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AN EVALUATION OF CONDITION MONITORING TECHNIQUES FOR LOW-VOLTAGE ELECTRIC CABLES*

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ABSTRACT

Aging of systems and components in nuclear power plants is a well known occurrence that must be managed to ensure the continued safe operation of these plants. Much of the degradation due to aging is controlled through periodic maintenance and/or component replacement. However, there are components that do not receive periodic maintenance or monitoring once they are installed; electric cables are such a component. To provide a means of monitoring the condition of electric cables, research is ongoing to evaluate promising condition monitoring (CM) techniques that can be used in situ to monitor cable condition and predict remaining life. While several techniques are promising, each has limitations that must be considered in its application. This paper discusses the theory behind several of the promising cable CM techniques being studied, along with their effectiveness for monitoring aging degradation in typical cable insulation materials, such as cross-linked polyethylene and ethylene propylene rubber. Successes and limitations of each technique are also presented.

INTRODUCTION

Aging of components in nuclear power plants is an important concern since degradation caused by aging can impact the performance of susceptible equipment. This is of particular concern for safety-related equipment since failure due to aging can compromise the continued safe operation of the plant. For active components, which are those containing moving parts to perform their function, periodic maintenance is typically performed to mitigate the effects of aging. In cases where aging degradation has already become pronounced, the equipment may be refurbished or replaced. However, there are many passive components that receive little attention in the way of maintenance or inspections. Electric cables are one such component.

There are many types of cable used in the typical nuclear plant, with the most common being instrumentation and control (I&C) cable, followed by low-voltage power cable. These cable types share a commonality in design and materials of construction, which is described in detail in other publications (Lofaro, 1999). In general, conductors are constructed of copper and are covered with a polymer insulation. Several insulated conductors may be bundled together and covered with an overall polymer jacket. Uninsulated shield and drain wires constructed of aluminum or copper may also be included in the cable. From an aging standpoint, degradation of the insulation's dielectric strength is of most concern since this is the component that isolates the conductors from ground and from each other. A breakdown in the insulation could cause erroneous signals or, in severe cases, short circuits leading to complete failure of the cable. The primary environmental factors that cause aging degradation of the insulating polymers are elevated temperature and radiation; both of which can be found in a nuclear plant.

In light of the potential impact of aging, methods of monitoring the condition of cables in situ are being studied. The goal of in situ cable condition monitoring (CM) is to determine the condition of a cable without damaging it or disturbing it significantly. This requires techniques that can measure material properties using little or no material samples from the cable. Techniques, such as elongation-at-break, have been shown to be effective at determining polymer condition; however, they require several inches of intact cable for destructive testing. Therefore, this technique is not unobtrusive and is not considered an in situ test.

As part of a research program being performed at Brookhaven National Laboratory (BNL), various CM techniques are being evaluated, and several have been shown to be promising as in situ CM tests for I&C cables in laboratory testing. Three promising CM methods discussed herein are the indenter test, oxidation induction testing, and visual inspection. These tests have limitations which must be considered in specific applications; however, they meet the criteria of an in situ CM test. Each test is discussed in detail below. It should be noted that

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research on other tests is ongoing, including electrical tests, and they may also be promising as in situ cable CM tests.

OVERVIEW OF THE BNL CABLE RESEARCH

In the BNL research, cable samples from various manufacturers were obtained. Insulation and jacket specimens were prepared from the cable samples and were tested in both the unaged and aged conditions. Results reported herein (Lofaro, 1998a, b) will focus on insulation results since this is the most important component of the cable in terms of aging degradation. For purposes of evaluating CM techniques, accelerated thermal and radiation aging were used to simulate aging degradation that would be experienced during actual service conditions for the cable specimens.

Insulation materials tested were cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR), which are commonly used in cables. For the XLPE insulation, artificial aging included thermal aging at 248°F (120°C) for approximately three hours followed by 0.6 Mrad of radiation at 0.33 Mrad per hour to simulate 10 years of service in a nuclear power plant. For the EPR insulation, artificial aging included 82 hours at 250°F (121°C) followed by 25.5 Mrad of radiation at 0.5 Mrad per hour to simulate 20 years of service. An additional radiation dose of approximately 150 Mrad was administered, in two separate 75 Mrad doses, to the test specimens after accelerated aging to simulate accident radiation conditions. CM measurements were taken for the unused condition (baseline), as well as periodically during the accelerated aging and accident radiation exposures.

ELONGATION-AT-BREAK

Elongation-at-break (EAB) is a measure of a material's resistance to fracture under an applied tensile stress. It is often termed the "ductility" of a material and is defined as the percent increase in elongation at the time of fracture. It is well known that cable insulation and jacket materials, like most polymers, lose ductility as they age. In a nuclear power plant environment, the aging process is a combination of thermal oxidation and gamma radiation effects. EAB has long been used to quantify the degradation of plastics. It is being used in this program as the reference method for determining the integrity of cable materials. It is also used as the reference against which other CM techniques are compared.

The EAB tests were carried out with an Instron tensile tester, using ASTM Standard D638-91 (ASTM, 1991) for guidance. The tests used 6-inch-long sections of insulation from which the conductor had been removed prior to aging and LOCA testing. The standard gagelength (deformable length) of the specimens was two inches. The initial standard deformation rate during the tests was 10 in./min. This was later increased to 20 in./min. to increase the speed of test completion. There was no noticeable difference in the EAB for the two strain rates. Usually, five replicate specimens were tested and the results were averaged for each CM point. All tests were conducted at room temperature.

Figure 1 presents the EAB as a function of the CM point for EPR and black XLPE insulation. Other studies in the program showed that the black insulation had the same EAB values as the white and red XLPE; therefore, only the results for black XLPE are reported herein. As shown, the EAB for the EPR remains unchanged after the relatively mild thermal aging (CM Point C); however, a continuous decrease is noted for the next three CM points, which involve large gamma radiation doses. Similar results were obtained for XLPE insulation.

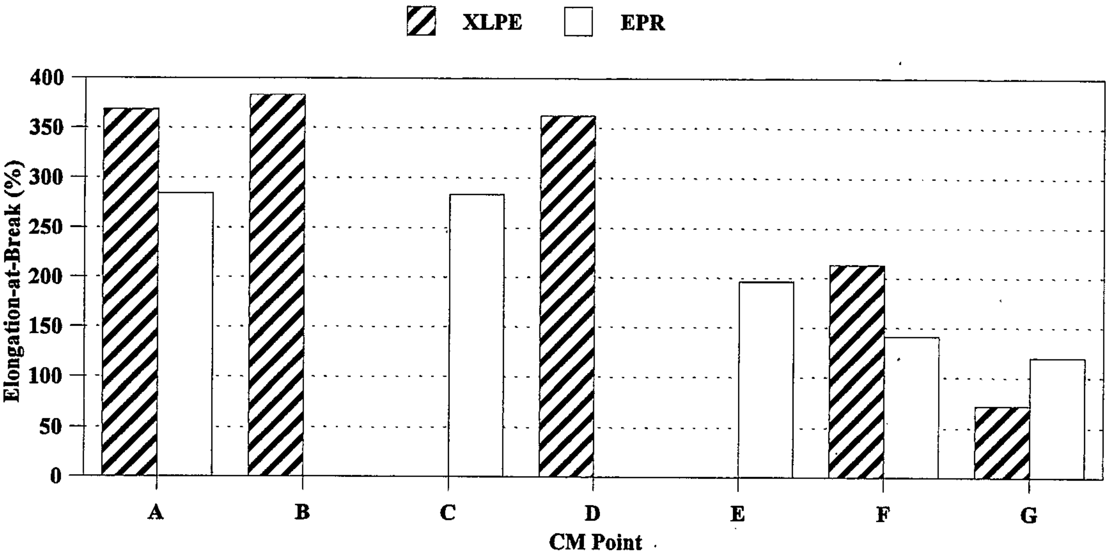
These results demonstrate that EAB can track changes in degradation with age for both EPR and XLPE materials, which makes it a useful CM technique. While the degradation from the thermal aging was often too small to be detected by EAB, the degradation due to radiation exposure was detected and showed a consistently decreasing trend with increased radiation aging for both materials.

While EAB is a good measure of a materials condition, its main limitation is that it is a destructive technique. Relatively large samples are needed to perform this test; therefore, it is not considered an in situ test. To implement EAB for periodic monitoring of cables installed in a plant, a source of sacrificial cable samples would have to be available. Some plants have installed cable deposits for just such a purpose.

OXIDATION INDUCTION TESTS

A test being studied for monitoring cable condition in situ is the oxidation induction test. Cable insulating materials typically contain anti-oxidants to protect them from oxidative degradation. However, these anti-oxidants are depleted from the material over time, leaving the material susceptible to oxidation. At that point, the main polymer chains become oxidizable, and a large exothermic peak appears in the oxidation curve (thermogram) if the material is maintained at elevated temperature in an oxidizing environment. By measuring the time or temperature required to initiate oxidation of the material, a correlation can theoretically be made with the condition of the material. It is expected that a material's resistance to oxidation will generally decrease with age.

The oxidation induction tests were carried out using a Shimadzu Model DSC-50 differential scanning calorimeter (DSC). The DSC is, essentially, a calibrated oven which allows controlled heating of small material samples with sensitive measurement of heat input or generation. Two types of test were run: an oxidation induction temperature (OITP) test and an oxidation induction time (OITM) test. The OITP test measures the temperature at which rapid oxidation is initiated in a specimen as the temperature is increased at a constant rate of 10°C/min in flowing oxygen. The OITM test measures the time required for the onset of rapid oxidation while the specimen is held at a constant temperature in flowing oxygen.



Notes for XLPE
A = Baseline (unaged cable)
B = After Thermal Aging 2.86 hours @ 120 °C
D = B + Service Radiation 0.6 Mrad @ 0.33 Mrad/hr.
F = D + Accident Radiation of 78 Mrad @ 0.8 Mrad/hr.
G = F + Accident Radiation of 79 Mrad @ 0.8 Mrad/hr.

Notes for EPR
A = Baseline (unaged cable)
C = After Thermal Aging 82.2 hours @ 121.1 °C
E = C + Service Radiation 25.5 Mrad @ 0.5 Mrad/hr.
F = E + Accident Radiation of 78 Mrad @ 0.7 Mrad/hr.
G = F + Accident Radiation of 77 Mrad @ 0.7Mrad/hr.

Fig. 1 Elongation-at-Break Versus Aging

Oxidation Induction Temperature Results

Figure 2 presents the results of the OITP tests on the EPR and XLPE materials. The OITP values are plotted versus the EAB. The highest value of EAB (right side of figure) represents the material in its baseline condition. Decreasing values of EAB (moving to the left) represent the various CM points during artificial aging of the material. As shown, the OITP for the XLPE, which received relatively mild aging to simulate 10 years of service, does not show any significant decrease in OITP from its baseline value for the thermal aging or the first radiation exposure. This is consistent with the EAB values, which remain close to the baseline value of approximately 370 percent. After the heavy doses of accident radiation (two points on the left of the curve), the OITP shows only a small decrease as the EAB decreases noticeably.

For the EPR insulation, which was aged to simulate 20 years of service, there is a more significant decrease in OITP. This is most noticeable after the two large accident radiation doses. A better correlation with EAB is noted for this material.

Oxidation Induction Time Results

Figure 3 presents the results obtained for OITM tests on the XLPE and EPR materials. The XLPE tests were run at a temperature of 428^{o}F (220^{o}C), whereas the EPR tests were carried out at 392^{o}F (200^{o}C). Compared to OITP measurements, the OITM results show a much larger change with aging. For both materials, the thermal aging and radiation exposures decreased the OITM by a factor of approximately four compared to the baseline value for unaged insulation. A good correlation with EAB values was found.

From the results obtained, the OITM measurements appear to be very promising with respect to estimating the current condition and remaining ductility of cable insulation. This is especially significant because it takes only about 10 mg of material to run a DSC test. This small amount of material can potentially be removed from installed cables without affecting their performance, which would effectively make OITM an in situ test. Compared to OIT, the OITP test appears to be less sensitive to changes in degradation caused by aging, which would make this type of test less useful for monitoring the degradation of cable insulation. Further testing is planned to examine this observation.

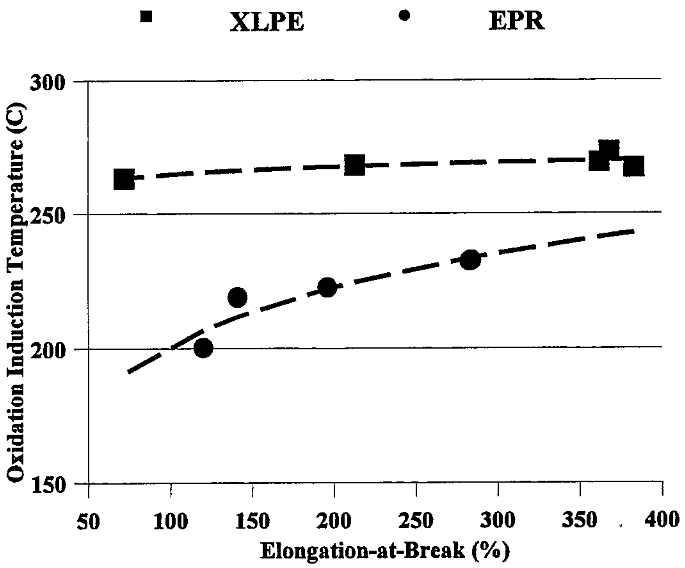


Fig. 2 Oxidation Induction Temperature Versus Elongation-at-Break

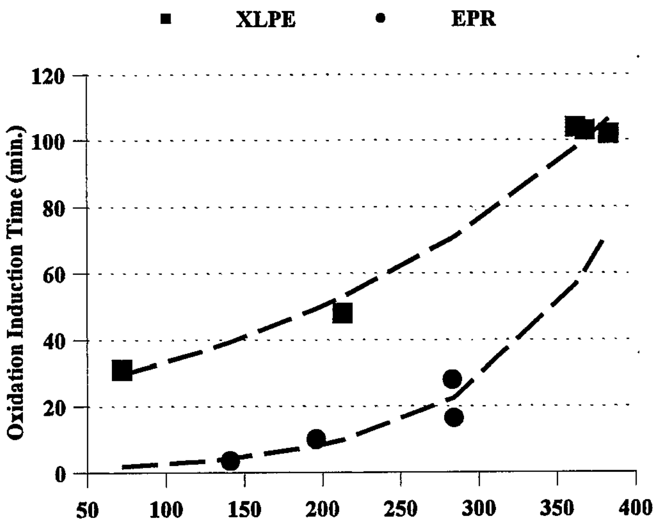


Fig. 3 Oxidation Induction Time Versus Elongation-at-Break

The limitation with both tests is that a sample of cable material must be obtained, which has several potential problems associated with it. First, the cable must be accessible. As noted previously, many cables are installed in closed conduits or are buried in cable trays beneath other cables. While samples can be obtained from accessible portions of the cable, such as junction boxes, these locations may not be representative of the area of interest. Typically, the cable locations of interest for condition monitoring are in areas of severe environmental conditions. If the cable cannot be reached to obtain a sample, a remote area of the cable would have to be used, which may be some distance from the desired location.

Another concern is that taking samples from installed cables could be met with reluctance from plant operators, particularly if the cable is for a safety-related application. While the samples required for this test are relatively small (<10 mg) and can be obtained from a surface scraping, there is concern that the taking of samples, no matter how small, could damage or disturb the cable.

Finally, any cable samples would probably come from the surface of the cable. If the cable was exposed to high aging rates, diffusion limited oxidation effects could be present. This would lead to a degradation gradient through the cable material, with the surface layer having the most degradation. Therefore, results obtained from a surface sample may not be representative of the general condition of the cable.

INDENTER TEST

The indenter test measures the compressive modulus of the cable material to detect degradation due to aging. In general, the polymers used for cable insulation will harden as they age. This will cause an increase in the compressive modulus. Thus, by trending the modulus measurements, an estimate can be made of the material's condition.

The device used in this research program is the Indenter Polymer Aging Monitor, which was developed by EPRI and manufactured by Ogden. This device contains a computer-controlled probe which is pressed into the material being measured. The force applied and the displacement of the probe are measured and used to calculate the compressive modulus of the material. Using a portable computer, the indenter can be used to obtain in situ measurements in the field. It does require access to the cable material being tested to allow the probe to contact the material, which is a limitation of this test.

Figure 4 presents the results of the indenter tests for the XLPE cable material. As shown, the data for the XLPE do not show a trend that is consistent with the EAB values for the initial phase of the artificial aging (right side of figure). After thermal aging, the modulus decreases slightly, indicating a softening of the material, which is consistent with the slight increase in EAB. However, after service radiation, the modulus again decreases, while the EAB also decreases. For the two exposures to accident radiation (left side of figure), there is a continuous increase in the modulus, which is consistent with the decrease in EAB. The results obtained are questionable with regard to whether this test is useful for monitoring degradation of XLPE. Further evaluation with different amounts of service aging is planned to determine if the indenter can effectively trend degradation in XLPE material.

Results for EPR do show a fairly consistent trend when correlated to EAB (Fig. 5). As the aging increases, the modulus consistently increases as the EAB consistently decreases. This indicates a good correlation with aging degradation, which would make this a good means of monitoring degradation of cables constructed of this material

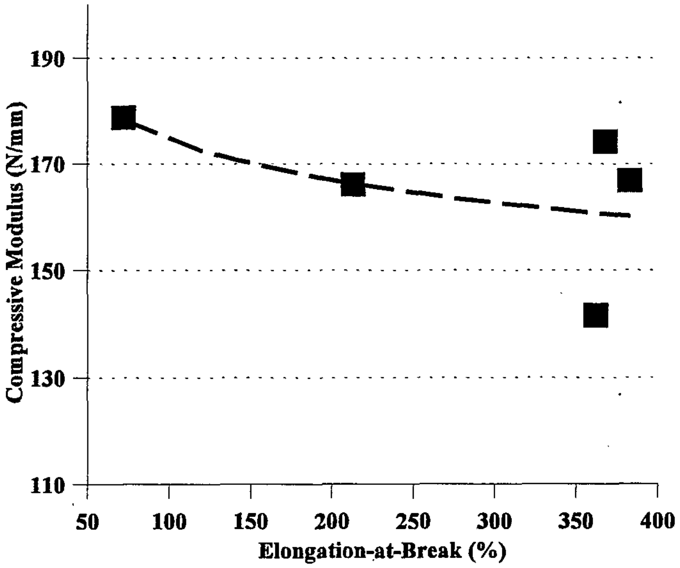


Fig. 4 Compressive Modulus Versus Elongation-at-Break for XLPE

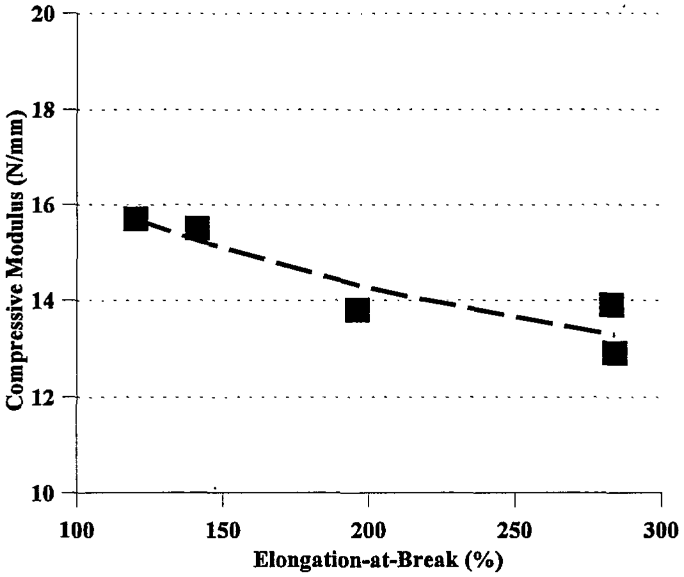


Fig. 5 Compressive Modulus Versus Elongation-at-Break for EPR

An important observation made during this testing is that significant variation in modulus values can be obtained between different lots of the same material from the same manufacturer. This can be due to many factors, such as changes in the material formulation, the use of different additives, or a change in processing procedures. For example, the baseline modulus for one sample of EPR material was 11.6 N/mm, while that from a different lot from the same manufacturer was 15.8 N/mm; a difference of 36 percent. Therefore, to provide accurate trending results, baseline modulus values for the material are necessary. In the absence of baseline values from new cable samples, measurements of cables from the same lot that are installed in mild environments can be used, if available.

As previously mentioned, a limitation of this technique is that the cable to be tested must be accessible. In some cases, the cable of interest may be buried under other cables in a cable tray or it may be installed in conduit. In these cases, an exposed area of the cable would have to be found, such as at a termination or in a junction box. However, these locations may not be subject to the same environment as the cable sections being investigated, and the condition may not be representative.

VISUAL INSPECTION

Visual inspection of electric cables is another promising in situ technique evaluated in the BNL research. In comparison to the other CM methods which produce quantitative results, visual inspections provide a qualitative assessment of cable condition. However, visual inspection is an in situ test which is inexpensive and relatively easy to perform and can provide useful information for determining cable condition. Therefore, it is considered an important element of any condition monitoring program.

For this evaluation, visual inspections of the test specimens were performed prior to testing (baseline), as well as periodically throughout the preaging and LOCA simulation processes. The results obtained were compared to the baseline to determine if visible changes in the cable can be correlated to degradation occurring as a result of aging.

The visual inspections are performed in a standardized, detailed manner in accordance with a BNL Test Procedure. The cable attributes which are inspected visually include:

- color, including changes from the original color and variations along the length of cable, and the degree of sheen,
- cracks, including crack length, direction, depth, location, and number per unit area,
- distortion, including dimensional changes that would indicate swelling or shrinking,
- visible surface contamination, including any foreign material on the surface,
- smell, to determine if any unusual odors are present indicating a chemical change to the material, and
- rigidity of the cable is qualitatively determined by squeezing and gently flexing it.

There are several advantages in using visual inspection as a condition monitoring technique. It is relatively easy to perform, and no sophisticated or expensive equipment is needed. Also, it is non-destructive and can be performed in situ. In this evaluation, visual inspections were performed in a manner which closely simulates actual plant conditions for installation in a cable tray. The cable specimens were installed in Unistrut® channels such that only the top half of the cable jacket was visible. Insulation was examined at exposed ends, similar to what would be found near an end device to which the cable would be connected in the plant.

The visual inspection results show that cable degradation can be detected visually. For example, comparison of the baseline results for XLPE insulation specimens discussed herein with those for the aged specimens shows that the white insulation on the aged specimen was slightly yellow as compared to the new condition. Also, the aged specimen was more rigid than the unaged specimens. Similar results were obtained for the EPR specimens. These observations can be documented and qualitatively tracked to monitor cable aging.

While the visual results provide useful information on the cable condition, there are limitations as to what can be determined from this information. One limitation of visual inspection, which was noted during plant walk downs, is that many cables are not easily accessible for inspection. Some cables are installed in closed conduits, and it is not possible to visually observe them. Also, cables installed in cable trays can be buried under other cables making it very difficult to visually inspect them without disturbing other cables in the tray. These limitations apply to all CM techniques that require access to the cable.

The results obtained thus far indicate that visual inspection is a useful tool in an overall evaluation of cable condition and should be part of any cable condition monitoring program.

CORRELATION OF JACKET CONDITION WITH INSULATION CONDITION

As seen from the previous discussions on cable monitoring, a significant limitation to the techniques discussed is limited access to the insulation. Even for cables that are accessible, typically only the jacket will be available for testing. In this case, a correlation between jacket condition and insulation condition would be necessary to provide information on the condition of the underlying insulation. This can be accomplished if the appropriate information is available.

To correlate jacket condition with the condition of the underlying insulation, several criteria must be met. First, it must be determined that both the jacket and the insulation material respond in a relatively consistent and predictable manner in terms of the material parameter being monitored. For example, if the indenter is to be used as the CM technique, both the jacket and insulation should exhibit an overall consistent change in compressive modulus with increasing amounts of aging. This can be determined by laboratory testing or from other research, as presented herein.

Second, the jacket material must exhibit the same or a higher rate of degradation than the insulation material when subjected to the same environmental conditions. For example, in the work reported herein, it was found that Hypalon jacket material ages at a slightly faster rate than EPR insulation under the same aging conditions. If these two conditions are met, jacket measurements can be used to provide a bounding estimate of insulation condition. It should be noted that once the jacket properties reach the minimum or maximum value of the parameter being measured, jacket measurements can no longer be used to predict insulation condition.

As an example, Fig. 6 presents indenter readings for Hypalon jacket material and EPR insulation material as a function of aging. The measurements have been normalized to show the relative change in modulus. As shown, the jacket modulus increases at a slightly faster rate than the insulation modulus. Recognizing that in an actual application the jacket will provide some shielding to the underlying insulation, the insulation modulus could be expected to increase at the same or slower rate than found in the laboratory tests. Therefore, indenter measurements on the jacket of a cable using a Hypalon jacket with EPR insulation could be used to provide a conservative estimate of the condition of the insulation. For example, if the jacket modulus was determined to have increased by 25 percent, it could be estimated with reasonable confidence that the insulation modulus had increased by less than 25 percent. If an acceptance criteria were known for the acceptable increase in modulus, this information could be used to determine if the cable was fit for continued service.

CONCLUSIONS

In situ monitoring of electric cables is of great interest to manage aging degradation of these passive, long-lived components. Currently, research is ongoing to evaluate various CM techniques, and several appear to be promising. Each of these techniques is able to detect aging degradation in a non-intrusive manner and, therefore, can be performed in situ.

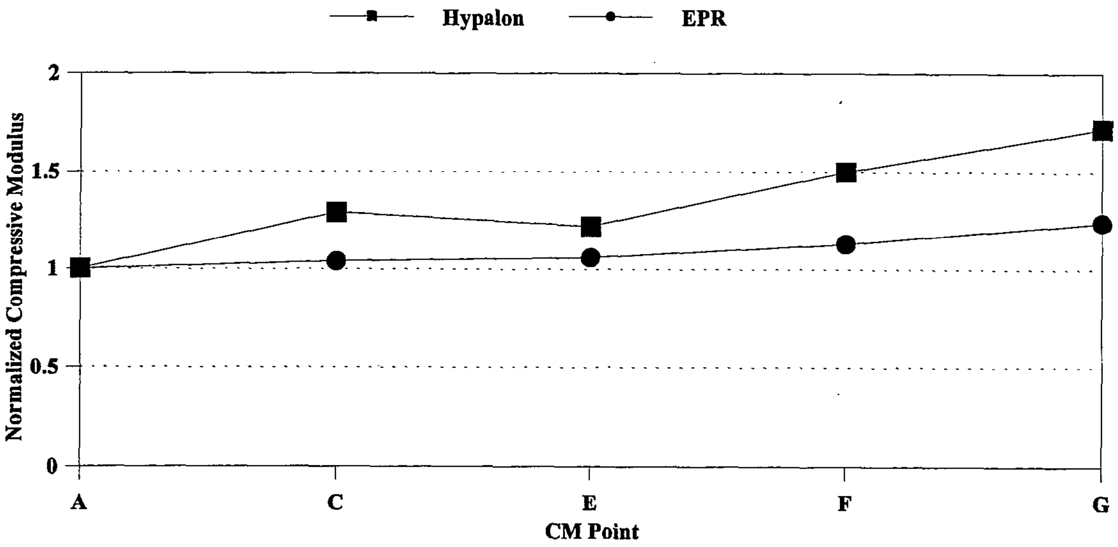
Elongation-at-break has long been recognized as a good technique for determining the condition of cable insulating materials. However, it is a destructive technique and cannot be performed without removing relatively large samples of the cable. This would be intrusive from the standpoint of interrupting plant operation.

Three non-intrusive techniques that have been shown to be promising in laboratory testing are oxidation induction testing, indenter testing, and visual inspections. The oxidation induction test can be performed in two modes: oxidation induction time or oxidation induction temperature. The data presented herein indicate that oxidation induction time is more sensitive to changes in degradation for XLPE and EPR materials. Only a very small sample (<10 mg) of cable material is required to perform this test. This amount of material can be obtained from a scraping of the cable; however, diffusion limited oxidation effects should first be considered if surface scrapings are used.

The indenter tester has been found to be a reliable test device that produces fairly repeatable results. Data for XLPE material are inconclusive with regard to the effectiveness of this technique to trend degradation of this material. Further evaluation is required. Data for EPR do show a good correlation with EAB; therefore, this test can be used to monitor aging degradation for this material.

Visual inspections have been shown to provide useful qualitative information on the condition of cables. Typically, a visual inspection would be the first activity performed to detect aging degradation of cables. If any indicators are found, further testing using other CM techniques would be warranted.

It should be noted that each technique has limitations that must be accounted for in its application. For the techniques presented herein, the most notable limitation is that the cable to be tested must be accessible. However, if sufficient information is available on the response of the cable materials to aging, jacket measurements can be used to provide a reasonably conservative estimate of the underlying insulation condition.



Notes: A = Baseline (unaged cable)
C = After Thermal Aging 82.2 hours @ 121.1 °C
E = C + Service Radiation 25.5 Mrad @ 0.5 Mrad/hr.
F = E + Accident Radiation of 78 Mrad @ 0.7 Mrad/hr.
G = F + Accident Radiation of 77 Mrad @ 0.7 Mrad/hr.

Fig. 6 Normalized Modulus Values for Hypalon and EPR Materials Versus Aging

Also, it should be noted that the conclusions presented are preliminary, and research on these techniques, as well as other CM techniques, is ongoing. There are other CM techniques being studied that may also be promising, including electrical techniques, such as insulation resistance and dielectric loss. These techniques may be able to detect degradation on cables that are not accessible.

Currently, there is no one technique that can be used to monitor degradation on all types of cables. A combination of techniques appears to be necessary.

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