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Mechanical Properties of Cables Exposed to Simultaneous Thermal and Radiation Aging*

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ABSTRACT

Sandia National Laboratories is conducting long-term aging research on representative samples of nuclear power plant Class 1E cables. The objectives of this program are to determine the suitability of these cables for extended life (beyond the 40-year design basis) and to assess various cable condition monitoring (CM) techniques for predicting remaining cable life. This paper provides the results of mechanical measurements that were performed on cable specimens aged at relatively mild, simultaneous thermal and radiation exposure conditions for periods of up to nine months. After aging, some of the aged samples, as well as some unaged samples, were exposed to accident gamma radiation at ambient temperature. The mechanical measurements discussed in this paper include tensile strength, ultimate elongation, and compressive modulus. The modulus measurements were performed using an indenter developed at Franklin Research Center under EPRI sponsorship. Results of the mechanical measurements indicate that elongation measurements correlate well with aging for all materials tested; indenter modulus measurements correlate well with aging for a number of these materials; and tensile strength correlates well for only a few materials tested. When both elongation and indenter modulus correlate well, the elongation is usually a better measure of aging at lower total doses, with modulus a better measure of aging at the higher total doses.

1.0 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 the results of mechanical measurements that were performed on cable specimens aged at relatively mild, simultaneous thermal and radiation exposure conditions for periods of up to nine

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months. After aging, some of the aged samples, as well as some unaged samples, were exposed to accident gamma radiation at ambient temperature. Aging was performed using a simultaneous thermal (95-100°C) and radiation (≈0.10 kGy/hr) exposure environment, while the accident radiation was performed at ambient temperature using high dose rate irradiation (≈6 kGy/hr). 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.

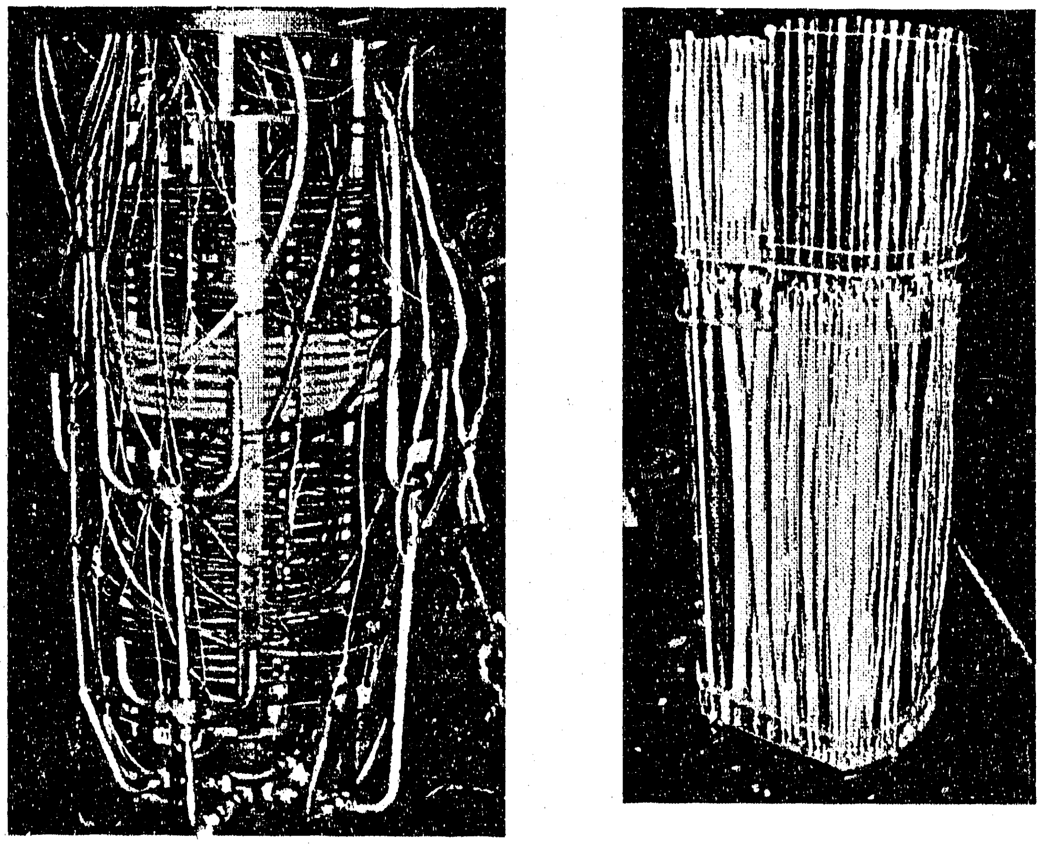
A list of the cables discussed in this paper is given in Table 1. Results from other cables included in the test program [5,6] will be briefly indicated where appropriate; complete details will be published in a future report.

2.0 EXPERIMENTAL ARRANGEMENT

For the overall test program, cables were wrapped on mandrels that were inserted into three different test chambers. A 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 detail in this paper.

Table 1: Cable Products Discussed in this Paper

Supplier	Description
Rockbestos	Firewall III, Irradiation Cross-Linked Polyethylene (XLPE), Neoprene Jacket, 12 American Wire Gauge (AWG), 3/Conductor (3/C), 600 V
Anaconda	Anaconda Y Flame-Guard FR-EP Flame-Retardant Ethylene Propylene Rubber (EPR) Insulation, Chlorinated Polyethylene (CPE) Jacket, 12 AWG, 3/C, 600 V
Rockbestos	Firewall Silicone Rubber Insulation, Fiberglass Braid Jacket, 16 AWG, 1/C, 600 V
Boston Insulated Wire (BIW)	Bostrad 7E, EPR Insulation, Chlorosulfonated Polyethylene (CSPE) Primary Jacket, CSPE Overall Jacket, 16 AWG, 2/C, Twisted Shielded Pair, 600 V



(a) (b)

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

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 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. The conductors remained in these specimens during all testing.

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 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%.

Some unaged, as well as some of the aged specimens, were exposed to an accident radiation simulation, with a desired total dose of 1100 kGy at a dose rate of 6 kGy/hr. As with the aging dose rate, the accident dose rate to the specimens was typically lower than desired. The estimated uncertainty in the accident radiation exposure data used in this paper is ±10%.

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 cobalt pool. The actual pressure in the test chamber was near ambient pressure at sea level.

3.0 MECHANICAL MEASUREMENTS

The following mechanical measurements have been performed on the material samples or on the completed cable samples:

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

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

Modulus tests using Franklin Research Center's indenter developed under EPRI funding [7,8] This test 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. A key advantage of this indenter modulus measurement is that it is a nondestructive test and therefore may be realistic for use in the field.

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 a data logger and computer for automated data acquisition and analysis.

4.0 RESULTS

In this section, plots of elongation, tensile strength, 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 (see section 2.0 for a discussion of the three test chambers).

The BIW EPR insulation material has a bonded CSPE primary jacket. All measurements given in this section are based on the insulation/primary jacket tested as a unit. The results of the composite material tests are indicated as results for the insulation. The overall (secondary) jacket was tested separately and the results of these tests are indicated as results for the jacket. Also, no measurements were performed on the fiberglass braid jacket of the Rockbestos silicone rubber product.

4.1 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

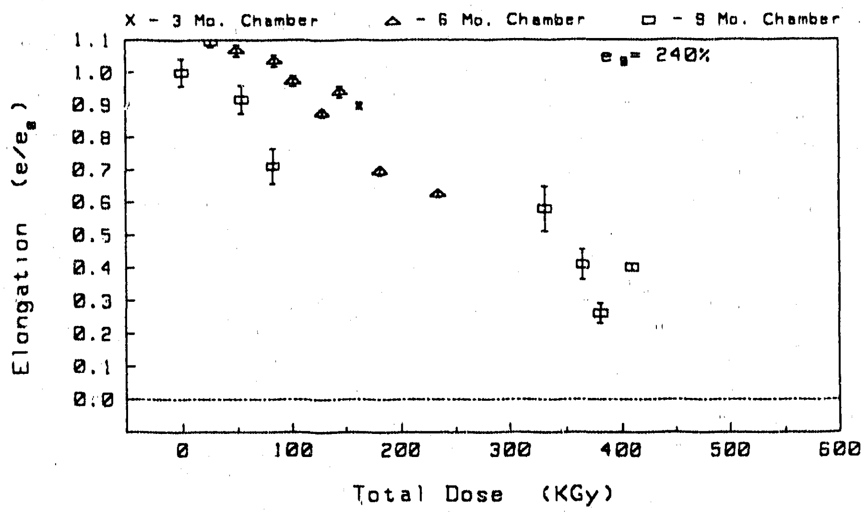


Figure 2 Elongation of Rockbestos XLPE Insulation

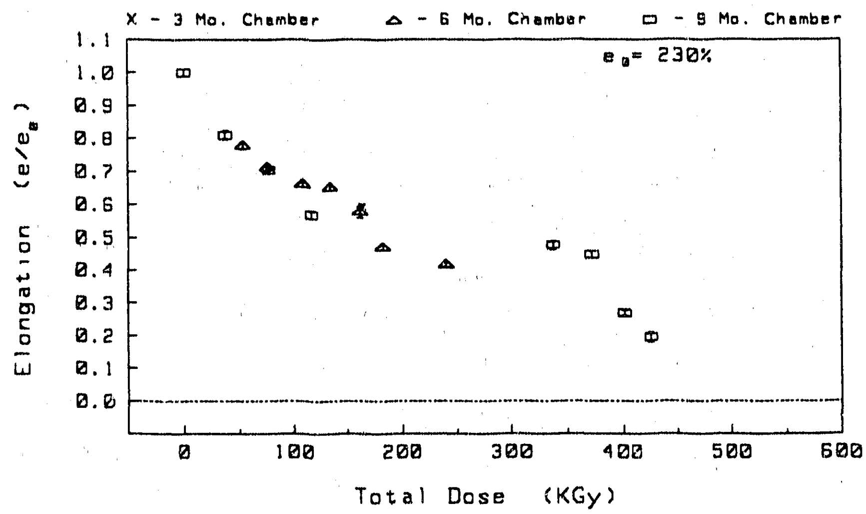


Figure 3 Elongation of Anaconda FR-EP Insulation

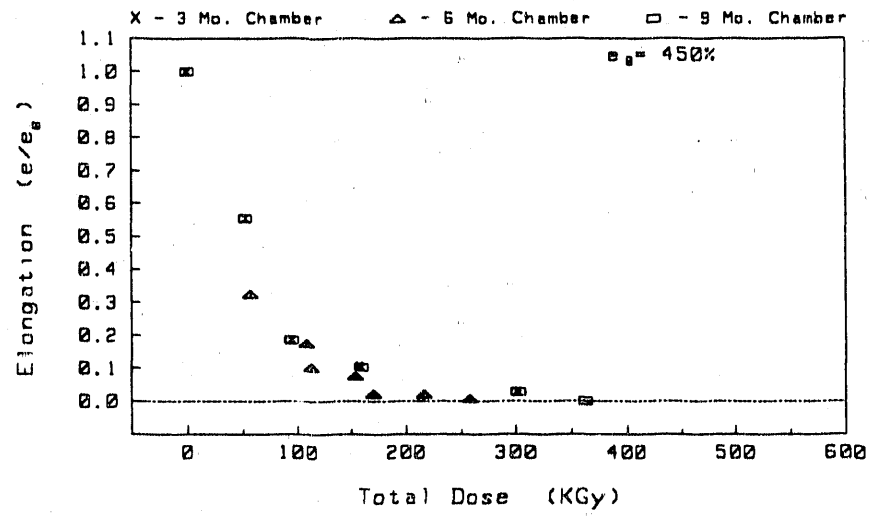


Figure 4 Elongation of Rockbestos Silicone Insulation

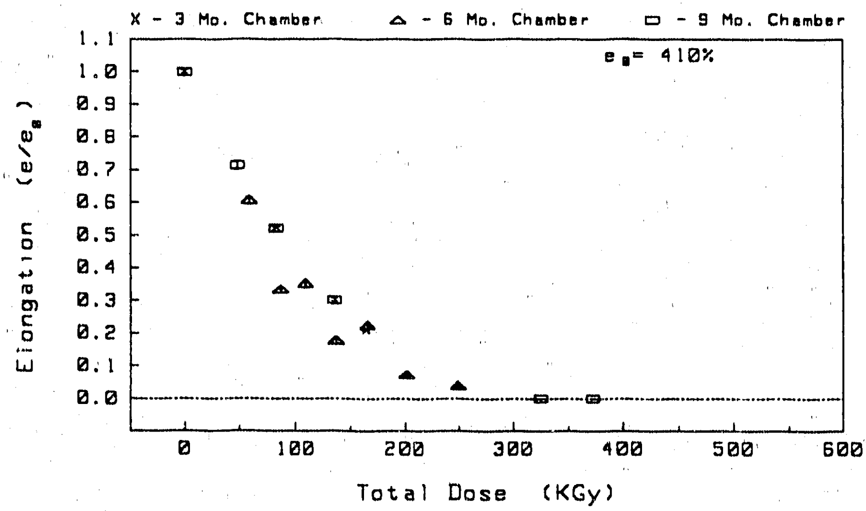


Figure 5 Elongation of BIW EPR/CSPE Insulation

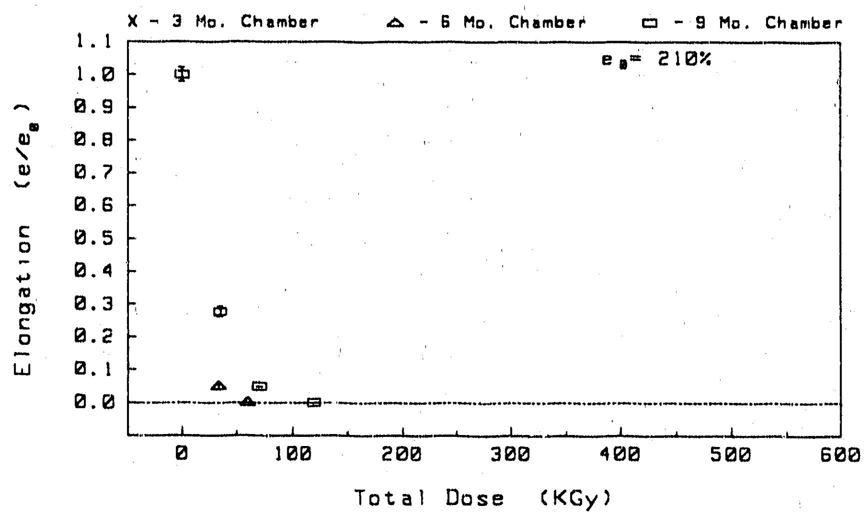


Figure 6 Elongation of Rockbestos Neoprene Jacket

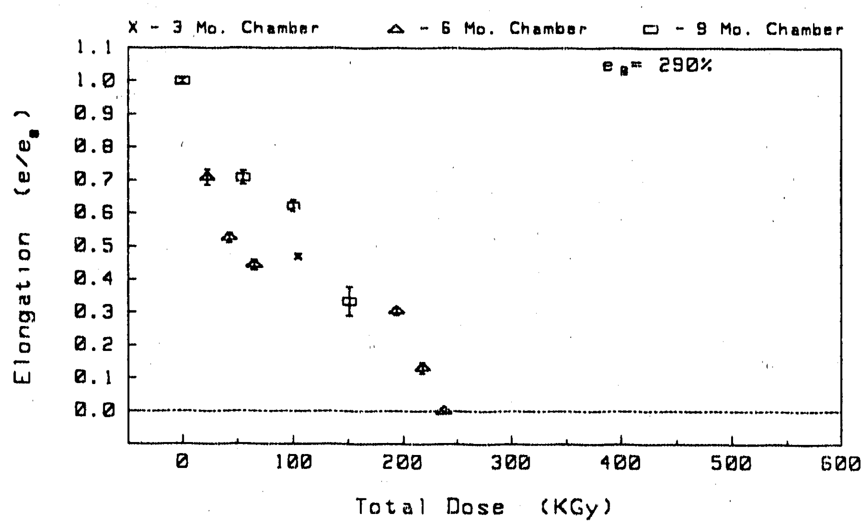


Figure 7 Elongation of Anaconda CPE Jacket

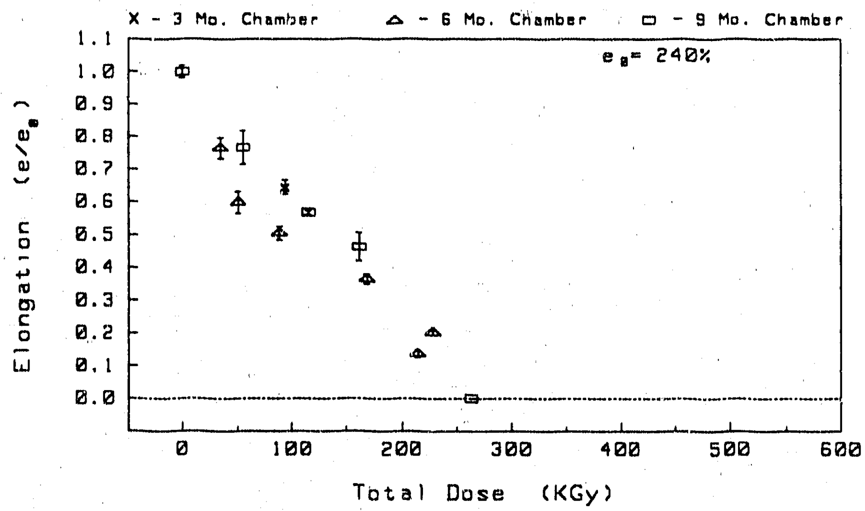


Figure 8 Elongation of BIW CSPE Jacket

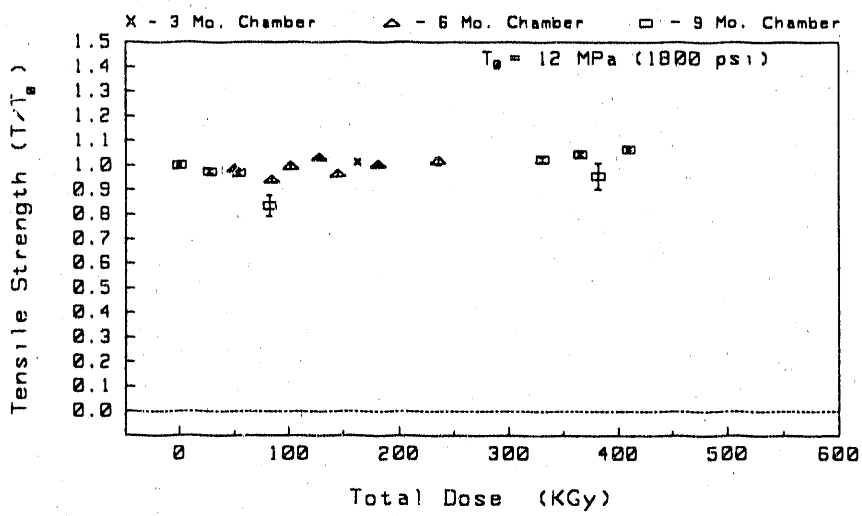


Figure 9 Tensile Strength of Rockbestos XLPE Insulation

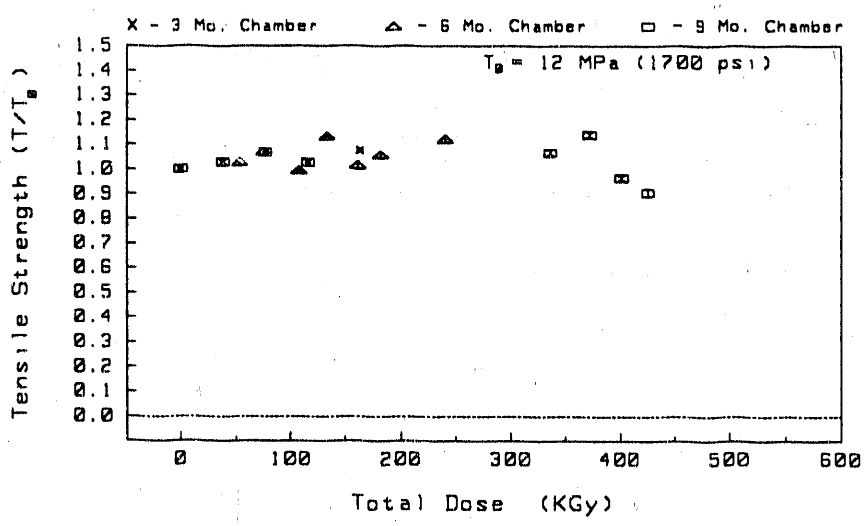


Figure 10 Tensile Strength of Anaconda FR-EP Insulation

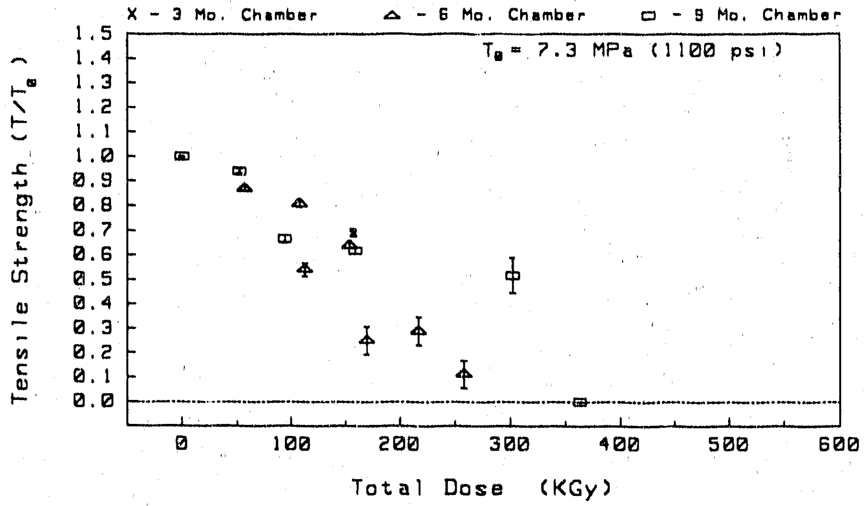


Figure 11 Tensile Strength of Rockbestos Silicone Insulation

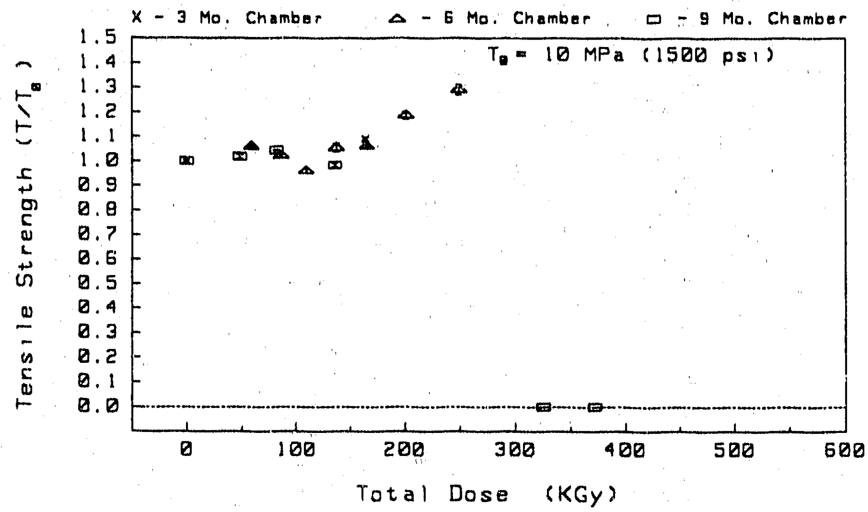


Figure 12 Tensile Strength of BIW EPR/CSPE Insulation

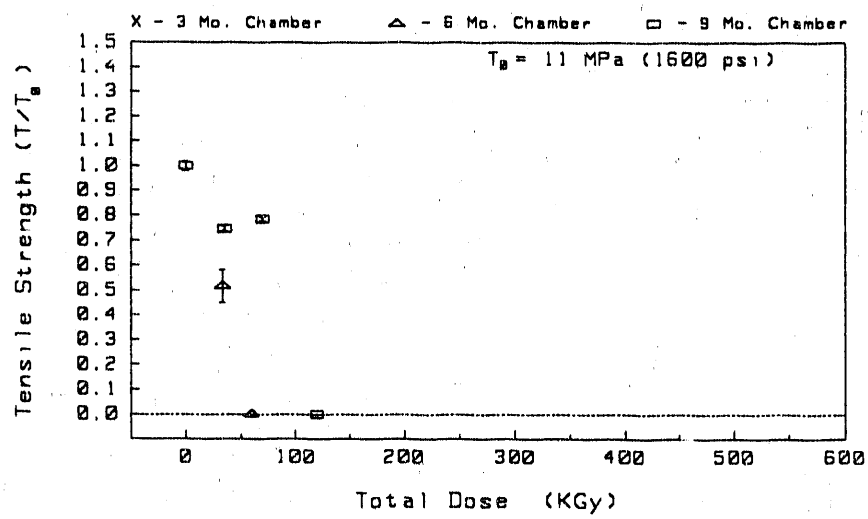


Figure 13 Tensile Strength of Rockbestos Neoprene Jacket

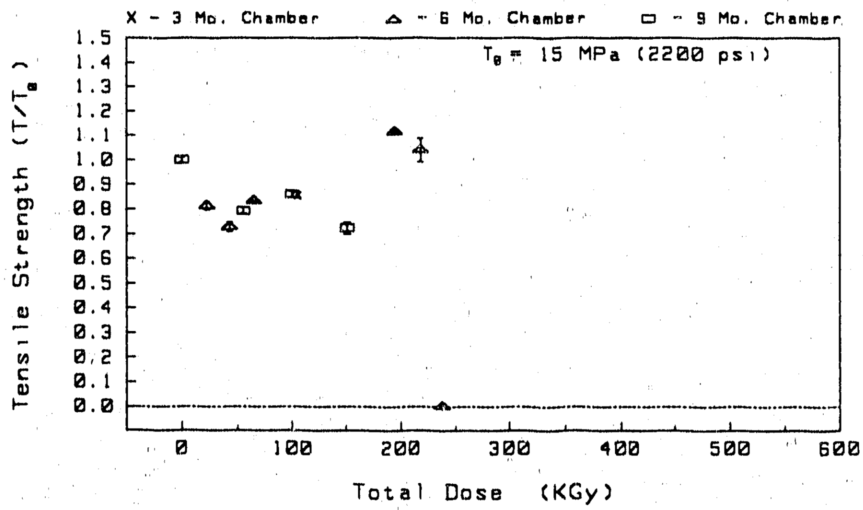


Figure 14 Tensile Strength of Anaconda CPE Jacket

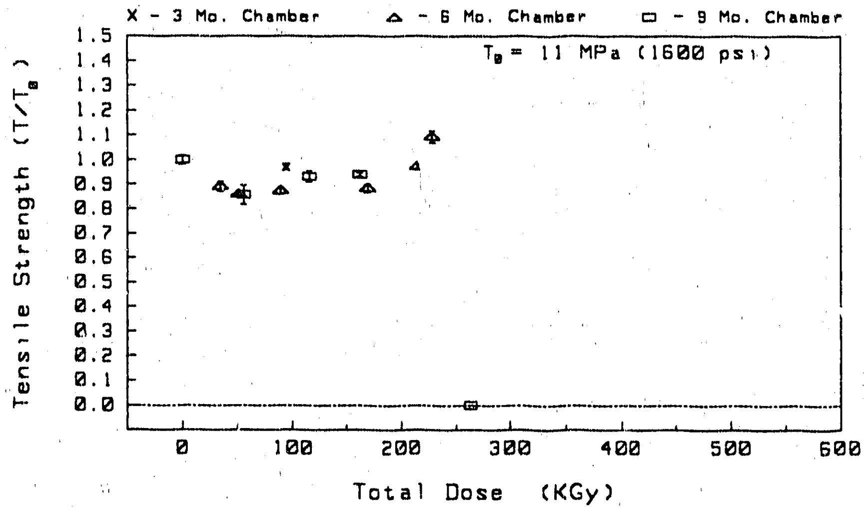


Figure 15 Tensile Strength of BIW CSPE Jacket

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 silicone rubber and the BIW EPR/CSPE insulations, no residual elongation was measurable near the end of the aging exposures (the resolution of our absolute elongation measurements is 10%). Note that unmeasurable residual elongation does not imply that a cable is no longer functional. Some results from accident testing of the cables wrapped on mandrels such as that shown in Figure 1a appear in Reference 10, and additional results will appear in future publications.

Based on the data in Figures 2-8, Table 2 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 material. The data in Table 2 and in the figures indicate that elongation is generally a fairly sensitive measure of the amount of aging up to some total dose. When using Figures 2-8 or Table 2 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 BIW EPR/CSPE insulation at $e/e_0 = 0.25$ correrponds to an absolute elongation of 100%.

Because measurement of elongation is destructive, utilities are generally unwilling to sacrifice samples of functional cables that would then have to be either 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 did for most materials. The Rockbestos silicone rubber material had the best correlation, with a drop to as low as 10% of initial tensile strength after 250 kGy total aging dose. The composite BIW EPR/CSPE insulation showed an upward trend of about 30% in tensile strength, and the Rockbestos neoprene jacket had a downward trend based on the few points where elongation data was obtained.

4.2 Modulus During Aging Using the EPRI/Franklin Cable Indenter

Figures 16-22 show the indenter modulus data for each of the insulation and jacket materials. The indenter modulus of the Rockbestos XLPE material shown in Figure 16 does not change greatly with aging and no

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Table 2 Estimated Total Doses to Retention of Various Elongations

Material	e_0	Total Dose (kGy) to e/e_0 of			
		75%	50%	25%	10%
Rockbestos XLPE	240%	200	300	400	***
Anaconda FR-EP	230%	50	200	400	***
Rockbestos Silicone	450%	30	50	70	100
BIW EPR/CSPE Insulation	410%	50	80	120	200
Rockbestos Neoprene Jacket	210%	10	20	30	30
Anaconda CPE Jacket	290%	50	100	200	200
BIW CSPE Jacket	240%	50	100	200	250

*** These material never reached $e/e_0 = 0.1$ during aging.

consistent trend is evident. Similar results were obtained for other XLPE cable materials tested. Figure 17 indicates that the range of indenter modulus change for Anaconda FR-EP insulation was similar to that of the Rockbestos XLPE material. In contrast, the EPR material showed a reasonably consistent increasing indenter modulus trend.

Figure 18 shows the indenter modulus for the Rockbestos silicone rubber insulation. A strong upward trend is evident, with the indenter modulus reaching 300% of its original value at about 400 kGy. Note that elongation measurements showed no change on this material beyond a total radiation dose of about 200 kGy (the material was at essentially 0% elongation). Between 200 and 400 kGy, the indenter modulus almost doubled, demonstrating that the indenter is a more sensitive indicator of aging than elongation for this material in this total dose range. For the first 100 kGy total dose, on the other hand, elongation goes down to 10% of initial, while the indenter modulus only changes by perhaps 30%. Thus, for this material at lower total doses, elongation measurements are a more sensitive indicator of aging, while for the higher total doses, indenter modulus measurements are the more sensitive indicator.

Figure 19 shows the indenter modulus of the BIW EPR/CSPE composite insulation. As with silicone rubber, a strong upward trend is evident, with the indenter modulus reaching 800% of its original value by 500 kGy. Note that the elongation was essentially at 0% by 300 kGy, but the indenter modulus doubled between 300 and 500 kGy. 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.

Figure 20 indicates that indenter modulus shows a very strong correlation to aging for Rockbestos neoprene jacket material, increasing by over 2000% from initial values. As for the silicone and BIW/CSPE

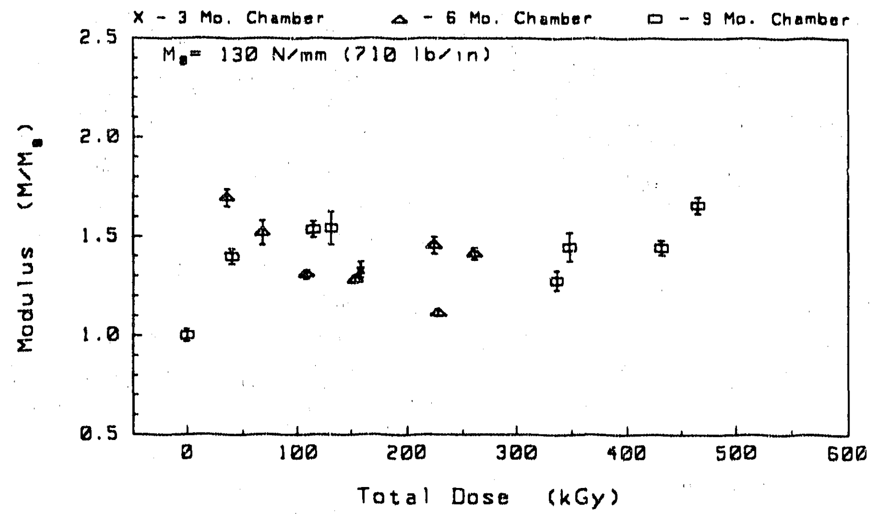

Figure 16 Indenter Modulus of Rockbestos XLPE Insulation

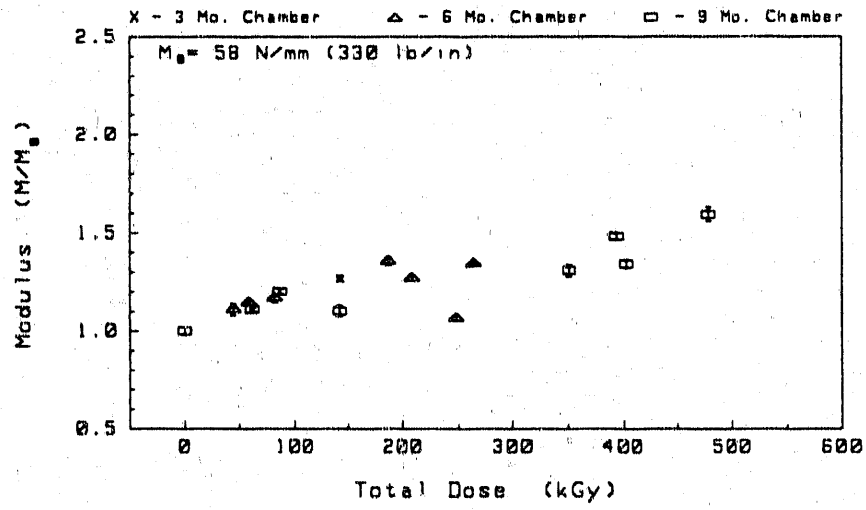

Figure 17 Indenter Modulus of Anaconda FR-EP Insulation

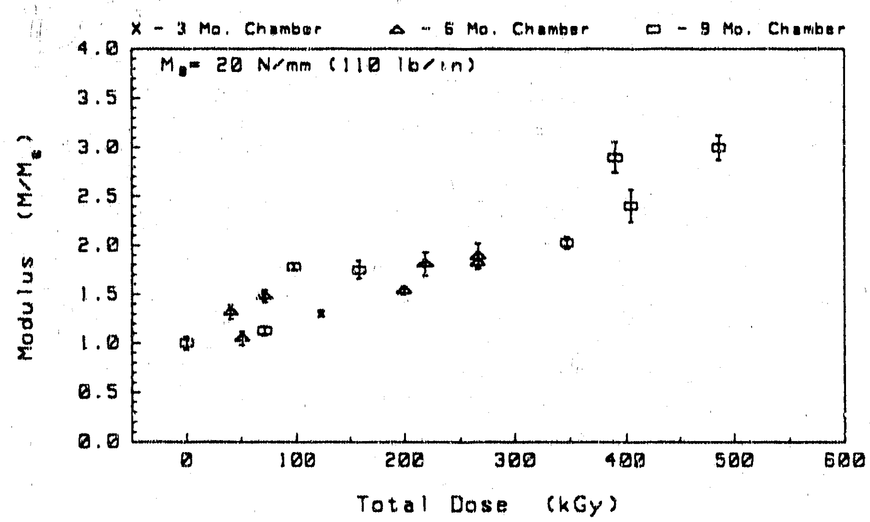

Figure 18 Indenter Modulus of Rockbestos Silicone Insulation

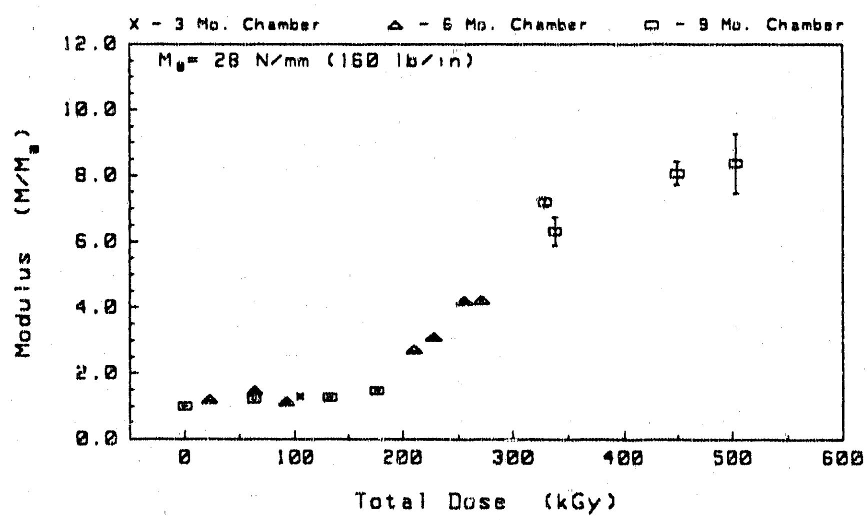

Figure 19 Indenter Modulus of BIW EPR/CSPE Insulation

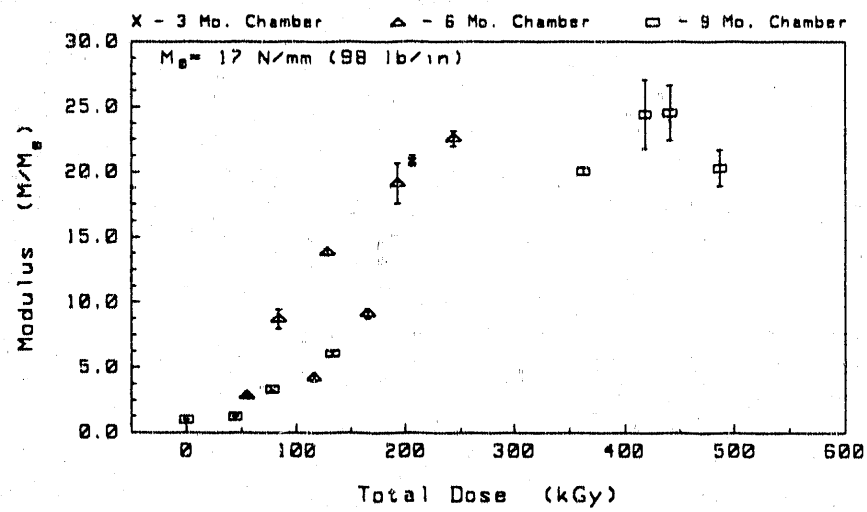

Figure 20 Indenter Modulus of Rockbestos Neoprene Jacket

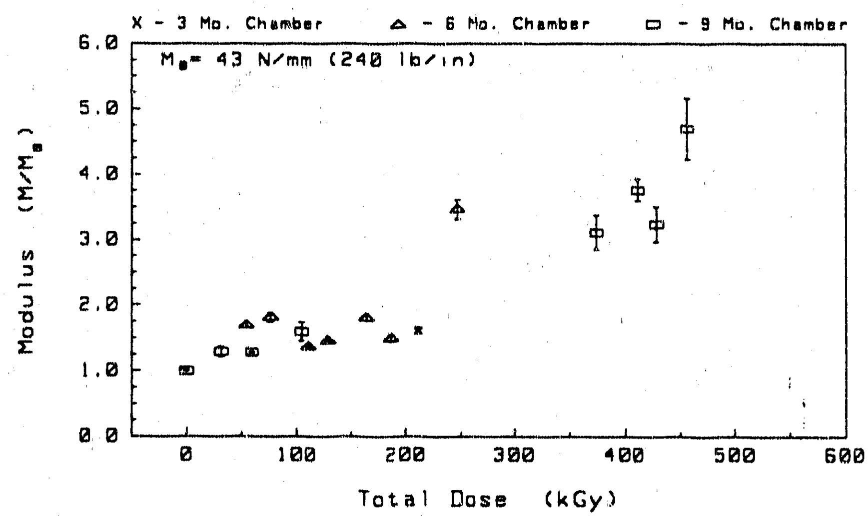

Figure 21 Indenter Modulus of Anaconda CPE Jacket

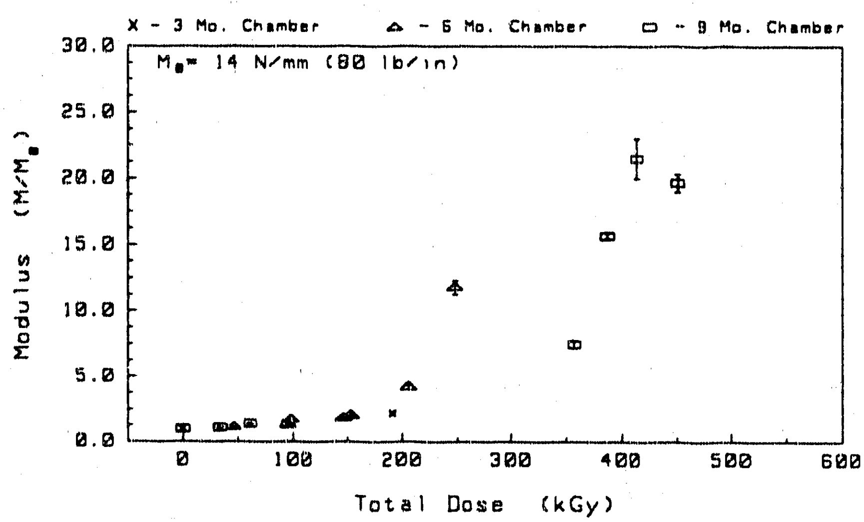

Figure 22 Indenter Modulus of BIW CSPE Jacket

materials described above, the indenter is capable of detecting aging changes well after elongation measurements were indicating 0% elongation. In this case elongation reached 0% by a total dose of less than 100 kGy. However, the indenter measured a 500% increase in indenter modulus between 100 kGy and 500 kGy.

Figure 21 shows the indenter modulus for Anaconda CPE jacket material. Again, a fairly strong upward trend in indenter modulus is evident, reaching 500% of initial by 450 kGy total dose. The trend is most significant above 200 kGy total dose, the point where elongation is near 0% of initial. Similar behavior is indicated by Figure 22, which is the indenter modulus of the BIW CSPE jacket material. For both of these materials, indenter modulus begins to show a strong trend just as the elongation is nearing 0%.

5.0 CONCLUSIONS

The following conclusions are evident from the data presented in this paper:

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 had only minimal correlation with aging for most materials. The one exception was silicone rubber, which had a fairly strong correlation with aging.

c. Modulus, which was measured with the EPRI/Franklin cable indenter, showed good correlation with aging for all materials discussed in this paper except XLPE. The trend in indenter modulus was most evident at higher aging doses.

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

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