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Innovative Development and Application of a Stress-Strength Model for Reliability Estimation of Aged LV Cables for Nuclear Power Plants

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ABSTRACT

As a part of the H2020 EU Project called "TeaM Cables" - which has, among its aims, modelling reliability of nuclear power plant cables - the goal of this paper is to develop a model for the prediction of residual reliability of Low Voltage cables for nuclear power plants subjected to gamma radiation stress. The model estimates the probability that such cables withstand random stress overshoots in-service which can occur, e.g., in case of nuclear accidents.

Index Terms — **reliability, cables, nuclear power plants, stress-strength model**

1 INTRODUCTION

LOW voltage (LV) cables have been widely used in nuclear power plants (NPPs) for power transmission, control, instrumentation and communication. In service they are continuously subjected to a wide range of stresses which continuously degrade their insulation layer. Due to the catastrophic consequences of the aging-related accidents (e.g. loss of coolant accidents (LOCA)) of LV cables which support control and safety measures in NPPs and due to the lifetime extension plans of current NPPs as well, the stresses applied to LV NPP cables have been extensively investigated [1–9]. In particular, the possibility to extend the current NPP life to another 20, or possibly 40 years, raises the need to verify the conditions of the installed LV cables inside the plants.

Under these circumstances, the modelling of the cable reliability over its application time is a key issue in order to efficiently schedule the cable replacement inside NPPs. Therefore, an accurate model to predict the life and reliability of LV NPP cables in service is highly desirable.

In order to formalize a life model, an end-of-life (EoL) criterion must be established. Up to now, there is no EoL criterion which is strictly defined. A commonly accepted rule is based on destructive tensile stress techniques, particularly elongation at break (EaB). It has been demonstrated that if the cable under test retains an EaB>50%, it could fulfill its required function and withstand random accidental conditions (e.g., LOCA) [10–13].

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Even so, this criterion has to face 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. Therefore, different techniques have been recently taken into account for cable aging evaluation i.e., dielectric spectroscopy [2, 3, 14–16].

Nonetheless, due to the extensive application of the EaB end-of-life criterion, a number of predictive models have been realized during the recent years [2, 12]. Besides them, no model, based on a stress-strength approach, for the prediction of the residual reliability of LV NPP cables has been successfully developed and formalized, to our knowledge.

Hence, this paper aims at building a first step for the development of a stress-strength model for the prediction of the residual reliability of LV NPP cables, based on the typical risk-assessment procedure of probabilistic insulation coordination.

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

2 THEORETICAL-EXPERIMENTAL BACKGROUND

2.1 NORMAL OPERATION STRESSES VS. DIAGNOSTIC PROPERTIES

Cable insulation aging in NPPs is affected by both the dose of nuclear radiation absorbed by cable insulation over a certain aging time *t*, $D(t)$, and the temperature T of cable insulation, whose effect is also cumulated over aging time. This dose is cumulated over aging time at a certain dose rate *DR* (radiation dose/time) which might vary over time. If the dose rate *DR* is assumed as constant during the normal operation of the plant, the total dose $D(t)$ cumulated after a service time *t* of the plant is equal to:

$$D(t) = DR.t \quad (1)$$

It must be pointed out that nuclear radiation for the NPP LV cables under exam essentially consists of gamma radiation. During the nominal operation of the plant, dose rate DR_n and temperature T_n of cable insulation can be assumed as known and constant deterministic quantities, with the exception of anomalous events where stress overshoots may occur (see next Sub-section 2.2). DR_n and T_n are responsible for the irreversible degradation of cable insulation with time, which makes the electrical, thermal, and mechanical properties of cable insulation worse over time with respect to their initial values (relevant to the unaged cable or reached after a proper initial period of pretreatment/ conditioning/ training), until cable failure occurs. Thus, DR_n and T_n can be referred to as "stress factors". Hereafter, focus will be on dose rate as the main stress factor, while the role of temperature will be tackled in future works.

Under this assumption, failure takes place as soon as – due to the radiation dose cumulated over service at nominal dose rate DR_n – one (or more) so-called "diagnostic property" *P* overcomes a critical limit, P_L, also referred to as "end point". Prospective diagnostic properties should be associated with aging, namely in this specific case they should be more or less strictly correlated to the worsening of the performance of NPP cable insulation over aging time due to the applied stress factors. In particular, a diagnostic property must be monotone with aging time and the end point should correspond to such a change – either a decrease or an increase – of the diagnostic property with respect to its value for the virgin insulation at the starting time of aging that the insulation is no more able to perform satisfactorily [2, 17]. The selection of the diagnostic property *P* and of its end point P_L is referred to as "failure criterion". Typical properties chosen as diagnostic properties are, e.g.:

- electric strength, *ES*;
- tensile strength, *TS*;
- elongation at break, *EaB*;
- dissipation factor, *tgδ*.

After one (or more) appropriate diagnostic property is selected for NPP cables, the concept of dose-to-equivalent- damage can be introduced [12, 18]. The dose-to-equivalent-damage, *DED*, is defined as the value of cumulated dose that, if exceeded after service (=aging) time *t*, gives rise to such a damage to NPP cable insulation that the selected diagnostic property *P* overcomes its end point P_L, namely: $ES \le ES_L$, or $TS \le TS_L$, or $EaB \le EaB_L$, or $tg\delta \ge (tg\delta)_L$. It must be emphasized that nuclear radiation and temperature are not per se destructive stresses, thus the selection of the end point is to some extent arbitrary.

2.2 FOCUS ON THE CONCEPT OF DOSE-TO-EQUIVALENT-DAMAGE

The concept of dose-to-equivalent-damage, DED, deserves more attention and requires an analysis of the experimental results obtained on samples of NPP LV cables. In this respect, it is worth pointing out that the first diagnostic property to be taken into account, is *EaB*. The initial value of elongation at break of the unaged cable is referred to as e_0, while the actual *EaB* at a certain aging time is referred to as *e*. Three limit values of relative *EaB* - calculated as e/e_0 – have been selected as limit values of EaB_L to be overcome for failure to take place:

- 40% of e_0. Then failure is said to take place as soon as relative e/e_0 =0.4;
- 50% of e_0 (preferred criterion). Then failure is said to take place as soon as e/e_0 =0.5;
- 60% of e_0. Then failure is said to take place as soon as e/e_0 = 0.6.

The focus hereafter is on the preferred failure criterion e_L/e_0=0.5.

2.2.1 Materials

The samples here analyzed are low-voltage Instrumentation & Control I&C coaxial cables with XLPE insulation used in NPPs, especially designed for the TeaM Cables Project. The geometry of the investigated cables is reported in Figure 1. The specimens are made of five concentric layers (reported in the caption). In particular the primary insulation is a silane crosslinked polyethylene stabilized with 1 "Part per hundred rubber" (phr) primary antioxidant (phenol-based) and 1 phr of secondary antioxidant (thioether-based). Each cable specimen is about 50 cm long.

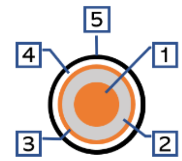

Figure 1. Multilayer structure of coaxial cables under investigation. (1) Conductor – copper, (2) Primary insulation – XLPE, (3) Polymeric film – PET, (4) Shielding – copper wire braid, (5) Sheath – low smoke zero halogen

2.2.2 Aging procedure

Analyzed cables were subjected to accelerated aging under three different dose rates, namely: high, medium and low dose rate corresponding to 400, 60 and 7 Gy/h respectively. In particular, radio-thermal ageing was performed in the Panoza (Medium and Low dose rate) and Roza (High Dose Rate) facility at UJV Rez, Czech Republic, through a ^{60}Co γ-ray source. Aging conditions are summarized in Table 1.

Due to the significantly harsh conditions, some cables aged under low dose rate aging could not be tested through tensile tests measurements. Indeed, the removal of the inner copper conductor from the primary insulation resulted to be not always possible.

Experimental graphs of e/e_0 vs cumulated dose *D* have been obtained at the three different dose rates [2]:

Table 1. AGING CONDITIONS

Aging type	Aging properties		
	Dose rate (Gy/h)	Sampling time (h)	Total absorbed dose (kGy)
Low	7	3456	81
Medium	60	864	286
High	400	167	334

- high dose rate HDR=400 Gy/h (see e.g. Figure 2 after [2]);
- medium dose rate MDR=66 Gy/h;
- low dose rate LDR=7 Gy/h.

The experimental graphs of e/e_0 vs D show:

- the decay of the mechanical property is linked to the degradation level of the considered material. This behavior is described in detail in [19]. Briefly reporting, the kinetics of the degradation reactions is ruled by the intensity of the aging stress, in this case radiation, leading to a faster polymer degradation with higher dose rates. This is expected since the dose rate may enhance oxidative reactions which bring to the depletion of the polymer properties at various scales e.g., mechanical strength, dielectric losses. Referring to the mechanical properties, the higher the aging severity - namely the dose rate - the faster the decrease of EaB with aging time.
- a sharp decrease of normalized elongation at break e/e_0 as the cumulated radiation dose D increases over aging time t, until e/e_0 reaches the end point e_L/e_0=0.5. The attainment of the end point yields the value of *DED*, as shown in Figure 2 for HDR. Similar values are obtained for MDR and LDR as well.
- a dependence of the slope of the "e/e_0 vs. D" plot on dose rate *DR*, i.e. on aging conditions. This is highlighted in Figure 3, which shows *DED* vs. dose rate *DR* as derived from Figure 2 for HDR, as well as from similar figures for MDR and LDR.
- the random nature of *DED*, emphasized by the upper and lower confidence bounds of the regression lines in Figure 2 and Figure 3. Indeed, due to the random inhomogeneities of cable insulation, *DED* is a random variable, like the diagnostic properties *ES*, *TS*, *EaB*, $tg\delta$, etc.

By considering the mean values of *DED* obtained for LDR, MDR, HDR by setting e/e_0=0.5, the following empirical relationship between the mean value of *DED*, μ_{DED}, and *DR* is obtained (see solid line in the plot of *DED* vs. *DR* reported in Figure 3):

$$\mu_{DED} = K \cdot DR^m = 159 \cdot DR^{0.19} \text{ (kGy)} \qquad (2)$$

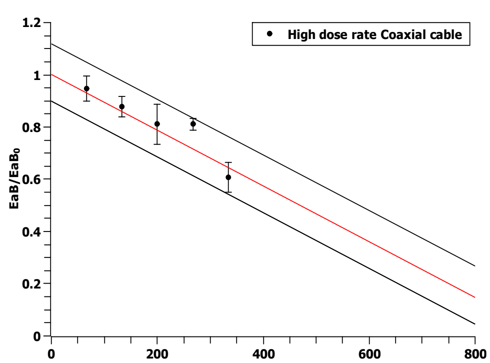

Figure 2. Relative elongation at break e/e_0 as a function of total dose D for HDR aging, with end point fixed at e/e_0 =0.5 [2]. The regression line of the mean values of tested samples, as well as the relevant upper and lower confidence bounds at 95% confidence degree are shown.

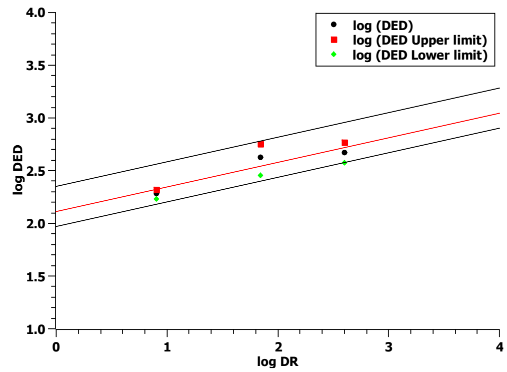

Figure 3. Dose equivalent to damage DED vs. dose rate DR. This plot has been derived from Figure 1 for HDR, as well as from similar figures for MDR and LDR [2] The regression line of the mean values of DED obtained for LDR, MDR, HDR, as well as the relevant upper and lower confidence bounds at 95% confidence degree are shown.

Of course, different values of parameters *K* and *m* can be obtained by performing different tests at different aging levels (i.e., dose rates) on different specimens of NPP LV cables. Therefore, it is opportune to make relationship (2) more general and such that "scale" parameter *K* has the same dimensions as dependent variable *DED*. To do so, let us rewrite the first- and second-hand side of (2) for a given reference value of dose rate, DR_0, at which μ_{DED} assumes a reference value $\mu_{DED,0}$, namely:

$$\mu_{DED,0} = K \cdot DR_0^m \qquad (3)$$

Then, by considering the side-by-side ratio of equation (2) over equation (3) one obtains:

$$\mu_{DED} = \mu_{DED,0} \left(\frac{DR}{DR_0}\right)^m \qquad (4)$$

For instance, by taking DR_0=1 Gy/h, then from equations (2), (4) it is obtained $K=\mu_{DED,0}$=159 kGy.

As highlighted above – and made clear from Figures. 2,3 – *DED* is a random variable. The cumulative distribution function of *DED* is required in the framework of the proposed reliability model for NPP LV cables subjected to radiation. The cumulative distribution function (cdf) of *DED* i.e., *P(DED)* is hypothesized here to be a 2-parameter Weibull function. Indeed, this is a quite flexible cdf, which can fit – by properly varying cdf parameters – very different sets of experimental data. Moreover, it is particularly appropriate for describing other random variables relevant to solid polymeric insulation, like time to failure, dielectric strength and breakdown voltage [20, 21]. Under this hypothesis, as done in [18] the cdf of *DED* can be written as follows:

$$P(DED; DR, T) = 1 - exp\left[-\left(\frac{DED}{\alpha_{DED}(DR,T)}\right)^{\beta_{DED}(DR,T)}\right] \qquad (5)$$

where $\alpha_{DED}(DR,T)$ and $\beta_{DED}(DR,T)$ are the scale and shape parameters of Weibull function and strictly speaking they depend on service stresses *DR* and *T*, but in practice, β_{DED} can be taken as stress independent.

Then, under the above assumption that, during the nominal operation of the plant, LV NPP cable insulation is subjected to known and constant nominal values of dose rate, DR_n, and temperature, T_n, equation (5) can be rewritten as follows:

$$P(DED; DR_n, T_n) = 1 - exp\left[-\left(\frac{DED}{\alpha_{DED}(DR_n, T_n)}\right)^{\beta_{DED}}\right] \quad (6)$$

Now, differently from the previous approach developed in [18], let us observe that the following relationship holds between the mean value, μ_{DED}, and the scale parameter, α_{DED}, of the Weibull distribution of *DED*:

$$\alpha_{DED} = \frac{\mu_{DED}}{\Gamma(1 + \frac{1}{\beta_{DED}})} \quad (7)$$

where $\Gamma(\dots)$ indicates the Euler Gamma Function [21].
Then, from equation (7) relationship (3) can be rewritten for the scale parameter $\alpha_{DED}(DR_n, T_n)$ as follows:

$$\alpha_{DED}(DR_n, T_n) = \frac{\mu_{DED}(DR_n, T_n)}{\Gamma(1 + \frac{1}{\beta_{DED}})} = \frac{\mu_{DED,0}\left(\frac{DR}{DR_0}\right)^m}{\Gamma(1 + \frac{1}{\beta_{DED}})} = \alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m \quad (8)$$

where $\alpha_{DED,0} = \alpha_{DED}(DR_0, T_n) = \mu_{DED,0}/\Gamma(1 + \frac{1}{\beta_{DED}})$ is the scale parameter of *DED* obtained at the reference dose rate value DR_0. By replacing equation (8) into (6), one obtains:

$$P(DED; DR_n, T_n) = 1 - exp\left[-\left(\frac{DED}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta_{DED}}\right] \quad (9)$$

Hereafter the cdf given by equation (9) is used for the random variable *DED*. Let us emphasize that in equation (9) the experimentally verified dependence of the scale parameter of the cdf, α_{DED}, on dose rate *DR* (see Figures 2, 3) is correctly accounted for. Such dependence was neglected in [18], and this makes the whole approach followed here more rigorous than - and significantly different from - that after [18], from both the theoretical and the practical viewpoint.

Let us close this subsection by pointing out that, in the framework of the TeaM Cables Project, also the value of *tgδ* was measured as a function of the total dose *D* for the analyzed aging conditions, so as to establish a connection between *EaB* and *tgδ* [19, 22, 23]. This approach has the ultimate goal of making *tgδ* another prospective diagnostic property, with the great advantage that *tgδ* – differently from *EaB*, *ES*, *TS* – is a non-destructive property, namely it can be measured without destroying the specimens. This requires the definition of end-of-life values of *tgδ* for various kinds of cables and aging conditions, as already done for *DED*, but it still needs further investigations and analysis of bigger amount of data.

2.2.3 Stress vs. strength

Stress overshoots may occur at aging time *t*, such that a burst of dose *DB* is suddenly released. In this respect, it is assumed that stress overshoots are random events, hence the release of a certain dose burst *DB* in the presence of this phenomenon can be described by a proper probability distribution function, which has dose burst *DB* as random variable: this random variable of stress is denoted as *X* in the framework of the probabilistic procedure hereafter. Therefore, if the sum of the dose cumulated so far at dose rate DR_n, equation (1), and the dose *DB* released as a burst during the overshoot is such that it exceeds *DED* (a random variable whose probability distribution is given by (9)), then cable insulation will fail. This means that the hypothesized event occurring after a service time *t* causes such a damage to cable insulation that the selected diagnostic property *P* (*EaB* in the framework of this study) reaches its end point P_L. This, by convention, corresponds to cable failure (end of life). Therefore, the critical condition for failure to occur can be written as follows, being *DB* a random variable:

$$DR\, t + DB \geq DED \quad (10)$$

Or alternatively as follows:

$$DB \geq DED - DR\, t \quad (11)$$

Hence it is readily seen that, in the framework of "stress-strength" models, the dose burst *DB* can be viewed as a sudden stress x; the residual dose that can be still cumulated by cable insulation at aging time *t* before it fails, namely $DED - DR\, t$, can be viewed as the residual strength y at aging time *t*.

From the above reasoning, it could be thought that the dose-to-equivalent-damage, *DED*, of cable insulation is a deterministic quantity, but actually - due to the random inhomogeneities of cable insulation - *DED* is a random variable, like the other diagnostic properties, *ES*, *TS*, *EaB*, *tgδ*, etc., as explained in detail later. Thus, the random variable *DED* makes the (residual) strength of the insulation of LV NPP cables a random variable as well. The random variable representing the strength at aging time *t*, equal to $DED - DR\, t$ (see equation (11) above), is denoted as *y*(*t*) in the framework of probabilistic "Stress-Strength" models (see below) and the relationship between strength and service time *t* is given by equation (11). Then, the failure criterion expressed by (11) becomes:

$$x = DB \geq y(t) = DED - DR\, t \quad (12)$$

and conversely the withstand criterion in the framework of probabilistic "Stress-Strength" models becomes:

$$x = DB < y(t) = DED - DR\, t \quad (13)$$

2.3 THE STRESS-STRENGTH RELIABILITY MODEL

The reliability assessment problem of LV NPP cables is dealt with in the framework of probabilistic "Stress-Strength" models [19, 20] i.e. by writing the Reliability Function (RF) denoted by *R*, for a given mission time t, as:

$$R = P(x < y(t)) \quad (14)$$

where:
x ("Stress") is dose burst DB released during the overshoot;
y(*t*) ("Strength" at aging time *t*) is $DED - DR.t$.
Denoting with:
f(*y*) = the probability density function (pdf) of strength *y*;
F(*y*) = the cumulative distribution function (cdf) of strength *y*;
g(*x*) = the pdf of stress *x*, namely dose burst *DB*;
G(*x*) = the cdf of stress x;

and assuming - as generally accepted for the applications under study - that the random variables x and y are statistically independent, the RF of the LV cable is given by:

$$R(t) = \int_0^{\infty} g(x)P(x < y(t))\,dx = \\ = \int_0^{\infty} g(x)\{1 - F[x(t)]\}\,dx \tag{15}$$

The latter equality in relationship (15) stems from the fact that stress and strength have the same physical dimension, hence shall be denoted by the same integration variable in (15) [24].

From the above hypotheses, $F[y(t)]$, the cdf of strength at time t, is not coincident with the cdf of *DED* - this latter being a Weibull cdf (see equations (6)-(9)), with scale and shape parameter respectively equal to $\alpha_{DED}(DR_n, T_n)$ according to equation (8) and β_{DED}. However, at a certain aging time t, it holds (see equation (12)):

$$y(t) = DED - DR.t \tag{16}$$

Hence:

$$F[y(t)] = F[DED - DR.t] \tag{17}$$

where – at a fixed aging time t – *DED* is a random variable distributed according to (9) and *DR* is a constant deterministic quantity. Thus, $y(t)$ at a fixed aging time t will also be Weibull-distributed according to (9), on condition that the cdf is shifted along the random variable axis by an amount + $DR.t$ so as to compensate for the reduction of $y(t)$ with respect to its initial value *DED*. Thus, it holds:

$$F[y(t)] = 1 - exp\left[-\left(\frac{DED + DR.t}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta_{DED}}\right] \tag{18}$$

An example of the cdf of $y(t)$ according to equation (18) is given in Figure 4, which shows the Weibull *cdf* of strength $y(t)$ at three aging times, namely:

1) $t = 0$, corresponding to initial strength ($y(t = 0) = y_0 = DED$, see equation (16)).
2) $t = t_1$, corresponding to 75% of initial strength.
3) $t = t_2$, corresponding to 50% of initial strength.

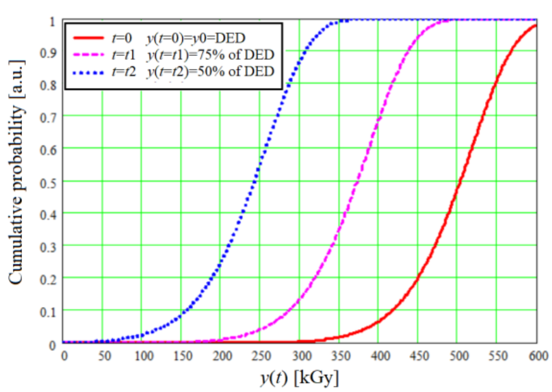

Figure 4. cdf of strength $y(t)$ at three aging times corresponding to initial strength (y_0=DED), 75% of initial strength, 50% of initial strength. α_{DED} (HDR=400 Gy/h,T_n)=522 kGy

The cdfs of $y(t)$ in Figure 4 are obtained with a parametrically assumed value for $\beta_{DED} = 10$ and with $\alpha_{DED}(\text{HDR} = 400\ \text{Gy}/h, T_n) = 522$ kGy; this value comes from equations (2),(4), which yield $\mu_{DED}(\text{HDR}, T_n)$=496 kGy, thus:

$$\alpha_{DED}(\text{HDR}, T_n) = \frac{\mu_{DED}(HDR)}{\Gamma(1+\frac{1}{\beta_{DED}})} = \frac{496}{0.951} = 522\ \text{kGy} \tag{19}$$

According to equations (4),(8), by varying the *DR* also the values of μ_{DED} and α_{DED} change. For instance, from equation (4) one gets:

- $\mu_{DED}(\text{MDR}, T_n)$=346 kGy with MDR=66 Gy/h;
- $\mu_{DED}(\text{LDR}, T_n)$=230 kGy with LDR=7 Gy/h;

Then from equation (8) with $\beta_{DED} = 10$ one gets, respectively:

- $\alpha_{DED}(\text{MDR}, T_n)$=364 kGy with MDR=66 Gy/h;
- $\alpha_{DED}(\text{LDR}, T_n)$=242 kGy with LDR=7 Gy/h.

Let us point out that the random variable $y(t)$ in equations (16)-(18) consists of a time-varying (and deterministic) part $DR.t$ plus a constant (and random) part *DED* – equal to the value of $y(t$=0$)$=y_0 –; this latter part is the one to be associated with stress x=DB in the convolution integral of (15). Hence, hereafter let us denote *DED* as y_0 and recast equation (18) as follows:

$$1 - F[y(t)] = exp\left[-\left(\frac{y_0}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta_{DED}}\right] \times \\ \times\, exp\left[-\left(\frac{DR\ t}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta_{DED}}\right] = \varsigma(t)\xi(y_0) \tag{20}$$

where we have defined:

$$\varsigma(t) = exp\left[-\left(\frac{DR\ t}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta}\right] \tag{21}$$

$$\xi(y_0) = exp\left[-\left(\frac{y_0}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta}\right] \tag{22}$$

$$\beta = \beta_{DED} \tag{23}$$

Then, from equations (15), (20)-(23), reliability $R(t)$ can be thus expressed as follows:

$$R(t) = \\ = \int_0^{\infty} g(x)\varsigma(t)\xi(x)dx \\ = \varsigma(t)\int_0^{\infty} g(x)\, exp\left[-\left(\frac{x}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^m}\right)^{\beta}\right]dx \tag{24}$$

Then, being $g(x)$ the pdf of stress, it can be pointed out that the reliability R (reliability function RF) of equation (24) is exactly the same as in [24], apart that:

- the deterministic multiplying factor $\varsigma(t)$ multiplies the integral.
- $\alpha = \alpha_{DED}$ is no more time dependent according to an IP model.

The above RF is the object of the proposed estimation procedure, together with other reliability parameters which are of great interest in assessing the performances of LV cables for nuclear power plants and possible maintenance strategies (e.g., selected failure time percentiles related to design practice, the hazard rate function, the residual reliability, the Mean Time To Failure MTTF, etc.).

In general, the RF (24) can only be evaluated numerically, unless proper simplifying assumptions are introduced. Hereafter, two different levels of approximation of the RF (24) are given, which can be useful for carrying our preliminary reliability analyses.

The first simplifying hypothesis is that also stress X is a Weibull random variable. Then, the pdf of stress, $g(x)$, in (24) can be derived from the following cdf of stress:

$$G(x) = 1 - \exp\left[-(x/\theta)^{\gamma}\right] \qquad (25)$$

whose scale and shape parameters are θ and γ, respectively; they are generally unknown, and must be estimated by means of a random sample. As hinted above, this assumption is reasonable since the Weibull distribution is a quite flexible cdf, which can fit different random features of polymeric dielectrics (time to failure, dielectric strength, etc.) [21], [23]. Under such hypothesis, the RF of equation (24) becomes:

$$R(t) = \varsigma(t)\times$$
$$\times\int_0^{\infty}\left\{-\exp\left[-\left(\frac{x}{\theta}\right)^{\gamma}\right]\right\} exp\left[-\left(\frac{x}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^{m}}\right)^{\beta}\right]dx \qquad (26)$$

As a further simplifying hypothesis, the equality of the shape parameters of X and Y is assumed, namely:

$$\gamma = \beta \qquad (27)$$

This second - and stronger - simplification enables the derivation of an analytical solution for the evaluation of the RF. Indeed, from equations (26), (27) it is readily obtained:

$$R(t) = \frac{\zeta(t)}{\left[1+\left(\frac{\theta}{\alpha_{DED,0}\left(\frac{DR}{DR_0}\right)^{m}}\right)^{\beta}\right]} \qquad (28)$$

Reliability functions (24), (26) and (28) represent three differently approximated levels of the proposed procedure for reliability estimation of LV NPP cables subjected to constant dose rate and dose bursts:

1) the first approximation level (equation (24)) is of course the most rigorous and general, but its use requires a numerical computation of the convolution integral.
2) the second approximation level (equation (26)) still requires a numerical computation of the convolution integral, but in a much more compact and amenable form.
3) the third approximation level (equation (28)) is the most strongly approximated, but it is analytical, thus it can serve as a reference for more sophisticated calculations.

Reliability estimation as a function of time can be carried out via (24), (26), (28) provided that the deterministic function of time $\zeta(t)$ (namely dose rate DR) is known. However, the validity of the proposed methodology for estimating reliability of LV cables for nuclear power plants in the presence of dose bursts causing high values of cumulated total dose D^* can be broadened by numerical solutions provided, for instance, by Monte Carlo simulation procedures. Moreover, observed stress distributions in some cases are not far from equation (25).

3 CASE-STUDY

As a parametric case-study chosen for illustrating the development of the stress-strength reliability model for aged NPP LV cables with respect to the first step put forward in [18], let us apply equations (26),(28) with the following values of the relevant parameters:

- DR=HDR=400 Gy/h, MDR=60 Gy/h, LDR=7 Gy/h after [2]. Note that these values and the relevant experimental results have been updated w.r.t. those used in [18] so as to account for the latest outcomes of ongoing tests;
- α(HDR)=522 kGy, α(MDR)=364 kGy, α(LDR)= 242 kGy after [2]. Note that these values - as reported above at Section 2.3 - are consistent with the values of μ_{DED} obtained from equations (2),(4) and Figure 3 under the assumption β=10;
- θ=0.7α, 0.8α, 0.9α, α, so as to scan a range of possible values of shape parameter of the stress distribution and assess the relevant effects.
- β=10;γ=20, reliability computed via equation (26), see Figure 5.
- β=γ=10, reliability computed via equation (28) (see Figure 6).

The time trend of the deterministic function of time $\zeta(t)$ for LDR, MDR, HDR, calculated according to equation (21), is shown in Figure 7; it should be noted that it also depends on α_{DED}. As expected, the higher the dose rate, the faster the decrease of function $\zeta(t)$ with aging time.

The values of reliability $R(t)$ vs. aging time t for HDR, MDR, LDR, calculated numerically according to equation (26) (first level of approximation of the proposed approach) are shown, respectively, in Figures 5a, 5b, 5c.

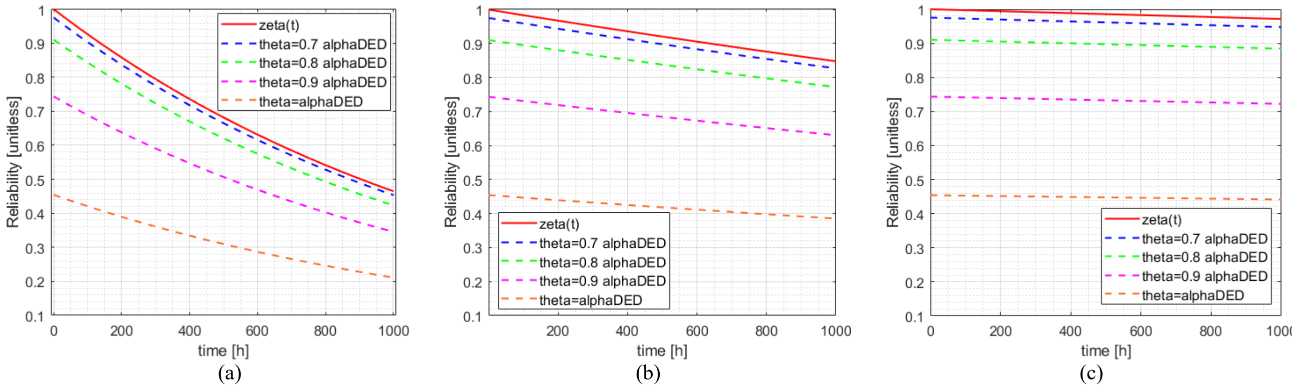

Figure 5. Reliability according to equation (26) for (a) HDR, (b) MDR, (c) LDR, at various values of θ. Function ζ(t) is also shown.

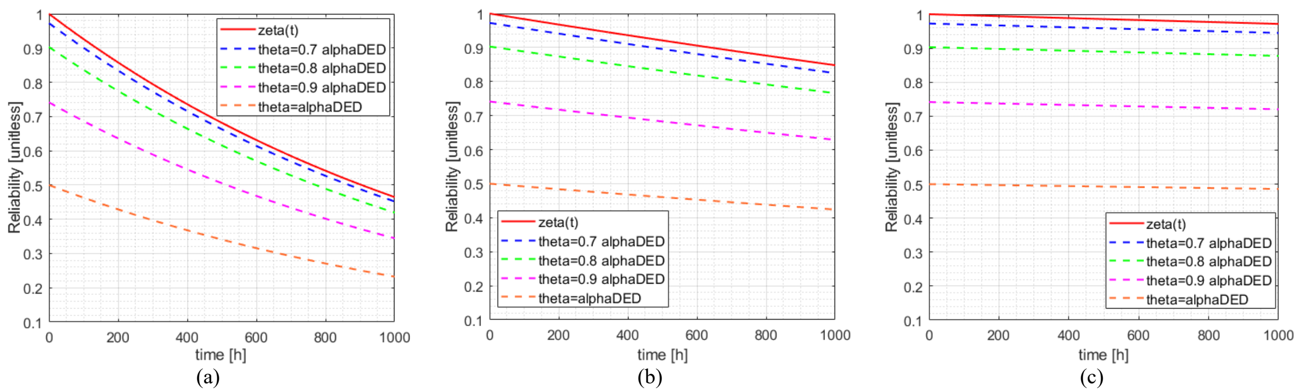

Figure 6. Reliability according to equation (28) for (a) HDR, (b) MDR, (c) LDR, at various values of θ. Function ζ(t) is also shown.

The values of reliability $R(t)$ vs. aging time t for HDR, MDR, LDR, calculated analytically according to equation (31) (second level of approximation of the proposed approach) are shown, respectively, in Figures 6a, 6b, 6c. For θ=0.7α, 0.8α, 0.9α, the differences between the output of equation (26) and equation (28) are very small (from 0.1% and 1%) and cannot be sensed when comparing Figure 5 with Figure 6: differences can be noted starting from $\theta \approx \alpha$, when percent difference becomes around +10%, with the reliability estimate from (28) being larger than that from (26), which seems to indicate that the more approximate reliability expression (31) is less conservative.

The figures clearly show that, as reasonably expected:

- the higher the dose rate, the lower the reliability at a given time for each value of stress scale parameter, θ;
- the whole-time dependence of reliability is given by function $\zeta(t)$ of equation (21), also shown for comparison in Figure 7. The decoupling between time and stress-strength was already clear from equations (24),(26);
- the higher the scale parameter of stress, θ, the lower the reliability at a given time and value of dose rate.

This latter point deserves more attention. Indeed, for $\theta = 0.6\alpha$ the reliability at a given time and value of dose rate is practically insensitive to the value of the scale parameter of stress, so that the relevant curve has been omitted in Figure 6 (being practically overlapped to the curve of $\zeta(t)$). The RF becomes appreciably sensitive to the value of the scale parameter of stress since $\theta \approx 0.7\alpha$ and it is strongly sensitive above such value.

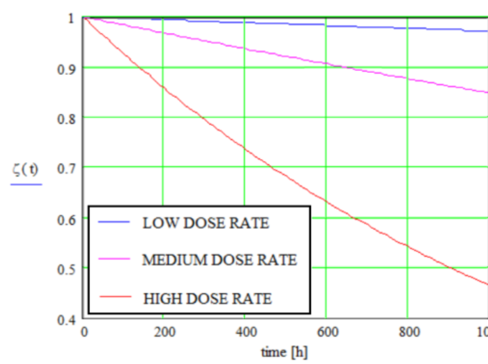

Figure 7. Time trend of the deterministic function of time $\zeta(t)$ for LDR, MDR, and HDR, calculated according to equation (21)

Moreover, since $\theta \approx 0.7\alpha$ initial reliability $R(t=0)$ starts being <1: thereafter, the higher is θ, the more $R(t=0)$ is below unity.

4 CONCLUSIONS

In this article, the development and application – started in a previous paper – of a stress-strength model of residual reliability of LV cables for NPPs subjected to random stress overshoots in-service has been made sounder and considerably broadened. Such broadening includes a wider theoretical analysis – with a novel analytical expression of cable reliability in the presence of random dose bursts – and a more extensive application, to assess the role played by model parameters, among which the shape parameter of the stress distribution. The application showed that the model simulates the behavior of real cables for NPPs in a realistic and accurate way.

Future work on this topic will encompass additional theoretical developments, aiming at considering the loss factor as a prospective diagnostic quantity beside the dose-to-equivalent-damage and at including temperature as a further stress. Moreover, the parametric analysis will be deepened, and the same approach will be applied to other cables with different additives composition and morphologies.

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