Proceeding of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 2002

Evaluation of Aging Degradation for Neoprene Cable Jacket in Isothermal and Intermittent Heating Condition

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ABSTRACT

Life extension of nuclear power plant is prevalent in the world nuclear industry. Consequently, life evaluation and lifetime management of cable to survive over 40 years become major concern. It is necessary to study the accelerated aging to simulate the natural aging in nuclear power plant. In this paper, evaluations of mechanical aging degradation for neoprene cable jacket were performed after accelerated aging at the isothermal and intermittent heating condition. Contrary to general expectation, intermittent heating to neoprene cable jacket showed low aging degradation, 50% of break-elongation and 60% of indenter modulus, compared with isothermal heating. With the plant outage of 1 month after every 12 or 18 months operation, it can be supposed that cable jacket of neoprene may have longer lifetime than expected in EQ test which adopts isothermal accelerated aging for the determination of cable life. Systematic approach which consider the actual environment condition of nuclear power plant is required to evaluate the expected life of each cable materials.

1. INTRODUCTION

It has passed almost 24 years since Kori Unit 1, the oldest nuclear power plant in Korea, started operation. Currently, 16 nuclear Units are operating in Korea. Consideration of aging degradation especially for old equipment is increasing in Korea nuclear industry. According to abroad operating experience of nuclear power plant, inadequate management of aging degradation can result in short life of equipment which induce poor capability of plant life extension. Aging degradation of plant structures and components has to be properly managed to assure the designated safety function of plant system during design life and extended life. Under the aspect of safety, management of aging is maintaining the aging degradation of major equipment and structure below the allowable limit and keep the capability to sustain the abnormal operating condition. Aging of cable was not a matter of concern in nuclear power plant due to its long life (40 years) which is almost same to plant design life. Life extension of nuclear power plant is prevalent in the world nuclear industry. Consequently, life evaluation and lifetime management of cable to survive over 40 years has become major concern. It is necessary to study the accelerated aging to simulate the natural aging in nuclear power plant. Test result of mechanical aging degradation after accelerated aging of neoprene cable jacket is described in this paper.

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2. Cables used in nuclear power plants

There are hundred types of cable in nuclear power plant. These cables can be categorized as medium/low voltage cable, low power cable, instrument & control cable, panel connect line cable, special cable, security line cable, phone line cable, light line cable and ground cable. According to the report of Sandia National Labs, distribution of circuit in an NPP is about 20% of instrument cables, 61% of control cables, 13% of AC power cables, 1% of DC power cables, 5% of communication lines. Insulation and jacket materials used in electrical cables are constructed based on polymer materials combined with a number of additives and fillers to provide the required mechanical, electrical and fire retardant properties. The most commonly used insulation materials are XLPE/EPR/EPDM and PVC. PVC was widely used as insulation, particularly in old plant, but not generally used in containment inside of modern plants. Neoprene/CSPE/ PVC are commonly used material for nuclear cable jacket.

3. Aging of polymer cable

3.1 Aging mechanism

For thermal aging at temperatures below 70-80℃ in the absence of radiation, the main aging mechanism for plasticized PVC is evaporation of plasticizers from the surface of external jacket of cable. At higher temperature(>80℃) and under irradiation, this mechanism is in competition with intramolecular elimination of hydrochloric acid from the macromolecular chains of PVC. Thus, increasing of temperature of the accelerated aging reduces the validity of the aging simulation.

Some of the polymeric materials used in cables are semi-crystalline which has a crystalline melting region close to the temperature range used in service. Studies have shown the influence of the crystalline phase on physical properties, particularly for polyethylene based materials. For this type of material, care must be taken in extrapolation of data from accelerated thermal aging tests. If the extrapolation goes through the crystalline melting region, the arrhenius equation will bot be valid and accelerated tests will not be a representative simulation of natural aging. In accelerated radiation aging, semi-crystalline polymers(such as XLPE) will often show a reverse temperature effect, with aging occurring more rapidly at lower temperature than at higher temperature. Main aging mechanisms of cable materials can be distinguished as chemical and physical. Chemical aging mechanism affects the molecular structure. Physical aging affects the composition of the compound. Scission of macromolecular chains, cross-linking reaction, oxidation diffusion, synergistic effect and elimination of hydrochloric acid correspond to chemical aging mechanism. Evaporation and migration of plasticizer correspond to physical aging mechanisms. The most common characterization of mechanical aging are elongation at break, tensile strength, compressive modulus. Insulation resistance, dielectric strength, dielectric loss is used for electrical measurements. FT-IR spectroscopy, oxidation time and temperature(OIT &OITP), swelling ratio, gel fraction, mass loss, visco-elasticity properties, NMR, density is major characterization of physical/chemical aging.

3.2 Aging effect

The aging of polymer materials is dependent on some factors like polymer system itself, service environmental condition, long time use. The external jacket and insulating materials are formulated of basic polymer and additives which provide the material with specific properties of anti-oxidant, thermal stabilizers, fire retardant. The most important factors of cable aging are temperature and radiation. The oxygen, presence of water vapor and vibration of cables connected to running machines also have to be considered. The environmental service conditions will induce chemical or physical processes at the molecular level of the material; these processes are the aging mechanisms. Typical macroscopic changes in the properties of common cable materials, which can lead to the functional failure of the cable, include decrease of tensile elongation, increase of hardness or compressive modulus, increase of density, small increase in dielectric loss. Any degradation of electrical property resulted from aging of cable material is not common before the aging degradation of mechanical properties. Surface crack of cable material generally found before the loss of insulation resistance. Loss of electrical function before surface crack is often found in the process of DBE test for PVC cable.

3.3 Aging simulation

It is the best way to evaluate the cable aging by taking out the installed cable from the nuclear power plant. But, There is rare chance to remove the installed cable if there is no special plan to replace the electric equipment or cable. In some nuclear power plant, spare cables are installed near to the operating cables for the periodic test of cable aging. Accelerated aging is another way to simulate the natural aging condition. Arrehenius equation is generally used as a physical model of lifetime prediction in accelerated thermal aging. Heating condition in accelerated aging has to follow the monitoring result of plant environment to prove that accelerated aging equals to natural aging. It assumes that the rate of the thermal aging mechanism decreases with the inverse of the temperature, such that the rate constant k can be described by the following equation

$$(\ln k = \ln A - Ea/RT)$$

where A is a constant for the material being tested, Ea(KJ/mol) is the activation energy for the process, R(J/mol °K) is the gas constant and T(°K) is the absolute temperature. A plot of the reaction rate on a log scale against 1/T should yield a straight line whose slope is determined by the activation energy Ea, The activation energy controls the temperature sensitivity of the degradation rate. Carrying out accelerated aging over a large range of temperatures will sometimes show a “break point” in the plot, which corresponds to a change in the kinetic regime. The value of the activation energy is not constant over the whole temperature. Most examples where changes in slope have been observed show lower values of Ea at lower temperatures. In such conditions, an extrapolation based on the data measured at high temperature would give a significant underestimation of the aging at lower temperatures. It is generally recommended that the interval between the lowest temperature used in the accelerated aging test and the temperature of actual should not exceed 25℃.

3.4 concerns in accelerated aging

Activation energy has to be measured prior to the aging test as part of test preparation. The aging degradation ratio can be varied in accordance with temperature and the complexity of insulation. The accuracy of evaluated life through laboratory testing is limited by the accelerating factors. The inaccuracy grows with increasing acceleration factor. A limit of 250 on the acceleration factor is recommended in a paper1). Care has to be taken that aging mechanism of accelerated aging is same as that of natural aging. Short time expose to high radiation has to be carried out to simulate the total dose rate during plant lifetime. The acceleration factor will be defined by the ratio between the dose rate used in accelerated aging and the dose rate in operating condition. If the dose rate is not proved as ignorable, dose rate will be limited in accelerated aging. Very low dose rates(20-30 Gy/h) will be necessary for particularly sensitive material to the dose rate.

4. Evaluation of cable aging

4.1 Test facilities

4.1.1 Electric oven

To simulate the actual environment condition in plant, an electric oven was manufactured which was equipped with air heating/fresh sir supply system and automatic temperature controller at isothermal or intermittent condition. Figure 4.1 and Figure 4.2 show the heat and cooling curve at the isothermal condition of 130℃ and intermittent conditions between 80℃ and 130℃.

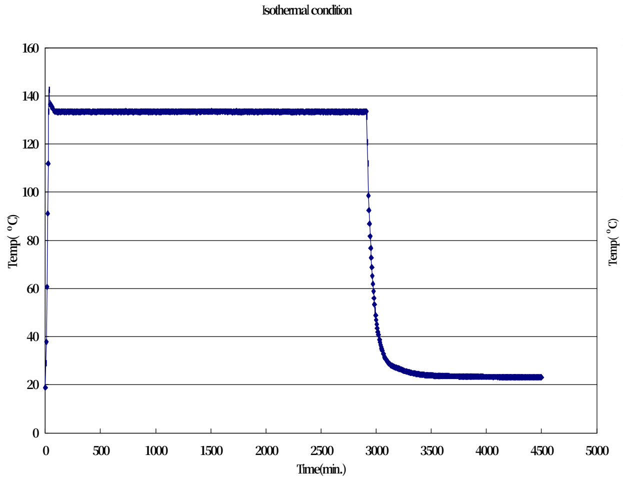

Fig. 4.1 Isothermal condition

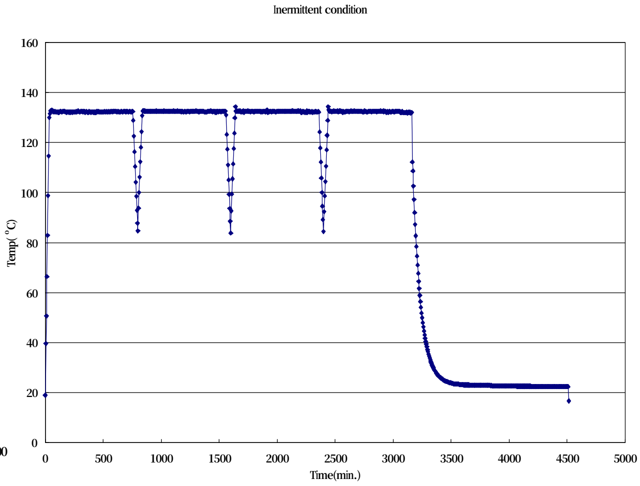

Fig. 4.2 Intermittent condition

4.1.2 TGA(Thermo Gravimetric Analyzer)

TGA is a convenient equipment for the calculation of activation energy. Continuous measuring of weight change was proceeded at the condition of heating the neoprene specimen from 50℃ to 700℃ at the rate of 10, 15, 20℃/min. Activation energy of neoprene cable jacket was calculated as 94.39KJ. Figure 4.3 and Figure4.4 show the weight change graph and the calculated activation energy by TGA.

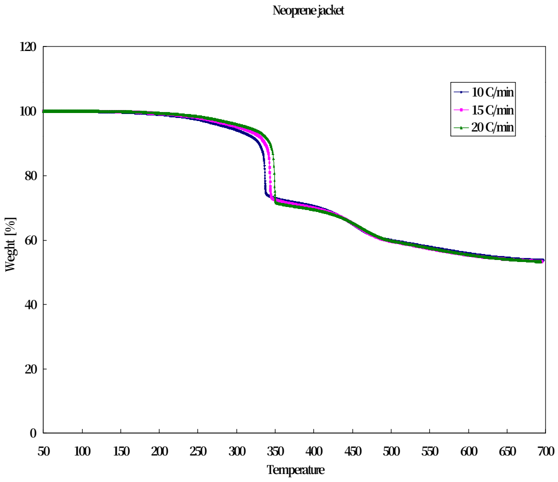

Fig. 4.3 TGA weight change graph

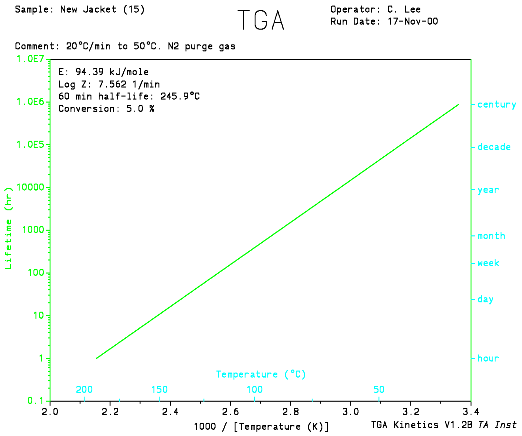

Fig. 4.4 Calculated activation energy

4.1.3 Electronic temperature recorder

Electronic temperature recorder for a special purpose was invented for temperature monitoring in nuclear power plant.[2]. This device was designed to measure the plant environment temperature during an outage period. Semiconductor sensor was equipped for low battery consumption. All the measured data can be transferred to PC. Compression methodology, that is, recording a data only when a difference from previous data detected, can reduce the need of IC memory capacity to 1/100. Figure 4.5 shows the picture of the electronic temperature recorder. Figure 4.6 shows the result of temperature monitoring on the surface of PZR power cable in Kori-1 during 395 days. It was found that environment temperature in operating power plant is not isothermal but intermittent based on the operating condition

Fig. 4.5 Electronic temperature recorder

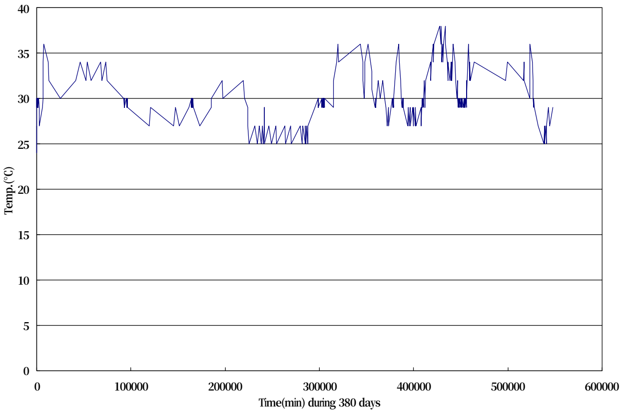

Fig. 4.6 Temperature monitored on PZR power cable

4.1.4 Elongation tester

Elongation test was proceeded in accordance with ASTM D412[3](Rubber properties in tension) which define the 500±50mm/min tension speed and 16 - 96 hour cooling after accelerated aging. The maximum and minimum value of 5 data were excluded and 3 data was selected for break-elongation test data. Figure 4.7 shows specially designed wedge type air power gripper of elongation tester. Figure 4.8 shows the actual picture of test specimen.

Fig. 4.7 Wedge type gripper of elongation tester

Fig. 4.8 Actual picture of test specimen

4.1.5 Cable indenter

Cables exposed in harsh environment of nuclear power plant show a indication of aging degradation. One of these symptoms is hardening of cable material. Indenter is designed to measure the hardness of cable jacket. Indenter is very convenient tool in condition monitoring of nuclear cables since it is a non-destructive tool. The indenter modulus, calculated by dividing the force by moving distance of anvil, is indication of aging degradation in cable indenter. Figure 4.9 shows picture of cable indenter made by KEPRI[4]. Figure 4.10 shows "force-distance" curve of cable indenter.

Fig.4.9 Picture of cable indenter(KEPRI made)

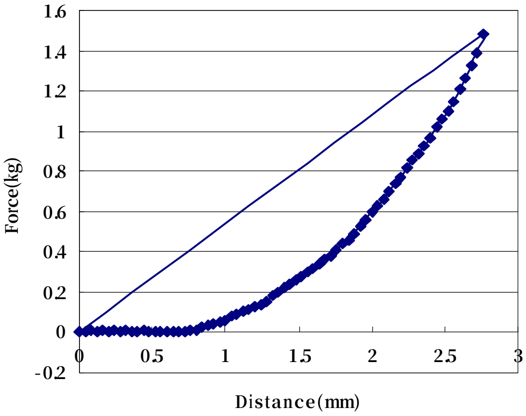

Fig. 4.10 Force-distance curve of cable indenter

4.2 Condition of accelerated aging

Accelerated heating condition is arranged based on the monitoring result of actual environment temperature in Kori Unit 1 as shown on Figure 4.6. Accelerated aging time in each step is calculated by using Arrhenius equation. Table 1 shows simplified pattern of actual environment condition and equivalent aging time at 130℃ isothermal heating. Table 2 shows intermittent heating temperature and time which has equivalent aging with actual environment condition in Kori Unit 1. Figure 4.11 shows monitoring results of accelerated aging at intermittent heating condition.

Table 1 Accelerated aging at isothermal condition

Step	Moni. Temp. (℃)	Moni. Date (day)	Accelerated aging time(hour)				
			20year life	40year life	60year life	80year life	100year life
1	30	148	6.5	13	19.5	26	32.6
2	25	46	1.1	2.2	3.2	4.3	5.4
3	30	84	3.7	7.4	11.1	14.8	18.5
4	38	22	2.5	5.1	7.6	10.1	12.7
5	30	7	0.3	0.6	0.9	1.2	1.5
6	35	58	4.7	9.4	14.1	18.8	23.4
7	25	30	0.7	1.4	2.1	2.8	3.5
Sum.		395	19.5	39.1	58.5	78	97.6

Table 2 Accelerated aging at intermittent condition

step	Moni. Temp. (℃)	Moni. Date (day)	Accelerated aging time(hour)					
			20 year life		40 year life		60 year life	
			Temp(℃)	Time(hour)	Temp(℃)	Time(hour)	Temp(℃)	Time(hour)
1	30	148	141	3	152	3	159	3
2	25	46	116	3	125	3	131	3
3	30	84	133	3	143	3	150	3
4	38	22	128	3	138	3	144	3
5	30	7	100	3	109	3	114	3
6	35	58	136	3	147	3	153	3
7	25	30	110	3	119	3	125	3

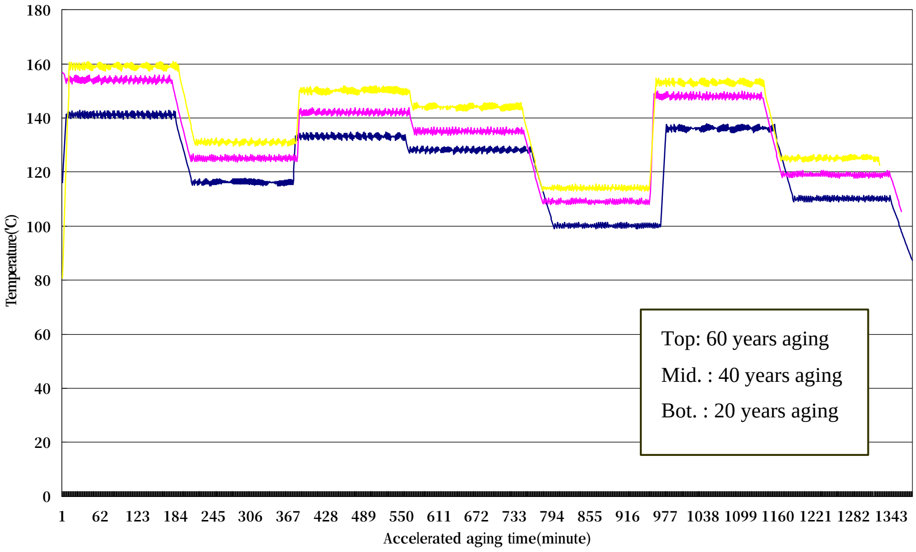

Fig. 4.11 Monitoring results of accelerated aging at intermittent heating condition

4.3 Test result of mechanical properties

4.3.1.1 Elongation

Elongation rates for isothermal aging of 0 to 100 years and intermittent aging of 0 to 60 years are shown in Figure 4.12. Rapid decline of elongation rate was observed during 0 to 40 aging years in the isothermal heating test, It was found that the elongation rate reached limit value of 50% at 30 years of aging. Relatively slow decline of elongation rate was observed in the intermittent aging test and it did not reached the limit value of 50% elongation. At 60 years of aging, the elongation rate in the isothermal aging was almost double to the value of the intermittent aging.

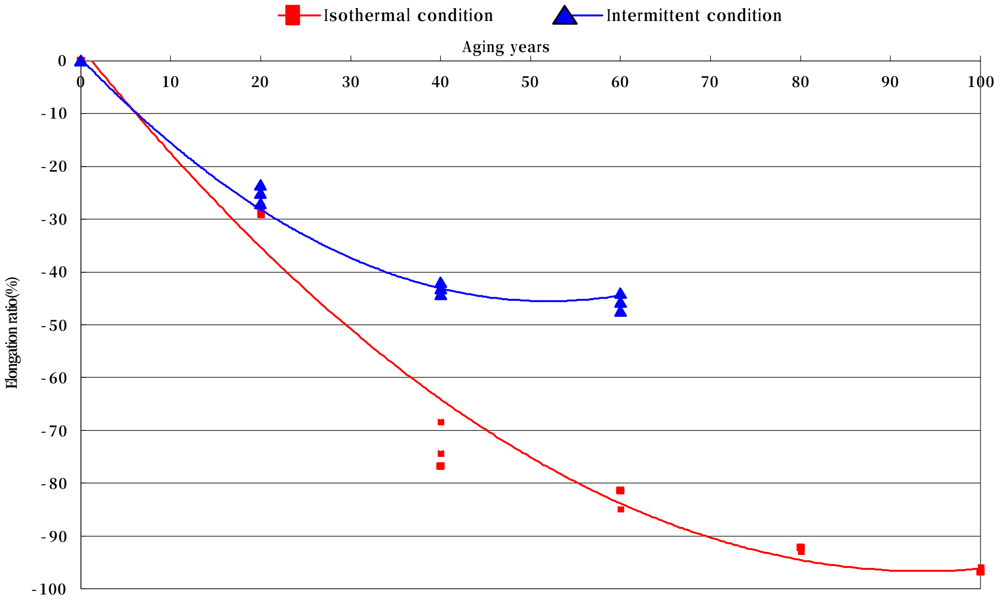

Fig 4.12 Break-elongation rate at isothermal and intermittent aging condition

4.3.1.2 Indenter

Indenter modulus in isothermal aging during 0 to 100 years and intermittent aging during 0 to 60 years are shown on Figure 4.13. No special indication of aging degradation before 20 years of aging is found for both heating conditions. Step increase of the indenter modulus was shown after 20 to 100 years for both of isothermal and intermittent condition. At 60 years of aging, the indenter modulus obtained from isothermal condition was almost one and half times to the value of intermittent condition.

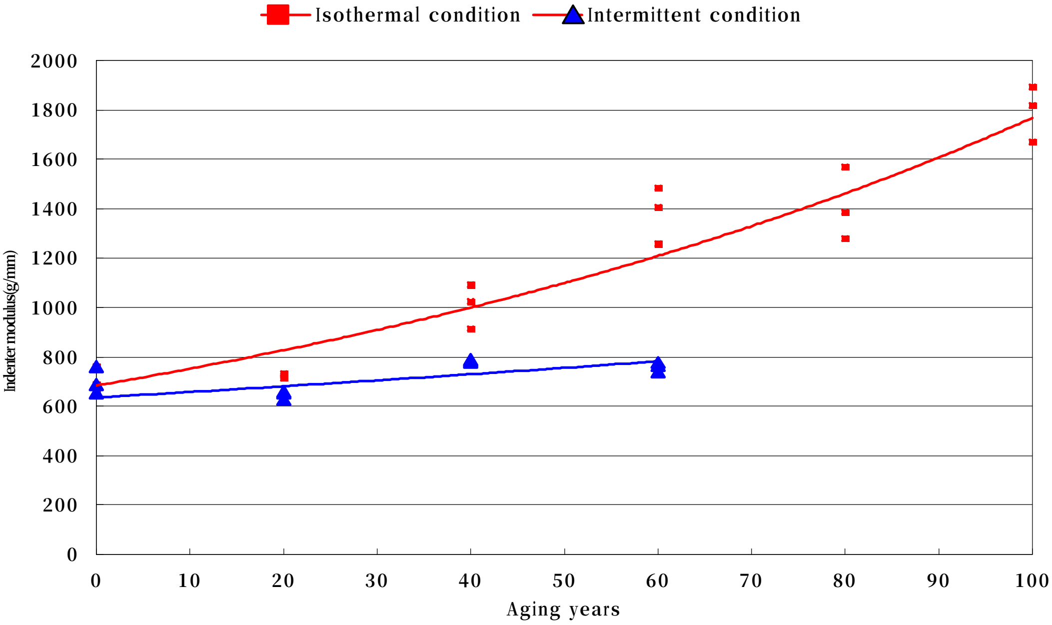

Fig 4.13 Indenter modulus at isothermal and intermittent aging condition

4.4 Additional test

To prove the justness of unexpected test result, additional elongation and indenter test were performed after accelerated agings in same heating time and different rest time. “Heating” means continuous heating step during 12 hours at same temperature and “Rest” means cooling and reheating step during 1 hour after the end of every heating step. As result of this experiment, it was proved that neoprene cable jacket had lower aging degradation in intermittent heating condition compared with isothermal heating condition even heated under the same temperature and same heating time. Figure 4.1 and Figure 4.2 show the history of 48 hours accelerated aging. Figure 4.14 and Figure 4.15 show test result of elongation and indenter for each case of isothermal and intermittent heating condition

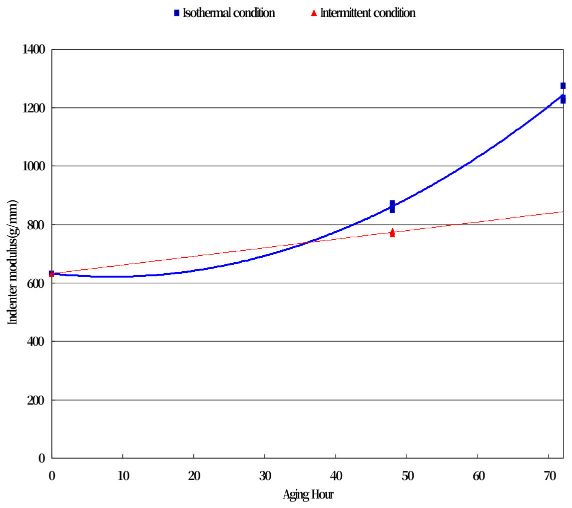

Fig. 4.14 Indenter modulus

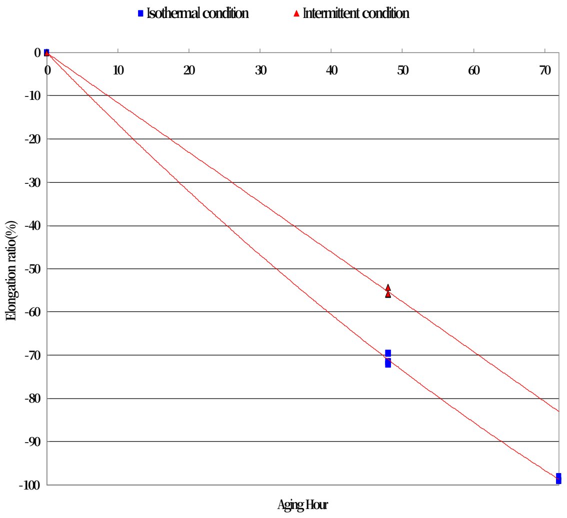

Fig. 4.15 Elongation rate

5. CONCLUSION

Evaluation of aging degradation was performed after accelerated aging test of neoprene cable jacket at the isothermal and intermittent heating condition. Contrary to general expectation, intermittent heating to neoprene cable jacket showed low aging degradation, 50% of break-elongation and 60% of indenter modulus value, compared with isothermal heating. With the plant outage of 1 month after every 12 or 18 months operation, it can be supposed that plant cable may have longer lifetime than expected in EQ test which use isothermal accelerated aging for the determination of cable life. Systematic approach which consider the actual environment condition of nuclear power plant is required to evaluate the expected life of each cable materials.

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