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Aging Modeling of Low-Voltage Cables Subjected to Radio-Chemical Aging

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ABSTRACT This article presents the development and application of a modelling approach based on quantities obtained from mechanical and electrical tests to assess the aging of low voltage cable insulation for nuclear applications. In order to obtain experimental data needed for the establishing of the models, accelerated aging is performed on coaxial cables. The first part of this paper focuses on the development of a predictive modelling for mechanical properties; this allows the evaluation of the Dose to Equivalent Damage (DED) as a function of the aging stress (dose rate). However, the use of mechanical tests for cable aging assessment presents some problems, being such tests destructive for the insulation and potentially affected by local defects. The novelty of this work lays on the introduction of a new model, allowing the definition of the end-of-life point in terms of electrical non-destructive tests. The second part of this article presents the development of aging modelling of cable insulation and correlation with experimental data obtained at different stresses, which allow the estimation of the expected life of the cable under test to be derived from diagnostic measurements of electrical properties like, e.g, tanδ. Finally, the application of the proposed life model to two typical real-condition nuclear environments is presented and discussed.

INDEX TERMS Modeling of insulations, LV cables, nuclear cables, radio-chemical aging, predictive modeling, cable life modeling, polymer aging, extruded cables.

I. INTRODUCTION

Current nuclear power plants (NPPs) were mainly built during the '70s and '80s and, since their designed life is supposed to be about 40 years, they are now approaching their designed end-of-life [1]–[4]. For this reason, NPP regulators are willing to extend the current NPP life to other 20, or possibly 40, years. To do so, all the equipment inside the nuclear environment needs to be verified or qualified for another 30–40-year term. Among them, low-voltage (LV) cables are very important due to their abundance and role inside the NPP. Indeed, these cables are mainly used to deliver power, control, and measurement signals to various part of the plant [5], and their amount is estimated in about 1500 km per each existing NPP.

Therefore, in order to ensure and guarantee a suitable life extension of NPPs, the health and suitability of the installed LV cables should be verified. However, due to the extensive application of such cables, aging conditions are not constant throughout the cable length, leading to a difficult *a priori* aging management of these cables [1], [6]. In point of fact, they are subjected to different aging stressors depending on the zone of the NPP they are placed, i.e., high temperatures, radiation, moisture and different mechanical stresses [6]–[11]. For this reason, a continuous monitoring of the cable status is strongly recommended in order to prevent unexpected cable failure. Among several methods, a non-destructive condition monitoring technique, which could be performed on site, is highly desired.

The following Research is part of the H2020 EU Project called "TeaM Cables". This aims at providing NPP operators with a novel methodology for efficient and reliable NPP cable aging management, developing, among others, acceptance criteria for nondestructive techniques and efficient cable aging modelling and algorithms based on multiscale models.

Up to know, there is no strictly defined end-of-life criterion to assess the health of LV cables. A commonly accepted rule is described in a report issued by IAEA in 2000 [12].

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In this report, lots of LV cables for nuclear applications have been subjected to accelerated aging and tested before and after a Design-basis event (DBE), e.g., a Loss of Coolant Accident (LOCA). It has been demonstrated that all the cables which could withstand the simulation showed an elongation-at-break (EaB) higher than 50%. For this reason, nowadays, the chosen end-of-life criterion is usually based on mechanical tests and, particularly on EaB, which must be higher than 50%, in order to guarantee the delivering of communication of data signals and the equipment power supplying also in case of accidental conditions.

Nevertheless, this criterion faces different problems, among them we could cite the fact that it is not representative of the entire cable and it is based on a destructive testing technique. Moreover, the recent advances in polymer science underlined the limitations of this technique which does not consider e.g., complex polymeric compounds and the actual electrical application of these cables [11]–[14].

This latter reasoning raised the possibility to explore other condition monitoring techniques which can overcome the EaB limitations. Among the different techniques, dielectric spectroscopy has been gaining more and more interest due to its numerous advantages, i.e., it is a nondestructive technique, it refers to the entire cable insulation and it has been successfully correlated to the aging development of the cable properties at various scales [3], [16]–[20].

However, the use of the tensile stress technique over many years allowed the development of a copious number of modelling approaches aiming at predicting the life of the LV cables through EaB [12]. Major part of them considers the applied stresses (e.g., dose rates) as constant throughout the cable life, which does not often occur in real conditions. As a matter of fact, seasonal environmental changes, dose bursts and accidental conditions can significantly modify the values of the aging stresses affecting the cable insulation.

The original contribution of this paper is given by the improvement of one of the most common predictive models for NPP cables by using only nondestructive testing techniques, particularly dielectric spectroscopy. The resulting predictive model is then applied to a nuclear-scale coaxial cable and expanded to become an aging model. This latter can account also for time-variant stresses which can occasionally occur during operation of a NPP.

II. EXPERIMENTAL SETUP

A. CABLE SPECIMENS

In this article, coaxial cables especially manufactured for the project's purposes are investigated. The geometry of these cables is reported in Figure 1. Cable specimens are made up of five parts: (1) the inner conductor (copper, Ø 0.88 mm), (2) primary insulation (Silane cross-linked polyethylene (Si-XLPE), thickness 1.05 mm), (3) polymeric film, (4) shielding (copper wire braid) and (5) external sheath (rubber). Each cable sample is about 50 cm long.

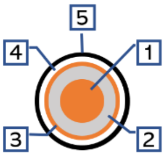

FIGURE 1. Multilayer structure of coaxial cables under investigation.

It is evident that the cable part to focus the analyses on is the primary insulation, since it guarantees the cable proper working, and it is the most subjected to the aging process. The Si-XLPE is the most common XLPE compound used for low-voltage cable because it is one of the fastest and cheapest technology for crosslinking PE. However, in order to simulate a typical industrial-scale cable, additives are included inside the polymeric compound. Table 1 reports the chemical composition of the analyzed compound.

TABLE 1. Specification of the insulating compound. *(phr - per hundred resin).*

Component	Name	Concentration
Polymer matrix	Silane XLPE	-
Primary antioxidant	Irganox ® 1076	1 phr
Secondary antioxidant	Irganox ® PS802	1 phr

B. ACCELERATED AGING

Cables were subjected to accelerated aging to replicate typical aging conditions inside nuclear environments. The proposed model suggests the use of three different dose rates for cable aging. Each dose rate should be one order of magnitude higher than the previous value. For this reason, cable specimens were aged under high (400 Gy/h), medium (66 Gy/h) and low dose rate (7 Gy/h). The aging temperatures were close to ambient (47°C and 21°C), so that the contribution of thermal aging can be considered as negligible. Radio-chemical aging was performed in Panoza and Roza facilities at UJV Rez, Czech Republic, through a ^{60}Co γ-ray source. Aging characteristics and durations are reported in Table 2.

TABLE 2. Accelerated aging conditions.

Aging type	Aging properties		
	Dose rate (Gy/h)	*Withdrawal time (h)*	*Total absorbed dose (kGy)*
Low	7	3456	48
Medium	66	864	286
High	400	167	334

C. TENSILE STRESS TESTS

Tubular specimens of the minimal total length L of 60 mm were prepared after transversal cutting the insulated wire samples to pieces with length of about 65 mm.

Tensile tests were performed by using an Instron 3366 machine equipped with pneumatic grips with smooth steel. Specimens were placed between two gauges and the following test parameters were applied:

a) Testing (cross-head) speed: 50 mm/min
b) Initial grip distance: 30 mm
c) Rate of tensile test data acquisition: 50 mm/min

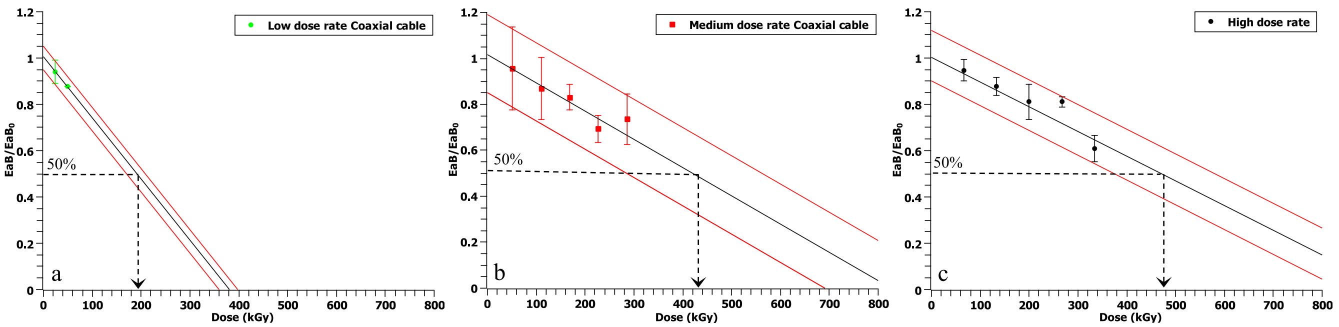

FIGURE 2. Relative elongation-at-break versus the total absorbed dose. (a) Low dose rate, (b) Medium dose rate, (c) High dose rate.

The test is considered as completed when the breaking of the sample occurs [21], [22]. Each test has been repeated five times, in order to take into account possible specimen inhomogeneities.

As a result, the stress/strain curve is registered and obtained, from this it is possible to calculate the ultimate elongation value (EaB) through the following equation:

$$\mathbf{EaB}\,(\%) = \frac{(\mathbf{l}-\mathbf{l_0})}{\mathbf{l_0}} \cdot \mathbf{100} \tag{1}$$

where l_0 and l are the initial and breaking useful lengths of the specimen, respectively.

D. DIELECTRIC SPECTROSCOPY TESTS

Dielectric spectroscopy measurements were performed by means of the Novocontrol Alpha Dielectric Analyzer v2.2. The tests were performed at 50°C, setting a voltage of 3 V_{rms} and a frequency range from 10 mHz to 1 MHz

For cable samples, the inner conductor was supplied with the applied voltage while the output signal was taken from the shielding layer. Each result is the average of five subsequent measurements.

III. PREDICTIVE MODELLING OF CABLE PROPERTIES

A. PREDICTIVE MODELING OF MECHANICAL PROPERTIES

As reported in the introduction, the most common predictive models for LV cables are based on mechanical tests. In particular, one of the most used technique is based on the power law extrapolation method [22]–[24], initially proposed by IAEA [12]. This approach is built through the extrapolation of test data obtained over a range of dose rates under isothermal conditions in air. The obtained data are then used to determine end point criteria at the service dose rate through graphical extrapolation.

In order not to face diffusion limited oxidation (DLO) [25]–[27] and, consequently, the premature mechanical failure of the analyzed material, the maximum dose rate at which homogeneous oxidation occurs must be assessed. Once selected, at least two (preferably 3) dose rates should be chosen, as in the case here considered.

This modeling procedure, which showed to be feasible on elastomers and thermoplastics, is based on the evaluation of the EaB with aging. To establish the end-of-life dose value per each dose rate, the relative elongation EaB/EaB_0 is plotted as a function of the absorbed dose (EaB_0 is the value of elongation at break of the unaged specimen), see Figure 2.

As reported in the introduction, a commonly accepted end-of-life criterion is EaB >50% (EaB absolute value). However, in this work it has been chosen to use a more conservative criterion, also proposed in IEC 60216-2, that is 50% of the initial value of the property (EaB relative value). Obviously, the EaB of the installed cables must be initially assessed in order to obtain the real limit value of the property (end-of-life point).

For some coaxial cables, the inner conductor could not be removed without damaging the insulation due to aging condition severity. Therefore, only two experimental points referred to e.g., the low dose rate condition, are reported here. After plotting, a linear regression line is drawn in order to obtain the end-of-life point at $EaB/EaB_0 = 0.5$. In addition, due to the confidence intervals of the EaB measurements, other two lines are drawn corresponding to the lowest and highest values of registered EaB/EaB_0, respectively. Consequently, the entire experimental dataset is placed inside the built confidence intervals.

The dose (kGy) values corresponding to the chosen end-of-life criterion, namely the Dose to Equivalent Damage (DED) are summarized in Table 3. Similarly, the dose values related to the upper and lower limits at $EaB/EaB_0 = 0.5$ are registered (Table 3). The obtained DED values are then plotted as a function of the dose rate in a logarithmic plot, see Figure 3.

Some materials, such as polyolefins show a linear behavior permitting the extrapolation to lower dose rates. This quantity can be formally written as:

$$\mathbf{DED} = \mathbf{K} \cdot \mathbf{DR^n} = \mathbf{159} \cdot \mathbf{DR^{0.19}} (\mathbf{kGy}) \tag{2}$$

where DR is the dose rate; K and n are regression parameters, found experimentally, related to the specific material under test. The parameter n often ranges between 0 and 0.3. In the case of the considered coaxial cable $K = 159\ kGy$ and $n = 0.19$.

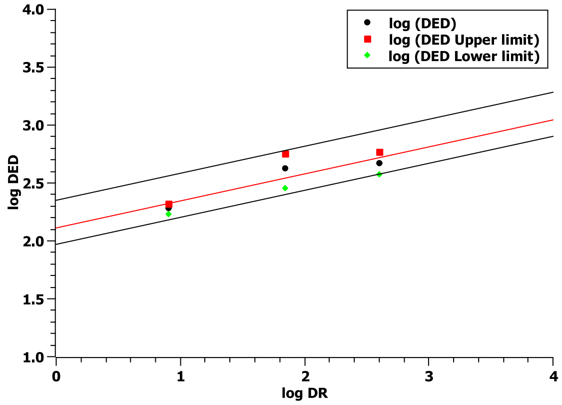

FIGURE 3. DED as a function of dose rate (DR).

TABLE 3. Dose to Equivalent Damage (DED) values for the three aging conditions considered.

	Regression DED (kGy)	Upper limit	Lower limit
Low	193	208	171
Medium	422	565	287
High	472	585	377

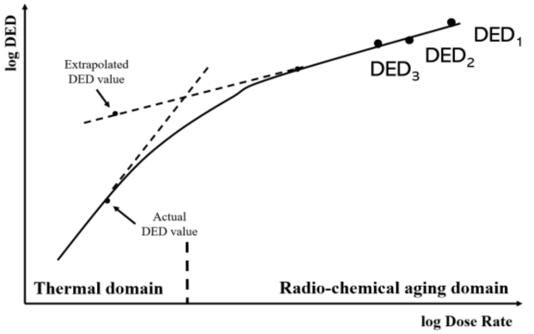

FIGURE 4. Limitations and extrapolation of DED near thermal aging limit.

As expected, the DED values increase as we increase the dose rate the cables are subjected to. The reason for that could be related to the fact that high dose rates bring to abrupt variation of the absorbed dose with little variations of the mechanical response, resulting into higher DED values.

This method permits the evaluation of polymer behavior with aging at very low dose rates. However, the threshold value, at which the radiation effects become dominant over the thermal aging effects, must be assessed.

In the logarithmic plot of DED vs. dose rate, obtained through the power law extrapolation method, the thermal-dominant area would be represented by a straight line with unitary slope [12]. In point of fact, the extrapolation of DED values within the thermal dominated region would be in certain cases too high. Hence, often two sets of data are used (thermal and radiation aging data) depending on the dominant stress in the investigated region. A schematic of this behavior is reported in Figure 4.

B. PREDICTIVE MODELING OF ELECTRICAL PROPERTIES

The novelty of this work lays on the possibility to upgrade the above-described predictive modelling using electrical nondestructive tests [23].

The chosen electrical quantity is the dissipation factor tanδ, which is a frequency dependent parameter. Among the various frequency values, 100 kHz was chosen since it is shown in literature [15], [16] and demonstrated in our previous works [3], [18], [29], to well represent the cable aging state and, thus, feasible to be used as an aging marker for cables.

The trend of tanδ is plotted as a function of absorbed dose, for the aging at different dose rates (Figure 5). Then, a linear regression line is built per each considered condition aiming at determining a tentative value of the electrical property at higher doses.

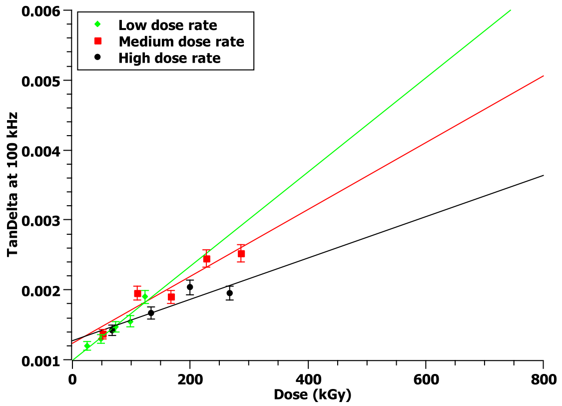

FIGURE 5. Dissipation factor at 100 kHz as a function of the total dose for the considered coaxial cable.

As presented in [3], [29], [30] during the first aging period various microstructural modifications i.e., removal of cross-linking by-products and antioxidant migration, can occur. These events are not related to the aging development of the insulation. For this reason, the initial tanδ value has been removed from the dataset, resulting into a monotonous trend of the property.

Once DED values are obtained through the method described in *Section III.A*, it is possible to graphically acquire the tanδ end-of-life points, finally providing the values of dielectric losses corresponding to the material failure. The found values will be the end-of-life points of the cable dielectric losses, i.e. tanδ at DED (tanδ_{DED}). Therefore, it can be claimed that if the cable shows an EaB larger than 50%$_{rel}$, then tanδ <tanδ_{DED} is verified. Consequently, it does not need to be replaced considering the chosen cable end-of-life criterion.

In addition, the values of lower and upper limits of tanδ corresponding to the relevant bounds of DED are derived in order to keep into account measurement uncertainties. Table 4 reports the acquired tanδ values.

These values are then displayed in a logarithmic plot as a function of DR, see II. Note that the y-axis is the absolute

TABLE 4. **Dissipation factor values corresponding to the dose equivalent to damage.**

	tanδ at DED	Upper limit	Lower limit
Low	0.0023	0.0024	0.0022
Medium	0.0032	0.0039	0.0026
High	0.0026	0.003	0.0023

value of the limit tanδ, since applying the logarithm to tanδ results into a negative amount.

It has been found that, also in the case of tanδ, a power law well fits the obtained tanδ_{DED} data:

$$\mathbf{tan}\delta_{\mathbf{DED}} = \mathbf{c}\cdot\mathbf{DR^{s}} = \mathbf{2.36\cdot10^{-3}\cdot DR^{0.03}} \tag{3}$$

Again, *DR* is the dose rate, *c* and *s* are experimental parameters proper of the material under test at a given temperature.

The obtained equation can allow the health assessment of the cable insulation under test, in terms of electrical properties, entirely through non-destructive electrical testing technique.

From Eq. 3, it is possible to notice that the slope parameter *s* is close to zero for the considered data. As a result, the variation of the limit value of tanδ with dose rate is quite small. This interesting behavior suggests that the limit value of the electrical property (tanδ_{DED}) is not dependent on the aging stress (dose rate), at least in the value range here considered, but it can be considered as an insulation property, depending only on the type of polymeric compound.

It could be reasonable to consider the electrical property limit values for the considered cable as the average of the values obtained from Eq. 3. It results $tan\delta_{DED} = 2.7\cdot10^{-3}$.

IV. AGING AND LIFE MODELLING OF CABLE

A. AGING MODELLING APPROACH

The life model approach used in this work is extensively described in [32]. For the sake of brevity, in this section only the key steps which are needed to formalize the used life modelling approach are reported.

Aging is defined as a function of a diagnostic property, which changes during time due to aging stress. Formally:

$$\mathbf{A(t)} = \boldsymbol{f}\,(\mathbf{p}) = \int_{0}^{t} \boldsymbol{R\,(S)\,dt} \tag{4}$$

where S is a generic stress, t is the time, p is the analyzed property and $R = {}^{dA}\!/_{dt}$ is the aging rate, which only depends on aging stress (dose rate in the case here considered).

Once the property p reaches its limit value (p_L), cable failure occurs. When this happens, aging time t becomes lifetime duration L.

Consequently, it is possible to derive the aging limit value A_L from:

$$\mathbf{A_L} = \boldsymbol{f}\,(\mathbf{p_L}) = \int_{0}^{\mathbf{L}} \mathbf{R\,(S)\,dt} \tag{5}$$

If the stress is constant over time, like in the case here considered, Eq. 4 and 5 become:

$$\mathbf{A(t)} = \boldsymbol{f}\,(\mathbf{p}) = \mathbf{R\,(S)\,t} \tag{6.a}$$

$$\mathbf{A_L} = \boldsymbol{f}\left(\boldsymbol{p}_{\mathbf{L}}\right) = \mathbf{R\,(S)\,L} \tag{6.b}$$

It is worth noting that, under these circumstances, *A(t)* = *f(p)* linearly varies with time. Finally, if we divide Eq. 6.a by Eq. 6.b, we can make the dependance between *A* and time explicit. Formally:

$$\mathbf{A(t)} = \mathbf{A_L}\left({}^{\mathbf{t}}\!/_{\mathbf{L}}\right) \tag{7}$$

Plotting Eq. 7, it is possible to observe the trend of the aging function with aging time. The intercept value of the aging function $A(t)$ with its limit value A_L, returns the lifetime value corresponding at the considered stress.

B. HYPOTHESIS FOR THE APPLICATION TO THE COAXIAL CABLE

In *Section IV.A*, the fundamentals of the used life model approach have been described. However, in order to apply the proposed modelling method to the coaxial cable, we need to get rid of the abrupt drop of the electrical property between the neat and early aged cable. As reported in the *Section III,* it has been proved that the first aging period is mainly relatable to microstructural modifications of the cable, such as antioxidant migration, which do not cause significant aging.

In this way, considering that the dose rates applied throughout the aging are constant, tanδ increases linearly with aging time, as it occurs with applied dose (Figure 5). Thus, it would be possible to consider the property itself as the aging function, which must be a function of the property linearly varying with time (see eq. (6.a)). However, in order to verify all the requirements, we define $A(t)$ as the variation of the property (tanδ) with respect to the value corresponding to the first aging period (tanδ_1), according to the abovementioned hypothesis. Consequently, the x-axis (reduced time) is given by t- t_1 where t is the aging time and t_1 is the time referred to the 1st aging period. This aims at relating the initial tanδ value (tanδ_1) with reduced time equal to zero. The aging function can be written then as:

$$\mathbf{A\,(t)} = \mathbf{tan}\delta - \mathbf{tan}\delta_{\mathbf{1}} = \mathbf{R(S)}\cdot(\mathbf{t}-\mathbf{t_1})\ \text{with } \mathrm{t} \geq \mathrm{t_1} \tag{8}$$

Through Eq. 8, it is possible to verify all the demanded requirements, e.g., *A(t)* = *0* for $t = t_1$, $A(t)$ linearly varies with aging time.

The value of tanδ_1 has been chosen as constant among the different dose rates. This should be usually verified since the initial value of aging of the cable depends only on the insulating compound.

As reported in *Section III.B,* the value of tanδ corresponding at the cable crisis, hence when $t = L$, is tanδ_{DED}. Hence, the limit value of the aging function $\mathrm{A_L}$ is defined as (from Eq. 6.b):

$$\mathbf{A_L} = \mathbf{tan}\delta_{\mathbf{DED}} - \mathbf{tan}\delta_{\mathbf{1}} = \mathbf{R\,(S)}\cdot(\mathbf{L}-\mathbf{t_1}) \tag{9}$$

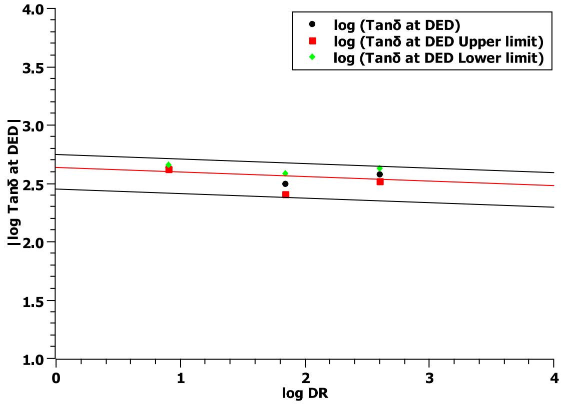

FIGURE 6. Dielectric losses at DED as a function of DR (logarithmic scale).

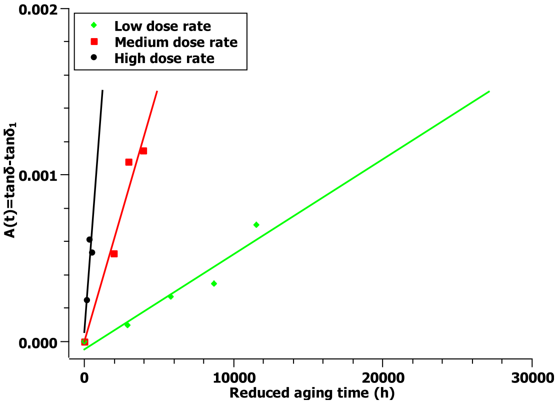

FIGURE 7. Aging function versus reduced aging time at different DR.

C. MODEL RESULTS ON COAXIAL CABLE

The value of the aging function limit value A_L defined by Eq. 9 results to be constant. Indeed, substituting the obtained $\tan\delta_{\mathrm{DED}}$ and $\tan\delta_1$ (from experimental data), we obtain that for the considered coaxial cable:

$$\begin{aligned} \mathbf{A_L} &= \mathbf{\tan\delta_{DED} - \tan\delta_1} \\ &= \mathbf{2.7 \cdot 10^{-3} - 1.2 \cdot 10^{-3} = 1.5 \cdot 10^{-3}} \end{aligned} \tag{10}$$

Then, it is possible to plot the aging functions $A(t)$ as a function of the reduced aging time, according to Eq. 6.a (Figure 7). It should be observed that the lines stop at $A(t) = A_L$.

D. PARAMETRIC STUDY OF THE AGING RATE R(S)

From Figure 7, it is possible to notice that, as we increase the aging severity, the slopes of the aging function curves ($R(S)$) increase. Contextually, it is possible to perform a parametric study of the aging rate (the slope of the aging function $A(t)$).

It is generally accepted to assume a power law for $R(S)$, as already reported in [32]. In the case here considered, the stress reaching the insulation is the dose rate. Hence, it could be formally written:

$$\mathbf{R(S) = R(DR) = R_0 \cdot \left(\frac{DR}{DR_0}\right)^k} \tag{11}$$

where R_0 and n are exponential factors which are function of the cable properties (e.g. chemical compound and geometry), DR_0 is a reference dose rate, set equal to 1Gy/h in order to obtain a dimensionless exponential argument.

For the considered coaxial cable, it results that $k = 0.766$ and $R_0 = 1.2 \cdot 10^{-8} h^{-1}$.

From the obtained equation, it is possible to get the values of the aging rate for different dose rates e.g., by extrapolating the values to the service conditions (very low dose rate) or by considering particular high dose bursts which will be accounted in the following of this paper, see Figure 8.

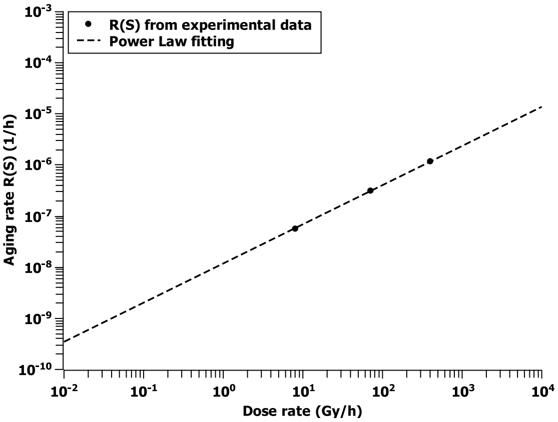

FIGURE 8. Aging rate R(S) trend vs applied DR.

Moreover, the parametric analyses could be significantly helpful during cable condition monitoring. Indeed, it usually occurs that the actual dose rate affecting the insulation is not constant towards the cable service life, due to the occurrence of different events e.g., maintenance, dose bursts and accidents. Hence, it would be difficult to efficiently predict cable maintenance, as models usually consider constant aging stresses. Under these circumstances, periodical tanδ measurements would allow a better evaluation of the remaining life. As an example, it would be possible to adjust the life curve in the case of variations of external aging conditions e.g., dose rate bursts due to accidents. This would lead to a more efficient assessment of the expected lifetime of the cable under test, scheduling maintenance in an efficient way.

E. LIFE MODELLING APPROACH

From Eq. 6.b, it is possible to obtain the lifetime once R(S) is known. Considering the hypothesis made for the coaxial cable, the cable lifetime reduced by the initial aging time can be calculated. Formally:

$$\mathbf{L' = L - t_1 = A_L \cdot R(S)^{-1} = L_0 \cdot \left(\frac{DR}{DR_0}\right)^{-k}} \tag{12}$$

where k is the same exponential factor as in Eq. 12. L_0 is defined as the cable lifetime, reduced by the duration of t_1, when the stress is equal to DR_0 (1 Gy/h) and it is given by $L_0 = A_L{\cdot}R_0^{-1}$.

As reported in *Section IV.A*, the intersections between the aging functions and the given limit value (A_L), returns the values of the lifetime of the cable per each aging condition. For the coaxial cable considered, results are reported in Table 5.

TABLE 5. **Lifetime values for the three dose rates. Coaxial cable.**

	L-t_1 (h)	L (h)
Low	27,090	29,970
Medium	4,830	5,700
High	1,230	1,400

Eventually, it is possible to plot the life curve as a function of the impacting dose rate at constant temperature (Figure 9). As expected, severer aging stresses cause shorter lifetimes.

The depicted curve follows the already presented inverse power law (Eq. 12), with $k = 0.766$ and $L_0 = 1.25{\cdot}10^5 h$, as expected.

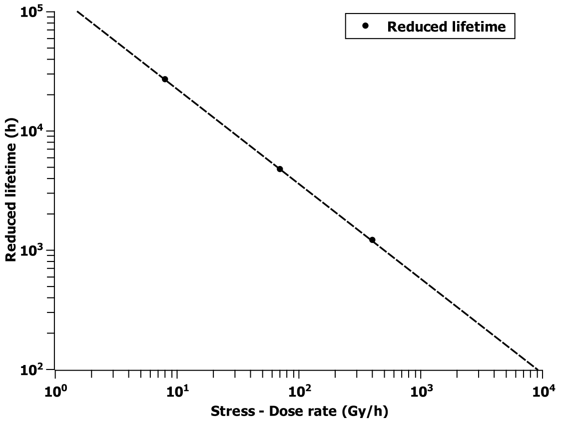

FIGURE 9. **Lifeline of the analyzed coaxial cable.**

V. CASE STUDIES

As known and discussed above, environmental conditions, e.g., dose rates and temperature, are not constant throughout the application life of LV cables. It is possible to define various conditions the cables are subjected to i.e., service, accidental, and failure conditions. In this section, two case studies are developed. In both cases the cables are subjected to service dose rate S_1 for 20 years. Then the cables have to face two different accidental conditions, simulating some typical DBEs.

Figure 10 reports a schematic of the simulating approach. The simulated events can be summarized as follows:

1. Cables are subjected to service conditions (DR_1 ~0.1 Gy/h) for 20 years. To the considered stress, it corresponds an aging rate $R(S_1)$;
2. After 20 years, an accident occurs, leading to a dose burst. Typical accident dose rates range between 1 and 3 kGy/h ($DR_2 \gg DR_1$). As a consequence, the aging rate becomes $R(S_2) \gg R(S_1)$;
3. After the accident, the cable is again subjected to service conditions with an aging rate $R(S_1)$.

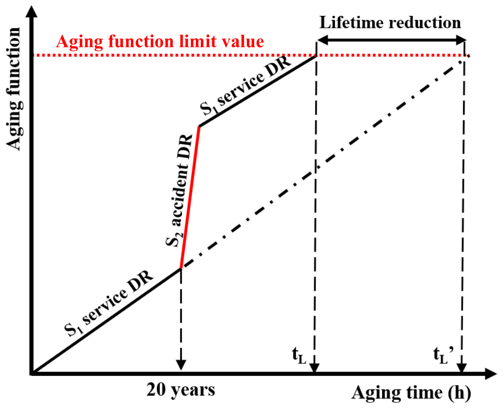

FIGURE 10. **Aging function trend with aging time. t_L is the lifetime of the cable subjected to accidental conditions, t_L' is the theoretical lifetime of the cable at service conditions.**

Given the applicability of the cumulative damage theory [22], [23], it would be possible to sum the aging levels obtained from the different stages. It is evident, that accidental stage (#2) brings to the abrupt increase of the cable aging, due to the significant stress increase. As a consequence, cables exposed to such conditions exhibit significantly decreased lifetimes with respect to cables subjected only to service conditions (dash-dot line).

Indeed, once the different cable aging reaches the corresponding limit value (red dashed line), it is possible to extrapolate the accident-exposed cable lifetime (t_L), which results to be dramatically reduced with respect to the case without accident (t_L').

A. SIMULATION OF THE SERVICE CONDITION

As presented, the desired simulation aims at obtaining the aging function of a 20-year aged cable under service conditions. From literature, a typical service condition for cables outside the containment area is ~0.1 Gy/h [6]. In order to apply Eq. 8, we need to define a time period corresponding to the first aging condition (t_1). For the sake of simplicity, we consider $t_1 = 0h$ in the following. Applying Eq. 11, we obtain the aging rate:

$$\mathbf{R\,(0.1) = 1.2{\cdot}10^{-8} \cdot 0.1^{0.766} = 2.056 \cdot 10^{-9} h^{-1}} \quad (13)$$

Hence, the aging calculated after 20 years (172,800 h) of service is (Eq. 6.a):

$$\mathbf{A\,(20y) = 2.056 \cdot 10^{-9}{\cdot}172,800 = 3.55 \cdot 10^{-4}} \quad (14)$$

From Eq. 6.b, we can obtain the theoretical lifetime of the given cable under service conditions:

$$\mathbf{L_{serv}} = \frac{\mathbf{A_L}}{\mathbf{R\,(S)}} = \frac{\mathbf{1.5{\cdot}10^{-3}}}{\mathbf{2.056{\cdot}10^{-9}}} = \mathbf{723,\,572h \sim 83years} \tag{15}$$

B. ACCIDENTAL CONDITION SIMULATION #1 (3 kGy/H)

A typical DBE can release ~600 kGy. In the following sections, we are simulating that accidental dose is achieved through two different dose rates, namely 3 kGy/h and 1 kGy/h. The aging rate related to the former dose rate is obtained applying Eq. 11:

$$\mathbf{R\,(3000) = 1.2{\cdot}10^{-8} \cdot 3000^{0.766} = 5.53 \cdot 10^{-6}h^{-1}} \tag{16}$$

Contextually, the aging related to the considered dose rate for a 200-h accident is (Eq. 6.a):

$$\mathbf{A\left(DBE_{3\mathit{kGy/h}}\right) = 5.53{\cdot}10^{-6}{\cdot}200 = 1.1 \cdot 10^{-3}} \tag{17}$$

Applying the cumulative damage theory [33], the final aging function becomes:

$$\mathbf{A_{tot1} = A\,(20y) + A\left(DBE_{3\mathit{kGy/h}}\right) = 1.46{\cdot}10^{-3} {<} A_L} \tag{18}$$

The obtained aging function value resulted to be lower than the limit value obtained through Eq. 10, claiming that the cable did not reach the chosen end-of-life criterion. Specifically, it is possible to conclude that the simulated aging condition would result into a cable EaB $>50\%_{\mathrm{relative}}$ and $\tan\delta < \tan\delta_{\mathrm{DED}}$.

After the accident condition, the cable is simulated to work under service conditions again (~0.3 kGy/h) until the reaching of the aging limit A_L. The resulting cable lifetime is obtained to be $L_1 = 192{,}455\ h \sim 22\ years$. Hence the lifetime reduction due to the simulated accidental condition is:

$$\mathbf{L_{reduction} = L_{service} - L_1 = 531,\,117h \sim 60.5years} \tag{19}$$

C. ACCIDENTAL CONDITION SIMULATION #2 (1 kGy/H)

Using the same approach described in the previous section, we can obtain the aging rate related to the considered dose rate (1 kGy/h) through Eq. 11.

$$\mathbf{R\,(1000) = 1.2{\cdot}10^{-8} \cdot 2000^{0.766} = 2.38 \cdot 10^{-6}h^{-1}} \tag{20}$$

Applying Eq. 6.a, the aging function related to the considered dose rate for 600 h becomes:

$$\mathbf{A\left(\mathit{DBE}_{1\mathit{kGy/h}}\right) = 2.38{\cdot}10^{-6}{\cdot}600 = 1.43 \cdot 10^{-3}} \tag{21}$$

Finally, we obtain the final aging function through the superimposition of the two aging events:

$$\mathbf{A_{\mathit{tot}2} = A\,(20y) + A\left(\mathit{DBE}_{1\mathit{kGy/h}}\right) = 1.8{\cdot}10^{-3} {>} A_L} \tag{22}$$

The obtained aging value is higher than the limit value obtained through the life modelling, thus indicating the failure of the cable according to the chosen end-of-life criterion.

D. DISCUSSION ON THE CASE-STUDIES

The two reported case-studies, obtained from the application of the aging modelling here presented, are significantly relevant for two main reasons. On the one hand, they efficiently depict real condition scenarios for the analyzed LV cables. On the other hand, they highlight how dose rate and aging time influence the final degradation state of the considered system. Specifically, it has been demonstrated that, besides equal absorbed doses, a longer aging period (a lower dose rate) may be more damaging than a higher dose rate aging (shorter aging time), resulting into a higher cumulative aging final value. This behavior is also confirmed by experimental data (Figure 5), where dielectric losses resulted to be higher as the aging stress (dose rate) is reduced.

The reason for that could be found in the fact that softer aging stresses, together with longer aging times, lead to homogenous aging throughout the insulation thickness. When this happens, thermo-oxidative reactions can take place reducing environmental oxygen and bonding reactive oxygen atoms with polymeric radicals. On the contrary, when the thermo-oxidative reaction kinetics is accelerated by significantly higher dose rates, environmental oxygen is not sufficient to accomplish all the occurring reactions. Due to this, oxygen molecules cannot reach the inner part of the insulation by diffusion phenomena. Macroscopically, this phenomenon, attributable to DLO [25], [26], causes a localized oxidized polymer zone on the outer layer of the insulation.

VI. CONCLUSION

In this article, the modelling of the mechanical and electrical response, together with an aging modelling approach, has been presented and discussed for LV cables used in nuclear environment. First focus has been paid on a life predictive modelling of mechanical quantities, from which DED values has been obtained as a function of dose rate. However, the limitations given by the using of mechanical destructive measurements for cable aging assessment raised the interest into using electrical nondestructive tests. Therefore, a predictive modelling based on electrical quantities has been developed considering the monotone behavior of $\tan\delta$ at 100 kHz with aging. A limit value of $\tan\delta$ calculated in correspondence of DED, namely $\tan\delta_{\mathrm{DED}}$ has been obtained. It is worth noting that $\tan\delta_{\mathrm{DED}}$ does not depend on the dose rate, but it seems more related to insulating material properties, at least for the dose rate intervals here considered.

Then, an aging model based on $\tan\delta$ has been developed. This could be able to evaluate the cumulative damage caused by changes of the dose rate due to abnormal and/or accidental conditions and estimate the residual life.

Two case-studies have been presented and discussed. The aging has been calculated for a 20-year-old cable under service conditions. Then, two different accidental scenarios with different dose rates but same absorbed dose have been discussed. It has been found that a lower dose rate applied for a longer period can bring to the cable to failure while in the other case can provide a dramatic reduction of residual life, even if the cable can be still kept in service. This aging modelling approach can be of great help in scheduling maintenance operations, in particular following an event which could be associated with the exposure of cable insulation to high dose rate of radiation.

Further development of this approach will include the introduction of aleatory stresses given by, e.g., accidental conditions through a Bayesian-based model and the development of a combined aging model which could account also for thermal stress besides radiation.

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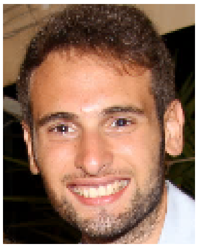

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