Methodology for Analyzing Electric Hardening Behavior of ChloroSulfonate Polyethylene (CSPE) Contaminated by Seawater

An-Gyoon Jeon

***Abstract*—The causes of the degradation of the insulation materials for the cables used in nuclear power plants include electric stress, thermal stress, mechanical stress, and environmental stress. The objective of the present study is to diagnose the health of cables and enable continuous follow-up management in the assessment of usability of seawater-contaminated nuclear power plants. The effectiveness of the measurement methods determined by the International Atomic Energy Agency was evaluated by analyzing the hardening behavior of the cable specimens. In particular, physical properties interpretation was conducted by using the electric properties, and the effectiveness was evaluated by satisfying the conditions of individual measurement methods. The electric properties were measured in terms of volume electrical resistivity, dielectric constant, dielectric strength, leakage current, and polarization index. In this study, the hardening behavior of cables contaminated by seawater was analyzed to investigate the degradation degree and characteristics. For the reestablishment of the ideal condition monitoring method, the operation span of chlorosulfonate polyethylene (CSPE) cables commercially used for nuclear power plants was designed (0, 40, and 80 years at 50℃), and a simulation of cables immersed in seawater was conducted by performing accelerated thermal aging at 100℃. The hardening behavior of the CSPE cables undergoing the accelerated thermal aging was evaluated by measuring five parameters of volume electrical resistivity, dielectric constant, dielectric strength, leakage current, and polarization index. The hardening behavior was analyzed depending on the number of days to investigate the degree of degradation as well as the general properties of the degradated specimens. For continuous follow-up management, the ideal cable condition monitoring method was reestablished, and effective measurement methods were proposed for the diagnosis of degradation and the evaluation of cable health. The result showed that contamination by seawater increased ionic elements and thus decreased the dielectric property, which was partly recovered by washing with fresh water. The change of ionic elements was due to salt, which was proved to be the aging factor of oxidation. As the accelerated thermal aging continued, some of the main chains or side chains of chlorosulfonate polyethylene (CSPE) were broken or loosened.**

The degree of change depending on the measurement period was investigated, and the result showed that the hardening behavior was changed in the measurements except dielectric constant and polarization index. Various condition monitoring methods for the cables used in nuclear power plants are classified with reference to the properties of cable insulation materials, including the electric, physical, and chemical properties. When you use the presented method, it is possible to analyze the physical and chemical properties.

***Index Terms*—CSPE, Volume electrical resistivity, Dielectric constant, Dielectric strength, Leakage current, Polarization index**

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A.G. Jeon is with NARA Elect. Company, Royal-town 603, 47, jeonjuGaigsa5-Gil, Wansan-gu, Jeonju, 54999, Korea

(e-mail: jeonak@hanmail.net)

I. Introduction

Since the commercial operation of a nuclear power plant started in 1978, 3 trillion kilowatt-hours (kWh) of electricity has been produced until April 2015 in Korea. The utilization rate is as high as 86.2%[1]. Nuclear power generation is increasing globally, because it enables to generate a huge quantity of energy with small fuel, is economically feasible since the cost of the fuel is relatively cheap, and the pollution generated is less than that of the power generation using fossil fuels. However, a huge accident took place at Fukushima Daiichi Nuclear Power Plants in March, 2011, as the seawater flooded due to the earthquake and tsunami of 13.1 m above the sea level which exceeded the nuclear power plant design standard of 6.1 m[2]. The main electric instruments as well as the cables were flooded, and thus electricity was not properly supplied to the system cooling the reactor core, which led to an explosion of the nuclear power plant. With respect to the cables frequently used in nuclear power plants, the cables should have useful condition in ideal cable condition monitoring method suggested by the International Atomic Energy Agency (IAEA). Also the cables have to be made by non-destructive and non-destructive materials as well as the materials and type that the measurement of the properties' change and the analysis of the change may be possible[3]. Previous studies have shown that the conditions of cables may be assessed on the basis of the electrical properties, physical properties, and chemical properties. Since the cables used in individual nuclear power plants have different insulating properties, it is important to investigate the physical property degradation characteristics adequate to each material, and the lifespan of cables is assessed through the degradation test[4]. In this study, the hardening behavior of cables contaminated by seawater was analyzed to investigate the degradation degree and characteristics. For the reestablishment of the ideal condition monitoring method, the operation span of

ChloroSulfonate Polyethylene (CSPE) cables commercially used for nuclear power plants was designed (0, 40, and 80 years at 50℃), and a simulation of cables immersed in seawater was conducted by performing accelerated thermal aging at 100℃. The hardening behavior of the CSPE cables undergoing the accelerated thermal aging was evaluated by measuring five parameters of volume electrical resistivity, dielectric constant, dielectric strength, leakage current, and polarization index. The hardening behavior was analyzed depending on the number of days to investigate the degree of degradation as well as the general properties of the degraded specimens. For continuous follow-up management, the ideal cable condition monitoring method was reestablished, and effective measurement methods were proposed for the diagnosis of degradation and the evaluation of cable health.

II. Degradation Characteristics of the Insulation Materials for Nuclear Power Plant Cables

The causes of the degradation of the insulation materials for the cables used in nuclear power plants include electric stress, thermal stress, mechanical stress, and environmental stress. Electric stress includes insulation material erosion by the ozone and nitrogen oxides generated by partial discharge, increased electric discharge by the expansion of the internal space of the insulation materials, and the input of surge and abnormal electric voltage. Thermal stress includes the oxidation, thermal decomposition, chemical reactions caused by the heat generated inside and outside the cables (breakage, defect, and decomposition products generation). Mechanical stress includes the separation between insulating layers and the weakening of supportive power due to the mechanical stress caused by electronic force and vibration as well as bending, tension, and damage at the time of cable establishment. Environmental stress includes not only the dust and impurities but also the direct exposure to the specific environmental conditions at the time of an accident at a nuclear power plant (immersion in seawater, radioactivity, temperature, vapor, pressure, moisture, and spraying of chemicals), which cause considerable degradation[5].

A. Degradation characteristics of nuclear power plant cables contaminated by seawater

The cables used in nuclear power plants are directly connected with electric devices related to safety. If the electric devices are not waterproof, seawater may permeate the terminal parts or the connecting parts. Even waterproof devices are vulnerable to the infiltration of seawater since the devices are difficult to completely seal. Polymers used as the insulation materials for the cables used in nuclear power plants have typically have low density and high flexibility. The representative insulation materials for cables used in nuclear power plants are polyethylene (PE) prepared by adding carbon black to the polymer, cross-linked polyethylene (XLPE) prepared by adding a cross-linking agent to PE, CSPE which is extensively used because of the excellent insulating properties, and ethylene propylene rubber (EPR), a representative synthetic rubber of which electrical insulation breakdown strength is almost equal to that of XLPE. Most of the accidents (failures) in the cables in nuclear power points are caused by the degradation of cable insulation materials. An accident takes place by the insulation breakdown of the coating of the cables used in nuclear power points due to an accelerated thermal aging process[6].

B. Methods of diagnosing degradation in nuclear power plant cable condition monitoring

Various condition monitoring methods for the cables used in nuclear power plants are classified with reference to the properties of cable insulation materials, including the electric, physical, and chemical properties. This classification is according to the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide (DG-1240, RG-1.218) and the IAEA report (IAEA TECDOC 1188)[7].

1) The methods based on electric properties include applying of an electric source to detect the degree of degradation of the cable insulation material properties, applying high voltage, injecting certain signals to a conductor to verify the reflective signals, and other methods of measuring insulation resistance, withstand voltage, dielectric loss, dielectric tangent, and partial discharge.

2) The methods based on physical properties include verifying the correlation between the mechanical (physical) property changes of cable insulation materials and the degradation, methods of measuring the change of temperature, compressibility, hardness, modulus of elasticity, and torsional torque, and methods of measuring density, elongation at break, and indenter modulus.

3) The methods based on chemical properties include verifying the correlation between the chemical property changes of cable insulation materials and the degradation, the method of changing the properties by varying the molecular structure of the material at the time of cable degradation, methods of measuring the reduction of synthetic substances such as a plasticizer and the change of material weight, and other methods such as infrared spectrophotometry, oxidative induction time methods, and thermogravimetry.

A standardization work is under progress by the collaboration of the Institute of Electrical and Electronics Engineers (IEEC) and the International Electrotechnical Commission (IEC) to prepare a new international standard for the nuclear power plant cable condition monitoring methods [8]. The IEEE/IEC 62582-1 (Part 1: General) classifies the nuclear power plant cable condition monitoring methods into the methods using electric properties, physical properties, and chemical properties. Another type of classification of the condition monitoring methods provided in the document is with reference to whether the cable samples are taken by a destructive method or by a nondestructive method. In this study, the experiment was performed by using electric properties[9].

III. METHOD OF MEASURING CSPE FOR NUCLEAR POWER PLANT CABLES CONTAMINATED BY SEAWATER

Among the 12 methods for nuclear power plant cable condition monitoring suggested by the U.S. NRC based on electric measurement, physical measurement, and chemical measurement, five methods based on the electric measurement were performed in the this study. The electrical properties measured were volume electrical resistivity, dielectric constant, dielectric strength, leakage current, and polarization index.

A. Degradation characteristics of nuclear power plant cables contaminated by seawater

a. Volume electrical resistivity

Generally, the electric insulation condition or property of insulation materials for electric devices including cable has been represented by resistance. However, resistance is dependent upon the shape, size, and measurement position of the insulation material of which resistance is measured. Therefore, resistance per a unit volume of 1×1×1cm3 is calculated as three-terminal volume electric resistivity, which is an absolute value unique to an insulation material and not dependent on various measuring conditions or characteristics. The unit of resistance is ohm (Ω), while the unit of three-terminal volume electric resistivity is ohm·centimeter (Ω·cm).

$$Resistance\ R[\Omega] = V[V]/I[A] \tag{1}$$

$$Volume\ electrical\ resistivity\ \rho[\Omega \cdot cm] = R[\Omega] \times w \times t\ /\ell \tag{2}$$

The parameter measured in the experiment is the change of volume electric resistivity of cable samples of which natural degradation process for 0 y, 40 y, and 80 y has been simulated. As the degree of cable sample degradation is increased, the change of the physical properties of the samples (insulation materials) is also increased, the insulation properties are decreased, and the sample volume electric resistivity is reduced. Based on this trend, the change of the volume electric resistivity of cable insulation materials depending on the degradation of the nuclear power plant cables is measured to be used as an indicator representing the degree of cable degradation. The measurements of volume electric resistivity indicate the degradation state of the cables operated at a high temperature relatively well and are considerably sensitive to the change of the cable insulation materials (measured in a range equal to or higher than 1013 Ω·cm).

$$electrical\ resistivity\ (\rho) = \frac{\pi d^2}{4t} \times \frac{V}{I} \tag{3}$$

In Equation (3), d refers to the diameter of the top electrode (cm), t refers to the thickness of the cable sample (cm), V refers to the applied voltage (V), and I refers to the measured electric current (A).Using three-terminal volume electric resistivity, Volume electric resistivity of the cable insulation materials was measured to identify the correlation between cable degradation and the measurements[10]. To verify whether it is possible to monitor the conditions of the cable used in nuclear power plants by measuring three-terminal volume electric resistivity, it is important to identify the correlation between cable degradation and the three-terminal volume electric resistivity measurements. The three-terminal volume electric resistivity of individual cable samples which had undergone accelerated thermal aging was measured at room temperature, 50℃, and 80℃. The measurement was repeated for 10 or more times by applying electric voltage (DC 500 V) for one minute at a predetermined measurement temperature.

b. Dielectric constant

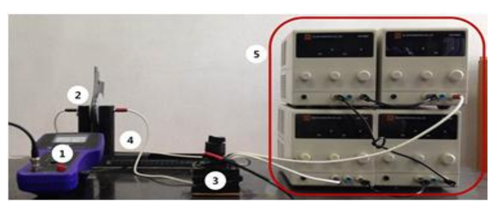
Since an electric dipole has non-zero electric potential and electric field strength, an induced electric dipole changes the electric field both inside and outside a dielectric. For the measurement of a dielectric constant, the electro-meter capacity should be first measured. An electro-meter may be basically considered as a combination of a voltmeter and a condenser having infinite impedance.

$$C_E = \frac{C(V-V_E)}{V_E} \Longrightarrow C = \frac{C_E - V_E}{V - V_E} \tag{4}$$

$$C = \frac{\epsilon_0 \epsilon_r}{d}[F], C_0 = \frac{\epsilon_0 A}{d}[F] \tag{5}$$

$$\frac{C}{C_0} = \epsilon_r \tag{6}$$

Where C denotes electric capacity of the condenser [F], and charging voltage [V] of VE. In addition, C0 denotes the electric capacity of the air [F], CE the electric capacity of the electro-meter [F], and ε0the vacuum dielectric constant. V denotes the applied voltage from the power supply [V], and εr the unique dielectric constant of a material. To investigate the effect of seawater on the nuclear power plant cable by using the method of measuring dielectric constant, 100 V of electric voltage was applied to the individual samples of the cable which had undergone accelerated thermal aging, and the dielectric constant was measured after 10 seconds for five or more times. The electric potential difference of the air was also measured for five or more times after removing the samples in the same distance by applying the same electric voltage and maintaining the state for 10 seconds.



(a) Dielectric constant measurement system

(b) Parallel plate electrode

(c) Insertion of the parallel plate rail and a dielectric

Fig. 1. Measuring system and electrode of dielectric constant

c. Dielectric strength

Dielectric breakdowns of a solid are classified into thermal breakdown and electric breakdown. In a thermal breakdown, temperature is increased by Joule heating through electric current, which decreases the resistance of a solid dielectric, further increasing the temperature by Joule heating through the increased electric current, and eventually leading to a thermal breakdown. In an electric breakdown, electrons accelerated by electric field collide with the crystal lattices of a solid dielectric, which produces more electrons to cause an electron avalanche as in the case of gas dielectric breakdown, eventually leading to an electric breakdown.

Figure 2(a) shown a breakdown voltage tester system (SM-60BDV, SM, Korea), and 2(b) shows different electrodes (spare electrode, needle electrode, and plate electrode)

(a)SM-60BDV

(b) electrode

Fig. 2. Break down voltage tester

d. Leakage current

To identify current-time curve, a current range of a pico-ammeter (Model 6485, Keithley, USA) was fixed between 10 and 12 V. Since the insulating resistance of CSPE is very high, the leakage current was measured in the unit of nA at every minute.[11]

e. Polarization index

Polarization index is used as a simple index representing the current absorption property. The US NRC Draft Regulatory Guide-1240 also suggests a cable condition monitoring method based on polarization index. In this study, polarization index was measured by using the three-terminal volume electric resistivity measurement system.

IV. RESULTS OF MEASURING PROPERTIES OF SEAWATER-CONTAMINATED CSPE

Five electric parameters were measured in this study. All the samples had undergone accelerated thermal aging at 100 ℃. The samples were contaminated with seawater for five days and washed with freshwater for five days. The volume electric resistivity and the dielectric constant were measured from the 120th day to the 720th day of natural drying. The abbreviations used in the figures are as follows. 0 y, 40 y, and 80 y: The simulated years were classified into 0 year, 40 years, and 80 years depending on the time of accelerated thermal aging.

A. Measurement of volume electric resistivity

As shown in Figure 3, the volume electric resistivity was measured from the 120th day to the 720th day of natural drying in an interval of 30 days to investigate the change of the measurements. The samples were contaminated with seawater for five days and washed with freshwater for five days, but the salts that were not completely removed from the samples affected the degradation through oxidation.

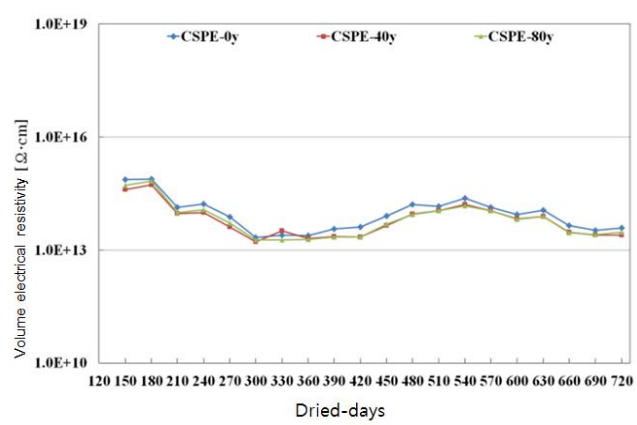


Fig. 3. Volume electrical resistivity of the ASF&F 100℃

B. Measurement of dielectric constant

Figure 4 is the diagram of the measured dielectric constant depending on the number of days of natural drying. Since it was not dependent on the years of the accelerated thermal aging, there is not effectiveness, even though there is a little change in the measurement.

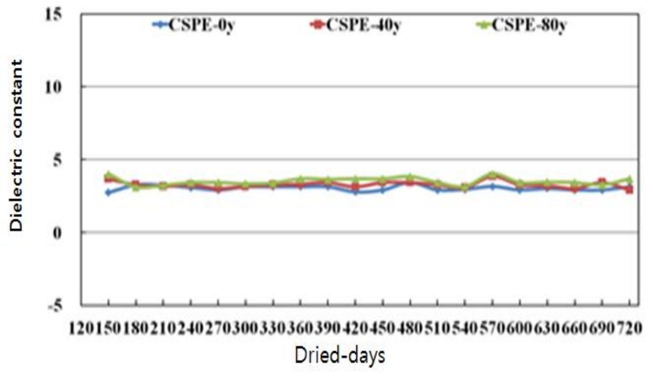


Fig. 4. Dielectric constant of the ASF&F at 100℃

C. Dielectric strength

As shown in Figures 5, 6, and 7, the measurement experiments performed for a few times for the different years of accelerated thermal aging showed that the mean value of the dielectric strength during the time of voltage supply decreased as the years of degradation increased with a little fluctuation.

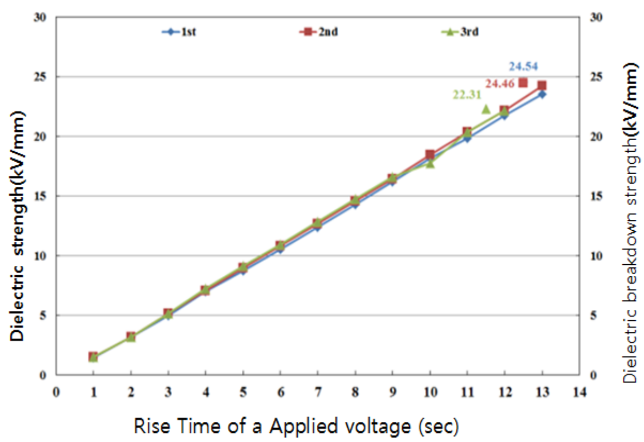


Fig. 5. Dielectric strength of ASF&F/NA0y/CSPE

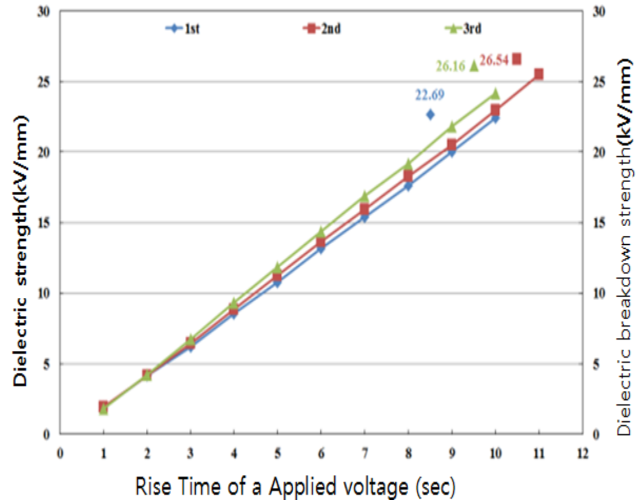


Fig. 6. Dielectric strength of ASF&F at 100℃ /A40y/CSPE

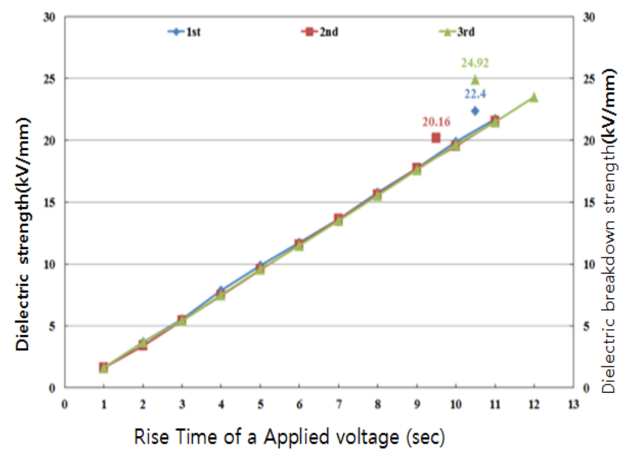


Fig. 7. Dielectric strength of ASF&F at 100℃/A80y/CSPE

D. Leakage current

Figure 8 shows that the leakage current was lower in the samples that had not undergone accelerated thermal aging than in the sample that had undergone accelerated thermal aging. However, the difference between the samples that had undergone 40 years of degradation and the sample that had undergone 80 years of degradation was not significant, indicating that the leakage current was increased by the change of the chemical structure due to the conductive ions included in the contaminating seawater.

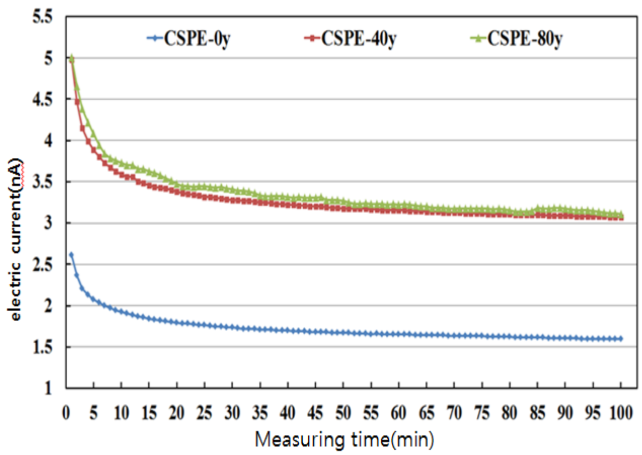


Fig. 8. Leakage Current of ASF&F at 100℃/CSPE

E. Polarization index

As shown in Figure 9, the polarization index was different each time of the measurement (seven times), and thus the effectiveness was hard to decide. However, the polarization index was within the suspicious stage (1.0~2.0) according to the degradation criteria

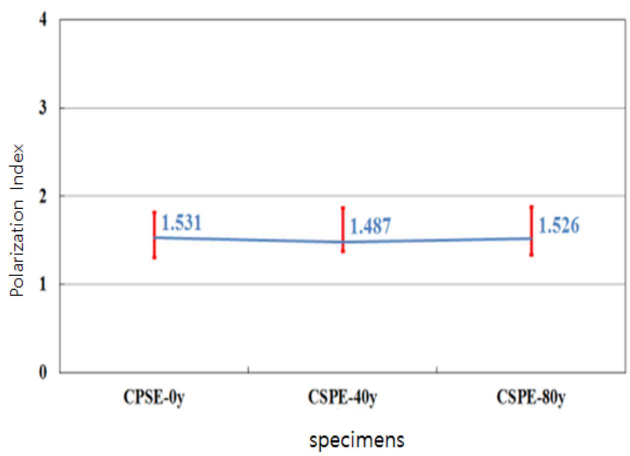


Fig. 9. Polarization Index of ASF&F at 100℃/CSPE

V. Conclusion

The objective of this study is to diagnose the health of cables and enable continuous follow-up management in the assessment of usability of seawater-contaminated nuclear power plants. The effectiveness of the measurement methods was evaluated by analyzing the hardening behavior of the cable specimens. After CSPE samples were prepared through accelerated thermal aging, the samples were immersed in seawater. After a simulation of follow-up management, experiments were performed to measure five electric properties. The effectiveness of individual measurement methods was determined by analyzing the physical properties. In addition, CSPE for the cables used in nuclear power plants had undergone accelerated thermal aging at 100℃ for a certain period of time. The CSPE samples were contaminated with seawater for five days and washed with freshwater for five days. The electric properties were measured by various condition monitoring methods while drying the sample at room temperature up to 750 days. The measured electric properties were volume electrical resistivity, dielectric constant, dielectric strength, leakage current, and polarization index. First, the result showed that the insulating property of the samples was decreased after contamination with seawater due to the increased ionic elements, and recovered to a certain degree after washing with freshwater. It was verified that the cause of the ionic element was salt, which is an aging factor of oxidation. It was also found that some of the main chains or side chains of CSPE were broken or loosened, as the accelerated thermal aging continued. Second, the degree of change depending on the measurement period was investigated, and the result showed that the hardening behavior was changed in the measurements except dielectric constant and polarization index. Therefore, the methods of measuring volume electrical resistivity, dielectric strength, and leakage current were proved to be efficient. For the diagnosis of degradation of the cables used in nuclear power plants, it is necessary to establish clear measurement criteria to decide the health of nuclear power plant cables immersed in seawater as a means of assessing the usability of seawater- contaminated nuclear power plants due to a tsunami.

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