RAPID ESTIMATION OF LIFETIME AND RESIDUAL LIFETIME FOR SILICONE RUBBER CABLE INSULATION

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Use of new insulating materials for electric equipment working under more intense and variable stresses requires a development of new methods to estimate their lifetime. In this paper, a rapid estimation method of the lifetime of a silicone rubber cable insulation for aircraft electric motors is presented. This method relies on the calculation of the activation energy by thermal analysis using the high-temperature exothermic peak from DSC measurements and the execution of an accelerated thermal ageing at the highest allowed temperature. The results show that the time necessary to perform the tests is relatively small and the costs are lower than in the case of classic methods. On the other hand, it is proved that the lifetime value of the insulation is shorter in the case of constant thermal stress than in the case of a variable one.

Keywords: Silicone rubber, Differential scanning calorimetry, Thermal ageing, Lifetime

1. Introduction

During service, the insulation systems of electric equipment (electric machines, transformers, etc.) are exposed to permanent stresses (electrical, thermal, mechanical, and environmental) and/or accidental ones (mechanical, electrical, etc.), which intensify their degradation mechanisms, facilitating insulation breakdown and the premature failure of the equipment. An analysis made by CIGRE Study Committee SC11 shows that from 69 generators out of order, 56% of the failed machines showed insulation damage [1]. Therefore, predicting lifetimes as accurately as possible and knowing the real-time condition of insulation systems is of a great importance for the users of this equipment.

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Lifetime estimation of the insulation systems was a continuous concern, especially for producers and users of electric machines for mining, metallurgy, drilling, aviation, navy etc. What stands out is the research (started in 1952) on the ageing of conductors insulation of aircraft electric motors, especially those of US Air Force [2-3] and US Navy [3-4], subjected to mechanical, thermal and environmental stresses, variable and of relatively important intensities [3, 5].

While at the beginning conductors for special applications were insulated with aromatic polyimide film helically wrapped and bonded with an fluoropolymer (FEP) adhesive [2, 4], later epoxy resins, polyesteric modified and silicone resins insulated conductors started being used [6-8]. On the other hand, new applications of electric motors are being developed, to permanently work at high temperatures, to work shortly under very high stresses, variable stresses of unpredictable duration, special security etc. Therefore, several studies concerning the conductors' insulation degradation and electric properties variations and lifetime estimation have been realized and presented in different papers.

For example, in [9-12] the effect of electrical stresses (voltage pulses) on insulations is studied, in [5, 11-12] - heat influence, in [12] - influence of mechanical stresses, in [13] - influence of environmental stresses, in [3, 12- 13] - influence of combined stresses etc. It must be marked too, the research conducted as part of the Project "Electrical Tail Drive - Modelling, Simulation and Rig Prototype Development", part of the European Programme CLEAN SKY, which aims to realize and evaluate a full-scale helicopter electric tail rotor (ETR) motor that is engineered for flight-critical operation and representative of an aircraft installation [14]. Already conducted research is more about coils insulations of electric motors than those of feeding cables of aircraft equipment. But early degradation and their failure take the equipment, and therefore the aircrafts, out of order regardless of their condition.

In this paper, we present an experimental study regarding lifetime and residual lifetime of feeding cables of electric motors insulated with silicone rubber, used for helicopter electric tail motors, subjected to permanent and variable thermal stresses.

2. Lifetime

The lifetime of an insulation is defined as the time during which, under certain stresses (stress factors), the value of a critical parameter (called diagnostic factor) is modified beyond a limit value, called end-of-life criterion [15, 22]. The first paper regarding the temperature action on electric insulation degradation has been published in 1913 [16-17]. In 1930, Montsinger establishes an empirical equation for calculating the lifetime of transformer paper L stressed (aged) thermally:

$$L = A \exp(-m\theta), \tag{1}$$

where θ is the ageing temperature (measured in $^{\circ}$C) and A and m are constants depending on the material [18].

In 1948, Dakin proposed a chemical rate theory interpretation of thermal deterioration of electrical insulation and a more descriptive relationship of the form [19]:

$$L = A \exp(E_a/k\,T), \tag{2}$$

respectively

$$\ln L = a + b/T, \tag{3}$$

where L is the insulation lifetime, A – material constant, $a = \ln A$ and $b = E_a/k$ - the ratio between the activation energy of the degradation reaction E_a and Boltzmann's constant k.

Experimental determination of insulation lifetime involves the study of electrical, mechanical, or chemical properties variations during thermal ageing for at least 3 temperatures, selected according to the IEC Publication 60216-1 [15] and IEC Publication 60505 [20]. Thus, the variation curves of the chosen property P (respectively, $p = P/P_0$, where P_0 represents the initial value of property P) are drawn in time, for each temperature value and the intersections of these curves with the horizontal line of the chosen end-of-life criterion p_{eol} are determined (Fig. 1) [21]. Intersection points $M_1(T_1, \tau_1)$, $M_2(T_2, \tau_2)$ and $M_3(T_3, \tau_3)$ are determined using the graphic method, then they are used to draw the thermal lifetime curve in semi-logarithmic coordinates $x = 1/T$ and $L = y = \ln \tau$ (Fig. 2). According to [15], one can determine the straight line of lifetime $\ln L = f(1/T)$, then the lifetime value at any operating temperature of the insulation.
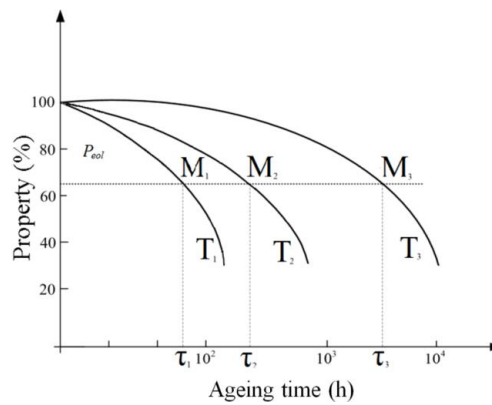

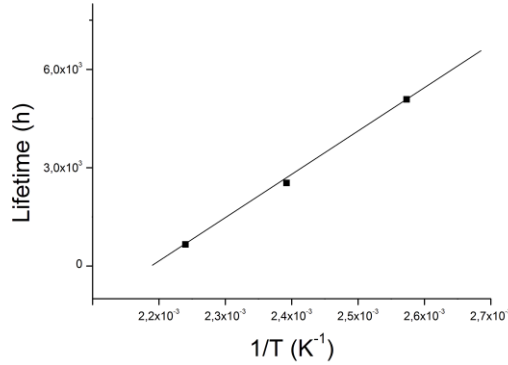
Fig. 1. Accelerated thermal ageing curves

Fig. 2. Lifetime curve drawn using the points $M_1(T_1, \tau_1)$, $M_2(T_2, \tau_2)$ and $M_3(T_3, \tau_3)$ from Fig. 1

Experimental determination of thermal lifetime's straight lines described by equation Dakin (3) involves conducting accelerated ageing at three temperatures, the lowest being as close as possible to the operating insulation temperature [21]. In general, in order to obtain a life-temperature characteristic curve, at least a year of experimental time is required. As this test is very long, in this paper we use a faster method, namely activation energy method (AEM), which requires only a thermal ageing test (lasting the lowest time) and experimental determination of activation energy E_a. For this, it is considered that the thermal degradation complies with Dakin equation (2) and the parameters a and b of the lifetime line (3) are determined based on experiments corresponding to an accelerated thermal ageing at the highest temperature [21].

Recently, an interesting question arose, in connection with naval aircraft wire ageing, as to whether life predictions could be made when the operating temperatures were variable. This was demonstrated to be possible by integrating the effects dictated by the Arrhenius laws [22].

Starting from equation (2), thermal degradation of the insulation per unit time W is defined by:

$$W = \frac{1}{L} = \frac{1}{A} e^{-b/T} . \tag{4}$$

The insulation wear $W^*(\Delta t)$ in the interval Δt, between t_a and t_b ($\Delta t = t_b - t_a$) is:

$$W^*(\Delta t) = \frac{1}{A} e^{-b/T(t)} dt. \tag{5}$$

where $T(t)$ is the temperature at time t within the interval Δt [22, 40].

Considering $\Delta t = 24$ h and knowing the curve $T(t)$ within this interval, using (5) it can be calculated the wear of the insulation in Δt ($W^*(\Delta t)$) and then the wear of the insulation per unit time W:

$$W = \frac{W^*(\Delta t)}{\Delta t}.$$ (6)

The lifetime of an insulation working at a variable temperature L^* is the inverse of the insulation wear per unit time, $L^* = W^{-1}$.

The relative lifetime elapsed within the interval Δt is:

$$L_{rc}^* = W^*(\Delta t).$$ (7)

The lifetime elapsed within the interval Δt is:

$$L_c^* = L_{rc}^*.L.$$ (8)

The lifetime reserve of the insulation L_R, corresponding to a variable temperature performance within the interval Δt is [39-40]:

$$L_R = L - L_c^*.$$ (9)

3. Silicone Rubber

Silicone rubbers are polysiloxanes with linear macromolecules (Fig. 3) and consist of a main chain of inorganic siloxane linkages (Si-O-Si) with a high bonding energy (444 kJ/mole) and side chains which contain organic groups (methyl etc.) [13, 23]. The ratio between the number of methyl and ethyl groups is between 0.1 and 0.2, and the ratio between the number of chemical crosslinkings and silicon atoms is approximately 0.01 [13].

The main chain of siloxane bonds gives silicone rubbers heat, flame and radiation resistance, chemical stability, weatherability and good electrical properties, and the molecular structure (helical structure and weak intermolecular forces) – water repellency, release properties, cold resistance and compression
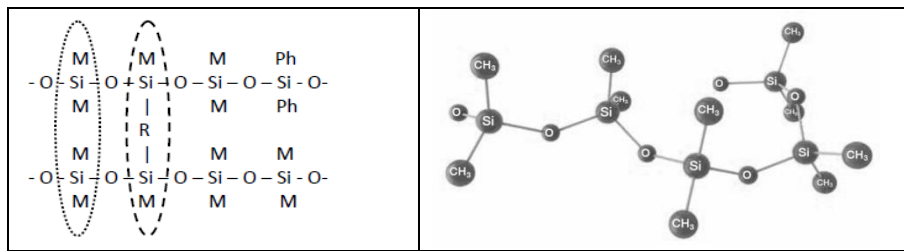

Fig. 3. Schematic (a) and spatial (b) representation of a linear polysiloxane molecule:
M - methyl (-CH$_3$), Ph - Phenyl (-C$_6$H$_5$), R - Chemical crosslinking (C$_n$H$_{2n}$) [13]

characteristics [23]. Superior properties of silicone polymers, compared to others [24], make these materials (possibly with different fillers) usable in electrical engineering, especially for medium and high voltage insulators, for conductors and cables insulation etc. [23]. The behavior of silicone materials for insulators

under the influence of electrical, thermal, mechanical and especially environmental (humidity, dust, acid rains, solar radiation, ozone, etc.) stresses is analyzed in many papers [25 – 34]. There are also studies conducted on silicone rubber bands regarding their behavior in electric field (of low or high frequencies) [35], the electric field effect on breakdown strength [25, 27, 36] and dielectric properties [8], the lifetime estimation [28] etc. To take into consideration, not only the material parameters, but also the effect of manufacture process of the cable on insulation lifetime, in the following, the results of estimating the lifetime based on some experiments conducted on samples taken from the silicone rubber insulation of a cable are presented.

4. Experiments

The experiments were carried out on samples taken from the silicone rubber insulation of a single wire cable with a multiple-wire tinned copper conductor (according to the SF 61/2000 standards) with nominal voltage $U = 300/500$ V. The cylindrically shaped samples, of length $L = 100$ mm, inner diameter $d = 1.6$ mm and outer diameter $D = 2.79$ mm. All the samples were conditioned at a temperature of de 180 ºC, for 48 h, in a Memmert VO 400 oven.

After conditioning, 80 samples were subjected to an accelerated thermal ageing at a temperature of $\theta_a = 260$ ºC, for 22 days. After 2 or 3 days, 10 samples were taken out and the resistance σ and breaking elongation through traction l (using a HOUNSFIELD H50KS Tensometer, the speed of the ferries being 25 mm/min) and mass loss m (with a PRECISA XT 22A, 0.1 mg accuracy) were measured. Resistance and breaking elongation through traction were determined according to the IEC 60811-501:2012 standard [37].

Differential scanning calorimetry (DSC) measurements were performed in non-isothermal mode on a Setaram 131 EVO (Setaram Instrumentation, France). The measurements were carried out in the presence of air atmosphere (air flow 50 ml/min.), in the temperature range 30 - 380 °C at 4 different heating rates β, respectively 2.5, 5, 10 and 15 °C/min. The exothermic peak at ca. 300 ºC, roughly related to oxidation, was used for activation energy evaluation. The oxidation onset temperature (OOT) was determined (according to ASTM E2009-08 2008) as the crossing point of the recorded baseline and the slope of the oxidation exotherm (Fig. 4), using the specific function (*Temperature determination*) of Calisto Data Processing (CDP) software (Setaram/AKTS) [38].
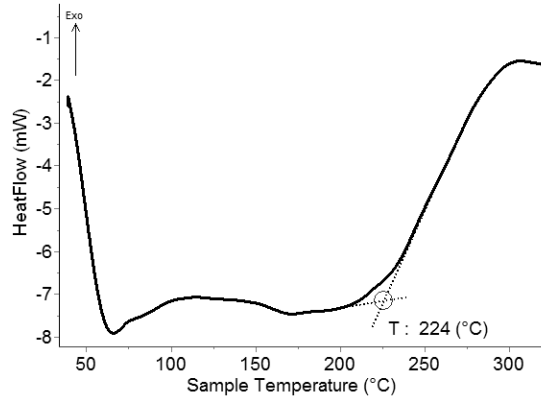
Fig. 4. DSC curve from silicone rubber recorded at 10°C/min,
under air atmosphere (air flow: 50 mL/min)

5. Results. Discussion

5.1. Thermal ageing

For different values of ageing time τ, groups of 10 samples were taken out of the oven and for each one breaking force ($F_R(\tau)$) and breaking elongation through traction ($l_R(\tau)$) and mass $m_R(\tau)$ were measured. Based on these, breaking resistance through traction ($\sigma(\tau)$), and relative resistance ($\sigma_r(\tau)$) and breaking elongation through traction ($l_r(\tau)$) and mass loss $m_r(\tau)$ at time τ were calculated using the equations:

$$\sigma(\tau) = \frac{F_R(\tau)}{S} \tag{10}$$

$$\sigma_r(\tau) = \frac{\sigma(\tau)}{\sigma(0)} \tag{11}$$

$$l_r(\tau) = \frac{l_R(\tau)}{l_R(0)} \tag{12}$$

$$m_r(\tau) = \frac{m_R(0) - m_R(\tau)}{m_R(0)} \tag{13}$$

$$S = \frac{\pi(D^2 - d^2)}{4}, \tag{14}$$

where $F_R(\tau)$ is the mean value of the breaking force of the samples aged for a time τ (for 10 samples), $\sigma(0)$, $l_R(0)$ and $m_r(0)$ – the values of resistance, breaking elongation through traction and unaged ($\tau = 0$) sample mass respectively and S - the area of the cross section of a sample. In Table 1, the mean values of $F_R(\tau)$, $l_R(\tau)$, $m_R(\tau)$, $\sigma(\tau)$, $\sigma_r(\tau)$, $l_r(\tau)$ and $m_r(\tau)$, obtained for silicone rubber samples at different values of the ageing time τ are presented.

Table 1

Values of $F_R(\tau)$, $l_R(\tau)$, $m_R(\tau)$, $\sigma(\tau)$, $\sigma_r(\tau)$, $l_r(\tau)$ and $m_r(\tau)$ obtained for silicone rubbersamples for different ageing time τ values

τ(h)	0	24	48	72	96	120	168	216	288
$F_R(\tau)$ (N)	19,74	19,53	19,45	19,43	19.29	19,44	18,64	12,66	6,43
$\sigma(\tau)$ (N/mm^2)	3,494	3,4566	3,442	3,4389	3.4141	3,441	3,299	2,241	1,130
$\sigma_r(\tau)$ (%)	100	98,93	98,53	97,72	97,71	98,48	94,42	64,13	32,34
$l_R(\tau)$ (%)	61,2	39,37	25,34	18,18	13,07	10,03	7,07	4,058	1,18
$l_r(\tau)$ (%)	100	64,33	41,40	29,70	21,35	16,38	11,55	6,63	1,92
$m_R(\tau)$ (g)	6,878	6,671	6,401	6,184	5,929	5,758	5,525	5,374	5,209
$m_r(\tau)$ (%)	0	2,53	6,93	12,21	14,18	16,43	19,67	21,86	24,26

It can be seen that the higher the ageing time, the lower the breaking resistance $\sigma_r(\tau)$ and breaking elongation through traction $l_r(\tau)$ and the higher the relative mass loss $m_r(\tau)$ (Table 1). The same variational tendencies were also recorded by Shimada in [13], for unvulcanized silicone rubber bands.

To explain these variations, it must be taken into consideration the structure of the samples and physical and chemical processes taking place inside the samples, depending on temperature value and exposure time to this temperature. Therefore, given that the thermal ageing of the samples took place in the presence of oxygen, by oxidation, bonds Si-CH$_3$ of the main chain are broken and a Si-O-Si crosslinking point is created (Fig. 5a). Methyl radicals CH$_3$- form carbon dioxide (CO_2) and water (H_2O). The free radical Si-CH$_2$• introduced by thermal activation would be a new initiator for oxidation [13]. On the other hand, it is known that for temperature values higher than 150 ºC (which is also the case of the accelerated thermal ageing presented in this paper, respectively $T = 260$ ºC), the crosslinking molecules (-R-) can be decomposed, with or without oxidation (Fig. 5b). Given that at temperatures higher than 200 ºC, the crosslinking probability (generally small) is much smaller than that for breaking a crosslink (-R-) [13], it comes out that the number of degraded molecules increases in time and, therefore, the values of mechanic properties decrease, and those of mass loss increase.

Variations of the diagnostic factors σ_r, l_r and m_r with ageing time τ are presented in Figures 6-8. Choosing for each diagnostic factor (DF) an end of life criterion (the value of the diagnostic factor starting from which it is agreed the insulation does not satisfy the necessary conditions of the working cable any longer) – denoted EOL -, from the curves plotted in these figures the time for which these criteria were achieved are determined, $\tau_{EOL\sigma}$, τ_{EOLl}, and τ_{EOLm} respectively (Table 2). As the values of τ_{EOL} were obtained for the ageing at $\theta_a = 260$ ºC ($T_a = 273 + \theta_a$ K), it results that the points $P_{\sigma,l,m}$, of coordinates ($1/T_a$, ln $\tau_{EOL\sigma}$), ($1/T_a$, τ_{EOLl}) and ($1/T_a$, τ_{EOLm}) are points on the lifetime lines corresponding

to the diagnostic factors σ_r, l_r and m_r and chosen EOL end of life criteria (EOL = 50 % for σ_r, EOL = 20% for l_r and EOL = 10% for m_r).

5.2. Activation energy

The calculation of the activation energy E_a was done based on the oxidation onset temperature (OOT) values deducted from the DSC curves (Fig. 4) for 4 values of the heating rate β (Table 3).

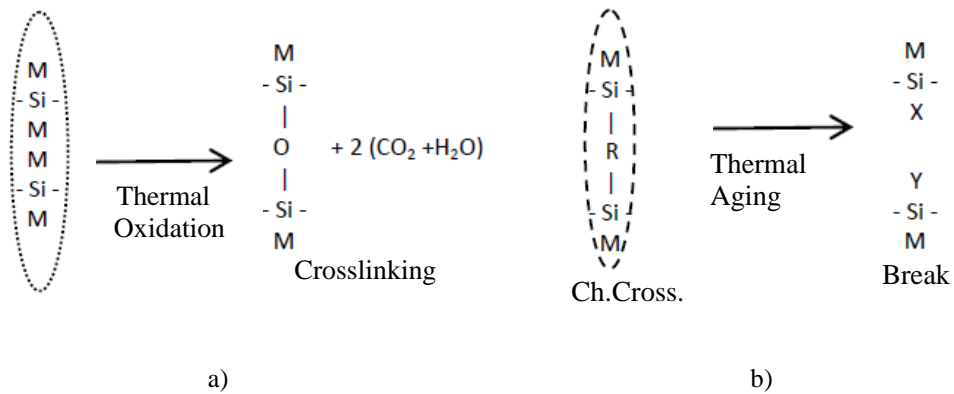a)   b)

Fig. 5. a) Crosslinking by thermal oxidation; b) Thermal decomposition of chemical crosslinking (-X and -Y can be -H or -CH$_3$).
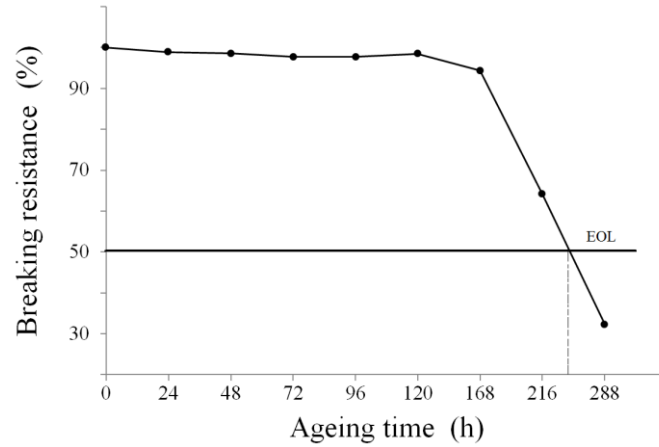

Fig. 6. Variation of the breaking resistance through traction σ_r versus ageing time
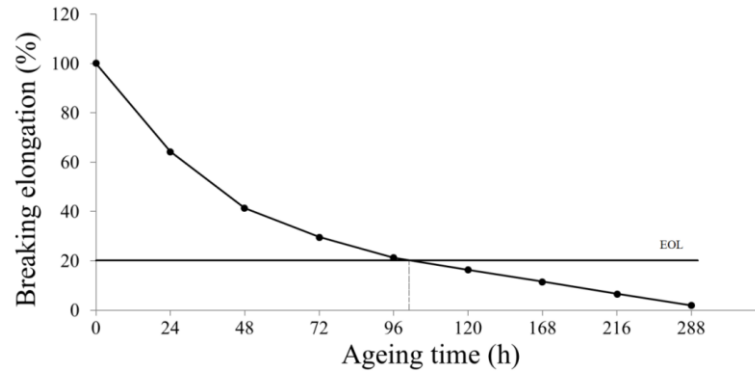
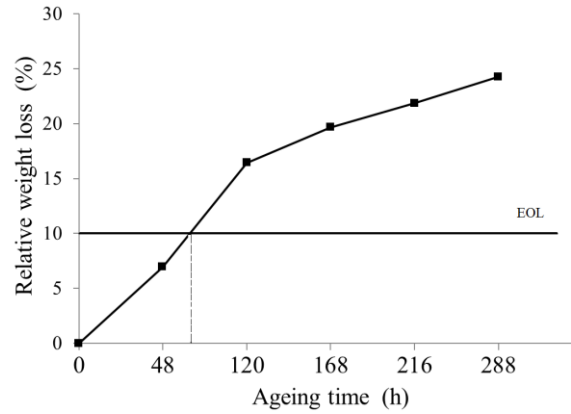Fig. 7. Variation of breaking elongation through traction l_r versus ageing time

Fig. 8. Variation of mass loss, denoted m_r versus ageing time

Table 2

Values of end of life criteria EOL, time taken to reach them τ_{EOL} and the parameters of the line of lifetime *a, A* and *b*, for the diagnostic factors (DF) σ_r, l_r and m_r.

DF	EOL	τ_{EOL} (h)	a	A (h)	b (K)
σ_r (%)	50	248	- 36.46	1.464×10^{-16}	22382
l_r (%)	20	105	-37.63	6.134×10^{-17}	22382
m_r (%)	10	71.31	-37.71	4.182×10^{-17}	22382

Table 3

Onset Oxidation Temperature (OOT) for different values of the heating rate β

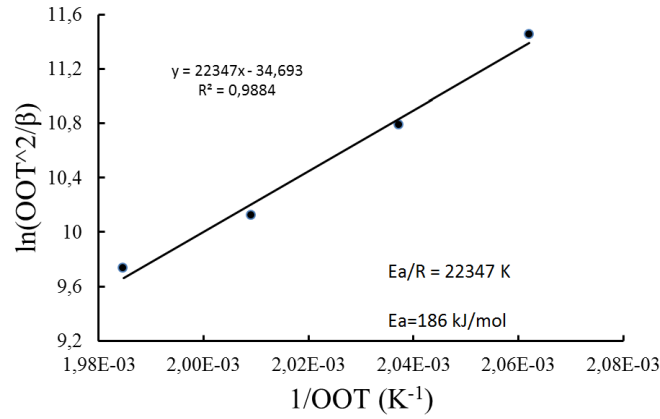| β (°C/min)	OOT (°C)	OOT (K)	$\ln(OOT^2/\beta)$	1/OOT	Ea (kJ/mol)
2.5	211.8	484.9	11.4518	0.002062	
5	217.7	490.8	10.7828	0.002037	186
10	224.6	497.7	10.1176	0.002009	
15	230.7	503.9	9.73651	0.001985	

Fig. 9. Determining of the activation energy E_a using the Kissinger method

5.3. Lifetime

To determine the equations of the three lifetime lines $\ln L_{\sigma,l,m} = f_{\sigma,l,m}(1/T)$, parameters a and b are necessary (see equation (3)). Parameter b (same for all three lines) was determined from the activation energy, $b = E_a/k = 186000/(6.022 \times 10^{23} \times 1.38 \times 10^{-23}) = 22382$ K^{-1}. Parameter a values, corresponding to the three diagnostic factors σ_r, l_r and m_r, and to the selected end of life criteria were determined using the equation (3):

$$a_{\sigma,l,m} = \ln L_{\sigma,l,m} - b/T_a, \tag{15}$$

and are presented in Table 2.

All the 3 lifetime lines have the shape of the one presented in Figure 10, for the diagnostic factor σ_r and the end of life criterion $EOL_\sigma = 50$ %.

Using the Kissinger method [21] the curve $\ln(OOT^2/\beta) = f(1/OOT)$ was plotted (Fig. 9) and the activation energy $E_a = 186$ kJ/mole was determined from its slope E_a/R (R being the gas constant). It should be noted that the E_a value is
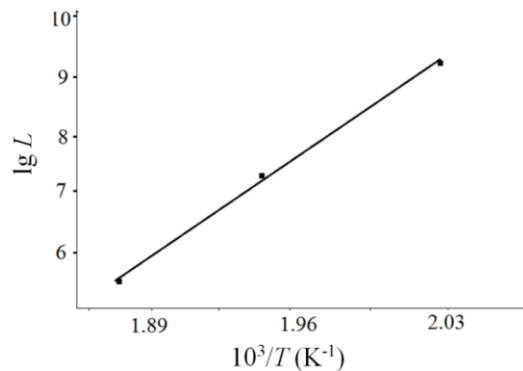

Fig. 10. Lifetime line for σ_r and $EOL_\sigma = 50$ %

Table 4

Lifetime values of the insulation *L* at different temperatures *T*, for the diagnostic factors σ$_r$, *l$_r$* and *m$_r$* and the end of life criteria EOL$_σ$ = 50 %, EOL$_l$ = 20 % and EOL$_m$ = 10 %.

T (°C)	260	240	220	200	180	160	140
L$_σ$ (hours)	248	1284	7527	51263	413547	4045535	49353664
L$_l$ (hours)	105	537	3152	21464	173154	1693878	20664531
L$_m$ (hours)	71.31	366.39	2148.72	14633.67	118051.5	1154842	14088534

higher than those determined by other researchers on unvulcanized and without stabilizer rubber bands, using the accelerated thermal ageing method at three temperatures [13].

Using the equation (3) the lifetime of the silicone rubber insulation *L* was calculated, considering that this works at different temperature values *T* (assumed constant), using the diagnostic factors σ$_r$, *l$_r$* and *m$_r$* and the end of life criteria EOL$_σ$ = 50 %, EOL$_l$ = 20 % and EOL$_m$ = 10 % (Table 4). It can be seen that a decrease in temperature *T* leads to a significant increase in lifetime, for any of the three diagnostic factors. For example, if temperature drops from 220 °C to 180 °C, lifetime increases 55 times.

It should be noted that the selection of end of life criteria is not standard, but related more to the experimenter expertise. For example, in [28], for the diagnostic factor breaking elongation through traction the end of life criterion EOL$_l$ = 50 % is chosen. On the other hand, lifetime values depend both on the diagnostic factor and EOL value (Table 5). It can be seen that lifetime takes the lowest values when mass loss is used as a diagnostic factor. When using the breaking resistance through traction as a diagnostic factor an increase of EOL$_σ$

Table 5

Temperature variation *T*(*t*) within different time intervals.

Time t_i, i=1,2,3... (min)	Interval	$T(t)$ within intervals $t_{i-1} - t_i$ (K)
$t_1 = 30$	$0 - t_1$	$T = 0{,}10555556{\cdot}t + 293{,}15$
$t_2 = 60$	$t_1 - t_2$	$T = -0{,}03333333{\cdot}t + 543{,}15$
$t_3 = 120$	$t_2 - t_3$	$T = 423{,}15$
$t_4 = 150$	$t_3 - t_4$	$T = 0{,}05{\cdot}t + 63{,}15$
$t_5 = 210$	$t_4 - t_5$	$T = 513{,}15$
$t_6 = 240$	$t_5 - t_6$	$T = -0{,}03333333{\cdot}t + 933{,}15$
$t_7 = 300$	$t_6 - t_7$	$T = 453{,}15$
$t_8 = 420$	$t_7 - t_8$	$T = -0{,}02222222{\cdot}t + 853{,}15$
$t_9 = 480$	$t_8 - t_9$	$T = 293{,}15$
$t_{18} = 960$, $t_{19} = 1440$	$t_{18} - t_{19}$	$T = 293{,}15$

from 50 % to 60 %, leads to a decrease in lifetime *L$_σ$* for working temperature *T$_f$* = 180 ºC by 8.1 %, and when using the breaking elongation through traction, an

increase in EOL_l from 20 % to 30 %, leads to a lifetime decrease L_l for working temperature $T_f = 180$ °C by more than 46 %.

5.4. Lifetime reserve

Knowing the elapsed lifetime and lifetime reserve of insulations are of the highest importance for electrical equipment users, in order to avoid taking them accidentally out of order. If the insulation works for a time Δt at a constant temperature T_o, then the consumed lifetime L_c is Δt, and the lifetime reserve is $L_R = L_o - \Delta t$, where L_o is the lifetime calculated at temperature T_o. But if the temperature varies within the considered time interval Δt, and its time variation $T(t)$ is known, then equations (4)...(9) are used to calculate the consumed lifetime L_c^* and the lifetime reserve L_R^*.

Considering that in a time interval $\Delta t = 24$ h the temperature of the silicone rubber insulation varies as in Figure 11, using the equations (5)...(9) and those presented in Table 5 and a Mathcad software, insulation wear $W^*(\Delta t)$ in the interval Δt, insulation degradation per unit time $W = W^*(\Delta t)/\Delta t$, relative lifetime L_{rc}^* consumed in Δt, lifetime L_c^* consumed in Δt, lifetime reserve of the insulation L_R corresponding to a performance at the variable temperature in Δt and the lifetime of the insulation working at the variable temperature L^* were calculated (Table 6). It can be seen that the lifetime consumed per day is 342 hours (14.24 times greater than that consumed during service at a constant temperature of 180 °C) and the lifetime at variable temperature is only 0.631 years, therefore about 75 times smaller than for service at variable temperatures. Of course, if another shape of the curve $T(t)$ is considered, then other lifetime values are obtained.
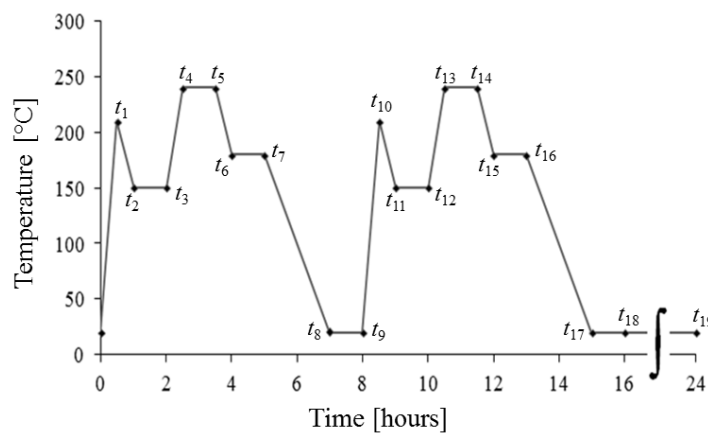

Fig. 11. Time variation of the insulation temperature for $\Delta t = 24$ h

Table 6

Silicone rubber insulation wear (W), lifetime (L) and lifetime reserve (L_R) values

Physical quantity	$W*(\Delta t)$	W (s^{-1})	L_{rc}^* (-)	L_c^* (hours)	L_R (hours)	$L*$ (hours)
Value	4.343x10^{-3}	5.027x10^{-8}	4.343x10^{-3}	342	413205	5525

It should be noted that to estimate lifetime value, only one accelerated ageing test was performed (at the highest temperature value $T = 260$ °C). Using only one thermal ageing test allows a shorter time and lower cost for estimating lifetime and lifetime reserve, compared to the classic method of the three temperatures. The experiments related to the proposed method required roughly 250 h of laboratory ageing, 30 h of DSC testing, data processing and interpretation. In terms of electrical energy, only around 200 kWh were consumed. Using the three temperatures method, the test time increases at about 12 times [21].

6. Conclusions

In this paper, a rapid and simple method to estimate lifetime and lifetime reserve for silicone rubber insulations of cables for special applications is presented. This method uses the activation energy calculated by thermal analysis (using the high-temperature exothermic peak from DSC measurements). Obviously, the value determined from this experiment is different from working stresses, when other types of stresses (electrical, mechanical, etc.) are added to thermal stresses. Using a thermal ageing test at the highest temperature allows a shorter time and lower costs for the tests necessary to estimate lifetime and residual lifetime (compared to the classic method of the three temperatures). Determining parameters *a* and *b* of the lifetime line allows the calculation of consumed lifetime and lifetime reserve of the insulation for variable temperatures.

Lifetime values depend on the operating conditions of the insulation, being greater for an operating at a constant temperature (corresponding to constant loads) than at a variable one (corresponding to overloads). Consumed and residual lifetime calculations allow the evaluation of the cable insulation condition and making decisions regarding the testing and/or replacing of the cable.

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