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Benefits and drawbacks of selected condition monitoring methods applied to accelerated radiation aged cable

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ABSTRACT

The cable constructed from two ethylene-vinyl acetate copolymer (EVA) based jackets and chemically crosslinked polyethylene (XLPE) insulation was accelerated aged by gamma rays with two dose rates up to 1.4 kGy (6.0 kGy/h) and 1.2 kGy (0.6 kGy/h). Several condition monitoring methods were evaluated and compared: tensile tests, gel fraction and oxidative induction temperature (OITp) measurements, degree of swelling, and isothermal thermogravimetric analysis TGA under air flow. The influence of dose rate, oxygen availability and crosslinking of polymeric constituents on the data obtained were analyzed and discussed. The experiments confirmed that the oxidative degradation extent enhanced the effects measured, particularly those determined by isothermal decay in aerobic conditions. It was found that isothermal thermogravimetry in air is promising potential diagnostic method which could replace currently applicable criteria based on mechanical tests. However, this method is not universal and it is recommended for severely oxidized polymer materials.

1. Introduction

Low and medium voltage I&C cables (*Instrumentation and Control cables*, <1 kV) play a significant role in each safety system of nuclear power plants (NPP) [1]. They are responsible for analog and digital signals transmission in many kinds of transducers, such as: resistance temperature sensors, pressure sensors or neutron radiation detectors. Moreover, I&C cables and wires are used to control circuits for valves, engines, switches, etc. The cables, whose length is approximately 1000 km per reactor, are exposed to many degrading factors, among which gamma radiation and heating are the most important. The stressors initiate radical reactions in polymeric matrices causing oxidative degradation at constant oxygen access, i.e. in an air atmosphere, at the course of their exploitation in NPP [2]. Oxidative degradation results in the deterioration of mechanical properties of polymeric composites used in insulations and jackets [3,4] what might trigger substantial disruption in the electrical functionalities of I&C cables. That makes a serious problem from the point of view of the safe NPP operation. Therefore, in each NPP I&C cables must be qualified to determine their service life-time basing on end-of-life criteria [4]. Usually two approaches are considered. The first one, called ongoing qualification, consists in periodical examination of the insulation and jacket quality during their exploitation. In order to conduct ongoing qualification, the additional cable deposits designed exclusively for testing should be predicted already during the design phase of reactor. The second approach is based on performing accelerated aging followed by laboratory tests. I&C cables are then exposed to the degrading factors of high intensity during much shorter time than the assumed service life (e.g. 40 + years) [5]. Both approaches have advantages and disadvantages. Ongoing qualification reflects the influence of all environmental degrading factors and their severity (radiation dose rate, temperature, humidity, mechanical stress, etc.). Thus, the scenario allows to monitor the real, cumulative deterioration of the cables operating at a given localization. Unfortunately, additional cable deposits are uncommon in the existing NPP. On the other hand, even in the newly constructed containment buildings, the space having the same nature and intensity of degrading factors for extra specimens of cables is very limited.

In accelerated radiation aging tests, cables absorb the same dose like during their exploitation in NPP, at a dose rate of two or even three orders of magnitude higher [6]. Unfortunately, the degrading factors of high intensities might cause responses different from those determined for operating cable conditions in NPP. For example, oxidative degradation strongly depends on dose rate

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because the process is controlled by oxygen diffusion. For accelerated thermal aging so called acceleration factor (ratio of the time of exploitation to the accelerated aging time) should not exceed 250 in order to ensure the reliable assessment of the safe service time, often based on the Arrhenius equation or its derivatives [7]. Additionally, application of the temperatures above phase transitions e.g. melting points for semicrystalline polymers (PE, EVA) makes a risk of changing a degradation kinetic regime. Moreover, simultaneous treatment with at least two degrading factors often results in synergistic or inverse effects [8]. That causes a significant error in the assessment of cable life time. On the other hand, accelerated aging tests allow to simulate failure state, e.g. MSLB (*Main stream line break*) or LOCA (*Loss of coolant accident*) in which the intensity of degrading factors rapidly increases [9].

The selection of condition monitoring methods is an important issue in cables qualification. It is recommended that the measured parameter has changed proportionally to the degradation progress. The tensile tests are still considered as an essential method and elongation at break (Eb) is regarded as the most reliable degradation indicator. Currently being used end-of-life criteria for determination of the cable failure base on Eb measurement which needs quite a big number of relatively large samples for the conclusive and accurate assessment. Apart from tensile tests, other methods such as indenter module measurements, differential scanning calorimetry DSC, oxidative induction time OIT and temperature OITp, physicochemical tests and electrical methods are used as the condition monitoring techniques but none of them is free from drawbacks and universal [10,11]. Thus, there is a need to develop novel reliable methods utilizing other degradation indicators and end-of-life criteria.

In 2014 we confirmed that isothermal decomposition of chemically crosslinked EVA jacket seemed to be promising method for monitoring the evolution of accelerated aging applied to electrical cables [12]. The data showed strong correlation with elongation at break, particularly for low dose rates. In order to explore possibility of using this technique with regard to other systems we compared the previous results obtained for crosslinked EVA with the data collected from the tests of non-crosslinked EVA and chemically crosslinked polyethylene (XLPE) which are respectively the components of the inner jacket and the insulation of the same cable, Fig. 1.

In this work potential application of thermogravimetry (TGA) in an isothermal mode used as a monitoring method is discussed and compared with other condition monitoring systems. The variable techniques allowed to evaluate the influence of crosslinking and oxygen accessibility on various constituents of the cable under test. Such an approach enabled to analyze versatility and adaptability of the tests for the accelerated aged cables operating in NPP.

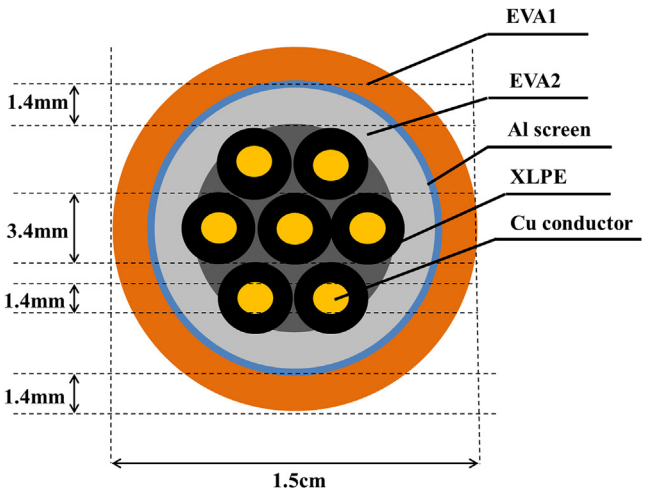

Fig. 1. A schematic cross section of EVA/XLPE cable.

2. Experimental

2.1. Materials, irradiation and thermal aging

The investigated cable for was composed of outer jacket made of crosslinked ethylene vinyl acetate copolymer (EVA1), inner jacket made of noncrosslinked EVA copolymer (EVA2), insulation made of crosslinked polyethylene (XLPE) and seven copper conductors of cross section $\phi = 1.5$ mm^2. The EVA jackets contained 40 $_{wt}$% powdery aluminum hydroxide $Al(OH)_3$ acting as a flame retardant and some additives, like antioxidant, stabilizers, calcite, pigment, etc. The thickness of EVA jackets and XLPE insulation was 1.40 mm and 1.05 mm, respectively.

For radiation aging both ends of the cable were sealed to prevent lengthwise diffusion of air, reproducing the real operational ageing condition. Irradiation was carried out by means of ^{60}Co gamma rays at ambient temperature in the air atmosphere. Two dose rates were applied, 6.0 kGy/h and 0.6 kGy/h, in order to irradiate the cable to the cumulative doses of 1.42 MGy and 1.20 MGy, respectively.

2.2. Thermogravimetric analysis (TGA)

For thermogravimetric analysis the specimens of outer jacket were cut across the thickness forming a disc with a diameter of 4.00 mm and thickness of 1.40 mm (33 mg). The specimens of XLPE insulation in the shape of ring (about 25 mg) were cut off perpendicularly to the axis upon removal of the conductors. Each sample was set into the oven of TGA apparatus in an open platinum pan. For the isothermal TGA analysis, the temperature increased with the rate of 50 °C/min up to 400 °C and then was maintained at this level under air flowing with a rate of 60 ml/min. TGA measurements were performed using a TA Instruments Q500 apparatus.

2.3. DSC measurement

Oxidative induction temperature (OITp) was measured using a TA Instruments differential scanning calorimeter (MDSC 2920) at a heating rate of 10 °C/min under oxygen atmosphere at a purge rate of 50 ml/min. OITp was carried out using small samples of about 10 mg. Oxidation of the sample was characterized by an increase in heat flow which raises above a certain temperature depending on the extent of degradation. The OITp values were determined as an intersection point of baseline and onset of degradation tangents.

2.4. Mechanical property

The tensile test was conducted using an Instron – 5565 machine. The EVA outer jacket stripped from the irradiated cable was punched out to the dumbbell shaped specimens (6 mm width, 45 mm length at measurement area). The rate of elongation was 50 mm/min 5 samples were measured for each specimen.

2.5. Gel fraction

Crosslinking yield as a function of dose absorbed was evaluated by the gel fraction measurements. Small-cut pieces of about 0.2 g were placed into porous bottom pans and the extraction process in the flask equipped with a reflux condenser was carried out. The extraction agent was a mixture of xylene isomers (mp. 137–143 °C).