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NUCLEAR CABLES AND LIFETIME SIMULATION

Carole MONCHY-LEROY, EDF R&D, (France), carole.monchy-leroy@edf.fr
Patrice THEROND,EDF SEPTEN, (France), patrice.therond@edf.fr

ABSTRACT

The aim of our studies is to appreciate the lifetime expectancy of cables installed in French nuclear power plants. For that, we follow the evolution in time of the elongation at break of sheaths and insulations of cables, in function of the temperature and dose rate. Experimental results obtained on cables test installed in the building reactor of Bugey during 1.3, 3 and 12 years are compared with simulation performed with the semi-empirical model based on chemical kinetic laws developed by EDF in the 90's. This study predicts a nuclear cable life expectancy upper than 60-year-old in service conditions.

KEYWORDS

EPR, Hypalon, kinetic model, mechanical and chemical analysis

INTRODUCTION

The ageing study of electric cables installed inside the building reactor of nuclear power plants is one of EDF's main concerns for many years. A semi empirical model based on the DAKIN's law was developed in the 90', to assess the evolution of elongation at break of the sheaths and insulation of cables, versus temperature and dose rate. This model applied to Hypalon and EPR materials was presented during Jicable in 1995. To coincide with these studies realized on materials with accelerated ageing conditions, test cables were installed for ageing in the reactor building of Bugey 4. Some samples were removed after 1.3, 3 and lately 12 years of aging on site. This paper presents the results of the different analyses done at the macro and microscopic level on test cables and leads to a comparison between the results from simulation and those from real ageing conditions, inaccessible conditions in a laboratory for such long period of time.

1. MACROSCOPIC ANALYSES

1.1 Identification of test cables

Test cables are EPR/Hypalon type cables K1 qualified similarly to those installed on site.

They were installed at the +20 meters level (near steam generators). Initially, different cable types were installed at that place : new cables and pre-aged obtained by thermal ageing at the temperature of 90℃ to 135℃ for 240 to 950 hours.

The test cables have been removed after 1.3, 3 and 12 years of ageing in the reactor building of Bugey.

1.2 Electric Analysis

Insulation resistance measurements have been performed on cables conductors (the core and the insulating envelop were taken separately and immersed in water). The measurement was performed between the core and the copper electrode immersed in water. A continuous tension of 500 Volts was applied during sufficient time to enable a stable measurement. At first, a visual inspection of the conductors is achieved.

Visual outcomes : Several pitting corrosion on the internal face of steel armour. No track of oxidation of the conductors

Insulation resistance : Ki > 60000 MΩ.km.

It seems that the EPR/Hypalon cables were submitted to corrosion phenomena as oxidation tracks are observed on the internal steel armour.

1.3 Mechanical Analysis

Operating Mode

The elongation and stress at break are determined on H2 type test tubes by applying the NF T 46002 norm using the following characteristics :

- distance between the jaws 50 mm,
- traction speed 250 mm/min,
- load applied of 0,2 kN.

Tests were performed in an air conditioned room at 20℃ +/- 1℃ and 50% +/- 5% of relative humidity.

Experimental Results

The two following tables present all the results of the mechanical tests done on the Hypalon sheath and the EPR insulation of the test cables.

The experimental results show the huge impact of the thermal pre-ageing, especially the one of 950 hours, on the residual mechanical properties of the Hypalon sheaths. The effects of pre-ageing seem negligible on EPR. The sheath plays perfectly its protective role, even against thermal solicitations.

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Ageing		t_0	+ 16 months	+ 36 months	+ 12 years
one	σ_r	17,3 ± 2,8	14,3 ± 6,1	17,3 ± 4,0	14,8 ± 0,5
	ε%	374 ± 2,5	402,7 ± 4,3	351,8 ± 4,0	318,6 ± 7,3
135℃ 240 h	σ_r	/	14,2 ± 3,3	17,2 ± 4,2	14,6 ± 0,1
	ε%	/	277,4 ± 3,7	246,3 ± 5,8	227,2 ± 0,1
135℃ 950 h	σ_r	/	9,6 ± 12,1	5,7 ± 7,6	10,7 ± 1,3
	ε%	/	97,9 ± 15,3	24,3 ± 15,0	114,8 ± 19

Table 1 : mechanical characterization results for HYPALON

Ageing		t_0	+ 16 months	+ 36 months	+ 12 years
one	σ_r	14,15 ± 2,9	10,7 ± 16,6	14,1 ± 2,8	10,8 ± 0,3
	ε%	309,6 ± 6,2	232,5 ± 42,4	294,0 ± 4,5	306,7 ± 7,6
135℃ 240 h	σ_r	/	11,5 ± 2,3	12,0 ± 2,8	10,8 ± 0,7
	ε%	/	303,8 ± 6,4	282,9 ± 5,3	281,1 ± 29
135℃ 950 h	σ_r	/	11,3 ± 1,9	11,7 ± 2,6	10,9 ± 0,6
	ε%	/	327,1 ± 4,6	279,7 ± 4,4	285,6 ± 21

Table 2 : mechanical characterization results for EPR

2. COMPARISON WITH THE 90' EDF MODEL

2.1 Mathematical formula

Experimental results obtained on Test cables, which were not pre-aged before their ageing in the building reactor of Bugey, were compared to the results obtained with the life expectancy model developed by EDF in the 90's [1]. Based on chemical kinetics, this model expresses the temporal dependence of a physical property according to variables like temperature (T) and irradiation dose rate (I). In the case of the evolution of the elongation at break, this temporal dependence can be written :

$$\frac{\varepsilon}{\varepsilon_0}=[1+(\beta-1).K_t(T,I).t]^{\frac{1}{1-\beta}} \quad \text{pour } \beta \neq 0;1 \qquad [1]$$

$$\frac{\varepsilon}{\varepsilon_0}=\exp[-K_t(T,I).t] \quad \text{pour } \beta=1 \qquad [2]$$

with $$K_t(T,I)=K_{th}(T)+K_r(T,I) \qquad [3]$$

and :

- ε the elongation at break at t, ε_0 the initial value,
- β characterizes the process of degradation responsible for ageing,

$K_t(T,I)$ corresponds to the constant of speed; it is a function of thermal Kth and radiative Kr contributions.

$$K_{th}(T)=k_0.\exp(\frac{E_a}{RT}) \qquad [4]$$

$$K_r(T,I)=k'_0.I^{\alpha}.\exp(\frac{-E'_a}{RT}) \qquad [5]$$

with :

- E_a and E'_a The energies of activation ($kJ.mol^{-1}$),
- k_0 and k'_0 The coefficients pre-exponential (J^{-1}).

The simulations were performed on materials Hypalon and EPR for average conditions of temperature and dose rate representative of inside conditions in the building reactor, temperature of 50℃ and a dose rate of 0,1 Gy / hou r, and with a set of values determined in previous studies in our laboratory (figures 1 and 2).

2.2 Application to Hypalon

For hypalon's sheath, the experimental results stemming from three Test cables of Bugey removed after 1.3, 3 and 12 years of ageing in the building reactor, are systematically above the curve of simulation obtained with the semi-empirical model developed by EDF in the 90s (figure 1). These results highlight the good behavior in time of mechanical properties for the cables sheath and allow to confirm the prediction of important and coherent life expectancy with the life expectancy of EDF power plants for this type of sheath in the normal conditions of temperature (50℃ and dose rate (0,1 Gy / hour) met in power plant.

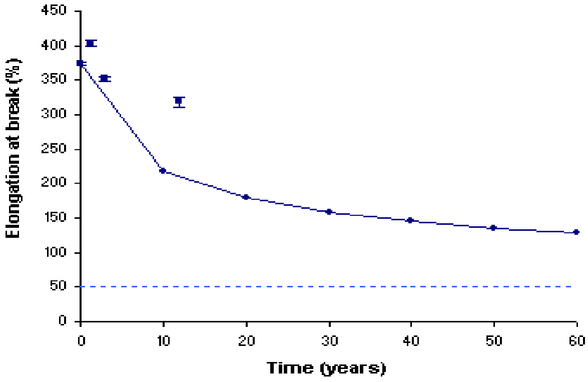

Figure 1: comparison of the experimental values (squares) to the values stemming from the model (curve)

2.3 Application to EPR

The same type of calculation was performed for the insulating material in EPR. The previous studies led to that type of material showed an influence of the formulation but also the rate of cristallinity on the results. And so two sets of extreme values for the model, were defined for materials rates of cristallinity of 5 and 40-50 %. The comparison of the simulations obtained with these two sets of values and the results stemming from analyses of the cables of Bugey brings to light an important difference (figure 2). Tests cables of Bugey present elongation at break sharply superior to the predictions established by the model.

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The observed differences between the modelling and the experimental results can be attributed to several factors such:

- the difference of formulation / cristallinity of the studied EPR (tests cables of Bugey and cables used to fit the model parameters,
- the conditions of ageing especially oxidation, are probably different between a test cable on-site installed and cables samples studied in laboratory.

However, whatever the origin of the observed differences is, the insulations EPR of tests cables of Bugey present excellent residual mechanical properties which allow to confirm the prediction of important and coherent life time expectancy.

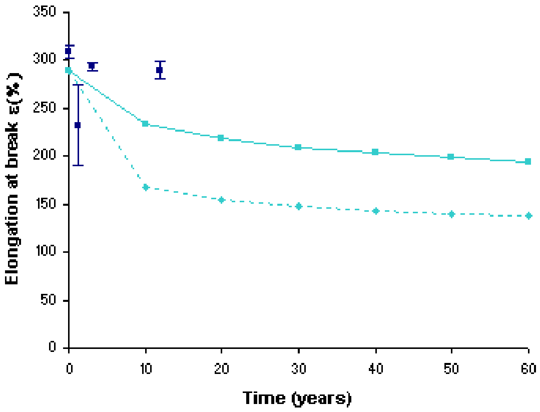

Figure 2: comparison of the experimental values (squares) to the values stemming from the model (curves)

3. MOLECULAR SCALE ANALYSES

The previous results based on the evolution of macroscopic properties are at present completed by an analysis at the molecular scale by infrared spectroscopy, DSC-OIT and RMN. The objective of these additional analyses is to study more accurately the oxidation of the aged materials.

3.1 DSC-OIT analysis

Measurements of oxidation induction time (OIT) were performed on sheaths and insulations of tests cables to correlate the ageing and the consumption of present antioxidants in the formulation of materials. The tests were realized according to the standard ISO 11357-6, 2002, following a well defined protocol:

- isotherm during 5 minutes under nitrogen in 40℃,
- heating under nitrogen from 40℃ to 210℃ at 20°/min,
- isotherm during 5 minutes under nitrogen in 210℃,
- isotherm under oxygen in 210℃,
- cooling under nitrogen from 210℃ to 40℃ at 20°/min.

The measurements on Hypalon could not be performed due to the evaporation of additives (probably some oil plastizers). This phenomenon pollutes DSC device and causes an oxidation of the DSC cells by evaporation of hydrochloric acid.

The results obtained on the fragments of available insulations are summarized in the following table :

	OIT (minutes)
Reference cable	102
Cable aged 12 years in building reactor	23
Cable aged 12 years in building reactor after a thermal pre-ageing (135℃, 950h)	15

The OIT results show that there are still antioxidants in the insulating material after 12 years of on-site ageing, even for samples having undergone a very drastic thermal pre-ageing. This confirms the good behaviour in the time of EPR material.

3.2 Infrared spectrometric analysis

The analysis by infrared spectrometry (ATR) allows to follow the evolutions of the polymer at the molecular scale in particular the evolution of oxidation products like hydroperoxides species. The absorption bands of the oxidation products are mainly situated in two spectral zones:

- 3600-3400 cm^{-1} = absorption of alcohols and hydroperoxides,
- 1800-1600 cm^{-1} = absorption of carbonyles products.

Experimentally, the study of these oxidation products represents two major difficulties :

- the bands of absorption relative to alcohol and hydroperoxide are not resolved on the IR spectra,
- the various carbonyl (acid, ketone, ester.) absorb at very close IR wavelengthes.

Most of the time, we use chemical transformations to move radically the absorption frequencies of OH of alcohol and OOH of hydroperoxide towards zones of the Infrared spectra better resolved. It is the case of the treatment by the monoxide of nitrogen NO that allows to transform hydroperoxides into nitrates which absorption frequencies are perfectly defined:

POOH + NO > POO° + HNO
POO° + NO > [POONO] > $PONO_2$ (nitrates)

There are three characteristic bands of absorption for nitrates according to their degree of replacement:

- 1642, 1279, 860 cm^{-1} for primary nitrates,
- 1633, 1277, 867 cm^{-1} for secondary nitrates,
- 1630, 1300, 860 cm^{-1} for tertiary nitrates.

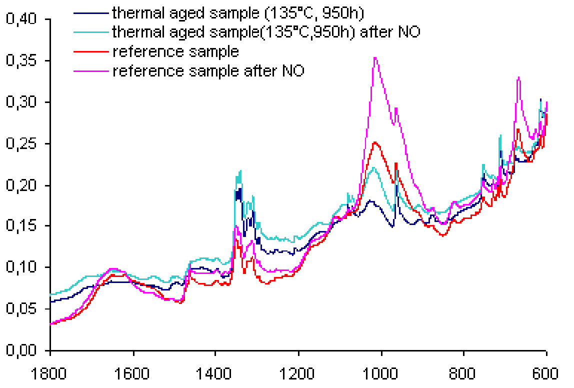

Figure 3 : FTIR spectra of the sheath Hypalon before and after NO treatment.

Hypalon sheath and insulations EPR of test cables were analyzed by Infrared spectrometry before and after NO treatment (figures 3 and 4). The obtained spectra do not reveal any peak induced by the oxidation products :

- for EPR, it is in agreement with the OIT measurements bringing to light the residual presence of antioxidants even on the pre-aged samples,
- for Hypalon the result is more difficult to interpret because the OIT analysis could not have been performed and because the observations at the macroscopic scale indicate a modification of the material.

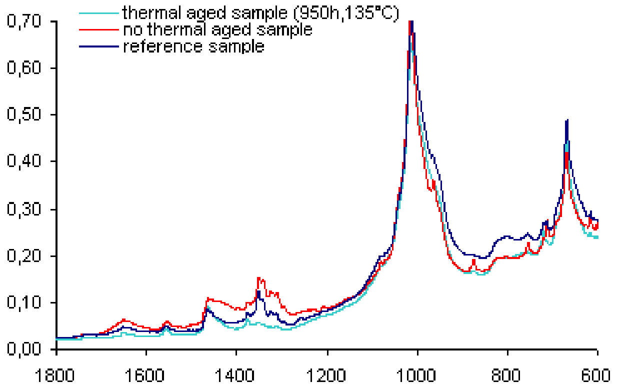

Figure 4: FTIR spectra of EPR insulation after NO treatment

The case of Hypalon certainly shows the limits of sensitivity of this analysis on industrial materials strongly formulated (fillers, additives).

3.3 NMR analysis

Forward-looking RMN tests are in progress to study the evolution of the radicals formed during the ageing. The analysis by RMN of the solid can notably bring information on:

- the identification and the quantification of the chemical evolution of the oxidized materials,
- the macromolecular mobility by relaxation measurements,
- the determination of the nature and the mobility of the chemical species close to fillers by RMN 2D technique.

3.4 New kinetic model

These experimental results will be the subject, in a near future, of a comparison with the first results stemming from the new model of kinetics oxidation of polymers, at present developed in partnership EDF-ENSAM Paris. The objective is to approach life time expectancy of nuclear cables by means of a complete physico-chemical ageing scheme rather than semi-empirical law used for the moment. This model is based on equations representative of the reactions of thermo-oxidation and radio-oxidation occurring during the ageing.

In a first step, the choice of the study material concerned polyethylene because it has the double interest to be used as insulating material in nuclear atmosphere and to have given place to a plentiful literature. However, the aimed objective is the prediction of life expectancy of polyolefins (i.e. presenting a fraction of PE ≥ 70 %) such as the industrial copolymers EPR and EPDM, EVA or still the Hypalon.

The first works elaborate a kinetic model allowing to predict the life expectancy of pure PE, for a large temperature (between 20℃ and the melting point) and dose rate range. For any time, the developed model predicts the concentration of various chemical species present in the polymer at the microscopic scale. The first results obtained with this model show a life expectancy of pure EP of the order of 20 years in regime of thermo-oxidation [2].

The current works consist in developing the model on one hand to the case of PE stabilized by antioxidants and on the other hand in co-polymers like EPR. For more information concerning the kinetic model of oxidation, the reader will refer to the article of X. Colin, ENSAM Paris, presented to Jicable2007.

CONCLUSION

The mechanical analysis, elongation at break, and functional measurements like insulation resistivity, show the excellent residual properties of EPR / Hypalon cables, aged 12 years in the building reactor of BUGEY. Only cables having undergone a strong thermal pre-ageing before their installation on the site of Bugey, present weaker mechanical characteristics but by maintaining good functional properties - it is necessary to note that this pre-ageing is not representative of a particular ageing situation but operated as an extreme condition for the materials.
These results bring to light their good behaviour in time. A comparison of the experimental results with the simulations of the model of life expectancy allows to estimate an important and coherent life expectancy of cables with the life expectancy of EDF power plants for the average conditions of temperature (50℃ and dose rate (0,1 Gy/h).

The analysis at the macroscopic and microscopic scales will allow to have a new and original approach of the life time expectancy of cables. We shall obtain, beyond the simple report of the good adequacy of our semi-empirical model, a finer understanding of the chemical phenomena, in particular the oxidation, induced by the ageing.

The objectives of EDF with this double approach are to have a numerical model allowing to simulate the ageing of the organic materials of cables insulation with pertinent results and for a cost much lower than with an empirical or semi-empirical method.

REFERENCES

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GLOSSARY

Hypalon : chlorosulfonated polyethylene
EPR : Ethylene Propylene Crosslinked