SAND91-0187C

Mechanical Property Condition Monitoring of Cables Exposed to Long-Term Thermal and Radiation Aging--XLPO Results *

SAND--91-0187C
DE91 009174

Mark J. Jacobus
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185

ABSTRACT

Sandia National Laboratories is conducting long-term aging research on representative samples of nuclear power plant Class 1E cables to determine the suitability of these cables for extended life (beyond the 40-year design basis) and to assess various cable condition monitoring techniques for predicting remaining cable life. This paper provides some results of mechanical measurements that were performed on cross-linked polyolefin (XLPO) cables and cable materials aged at relatively mild, simultaneous thermal and radiation exposure conditions for periods of up to nine months. The mechanical measurements discussed in this paper include tensile strength, ultimate elongation, hardness, and compressive modulus. The modulus measurements were performed using an indenter developed at Franklin Research Center under EPRI sponsorship.

INTRODUCTION

Many types of cable are used throughout nuclear power plants in a wide variety of applications. Cable qualification typically includes thermal and radiation aging intended to put the cable in its end-of-life condition. The radiation dose is typically applied at fairly high dose rates (1-10 kGy/hr) with Arrhenius methods used to establish artificial aging times and temperatures. Generally, the radiation and thermal aging are applied to the specimens sequentially, but some (primarily research) programs have applied the environments simultaneously.[1-4]

This paper provides some results of mechanical measurements that were performed on cross-linked polyolefin (XLPO) cables and cable materials aged at relatively mild, simultaneous thermal (95-100°C) and radiation (≈0.10 kGy/hr) exposure conditions for periods of up to nine months. The mechanical measurements discussed include tensile strength, ultimate elongation, hardness, and compressive modulus. The aging conditions were determined by equating six months of exposure to a 40-year life and assuming an activation energy of 1.15 eV, a plant ambient temperature of 55°C, and a 40-year radiation dose of 400 kGy.

* The Long-Term Cable Aging Program is supported by the United States Nuclear Regulatory Commission and performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under contract number DE-AC04-76DP00789.

A list of the cables discussed in this paper is given in Table I. Other non-XLPO cables were included in the test program,[5,6] but they will not be discussed in this paper.

EXPERIMENTAL ARRANGEMENT

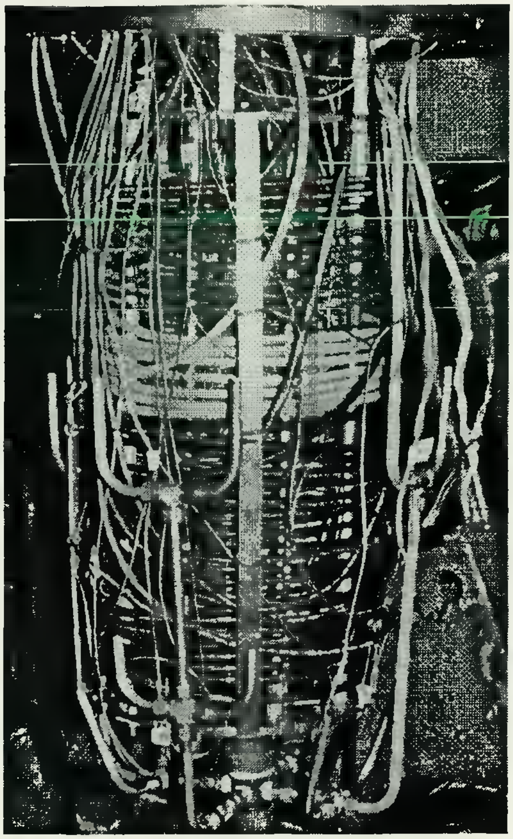
For the overall test program, cables were wrapped on mandrels that were inserted into three different test chambers. One basket, containing completed single and multiconductor cable specimens, and a second basket, containing insulation and jacket material specimens, were inserted together up into the center of the mandrels. Figure 1a shows a typical mandrel prepared for testing and Figure 1b shows a pair of mated sample baskets that have been prepared for insertion into the center of a mandrel. The lower part of Figure 1b shows a sample basket with completed cable specimens, which were 36 cm (14 in.) long. The upper part of Figure 1b shows a sample basket with insulation and jacket material specimens, which were 15 cm (6 in.) long. The results discussed in this paper are based on samples taken from these sample baskets; the cables wrapped on the outside of the mandrels, shown in Figure 1a, were used for other parts of the test program and are not discussed in this paper.

The 15-cm insulation and jacket material samples were used for tensile strength and elongation measurements. In preparing the insulation material samples, the center conductors were removed from insulated single conductor samples prior to the beginning of aging. Jacket material samples were cut from the jackets of multiconductor cable products.

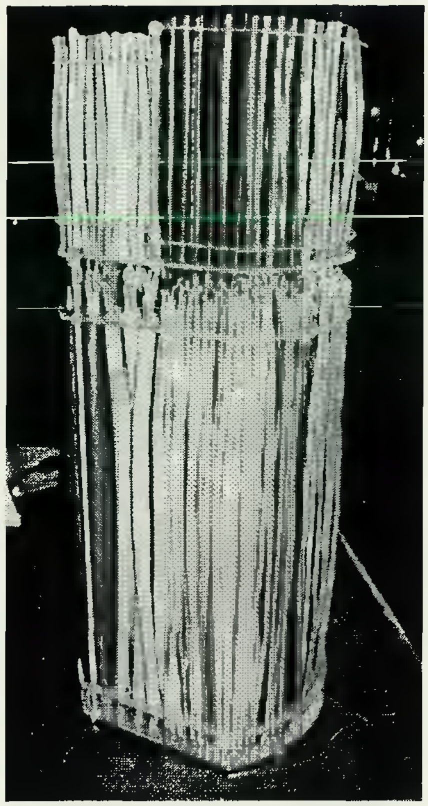
The 36-cm cable specimens were used for hardness and for indenter modulus testing. These completed cable samples were prepared by simply cutting the cables to the desired length and stripping the insulation from the ends of the sample to allow easy access for electrical testing after aging. Single conductor samples from multiconductor cable products were prepared similarly after removing the outer jacket. The conductors remained in these specimens during all testing.

Table I Cable Products Discussed in this Paper

Supplier	Description
Brand Rex	Cross-Linked Polyethylene (XLPE) Insulation, Chlorosulfonated Polyethylene (CSPE) Jacket, 12 AWG, 3/C, 600 V
Rockbestos	Firewall 3, Irradiation XLPE, Neoprene Jacket, 12 AWG, 3/C, 600 V
Raychem	Flamtrol, XLPE Insulation, 12 AWG, 1/C, 600 V
Samuel Moore	Dekoron Polyset, XLPO Insulation, CSPE Jacket, 12 AWG, 3/C and Drain



(a)



(b)

Figure 1 Typical Test Configuration (a) Mandrel and (b) Sample Baskets

Cable aging consisted of simultaneous thermal and radiation aging of the samples. The samples in one chamber were aged for up to 3 months (3-month chamber), the samples in the second chamber were aged for up to 6 months (6-month chamber), and the samples in the third chamber were aged for up to 9 months (9-month chamber). At various intervals during the aging, material samples and completed cable specimens were removed from the test chambers. For example, specimens were removed from the 9-month chamber after aging times of 6, 7, 8, and 9 months. By replacing the removed cables with additional unaged cables, we also obtained specimens with 3, 2, and 1 months of aging from this same chamber.

All aging was performed in Sandia's Low Intensity Cobalt Array (LICA) facility. Although simulated lifetimes of up to 60 years were desired, actual simulated lifetimes at any given set of exposure conditions vary greatly because of different activation energies of the specimens (a single activation energy of 1.15 eV was assumed in aging calculations); because of the assumed service temperature; and because of test temperature gradients. Based on meeting a realistic schedule together with accelerating the aging of the cables as little as possible, periods of three, six, and nine months were chosen as the accelerated aging times for the cables in the three chambers.

These correspond to nominal life conditions of 20, 40, and 60 years, respectively. The aging conditions were based on a plant ambient temperature of 55°C with no conductor heat rise. A single value of activation energy was necessary to keep aging times and temperatures constant for different cables materials, which were all located in common test chambers for each exposure. With the desired aging times, the assumed activation energy, and the assumed ambient conditions, the aging temperature was calculated to be 95°C based on the Arrhenius equation. For a desired total dose of 400 kGy for a 40-year simulation, the aging required a dose rate of about 0.09 kGy/hr. The actual dose rates to the various samples were lower on average than the desired values, largely because of the locations of the samples in the test chambers and because of shielding effects due to the high density of cables in the test chambers. The estimated uncertainty in the radiation aging exposure data used in this paper is ±20%.

During aging, the temperature in the test chambers was maintained using electric wall heaters and electric inlet air heaters. Temperature uniformity was controlled to the extent possible by insulating the chamber and by providing internal air circulation. About 10 cfm of outside air (about 1 air change every 8 minutes) was introduced into the chamber to maintain circulation and ambient oxygen concentration and to maintain a slightly positive pressure in the test chambers to prevent in-leakage of water from the LICA pool. The actual pressure in the test chamber was near ambient pressure at sea level.

MECHANICAL MEASUREMENTS

The following mechanical measurements were performed on samples of cables and cable materials removed periodically during aging:

Elongation at break of material specimens determines the amount that the cable will stretch prior to failure. We performed these measurements with an Instron Model 1000 tester and an incremental extensometer with a resolution of 10% absolute elongation. This is, of course, a destructive test.

Tensile strength of material specimens was defined as the force at break divided by the initial cross sectional area of the material. This measurement was made together with elongation measurements.

Hardness tests of complete cable specimens were performed using a Shore Durometer Hardness Type "A-2" tester. This hardness test gives a measure of a material's resistance to local penetration on a scale of 0 to 100. Key advantages of this measurement are that it is nondestructive and simple to perform. Consequently, it may be realistic for use in the field.

Modulus tests using Franklin Research Center's indenter developed under EPRI funding[7,8] measures penetration force of a blunt conical probe as a function of penetration depth. The compressive modulus is defined as $\Delta F/\Delta x$, where Δx is the change in depth of penetration for a given change in force ΔF. In all of our tests, ΔF was defined as 1.5 pounds, beginning at 0.5 pounds and ending at 2.0 pounds. As for hardness, a key advantage of this measurement is that it is a nondestructive test that may be realistic for use in the field. However, it is more complex and time consuming to perform than hardness.

Another technique, known as modulus profiling,[9] uses the same basic principle as the indenter. Modulus profiling measure the compressive modulus across the cross section of a polymer and has been used as an indicator of the uniformity of the aging process.

For all of the above measurements, the test equipment was connected to data loggers and computers for automated data acquisition and analysis.

RESULTS

In this section, plots of elongation, tensile strength, hardness, and indenter modulus are shown versus total radiation dose. Because of radiation gradients in the test chambers, some samples at similar total radiation doses can have somewhat different amounts of thermal aging. If the degradation is dominated by the radiation exposure, then this effect will not be noticeable on the plots. However, if the degradation happens to be thermally dominated, then the plots can be affected to some extent by differences in thermal exposure time. In each of the plots, the legend indicates which test chamber each group of samples was exposed in.

TENSILE STRENGTH AND ELONGATION DURING AGING

Plots of e/e_0, ultimate tensile elongation relative to the unaged values, are shown in Figures 2-8 for each of the cable insulation and jacket materials. Plots of T/T_0, tensile strength normalized to unaged values, are shown in Figures 9-15. In Figures 9-15, tensile strength is defined as the force at break of the specimen divided by the cross-sectional area of the unaged specimen. Although the force at break is also usually the maximum force applied to the specimen, such is not always necessarily the case. Since the cross-sectional areas of aged and unaged cables are nominally the same for a given cable type, T/T_0 reduces to the ratio of the force required to break an aged specimen to the force required to break an unaged specimen. Thus, the precise cross-sectional area is only necessary to provide absolute scaling for the plots. For reference, the tensile strength of the unaged specimens is noted on each plot. Similarly, the absolute elongation of unaged specimens is noted on the e/e_0 plots.

In general, elongation for each cable type decreases with increased radiation dose during aging. The one exception to this is the Rockbestos XLPE insulation, which has an initial increase in elongation of about 10% during the first 50 kGy of radiation exposure, followed by the expected decrease in elongation with higher radiation doses. For the Rockbestos and Brand Rex jackets, no residual elongation was measurable by the end of the aging exposures (the resolution of our absolute elongation measurements is 10%). Note that unmeasurable residual elongation, especially of the jacket material, does not imply that a cable is no longer functional. Some results from accident tests of cables wrapped on mandrels such as that shown in Figure 1a are in Reference 10; additional results will appear in future publications.

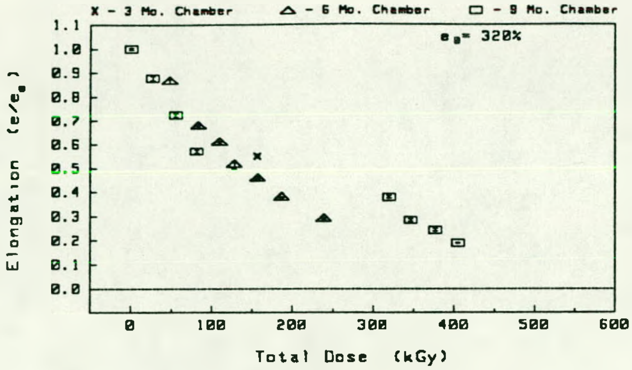


Figure 2 Elongation of Brand Rex XLPE Insulation

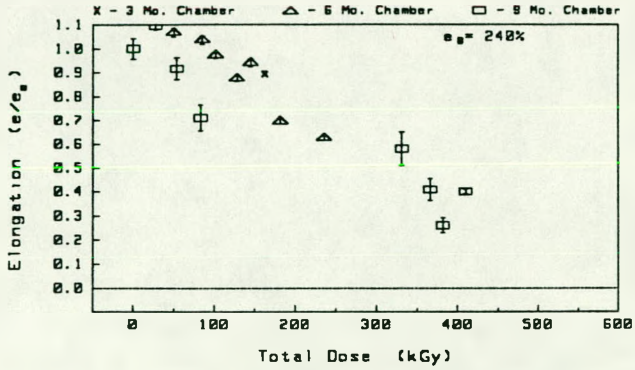


Figure 3 Elongation of Rockbestos XLPE Insulation

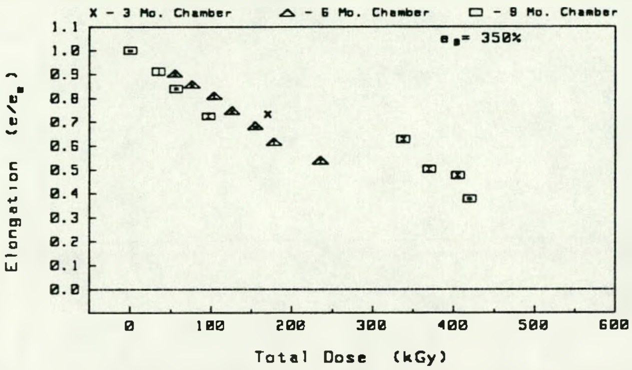


Figure 4 Elongation of Dekoron XLPO Insulation

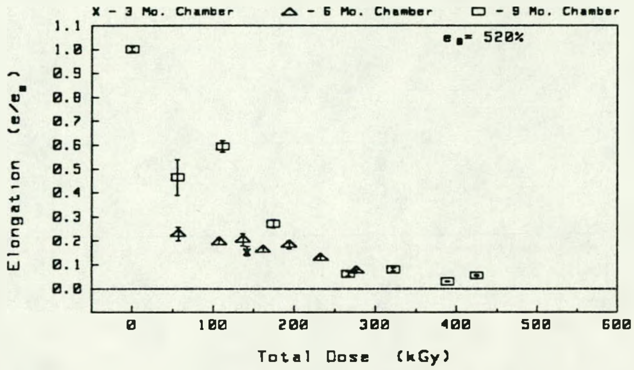


Figure 5 Elongation of Raychem XLPE Insulation

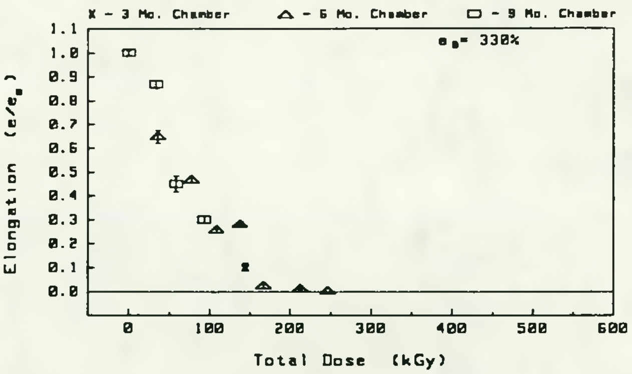


Figure 6 Elongation of Brand Rex CSPE Jacket

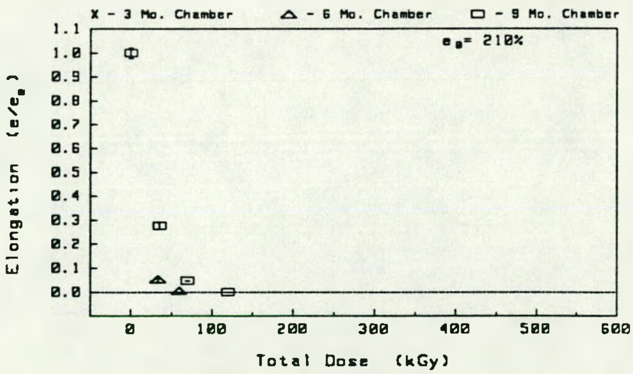


Figure 7 Elongation of Rockbestos Neoprene Jacket

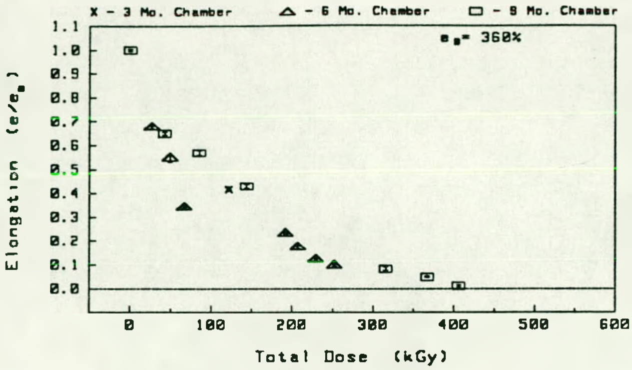


Figure 8 Elongation of Dekoron CSPE Jacket

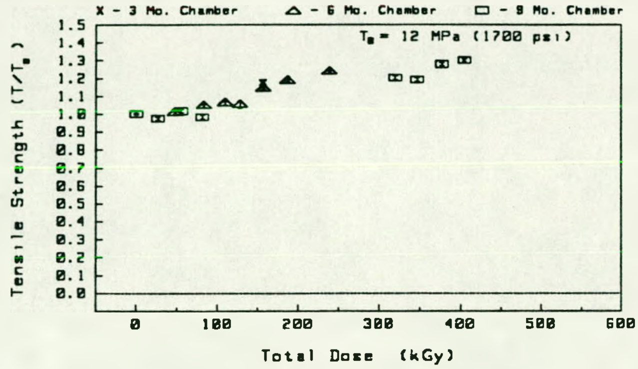


Figure 9 Tensile Strength of Brand Rex XLPE Insulation

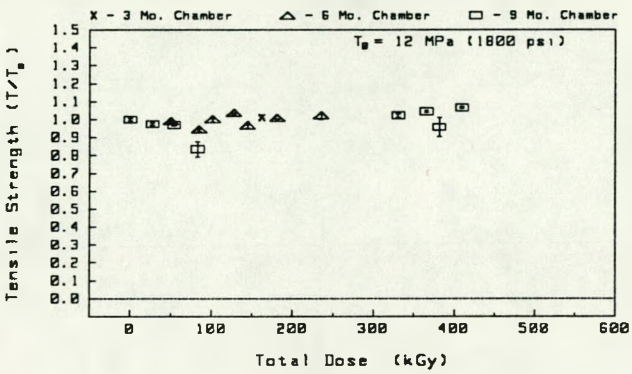


Figure 10 Tensile Strength of Rockbestos XLPE Insulation

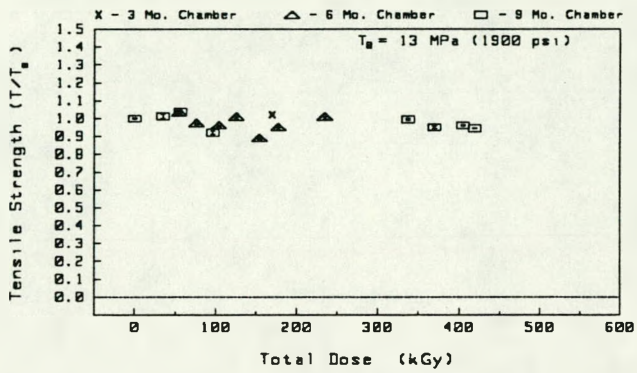


Figure 11 Tensile Strength of Dekoron XLPO Insulation

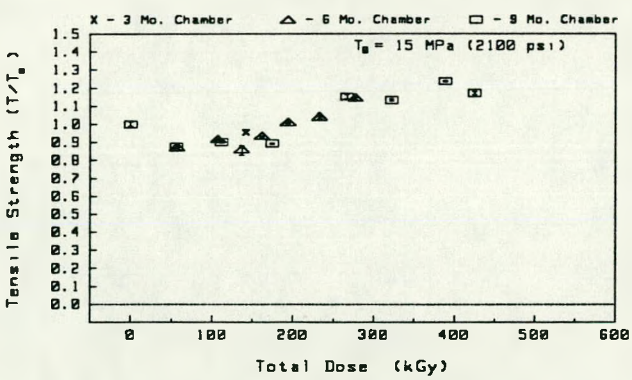


Figure 12 Tensile Strength of Raychem XLPE Insulation

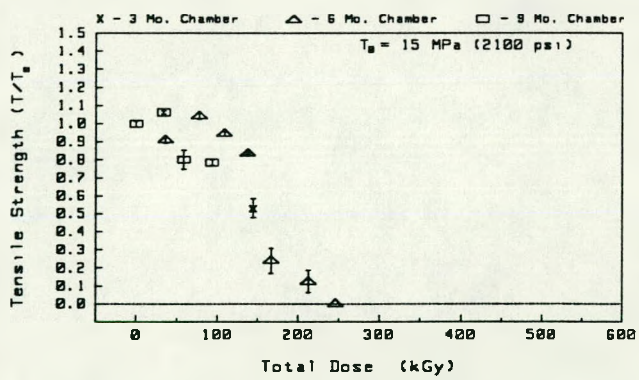
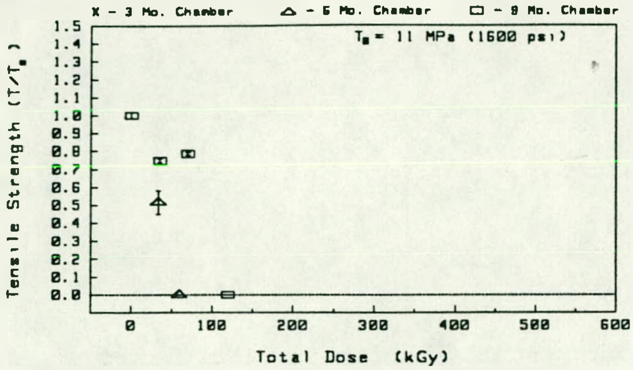


Figure 13 Tensile Strength of Brand Rex CSPE Jacket



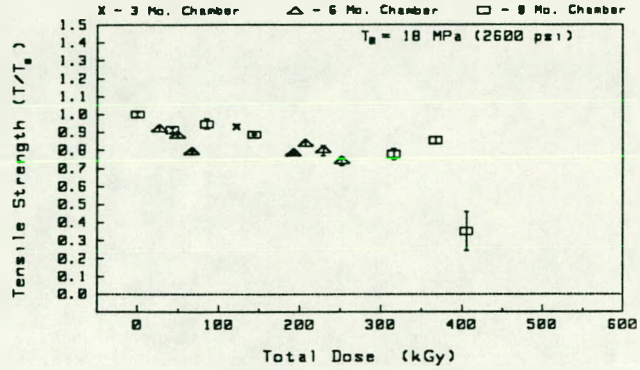


Figure 14 Tensile Strength of Rockbestos Neoprene Jacket

Figure 15 Tensile Strength of Dekoron CSPE Jacket

Based on the data in Figures 2-8, Table II gives estimates of the total dose (under our simultaneous aging conditions) to retention of 75%, 50%, 25%, and 10% of initial elongation of each insulation and jacket materials, except for the Rockbestos neoprene jacket. The neoprene is not included because under the conditions of our test, thermal aging dominates the degradation for neoprene. The data in Table II and in the figures indicate that elongation is generally a fairly sensitive measure of the amount of aging up to the total dose where very little residual elongation remains. When using Figures 2-8 or Table II to compare different cable materials, it is important to note baseline elongation differences. For example, Rockbestos XLPE insulation at $e/e_0 = 0.25$ corresponds to an absolute elongation of 60%, while Raychem XLPE insulation at $e/e_0 = 0.25$ corresponds to an absolute elongation of 130%.

Because measurement of elongation is destructive, utilities are generally unwilling to sacrifice samples of functional cables that would then have to be spliced or replaced. Thus, although they can be used as a reasonably effective condition monitoring method in theory, elongation measurements are difficult to use in actual power plant applications.

Figures 9-15 show that tensile strength does not correlate with aging as well as elongation does for most materials. Tensile strength showed some change with aging for the Brand Rex and Raychem XLPOs, but almost no change for the Rockbestos and Dekoron materials. Tensile strength of the Rockbestos jacket showed a rapid decrease, but only a few points could be measured because the elongation quickly fell to 0%. The Brand Rex jacket had a fairly consistent and significant decrease in tensile strength while the Dekoron jacket had only a slight decrease in tensile strength.

HARDNESS AND INDENTER MODULUS DURING AGING

Figures 16-18 show hardness data and Figures 19-23 show indenter modulus data for selected insulation materials and all of the jacket materials. The hardness of the XLPO insulations is not presented because they were all too hard (Shore "A2" readings of 88-96) prior to aging to detect any significant

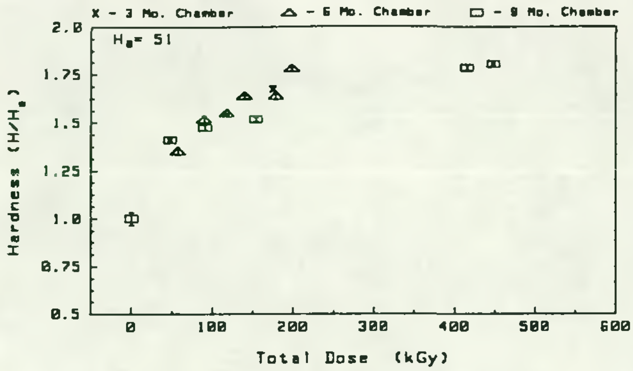


Figure 16 Hardness of Brand Rex CSPE Jacket

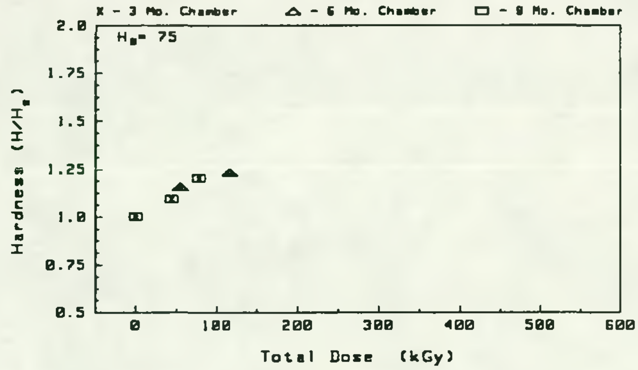


Figure 17 Hardness of Rockbestos Neoprene Jacket

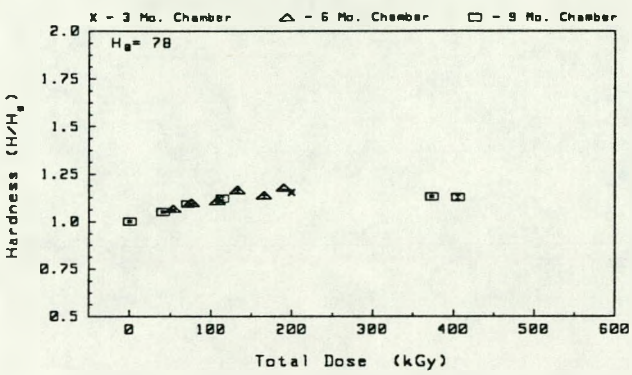


Figure 18 Hardness of Dekoron CSPE Jacket

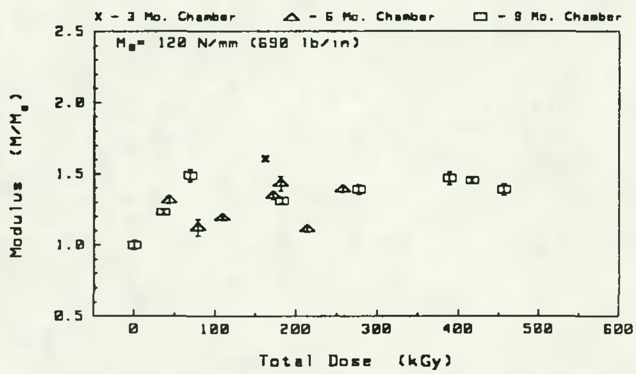


Figure 19 Indenter Modulus of Brand Rex XLPE Insulation

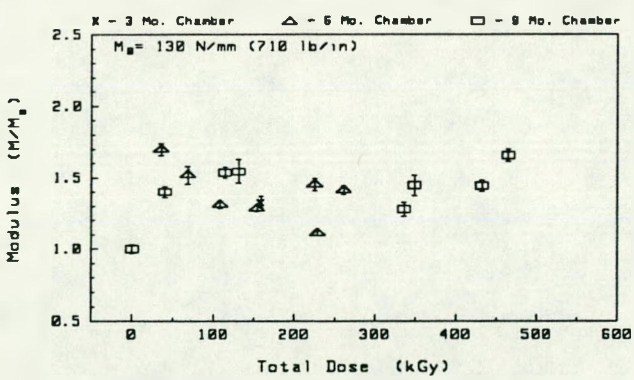


Figure 20 Indenter Modulus of Rockbestos XLPE Insulation

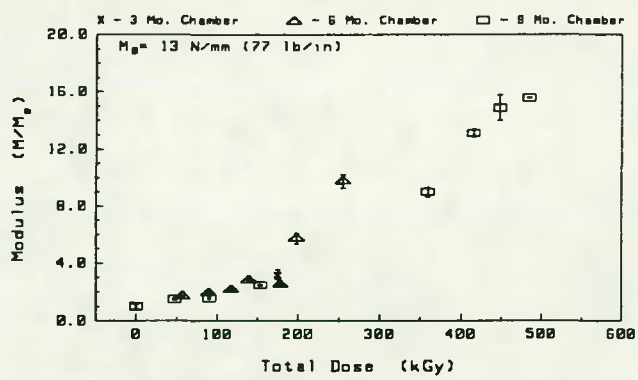


Figure 21 Indenter Modulus of Brand Rex CSPE Jacket

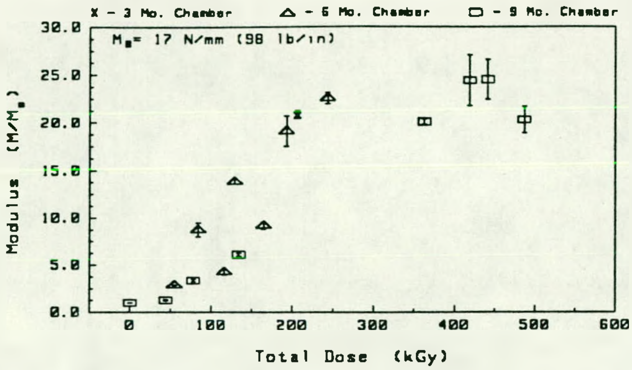


Figure 22 Indenter Modulus of Rockbestos Neoprene Jacket

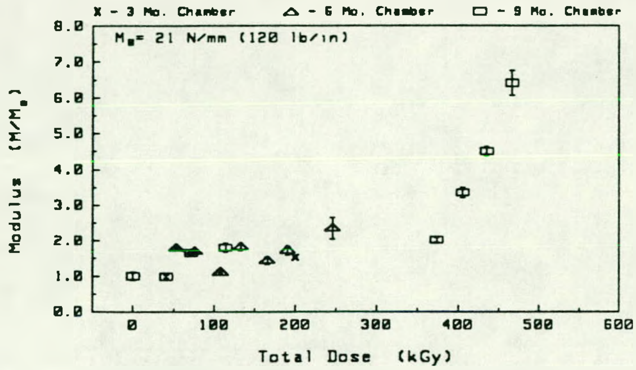


Figure 23 Indenter Modulus of Dekoron CSPE Jacket

changes with the tester we were using (effective upper limit of our tester was about 92). Hardness of the Brand Rex jacket (Figure 16) increased by 75% during aging, hardness of the Rockbestos jacket (Figure 17) increased by 25% during aging, and hardness of the Dekoron jacket (Figure 18) increased by 15% during aging. It is important to note that some of the measurements were close to or beyond the effective upper limit of the tester range. Readings above 92 are not included on the plots.

The indenter modulus of the Brand Rex XLPE insulation material shown in Figure 19 and the indenter modulus of the Rockbestos XLPE insulation material shown in Figure 20 do not change greatly with aging and no consistent trends are evident. Similar results were obtained for the other XLPO cable materials tested. Figure 21 shows the indenter modulus of the Brand Rex CSPE jacket. This material shows a strong upward trend with aging, especially when the total dose exceeds 200 kGy. It is interesting to note that 200 kGy is just about the point where the elongation has fallen to near 0%.

Figure 22 shows the indenter modulus for the Rockbestos neoprene jacket. A strong upward trend is evident, with the indenter modulus reaching 2000% of its original value at about 400 kGy. Note that elongation measurements

Table II Estimated Total Doses to Retention of Various Elongations

Material	e_0	Total Dose (kGy) to e/e_0 of			
		75%	50%	25%	10%
Brand Rex XLPE	320%	80	140	300	***
Rockbestos XLPE	240%	200	300	400	***
Dekoron XLPO	350%	100	230	***	***
Raychem XLPE	520%	50	80	100	230
Brand Rex CSPE Jacket	330%	20	80	100	140
Dekoron CSPE Jacket	360%	20	70	200	280

*** These material never reached the indicated e/e_0 during aging.

showed no change on this material beyond a total radiation dose of about 50 kGy (the material was at essentially 0% elongation). Between 50 and 400 kGy, the indenter modulus jumped dramatically, demonstrating that the indenter is a more sensitive indicator of aging than elongation for this material at the higher total doses. For the first 50 kGy total dose, on the other hand, elongation goes down to almost 0%, while the indenter modulus only changes slightly.

Figure 23 shows the indenter modulus of the Dekoron CSPE jacket. The initial trend is upward but inconsistent. At about 400 kGy, a sharp upward trend occurs. Note that the elongation was essentially at 0% by 400 kGy, just where the indenter modulus began its most significant changes. Again, indenter modulus is a more sensitive aging indicator for this material at higher total doses, while elongation is the more sensitive indicator at lower total doses.

CONCLUSIONS

The following conclusions are based on the data presented in this paper and apply under the conditions of our tests:

a. Of the parameters tested, elongation at break tends to show the most correlation with amount of aging for all insulation and jacket materials. This is particularly true at lower radiation doses. Unfortunately, the test is destructive.

b. Tensile strength generally has only minimal correlation with aging. The major exceptions were the Brand Rex and Rockbestos jacket materials.

c. Hardness increased by 15-75% with aging for the jacket materials. In some cases, the hardness was above the effective measuring range of our instrument. This was the case for essentially all of the XLPO insulation materials.

d. Modulus, which was measured with the EPRI/Franklin cable indenter, showed good correlation with aging for the jacket materials discussed in this paper, but not for the XLPOs. The trend in indenter modulus was most evident at higher aging doses.

d. For the jacket materials, which had good aging correlations using both elongation and indenter modulus, elongation was the more sensitive aging indicator up to the total dose where the elongation approached 0%, with indenter modulus the more sensitive aging indicator beyond that point.

REFERENCES

1. P. R. BENNETT, S. D. ST. CLAIR, and T. W. GILMORE, *Superheated-Steam Test of Ethylene Propylene Rubber Cables Using a Simultaneous Aging and Accident Environment*, NUREG/CR-4536, SAND86-0450, Sandia National Laboratories, June 1986.

2. K. T. GILLEN and R. L. CLOUGH, *Time-Temperature-Dose Rate Superposition: A Methodology for Predicting Cable Degradation Under Ambient Nuclear Power Plant Aging Conditions*, SAND88-0754, Sandia National Laboratories, August 1988.

3. L. D. BUSTARD, et al., *The Effect of Thermal and Irradiation Aging Simulation Procedures on Polymer Properties*, NUREG/CR-3629, SAND83-2651, Sandia National Laboratories, April 1984.

4. L. D. BUSTARD, et al., *The Effect of Alternative Aging and Accident Simulations on Polymer Properties*, NUREG/CR-4091, SAND84-2291, Sandia National Laboratories, May 1985.

5. M. J. JACOBUS, G. L. ZIGLER, and L. D. BUSTARD, "Cable Condition Monitoring Research Activities at Sandia National Laboratories," SAND88-0293C, San Francisco, CA, February, 1988, Appears in *Proceedings: Workshop on Power Plant Cable Condition Monitoring*, EPRI EL/NP/CS-5914-SR, July 1988.

6. M. J. JACOBUS, *An Aging Assessment of Cables, Connections, and Electrical Penetration Assemblies Used in Nuclear Power Plants*, NUREG/CR-5461, SAND89-2369, Sandia National Laboratories, June 1990.

7. G. J. TOMAN and G. SLITER, "Development of a Nondestructive Mechanical Condition Evaluation Test for Cable Insulation," *Proceedings: Operability of Nuclear Power Systems in Normal and Adverse Environments*, Albuquerque, New Mexico, September 29-October 3, 1986.

8. J. B. GARDNER and T. A. SHOOK, "Status and Prospective Application of Methodologies from an EPRI Sponsored Indenter Test Project," Appears in *Proceedings: Workshop on Power Plant Cable Condition Monitoring*, EPRI EL/NP/CS-5914-SR, July 1988.

9. K. T. GILLEN, R. L. CLOUGH, and C. A. QUINTANA, "Modulus Profiling of Polymers," *Polymer Degradation and Stability*, Vol. 17, p.31, 1987.

10. M. J. JACOBUS, "Loss-of-Coolant Accident (LOCA) Testing of Aged Cables for Nuclear Plant Life Extension," Appears in *Proceedings of the U.S. Nuclear Regulatory Commission Seventeenth Water Reactor Safety Information Meeting*, NUREG/CP-0105, Vol.3, March 1990.