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〈Technical Note〉

Evaluation of Nuclear Plant Cable Aging Through Condition Monitoring

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Abstract

Extending the lifetime of a nuclear power plant [(hereafter referred to simply as NPP)] is one of the most important concerns in the global nuclear industry. Cables are one of the long - life items that have not been considered for replacement during the design life of a NPP. To extend the cable life beyond the design life, it is first necessary to prove that the design life is too conservative compared with actual aging. Condition monitoring is useful means of evaluating the aging condition of cable. In order to simulate natural aging in a nuclear power plant, a study on accelerated aging must first be conducted. In this paper, evaluations of mechanical aging degradation for a neoprene cable jacket were performed after accelerated aging under tcontinuous and intermittent heating conditions. Contrary to general expectations, intermittent heating to the neoprene cable jacket showed low aging degradation, 50% break-elongation, and 60% indenter modulus, compared with continuous heating. With a plant maintenance period of 1 month after every 12 or 18 months operation, we can easily deduce that the life time of the cable jacket of neoprene can be extended much longer than estimated through the general EQ test, which adopts continuous accelerated aging for determining cable life. Therefore, a systematic approach that considers the actual environment conditions of the nuclear power plant is required for determining cable life.

Key Words : cable aging, break-elongation test, indenter test, arrhenius curve

1. Introduction

Almost 26 years has passed since the Kori Unit 1, the oldest NPP in Korea, commenced operation. At present, 18 nuclear units are operated in Korea. Accordingly, within the Korean nuclear industry, increasing interest has been drawn to degradation of these units from aging. Based on operating experiences of overseas NPPs, it has been found that the inadequate management of aging degradation causes shortening of the lifetime of equipment, which in turn, hinders plant life extension. Aging degradation of plant structures and components should be properly managed to ensure the designated safety functions of plant systems during design life and extended life.

From a safety perspective, aging management means maintaining the level of aging degradation of major equipment and structures below the allowable limit and holding the capacity to sustain abnormal operating conditions. Aging of cable has not been considered as a factor in relation to the maintenance of nuclear power plants due to its long life (40 years), which is almost the same as the plant design life. Attempts to extend the lifetime of NPPs have become major concern in the global nuclear industry. Consequently, life evaluation and lifetime management of cable in order that it survive over 40 years has become a major topic of discussion. In relation to this, accelerated aging must be studied in detail in order to simulate natural aging in a NPP. The test results of mechanical aging degradation after accelerated aging of neoprene cable jacket are described herein.

2. Cables in NPPs

There are roughly a hundred types of cables in NPPS. 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 a Sandia National Labs°· report [1], the distribution of circuits in an NPP is comprised of about approximately 20% instrument cables, 61% control cables, 13% AC power cables, 1% DC power cables, 5% communication lines. Insulation and jacket materials 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 has been widely used as an insulation material, particularly in old plants, but is less generally used in containment inside of modern plants. Neoprene/CSPE/PVC are commonly used material for nuclear cable jackets.

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 the evaporation of plasticizers from the surface of external jacket of the cable. At higher temperatures (>80 ℃) and under irradiation, this mechanism is in competition with intramolecular elimination of hydrochloric acid from the macromolecular chains of PVC. Thus, increasing the 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. Studies[2] have demonstrated the influence of the crystalline phase on physical properties, particularly for polyethylene-based materials. For this type of material, great care must be taken in extrapolating data from accelerated thermal aging tests. If the extrapolation extends beyond the crystalline melting region, the arrhenius Arrhenius equation would become invalidated,consequently rendering accelerated tests less credible as a representative simulation on natural aging.

In accelerated radiation aging, semi-crystalline polymers (such as XLPE) often show a reverse temperature effect, with aging occurring more rapidly at lower temperatures than at higher temperatures.

The main aging mechanisms of cable materials can be distinguished as chemical and physical. Chemical aging mechanisms affects the molecular structure while physical aging mechanisms affect the composition of the compound. Chemical aging mechanisms include scission of macromolecular chains, cross-linking reactions, oxidation diffusion, synergistic effects, and elimination of hydrochloric acid, while examples of physical aging mechanisms are evaporation and migration of plasticizer. The most common characterizations of mechanical aging are elongation at break, tensile strength, and compressive modulus. Insulation resistance, dielectric strength, and dielectric loss are used for electrical measurements. Fourier Transform Infrared Spectroscopy (FT-IR), oxidation time and temperature (OITT), swelling ratio, gel fraction, mass loss, visco-elasticity properties, Nuclear Magnetic Resonance (NMR), and density constitute the major characterizations of physical/chemical aging [3].

3.2. Aging Effect

The aging of polymer materials is dependent on factors such as the polymer system itself, service environmental conditions, whether the material had been used for long periods, etc. The external jacket and insulating materials are composed of basic polymers and additives, which endow on the material with specific properties such as, thermal stability, and anti-oxidant and fire retardant traits. The most important factors that determine the speed of cable aging are temperature and radiation. Other factors to be considered include presence of oxygen, presence of water vapor, and vibration of cables connected to running machines.

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 bring about functional failure in the cable, include decrease of tensile elongation, increase of hardness or compressive modulus, increase of density, small increase in dielectric loss, etc. In most cases, degradation of electrical property resulting from aging of cable material does not occur before the aging degradation of mechanical properties.

For example, cracking on the surface of the cable material is generally found to occur before the loss of insulation resistance. A loss of electrical function occurring before surface cracking is often found in the process of the design base event test for PVC cable.

3.3. Aging Simulation

The best way to evaluate the extent of cable aging is to remove the installed cable from the NPP. However, unless there arises a reason to replace the electric equipment or cable, there is no opportunity to remove an installed cable. In some NPPS, spare cables are installed near the operating cables so that periodic tests can be conducted to verify the extent of cable aging.

Accelerated aging is one ways to simulate natural aging conditions. Arrhenius equation is generally used as a physical model for making predictions regarding lifetime in accelerated thermal aging. Heating for accelerated aging has to follow the monitoring results of the plant environment to prove that accelerated aging corresponds with natural aging. It is assumed that the rate of thermal aging decreases in an inverse manner with temperature, such that the rate constant " K" can be described as follows. :

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

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, "k" is the Boltzman constant, and
T°(K)°· is the absolute temperature. A graph of the reaction rate on a log scale against "1/T"· should show a straight line whose slope is determined by the activation energy Ea. Activation energy controls the sensitivity of the degradation rate.

Conducting an accelerated aging over a large range of temperatures sometimes show a Ó‚reak 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. An example is shown in Fig. 3.1. It is, therefore, generally recommended that the interval between the lowest temperature used in the accelerated aging test and the actual temperature should not exceed 25° C[4].

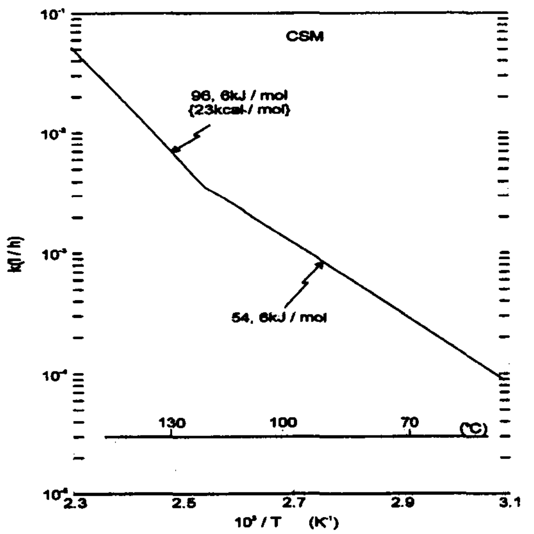

Fig. 3.1 Arrhenius Plot for Thermal Degradation Rate for CSPE Material [From Ref 4]

3.4. Considerations During Accelerated Aging

The accuracy of evaluated life through laboratory testing is limited by the accelerating factors. This inaccuracy is exacerbated with increasing acceleration factor. A limit of 250 on the acceleration factor has been recommended [5]. In addition, extra care should be taken so that the aging mechanism of accelerated aging corresponds with that of natural aging. Exposure to high radiation should be for a short period of time to simulate the total dose rate during a lifetime of a NPP. The acceleration factor is defined by the ratio between the dose rate used in accelerated aging and the dose rate in the operating conditions. If it is not proven that the dose rate can be ignored, the dose rate will be limited in the accelerated aging. Very low dose rates (20-30 Gy/h) are particularly important for those materials that are sensitive to the dose rate.

4. Evaluation of Cable Aging

4.1. Test Facilities

4.1.1. Electric Heating Oven

To simulate the environmental conditions of a plant, an electric oven was specially built. This oven consists of a heater, a fresh air supply damper, and automatic temperature control device. Fig. 4.1 and

Fig. 4.2 show the heat and cooling curve at the continuous heating condition of 130℃ and intermittent conditions between 80℃ and 130℃, respectively.

4.1.2 TGA (Thermo Gravimetric Analyzer)

The use of a TGA is a convenient means of calculating the activation energy. Measurement of the change in weight was carried out continuously during the heating process of the neoprene specimen from 50℃to 700℃ at heating rates of 10, 15, 20℃/min.

Activation energy of the neoprene cable jacket was calculated as 94.39KJ. Fig. 4.3 and Fig. 4.4 show the graphs displaying the weight change and the calculated activation energy by TGA [6][7].

4.1.3. Electronic Temperature Recorder

A special electronic thermometer was invented for temperature monitoring in NPPs [8]. This device was designed to measure the plant environment temperature during a single outage period (12-

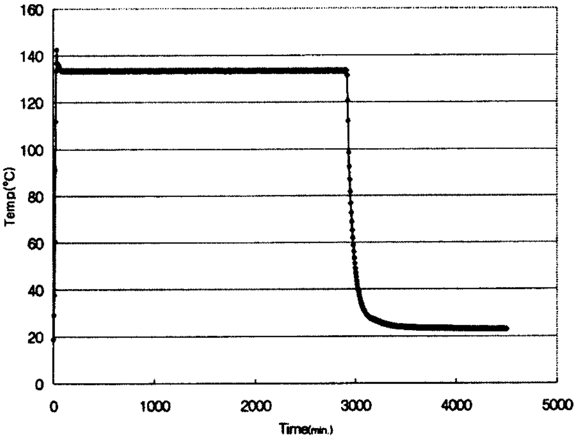

Fig. 4.1. Continuous Heating Condition

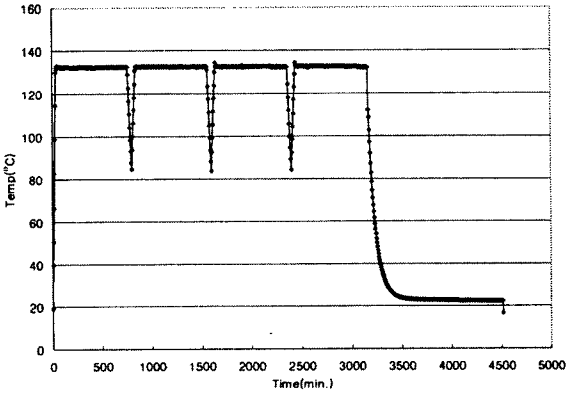

Fig. 4.2. Intermittent Heating Condition

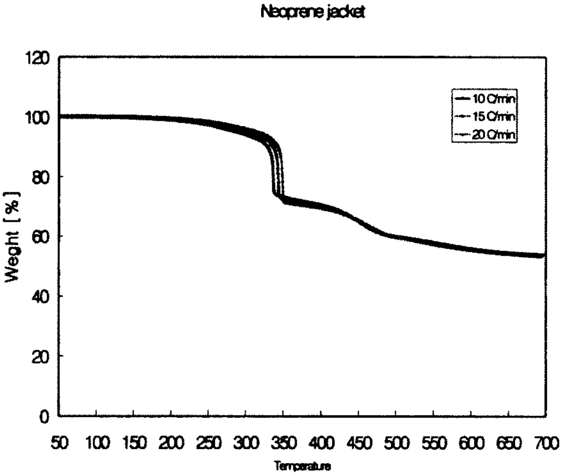

Fig.4.3. TGA Weight Change Graph

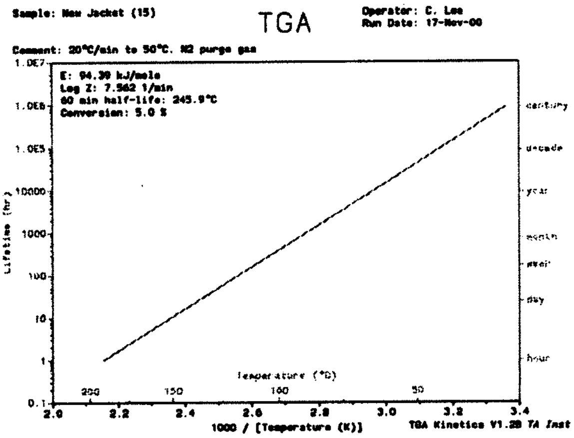

Fig. 4.4. Calculated Activation Anergy

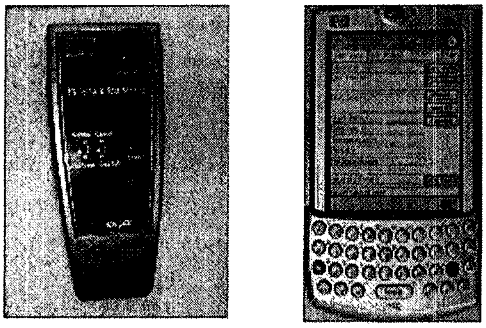

Fig. 4.5. Electronic Temperature Recorder

18months). In addition, a semiconductor sensor is equipped to detect low battery consumption. Measured data can be transferred to a PC by infrared transmission. Compression methodology, which is a way to record any new data that is different from a previous data, can reduce the IC memory requirement by 1/100. Fig. 4.5 shows pictures of the electronic temperature recorder and a PDA for remote control record setting. Fig. 4.6 shows the result of temperature monitoring conducted for 395 days on the surface of pressurizer (PZR) power cable in Kori-1. From the monitoring results, we found that environment temperature in an operating power plant does not remain constant but changes depending on the operating conditions.

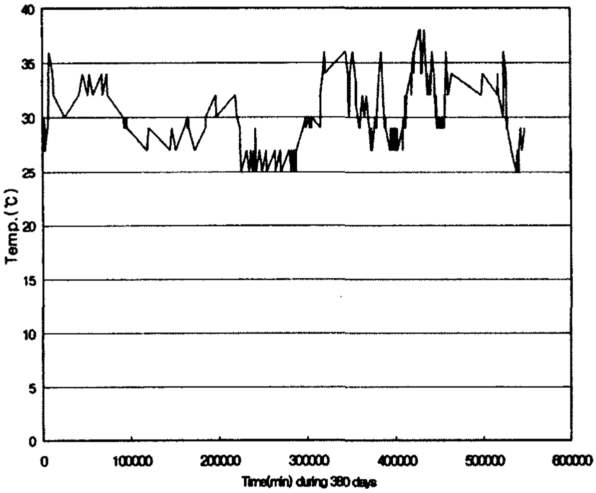

Fig. 4.6. Temperature Monitored on PZR Power Cable

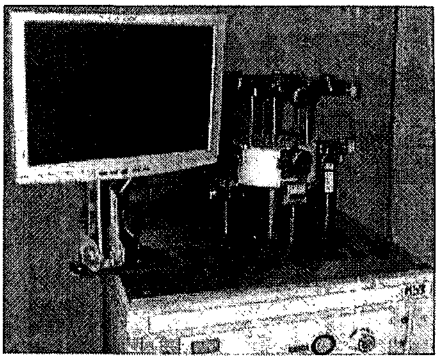

Fig. 4.7. Break-Elongation Test Machine

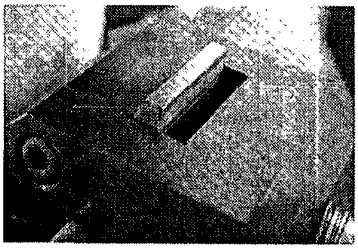

Fig. 4.8. Wedge Type Manual Grip

4.1.4. Elongation Tester

An elongation test is was performed in accordance with the ASTM D412 (Rubber properties in tension) [9]. Fig. 4.7 shows the break-elongation test machine and Fig. 4.8 shows a wedge type manual grip of the break-elongation tester. After 5 break-elongation tests, 3 medium value data were selected to evaluate the cable life.

4.1.5. Cable Indenter

Cables exposed to a harsh environment in a NPP

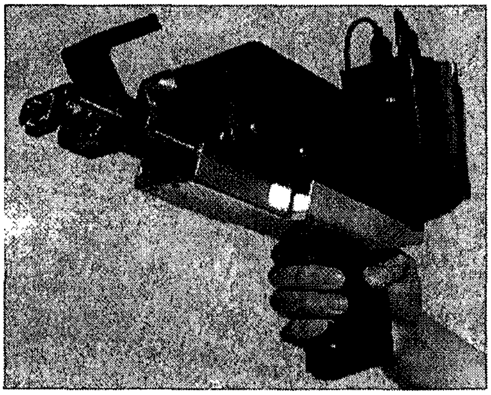

Fig.4.9. Portable Cable Indenter at KEPRI

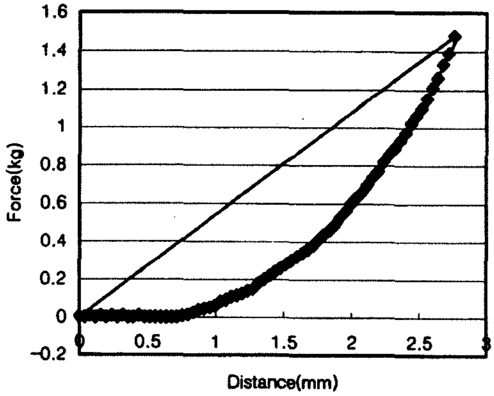

Fig. 4.10. Force-Distance Curve of Cable Indenter

tend to show signs of aging degradation. One of these symptoms is the hardening of the cable material. An indenter was designed to measure the hardness of the cable jacket. It is a very convenient tool for condition monitoring of nuclear cables since it uses a non-destructive method for diagnosing the extent of cable aging. This tool uses the modulus value, which is is calculated by dividing the force by the moving distance of the anvil, to detect aging degradation of the cable. Fig. 4.9 shows a picture of a portable cable indenter used at KEPRI [10]. Fig. 4.10 shows the "Force-distance" curve of the cable indenter.

4.2 Condition of Accelerated Aging

Accelerated heating conditions is were set based on the monitoring results of the actual environment temperature in Kori Unit 1, as shown on Fig. 4.6. Accelerated aging time at each step was calculated using the Arrhenius equation. Table 1 shows a simplified pattern of the actual environment conditions and equivalent aging time at 130℃ continuous heating. Table 2 shows intermittent heating temperature and time; equivalent aging is

Table 1. Accelerated Aging at Continuous Heating

Step	Moni. Temp (℃)	Moni. Date (days)	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 Heating

Step	Moni. Temp (℃)	Moni. Date (days)	Accelerated aging time (hour)					
			20 year life		40 year life		60 year life	
			℃	hr	℃	hr	℃	hr
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

displayed with the actual environment conditions in Kori Unit 1. Fig. 4.11 shows the monitoring results of accelerated aging under intermittent heating.

4.3. Test Result of Mechanical Properties

4.3.1. Elongation

Elongation rates for continuous aging for a period of 0 to 100 years and intermittent aging for a period of 0 to 60 years are shown in Fig. 4.12. We can see a rapid decline in the elongation rate during the 0 to 40 year aging period continuous heating. Elongation rate reached a 50% of intial value at the 30 years mark for continuous aging. Then, a moderately slow decline of elongation rate was observed for intermittent aging and the limit value of 50% elongation was not reached until the 60 years mark. At 60 years of aging, the elongation rate for continuous aging was almost double that of intermittent aging.

4.3.2. Cable Indenter

The indenter modulus for continuous aging during a period of between 0 to 100 years and that for intermittent aging during a period of 0 to 60 years are shown in Fig. 4.13. We could not see any unusual indication of aging degradation before 20 years of aging for both heating conditions. However, after the 20 years mark and up to the 100 years mark, we could observe a step increase of the indenter modulus for both the continuous and intermittent condition. After 60 years of aging, the

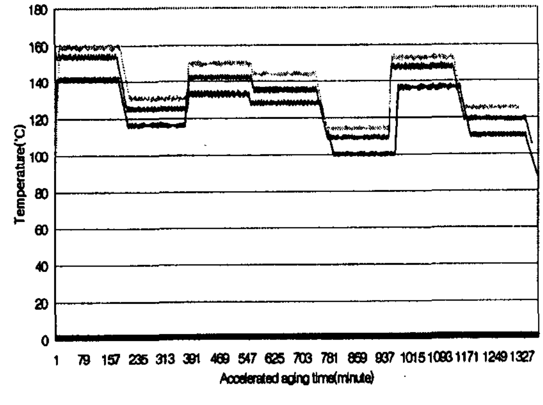

Fig. 4.11. Intermittent Heating Condition

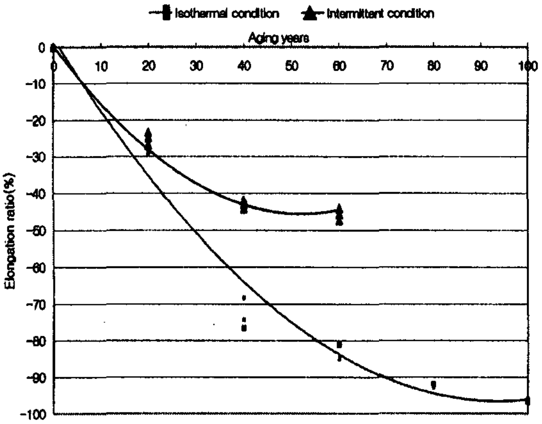

Fig. 4.12. Break-Elongation Rate at Continuous and Intermittent Aging Conditions

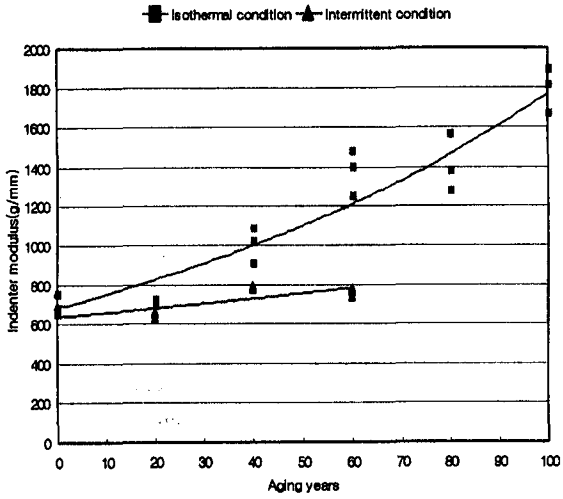

Fig. 4.13. Indenter Modulus at Continuous and Intermittent Aging Conditions

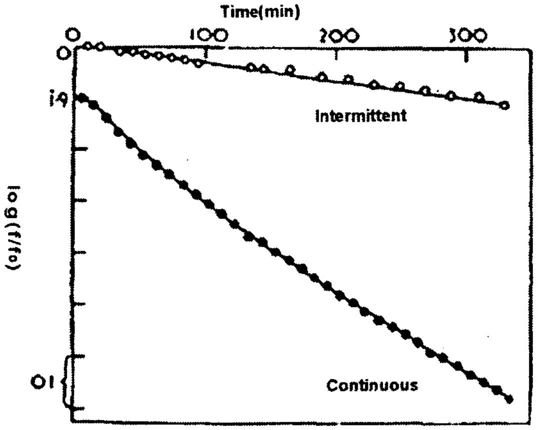

Fig. 4.14. Comparison between Continuous and Intermittent stress

indenter modulus obtained from the continuous condition was almost one and half times the value of that for the intermittent condition.

4.4. Analysis of Test Result

We have obtained unexpected test results for both continuous and intermittent aging conditions. The intermittent heating resulted in a low aging compared with continuous heating. This indicates that the short time rest after thermal stress allowed the rubber material to recover .This result corresponds with those from a study on aging effects from various stresses, on a rubber material [11]. Fig. 4.14 provides a comparison of strengths between continuous and intermittent stress, as outlined in.

5. Conclusions

We evaluated aging degradation after accelerated aging of a neoprene cable jacket under continuous and intermittent heating conditions. Contrary to general expectations, we found that intermittent heating of the neoprene cable jacket showed low aging degradation, 50% break-elongation, and 60% indenter modulus value, compared with continuous heating. With a plant maintenance period of 1 month after every 12 or 18 months operation, we can easily deduce that the lifetime of plant cable could be extended to be much longer than estimated through the EQ test, which adopts continuous accelerated aging for determining cable life. Based on the above test results, we concluded that the monitoring of plant environment conditions is essential for accurate evaluation of cable life.

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