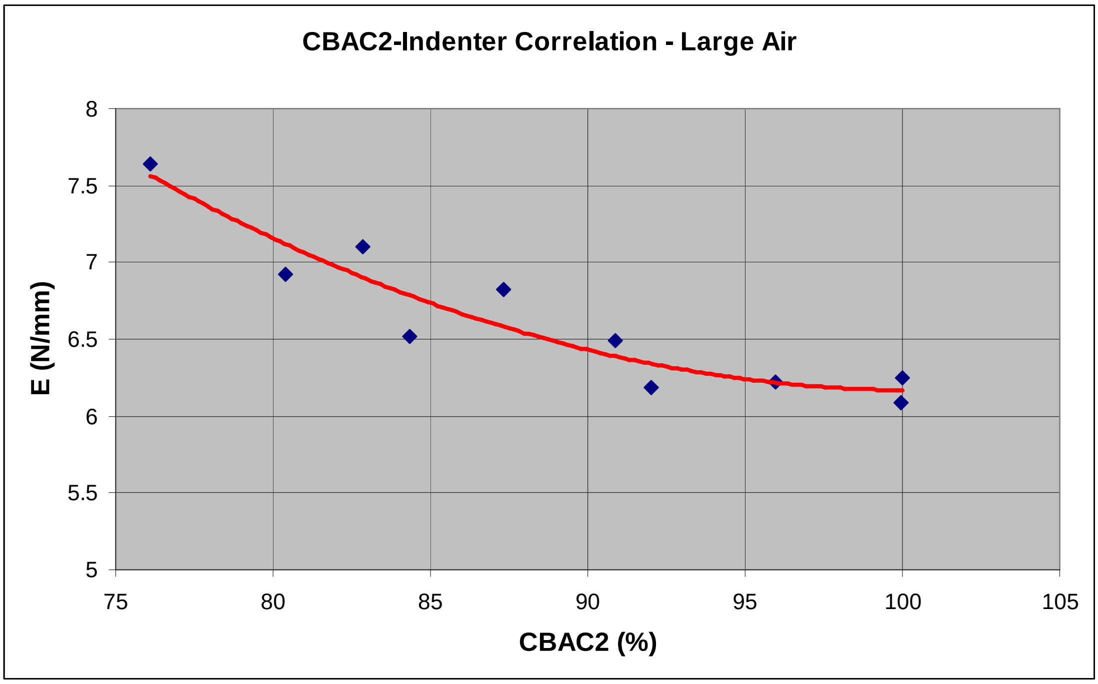

Figure 44 CBAC2/Indenter correlation for the largel type, air environment

In the large type case (Figure 43 and Figure 44), CBAC2 correlates well with both EAB and the indenter, except for the EAB correlation in the range 92%-100% CBAC2 (low ageing time), due to the EAB uncertainty in that region.

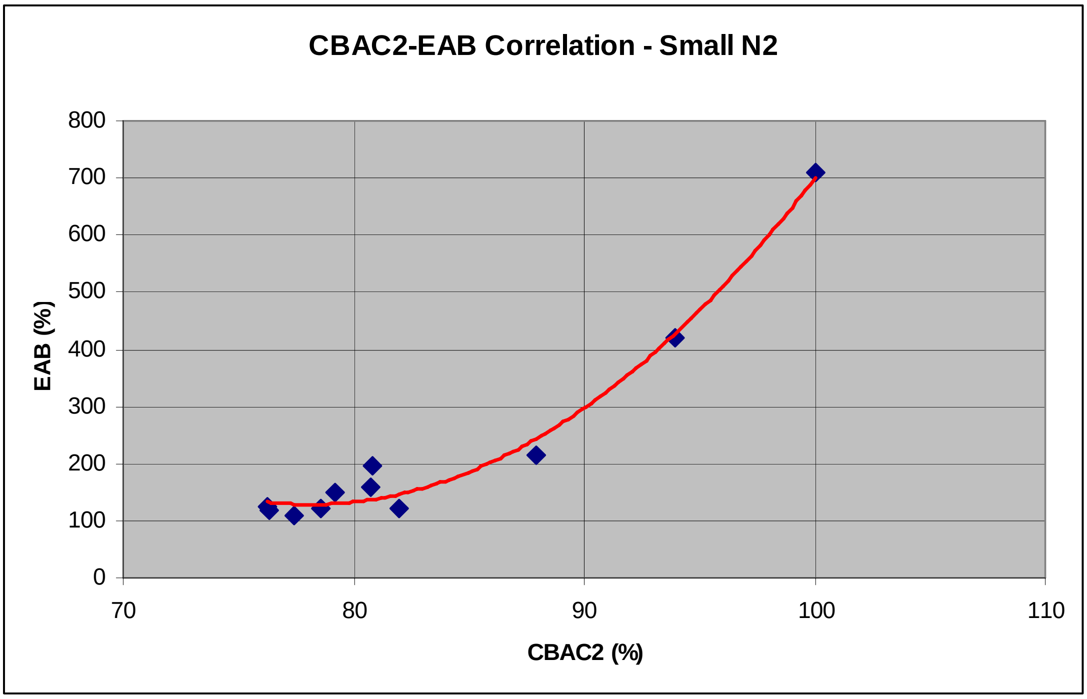

Figure 45 CBAC2/EAB correlation for the small type, N2 environment

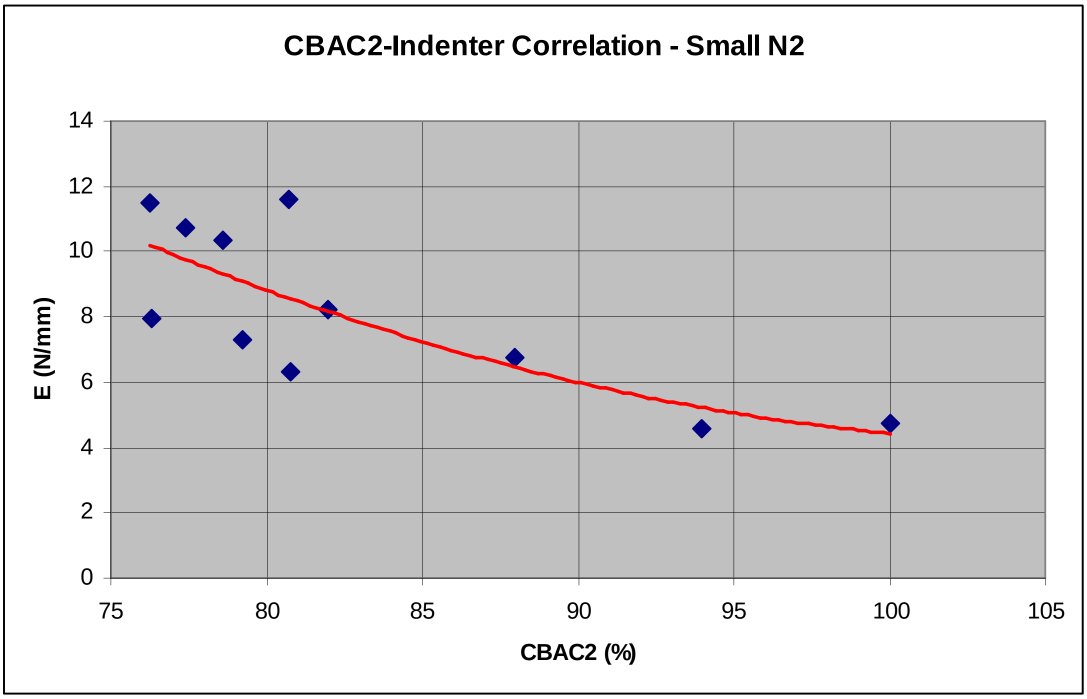

Figure 46 CBAC2/Indenter correlation for the small type, N2 environment

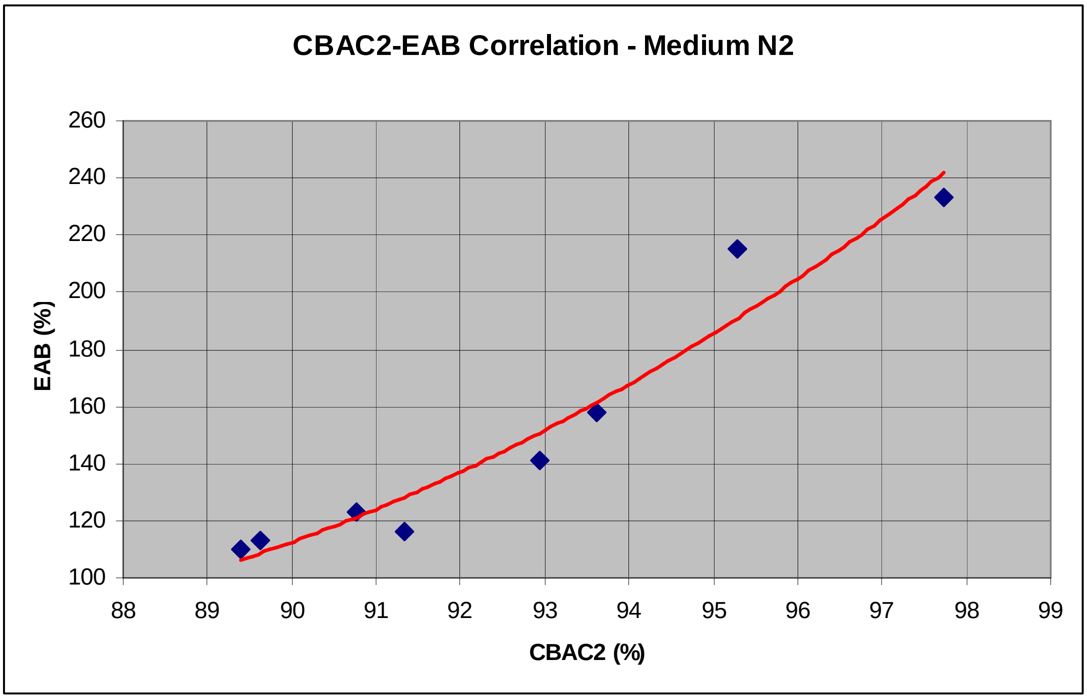

Figure 47 CBAC2/EAB correlation for the medium type, N2 environment

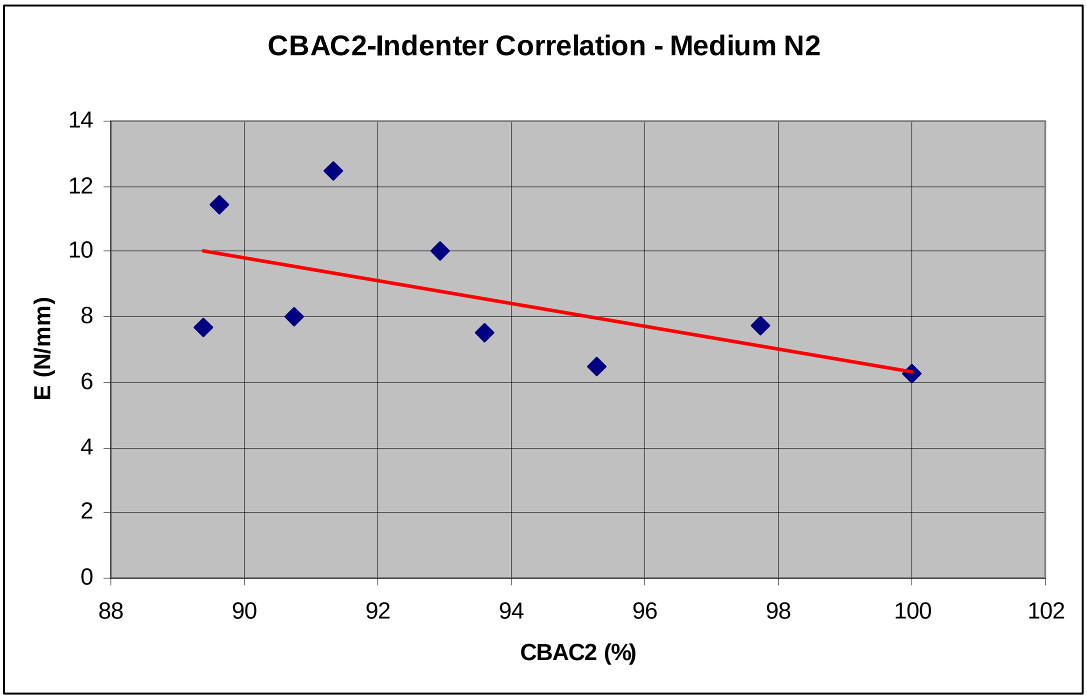

Figure 48 CBAC2/Indenter correlation for the medium type, N2 environment

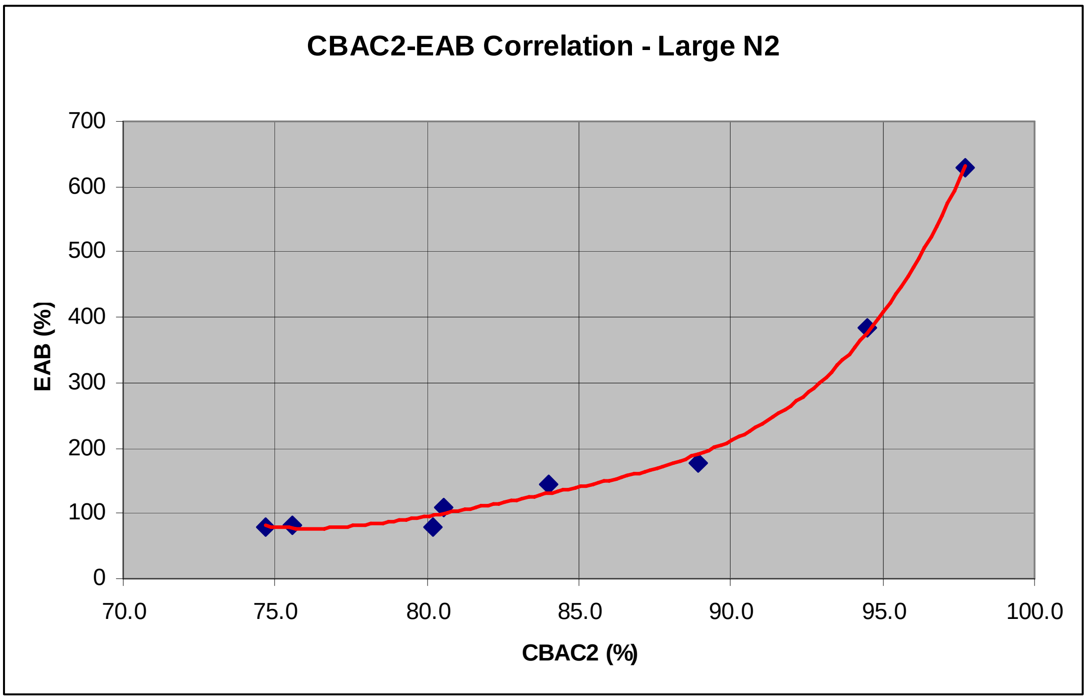

Figure 49 CBAC2/EAB correlation for the large type, N2 environment

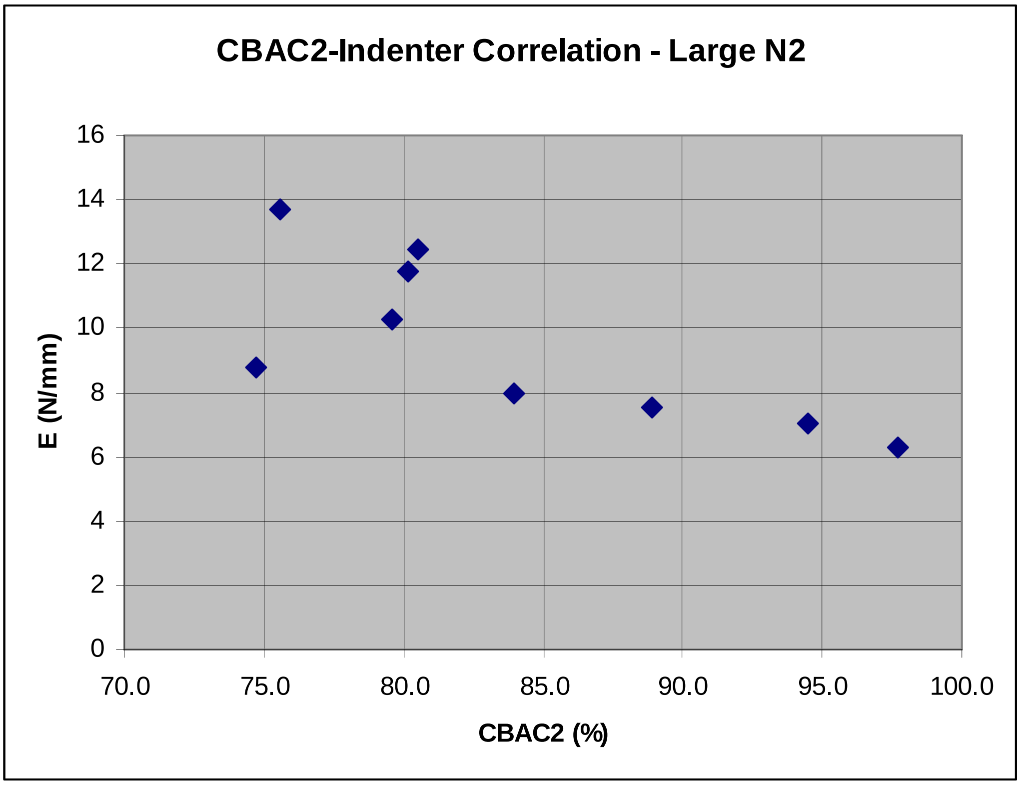

Figure 50 CBAC2/Indenter correlation for the large type, N2 environment

In N2 environment, LIRA correlates very well with the EAB measurements in the entire ageing spectrum, while the correlation with the indenter is somehow lost in the high exposure part of the spectrum.

6.6 Trend comparison among the three methods

The following graphs show the traces of the 3 condition indicators on the same plot, to visually evaluate the correlation existing among the different methods. In all these plots, the y-axis scale has been adjusted so that the 3 indicators trend toward the same side (downtrend) and the total deviation in the ageing period is similar.

The first 3 plots, Figure 51-53, refer to the air environment. In the small type, the 3 methods correlate well, although EAB and CBAC2 at a better degree. Note the reverse trend of CBAC2 and Indenter in the first 20 hours. EAB and CBAC2 seem to give a better indication then IND, up to 95 hours (accelerated). After that, EAB and CBAC2 tend to flatten out, while IND is still trending well.

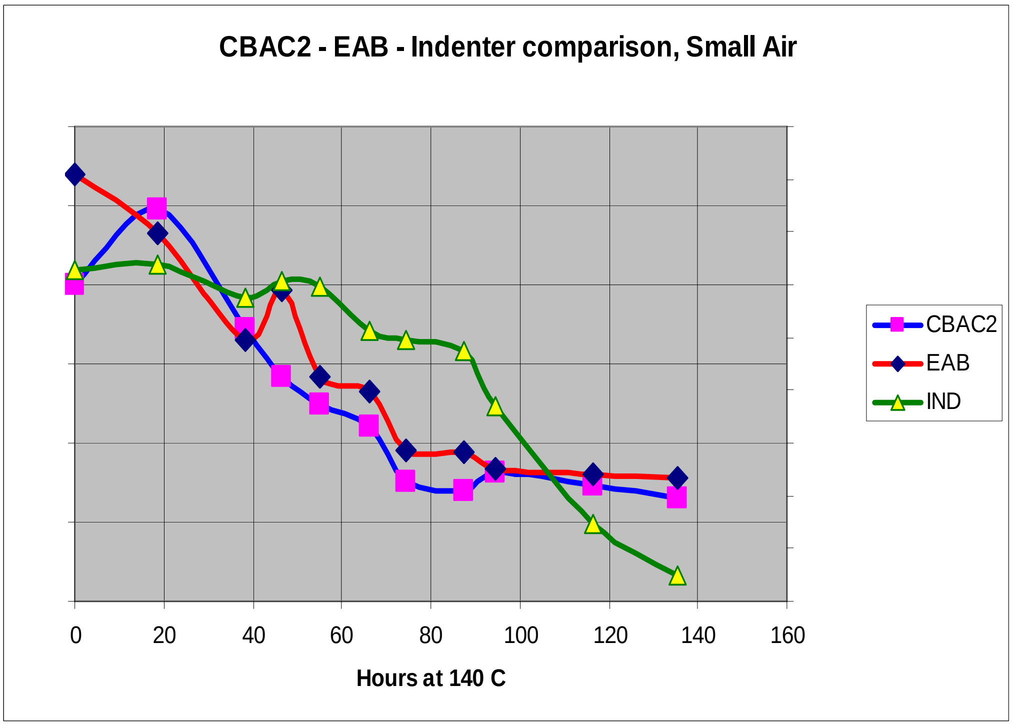

Figure 51 Small air comparison among the 3 methods

In the Medium Air case, CBAC2 has an initial sharp change during the first 20 hours, but all methods have a flat behavior between 20 and 95 hours, and then drop consistently. Note the reverse peak at 96 hours, visible in all the 3 indicators.

Except for the first 20 hours, the 3 indicators are well correlated but, unfortunately, very little information can be achieved in the 20-96 hours period.

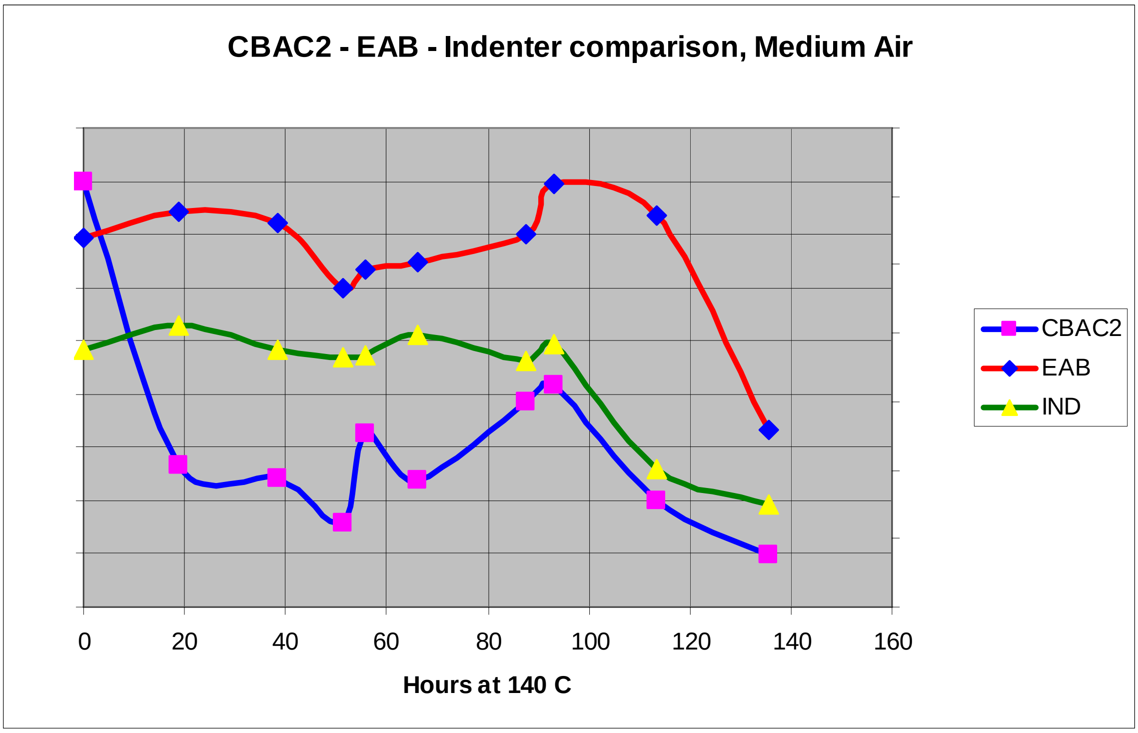

Figure 52 Medium air comparison among the 3 methods

In the Large Air case, IND and CBAC2 correlate quite well. EAB has a significant reverse trend in the 20-55 hours period. CBAC2 is the only indicator not suffering any reverse trend in the entire time window.

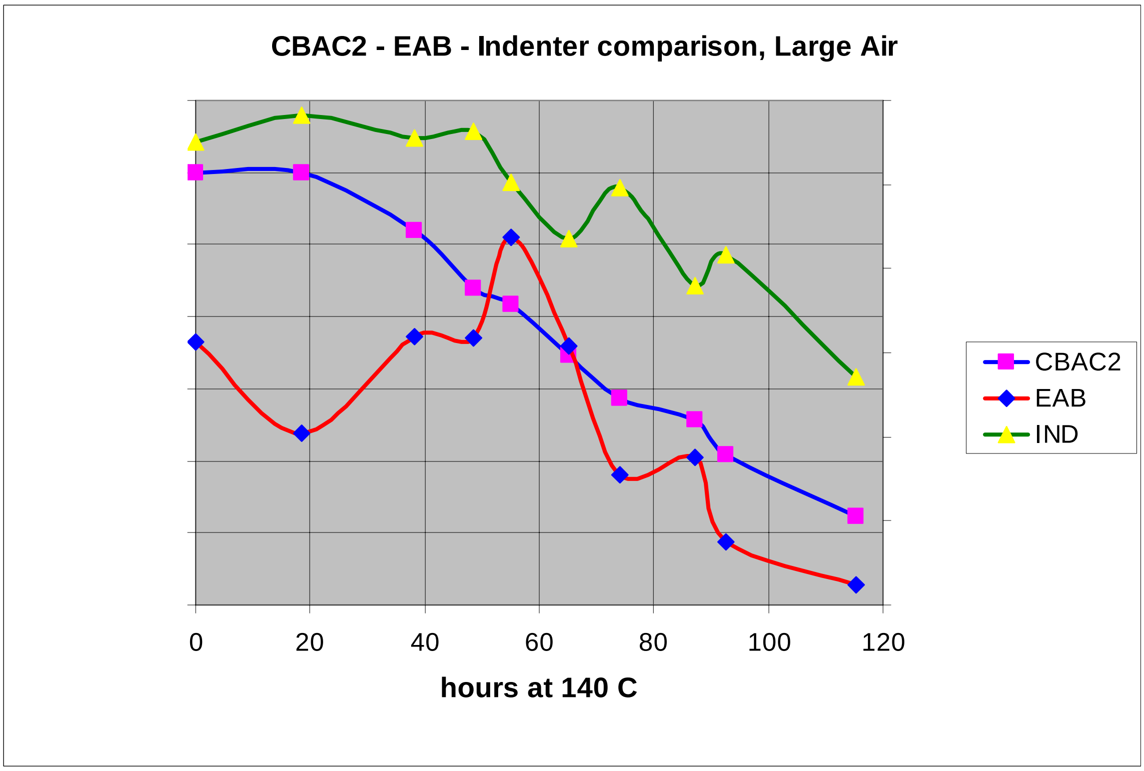

Figure 53 Large air comparison among the 3 methods

About the nitrogen cases, Figure 54-56, EAB and CBAC2 correlate very well in all the three types, with consistent small reverse trends at the same time.

IND has a consistent, significant reverse trend up at 350 hours, in all the three cases. A

remarkable behavior that appears in these N2 plots, is that, while the three indicators trend to the same side with time, the reverse peaks in IND appear to be in counter phase respect to EAB and CBAC2. This is a strange phenomenon that would be worth to investigate further.

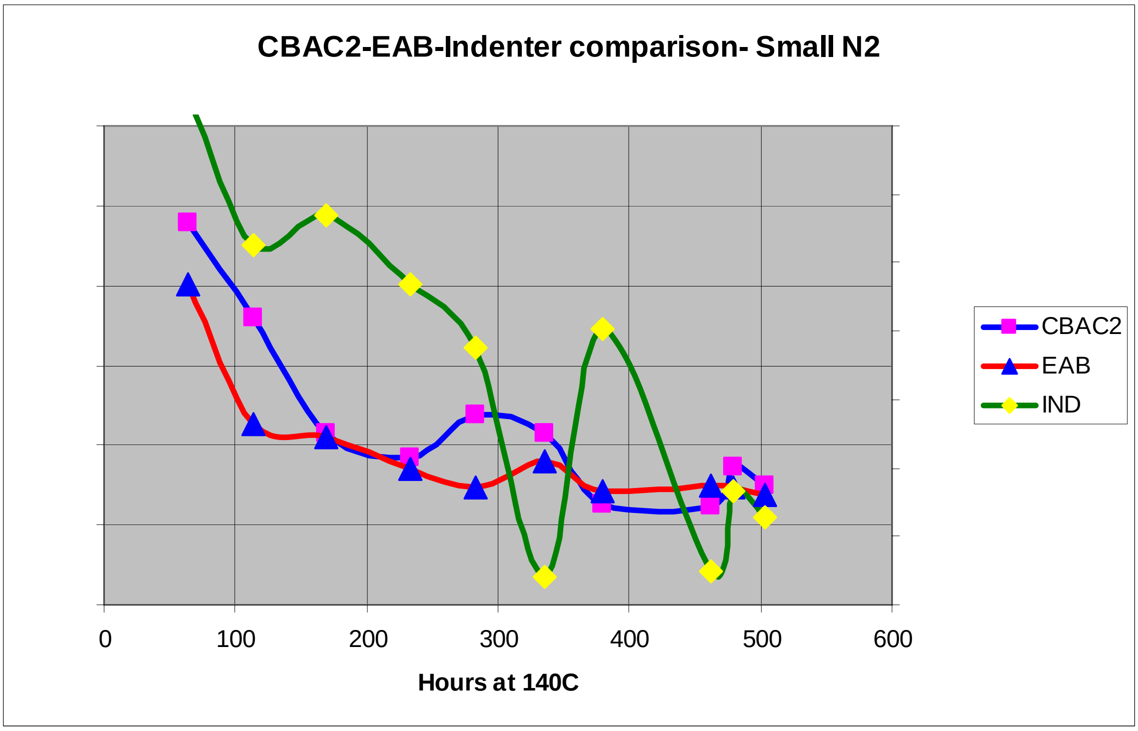

Figure 54 Small N2 comparison among the 3 methods

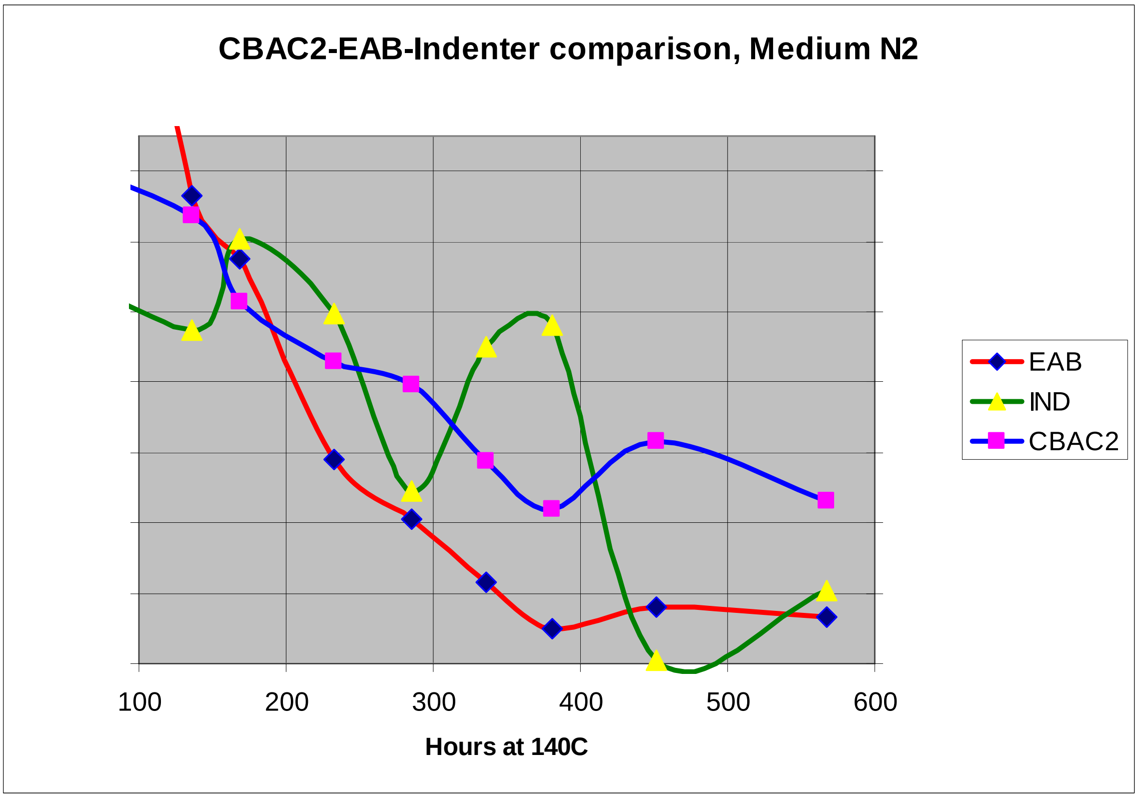

Figure 55 Medium N2 comparison among the 3 methods

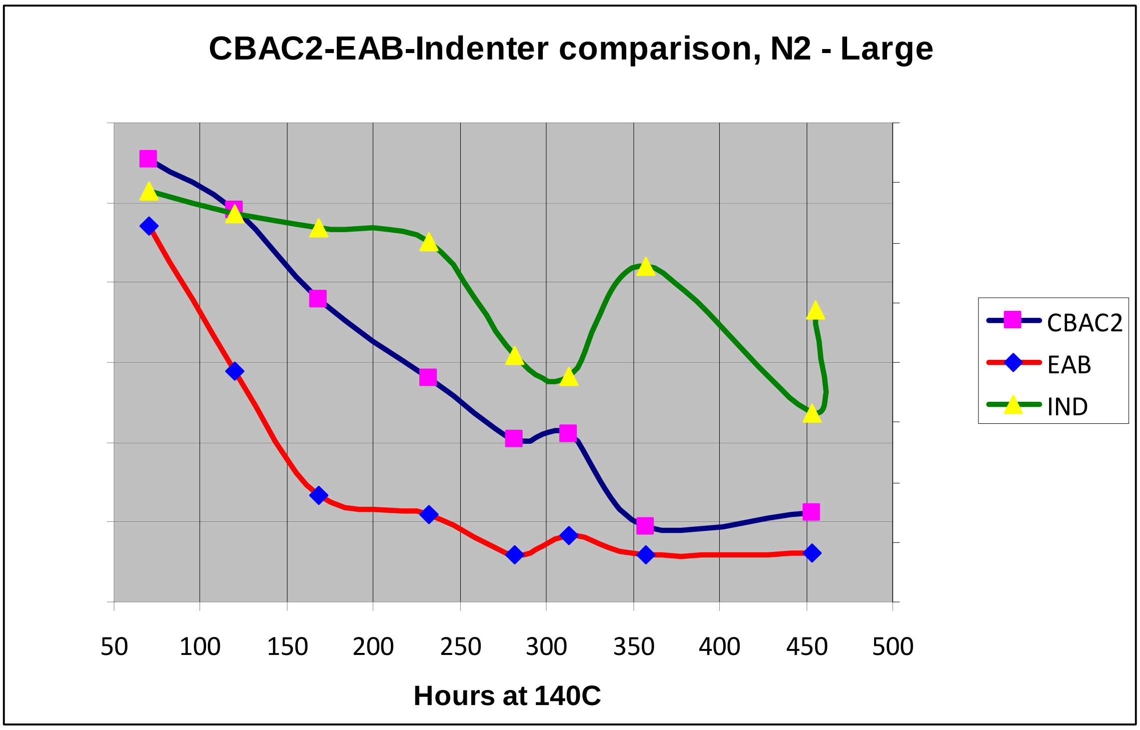

Figure 56 Large N2 comparison among the 3 methods

7 Conclusions

In this report 3 techniques for cable global ageing assessment were tested and evaluated. The EAB technique is a destructive, local technique that is often used as a reference for other methods. The indenter is a local, in-situ mechanical technique that is currently quite often used in NPPs. LIRA is an electrical method, full line, in-situ.
LIRA correlated quite well with EAB and both tend to flatten when the ageing time reaches 40 years. The only cable type that was difficult to assess for all the 3 methods was the medium type in air environment.
These tests considered only thermal ageing, up to 50 years and should be completed by considering also gamma irradiation ageing.

8 Acknowledgements

This work was performed by the authors with the financial support of NKS (Nordic Nuclear Safety Research), Ringhals AB and Forsmark AB. The cable samples used in these tests have been supplied by Ringhals AB.

9 References

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Abstract	Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. In this report 3 techniques for cable global ageing assessment were tested and evaluated. The EAB technique is a destructive, local technique that is often used as a reference for other methods. The indenter is a local, in-situ mechanical technique that is currently quite often used in NPPs. LIRA is an electrical method, full line, in-situ. LIRA correlated quite well with EAB and both tend to flatten when the ageing time reaches 40 years. The only cable type that was difficult to assess for all the 3 methods was the medium type in air environment. These tests considered only thermal ageing, up to 50 years and should be completed by considering also gamma irradiation ageing.
Key words	Condition monitoring, cable aging, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA, positron