ADVANCE – Publishable summary

(Extracted from project final report)

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1.1. Executive summary

ADVANCE (Ageing Diagnostics and Prognostics of low voltage I&C cables) is a collaborative project co-funded by the European Commission under the Euratom 7th Framework Program (FP7) for R&D in nuclear fission and radiation protection. The project started on the 1st of January 2011 and finished on the 31st of December 2013. The total budget of the project was 4 M€ with over half funded by the EU.

The ADVANCE consortium was composed of a mix of European research and technology actors with significant experience in the area of cable ageing and diagnostic techniques. It gathers eleven partners from eight different countries led by EDF and represents nuclear utilities with their associated competence centres (EDF, FORSMARK, LABORELEC), research and engineering institutes (CEA, INCT, NRI, TECNATOM) and universities (KTH, UNIBO,) one cable manufacturer (NEXANS) and one provider of nuclear products and services (WSE).

ADVANCE project was addressing open issues regarding the assessment of safety-related cables that are required to operate not only during normal operating conditions but also under accident conditions, like in the case of the Loss Of Coolant Accident (LOCA). The main goals of the project were to:

- adapt, optimize and assess promising electrical condition monitoring (CM) techniques for nuclear cables that are non-destructive and can be used in the field to determine the current condition of installed cables over their entire length;
- establish acceptance criteria by correlating physical cables properties to electrical properties in order to evaluate the degree of degradation and to provide information about the cable remaining useful life.

Obtained results

Six cables (safety-related low voltage power, instrumentation and control cables) representative from those currently employed in European NPPs have been selected from the storage (one also from operation), studied and tested in the project. Cable environmental conditions and function requirements were described as well as accelerated ageing protocol for short and long samples.

These cables were used in two main test programs. In the first, long cables were aged and different CM techniques were used to track the different stages of ageing. In the second, short cables were aged to provide a multi-stress modelling under various ageing factors.

Investigations carried out on short samples 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 aging indicator. Nevertheless, more study is necessary to know the limit values of electrical parameters in the view to estimate time to replacement of cables used in NPPs. Suggestions for future work are proposed.
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. In general it is difficult to achieve a representative accelerated ageing test in a short time period. Nevertheless, it is considered at the moment more adapted to focus TDR/FDR techniques on the study of local defect evolution rather than global aging. To conclude, further developments are required to improve measurement techniques and analysis. Guidance and propositions for future work built on the analysis of results are suggested. Cable samples and test results are stored and available on request to ADVANCE partners for further studies. In parallel a new cable design has been developed for online monitoring of NPP cable conditions.

Actions for training and to encourage mobility of new scientists or engineers have been organised and implemented during the project. It comprises a special seminar on cable ageing and short visits in the partner’s institutions. Furthermore, dissemination of the project results has been achieved through the publication of articles/posters during conferences, participation to a large symposium, and collaboration with IAEA. A new project continuing the work achieved in the ADVANCE project is under discussion in the scope of the NUGENIA technical area 4 program.

Unfortunately, the parallel program in cooperation with China has not been achieved due to the huge delays from the Chinese side (difficult negotiation phase of the Chinese ANTIAGE project concerning both organisation and funding).
1.2. Summary description of the project context and objectives

1.2.1. Context
Extending the lifetime of a Nuclear Power Plants (NPPs) to 60+ years is among one of the most important concerns in the global nuclear industry. As electric cables are one of the long life items that have not been considered for replacement during the design life of NPPs (typically 40 years), assessing their degradation state and predicting their remaining lifetime are very critical issues.

1.2.2. Project organization
The project was organized in 8 work packages (WP), as described in Figure 1.

WP1 and WP7 were respectively dedicated to ADVANCE project management and scientific and technical coordination of the project.

The state of the art of CM techniques and a review of environmental conditions were carried out in WP2. It allowed the choice of 6 different representative cables that were later studied and tested in the project.

Most of the technical work was performed in WP3, WP4 and WP5. WP3 was focused on a large ageing program, including thermal and radiation constraints, applied both on short samples dedicated to studies in WP4 and on long cables samples dedicated to studies in WP5. DBE tests
were applied to long cable samples at different ageing steps in the view to determine the acceptable limits of condition indicators.

WP6 was dedicated to training, mobility and dissemination activities. In particular, exchanges of young scientists between partners were organised providing valuable results for the project.

A cooperation with China was foreseen in parallel to the ADVANCE project and managed in the WP8. The activities of the Chinese consortium were planned to be carried out in a project (ANTIAGE) with a comparable structure to ADVANCE but on different cables. The parallel Chinese project was mainly focussed on HFFR cables.

1.2.3. Project objectives

The overall objective of the ADVANCE project was to adapt, optimise 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.

To this extent, the project consisted in studying with accelerated ageing tests a representative selection of cables already installed in European Nuclear Power Plants (NPPs) in order to evaluate the ability of electrical CM techniques to detect local and global cable ageing. The results were compared and correlated to those obtained with more conventional CM techniques for validation and residual life estimation. These tests were supported by the study of the impact of cable polymers ageing on the electrical properties.

The objective of these studies was not only to allow to guide the adaptation and the optimisation of existing CM techniques, but also to interpret the results of the electrical measurements, to extend the validity of the results to other similar cables and to adapt the future cable design and formulations to electrical CM techniques. This particular objective was to investigate on innovative cables for future plants that could open the way to a new generation of "intelligent" cables with improved diagnostic capability.

The ADVANCE project was organised in WP as described in §1.2.2. Most of the essential technical work as been achieved in WP3, WP4 and WP5.

WP3 was dedicated to the selection and the ageing of cables. The first objective was to select cables representative of those installed in European NPPs and of course available in the stocks of the utilities. The second objective was to define the most appropriate accelerated ageing protocols and to issue the tests procedures (design of experiments including ageing procedure and DBE tests). Then, short and long cable samples were tested according to the design of experiments.

The main focus of studies and tests conducted in WP4 was to understand the relation between ageing processes observed on short samples of cable insulation and the evolution of the
corresponding material properties (mechanical, chemical, physical, electrical). The objective was to choose the electrical diagnostic properties that correlate the best with ageing, to understand the relation between chemical/physical ageing and time evolution of electrical characteristics, and later to estimate the time to replacement of cables based on the developed models. Another important issue was to prepare the future by investigating how to adapt future cable design and composition to electrical CM techniques.

The aim of WP5 was to adapt and optimize promising electrical CM techniques for ageing detection. To do so, tests and results conducted in WP5 on long cable samples both with conventional CM techniques (Elongation at Break, Oxidation Induction Time, density, ...) were compared with tests and results obtained with new electrical CM techniques. Other objectives were to improve electrical CM techniques (also through results issued from WP4), to provide a prototype that could be used in the field, to perform electrical CM measurements in NPPs and to provide cable electrical CM guidelines. Finally, cable samples with different degree of ageing have to be stored for future use as well as data issued from CM measurements to be recorded in a database.

The other “non management” WP objectives were dedicated exchanges and dissemination within the consortium, within scientific community and with China through a dedicated cooperation.

The main goals of WP6 were to facilitate the training and the mobility of eligible new scientists and engineers and to provide efficient dissemination of project results. 4 tasks were defined:

- to organise and implement a student and early career program
- to provide training courses during short visits
- to organise a training seminar on CM diagnostic techniques for cable ageing assessment
- to disseminate the results of the project among the scientific community through participation to conferences,

The main objectives of WP8 (cooperation with China) were to define a detailed work program with Chinese parallel project on selected topics and to establish an efficient information exchange between EU and Chinese consortium.
1.3. **Main S&T results/foregrounds**

1.3.1. **Cable description and environmental conditions**

A cartography of the cable types and materials and the associated environmental conditions of European NPPs has been established (data have been collected from Sweden, Belgium, France, Czech Republic, Spain and Finland). The results were used for choosing representative cables to be studied and tested in the project. Six different cables (safety-related low voltage power, instrumentation and control cables) have been selected from those cables available from the maintenance storage of European utilities and, in addition, a cable of the same type of the one taken from the storage was removed from a plant after having spent 30 years in operation. A preliminary in-depth characterization of the selected cables was done to determine the nature of the additives (e.g. antioxidants, stabilizers, fire-retardants and pigments) and their approximate concentration in the compounds. No significant differences have been initially found between the cable aged 30 years in storage and the one aged 30 years in operation using the preliminary characterization by physical and chemical analyses.

**Description of cables, environmental conditions and function requirements**

In order to obtain information about the cables and the environmental conditions in reactor containment of different NPPs in Europe, the project has sent out a questionnaire to various EU nuclear utilities. The targeted utilities represent most of the countries in Europe which have NPPs. Answers came from partners’ countries (Sweden, Belgium, France, Czech Republic and Spain) and also from Finland (TVO and Lovisa). These NPPs have various types of reactor (e.g. BWR, PWR and VVER), different cables types and different environmental conditions.

The information gathered has shown that:

1) Cables in the containment of the European NPPs were often manufactured in the same country where the plant was built. The main cable materials used are EVA, XLPE, CSPE (Hypalon), PVC, EPDM and EPR in different combinations. For old plants in Europe still using the original cables, it was found that they have very few cables types in common with other plants in different European countries. In average, for LOCA cables, one single reactor uses around 15-20 different types of cables that reach a cumulative length often more than ten km.

2) The NPPs have a large variety of normal and accident (DBE) environmental conditions of the reactor containment. These differences are not only related to the fact that the reactor types are different (BWR, VVER and PWR), even for the same type of reactor the environmental conditions vary a lot especially for accident conditions due to different simulated data and the safety margins that have been taken (or imposed by local regulation).

3) The NPPs often use isolation resistance as functional acceptance criteria. For normal environmental condition the value is in the MΩ range and for DBE about 100 kΩ depending on the cable length and its application. Other functional acceptance criteria's that are used in some of NPPs are EAB (50 % absolute value) and indenter modulus (2 times the baseline value,
N/mm). The insulation resistance values for instrumentation cables are based on the quality of the signal needed and for power cables on the power needed to operate different devices. The correlation between these mechanical indicators (EAB and indenter) and the electrical parameters is not straightforward.

State of the art of ageing mechanisms

A large variety of organic materials, such as EVA, XLPE, CSPE, PVC, EPDM, are present in cables used in nuclear environments. During exposure to ionizing radiation it is found that polymers undergo degradation. Usually, organic polymers are the “weak link” as compared with other materials (ceramics, metals, ...). As a result, it is often the degradation of organic materials which can cause the failure of components of the system in which they are used.

The basic degradation mechanisms and factors affecting ageing degradation are well understood in the scientific community. There are several scientific articles and reports dealing with this issue but only few giving an exhaustive analysis of all the mechanisms acting during ageing.

The similar final consequences of aging are observed in most of polymers like chain scission, oxidation or cross-linking. Temperature and radiation have various contributions in the material degradation and their combination in some cases provides synergistic effect. Concerning the accelerated ageing, attention must be paid to the fact that the ageing mechanisms including thermally and radiation initiated processes ought to be the same as those encountered in service.

State of the art of cable condition monitoring methods

A state of the art of cable condition monitoring methods has been achieved at the beginning of the project. Laboratory techniques can be divided in two families. First, the laboratory techniques which require some form of sample removal or intrusion to perform the measurement properly. It comprises elongation at break (EAB), tensile strength, oxidation induction time and temperature, thermogravimetric analysis, infrared analysis, density measurement, oxygen consumption rates, electron microprobe analysis. Advantages/disadvantages, benefits/limitations of techniques are exposed. Then, laboratory techniques which not require some sample removal are presented: indenter modulus, recovery time, near infrared reflectance. The experience has shown some correlation with polymer or elastomer degradation. These methods are local methods (i.e., they test the condition at the specific location along a cable where the measurement is made) and are usually able to test only the cable jacket.

The state of the art was also focused on techniques based on electrical measurements. Classical electrical techniques are described with their principles and application to the diagnostic of cables. The following techniques with their advantages and disadvantages are exposed: space charge measurement, partial discharge measurements, insulation resistance and polarization
index, dielectric loss measurement, voltage withstand test, dielectric spectroscopy, return voltage measurement. It was found that the literature regarding the effect of aging on electrical properties of low voltage (LV) insulation is still lacking. Most of the diagnostic tools and dielectric characterization techniques have been developed and optimized for HV and MV cables. Only a few diagnostic techniques, in fact, have been investigated in the past focusing on low voltage cables insulator ageing. Even if few techniques exist, most of the time the main difficulty is to interpret the results of the measurements and to make a correlation with the degree of cable ageing. The long-term relation between physical/chemical degradation mechanisms and the electrical properties variations have not been studied in detail for LV cable materials.

A few non-destructive in-situ methods that have a low level of intrusion are available today (indenter and recovery time, portable FTIR), each having some limitations. On the other hand, electric CM methods have the potential to detect global and local insulator ageing with a full-length cable assessment from its terminals. Despite their limitations, recent advances of electrical diagnostic techniques have shown that it is now feasible to measure smaller changes of cables electrical characteristics. Diagnosis of local and global cable ageing is today an open and challenging task and some recent studies have provided new insights towards an effective adaptation of TDR-based techniques to ageing detection or other promising electrical technique based on reflectometry like LIRA.

These methods based on reflectometry and under development in the project are presented in a more detailed way: reflectometry is a generic high-frequency method that consists to inject a wave in a transmission medium under test in order to detect and locate some types of abnormalities by analysing the wave reflected back to the input. Reflectometry has been used for a long time to detect the location of a cable failure ("hard fault") but it’s quite a new and challenging approach to use reflectometry to analysis of the condition of electric cables (under development in the framework of ADVANCE project) or to detect "soft faults". Reflectometry is generally divided in two categories: time domain reflectometry (TDR) and frequency domain reflectometry (FDR). The difference between TDR and FDR lies essentially in the shape of wave injected in the transmission line. LIRA (Line Impedance Resonance Analysis) is a variation of a FDR method based on transmission line theory and the analysis of the complex line impedance as a function of the applied signal frequency (through a proprietary algorithm). It is used for detection and location of local degradations or faults in the insulation material of electrical cables and under development concerning the analysis of the condition (aging) of electric cables. LIRA has attracted the interests of many nuclear utilities and laboratories (EPRI, Laborelec-SCK, Tecnatom, Ringhals, Forsmark, Fortum Oyj, Leibstadt-KKL, Vuje). Today LIRA is used in some plants mainly for cable local degradation detection and localization, but the interpretation of the results in terms of degradation level is often difficult and requires further investigations.

**Cable selection**

For the ageing study 6 important types of safety related cables that are currently employed in European NPPs have been selected. The chosen cable materials represent the most often used combination of cable materials in NPPs. Following materials were subjected to the
study: EVA, PE, XLPE, EPDM, CSM (CSPE), EPR. These cables do not cover only most typical cables and materials, but also represents wide scale of cable types like coaxial, I&C and/or power cables.

Table 1: Selected NPP cables in ADVANCE project

<table>
<thead>
<tr>
<th>Cable Name</th>
<th>Producer</th>
<th>Type</th>
<th>Sheath/Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG - 59 B</td>
<td>Alcatel France</td>
<td>Coaxial</td>
<td>EVA/PE</td>
</tr>
<tr>
<td>Nexans</td>
<td>Nexans</td>
<td>Measurement / Instrumentation</td>
<td>HFPE/HFPE</td>
</tr>
<tr>
<td>ERR</td>
<td>Kabelwerk Eupen</td>
<td>LV power cable</td>
<td>EPDM/EVA</td>
</tr>
<tr>
<td>FSSR</td>
<td>ASEA-Sweden</td>
<td>Measurement / Instrumentation</td>
<td>CSP(Hypalon)/ EPDM</td>
</tr>
<tr>
<td>Alcatel power</td>
<td>Alcatel</td>
<td>LV power cable</td>
<td>EPR/Hypalon</td>
</tr>
<tr>
<td>AFUMEX</td>
<td>Pirelli (Prysmian)</td>
<td>Instrumentation</td>
<td>EVA/EPDM EVA</td>
</tr>
</tbody>
</table>

1.3.2. Test programs

The selected NPP cables have been submitted to an ageing program mainly cumulating irradiation and thermal constraints in the view to:

- generate different level of degradation,
- simulate common condition in normal operation,
- simulate accident conditions of European NPPs.

At the different stages of ageing the cables have been analyzed and characterized with conventional as well as new condition monitoring (CM) techniques for tracking the degradation during ageing and during DBE simulation.

One of the objectives was to correlate CM results obtained during accelerated ageing with those obtained during field measurements.

The cables were used in two main experiments that were conducted in parallel:

- An accelerated thermal and radiation ageing test program performed on long cable samples (about 20 meters) with the particular view to characterize the cables with new electrical techniques (reflectometry) all along the ageing. Long cable samples were also submitted to a design basis events (DBE) test in the view to correlate condition indicators measured near the cable end of life with cable survivability,
- An accelerated thermal and radiation ageing test program performed on short cable samples (about 0.3 meter) to achieve a multistress ageing (combination of temperatures,
dose rates, doses) and to allow life modelling (through correlation of electrical parameters vs. chemical changes/mechanical changes).

Long cables ageing

Six old but non aged cables from the NPP storage were tested. One cable type was cut out from the NPP containment, where it had been 30 years in operation at elevated temperature and irradiation. This cable was subjected to the accelerated ageing together with the same un-aged one. Such a comparison is important to help to improve the simulation reliability and to check the ageing models.

At first, operation and accident conditions of European NPPs were summarized. To simulate environmental and accident conditions of individual cables at respective NPP, ageing processes (temperature, time, dose, dose rate, sampling intervals, accident dose thermodynamic conditions etc.) were carefully selected.

Four cable types aged sequentially, thermal ageing followed by irradiation. Two cable types aged simultaneously; they were irradiated at very low dose rate around 4.5 G/h and at elevated temperature 85°C. The ageing process simulated the operation at normal parameters in some time intervals 10, 20, 30 etc. years of operation and for some samples up to total period of 100 years. The ageing time took, for some samples, more than 2 years. Some cable samples aged with an artificial damage to study the ability of CM techniques to detect defects and their time development. NPP possible defects like local overheating (Figure 3, Figure 2), pressing (Figure 4), bending were applied.

During the ageing, a lot of different CM techniques were applied. These CM techniques were destructive, nearly non destructive as well as non destructive. The cable length was up to 40 m to be able to use effectively different electrical and reflectometry methods (Figure 5). In this way it was expected to establish a correlation between CM results during accelerated ageing and those during field measurements. Applied methods and their evaluation is described bellow within other work packages.

Tests under accident and post-accident conditions

Aged and thoroughly measured cables were subjected to DBE. They were irradiated with accident dose and thermodynamic DBE profile was carried out which followed the respective NPP DBE and post-DBE profiles (Figure 6). During the simulation of thermodynamic conditions the cables were energized, most important functional properties were tested and measured (insulation resistance for example). Besides, different CM techniques were used during the tests like TDR/FDR, LIRA etc. Important part of these tests was DBE simulation on partially locally damaged and aged cables. The damage was in some cases really hard (see Figure 3 and Figure 4).

The thermodynamic shocks were carried out at NRI (UJV Rez), Tecnatom and WSE.
Small samples ageing

In order to study the impact of cable ageing on electrical properties and their correlation with physical/chemical changes, small cable samples were aged. Samples were irradiated at 4 different dose rates ranging from 0.28 to 2.8 kGy/h, at temperatures 56°C and/or 86 °C and at different ageing times up to 1000 hours. The samples in the form of strips, dumb-bells, insulated wires etc. were fixed on perforated cylinders, which were placed in a thermobox in irradiation facility Roza (Figure 7). Irradiated samples were successively removed from the irradiation facility, packed in nitrogen environment and stored in dark up to the evaluation.

Figure 2: Irradiation facility for simultaneous irradiation of long samples at elevated temperature

Figure 3: Local overheating of a cable by applying a burner with flame temperature 1800 °C for 2 minutes.

Figure 4: tested cable exposed to 25% deformation in order to simulate a damage.

Figure 5: Improved TDR/FDR on-line measurement of long cables during simultaneous radiation and thermal ageing
1.3.3. Data collection
Aged samples are a very important source of information that could be utilized also in the future. Therefore, it was decided to store:

- results of tests performed on cables in a database. At the same time as CM measurements were performed, all the test results were saved (mainly in Excel files). Results have been introduced (or referenced) in a specially prepared database for future use. The database comprises the list of tested cables, information about the cables, how we expect the cables to be aged, where were measured the properties, real values of the ageing (real temperatures, non-homogeneity, time of ageing, date of sample sending etc ...), and of course the test results.
- cable samples (clearly labelled) and to make them available to ADVANCE partners on request in the future.

As agreed by ADVANCE consortium, detailed information about the results, including test records, results and conclusions are not available to public.

1.3.4. Results on short samples
A representative selection of safety-related LOCA cables was studied in order to investigate electrical properties for ageing diagnosis and to understand the correlation of these properties with polymer physical/chemical ones.

Cable jackets were removed, and only the insulations were subjected to accelerated aging, under the simultaneous application of thermal and gamma-radiation stresses.

The impact of cable aging on the electrical parameters was monitored and characterized adapting and optimizing condition monitoring techniques developed mainly for HV and MV
cables, i.e. dielectric spectroscopy, polarization-depolarization current measurements and space charge measurements. Insulation aging is defined as the irreversible process resulting in the variation of insulation structure (physical and/or chemical) and properties, compromising its function. A good condition indicator should present a monotone and remarkable trend with degradation. The aging marker should be sensitive to the effects of aging for the particular material at different stress levels and its variation must be irreversible.

Space charge measurements performed with Pulse-Electro-Acoustic (PEA) method did not reveal useful aging markers. Samples aged with low stress levels present an almost negligible variation of the extracted quantities (e.g. maximum stored charge density, apparent trap-controlled mobility) and the interpretation of the results is often not easy. The application of space charge measurements to low-voltage NPP cables can give only a qualitative evaluation of material degradation, through the space charge density pattern (Figure 8). The main concerns consist in the low-voltage cable design: loose contacts, small thickness, dispersive materials (additives) blur the results of HV tests like space charge measurements.

![Figure 8: Space charge density pattern. Space charge measurement patterns of EPR-based insulation after 600 h at 55°C with irradiation dose rate of 1.58 kGy/h. Pattern scale: ± 2 C/m³. Hetero-charge formation at the anode (interface between insulation and PET film used by cable manufacturers to improve the extrusion process. This hetero-charge increases with aging.](image)

Polarization-depolarization current measurements provide other electrical quantities like conductivity and very-low-frequency dielectric response. Conductivity cannot be a suitable aging indicator. In general, after an initial variation, it usually fluctuates without a clear trend. Only in one case, i.e. an EPDM-based insulation, conductivity increased gradually with aging, but these specimens appeared particularly weak to irradiation at high temperature.

The depolarization characteristic varies with aging only for XLPE, EPR-based and EPDM-based insulations. The interfacial contribution to the real part of susceptibility and the dielectric losses increase with aging, but their behaviour is not clearly correlated with the applied stresses: when these electrical properties are correlated with elongation at break or density, they do not fit to the same curve. This means that the value of the electrical
aging marker corresponding to the mechanical end-point (typically 50% absolute elongation) could change with the aging stress applied.

**Dielectric spectroscopy is the most promising electrical condition monitoring technique among those investigated in this work.** Between $10^{-2}$ Hz and $10^6$ Hz, both real ($\epsilon'$) and imaginary ($\epsilon''$) parts of permittivity of XLPE (Figure 9a), EPR-based (Figure 9b) and EPDM-based insulations increase over the whole frequency range. The variation of $\epsilon'$ is more evident at low frequency, while $\epsilon''$ increases remarkably also in the high frequency range. For samples containing EVA (Figure 9c), even if EVA is not the main constituent, the effects of aging on the dielectric losses are found only at high frequency, while the real part of permittivity presents almost negligible variations. From these observations it is possible to understand why electrical measurements at power frequency are commonly considered not useful for condition monitoring: dielectric spectroscopy revealed that at power frequency the variation of the cable electrical properties with aging is very limited.

![Graphs showing imaginary part of permittivity vs. frequency for (a) XLPE, (b) EPR-based and (c) EVA specimens aged in the framework of WP4.](image)

**Figure 9:** Imaginary part of permittivity vs. frequency for (a) XLPE, (b) EPR-based and (c) EVA specimens aged in the framework of WP4.
From the correlation of electrical quantities with mechanical properties and density, some important conclusions can be drawn. **Diffusion-limited oxidation (DLO) strongly affects the elongation at break:** cable outer surface is more oxidized and cracks can be initiated and quickly propagated through the sample, whereas electrical measurements are averaged over the sample cross-section. This in turn means that comparing elongation to electrical properties for samples where DLO-effects are present can result in comparing the worst aged part to the average, which does not necessarily behave in the same way (Figure 10a).

The good correlation with density (Figure 10b, Figure 12b) suggests that dielectric spectroscopy can give a good indication of the average level of oxidation in the sample, since density increases through the introduction of oxygen atoms into the polymer chains. For a homogeneously aged sample, the oxidation can likely be correlated with the reduction of elongation-at-break, and dielectric spectroscopy is a viable option for the condition monitoring of these cable insulating materials. DLO is known to be lower for EPR-based materials, allowing the correlation of elongation-at-break with $\varepsilon''$ at 100 kHz (Figure 12a).

At high frequency, the imaginary part of EVA-based insulation correlates well with oxidation induction temperature (Figure 11b), whereas the correlation with elongation becomes feasible only when this mechanical property value is already below 100% absolute (Figure 11a). Some data revealed so called "inverse temperature effect" meaning that the determined degree of degradation of the insulation is smaller when the irradiation is performed at higher (85 °C) than at lower (55 °C) temperature.

Concluding, **dielectric spectroscopy showed that the imaginary part of permittivity at high frequency could be used as an aging indicator,** at least for the materials investigated in this work, which are widely used as NPP low-voltage cable insulation. In the high frequency range, the increment of $\varepsilon''$ is related to oxidation, i.e., the main degradation mechanism of cable insulations. However, it is necessary to prove the sensitivity of this aging marker at lower stresses, more similar to those found in NPP during operation. On the one hand, dielectric spectroscopy could be applied as non-destructive test on "pace" cables for ongoing qualification, considerably reducing the amount of samples required by these programs. On the other hand, its application as in-situ condition monitoring technique is limited to shielded cables, which presents a fixed ground reference.

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1 A "pace" cable is a cable specimen placed in a very severe natural environment where its aging occurs quickly enough to permit early, but more reliable, life estimates. They are used for ongoing qualification tests.
Figure 10: Cross-plots of the imaginary part of permittivity at 100 kHz vs (a) elongation-at-break and (b) density for the XLPE insulation. Properties are reported in relative value to the one measured on the unaged sample.

Figure 11: Cross-plots of the imaginary part of permittivity at 100 kHz vs (a) elongation-at-break and (b) oxidation induction temperature for the EVA-based insulation. Properties are reported in relative value to the one measured on the unaged sample.
1.3.5. Results on long samples

A representative selection of long cable samples was studied in order to investigate the ability of electrical CM techniques to detect local and global ageing.

The impact of cable aging on the electrical parameters was monitored and characterised through TDR and FDR measurements performed at different partners places (UJV Rez, Tecnatom and Westinghouse) and under 3 different test conditions: accelerated aging (thermal, thermal and irradiation), DBE - post DBE aging and aging in real condition (NPP).

Environmental effects were noticed on cables under test:

- Some effects more or less important cause false detection of soft fault like objects close to the cable, measurement condition effect, disturbed measurement, ...
- External temperature is impacting the measurements.

These effects disturb local and global aging analysis.

Many reflectometry signals have been acquired at different stages of the ageing of the cables. Not valuable effects on cables were noticed during the accelerated ageing process. A heterogeneous evolution is noticed for global or local ageing even when considering the measurements with external temperature practically identical. There is no monotonic correlation and practically no evolution of cable signal during accelerated aging test.

Figure 12: Crossplots of the imaginary part of permittivity at 100 kHz vs (a) elongation-at-break and (b) density for the EPR-based. Properties are reported in relative value to the one measured on the unaged sample.
Other more conventional CM techniques have been investigated in the ADVANCE project. Results obtained for each techniques used in the project are summarized in Table 2. Looking at all of them, it seems that for some cables, the ageing conditions used were not sufficient enough to generate a significant degradation, explaining why some methods which are more sensitive to the later stages of degradation don't show large variations (it is probably the case for electrical CM monitoring techniques on the cable investigated in the project). Moreover, the combination of constraints (thermal and irradiation) can lead to behaviours significantly different from a single one. So synergistic effects should be considered in future test protocols.

Among electrical techniques, dielectric spectroscopy shows promising results. LIRA and reflectometry techniques could be interesting to detect hotspots. Some others, like TGA, FTIR or density need to be investigated more deeply to draw final conclusions. Further work should also be considered to better establish test protocols and reduce standard deviation in order to have reproducible and reliable results.

There is no single method that could track the degradation at all stages. Some are better for the early stages whereas some others are more sensitive to the later stages of aging. As a consequence, using a combination of techniques is recommended. Besides, each cable behaves differently. Hence, the best monitoring method has to be found for each one.
<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential indicator?</th>
<th>Feasible on field</th>
<th>Stage of development</th>
<th>remark</th>
</tr>
</thead>
</table>
| Elongation at Break        | - Decreasing trend for some cables  
- Some cables not affected               | No                | The current reference test | For some cables, the combination of TH & IR has an important impact.    |
| OIT/OITp                   | - Decreasing trend for some cables  
- Some cables not affected               | No                |                            | For some cables, the combination of TH & IR has an important impact.    |
| TGA                        | Does not seem relevant with present analysis. Requires further investigations.       | No                | More dedicated to research |                                                                                        |
| FTIR                       | Does not seem relevant with present analysis. Requires further investigations.       | No                | - More dedicated to research 
- Sensitivity and repeatability need to be improved | Difficult to interpret. Need a high skill analysis.                      |
| HPLC/HPTLC                 | No                                                                                   | No                | Difficult to implement     |                                                                                        |
| IM                         | - Decreasing trend for some cables  
- Some cables not affected  
- Can be correlated with EaB for some cables | Yes               | The standard deviation needs to be decreased. | For some cables, the combination of TH & IR has an important impact.    |
| Recovery time              |                                                                                      | Yes               | Need to be investigated further |                                                                                        |
| Insulation Resistance      | - Correlation with EaB for the most degraded samples (Lipalon cable)  
- Some cables not | Yes               | Need improvement to be applied further | Environmental and test conditions need to be kept well under control. |
<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential indicator?</th>
<th>Feasible on field</th>
<th>Stage of development</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tan delta</td>
<td>Potential indicator at low frequency</td>
<td>Yes</td>
<td>The optimum frequency needs to be found for each kind of material.</td>
<td>Humidity needs to be kept well under control.</td>
</tr>
<tr>
<td>Capacitance</td>
<td>Potential indicator at low frequency</td>
<td>Yes</td>
<td>The optimum frequency needs to be found for each kind of material.</td>
<td>Humidity needs to be kept well under control.</td>
</tr>
<tr>
<td>Space Charge</td>
<td>No</td>
<td>No</td>
<td>Further development needed</td>
<td></td>
</tr>
<tr>
<td>Dielectric Spectroscopy</td>
<td>Yes. The evolution of the absolute value and of the frequency of the polarization technique can be used.</td>
<td>Depends on the configuration</td>
<td>The best frequency range needs to be found for each material.</td>
<td></td>
</tr>
<tr>
<td>Charging/Discharging current</td>
<td>Yes. The evolution of the absolute value and of the frequency of the polarization technique can be used.</td>
<td>Depends on the configuration</td>
<td>The best frequency range needs to be found for each material.</td>
<td>Environmental conditions need to be kept well under control.</td>
</tr>
<tr>
<td>Reflectometry</td>
<td>For local hot spots</td>
<td>Yes</td>
<td>Further investigation is needed to see if it can be used to monitor global aging</td>
<td>Environmental conditions (Temperature) need to be kept well under control.</td>
</tr>
<tr>
<td>LIRA</td>
<td>For local hot spots</td>
<td>Yes</td>
<td>CBAC2 is difficult to analyze</td>
<td></td>
</tr>
</tbody>
</table>
1.3.6. Field test results

Field measurements were performed during the outages on 4 nuclear power plants (Temelin Unit 3, Tihange Unit 3, Trillo Unit 1, Forsmark Unit 2). It was intended to apply the field measurements as close as possible on the same type of cables that already have been tested at the laboratories and then to compare the results. The techniques that had been used are: Insulation Resistance, Capacitance, Tanδ, Indenter, Lira and TDR/FDR.

Operating constraints in NPPs are severe. Measurements are not always possible in the same way than in laboratories. It has been confirmed in the present study and should remain considered for future studies (and also to be taken into consideration when developing new CM equipment/procedures).

Beside that the results didn’t show a clear trend in many cases, there were some differences between the measured cables and the test conditions on field and at the laboratories. Thus the correlation and comparison between the field and laboratory results were not conclusive.

1.3.7. Simulation activities

In parallel with tests on cables, simulations of the electrical propagation in new, damaged and aged cables have been performed. By doing so, two goals were followed:

- To improve the confidence or methods (algorithms, criteria) applied in electrical condition monitoring techniques.
- To show that a long cable could be modelled through the simulation of only a small section of it.
- To find electrical parameters that could enable us to characterize the aging of cables and then forecast their life expectancy.

Two kinds of simulations have been done:

- Direct simulation of a 3D cable with the software CST Microwave studio.
- Modelisation and optimization of the frequency behaviour of the permittivity.

A 3D simulation of a RG-59B coaxial cable, similar to the one tested in the ADVANCE project, has thus been performed. Just a short section of it (several centimetres) has been modelled. This has enabled us to compute the scattering parameters (that characterize the electrical behaviour of a cable) of a longer cable (about 2.5 m). Finally, this result has been compared with measurements, showing good accordance (cf. Figure 13). This proves that it is not necessary to simulate the entire length of a cable. Just a short section is needed, saving a lot of time.
Some work has also been done to model the frequency dependence of the electrical permittivity of Advance cables. The goals were to fit measurement data and find a parameter that could be used to characterize aging. As a first step, simple electrical models composed of resistors and capacities have been considered. It has been found that they were too simple to correctly model the dielectric’s behaviour. An advanced model called the Jonscher model has then been considered. An algorithm has been implemented in order to fit measurement data and good agreement has been achieved (cf. Figure 14). However, no parameter of this model has exhibit any trend with aging. As a future work, this approach could probably be enhanced using other kinds of optimization techniques.
1.3.8. Development of new electrical CM technique

A cable can be seen like a chain. The weakness is local and a failure results from a particular part of the cable that transforms in a hard defect. Then the cable loses its functionality. So it is important for the CM technique to monitor the evolution of this particular part (soft defect).

So, with the aim to improve and optimize electrical CM techniques based on reflectometry measurements, the following developments were achieved and set-up to analyze reflectometry measurements:

- Default localization function:
  it was applied on TDR/FDR measurements made on Alcatel RG213 in Temelín NPP and no notable soft defect was detected (Figure 15).

![Figure 15: detection and localization of soft defect](image)

- RLCG computation:
  The method consisting in assessing and monitoring the RLCG parameters of the cable (considered as constant all along the line) is useful if the cable suffers from global aging but less adapted to detect a local modification of the cable.

![Figure 16: RLCG computation on this TDR measurement to evaluate the global aging](image)
In practice, reflectograms show many local variations. Based on this observation, it is considered more adapted to focus TDR/FDR techniques on the study of local defect evolution rather than global aging. Taking into account also that long cable samples were not enough aged during accelerated ageing process defined in the project, it was difficult to detect a global ageing with these new electrical CM techniques.

To conclude, **further developments are required to improve TDR/FDR measurement analysis, particularly considering a global ageing detection.**

### 1.3.9. Development of new cables

One issue of the project was to investigate some modification of the cable construction to facilitate an efficient ageing monitoring. Therefore, a new cable design has been developed for online monitoring of nuclear power plant cable conditions. The cable prototype comprises 3 sensor elements:

- Sensor showing change of electrical properties, which can be correlated to mechanical properties of insulation and sheathing compounds.
- Radiation resistant Optical fibre can be used for online temperature monitoring. The measured temperatures can be correlated to classical Arrhenius data from cable qualification.
- Optical fibre which is sensitive to radiation can be used as sensor for applied radiation dose. The data can be correlated to radiation ageing data for cable.

![Schematic design of the LV I&C cable prototype and its sensor elements (left) and cross-section of the LV I&C cable prototype (right).](image)

The cable prototype has been manufactured. Preliminary characterisation tests have been performed. The next step is to investigate deeper the behaviour of the complete cable prototype and its sensor elements under different ageing conditions.
1.3.10. Summary of analysis of results and conclusions

As shown in Table 1, the cables studied in the ADVANCE project present different types, structures and material compositions. They cover a large range of cable types and material compositions making the analysis of results more difficult. Furthermore, a lot of characterisation techniques have been applied to cables samples all along the project. It was experienced that some of the current experimental procedures are not robust enough at the moment. It makes also the analysis of results more difficult.

Looking at results on short samples, among electrical techniques, dielectric spectroscopy has shown promising results.

It was noticed on short samples that some materials have shown an inverse temperature effect behaviour, as reported in other studies.

Ageing conditions applied to long cable samples were less severe than ageing conditions applied to short cable samples. Looking at the results on long samples, ageing conditions for some of the cable materials did not introduce significant ageing (conditions were intended to simulate conditions in plant not necessarily to age the materials). For those materials that showed little change in EaB (primarily because of this), only CM methods that are sensitive to early stages of degradation demonstrate sufficient correlation. It makes the analysis of results more difficult and justifies the need of further studies.

For some cables, a trend of ageing condition indicator has been observed but the evolution is quite fast. After the first aging steps the value of the indicator remains quite stable. Techniques showing such an evolution are more suited to monitor early aging.

No single CM method seems to be able to track the degradation at all stages. It is recommended to use a combination of techniques so long as ageing mechanisms are not sufficiently identified.

No general behaviour has been observed on long samples. Therefore, a condition monitoring method has to be defined or at least tuned for each cable.

Concerning aging test constraints, results have shown the combination of constraints (thermal and irradiation) can lead to significantly different behaviours than a single one (thermal). Synergistic effects should be considered with care in future test protocols.

In general, there is a need to establish the best experimental procedure for each of the test methods to get reproducible results.

Results obtained with some techniques (TGA, FTIR, density) need to be more deeply investigated. It is too early to draw conclusions.

Concerning reflectometry methods (TDR/FDR, LIRA) they do not seem to be mature enough at the moment to characterise global aging. Nevertheless, reflectometry could be interesting to detect “hotspots” or local mechanical defects.
1.3.11. Recommendations/Guidelines

At the end of the project, some guidelines and recommendations were given in order to do an ageing cable plan in a Nuclear Plant to evaluate the real ageing of cables. Some suggestions for future works needs have been also implemented in these Guidelines.

As part of that, deposits of sacrificial cable samples can be installed and periodically tested with local condition monitoring techniques which have proven capabilities in estimation of cable residual life (EAB, indenter), and afterwards compared with the results of electrical measurement techniques.

1.3.12. Proposed future work

As future recommended activities, it is proposed to perform more measurements on a limited number of cables/materials to access and get a deeper explanation of ageing mechanisms. The accelerated ageing protocols have to be adapted, probably with longer accelerated ageing test periods (conditions closer to those observed in NPPs) and also with a particular preliminary focus of the study on the evaluation of activation energy.

Some of the current experimental procedures are not robust enough to be useful (even when considering the classical mechanical techniques). As a consequence, further work should be considered to better establish test protocols in order to have reproducible and reliable results with as far as possible small standard deviation.

As a result of that, enough data will be obtained to allow to:

- Verify the correlation of technique with ageing.
- Correlate results obtained with new methods with results obtained with proven methods, in order to validate the new methods for the estimation of residual life and calculate the acceptance criteria (probably from the criteria already established in these conventional methods).

Synergistic effects of combinations of constraints should be considered in future test protocols. As part of that, the impact of $\beta$ radiation could be investigated in further studies.

Concerning chemical characterisation, some techniques (TGA, FTIR, density) need to be further and more deeply investigated to get access to the changes that occur in the materials.

Concerning electrical techniques, dielectric spectroscopy has shown promising results and should be investigated more deeply. Further investigations are also required concerning reflectometry. It seems difficult at the moment to access to the global ageing characterisation. Local defect detection and localisation is of interest when considering deviations observed in NPPs and perhaps less challenging. A future activity could be dedicated to determine how severe a local defect is and to improve the detection level of local defects.
1.4. Potential impact and main dissemination activities and exploitation of results

The cables are essential components of the nuclear power plants but there are only few experts in this field in the European Union. Moreover, these experts are not all in the nuclear industry but also spread in research centres or universities. They don’t have therefore many opportunities to meet and to maintain an excellence network. The FP7 EU funded ADVANCE project succeeded in gathering experts coming from the nuclear industries (utilities, cables manufacturer or research labs) as well as from universities.

To illustrate this networking achievement, the cooperation in the mobility and disseminations activities can be underlined and especially the mobility of young people. A special focus was given to education and training during the organised visits. All of the participants were very satisfied by this experience which was possible thanks to the financial support of the project. The contribution of these young scientists was highly appreciated by the different organizations.

Next to the promotion of contacts, experience and expertise were dealt among the partners. Several articles were published in cooperation between the universities and the research centres. Members of electrical utilities found that some ageing issues are common problems and are easier to solve in common, especially in the current difficult financial times.

Figure 18: Kick off meeting – Prague, January 2011
1.4.1. **Transmission and preserving the knowledge by educating and training students and young scientists**

Two options were proposed to fulfil this objective:

- The first one offered the opportunity to young scientists to participate to an exchange program supported by the research centres and the universities involved in the ADVANCE project. Thanks to the financial contribution of the European Commission, several grants were allowed to the participants in order to cover their subsistence and mobility costs. The young scientists who took part to the program were globally very satisfied by the exchanges. It was considered as a unique opportunity to improve their knowledge in very specific fields as well as to discover other organizations and people. The technical content of the work performed in the framework of those exchanges was at a high level and valuable for the partners.

- The second option was the implementation of a training seminar dedicated to the problem of cable ageing. It gave to the young scientists more perspective with respect to the work they performed for the ADVANCE project. They also found that there was a good balance between theoretical explanations and practical examples.
1.4.2. Promotion of the national and transnational mobility of students and young professionals

A mobility program for young scientists was set up by the partners. Based on the different proposals formulated, five young scientists applied for a grant involving EDF, UNIBO, UJV and the SCK.CEN (Nulife member) via Laborelec.

![Image of young scientists at NRI test facilities](image)

**Figure 20**: Young scientists at NRI test facilities

Besides this initiative, a training seminar was organized in the Nexans factory of Mehun-sur-Yèvre with a special focus on students and young professionals (see §1.4.3). It was greatly appreciated by the participants to have the opportunity to visit an industry and its research laboratories.

1.4.3. Organisation of a training seminar

The third action was the organization of a training seminar on CM diagnostic techniques for cable ageing assessment which has also been opened to external persons and publicized through ENEN website (European Nuclear Education Network, www.enen-assoc.org). The training has been divided in 2 parts: the first one dealt with nuclear cables qualification, cable design, polymers degradation, electrical properties and ageing indicators; the second one was about cable manufacturing with a guided visit of the Nexans production plant in Mehun. The training seminar was oriented towards students, young professionals and members of the ADVANCE organization. Four students asked for a special grant in order to attend the lectures given during the seminar. The interest of the community for this topic was confirmed by the presence of 29 scientists.

Next to this seminar, a large symposium was also organized by some partners, the MAI (Material Ageing Institute) and the EPRI (Electrical Power Research Institute). Several references to the ADVANCE program were made during this symposium and a several presentations were given by project members.
1.4.4. Provide links with NULIFE training activities
This action was achieved towards the NUGENIA and NULIFE excellence networks.

Coordinators and partners of the ADVANCE project had many contacts with members of the NULIFE excellence network and the NUGENIA association, especially for the mobility program and the training seminar for which the promotion was partly done through the NULIFE network. The contacts for the mobility program concluded in the participation of a PhD student from the SCK.CEN (NULIFE member).

1.4.5. Disseminate the acquired knowledge among the scientific community
A special focus was dedicated to the dissemination of the acquired knowledge among the scientific community. To support it, two axes were defined:

- In the academic field, fifteen articles were published with a reference to the ADVANCE project, six posters were presented during conferences and sixteen presentations were made during the project. Moreover, a training seminar was organized in the framework of the dissemination activities foreseen in the WP6 and a large symposium was also organized by some partners, the MAI and the EPRI.
- Collaborations were conducted with other international actors like the IAEA, the OECD NEA (CADAK group) and Atomic Energy Canada Limited (AECL).
1.5. Project website

Project website is available at [http://www.advance-fp7.eu](http://www.advance-fp7.eu)