MONITORING TECHNIQUES FOR NPP ELECTRICAL CABLES CONDITION

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Abstract

The international practice for ageing assessment is monitoring the mechanical, physical or chemical parameters of the insulation materials. Due to the influence of the external factors, the equipment, the measurements results are different from one laboratory to another, a comparison between them being difficult. Therefore, it is necessary for each Nuclear Power Plant (NPP) to preserve the data referring to the condition indicator value of the cable material ageing. For monitoring techniques development, the considered cable samples have already an accelerated thermal aging. The readiness cable types were: HXH 180 E90, 3x25 mm+16 mm and PVC 3x25 mm. The cables have accelerated thermal aged into enclosure facilitating the thermal aged evenly at full length of the samples. The samples' length was 4 m. The thermal ageing of the electric insulating materials for the four cable samples has carried out by an over-rated electric current injection into conducting wires. The service limit values for the accelerated thermal aged cables found out by development of the condition monitoring techniques for the electric cables were: PVC cable type: IM = 110 N·mm; TGA 5% isn't sensitive versus ageing; HXH cable type: IM = 121.1 N·mm; TGA 5% = 271 °C. For checking the ageing condition of the NPP cables and if these have reached the lifetime service limit, the TGA 5% and IM parameters' values have to be measured, and then compared with the values determined at the accelerated thermal ageing.

Keywords: *Cables, Ageing, Accelerated thermal age, Monitoring, Breaking elongation*

Introduction

There is an ageing boundary of the electrical cables materials for their maintaining in operation. This boundary is given by the parameter value monitored which is following so-called condition indicator (CI).

Due to the influence of the external factors, the equipment, the measurements results are different from one laboratory to another, a comparison between them being difficult to be carried out. Taken this aspect into consideration, each Nuclear Power Plant has to keep the data referring to the condition indicator value of the cable material ageing.

A non-effective ageing degradation check of the main component parts can compromise the NPP safety and also the NPP lifetime, as specified in [1]. The reference is a guidance reports series published by the International Atomic Energy Agency (IAEA), where the current practices to determine the boundary for maintaining their safe operation are documented. The information referring to current assessment and management methods on the ageing degradation of the safety circuit systems are shown. The effort to identify the most adequate monitoring techniques for materials failure is described.

The standards for measuring and monitoring circuit qualification specify the testing procedures dedicated to determine their operating capability after Design Base Earthquake (DBE), after normal operating condition exposure for their scheduled lifetime (40 years, often).

According to [2], the environmental qualification of the electrical cables has been evaluated lately and this is based on using condition monitoring techniques for recording the cable failure level after each stage of the qualification process, parallel to operating capability checking after DBA testing, inclusively.

The current economic pressures consist in operating lifetime increasing up to 60 years, [1, 3-5]. An actual cable ageing management programme has to be carried out, additional to environmental qualification, providing the operating capability during service lifetime of NPP, including any lifetime extension.

The usability and limitations of monitoring techniques for NPP cables ageing condition are also described in [1].

Plant practice with most cable types has proved that the electric parameters are not characteristic for the cable insulation and jacket ageing; the electric failure usually follows after a mechanical degradation. Therefore, the international practice for ageing assessment is monitoring the mechanical or chemical parameters of the insulation materials.

Monitoring techniques for electrical cables condition

The condition monitoring activities (CM) provide the information required to establish the ageing degree of the power cables.

For a condition monitoring technique to be useful, the condition indicator, the measured parameters, have to be sensitive versus the material ageing.

For development of monitoring techniques, the chosen cable samples were already accelerated thermal aged. The readiness cable types were: HXH 180 E90, 3x25 mm+ 16 mm and PVC 3x25 mm, shown in the Fig. 1.

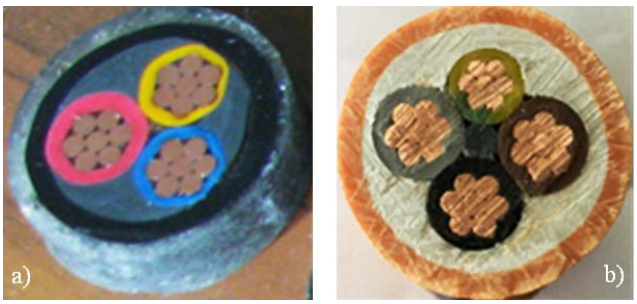


Fig. 1. Cable types chosen for development of the power cable monitoring techniques

The cables have accelerated thermal aged into enclosure facilitating the thermal aged evenly at full length of the samples. The samples' length was 4 m. In Fig. 2 is shown the arrangement of cable samples into enclosure.



Fig. 2. The enclosure for accelerated thermal ageing of the power cables

The thermal ageing of the electric insulating materials for the four cable samples has been carried out by an over-rated electric current injection into conducting wires. The basic diagram is shown in the Fig. 3.

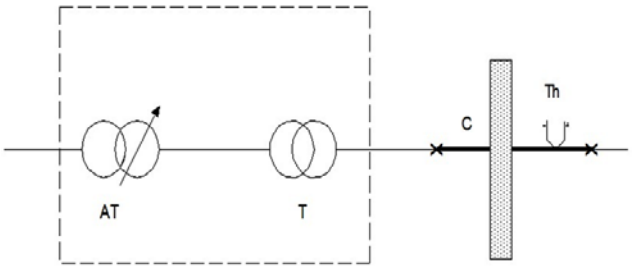


Fig. 3. The basic diagram for energy supply of the power cables

The temperature top limits for thermal ageing have been chosen so that the material's degradation resulting homogenous all over the material thickness. This had to be confirmed by adequate techniques for monitoring the diffusion –limited oxidation [6].

The lifetimes and temperatures for the accelerated thermal ageing of the HXH and PVC cables are given in Tables 1 and 2. To determine the equivalent operating lifetime of the installed cables, at NPP temperature, the Arrhenius relation was applied [7-12]:

$$t_1 = t_2 \cdot e^{\frac{E}{R}\frac{T_1 - T_2}{T_1 \cdot T_2}} \quad (1)$$

where:

t_1 - calculated lifetime of the installed cables insulation [years],

t_2 - time for accelerated thermal ageing condition [years],

E = 26300 cal/mol - activation energy of a thermal oxidation reaction for HXH cable for temperatures greater than 100 °C,

E = 18900 cal/mol - activation energy of a thermal oxidation reaction for HXH cable and temperatures smaller than 100 °C,

E = 23000 cal/mol - activation energy of a thermal oxidation reaction for the PVC cable,

R = 1.987 cal/K·mol - the universal gas constant,

T_2 - absolute temperature of the thermal accelerated ageing cable insulation [K],

T_1 - absolute temperature of installed cables insulation [K]

Table 1. The lifetime values of the HXH cable materials for the T_1 temperature values

Shield	T_1 **[K]**	T_2 **[K]**	t_2 **[hours]**	t_1 **[years]**
insulating	326	378.8	1511	9.80
		379.8	2975	20.4
		379.6	4486	30.2
		379.8	5908	40.3
jacket	320	359.5	1511	3.70
		359.5	2975	7.30
		359.5	4486	11.0
		359.5	5908	14.5

Table 2. The lifetime values of the PVC cable materials for the T_1 temperature values

Shield	T_1 [K]	T_2 [K]	t_2 [hours]	t_1 [years]
insulating	318	369	626	9.91
		369.5	1272	21.13
		369	1887	29.86
		369.5	2533	41.09
jacket	313	369.5	3179	50.99
		351	626	3.90
		351	1272	7.92
		351	1887	11.75

The most applied monitoring techniques for the electrical cable condition are the following: breaking elongation test, indentation technique and material thermal analysis.

The indentation method

The equipment

The solutions to carry out portable equipment for condition monitoring of the installed cables, by measurement of the jacket material's compression properties, have been found following a technical study; the equipment is shown in Fig. 4.

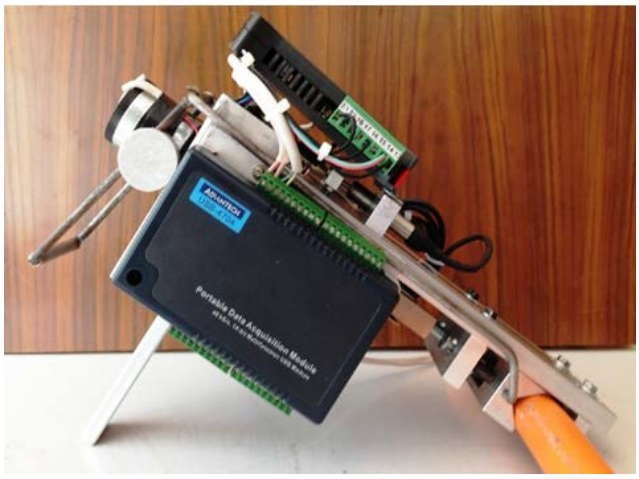


Fig. 4. The equipment for IM measurement of the power cable materials

For calculus and display the Indentation Modulus (IM) on-line, the data acquisition, referring to indentation force value F [N] and indentation depth d [mm], were registered into a MS-Excel file using the data acquisition system (SAD). The recording rate of the measured values was about 5 reading /sec.

Indentation Modulus display on-line is shown in Fig. 5.

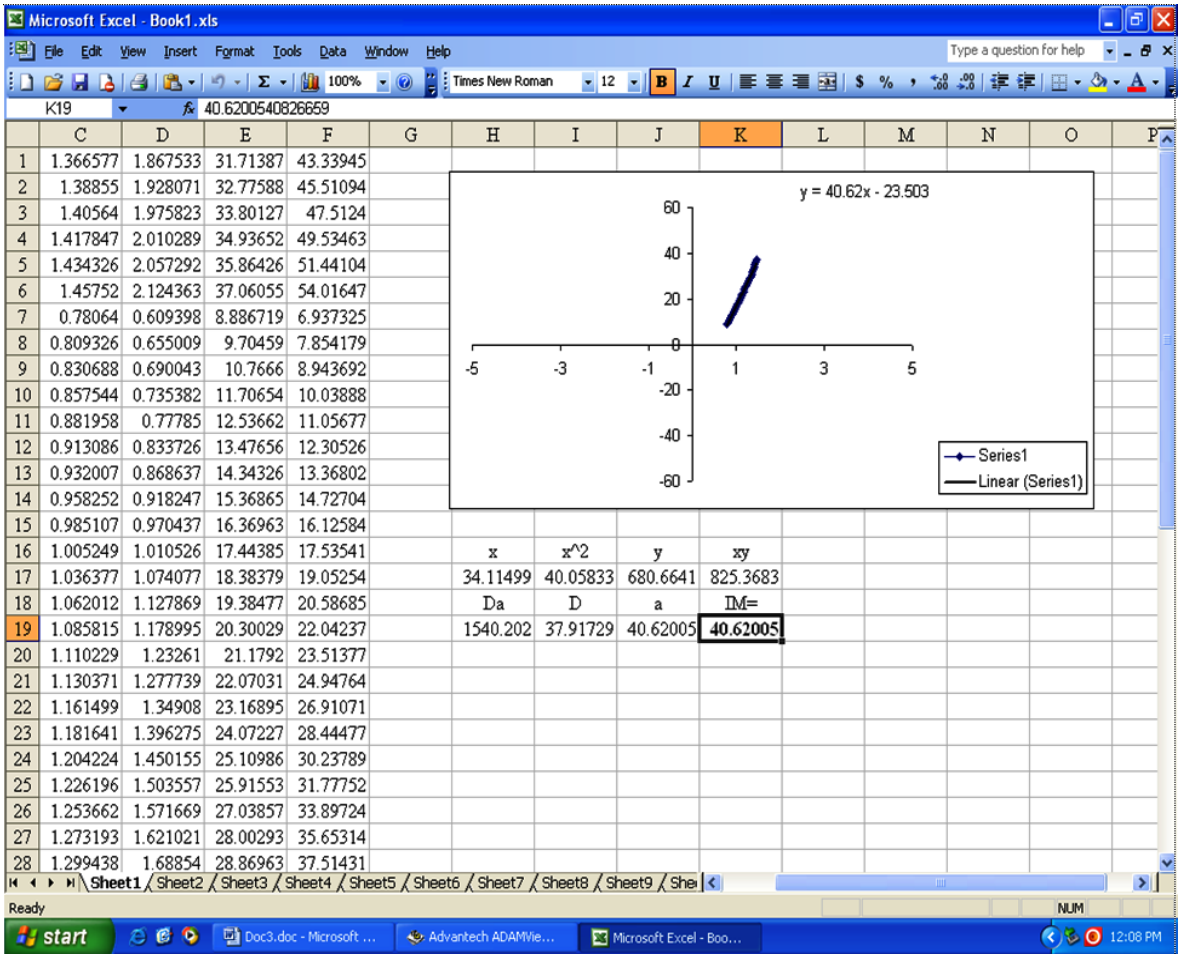


Fig. 5. The data display for Indentation Modulus (IM)

Results

The indentation modulus (IM) measurement was carried out in points placed on 90° on the cable circumference, in two areas at about 360 mm. For every cable sample, eight measurements of the IM have been performed, and then the measurements average value was calculated.

The measurements have been carried out on the five thermal aged samples and on the non-aged cable, six cable samples in all. The IM values for the electric cable material made of PVC are presented in Table 3, [13].

Table 3. IM value for the six samples of PVC cable

Sample / points number	**IM [N/mm]**					
	0	***1***	***2***	***3***	***4***	***5***
1	32.40	38.70	32.40	40.50	53.10	106.3
2	45.00	39.40	68.30	27.70	66.20	64.80
3	26.33	33.90	36.60	55.10	73.70	58.30
4	28.10	25.70	28.30	60.40	66.20	68.50
5	40.60	19.90	63.50	22.90	29.11	65.80
6	49.00	47.20	20.30	44.10	70.20	28.30
7	37.70	43.00	22.60	52.60	73.50	56.40
8	30.20	34.00	68.00	52.60	23.10	64.30
Average	36.17	35.23	42.50	44.49	56.89	64.09
Deviation	9.14	9.76	17.70	13.48	19.72	6.97
***t* [°C]**	23.10	23.10	23.10	23.60	23.60	23.60

IM evolution versus ageing time is shown in Fig. 6.

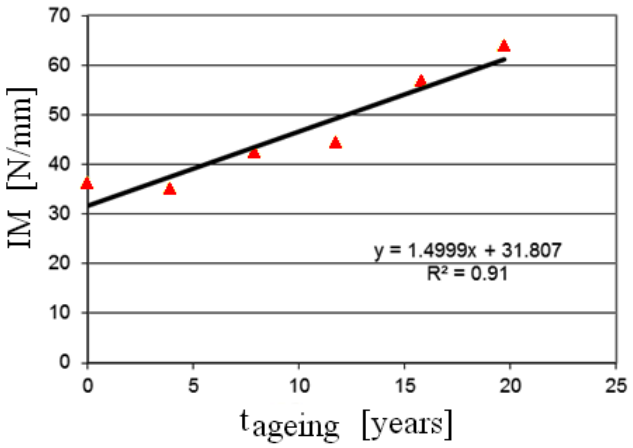


Fig. 6 Graphical representation of the IM evolution versus ageing time for PVC cable

For the HXH cable, the indentation modulus measurement was carried out also at points placed at 90° on the cable circumference. For every cable sample, four measurements of the indentation modulus were performed; the IM value for cable resulting by calculating the average value of the measurements.

The measurements were carried out both on the thermal aged samples and the standard cable, 5 samples of cable in all. The IM values for the electric cable jacket material HXH are presented in Table 4, [14].

Table 4. IM value for the five samples of HXH cable

Sample / points number	**IM [N/mm]**				
	0	***1***	***2***	***3***	***4***
1	77.35	104.15	99.29	89.40	96.10
2	73.38	97.01	94.03	97.82	103.75
3	77.64	95.93	94.63	97.33	90.44
4	74.52	105.43	92.13	76.71	97.61
Average	75.72	100.63	95.02	90.31	96.97

IM evolution versus ageing time is shown in Fig. 7.

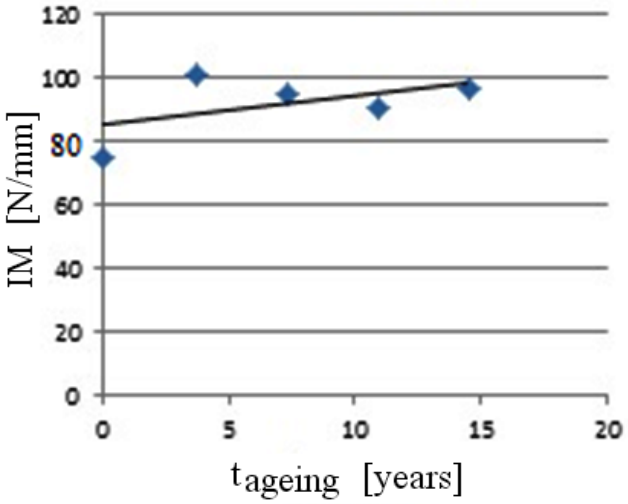


Fig. 7 Graphical representation of the IM evolution versus ageing time for HXH cable

The breaking elongation technique

The samples preparation

The samples have been taken out from the conductors' insulation. The cable sections from which the samples were obtained have been placed at 1200 mm from ends; the ends have not been sealed during ageing process. The shape and sizes of the testing samples are shown in Fig. 8.

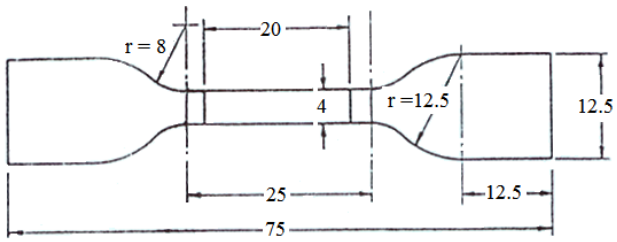


Fig. 8 The shape and sizes for samples tested at breaking elongation

The equipment

The test samples to determine the elongation at break were analysed on a INSTRON 25 KN tension test equipment (see Fig. 9). The equipment grips are with self-clamping, avoiding the sample sliding from tightening.



Fig. 9. The Material Testing System

The breaking elongation test has been carried out as follows: pre-tightening at 5 N; initial speed = 5 mm/min; Lgrip = 50 mm; testing speed = 50 mm/min.

The acquisition data referring to the draw force *F* and *A%* elongation test have been recorded using an automatic system and the curve *F = f (A%)* was displayed (see Fig. 10). The test followed up until the sample was broken.

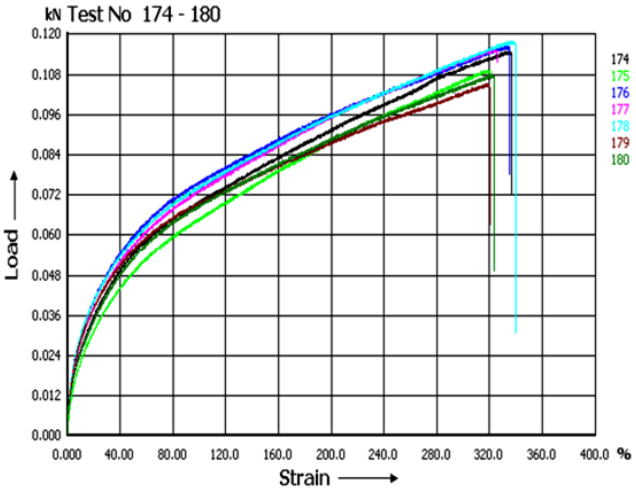


Fig. 10. The curves *F = f (A%)*

Results

The values of *A (%)* at breaking for HXH cable are shown in Table 5, [15]. For every cable sample, six determinations were carried out. The sample 1.1 broke beyond the limits and for this reason it was not considered.

The *A%* evolution at breaking (the average value on cable sample) versus the ageing time for the HXH cable is shown in Fig. 11.

Table 5. *A%* values for the HXH cable samples

Determination	**Sample**				
	0	***1***	***2***	***3***	***4***
1	344.4	-	265.7	190.3	180.9
2	338.9	169.8	243.1	203	140.9
3	392.1	195.3	228.7	289.1	193.5
4	341	208.7	184.1	188.8	239.1
5	341.6	198.7	250	273.9	209.3
6	427.8	149.5	252.9	251.4	154.9
Average	364.3	184.4	231.76	241.24	187.54
Temperature	23°C	24°C	24°C	24°C	25°C

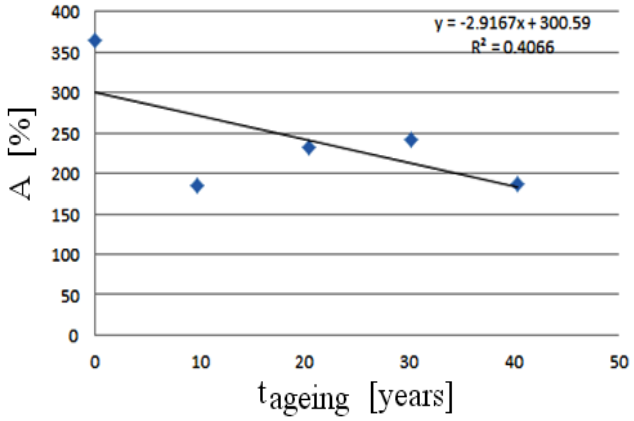


Fig. 11. The evolution of elongation *A%* at break versus the ageing time for HXH cable

The A% values at breaking for the six PVC cable samples are given in Table 6, [16]. For every cable sample, seven determinations were carried out.

Table 6. *A%* values for the PVC cable samples

Determination	**Sample / temperature / time [years]**					
	0	***1***	***2***	***3***	***4***	***5***
	21 °C	21°C	22°C	25°C	25°C	26°C
	0	9.91	21.13	29.86	41.09	50.99
1	335.0	277.8	327.1	267.0	135.3	298.4
2	316.7	228.1	313.2	180.3	313.8	350.5
3	333.5	303.2	182.4	292.5	303.3	322.6
4	324.3	273.3	314.4	260.4	250.5	49.67
5	339.4	248.2	277.5	337.6	236.0	261.6
6	320.2	253.6	225.3	138.8	324.5	324.8
7	322.7	333.0	280.6	343.1	223.4	254.3
Average	327.4	273.9	274.4	260.0	255.3	266.0

The graphical representation of the A% evolution at breaking (the average value on cable sample) versus the ageing time for PVC cable is shown in Fig. 12.

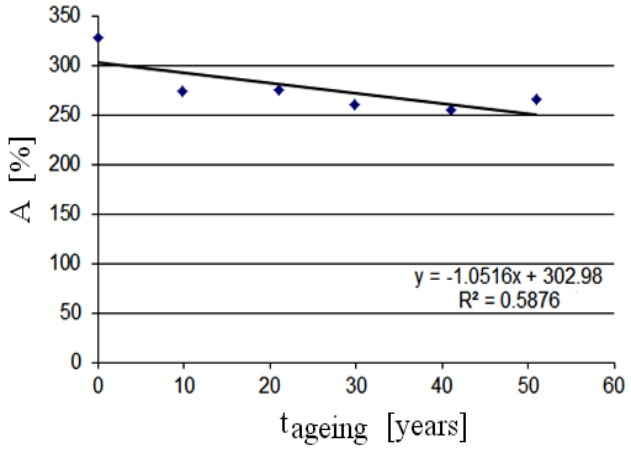


Fig. 12. The evolution of elongation *A%* at break versus the ageing time for PVC cable

A 50% decrease of the breaking elongation for electrical cables materials is international acknowledged as service life of the electrical cables, [1].

This life limit is reached for a NPP service lifetime of 51.5 years for HXH cable and of 100.3 years for PVC cable, respectively.

The evolution of the parameter *A%* versus the ageing time is given by the relations written on Figs. 11 and 12.

Thermo-gravimetry analysis (TGA)

The samples preparation

The samples have been taken out from the cable jacket by scratching with a cutter, an amount of about 10 mg/sample being necessary.



Fig. 13. The material sample taken from cable jacket for TGA

The estimated liquid nitrogen requirement for forming an ice plug inside a 400 mm pipe with stationary water at an initial temperature of 20 °C is 356.9 kg.

The equipment

For the thermo-gravimetry analysis of the electrical cable materials, a SETARAM SETSYSEVOLUTION 2400 equipment has used.

The calibration and TGA value adjustment of the equipment have carried out due to changing the pot weight with temperature. The heating speed was of 5 °/min, at an Oxygen flow rate of 50 ml/min, the maximum temperature being 1000 °C.

While the sample has been heated into the equipment, the data acquisition referring to temperature T around sample and of the weight sample decrease Δm has been recorded. The parameter TGA 5% is defined quantitative as the temperature on the thermo-gravimetric graph $T = f(\Delta m)$ for which the weight decrease of the micro-sample is 5%.



Fig. 14. SETARAM SETSYSEVOLUTION 2400 Equipment

Results

The TGA 5% values for the five samples of HXH cable are given in Table 7, [17]. For every cable sample, six determinations were carried out.

Table 7. *TGA 5%* values for the HXH cable samples

Determination	**Sample**				
	0	***1***	***2***	***3***	***4***
1	261.90	263.80	260.17	264.24	264.52
2	259.1	260.48	265.13	266.73	265.25
3	259.50	264.77	267.84	259.9	261.39
4	263.46	263.76	253.41	265.03	263.98
5	256.80	263.40	267.05	262.16	265.93
6	-	-	263.67	264.29	264.49
Average	260.17	263.24	263.08	263.73	264.26

The evolution of the TGA 5% parameter's values versus the ageing time for HXH cable is shown in Fig. 15.

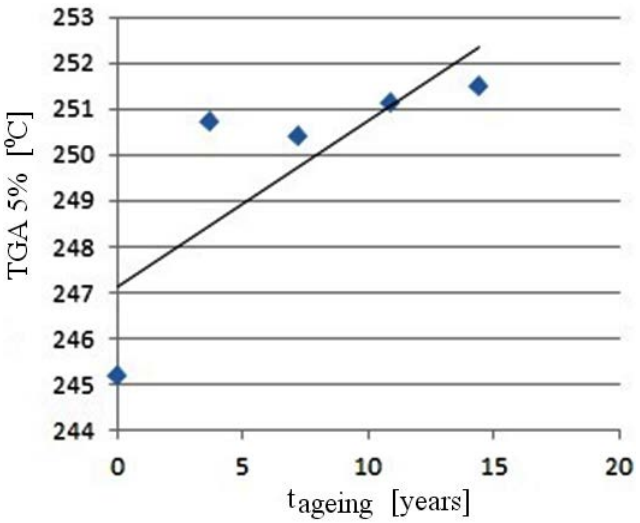


Fig. 15. The evolution of TGA 5% parameter versus the ageing time for HXH cable

The TGA 5% values for the six samples of PVC cable are given in Table 8, [18]. For every cable sample, a single determination was carried out.

Table 8. *TGA 5%* values for the PVC cable samples

Sample	***0***	***1***	***2***	***3***	***4***	***5***
TGA 5% [°C]	275.2	275.1	276.9	274.5	278.9	273.0

The evolution of the TGA 5% parameter versus the ageing time for PVC cable is shown in Fig. 16.

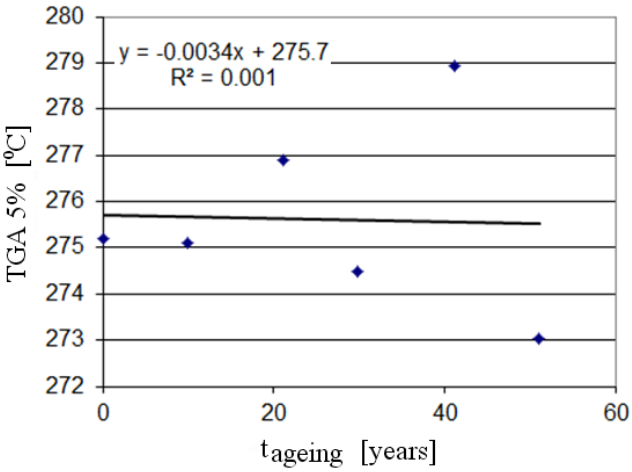


Fig. 16. The evolution of TGA 5% parameter versus the ageing time for PVC cable

Conclusions

The present work is approaching the predetermination matter of lifetime in safety condition for the NPP electrical system's components, particularly for the electric power cables. The NPP specific operating rules indicate a lifetime up to 40 years; increasing of the lifetime up to 60 years and upwards is presently wanted.

One of the factors that negatively influence the NPP's operation and lifetime is represented by the ageing process for critical system components. The cables system can't be replaced and is vital for the security and safety operation of the NPPs. Thus, for each NPP in addition to the environmental qualification, an Ageing Management Program (AMP) has to be implemented. The AMP allows the monitoring and the damage assessment caused by cable ageing; it also allows the determination of the parameter evolution and eases the real time implementation for corrective actions.

An AMP implementation includes laboratory research and in-situ activities. The laboratory activities are focused on the development of methods and instruments for the power cable condition monitoring. The in-situ activities are focused on the environment monitoring and on measurements regarding the condition indicators for the cable jacket, and the comparison against their allowable limits. The limits are determined in laboratory conditions using accelerated ageing and represent the equivalent real time operation duration inside an NPP.

When these limits are not reached or if the operating conditions are less severe than those beforehand, can be eventually performed additional reviews of the power cables environmental qualification and, consequently, extensions of their period of service.

The environmental characteristics are settled in technical specification, the basis for the design documentation development. NPP real conditions knowledge can indicate on which power cables to extend the research, these being subjected to a faster ageing than the electro insulating material initial estimated based on the specifications.

For the power cables it cannot monitoring only the temperature value of their components to the protective jacket level of the electric cable. The temperature of the bottom electric insulation layers can be determined by a thermal calculus. Therefore, power cable temperature calculus models need to be developed. The thermal characteristics values for each electric insulating material type used in electric cable structure are also required.

The goal of the methods and instruments used in the power cables insulation condition monitoring is to assess the effects of damage process caused by the cables ageing, in order to maintain the design degradation rate. They are based on the measurement of the mechanical, physical, chemical, thermal and electric properties of the cables.

For checking the NPP cables ageing condition and if they have reached the lifetime service limit, TGA 5% and IM parameters' values have to be measured and compared against those determined at the accelerated thermal ageing. The service limit values for the accelerated thermal aged cables found out by development of the condition monitoring techniques for the electric cables were:

- PVC cable type 3x25 mm: IM = 110 N·mm; TGA 5% is not sensitive to ageing;
- HXH cable type 3x25 mm +16 mm: IM = 121.1 N·mm; TGA 5% = 271 °C.

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