論文の内容の要旨

Summary

Study on Ageing Degradation of Nuclear Power Plants Cables using Accelerated Tests
(原子力発電プラントケーブル経年劣化に関する加速試験を用いた研究)

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1. Introduction

Degradation of polymeric-based cable insulator is a key concern for nuclear power plants (NPPs) operation and life management. Survey of good international practices 1-4) resulted in 6 attributes for effectively managing insulator ageing: Cable structure/ materials, environment, category, degradation mechanisms, condition monitoring, and modeling. Management activities through these attributes rely on estimated integrity margins from accelerated ageing tests. Besides, cable integrity is evaluated before installation through the so called environmental qualification (EQ) to assure cable remains functional at design lifetime and design basis accident (DBA). During EQ, integrity is evaluated by accelerated thermal and radiation test simulating normal operation, followed by DBA test that envelop loss of coolant accident (LOCA) conditions, and finally the cable integrity is judged by bending submergence withstand voltage test 3).

On the other hand, the main issues of current EQ as well as relevant research activities on accelerated ageing tests are extracted below:

1-Obtained knowledge from thermal accelerated tests focuses only on insulator material ageing. But during EQ process and real operation, cables are aged including jacket material. Thus, insulator ageing must be well considered within whole cable structure.

2-The equivalency between accelerated test and real conditions is limited to insulator mechanical properties, in particular elongation at break (EAB). Thus, activation energy (E_a) estimations by Arrhenius modeling is mainly dependent on induced mechanisms altered by EAB. But real E_a may differ due to insulator colorant variance, or at extrapolation region due to physical transition mechanisms. Besides, during integrity test, the final judgment relies on electrical properties since they are most vital parameters 1). Nevertheless, it is difficult to evaluate their time-dependent degradation due to inaccuracies of their conventional measurements by Mega ohmmeter. With above in mind, it is vital to update current knowledge by insulator properties variety and cable structure.

3-Current DBA test only covers LOCA. Some scenarios beyond-DBA (BDBA) conditions may be included in new regulations through the so called design extension conditions (DECs)

Accordingly, this study aims at properly customizing accelerating test to understand cable real degradation during normal operation, and modify cable EQ process to suit with recent progress of NPP safety design. For achieving this goal it is required to:

1-Clarify impact of cable structure on insulator mechanical and electrical properties.

2-Assess utilization of insulator electrical and mechanical properties degradation for trending accelerated ageing from engineering evaluation methods and recent knowledge database.

3-Identify important cables for DECs and propose modification of EQ to suit with some elevated scenarios accompanying DECs.

2. Experimental studies on cable structure impact by accelerated ageing

2.1 Cable materials and test environment

Flame-retardant ethylene propylene rubber (FR-EPR) insulated cables are selected due to their vast usage in NPPs 4). Jacket material is polyvinyl chloride (PVC). Cable category is nuclear grade

1E, 3 core, low voltage (LV) (< 600 V) power/control.

Thermal accelerated ageing tests were performed using air-circulated oven at 125 ˚C, 150 ˚C, and 160 ˚C for 5040 hours, 336 hours, and 264 hours, respectively. The assumed degradation mechanisms are chain scission, cross linking, additives immigration while diffusion limited oxidation (DLO) is more efficient at higher test temperatures. Full cable-type (insulator and jacket) ageing is focused, considering that whole cable structure is aged in real NPP environments. But to compare effect of insulator's ageing environment (jacket or air), some specimens were heated after removing their jacket. Maximum scattering of oven temperature is ±4 ˚C.

2.2 Parameters for insulator properties evaluation

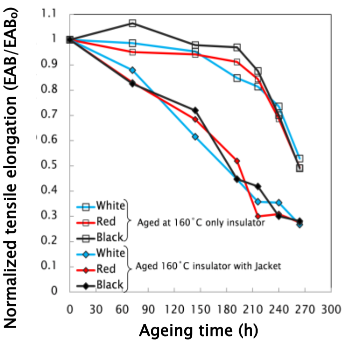
Insulator electrical properties were evaluated by volume resistivity (ρ) .Although the induced charged particles from chain scission reactions (i.e. chain scission moieties) by ageing stressors can alter insulator volume resistivity (ρ), conventional insulation resistance (IR) measurements are only pass/fail test and not counted for trending time-dependent ageing, because uncertainty of IR due to the leakage current over cable surface is large. To solve this issue, new electrode for tubular insulator was developed to guard the influence of surface current 5). By using this electrode and Wheatstone bridge circuit, measurement of ρ in tubular insulator became plausible, provided, however, that $\rho < 1\times10^{15}$ Ωm.

EAB is utilized to evaluate insulator mechanical properties since it is well-known as excellent ageing indicator. Tubular shape tensile samples were made for the three aged insulator colors at each ageing point according to IEC 62582-3:2012.

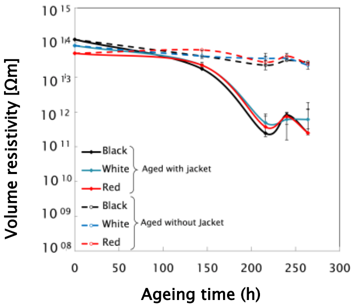
2.3 Impact of insulator environment on insulator properties

Fig. 1 shows FR-EPR insulator properties behavior with ageing time at 160 ˚C. EAB and ρ slightly varies between insulators colors due to colorant (pigment) variance. But degradation trends are similar implying that degradation mechanisms are identical through insulator environment. However, EAB degradation rate is higher through ageing time when insulator is aged with jacket, revealing that chain-scission and cross linking reactions rate is higher that lead to insulator embrittlement after 210 hours heating. ρ degradation is also more severe after 150 hours heating for insulator aged with jacket, hence chain scission reactions are evident from trending ρ. Mechanisms of large ρ reduction for insulators aged with jacket is attributed to high production of chain-scission moieties, difficulty to cease chain-scissions radicals by anti-oxidants, or induced charged particles from catalyst reactions between insulator and jacket. The increment tendency of ρ after 210 hours heating is due to the change of insulator shape as a result of embrittlement that is trended by EAB reduction. Thus, it is neither correlated to ρ degradation nor recovery.

Similar trend behavior of both EAB and ρ with ageing time was observed for ageing at 125 ˚C even though DLO impacts are less significant. Therefore, jacket-insulator environment enhance degradation reactions more severely than air environment. This vital



(a) EAB



(b) ρ

Fig. 1 Mechanical properties ((a) EAB) and electrical properties ((b) ρ) versus ageing time for FR-EPR insulators aged at 160 ˚C with and without PVC jacket finding is utilized in this study for further evaluations of activation energies (E_a) for equivalent time modeling

3. Thermal ageing estimations from insulator properties degradation

3.1 Activation energy (E_a) estimation from EAB and ρ degradation

Equivalent time predictions are influenced by E_a determinations from insulator properties degradation. Since both EAB and ρ degradation showed identical trends at 125 ˚C, 150 ˚C, and 160 ˚C ageing, then time-temperature (T-t) superposition approach can be applied to determine E_a as in Fig. 2. However, EAB degradation is continuous with ageing time and exceeds its half-initial value (end-of-lifetime) criterion 1), while ρ degradation is still higher than insulation function acceptance criterion (i.e 1×10^8 Ωm) 1). Thus, EAB is better indicator for cable integrity at uniform-thermal degradation.

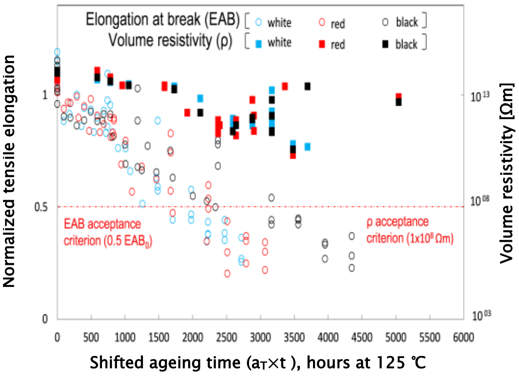


Fig. 2 T-t superposition for FR-EPR insulator thermally aged with PVC jacket from EAB and ρ degradation trends. [Superposed at 125 ˚C]

Time to end-of-lifetime criterion (0.5 EAB_0) at each ageing temperature can be utilized to calculate E_a by Arrhenius model. The values of E_a by T-t approach and Arrhenius model from EAB and ρ degradation are summarized in table 1. Estimated E_a from ρ are different from EAB due to different mechanisms that alter each property. E_a values are very close for each color by T-t approach and Arrhenius model from EAB degradation. This emphasizes that both methods are appropriate for E_a estimation reflecting similar induced mechanisms. E_a for black insulator is largely deviated from other colors when estimations are from EAB due to presence of carbon-black as colorant pigment that acts as anti-oxidant, thus slower degradation rate. But E_a values are very close when estimations by ρ degradation which reveals that impacts of colorant additives are less important.

Table 1 E_a (KJ/mol) estimations for thermally aged FR-EPR insulators

Insulator color	E_a by T-t approach		E_a by Arrhenius model from EAB degradation
	EAB	ρ	
White	90	108	90
Red	93	104	87
Black	113	108	105

3.2 Comparison of thermal ageing estimations with EAB degradation data base

Thermal ageing estimations in current EQ rely on E_a and equivalent time calculations from EAB degradation data base. Accordingly, to evaluate real cable degradation during thermal ageing test, Arrhenius model was utilized to compare E_a and ageing times between EAB degradation for FR-EPR insulators aged with their jacket as in this study with EAB degradation data base for same material but aged with no jacket3) as shown in Arrhenius plot in Fig. 3. Most E_a values are almost in same range even when ageing method is different. This reveals low possibility for physical transition mechanisms through crystalline melting point1,6,7) at extrapolation region, and Arrhenius model can be utilized to extrapolate and compare ageing times at 100 ˚C (i.e time to 0.5 EAB_0 at 100 ˚C). For

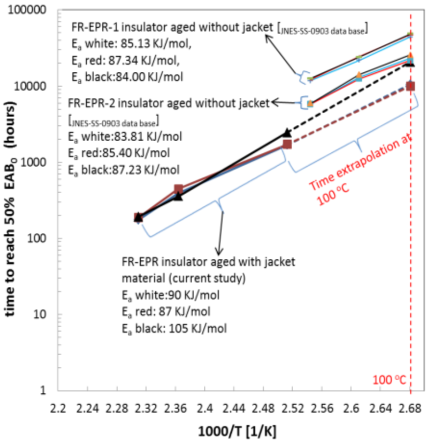


Fig.3 Arrhenius plot of ageing times to 0.5EAB_0 for FR-EPR insulators aged with and without jacket materials

FR-EPR insulators aged with jacket, the ageing times of black insulator was largely deviated above white and red, due to effect of colorant on EAB degradation and E_a estimations. Nevertheless, ageing times of insulators aged with jacket are less than those for insulators aged without jacket. This reveals that the current EQ misestimates degradation of cable insulator due to presence of jacket. But EQ is still suitable considering that cable will pass final integrity withstand voltage test. Thus, excessive ageing time margins at thermal ageing phase can be utilized for DECs.

4. In search of design extension environments for NPPs cables

For BWR-4 case study, 18 targeted electric equipment/cables for DECs were identified from engineering judgment between plant systems understanding with 14 severe accident sequences event trees initiated from LOCA, station black out (SBO) and anticipated transients [8]. These targeted cables were coordinated with other items, as seen in Fig. 4, which can lead to establish knowledgeable-base guideline and predict cable failure behavior based on target accident, cable category, and auto-logic connections with other equipment. Besides, considering cable polymeric based structure, both BDBA temperature and flooding are main stress factors of interest for DECs. Thus, current EQ was reevaluated for both DBA peak temperature and submergence withstand voltage. Cable mechanical integrity criteria limits at 50% absolute and normalized EAB were utilized to extend current DBA peak temperature from 171 ˚C to 230-250 ˚C for thermoset insulator materials. Besides, it was found that targeted cables are LV with withstand voltage (1-2 KV/mm) specified by maker standards, while the current EQ recommendation tests cables by higher values at 3.2 KV/mm. This reveals that current EQ settings for voltage stress include ultimate corresponding environments that can be encountered at any accident scenario of DECs.

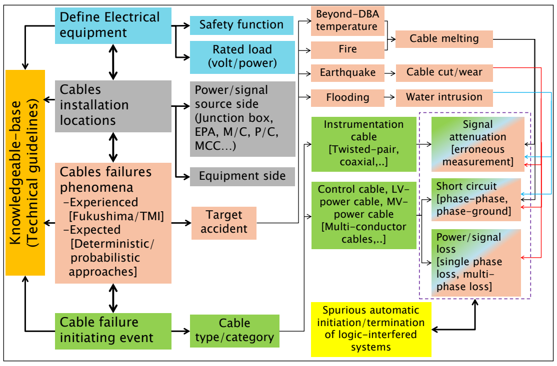


Fig.4 Proactive approach for establishing knowledgeable-base guidelines from targeted cables regarding DECs

5. Conclusions

1-Effect of cable structure on thermal ageing was examined by EAB and ρ. Jacket impact on insulator degradation was very significant, even though colorant pigments effects were evident.

2-Recent EQ process misestimates insulator degradation due to existence of jacket material.

3-Tageted cables for DECs were selected and suitable modification of DBA test was proposed considering BWR plant. DBA peak temperature can be extended from 171 ˚C to 230-250 ˚C for FR-EPR cables inside BWR containment vessel.

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