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ALT Data Fitting for Polypropylene-based HVDC Cable Insulation Developed in the HEU-NEWGEN Project

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***Abstract*- This study aims at a preliminary validation of the electro-thermal cable life model developed in the HEU-NEWGEN research project by fitting the Inverse Power Model to Accelerated Life Test (ALT) data relevant to Polypropylene-based flat specimens tested under different voltages and temperatures. The goal is to know better how these materials behave over time under different steady electro-thermal stresses, which is crucial for developing more reliable HVDC cable systems. The results show a strong correlation between electric field and time-to-failure at each test temperature, although failure times are fairly scattered – as proved by the low value of the Weibull shape parameter. Life exponent values are found to be greater than 28, which is an indication of very good electrical endurance of the tested materials.**

I. INTRODUCTION

The recent increase in power generation from renewables in addition to the booming energy demand highlighted the importance of the reliability of HV power cables in general, and HVDC extruded cables in particular [1]. The Horizon Europe (HEU)-NEWGEN research project emphasized this importance by a dedicated work package (WP), i.e. WP4, to study the reliability and modelling of HVDC extruded cables [2]. In the early stages of NEWGEN, WP1 focused on the preliminary screening of a significant number of Polypropylene (PP) blend formulations for HVDC cable insulation [3],[4] leading to the selection of a few best blends and upscaling them from mini-scale hot-press to pilot-scale cast film extrusion [5]. This study aims at assessing the aging behavior of one of these innovative PP-based cast-film blends, as well as at a preliminary validation of the electrothermal cable life and reliability model developed in the HEU-NEWGEN project, by means of Accelerated Life Tests (ALTs) on the selected blend subjected to various combinations of constant voltage and temperature. Since the electro-thermal cable life model developed in the NEWGEN research project is based on the Inverse Power Model (IPM)-Arrhenius model for constant electro-thermal stress, the ALT data at each test temperature (times to failure of 100 µm- thick flat specimens vs. applied electric field) were fitted to the IPM through the Least-Square Regression (LSR) technique using a MATLAB™ code, in order to determine the characteristic life (L_h) and the life exponent (n) of the IPM at each of the three test temperatures, namely 90°C, 70°C, and 50°C [6].

II. MATERIAL COMPOUNDING

The Accelerated Life Tests have been carried out using extruded cast films produced by VTT Technical Research Centre of Finland using a new clean compounding environment during the pilot-scale upscaling process (up-scaled from mini scale hot press compounding, for further up-scaling the best performing insulation compounds to produce mini-cables and HVDC cable prototypes). The compounding equipment comprised of a Leistritz ZSE18 MAXX twin-screw extruder (48D) equipped with precision gravimetric feeders, a melt pump and a screen changer. The extruder nozzle, cooling and pelletizing sections were placed inside a mobile soft-wall clean room with ULPA air filtering (ISO 6 class clean room). All raw material handling (pre-treatment, weighing, dry mixing) was performed in the same room, inside a fume cupboard. Fig. 1 shows photographs of the clean compounding environment. For pilot-scale compounding and cast film extrusion, the twin screw extrusion line was equipped with a melt pump, a screen changer, a 120 mm wide flat film die and a tempered chill roll unit. In this paper, the investigated ternary PP blend consists of:

- 55% homophasic PP random copolymer (RACO) with ethylene content of <5 wt-%,
- 20% heterophasic PP copolymer (HECO) essentially comprising of PP homopolymer matrix with dispersed ethylene-propylene rubber (EPR) phase,
- 25% propylene-based elastomer (PBE) with 16 wt-% ethylene content.

An antioxidant (AO) comprising of a synergetic 1:1 blend of a hindered phenolic antioxidant (Irganox® 1010) and a phosphite processing antioxidant (Irgafos® 168) was added to the blends to prevent thermo-oxidative degradation. Compounding and cast film extrusion was performed for the ternary PP blend RACO/HECO/PBE at 220–230 °C (throughput 2.5 kg/h, specific energy input ~0.20–0.22 kWh/kg, 84 mesh filter, chill roll temperature 70–85 °C). Two different film thicknesses were produced, with the target thicknesses of 100 µm and 200 µm.

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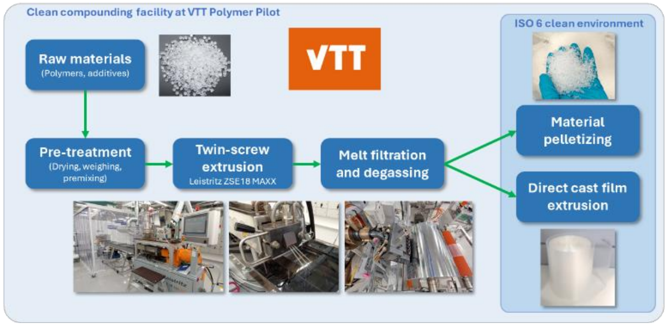


Fig. 1 Flow chart of the clean compounding facility at VTT Technical Research Centre of Finland.

III. ACCELERATED LIFE TESTS

The test setup has been established at Tampere University to carry out the ALTs. Fig. 2 presents the developed test system which consists of test chambers, sample cells, power supplies, as well as a control and safety system. In each test chamber, eight sample cells with cylindrical electrodes (a diameter of 25 mm, edge radius of 3 mm) can be placed. In the cell, the PP samples are immersed in silicon oil. The upper electrodes of the test cells are connected to the high voltage source and the cells are placed in oven. Three different fields, four different temperatures and altogether 32 samples can be tested at the same time using three high voltage sources and four test ovens, respectively. The ALT test system is developed according to IEC 60243 [7]. Table I reports the temperatures and the electric fields of the ALTs. Four experiments were carried out at 90°C, three at 50°C, while tests are still ongoing at 70 °C to obtain at least three experimental results. At each field and temperature, the test was ended after a pre-defined time of ≈1 month to keep the overall testing time within acceptable limits – also considering that other two/three selected blends are expected to be tested at the flat specimen and cable-model level by the end of the project in October 2026. For the ALTs where some specimens did not fail by the end of the test, the relevant samples were singly censored in the statistical analysis [8], see next Section IV.A. Similar tests are ongoing at Supergrid Institute, France. Their results will be illustrated in forthcoming papers.

TABLE I
ACCELERATED LIFE TEST PLAN ON PP TERNARY BLEND

Electric Field (kV/mm)	**Temperatures (°C)**		
	50	70	90
260	x	x	x
240	-	-	x
220	x	x	x
207	x	-	x

Fig. 2. ALTs test system developed at Tampere University, consisting of the test chambers in the top corner and the test cells at the lower row.

IV. FITTING AND POST-PROCESSING

A. *Theoretical*

The statistical analysis aims at processing the ALTs conducted on samples consisting of up to 8 specimens, tested at the 9 combinations of temperature and electric field listed in Table I. As hinted at above, singly censored (right-censored) samples are considered in the statistical analysis for the combinations where some specimens did not fail at the end of the ALTs. In the literature, few methods are available for the calculation of the 2-parameter Weibull function parameters in the case of singly censored samples compared to the case of complete samples [8]. This includes the Maximum Likelihood Estimation (MLE) [9], and the LSR [8]. LSR is considered here for its simplicity, as it can be easily implemented with different softwares (e.g. in this study it was implemented in Excel^{TM} and MATLAB^{TM} environments for the sake of comparison). According to LSR, the expressions of scale and shape parameters of the 2-parameter Weibull distribution α_{LSR} and β_{LSR} for singly censored samples consisting of *N* specimens, of which only *r* have failed by the end of the test, are the following [10]:

$$\beta_{LSR} = \frac{\sum_{i=1}^{r}(Y_i' - \overline{Y'})(X_i' - \overline{X'})}{\sum_{i=1}^{r}(X_i' - \overline{X'})^2} \tag{1}$$

$$\alpha_{LSR} = exp(-\overline{Y'}/\beta_{LSR} + \overline{X'}) \tag{2}$$

Where:

$$\overline{Y'} = \sum_{i=1}^{r} Y_i'/r \tag{3}$$

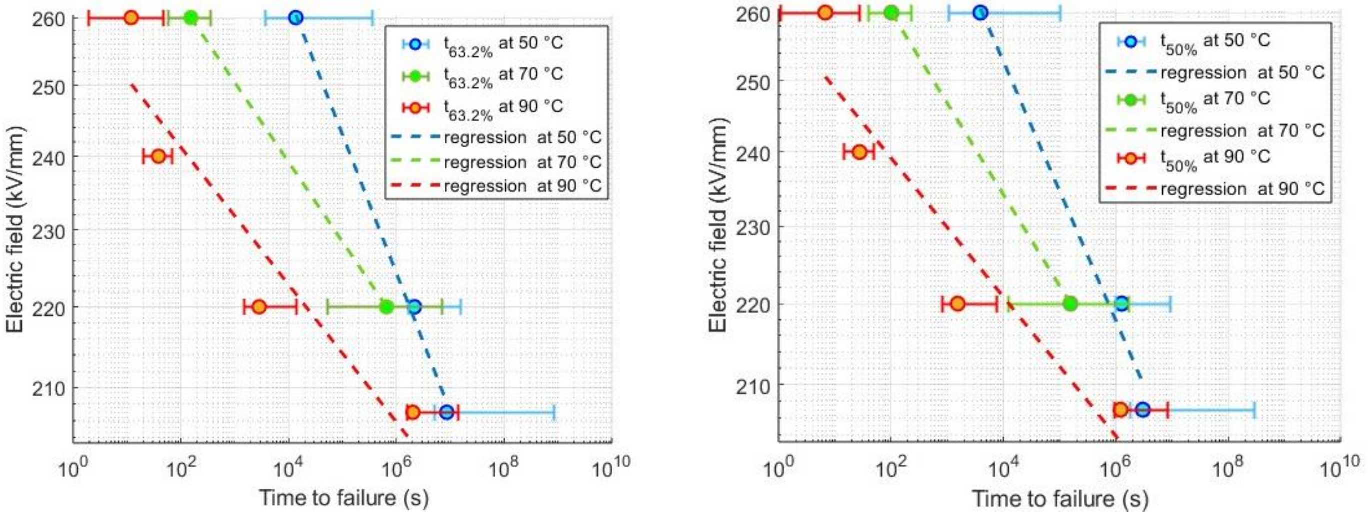
$$\overline{X'} = \sum_{i=1}^{r} X_i'/r \tag{4}$$

$$Y_i' = ln\big(ln(1/(1 - F\_i\,))\big) \tag{5}$$

$$F_i = (i - 0.3)/(N + 0.4) \tag{6}$$

$$X_i' = ln(X_i) \tag{7}$$

Where: *i* is the rank, X_i the failure time and F_i the Bernard cumulative probability estimator of the i^{th} failed specimen. For each of the 9 ALTs listed in Table I, relationships (1)-(7) provide the estimates of α_{LSR} and β_{LSR}, from which the values



(a) (b)

Fig. 3 Accelerated life test plot in log-log scale of (a) $t_{63.2\%}$, and (b) $t_{50\%}$ at 50°C, 70°C and 90°C with 90% confidence bounds and a linear regression.

of the 50th failure time percentile $t_{50\%}$ (or median failure time) are obtained. In fact, typically α and $t_{50\%}$ are considered as the most representative failure time percentiles in 2-parameter Weibull analyses [8]-[10],[11]. The 90% confidence intervals of the estimates of α and $t_{50\%}$ are found using Monte Carlo MATLAB™ simulation with 10^6 samples having the same values of α and β as the experimental data. The samples singly censoring is also considered in the confidence intervals calculation. Thereafter, the failure time percentiles at each temperature are fitted to the Inverse Power Model (IPM) through the LSR technique using a MATLAB™ code. The IPM is used since the electro-thermal cable life model developed in the NEWGEN project is based on the IPM-Arrhenius model for constant electro-thermal stress [2]. By defining the applied electric field as E, electrical life=failure time as $L(E)$, E_H as the highest test field and L_H as the relevant life=characteristic life, n as the life exponent, the IPM can be written as follows [2]:

$$L(E) = L_H(E/E_H)^{-n} \tag{8}$$

and linearized in log(E)-log(life) coordinates as follows:

$$log(E) - log(E_H) = -\frac{1}{n}\left[log\big(L(E)\big) - log(L_H)\right] \tag{9}$$

Thus, life exponent n at each temperature can be calculated by taking the inverse of the reciprocal of the slope of the regression line in log(E)-log(life) coordinates.

B. Application

Statistical processing and data fitting has been performed at the University of Bologna. For each of the 9 ALTs listed in Table I, Table II reports: the temperature (T) and electric field (E); the total number of tested specimens (N) and the failed specimens (r); the shape parameter (β), the scale parameter α (corresponding to $t_{63.2\%}$) and the median value $t_{50\%}$ of the Weibull distribution of failure times, along with their 90% confidence bound limits i.e., $t_{5\%}$ and $t_{95\%}$ found from Monte Carlo simulations as described above. At 90 °C, breakdown times ranged from a few to tens of seconds at 260 kV/mm to hundreds of hours at 207 kV/mm, while at 50 °C, breakdown times ranged from a few hours at 260 kV/mm to thousands of hours at 207 kV/mm. At 70 °C the breakdown time ranges between a few minutes at 260 kV/mm to hundreds of hours at 220 kV/mm. Figure 3 shows the ALT plots in log(E)-log(life) scale and the relevant IPM fitting at each temperature (50°C, 70°C, and 90°C, in blue, green, and red, respectively) obtained from relationship (9) via the LSR technique as described above. The failure-times corresponds to $\alpha=t_{63.2\%}$ (scale parameter) in Fig. 3(a), and $t_{50\%}$ in Fig. 3(b) along with the relevant 90% confidence bounds. Failure times are mostly quite scattered, as proved by the low value of the Weibull shape parameter β:

TABLE II

STATISTICAL ANALYSIS OF THE ACCELERATED LIFE TESTS ON PP TERNARY BLEND

T (°C)	E (kV/mm)	N	r	β	α (s)	α (h)	Confidence bounds		$t_{50\%}$ (s)	$t_{50\%}$ (h)	Confidence bounds	
							$t_{5\%}$ (s)	$t_{95\%}$ (s)			$t_{5\%}$ (s)	$t_{95\%}$ (s)
50	260	8	7	0.293	1.360E+04	3.779	3.71E+03	3.66E+05	3.902E+03	1.084	1.06E+03	1.05E+05
	220	8	6	0.705	2.157E+06	599.108	1.70E+06	1.60E+07	1.282E+06	356.194	1.01E+06	9.49E+06
	207	7	5	0.351	8.611E+06	2391.901	5.00E+06	8.51E+08	3.030E+06	841.632	1.76E+06	2.99E+08
70	260	5	5	0.901	1.529E+02	0.042	5.98E+01	3.48E+02	1.018E+02	0.028	3.98E+01	2.31E+02
	220	8	8	0.255	6.561E+05	182.255	5.24E+04	7.10E+06	1.559E+05	43.300	1.24E+04	1.69E+06
90	260	3	3	0.647	1.192E+01	0.003	1.95E+00	4.78E+01	6.765E+00	0.002	1.11E+00	2.71E+01
	240	7	7	1.113	3.838E+01	0.011	2.06E+01	6.83E+01	2.761E+01	0.008	1.48E+01	4.91E+01
	220	8	7	0.598	2.837E+03	0.788	1.49E+03	1.42E+04	1.537E+03	0.427	8.07E+02	7.71E+03
	207	8	6	0.723	2.022E+06	561.723	1.60E+06	1.42E+07	1.218E+06	338.369	9.62E+05	8.54E+06

overall, the scatter is greatest at 50°C - which gives rise to the largest confidence bounds of α in Fig. 3(a) and $t_{50\%}$ in Fig. 3(b) – and lowest at 90°C. Table III shows the life exponents of the IPM calculated at 50 °C, 70 °C and 90 °C from (9), together with the relevant value of correlation coefficient. Surprisingly the values of n rise as temperature increases [2] but let us note the following points:

1. At 70°C only 2 ALT tests were completed, giving rise to 2 points in the log-log plot of Fig.3, which makes the statistical processing unfeasible, the fitting and the value of n is uncertain and unreliable. For this reason, as hinted above, a 3rd ALT at 70°C on the same PP blend is ongoing.
2. The life exponent at 50°C and 70°C ranges from 29 to 50 for the 63.2th failure time percentiles, from 30 to 44 for the median failure times: very high values which indicate very good voltage endurance of the tested materials. The confidence bounds at 50°C are very large and asymmetric, suggesting a possible increase in the value of n at lower electric fields. Tests at lower electric fields are presently being planned to assess this trend.
3. The ALT point at 90°C at 207 kV/mm (the lowest test field) is much closer to the failure times at 50°C than at higher fields, thus deviating a lot from the other three points. This suggests that it is an outlier, also because it is responsible for the fact that, following the dashed fitting lines in Fig. 3, at lower electric field the lifetime at higher temperatures would be longer than lifetime at lower temperatures - which is counter-intuitive and opposite to common experimental evidence. Here again, further tests at lower electric fields and/or on different PP-based blends with or without additives – also developed in the NEWGEN project - are either ongoing or being planned at Tampere University and at Supergrid Institute.

It can be noticed that, at all temperatures, life exponents are greater than 28, which is an indication of very good electrical endurance of the tested material. The values of n are far greater than 10 which is deemed as a conservative value considered for life calculations in prequalification and type test of HVDC extruded cables according to CIGRE TB 852 [12]. However, the life exponent at 90°C is still comparable to values found in the literature on other PP blends for DC cables in [6].

TABLE III

LIFE EXPONENTS WITH CORRELATION COEFFICIENT

T (°C)	n ($t_{63.2\%}$)	n ($t_{50\%}$)	**Correlation coefficient** ($t_{63.2\%}$)	**Correlation coefficient** ($t_{50\%}$)
90	51.4	51.2	0.9407	0.9419
70	50	43.9	1	1
50	28.7	30.4	0.9984	0.9899

V. CONCLUSION

This paper has illustrated a preliminary validation of the electro-thermal cable life model developed in the HEU-NEWGEN research project by fitting the IPM to ALT data relevant to PP-based flat specimens tested under different voltages and temperatures; this work has provided useful indications that will serve as a basis for further investigation.

At all temperatures, life exponent values of the IPM are greater than 28, which is an indication of very good electrical endurance of the tested material. Surprisingly the values of n rise as temperature increases, but more comprehensive investigations are ongoing to draw a solid conclusion by considering more informative data points in the life plot at various temperatures. Indeed, the wide upper confidence bound at 50 °C (in blue in Fig. 3(a) and (b)) suggests a possible shift towards a lower life exponent at lower temperatures. An in-depth statistical analysis of future ALT results will extend these initial findings.

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