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Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets

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Technical Report

Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets

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REPORT SUMMARY

The cables installed in nuclear plants have long lives in most applications. However, the service conditions for some applications can cause the jackets and insulations of cables to age more rapidly than normal. It is desirable to have acceptance criteria for continued service of those cables experiencing significant aging. This report establishes a basis for acceptance criteria, provides a method for estimating remaining cable life, and provides aging profiles under various thermal and radiation conditions for available cable polymer condition-monitoring techniques. This report is not meant to be the final comprehensive source of acceptance criteria, but rather is intended for trial usage so that it can be further refined for easier reference in the future.

Background
Research on cable insulation and jacket material aging and associated condition-monitoring techniques has been ongoing since the mid-1970s. During the last decade, the intensity of research has increased. Large volumes of data have been generated for a number of condition-monitoring techniques and many different materials. Much of the data has been gathered into the *Cable Polymer Aging Database*, which was developed under the cosponsorship of EPRI and the U.S. Department of Energy. While the database brings together data from multiple researchers on most of the commonly used cable insulation and jacket materials, the data are not in a form that allows a plant engineer to readily determine the degree of aging of an installed cable or its acceptability for continued service. This report develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers.

Objectives
- To develop a basis for acceptance criteria for continued use of aged cable
- To establish a means of estimating the remaining life of a cable
- To determine the applicability of specific condition-monitoring techniques to specific jacket and insulation polymers
- To provide typical aging profiles for thermal and radiation aging of common materials

Approach
Acceptance criteria for aged cable materials were developed based on minimum material properties to allow the manipulation of cable during the maintenance of associated components and to ensure the ability of safety-related in-containment cables to function through loss-of-coolant accident (LOCA) conditions. The primary effort for the remaining objectives was based on plotting and interpreting numerous aging curves from insulation and jacket aging research data. The plots showed those condition-monitoring techniques that were applicable to specific

materials and those that were not applicable. The plots also showed the nature of the aging curves and allowed comparisons between the various materials used in the cables. This effort relied on interpreting the data rather than on using the data to support preexisting assumptions about the nature of aging or the applicability of condition-monitoring techniques.

Results

The effort refuted a number of preconceptions about the aging of some of the materials and the applicability of certain monitoring techniques. Fifty-percent remaining elongation at break (E-at-B) has been supported as a conservative normal end of life for jackets and insulations. Lower limits may be used if manipulation during maintenance is carefully performed and the cables are inspected prior to return-to-service. With regard to LOCA functionality, even lower limits may be used if manipulation is required. A table showing the applicability of condition-monitoring techniques to the various types of cable polymers has been prepared, and numerous plots showing aging trends and correlations between E-at-B and other monitoring techniques have been developed. Guidance for estimating the remaining life of a cable has also been prepared.

EPRI Perspective

This report has been developed to support the assessment of low-voltage cable longevity by plant personnel without requiring interpretation of data by experts. The report provides methodology for trial use. After use and comment, further refinements will be developed and published.

Keywords

Acceptance criteria
Cable condition monitoring
Estimation of remaining cable life
Insulation aging
Low-voltage cable insulation

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1
INTRODUCTION

In the past two decades, a vast amount of aging data has been generated for polymers used for insulation and jacketing of electrical cables. Some data are linked to accident environment capability, and some data describe only the degree and rate of aging for a given set of thermal and radiation conditions related to normal service aging. The data pertain to numerous condition indicators such as elongation at break (E-at-B), indenter modulus (IM), density, and oxidation induction time (OITime). The data are highly useful to cable experts for evaluating the condition of cable insulation and remaining life. However, the data are not in a format useful to station personnel responsible for cable system aging management. This report converts the data to a format that can be used directly by station personnel. The volume of data available for conversion to acceptance criteria far exceeds the scope of this project. Accordingly, this report concentrates on developing a useful format for acceptance criteria and presenting a method for estimating remaining life for key polymers used in plant cables. Aging plots are provided for the commonly used polymers. The report also indicates which of the condition indicators are most applicable for assessment of current condition and end of life.

A basis for the end-of-life condition of materials is proposed beyond which further use should be approached with caution, especially if the insulations may be subject to manipulation or accident environments. The intent of the report is to provide a basis for a readily useful set of acceptance criteria for field use. Further development is expected to improve ease of use.

Numerous figures are provided in this document. Unless otherwise noted on the plots, the data have been taken from the *Cable Polymer Aging Database* [1]. This database, which was cosponsored by EPRI and the U.S. Department of Energy, contains cable aging data from national and international cable research. The data used to develop the figures in this report were originally supplied by the following organizations:

- Sandia National Laboratories (E-at-B, NMR T2, percent gel, uptake factor, edge modulus)
- Pacific Sierra Research Corporation (OITime, OITemp)
- Swedish Nuclear Power Inspectorate (Indenter)
- Electric Power Research Institute (Indenter)

2
ACRONYMS AND ABBREVIATIONS

AWG	American Wire Gauge
BIW	Boston Insulated Wire Company
BNL	Brookhaven National Laboratory
Chloroprene	Neoprene
CPE	Chlorinated polyethylene
CSPE	Chlorosulfonated polyethylene (Hypalon[1])
E-at-B	Elongation at break
EPR	Ethylene propylene rubber
FR-EP	Fire-retardant ethylene propylene rubber
HELB	High-energy line break
Hr	Hour
IM	Indenter module
KCM	1000 circular mils
krd	Kilorad (1000 rads)
LOCA	Loss-of-coolant accident
mA	Milliampere(s)
Mil	One-thousandth of an inch Mrd (0.0254 mm)
Min	Minutes

[1] Hypalon is a trademark of DuPont Dow Elastomers.

Mrd	Megarad (1,000,000 rads)
Neo	Neoprene
NMR	Nuclear magnetic resonance
N/mm	Newtons/millimeter (indenter modulus units)
OITemp	Oxidation induction temperature
OITime	Oxidation induction time
psi	Pounds per square inch (1 psi = 6.895 kPascals)
PVC	Polyvinyl chloride
rd	Rad, a unit of absorbed radiation (0.01 rad/Gray)
SR	Silicone rubber
Vac	Volts, alternating current
XLPE	Cross-linked polyethylene
XLPO[2]	Cross-linked polyolefin

[2] To a limited extent, XLPE and XLPO are interchangeable. Some manufacturers have called their XLPO formulation XLPE. XLPO materials tend to be a blend of XLPE and other related materials that provide the desired properties rather than just pure XLPE.

3
COMMONLY USED CABLE POLYMERS

Table 3-1 provides a list of common cable polymers and their uses. The material type column indicates if the material is plastic or rubber. This designation helps someone evaluating the condition of a cable to understand the basic nature of the material when new. The plastics used in cables tend to be hard and smooth to the touch when new. However, they are flexible and can be stretched greatly before they break. The rubber materials tend to be compressible and much less hard when new. They are also flexible and can be stretched greatly before they break. Understanding the condition of new materials is important when trying to assess the serviceability of an aged cable.

Table 3-1
Polymer Use As Cable Insulation and Jacket Material

Material	Material Type	Insulation Use	Jacket Use
Cross-linked polyethylene (XLPE)	Plastic	Common	Limited
Cross-linked polyolefin (XLPO)	Plastic	Common	Limited
Chlorinated polyethylene (CPE)	Rubber	Never	Limited
Chlorosulfonated polyethylene (Hypalon) (CSPE)	Rubber	Limited as primary insulation; more commonly used as bonded jacket on EPR insulation as a fire retardant	Common
Ethylene propylene rubber (EPR)	Rubber	Common with a bonded neoprene or CSPE covering	Never
Fire-retardant ethylene propylene rubber (FR-EP)	Rubber	Common	Never
Neoprene (Chloroprene)	Rubber	Not used as primary insulation; commonly used in 1970s as bonded jacket on EPR insulation as a fire retardant	Common during 1970s
Polyvinyl chloride (PVC)	Plastic	Rare in U.S. plants for safety circuits; more common outside of the United States	Limited
Silicone rubber (SR)	Rubber	High-temperature applications	Never

Tables 3-2 and 3-3 provide the basic response of the plastic and rubber cables to thermal and radiation exposures, which also helps to provide a basic understanding of how materials age and what to expect of them.

Table 3-2
Relative Properties of Plastic Cable Materials

Material	Long-Term Stability Under Thermal Stress	Long-Term Stability Under Radiation Stress
Cross-linked polyethylene (XLPE)	Long-lived. Mechanical properties appear stable but actually are gradually degrading. Degradation rate increases slightly at mid-life.	Radiation increases degradation rate significantly. Radiation degradation is additive to thermal degradation.
Cross-linked polyolefin (XLPO)	Long-lived. Mechanical properties appear stable but actually are gradually degrading. Degradation rate increases slightly at mid-life.	Radiation increases degradation rate significantly. Radiation degradation is additive to thermal degradation.
Chlorinated polyethylene (CPE)	Mechanical properties slowly degrade. Relatively long-lived material.	Radiation increases degradation rate significantly. Radiation degradation is additive to thermal degradation.
Polyvinyl chloride (PVC)	Material hardens under long-term thermal stress; plasticizer from material may leave surface sticky or accumulate at low spots.	Material generates hydrogen chloride (HCl) when exposed to relatively high radiation dose rates, causing material to become conductive when subsequently exposed to steam.

Table 3-3
Relative Properties of Rubber Materials Used in Cable Applications

Material	Long-Term Stability Under Thermal Stress	Relative Rate of Thermal Aging	Long-Term Stability Under Radiation Stress
Neoprene (Chloroprene)	Hardens with thermal exposure	Fastest	Hardens over time at elevated dose rates
Chlorosulfonated polyethylene (Hypalon) (CSPE)	Hardens with thermal exposure	Slower	Hardens over time at elevated dose rates
Ethylene propylene rubber (EPR)	Hardens with elevated thermal exposure	Much slower	Hardens over time at elevated dose rates
Fire-retardant ethylene propylene rubber (FR-EP)	Hardens with elevated thermal exposure	Much slower	Hardens over time at elevated dose rates
Silicone rubber (SR)	Hardens with very elevated thermal exposure	Very slow to extremely slow	Hardens over time at elevated dose rates

4
ACCEPTABLE END OF USEFUL LIFE BASED ON CONDITION AND LOCA FUNCTIONALITY

For common plastics and rubbers used in nuclear plant cable insulation, traditional wisdom has indicated that 50% retained E-at-B is a conservative end of life. E-at-B ranges from 250 to 650% for these materials when new. When the materials are new, a higher E-at-B does not reflect superiority of a material. Rather it reflects the basic properties of the material and a tradeoff by the manufacturer to achieve an overall range of desired properties including flexibility, chemical resistance, toughness, and aging rate. However, the E-at-B allowed at end of life should be nearly the same for the common insulation and jacketing materials to ensure adequate flexibility for manipulation of cables and leads during maintenance of associated equipment. In addition, for safety-related cables located in containment, retention of adequate mechanical properties is necessary to be able to withstand accident environments. A basis for end-of-life criteria is developed in Section 4.1, showing that 50% retained E-at-B is conservative and allowing options for lower values in specific cases.

4.1 E-at-B and LOCA Functionality

Relatively little data exist regarding the condition of cable polymers just prior to loss-of-coolant accident (LOCA) simulation. However, LOCA test results from the Brookhaven National Laboratory [2] included condition-monitoring assessment prior to LOCA simulation. Data are included on condition when new, post-thermal aging, and post-radiation aging. The environmental qualification tests [2] included replication of 50%, 100%, and up to 150% of the aging simulated in the cable manufacturers' environmental qualification program. The specimens were exposed to a standard LOCA simulation. Table 4-1 summarizes the results from the tests. Some manufacturers did not age their insulations to the thermal degradation limit of their materials during performance of their qualification programs. Accordingly, direct comparison between the end-of-life capabilities of insulations of similar cables (for example, EPR from manufacturer A to EPR from manufacturer B) is not possible from the research [2]. Table 4-2 provides a capsule summary of the data and some interesting insights with respect to degree of damage and LOCA survivability.

The Okonite bonded EPR/CSPE cable is the only one of the EPR-based cables that was aged to the full extent of the capability of the materials and beyond. The Samuel Moore and Anaconda EPR/CSPE cables were aged to a much more limited degree than the Okonite cable as explained in the following discussion. For the Okonite cable, 50% of the manufacturer's aging (252 hours at 150°C) resulted in a retained elongation at break of 12%. Post-radiation aging of the material resulted in 8% E-at-B. While these values indicate severe degradation in comparison to that of the new condition, they were adequate to allow the EPR/CSPE bonded insulation to function acceptably through the LOCA simulation.

The 100% of manufacturer's aging specimen (504 hours at 150°C) had 6% E-at-B following thermal aging and <5% following radiation aging. This specimen failed the LOCA test. The original qualification test by Okonite included only the EPR layer and did not include the bonded CSPE layer. The EPR insulation functioned acceptably under LOCA conditions after 504 hours at 150°C of thermal aging. However, it was found that when the CSPE layer is bonded to the EPR, the bonded CSPE layer becomes controlling in the LOCA simulation when it becomes highly aged. The 504 hours at 150°C of thermal aging causes too much damage to the CSPE layer and results in the rupture of the CSPE layer during LOCA simulation that propagates through the EPR.

The other EPR/CSPE specimens were not aged by the manufacturers to the limits of their capability. Anaconda aged their unbonded EPR/CSPE configuration to 169 hours at 150°C, which may be roughly compared to the 50% aging point for the Okonite. The Samuel Moore bonded EPR/CSPE specimens were aged to no more than 169 hours at 121°C in the manufacturer's qualification test. The program [2] aged the material to 150% of manufacturer's aging as well, but even that is a very limited degree of aging for the material. No useful end of life based on capability of the material is available from the research [2] for the Anaconda and Samuel Moore EPR cables.

The results for the Rockbestos specimens [2] are very interesting in that the E-at-B at the end of aging, whether 50%, 100%, or 100+% of the manufacturer's thermal aging, is consistently less than 5% and yet the material consistently passes the LOCA tests. In this case, 100% aging is in excess of 1300 hours at 150°C.

The test data [2] indicate that degradation of XLPE and composite EPR/CSPE can be quite severe and yet the materials will function through a LOCA simulation. For the EPR/CSPE bonded (the worst case configuration), the E-at-B can be as low as 12% post-thermal aging and 8% post-radiation aging and still pass the LOCA test. However, failure is likely below those points. For the XLPE, passing the LOCA simulation is possible with essentially a total loss of elongation at break (<5%). These results lead to the conclusion that acceptable function through a LOCA test for XLPE and EPR insulation cable will occur if 15% or more elongation at break remains. However, further conservatism is necessary if the drop in elongation at break is precipitous near the end of life. The aging plots in Section 5 of this report for XLPE indicate that the change in E-at-B for XLPE is gradual rather than precipitous. The aging plots for EPR (see Section 7.5 and Figure 7-55 for further detail) indicate that the rate of aging may increase slightly as EPR nears the end of life. However, for lower temperature aging, the increased rate of aging does not seem to occur near the end of life (that is, the increased rate of change in aging occurs only in high-temperature, accelerated-rate aging).

The test results [2] indicate that the current belief in the industry (that 50% remaining E-at-B constitutes an acceptable end of life) is conservative with respect to LOCA functionality. Satisfactory function should occur as long as E-at-B remains above 15%.

Table 4-1
Condition Pre-LOCA and LOCA Performance Results [2]

Cable	Aging	Insulation Condition	LOCA Result	Comment
Unbonded EPR/CSPE				
Anaconda (BNL-408) I/C #I2 AWG 30 mil EPR insulation 15 mil CSPE unbonded individual jacket 1,000 V	Thermal aging: 150°C, 169 hrs Radiation: 53.6 Mrd at 0.34 Mrd/hr Accident: 154 Mrd at 0.6 Mrd/hr (Total 207.6 Mrd)	E-at-B new: 356% Post-thermal: 21% Post-radiation aging: 13%	Passed 2400 Vac submerged withstand: 1.0–1.4 mA leakage	
Anaconda (BNL-508) 3/C #12 AWG 30 mil EPR insulation 15 mil CSPE unbonded individual jacket 45 mil CSPE overall jacket 1,000 V	Thermal aging: 150°C, 84 hrs Radiation: 25.8 Mrd at 0.62 Mrd/hr Accident: 154 Mrd at 0.6 Mrd/hr (Total 179.8 Mrd)	E-at-B new: 476% Post-thermal: 287% Post-radiation aging: 166%	Passed 2400 Vac submerged withstand: 0.7–1 mA leakage	50% of manufacturer's EQ thermal and radiation aging
Bonded EPR/CSPE				
Okonite (BNL-504) I/C #12 AWG 30 mil Okonite (EPR) insulation 15 mil Okolon (CSPE) bonded individual jacket 600 V	Thermal aging: 150°C, 252 hrs Radiation: 25.8 Mrd at 0.62 Mrd/hr Accident: 154 Mrd at 0.6 Mrd/hr (Total 179.8 Mrd)	E-at-B new : 471%, Post-thermal: 12% Post-radiation aging: 8%	Passed 2400 Vac submerged withstand: 1.0 mA leakage	50% of manufacturer's EQ thermal and radiation aging
Okonite I/C #12 AWG 30 mil Okonite (EPR) insulation 15 mil Okolon (CSPE) bonded individual jacket 600 V	Thermal aging: 150°C, 504 hrs Radiation: 51.5 Mrd at 0.59 Mrd/hr Accident: 154 Mrd at 0.6 Mrd/hr (Total 205 Mrd)	E-at-B new : 471%, Post-thermal: 6% Post-radiation aging: <5%	Failed in LOCA	100% of manufacturer's EQ thermal and radiation aging; small difference in remaining E-at-B critical to passing LOCA

Table 4-1 (continued)
Condition Pre-LOCA and LOCA Performance Results [2]

Cable	Aging	Insulation Condition	LOCA Result	Comment
Okonite (BNL-605) I/C #12 AWG 30 mil Okonite (EPR) insulation 15 mil Okolon (CSPE) bonded individual jacket 600 V	Thermal aging: 150°C, 756 hrs Radiation: 77.3 Mrd at 0.59 Mrd/hr Accident: 156.6 Mrd at 0.58–0.69 Mrd/hr (Total 233.9 Mrd)	E-at-B new: 471% Post-thermal: <5% Post-radiation aging: <5%	Failed in LOCA	150% of manufacturer's EQ thermal and radiation aging
Samuel Moore (BNL-513) 2/C #16 AWG with shield and ground 20 mil Dekoron (EPDM) insulation 10 mil Dekorad (CSPE) bonded individual jacket 45 mil Dekorad (CSPE) overall jacket 600 V	Thermal aging: 150°C, 169 hrs Radiation: 51.6 Mrd at 0.75 Mrd/hr Accident: 54 Mrd at 0.6 Mrd/hr (Total 205.6 Mrd)	E-at-B new: 418% Post-thermal: 186% Post-radiation aging: 94%	Passed 2400 Vac submerged withstand: 1.0–1.4 mA leakage	100% of manufacturer's EQ thermal and radiation aging; thermal aging limited with respect to capability of materials
Samuel Moore (BNL-404) 2/C #16 AWG with shield and ground 20 mil Dekoron (EPDM) insulation 10 mil Dekorad (CSPE) bonded individual jacket 45 mil Dekorad (CSPE) overall jacket 600 V	Thermal aging: 121°C, 85 hrs Radiation: 26 Mrd at 0.65 Mrd/hr Accident: 154 Mrd at 0.6 Mrd/hr (Total 180 Mrd)	E-at-B new: 467% Post-thermal: 397% Post-radiation aging: 261%	Passed 2400 Vac submerged withstand: 1.0 mA leakage	50% of manufacturer's EQ thermal and radiation aging; thermal aging limited with respect to capability of materials
Samuel Moore (BNL-608) 2/C #16 AWG with shield and ground 20 mil Dekoron (EPDM) insulation 10 mil Dekorad (CSPE) bonded individual jacket 45 mil Dekorad (CSPE) overall jacket 600 V	Thermal aging: 121°C, 252 hrs Radiation: 77.3 Mrd at 0.59 Mrd/hr Accident: 156.6 Mrd at 0.58–0.69 Mrd/hr (Total 233.9 Mrd)	E-at-B new : 418% Post-thermal: 168% Post-radiation aging: 68% IM New: 14 N/mm Post-thermal: 27 N/mm Post-radiation aging: 37 N/mm	Passed 2400 Vac submerged withstand: 2.2–4.0 mA leakage	150% of manufacturer's EQ aging; aging still limited by comparison to material capabilities

Table 4-1 (continued)
Condition Pre-LOCA and LOCA Performance Results [2]

Cable	Aging	Insulation Condition	LOCA Result	Comment
XLPE				
Rockbestos (BNL-314) 2/C #14 AWG Firewall III 30 mil XLPE insulation 45 mil Neoprene overall jacket 600 V	Thermal aging: 150°C, 1301 hrs Radiation: 51.48 Mrd at 0.45 Mrd/hr Accident: 153 Mrd at 0.64 Mrd/hr (Total 205 Mrd)	E-at-B new: 620% Post-thermal: <5% Post-radiation aging: <5% IM new: 100 N/mm IM post-thermal: 150 N/mm	Passed 2400 Vac submerged withstand: 1.1–2 mA leakage	Neoprene fully deteriorated by aging regimen
Rockbestos (BNL-315)* 2/C #14 AWG Firewall III 30 mil XLPE insulation 45 mil Neoprene overall jacket 600 V	Thermal aging: 150°C, 1301 hrs Radiation: 51.48 Mrd at 0.45 Mrd/hr Accident: 153 Mrd at 0.64 Mrd/hr (Total 205 Mrd)	E-at-B new: 620% Post-thermal: <5% Post-radiation aging: <5%	Passed 2400 Vac submerged withstand: 1.3–1.4 mA leakage	Neoprene fully deteriorated by aging regimen
Rockbestos (BNL-621) 2/C #14 AWG Firewall III 30 mil XLPE insulation 45 mil Neoprene overall jacket 600 V	Thermal aging: 150°C, 1363 hrs Radiation: 77 Mrd at 0.39 Mrd/hr Accident: 156.6 Mrd at 0.58–0.69 Mrd/hr (Total 233.6 Mrd)	E-at-B new: 574% Post-thermal: <5% Post-radiation aging: <5%	Passed 2400 Vac submerged withstand: 1.8–2 mA leakage	105% of manufacturer's EQ thermal aging; 150% radiation aging (Neoprene fully deteriorated by aging regimen)
Rockbestos (BNL-623) 2/C #14 AWG Firewall III 30 mil XLPE insulation 45 mil Neoprene overall jacket 600 V	Thermal aging: 150°C, 1363 hrs Radiation: 77 Mrd at 0.39 Mrd/hr Accident: 156.6 Mrd at 0.58–0.69 Mrd/hr (Total 233.6 Mrd)	E-at-B new: 574% Post-thermal: <5% Post-radiation aging: <5%	Passed 2400 Vac submerged withstand: 3–3.6 mA leakage	105% of manufacturer's EQ thermal aging; 150% radiation aging (Neoprene fully deteriorated by aging regimen)

* Note: BNL-315 refers to the test specimen number from the LOCA test results [2].

Table 4-2
Summary of Condition and LOCA Results

Insulation	Aging Level	Insulation E-at-B Post-Thermal	Insulation E-at-B Post-Radiation Aging	LOCA Result
Anaconda EPR/CSPE unbonded	100% manufacturer's aging (169 hours at 150°C)	21%	13%	Passed
Anaconda EPR/CSPE unbonded	50% manufacturer's aging (84 hours at 150°C)	287%	166%	Passed
Okonite EPR/CSPE bonded	100% manufacturer's aging (504 hours at 150°C)	6%	<5%	Failed
Okonite EPR/CSPE bonded	50% manufacturer's aging (252 hours at 150°C)	12%	8%	Passed
Samuel Moore EPR/CSPE bonded	100% manufacturer's aging (169 hours at 121°C)	186%	94%	Passed
Samuel Moore EPR/CSPE bonded	50% manufacturer's aging (85 hours at 121°C)	397%	261%	Passed
Samuel Moore EPR/CSPE bonded	150% manufacturer's aging (252 hours at 121°C)	168%	68%	Passed
Rockbestos XLPE	100% manufacturer's aging (1301 hours at 150°C)	<5%	<5%	Passed

4.2 E-at-B and HELB Withstand

Two reports previously published by EPRI [3, 4] assess the fragility point for BIW and Okonite bonded EPR/CSPE insulation. EPRI Report 1001002 [3] identified that both the BIW and Okonite insulations had a thermal aging limit beyond which splitting failures would occur when subjected to a LOCA exposure with a peak temperature of 177°C (350°F) and a peak pressure of 73 psig. However, when exposed to a high-energy line bank (HELB) condition with a peak temperature of 144°C (291°F) with a short duration peak pressure of 2 psig, the insulation did not split even at aging levels twice those where failures occurred in the LOCA simulation. Prior to the HELB exposure, the insulation was physically intact but was rigid and could not be extended. The E-at-B for these highly aged specimens was zero. These results indicate that HELB conditions with a short, low-pressure (2 psig) profile will not cause splitting and the failure of highly aged specimens that would fail under LOCA conditions. While it is not recommended that insulation be allowed to deteriorate to the point of no remaining E-at-B, the insulations are likely to function under low-pressure HELB conditions as long as they have not lost physical integrity (that is, aged to the point of cracking or crumbling).

4.3 E-at-B and Manipulation

Manipulation of cables and their leads during maintenance of connected equipment can cause severe flexure of the leads. The jackets and insulations must retain adequate residual E-at-B to preclude cracking at the outer edge of the bend. The percent elongation (strain) at the outer edge of the bend is given by Equation 4-1 [5].

$$\%\ \text{E-at-B outer fiber} = 1/(1+2R/d) \qquad \textbf{Eq. 4-1}$$

Where:

R = bend radius of the insulated conductor

d = diameter of the insulated conductor

If the bend radius equals the diameter of the insulated conductor, the necessary E-at-B to preclude cracking must be at least 33%. Such a tight bend would be unusual in a maintenance activity. At a bend radius of four times the diameter of the insulated conductor, the necessary E-at-B drops to 11%. These values assume smooth bends with no point loads. However, manipulations of insulated conductors rarely involve smooth bends unless bending tools are employed. Most bends during equipment maintenance are performed by hand to move leads out of the way to allow removal of or access to components. Such bends include point loads between the maintainer’s hands or other constraints and the insulated conductors. These point loads increase the local radius of bending such that a greater E-at-B at the outer radius of curvature occurs than would be expected from a smooth curve, mandrel bend.

During the development of the cable training aids for visual/tactile inspection [6], mandrel bend testing was performed to determine when flexing (as in manipulation) would cause failure. Bending even highly aged insulated singles around the smooth bends did not cause cracking. However, when the same specimens were bent by hand, they immediately cracked. The reality of manually bending a cable lead is that it is nothing like a mandrel bend. Rather, there are point loads in which the bend is concentrated in a small segment of the cable and the residual E-at-B is readily exceeded, leading to cracking. In a mandrel bend, the elongation is distributed along the entire sweep of the contact with the mandrel and successful bending occurs even with materials having quite low E-at-B.

Accordingly, even though maintenance personnel may not seem to be bending leads tightly, the point loading of bends requires a higher E-at-B capability than if the bends employ a mandrel. Retaining at least 50% E-at-B is desirable to preclude cracking during maintenance. Training of maintenance personnel is recommended to increase awareness of the manipulation limits of aged insulations. In addition, if significant aging has occurred, visual inspection of the surfaces of the leads for cracks is also desirable.

4.4 Conclusions Related to End-of-Life Criteria and LOCA Functionality

Retaining adequate mechanical properties as indicated by E-at-B is critical to precluding cracking of insulations that could lead to service failures. Different requirements exist depending on the possible conditions of exposure of the cables. For leads and cables that must be manipulated during maintenance, retaining 50% absolute E-at-B is desirable. For leads and cables that must function through LOCA conditions, retention of at least 15% E-at-B is desirable through end of service. For cables that could be exposed to HELBs with short, low-pressure transients, retention of 15% E-at-B is conservative. Cables will survive HELBs even if they have lower E-at-B capability; however, allowing degradation to such levels is not recommended.

While these 50% and 15% E-at-B limits are allowable, understanding when such conditions could be reached and monitoring the approach of the degradation to these points is recommended. When the condition of an in-service cable indicates that elongation is approaching 50% E-at-B, an action plan should be put in place based on the period of service to the point of measurement. The action plan could include periodic monitoring or scheduled replacement.

These acceptance criteria apply to commonly used nuclear plant cable materials including EPR, CPE, CSPE, neoprene, and XLPE. They do not apply to materials such as Kapton[1], which is a hard plastic that has limited E-at-B when new and has totally different aging characteristics from the materials evaluated in this report.

[1] Kapton is a trademark of E. I. du Pont de Nemours and Company.

This discussion has been based on E-at-B because retained E-at-B directly relates to resistance to cracking during manipulation and accident environment exposure. In this report, all other properties that may be monitored to establish the degree of aging will be related to E-at-B, not because they are necessarily less useful for indicating the degree of aging, but rather to provide a link to the more readily understandable E-at-B indicator.

5 REMAINING LIFE AND RATE OF AGING

5.1 Remaining Life Based on Elongation at Break

The mechanical condition of a cable insulation or jacket, as represented by E-at-B at any particular time, is only a part of the information necessary to estimate remaining life. Of course, if the observed E-at-B is extremely low, the material is at the end of its life. However, for a material with a 75–100% E-at-B, the period of service up to the point of the observation is needed to determine the rate at which life is being consumed. Identifying 80% E-at-B at 40 years is quite different from identifying it at eight years. In the first case, a long life will have occurred and a reasonable period of continued service is possible before replacement is necessary. In the second case, the level of stress affecting the cable materials is exceedingly high and replacement may be necessary almost immediately.

To fully understand the rate of aging, the nature of the degradation profile must be understood. Some materials gradually degrade. Others retain their properties for long periods and then degrade quite quickly, so that if any significant change in property is identified, the time remaining to total degradation may be quite short. Figure 5-1 shows a comparison of material behavior under 110°C thermal aging. XLPE has an exceedingly long life at this temperature. The plot shows that XLPE has a limited change in E-at-B for the 10,000 hours of exposure and then gradually loses E-at-B, reaching 50% at approximately 50,000 hours.

By comparison to XLPE, neoprene, CSPE, and EPR seem to have very short lives with sudden drops in E-at-B. Figure 5-2 focuses on the first 6000 hours of aging. In this figure, XLPE seems not to degrade at all. Neoprene ages gradually, but fastest. CSPE ages more slowly than neoprene. The EPR ages more slowly, but after a gradual decay in E-at-B, a sudden drop in E-at-B occurs after 5700 hours and the material drops from 150% to essentially zero extremely rapidly. For this particular EPR, care must be taken when considering current condition and estimating the remaining life of the insulation. Other EPRs exhibit less pronounced rate of aging near the end of life but do have a more rapid rate of degradation in later life.

A further complication in understanding behavior occurs when a cable is subjected to a significant dose of radiation over the course of its life. Below a few megarads over the course of a cable's life, the effect of irradiation is limited. However, 10 or more megarads of irradiation will have an appreciable effect on the degradation of the mechanical properties of a cable. Generally, radiation aging will be additive to the thermal aging so that the combined aging rate is worse than thermal aging alone. However, for some of the XLPE/XLPO materials, radiation aging may be partially counteracted by thermal aging. The degree to which this is true is not fully clear because research has not been performed to fully evaluate the effect.

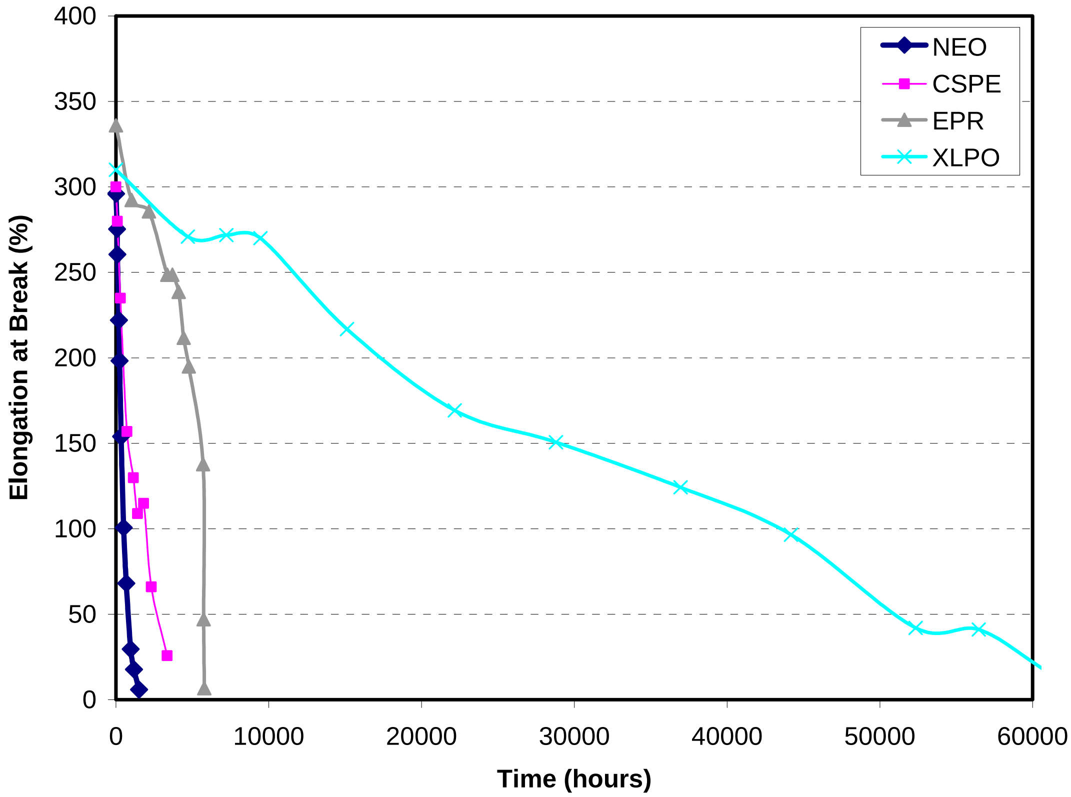


Figure 5-1
Nature of Aging of Cable Materials, 110°C Aging

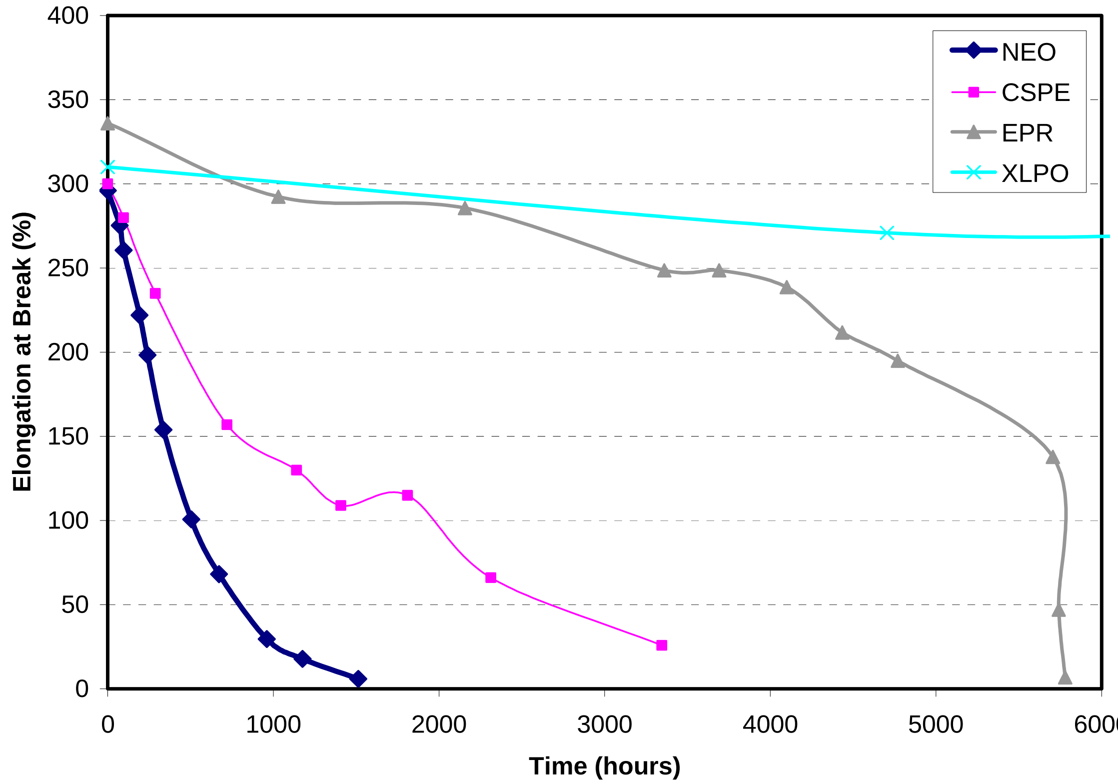


Figure 5-2
Nature of Aging of Cable Materials, 110°C Aging: Neoprene, CSPE, and EPR Subset

Fortunately, for the most part, nuclear plant cables are not subject to large radiation doses and the more significant long-term aging concern is thermal damage. Figures 5-3 through 5-6 provide separate life curves for neoprene, CSPE, EPR, and XLPE material. They show a means for determining an approximate remaining life that may be used in conjunction with the period of service at the time of measurement to estimate the period of remaining life. The approximate period of life remaining is calculated using Equation 5-1.

$$P_R = P_S \times \left(\left[\frac{1}{1 - \frac{\%RL}{100}} \right] - 1 \right) \qquad \textbf{Eq. 5-1}$$

Where:

P_R = period of remaining life

P_S = period of service to point of measurement

$\%RL$ = % remaining life at time of measurement

Figure 5-3 shows the life curve for neoprene. For the "practical" end of life, 50% E-at-B was chosen. The material can still be used after that point but with caution because it is approaching the point where the cable cannot be bent without cracking. Based on the practical end of life at 800 hours, 75%, 50%, and 25% remaining life points are shown. Neoprene is used as a jacket rather than as an insulation. Accordingly, if the neoprene is used as the end-of-life control for the overall cable, the end of life for the cable will be very conservative because at 800 hours at 110°C, 75% of an EPR material's capability and nearly 100% of an XLPE material's capability remains.

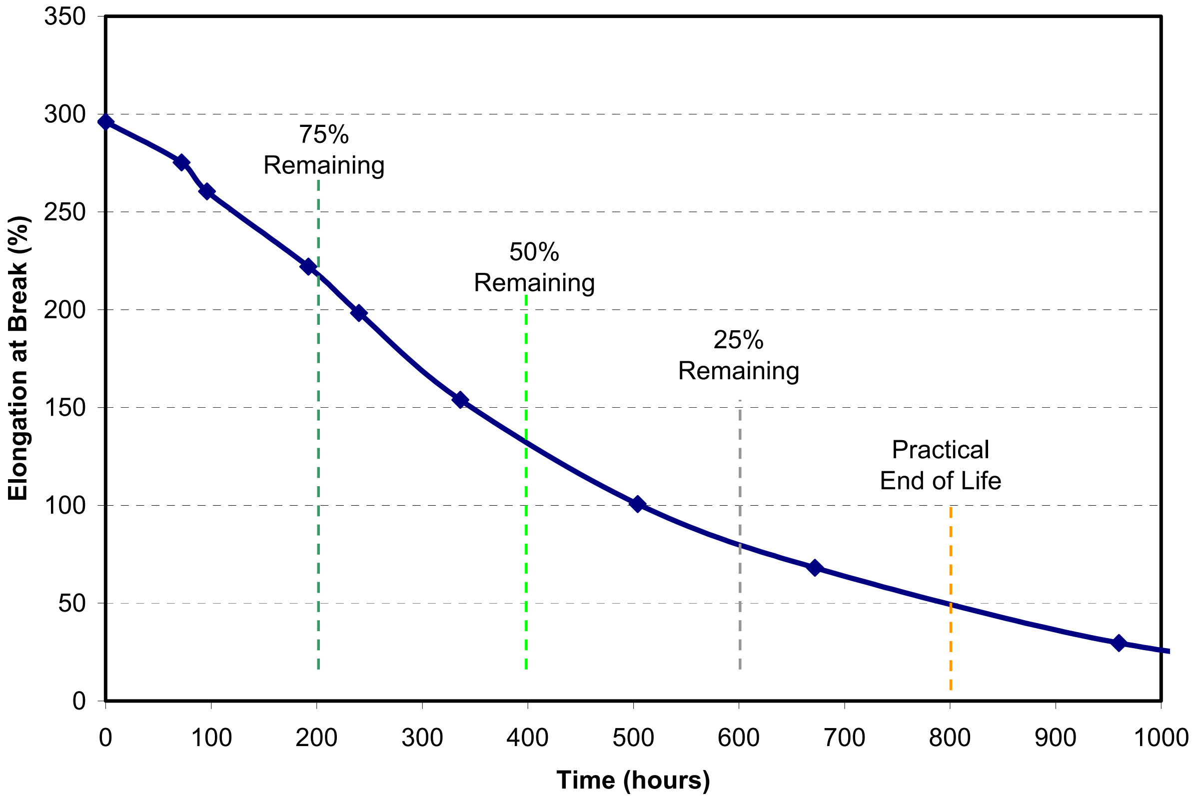


Figure 5-3
Remaining Life Curve for Neoprene, 110°C Aging

Figure 5-4 shows the remaining life curve for a CSPE. The practical end of life occurs at 2700 hours. The rate of change is gradual (as it was in the neoprene case). Between 50% and 25% remaining life, the fluctuation in the curve causes an uncertainty with respect to whether 110% E-at-B indicates 50% remaining life or 30% remaining life. For conservatism, the lower remaining life should be chosen.

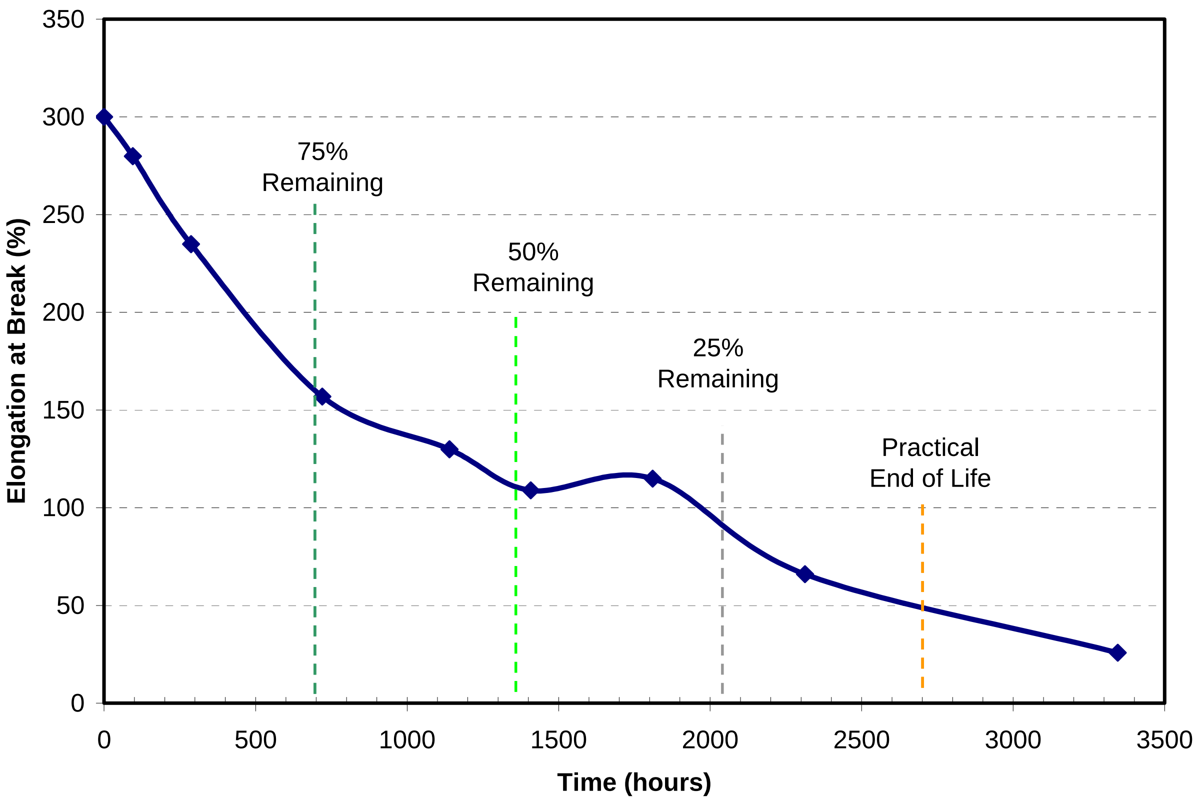


Figure 5-4
Remaining Life Curve for CSPE, 110°C Aging

Figure 5-5 shows the remaining life curve for an EPR. This material has a precipitous change near the end of its life. Accordingly, the practical end of life has been chosen at a point where the E-at-B is quite high (170%). A sudden loss of life occurs below 150% E-at-B. At 250% E-at-B, 25% remaining life occurs and at 275% E-at-B, 50% remaining life occurs. Resolution is not good for determining a useful 75% remaining life. For this EPR, the proposed remaining life system is somewhat less than satisfactory. However, EPR is used only for insulation and will always have a neoprene or CSPE jacket that may be used as an early indicator of degradation. For control and instrumentation cables, if the neoprene or CSPE jacket has a significant remaining life, there is no concern for the EPR insulation. For lightly loaded power cables, the same holds true. However, if an EPR power cable is heavily loaded, ohmic heating may increase the rate of aging of the EPR and the condition of the neoprene or CSPE jacket may not be fully indicative of the degree of aging.

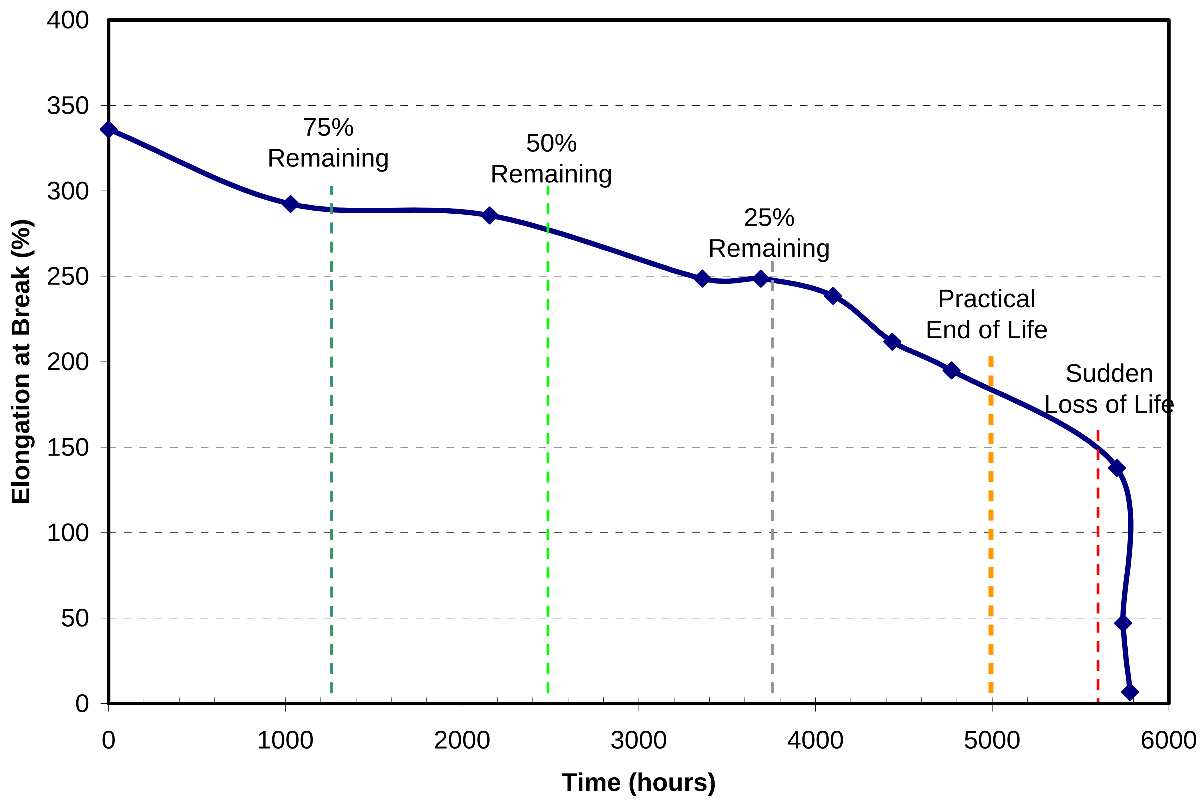


Figure 5-5
Remaining Life Curve for an EPR, 110°C Aging

Figure 5-6 shows the remaining life plot for an XLPE. The plot shows a gradual decline in E-at-B through the bulk of the life of this material. E-at-B is a useful indicator for XLPE material; however, aging occurs over a very long period. A neoprene or CSPE jacket will be totally degraded before any significant aging occurs to this material.

Figures 5-3 through 5-6 have been presented to show a concept for using aging curves to estimate remaining life. Relatively low-temperature (110°C) aging data was chosen for these examples to provide results that are most closely related to normal plant temperatures. Some materials have different aging rates at higher temperatures than at lower temperatures. Where data are available, this report has evaluated such effects. If only high-rate aging data (140–60°C) are available, caution should be used when estimating remaining life.

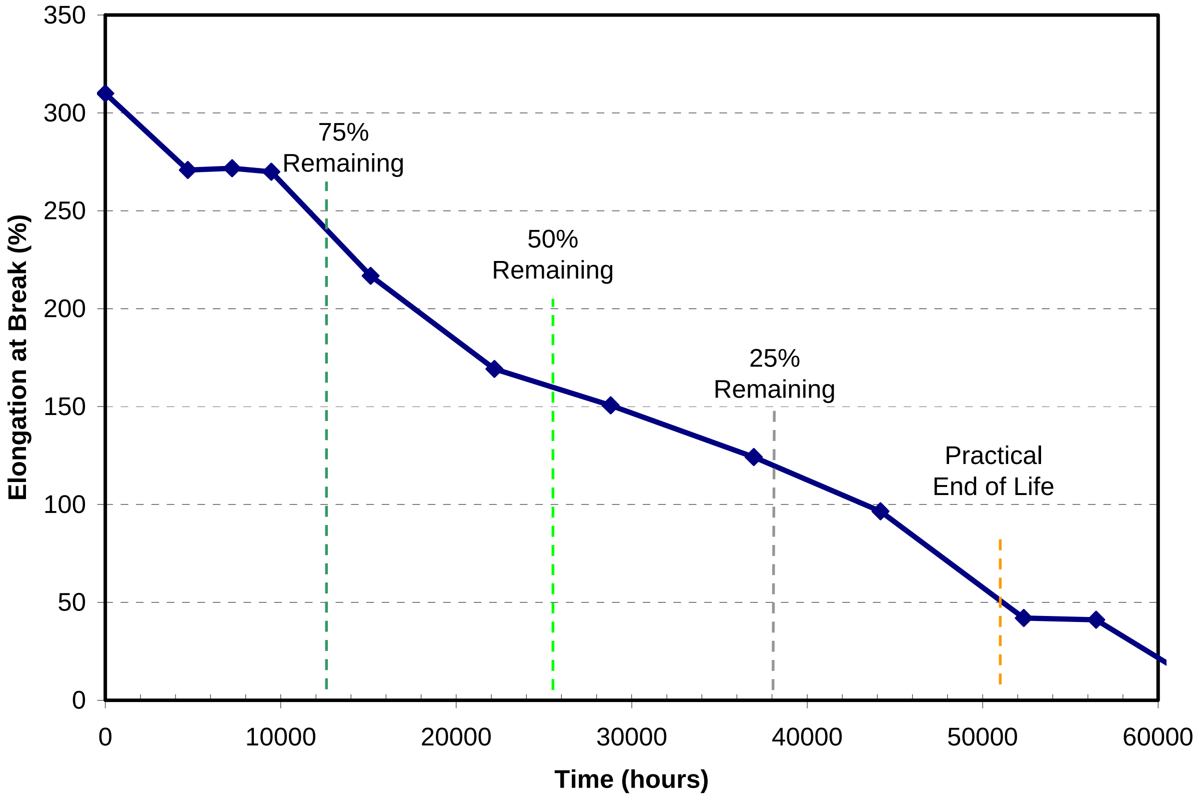


Figure 5-6
Remaining Life Curve for an XLPE, 110°C Aging

5.2 Extension of Remaining Life Concept to Other Monitoring Techniques

E-at-B is directly related to the ability of an insulation or jacket material to allow bending without cracking. As such, it is a highly useful laboratory test that is easy to rationalize. However, E-at-B requires large specimens that must be removed from a cable. Removal of such specimens is rarely practical. However, when the relationship of other monitoring techniques can be correlated to E-at-B, the results of these alternate monitoring techniques can be used to assess remaining life. Section 6 provides numerous plots of aging data related to available monitoring techniques. Whenever these plots allowed the evaluation, practical end of life (that is, 50% E-at-B) and 25% remaining life were determined for E-at-B and any related monitoring method. The point of 25% remaining life was determined by taking three-fourths of the time to the practical end of life. These data have been summarized in Tables 5-1 through 5-6.

Table 5-1
Cross-Linked Polyethylene Insulation 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
Brand Rex XLPE	120	-	-	-	72	3.4	2.4	-
Eaton Dekoron Polyset	80	-	-	-	-	-	-	-
ITT Suprenant Exane II	65–80	-	-	-	-	-	-	-
Rockbestos Firewall III	160	-	-	-	-	-	-	212

Note: - = No data were evaluated.

Table 5-2
Chlorinated Polyethylene Jacket 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
Anaconda CPE	80	-	-	-	~67	-	-	-

Note: - = No data were evaluated.

Table 5-3
Chlorosulfonated Polyethylene Jacket 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
Anaconda	95–105	-	18–24	-	-	-	4.4–5.2	-
BIW Bostrad Overall Jacket	75–120		12–13	NR	76.5–79.5[1]	1.7–1.85	-	-
Brand Rex Jacket	165–180	-	-	-	-	-	-	-
Kerite Jacket	75–115	-	-	-	-	-	-	-
Rockbestos Jacket	80–110	14	12–23	1.69–1.715	86.0–90.5	1.62–1.86		
Samuel Moore Dekoron	100–120		31–37	1.488–1.50	82–88[1]	1.90–2.25[2]		

Note: - = No data were evaluated.
[1] Resolution low and significant scatter.
[2] Scatter in 100°C aging data causing elevated uncertainty.

Table 5-4
Bonded CSPE/EPR Composite Insulation 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
BIW Bostrad	160	16	-	-	-	-	-	-
Okonite Okolon	120	20	-	-	-	-	-	-

Note: - = No data were evaluated.

Table 5-5
Ethylene Propylene Rubber Insulation 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
Anaconda Flameguard	200–250	-	-	-	-	-	-	-

Note: - = No data were evaluated.

Table 5-6
Neoprene 25% Remaining Life Correlations

Manufacturer/Model	E-at-B 25% Remaining Life	Correlation to E-at-B for 25% Remaining Life						
		IM (N/mm)	Edge Micro Modulus (MPa)	Density (g/cc)	% Gel	Uptake Factor	NMR T2 (msec)	OITemp
Okonite Neoprene	80–95	-	-	-	-	-	-	-
Neoprene	110	16	-	-	-	-	-	-
Rockbestos	65–90	-	19–24	-	93.0–94.5[1]	1.72–1.9[2]	3.0–3.2	-

Note: - = No data were evaluated.
[1] Little resolution and high scatter.
[2] Scatter in 80°C aging data causing elevated uncertainty.

6
AVAILABLE CONDITION-MONITORING TECHNIQUES

Numerous condition-monitoring techniques have been investigated for cable polymers. There is not one technique that may be utilized to assess the aging of all the polymers used as cable insulation and jackets because of differences in their physical and chemical properties. Accordingly, appropriate condition-monitoring techniques must be chosen for each polymer type. Table 6-1 provides a correlation between insulation and jacket materials and possible test methods. Table 6-1 is based on the data assessment contained in Section 7 of this report.

While many tests are listed as applicable or possible, practicality may point to one test or another. For example, E-at-B is of limited use because relatively large samples (3–6 in/ 8–15 cm) tubes or strips of insulation or jacket are needed to perform tests. Removal of such large pieces of insulation or jacket from an in-service cable is difficult. Accordingly, a nondestructive test based on jacket condition such as IM or acoustic velocity[1] testing would be more useful. If the neoprene or CSPE jackets of numerous cables were found to be deteriorated, sampling of the insulation of representative cable for laboratory testing would be warranted to determine a more precise age for the underlying insulations. In such cases, small sample (mg) laboratory tests could be used to limit the amount of repair necessary. Alternatively, a few cables could be removed from service, and standard testing including E-at-B could be performed.

[1] The acoustic velocity of sound changes as polymers harden or soften. Mitsubishi Heavy Industries is developing an acoustic velocity monitoring device for in-plant use. Data are unavailable for presentation at this time.

Table 6-1
Applicability of Condition-Monitoring Techniques to Polymer Aging

Test Name	Nature of Test	XLPE/ XLPO	CPE	CSPE	EPR/CSPE EPR/NEO (Bonded)	FR-EPR	Neoprene	PVC	SR
Mechanical Tests									
Elongation at break	Lab test, large sample required	Yes (after long period of severe aging)	Yes	Yes	Yes	Yes (severe aging)	Yes	Yes (thermal damage)	Yes (radiation damage)
Indenter modulus	Nondestructive field or lab test	No data[1]	No data	Yes	Yes (via outer layer)	Yes (severe aging)	Yes	Yes (thermal damage only)	Not known
Micro-modulus	Small sample, lab test	No	No data	Yes	Yes (via outer layer)	Yes (severe aging)	Yes	Yes (thermal damage)	Not known
Acoustic velocity	Nondestructive field or lab test	No data	No data	Yes	Yes (via outer layer)	No data	Yes	Yes (thermal damage)	Not known
Thermal Tests									
Oxidation induction temperature	Small sample, lab test	Yes (partial degradation only)	No data	No data[2]	No data	Yes	No data	No data	No data
Oxidation induction time	Small sample, lab test	Yes (partial degradation only)	No data	No data	No data	Yes	No data	No data	No data

Table 6-2 (continued)
Applicability of Condition-Monitoring Techniques to Polymer Aging

Test Name	Nature of Test	XLPE/ XLPO	CPE	CSPE	EPR/CSPE EPR/NEO (Bonded)	FR-EPR	Neoprene	PVC	SR
Chemical Tests									
Density	Lab test	Yes[3]	No data	Yes[4]	Yes (when separated)	Yes[3]	No data	Yes[3]	Yes (radiation damage)
% Gel	Lab test	Yes	No data	Yes[4]	-	No data	Yes[4]	Yes[3]	Yes (radiation damage)
Uptake factor	Lab test	Yes	No data	Yes	-	No data	Yes		Yes (radiation damage)
NMR T2	Small sample, lab test	Yes	No data	Yes	-	No data	Yes	No data	

[1] Indenter data exist for only limited aging of XLPE. It is not known whether long-period aging of XLPE can be assessed by indenter measurement. A 70% increase in indenter modulus occurs after 1300 hours at 150°C [2]. However, too few data points exist to determine the shape of the degradation profile.
[2] Only limited OITime data exist [2]. Data seem to indicate that OITime would be useful.
[3] See EPRI Report TR-105581 [7].
[4] Measurements may have significant scatter for some formulations.

7
MATERIAL DISCUSSIONS AND ACCEPTANCE CRITERIA

7.1 Cross-Linked Polyethylene/Cross-Linked Polyolefin

XLPE and XLPO are thermoset plastic insulation materials that are physically tough and have excellent dielectric strength and chemical resistance. The materials are cross-linked by either chemical or irradiation processes. The cross-linking increases heat resistance and stiffness [8].

Degradation Under Thermal Exposures

Under thermal exposure conditions, the mechanical properties of XLPE and XLPO insulations degrade very slowly for an extended period. XLPE and XLPO are relatively hard plastics due to their partial crystalline structure. Further cross-linking of the polymer with thermal aging is masked by the crystalline structure of the material.

In general, XLPE and XLPO insulations will provide very long life at ambient temperatures up to 65°C for low-current operations. For power circuits with high ohmic heating, life may be reduced in elevated temperature environments.

Degradation Under Radiation Exposures

The physical properties of XLPE/XLPO do degrade with significant radiation exposure. Radiation doses below 1 Mrd produce no significant effect. Effects are observable above 5 Mrd. For example (as shown in Figures 7-4 and 7-5), an XLPE insulation aged at 110°C has an E-at-B drop from 320% to 125% in 38,000 hours. When aged at the same temperature and irradiated at 2540 rd/hr, the 125% E-at-B occurs at 7500 hours, a reduction in life by a factor of 5. Accordingly, elevated normal radiation doses will have a significant effect on the life of XLPE/XLPO. Very long normal lives will occur at total doses below 5 Mrd under moderate temperature conditions (50°C/120°F). Above 5 Mrd, life will be shortened significantly in comparison to temperature-alone exposures.

In exposures involving significant dose rates (>15 rd/hr for 40 years or >9.5 rd/hr for 60 years), mechanical testing (elongation at break and hardness) will be useful in determining the degree of degradation. In cases where radiation levels are not so high, mechanical testing may not be useful. Of course, the life of the material may be so long as to make testing unnecessary if service temperatures are low (for example, 50°C or less).

End-of-Life Data

XLPO/XLPE insulations have typical initial E-at-B of 240–370% [1]. The following sections indicate that XLPO/XLPE materials have long thermal lives. Table 7-1 summarizes thermal life at various temperatures. Data for one temperature do not exist for all the materials. To allow comparisons, temperatures that apply to two or more materials are provided. The results show that while all XLPOs/XLPEs have long thermal lives, these lives vary considerably. Eaton Dekoron Polyset data are not presented in the table because the available data end well before 50% E-at-B occurred. Table 7-2 shows the effects of adding radiation. Significant reductions in life occur when a 25-Mrd dose is added to the thermal aging (simultaneous thermal and radiation aging in this case). For the Rockbestos Firewall III insulation, there is no comparable thermal-only case. However, two different doses are available for 40°C aging showing a near-linear effect in this case (one-half the life for double the dose). The following report subsections provide manufacturer-specific plots for thermal and radiation capability as monitored by E-at-B and other available techniques.

Table 7-1
XLPO/XLPE Thermal Life Comparison

Manufacturer	Initial E-at-B (%)	Aging Temperature (°C)	Time to 50% E-at-B Remaining (Hours)
Brand Rex	310	110	51,000
ITT Suprenant Exane II	240	110.6	7900
Brand Rex	345	150	1000
Rockbestos Firewall III	300	151	1350
Brand Rex	345	160	490
ITT Suprenant Exane II	240	161.5	150

Table 7-2
XLPO/XLPE Radiation Capability Comparison

Manufacturer	Initial E-at-B (%)	Aging Temperature (°C)	Time to 50% E-at-B Remaining (Hours)	Time to 50% E-at-B with Radiation (Hours, Dose)
Brand Rex	310	110	51,000	7400, 24 Mrd
ITT Suprenant Exane II	240	110.6	7900	400, 20 Mrd
Rockbestos	300	40	3500, 27 Mrd	1700, 60 Mrd

Manufacturer-Specific Aging Data

Brand Rex

Figure 7-1 shows E-at-B for Brand Rex XLPE for thermal aging at 110°C. An initial review of the data appears to indicate a steadily declining E-at-B with time at temperature. However, the E-at-B stays above 270% for the first 10,000 hours of aging. Under pure thermal aging, this XLPE has a life of approximately 50,000 hours (5.7 years) at 110°C. Figure 7-1 also shows the NMR T2 time for the material, which drops from 13.5 to 1.7 msec at 50% E-at-B. NMR T2 appears to have an excellent correlation with the degree of thermal aging.

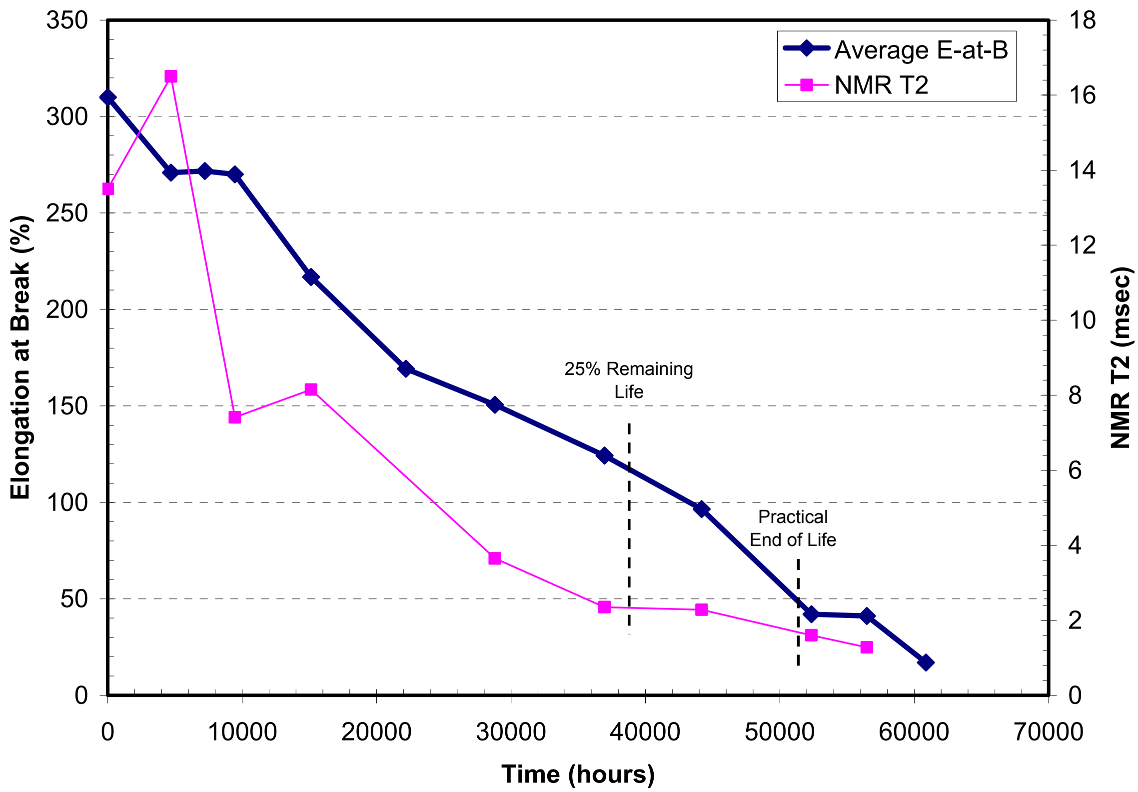


Figure 7-1
Brand Rex XLPE E-at-B Versus NMR T2, 110°C, 0 rd/hr Aging

Figure 7-2 shows the comparison of percent gel to E-at-B for the material. The percent gel increases from 57% at the start of aging to 73% when the material has 50% retained E-at-B. The correlation between E-at-B and percent gel is good.

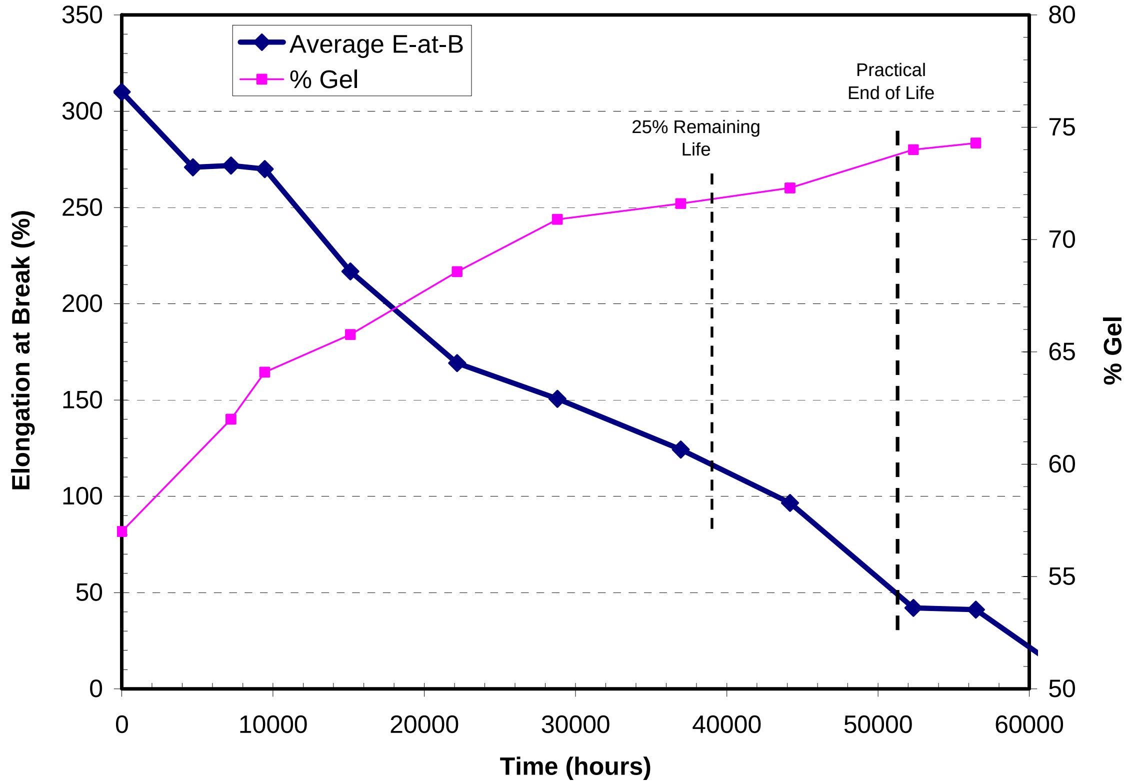


Figure 7-2
Brand Rex XLPE E-at-B Versus % Gel, 110°C, 0 rd/hr Aging

Figure 7-3 shows the comparison of uptake factor to E-at-B for the Brand Rex. The uptake factor decreases from 8.0 when new to 2.7 at the point of 50% remaining E-at-B. The correlation is strong and resolution seems good, therefore allowing ease of interpretation.

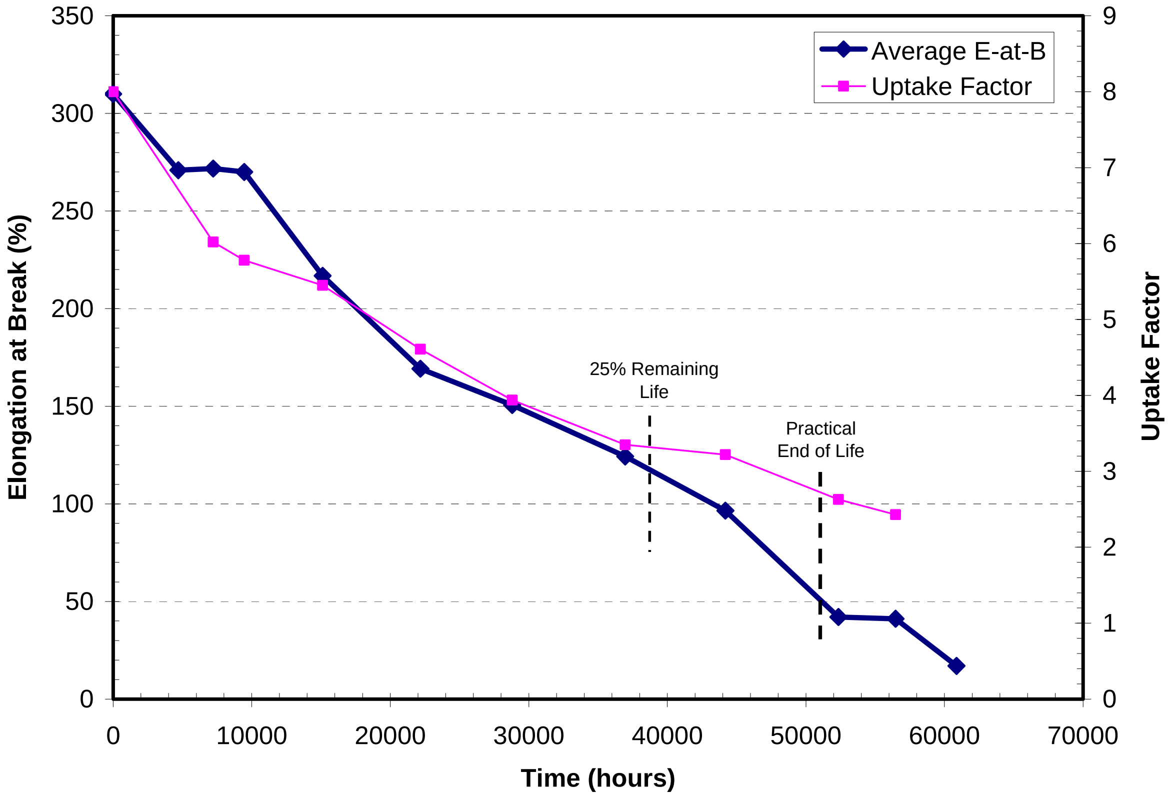


Figure 7-3
Brand Rex XLPE E-at-B Versus Uptake Factor, 110°C, 0 rd/hr Aging

Figures 7-4 and 7-5 show the effects of radiation on E-at-B for Brand Rex XLPE. The time to reach 150% remaining E-at-B is drastically reduced by irradiation as shown in Figure 7-4. Interestingly, the tensile strength improves slightly and is retained throughout aging. Review of the overall data for the insulation indicates that even when very little E-at-B remains, 50–80% of original tensile strength remains.

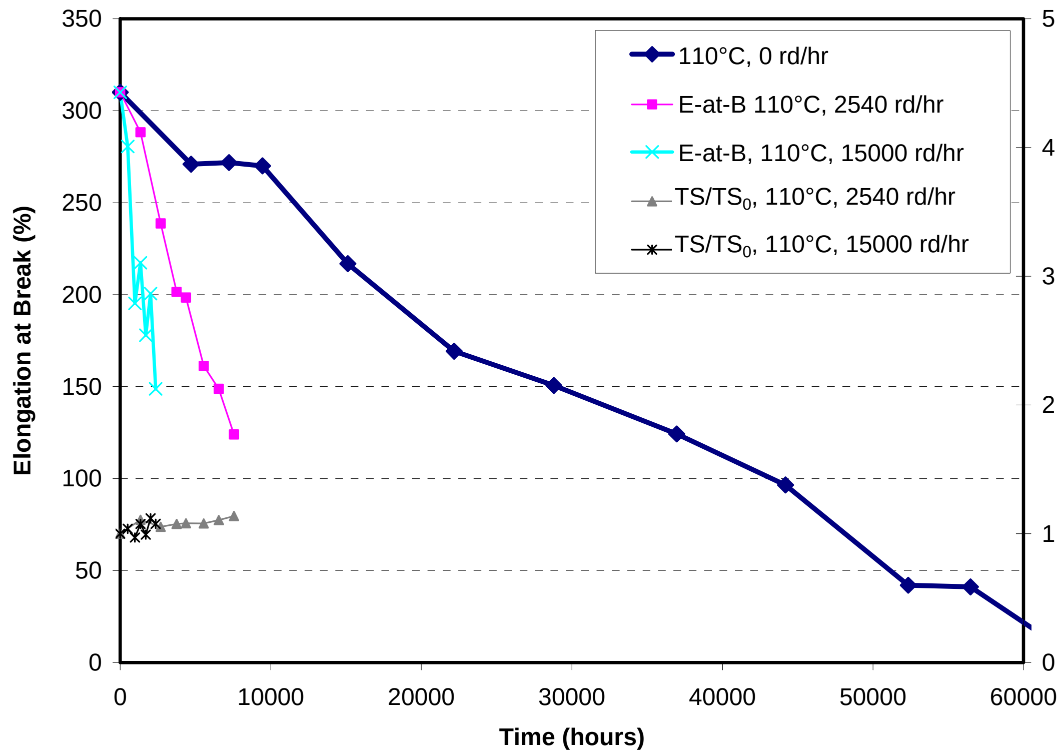


Figure 7-4
Brand Rex XLPE E-at-B, Various Dose Levels, 110°C

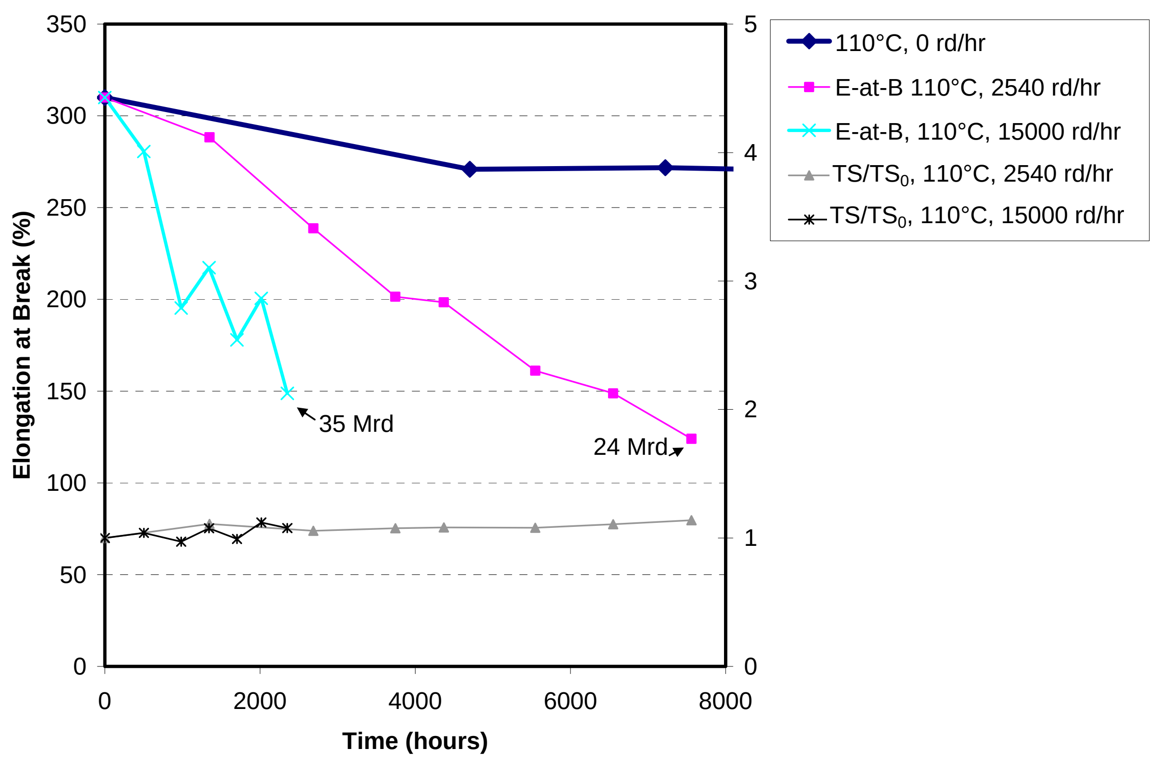


Figure 7-5
Brand Rex XLPE E-at-B, Various Dose Levels, 110°C

Figure 7-6 shows E-at-B versus oxidation induction time (OITime) for Brand Rex XLPE. The data are from two separate tests (E-at-B performed by Sandia at 160°C and OITime performed by Pacific Sierra Research Corporation at 158°C). While the differences in aging temperatures will produce somewhat different aging, the tests are close enough to show a comparison between the two techniques. Figure 7-6 shows that the OITime drops from 75 minutes under thermal aging alone to 5 minutes for a single conductor specimen. This point equates to the point where the XLPE has ended its period of little aging and more rapid aging has begun. Unfortunately, only one-third of the life of the polymer has been expended at this point and there is little ability to assess the aging of the remaining two-thirds of life. Figure 7-6 also shows results for single conductors that were aged under an overall jacket. The plot shows that much less aging has occurred. Because these tests were performed at very high temperature, it is unclear whether a similar effect would result (for example, the jacket provides a large amount of protection for the conductor insulation) if the aging occurred at moderately high to very low temperature (100–40°C).

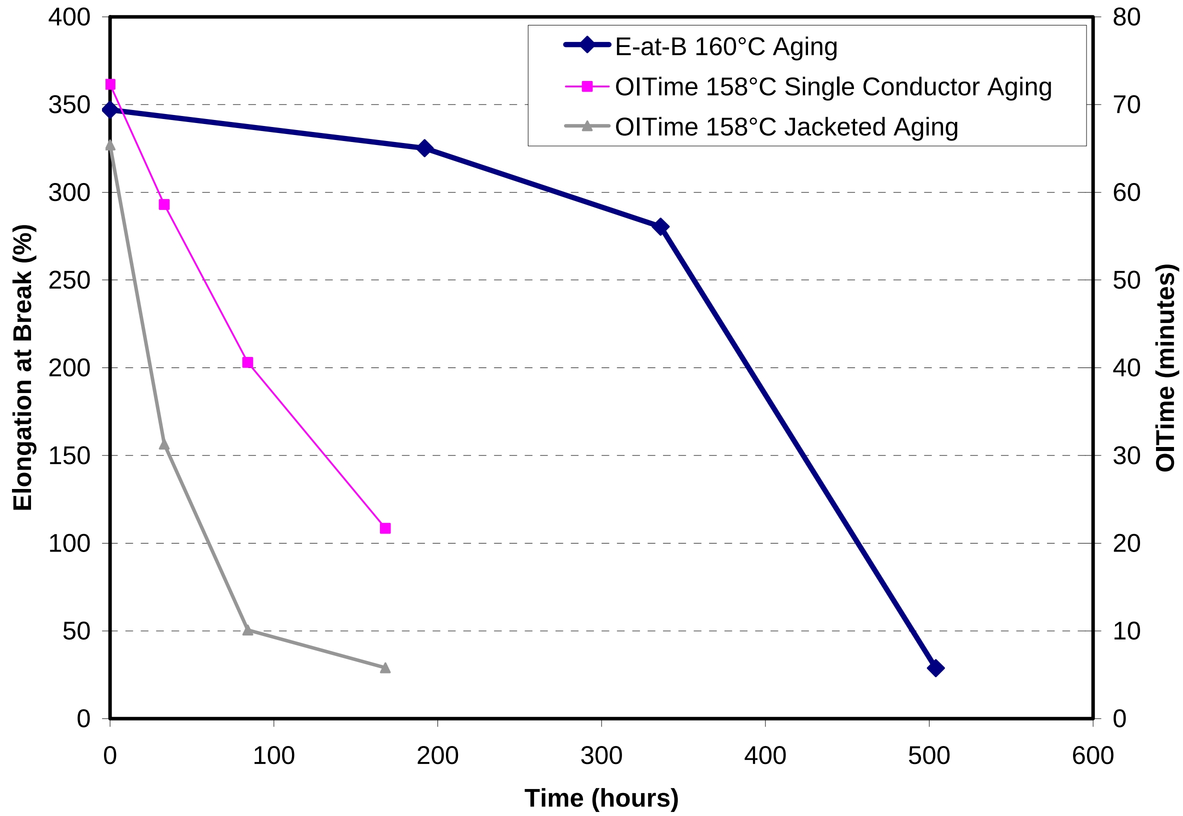


Figure 7-6
Brand Rex XLPE OITime, 225°C Test Temperature

Figure 7-7 shows oxidation induction temperature (OITemp) versus E-at-B for the Brand Rex XLPE including the effects of radiation. When the material is new, the exothermic reaction occurs when the temperature ramps to 277°C at 10°C/min. When aged for 168 hours at 158°C, the OITemp drops to 236°C. Figure 7-7 is also based on Sandia and Pacific Sierra testing. Irradiation adds some confusion to the data in that at 10 Mrd, the material seems less aged (OITemp of 244°C) than the test of thermal alone and at 50 Mrd seems somewhat more aged (OITemp of 234°C). It is not clear if further aging would have resulted in significantly lower OITemp results or if the OITemp results will stabilize at 230°C with further aging. The 168-hour endpoint of aging has essentially consumed only one-third of the total available capability of the material.

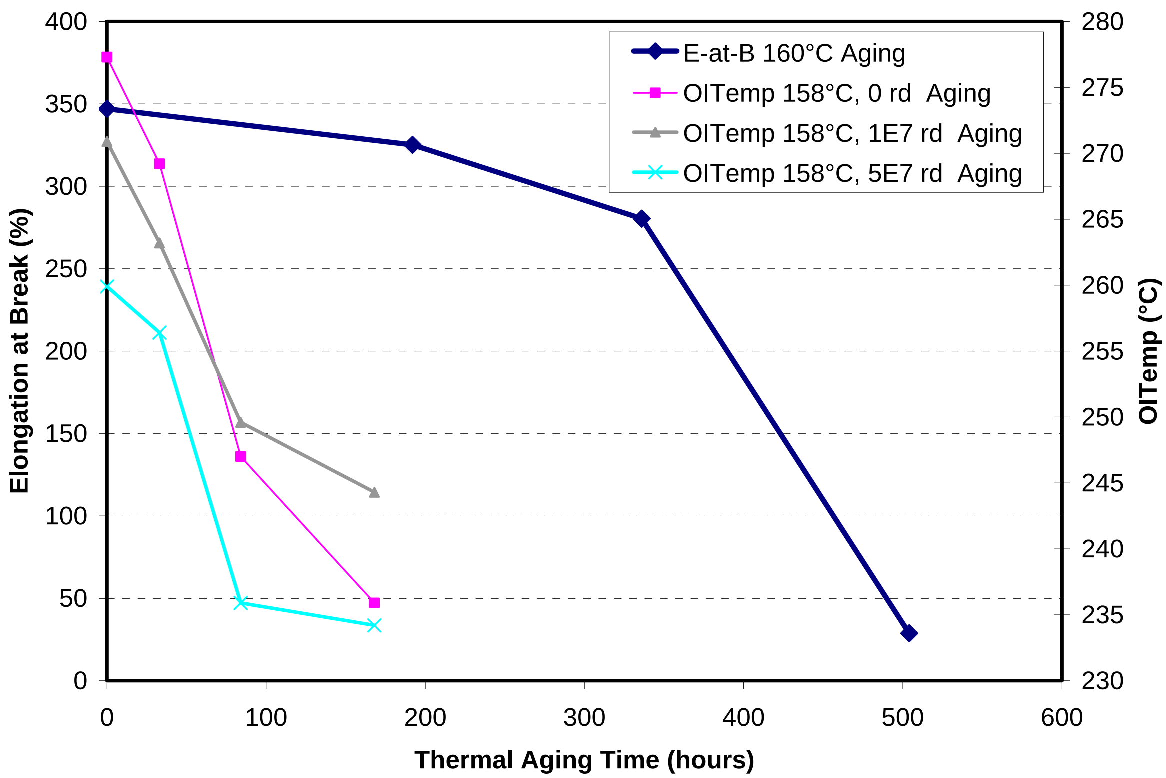


Figure 7-7
Brand Rex XLPE OITemp, 10°C/Min Test Ramp Rate

Eaton Dekoron Polyset

Figure 7-8 shows thermal aging and combined thermal and radiation aging at 120°C. The duration of the thermal aging alone is too short to cause severe aging. The aging ends while the Polyset material still has 250% E-at-B remaining. However, when a 50-Mrd dose is simultaneously added during thermal aging, 50% E-at-B occurs at 5700 hours. Figure 7-9 shows the same plots with an additional level of irradiation that is approximately three times the original (25.2 krd/hr versus 8.8 krd/hr). At the higher dose rate (50 Mrd), 50% E-at-B occurs at 2000 hours. The effect of tripling the dose rate essentially has an inverse linear effect of causing the life to be reduced to one-third.

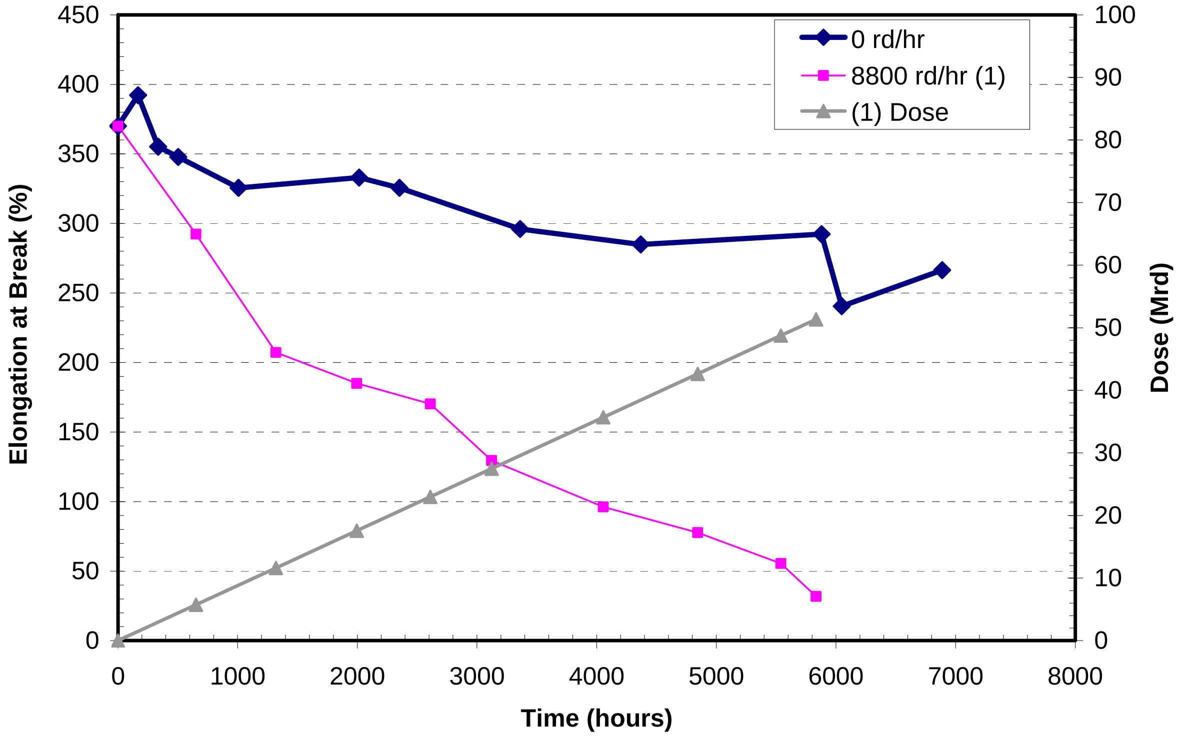


Figure 7-8
Eaton Dekoron Polyset E-at-B – 120°C, 0 rd/hr and 120°C, 8800 rd/hr Aging

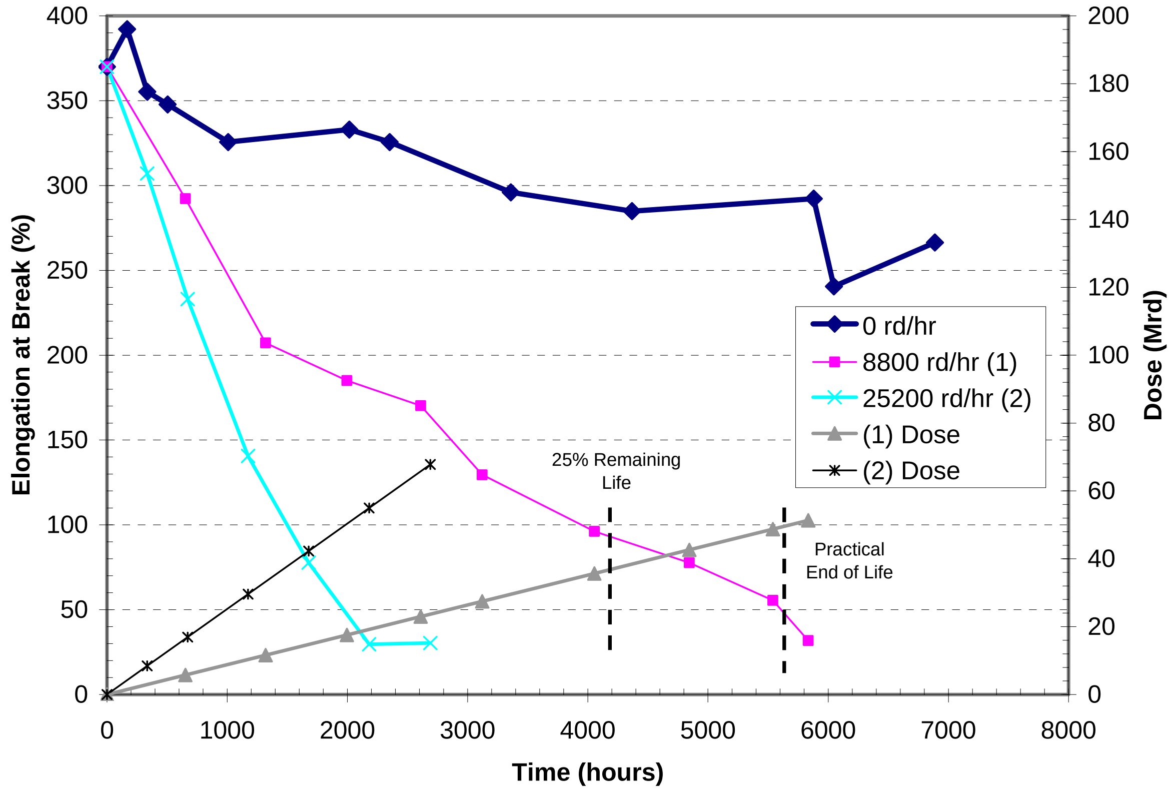


Figure 7-9
Eaton Dekoron Polyset E-at-B – 120°C, 0 rd/hr; 120°C, 8800 rd/hr; and 120°C, 25200 rd/hr Aging

Figure 7-10 shows E-at-B for 110°C thermal aging with simultaneous irradiation at 2.88 krd/hr. At the end of the aging, 140% E-at-B remains at 7500 hours with a total dose of 22 Mrd.

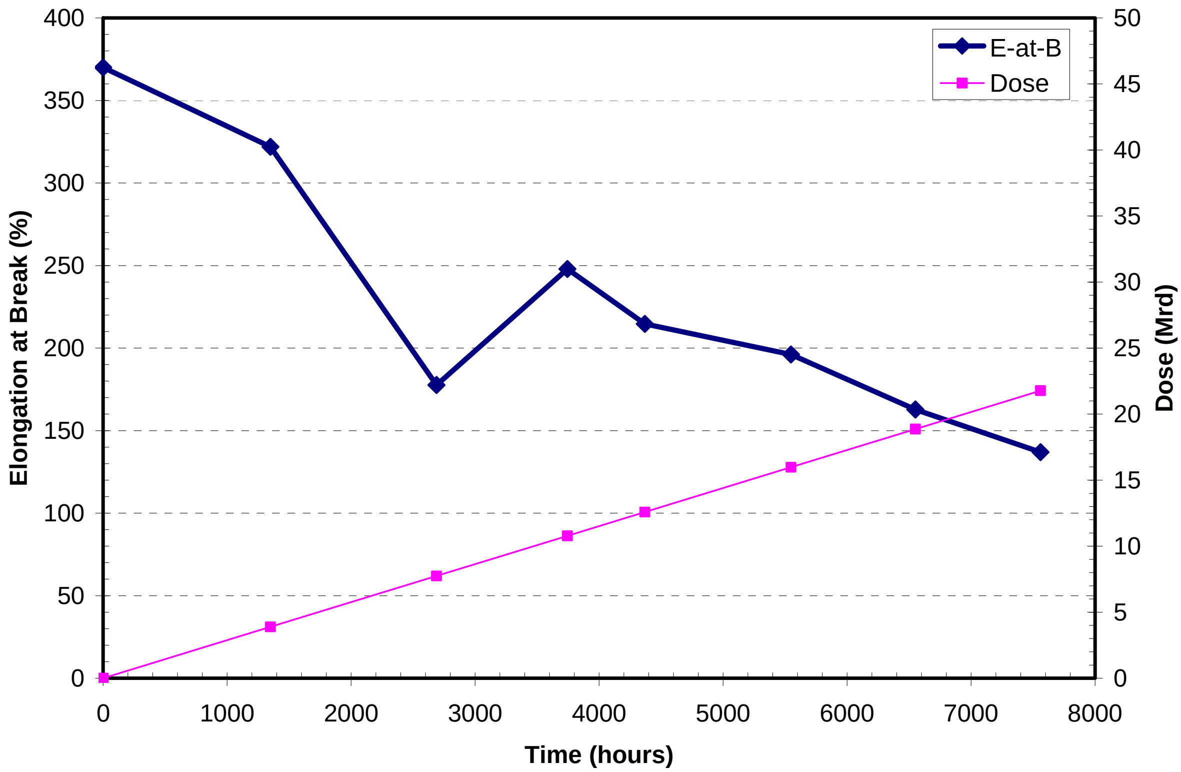


Figure 7-10
Eaton Dekoron Polyset E-at-B, 110°C, 2880 rd/hr Aging

ITT Suprenant Exane II

Figures 7-11 through 7-13 apply to ITT Suprenant Exane II insulation (currently available from Rockbestos). Figure 7-11 shows elongation and normalized tensile strength (TS/TS_0) with 110.6°C thermal aging. At approximately 8000 hours of aging, the E-at-B has decreased to 50%. Interestingly, the tensile strength has remained essentially that of the new insulation. Accordingly, while the material is stiffening, it is still strong. Figure 7-12 shows the E-at-B and tensile strength at differing thermal aging temperatures from 110.6°C through 161.5°C. At each increase of aging temperature, the life is shortened as would be expected. Again, the tensile strength remains constant through end of life at each temperature. Figure 7-13 shows the aging curve shifted to 110.6°C with multiplication of the aging time by a factor. (Note that time shift multipliers are listed in parathenses in the legends of each figure where this is a factor.) The factor was chosen by making the best fit at 50% remaining E-at-B. The aging curves align reasonably well. However, some distortion in the curves at 130°C and 140°C is noted in the mid-aging range, which appears to indicate that the material ages faster at these temperatures. The 110.6°C, 121.5°C, 151.2°C, and 161.5°C curves align well.

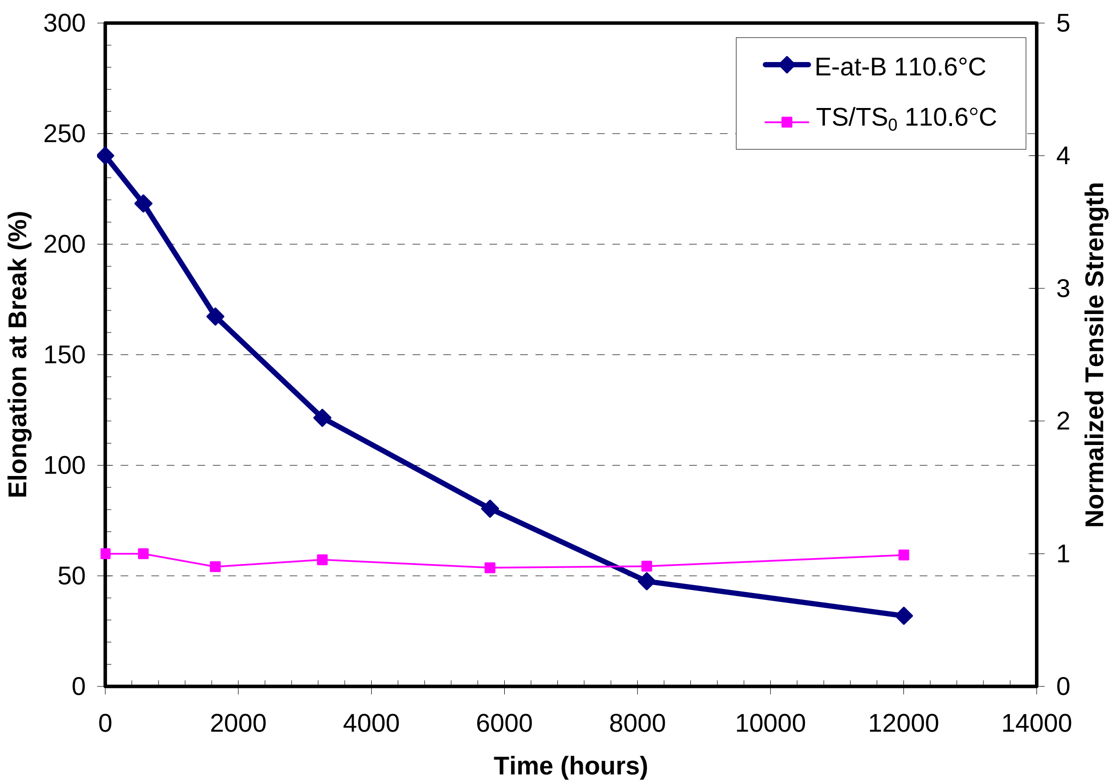


Figure 7-11
ITT Suprenant Exane II E-at-B Versus Relative Tensile Strength, 110.6°C, 0 rd/hr Aging

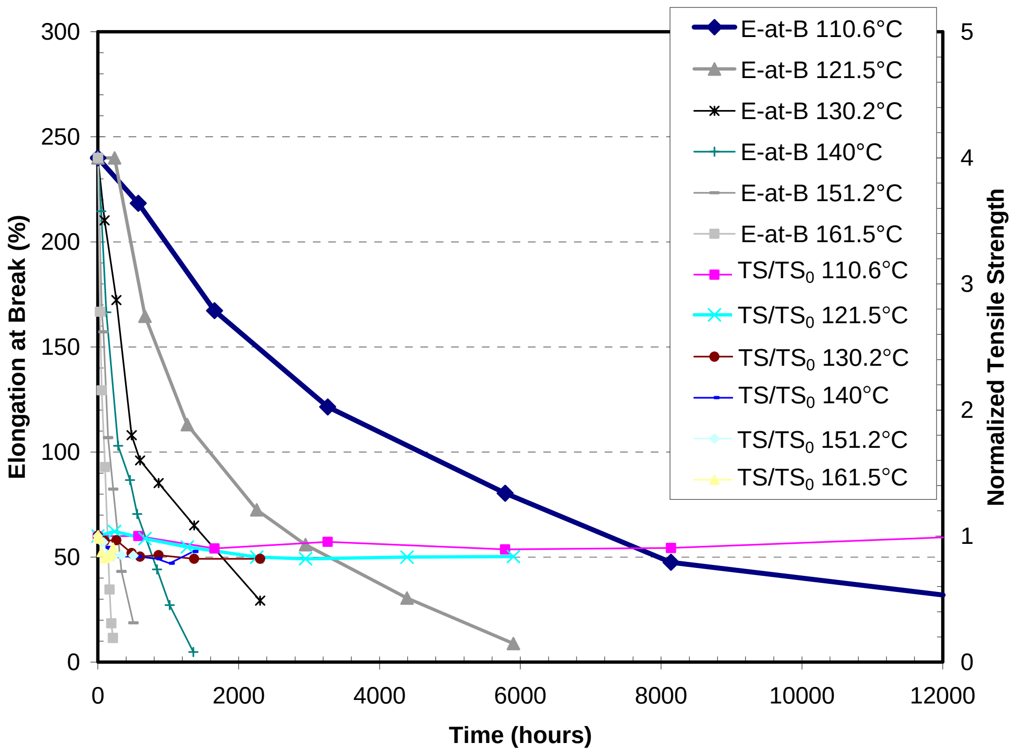


Figure 7-12
ITT Suprenant Exane II E-at-B and Tensile Strength for Multiple Aging Temperatures

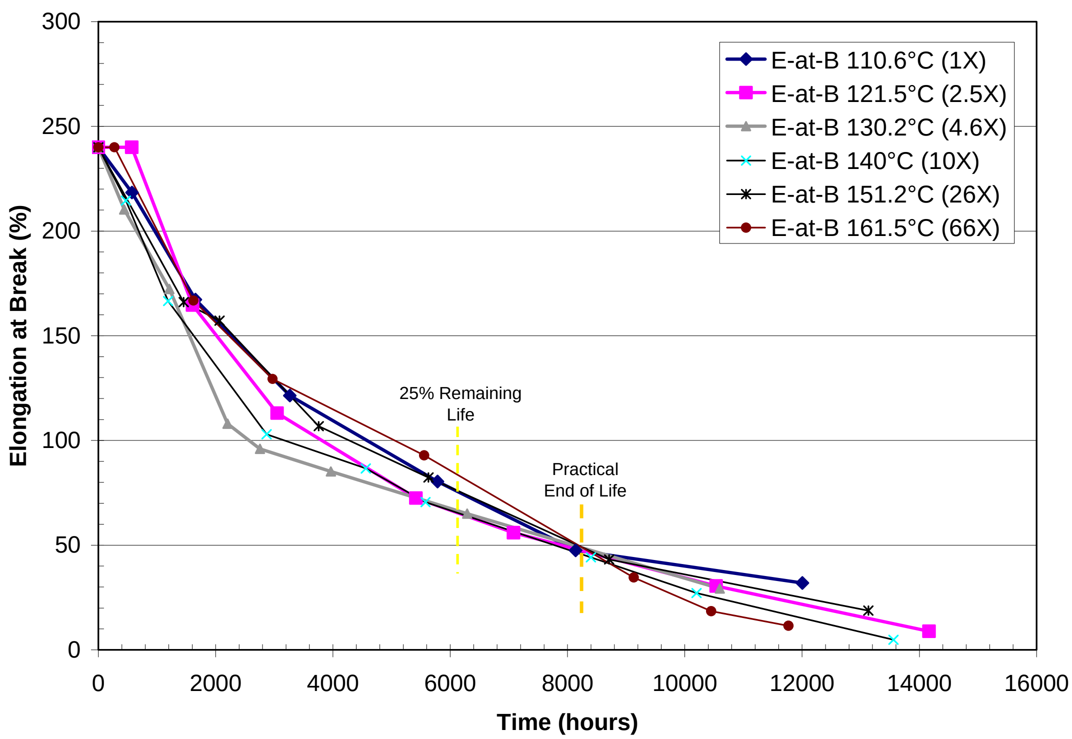


Figure 7-13
ITT Suprenant Exane II E-at-B and Tensile Strength Shifted to 110°C

Figure 7-14 compares thermal aging to combined thermal and radiation aging at 110°C and 130°C and approximately 50 krd/hr irradiation. The radiation significantly reduces life by a factor of approximately 10 at 110°C. The effect is not linear. Below 9 Mrd, there is effectively no difference between thermal aging alone and combined thermal and radiation aging. Beyond 9 Mrd, the effects of radiation are significant.

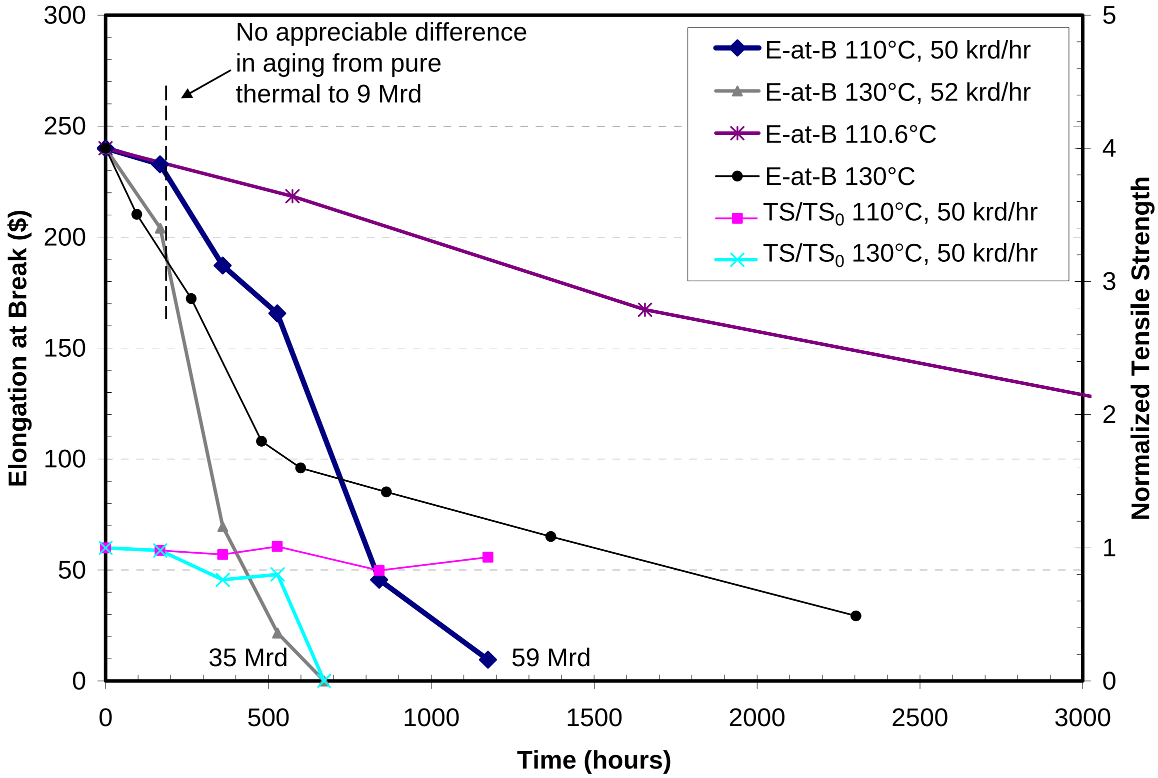


Figure 7-14
Exane II E-at-B with and Without Radiation

Rockbestos Firewall III

Aging data at lower temperatures without irradiation are not yet available for Rockbestos Firewall III cable. Figure 7-15 shows the effects of aging at 151°C. At approximately 1350 hours, 50% E-at-B occurs, which indicates a very long life at normal operating temperatures. Figure 7-16 shows the effects of irradiation at low temperatures and two different dose rates. Thermal aging at 23°C and 40°C at the same dose rate (21 krd/hr) shows that the age temperature at low temperatures has no significant effect, but the irradiation does. Aging at two different dose rates at approximately 40°C shows that the lower rate has the same effect when the same dose is achieved in both aged specimens.

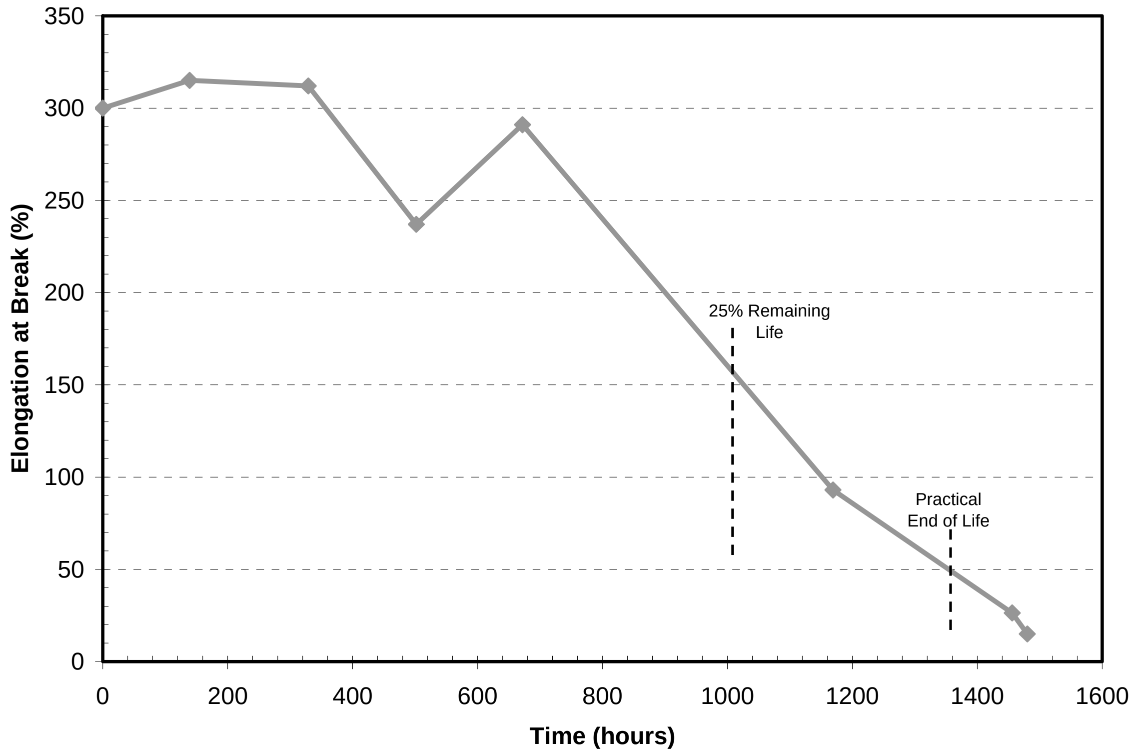


Figure 7-15
Rockbestos Firewall III E-at-B, 151°C, 0 rd/hr Aging

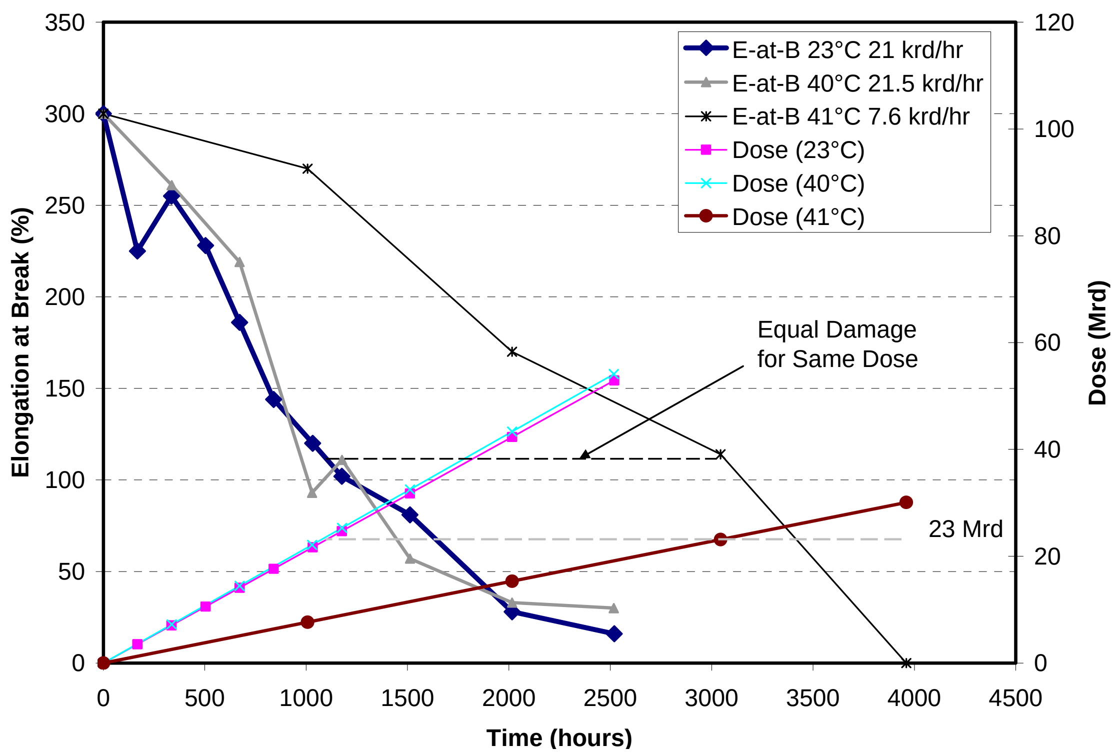


Figure 7-16
Rockbestos Firewall III E-at-B, Radiation Effects

Figure 7-17 shows the effects of higher temperature irradiation in comparison with lower temperature irradiation. Two 40°C plots at 7.6 and 21.5 krd/hr are shown along with a 100°C, 35 krd/hr and a 120°C, 36 krd/hr plot. The two 40°C plots bracket the higher temperature plots. Logically, the lower dose rate 40°C plot shows the same damage when equal doses are examined. However, the higher temperature/higher dose plots show less degradation than the 40°C plots when equal doses are examined. For a 20-Mrd dose, Figure 7-17 indicates that the 40°C plots result in 140% E-at-B, but that the higher temperature plots show 230% E-at-B. This means that less damage occurred even though the samples were aged at significantly higher temperatures. As the aging time increases, the divergence in the plots becomes more obvious with the higher dose/higher temperature plots continuing to exhibit less aging until near end of life where convergence seems to be occurring. The damage caused by high-level normal irradiation seems to be partially negated by the slightly elevated temperature in the exposure.

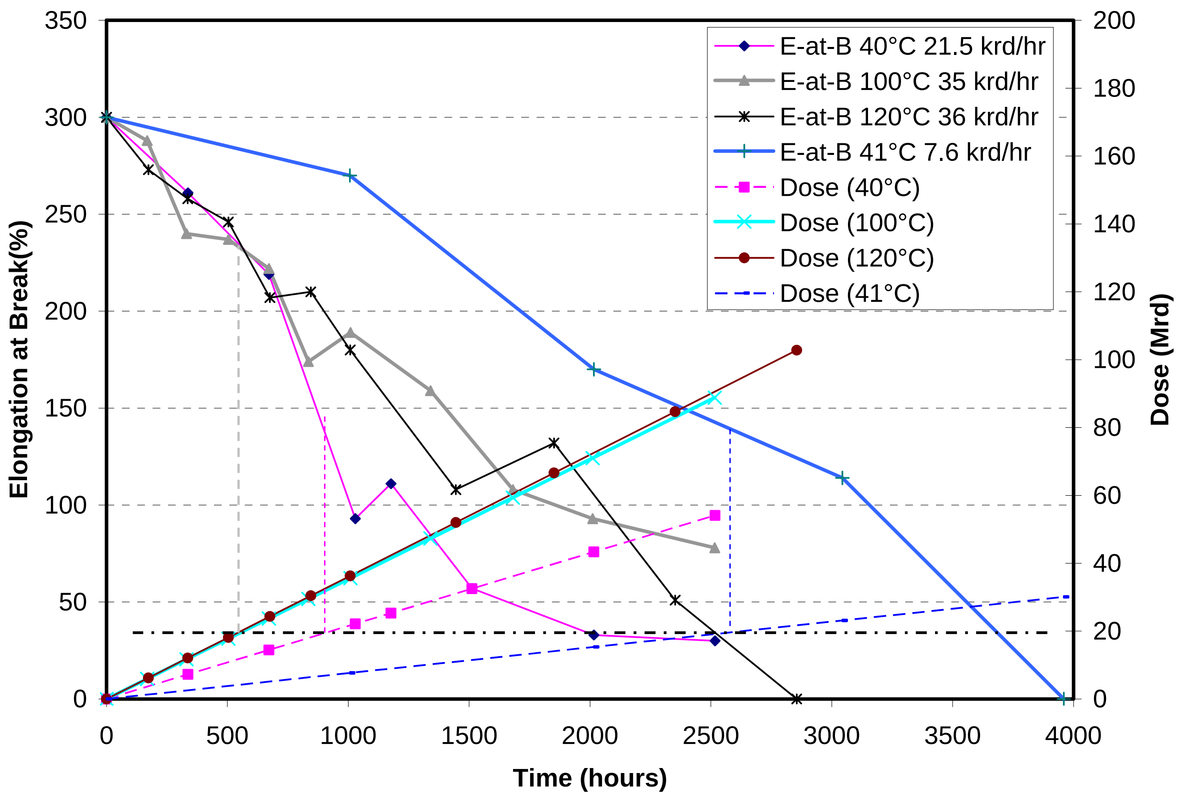


Figure 7-17
Rockbestos Firewall III E-at-B, Radiation Effects, Higher Temperatures

Figure 7-18 shows E-at-B and OITime for Rockbestos XLPE. It is a combined plot based on Sandia E-at-B and Pacific Sierra OITime. Both programs used a 150°C aging temperature. In this case, the OITime for the single conductor specimen dropped to one minute at 456 hours. At this point in the aging, essentially one-third of the capability of the XLPE had been expended and there is no further ability to discern continued aging of the material. Figure 7-19 shows E-at-B versus OITemp and includes radiation effects. It is also based on Sandia E-at-B and Pacific Sierra data. In this case, the OITemp data are well-behaved and cover much of the life of the material. The aging ends at 912 hours. The thermal-aging-only OITemp at this point is

214°C. With 10 Mrd included, the OITemp drops to 208°C. With 50 Mrd included, the OITemp is 205°C. The OITemp data cover about two-thirds of the useful life of the insulation.
If further aging had been performed, the plots indicate that resolution would be available through most if not the entire life of the material.

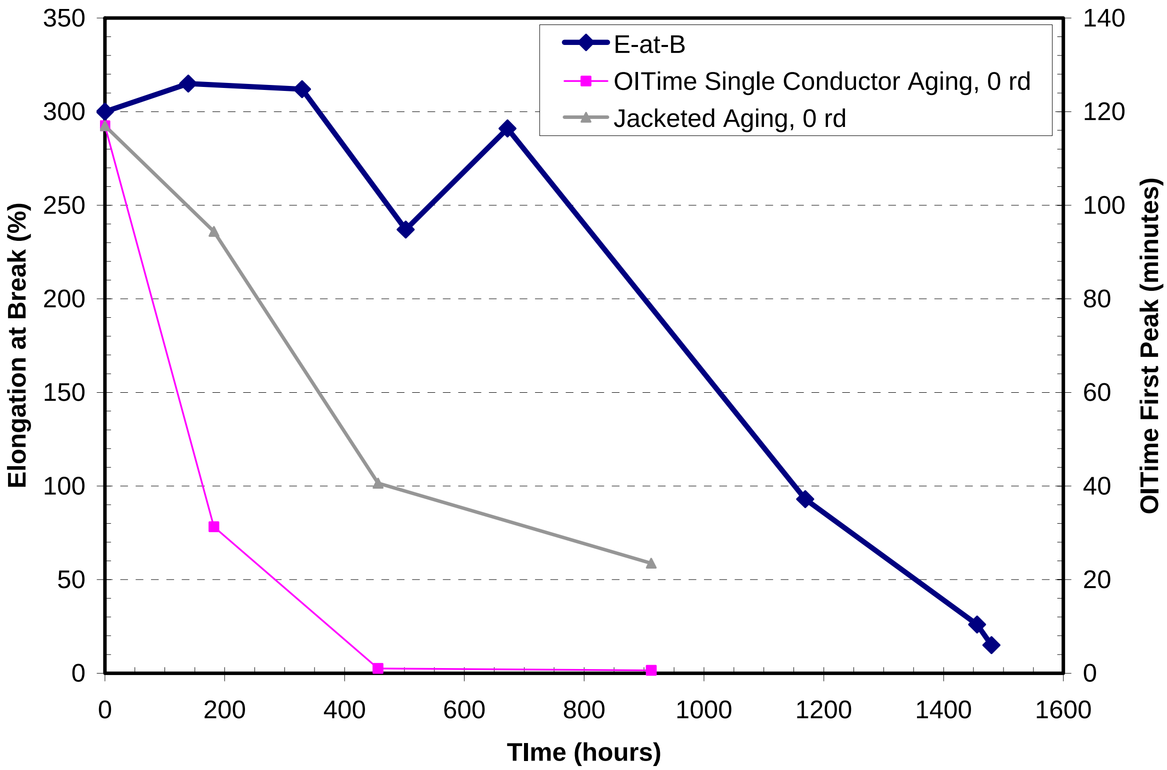


Figure 7-18
Rockbestos XLPE OITime, 150°C, 0 rd Aging

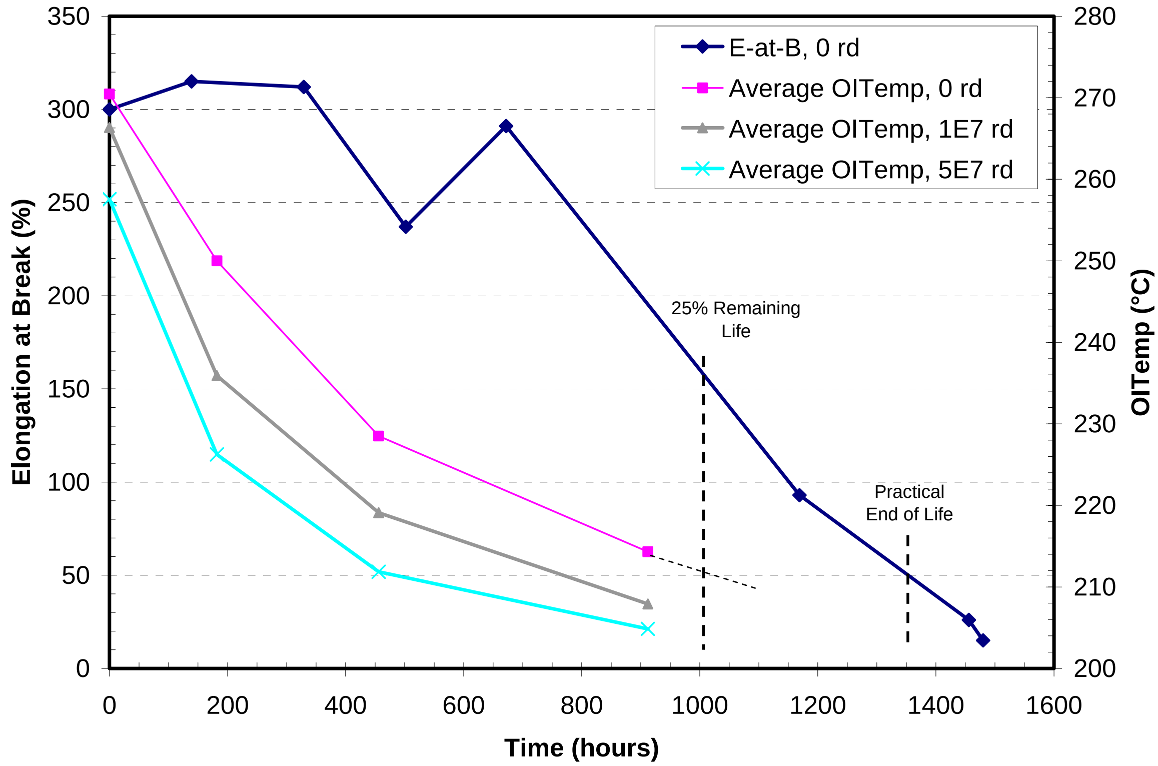


Figure 7-19
Rockbestos XLPE OITemp, 150°C, 0 rd, Single Conductor Aging, 10°C Ramp Rate

Comparison of Properties

Figure 7-20 shows a comparison between Brand Rex and Eaton Dekoron Polyset insulation when aged at 110°C. Figure 7-21 compares Brand Rex to Rockbestos insulation when aged at 150°C. Unfortunately, data are not available at a consistent temperature for all three materials.

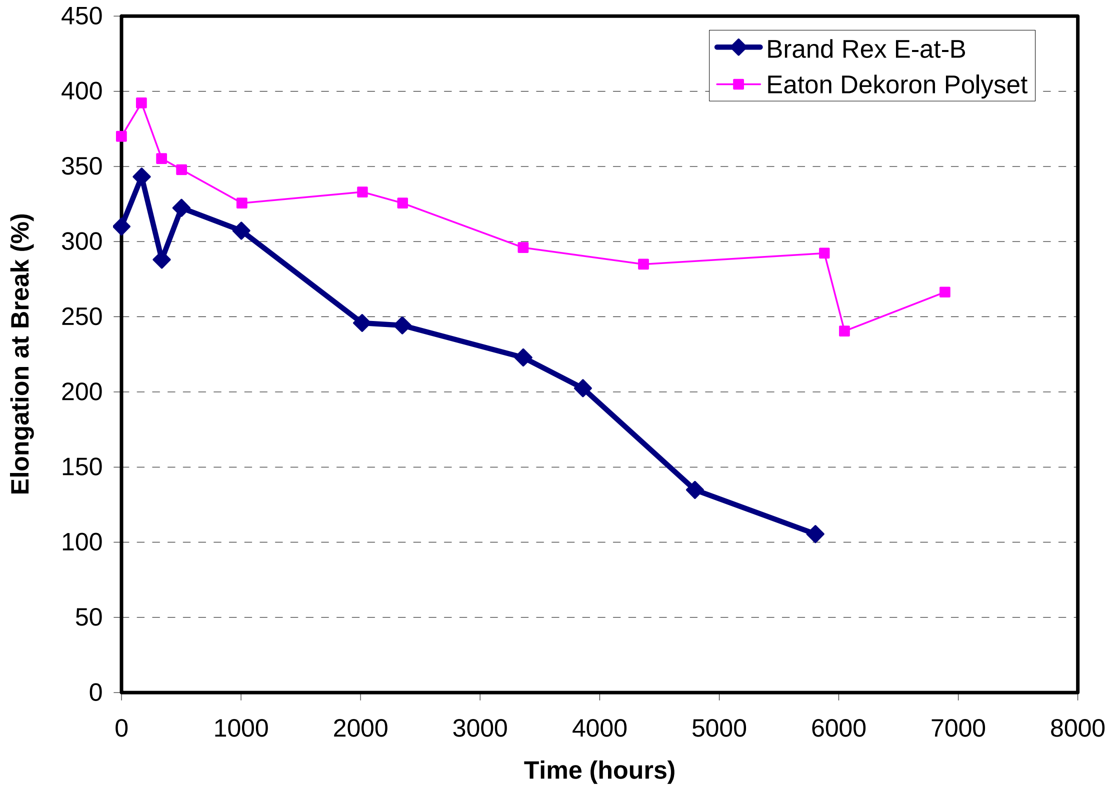


Figure 7-20
Comparison of Brand Rex and Eaton Dekoron Polyset, 110°C Aging, XLPE

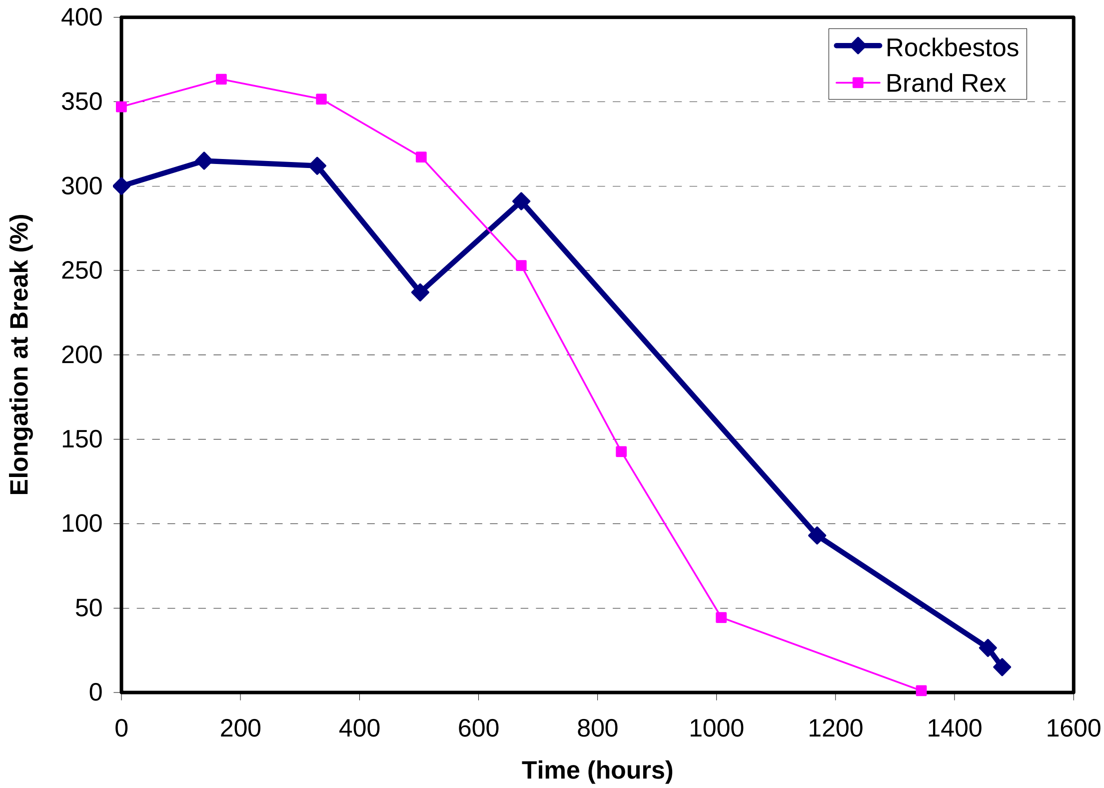


Figure 7-21
Comparison of Brand Rex and Rockbestos XLPE, 150°C Aging, XLPE

7.2 Chlorinated Polyethylene

Chlorinated polyethylene (CPE) has been used as a jacket for nuclear plant cabling by one cable manufacturer. It is a tough elastomeric material that is oil resistant and has good abrasion resistance.

Degradation Under Thermal Exposures

The limited data available indicate moderately good thermal aging characteristics with 50% E-at-B occurring at a time similar to that of CSPE.

Degradation Under Radiation Exposures

The limited data available indicate similar radiation characteristics to other jacket materials.

Manufacturer-Specific Aging Data

Anaconda Flameguard-EP Y Jacket

Figure 7-22 shows E-at-B and percent gel for Anaconda CPE Flameguard-EP Y jacket material. The reversal in the 3500 to 4000 hour period may be a recording error in the original data. (Figure 7-23 is based on the same data. Figure 7-24 is based on a separate test and shows the expected progression of aging.) Figure 7-22 indicates that percent gel provides a good indication of the degree of aging through and somewhat beyond 50% E-at-B. Figure 7-23 shows E-at-B, uptake factor, and density. While the uptake factor shows a useful correlation with E-at-B, density is essentially unchanged and does not provide a useful trend. Figure 7-24 shows the correlation of percent gel with E-at-B with 140°C aging.

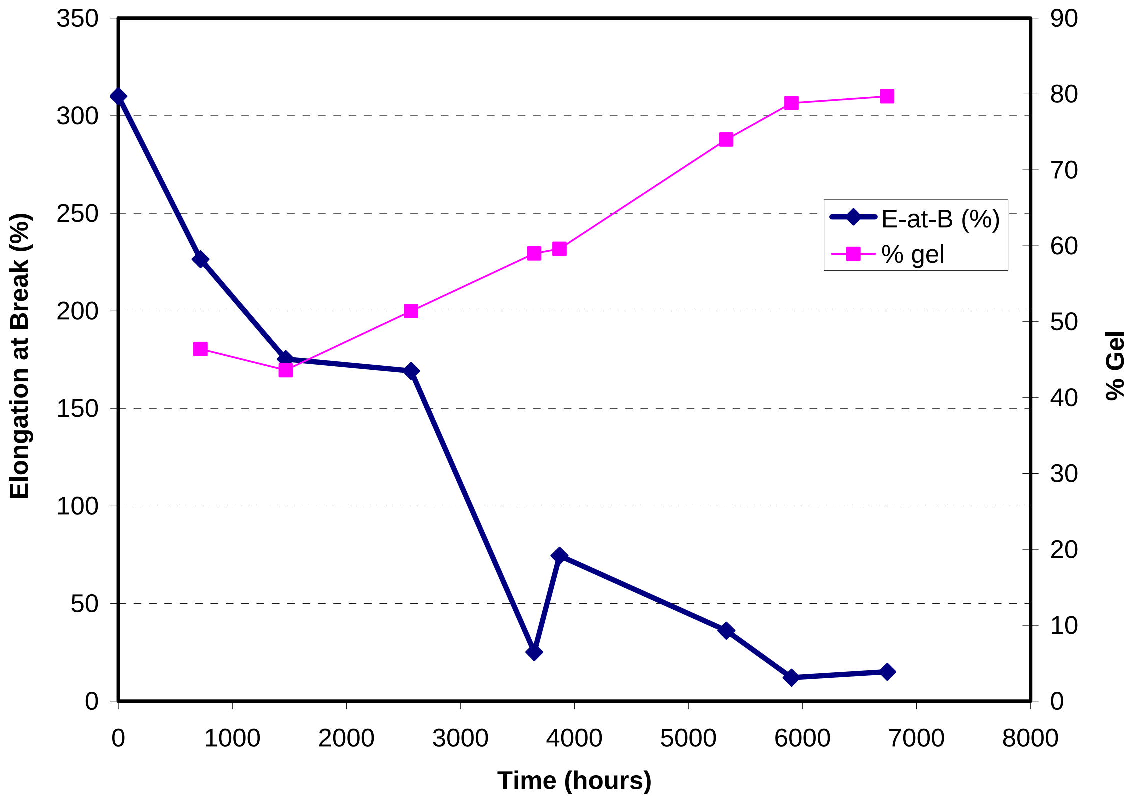


Figure 7-22
Anaconda CPE E-at-B Versus % Gel, 125°C, 0 rd/hr Aging

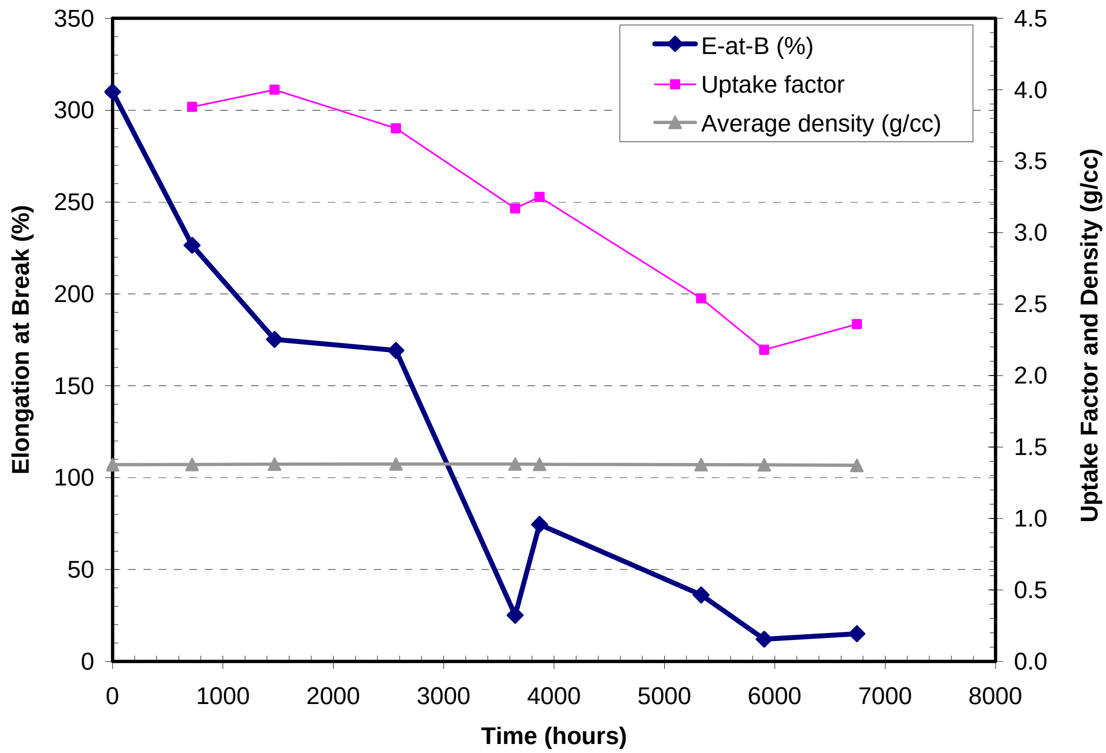


Figure 7-23
Anaconda CPE E-at-B Versus Update Factor and Density, 125°C, 0 rd/hr Aging

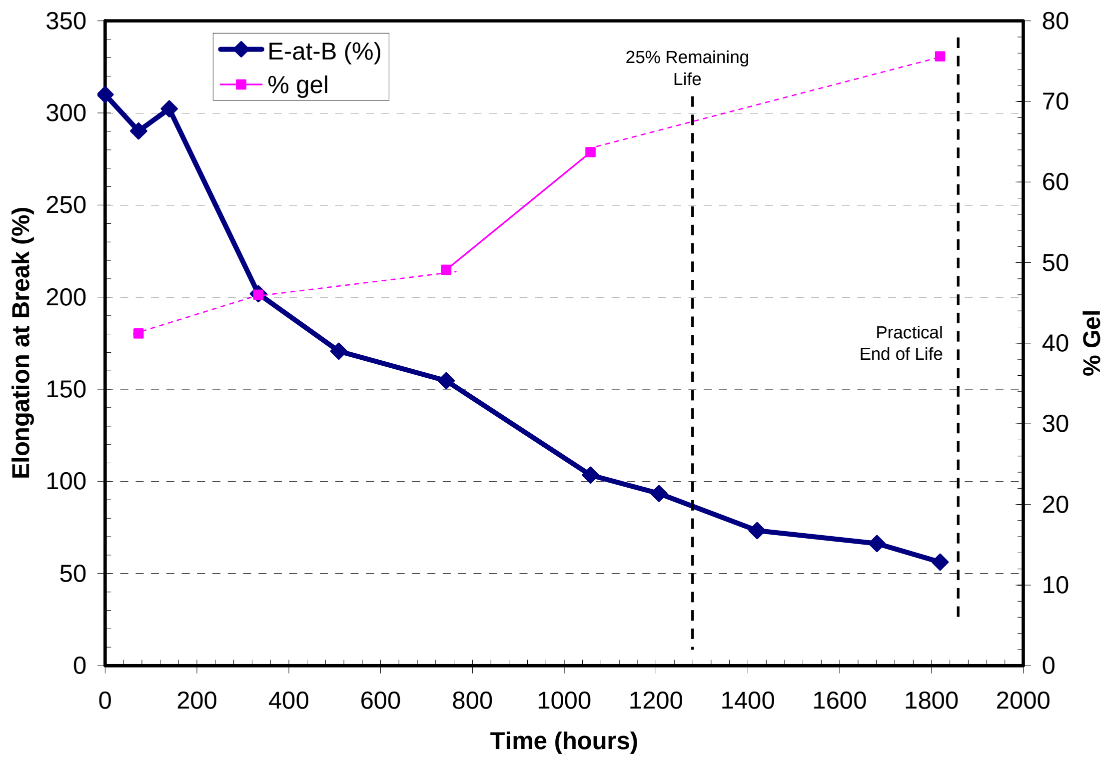


Figure 7-24
Anaconda CPE E-at-B Versus % Gel, 140°C, 0 rd/hr Aging

Figure 7-25 shows the effect of simultaneous irradiation at 70°C at 12.8 and 92 krd/hr; 50% E-at-B is reached at 3500 hours and 45 Mrd at 12.8 krd/hr. At 92 krd/hr, 50% E-at-B is reached at 400 hours and 25 Mrd. In this case, the higher dose rate had a larger effect than the lower dose rate (which is unusual).

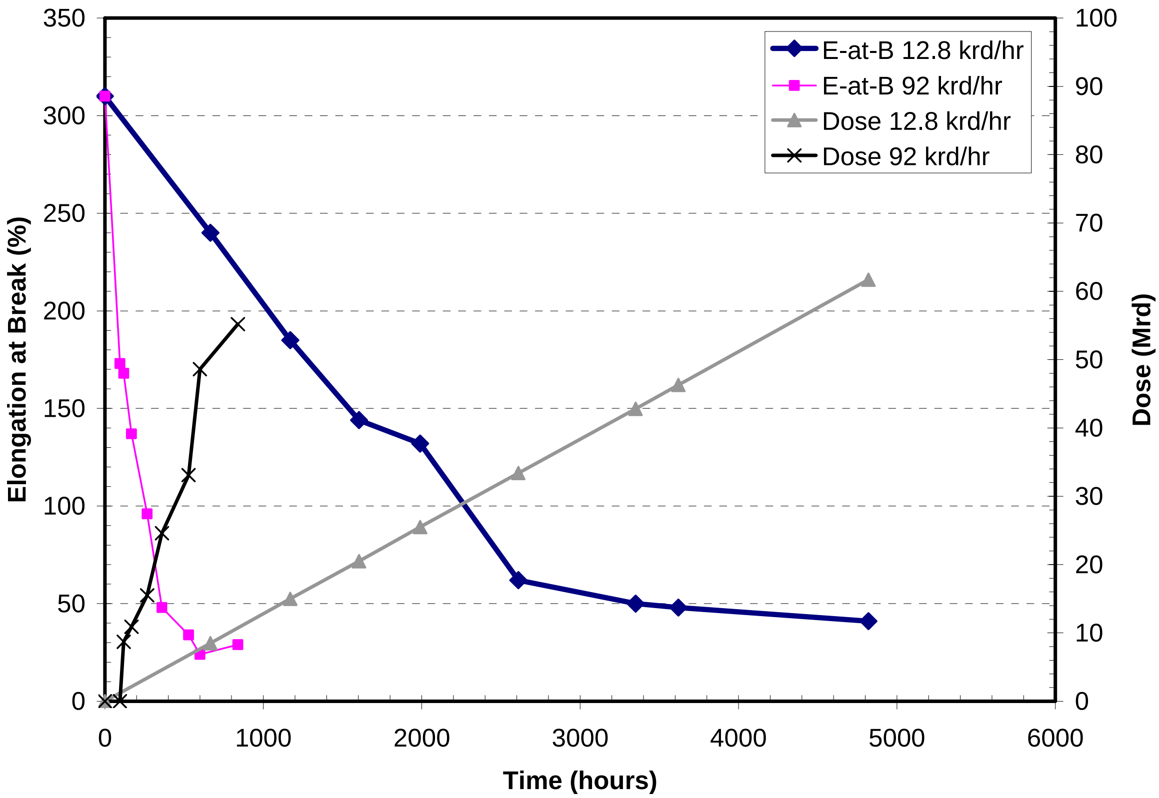


Figure 7-25
Anaconda CPE E-at-B, 70°C Aging with Radiation

7.3 Chlorosulfonated Polyethylene (Hypalon)

Chlorosulfonated polyethylene (CSPE) (Hypalon) has been used as a jacket for nuclear plant cabling. Some cable designs have used it as an insulation (Bostrad 7, Lipalon). A few companies have used it as a conductor insulation jacket over ethylene propylene rubber (EPR) to provide fire-retardant qualities. It is an abrasion-resistant and chemical-resistant rubber.

Degradation Under Thermal Exposures

CSPE has a reasonable thermal life under thermal stress. It is superior to neoprene and comparable to CPE, but has a much shorter thermal life than EPR and XLPE. Depending on the compound, the thermal life of different manufacturers' CSPE varies with 50% E-at-B occurring as soon as 5000 hours at 100°C aging to as many as 10,000 hours. Degradation takes the form of hardening and loss of remaining elongation. Generally, cracking does not occur spontaneously even under extreme aging. However, manipulation at this point will cause cracking, although some effort is required to crack a cable jacket. When used as a bonded conductor jacket over a layer of EPR on a small conductor (for example, 16–10 AWG conductor [2–4.5 mm in diameter], little force is needed to crack a highly aged 15 mil (0.6 mm) layer of CSPE.

Degradation Under Radiation Exposures

Limited data are presented here regarding radiation degradation. CSPE hardens from radiation exposure. Limited effects occur for low doses (<5 Mrd). As is discussed in more detail later in this section in regard to Rockbestos CSPE Jacket (and as shown in Figure 7-45 in that section), 50% E-at-B occurs at 10,000 hours for 100°C aging. When simultaneously irradiated at 6.4 krd/hour, 50% E-at-B occurs at 3500 hours with a 20-Mrd dose.

End-of-Life Data

CSPE typically has an initial E-at-B of 260–400%. The following sections indicate that CSPE materials have moderately long thermal lives. Table 7-3 summarizes thermal life at various temperatures. Not all materials have data available for the same temperatures. Therefore, to allow comparisons, temperatures that apply to two or more materials are provided. The results show that while all CSPEs have moderately long thermal lives at 100°C, the lives vary considerably.

Table 7-3
CSPE Thermal Life Comparison

Manufacturer	Initial E-at-B (%)	Aging Temperature (°C)	Time to 50% E-at-B Remaining (hours)
Anaconda	400	100	7200
BIW	260	100	5800
Brand Rex	380	100	22,000
Kerite	300	101	6818
Samuel Moore Dekoron	380	100	9000
Rockbestos	370	100	10,000

Manufacturer-Specific Aging Data

Anaconda Flameguard Insulation Jacket

These data are for a thin layer of CSPE (0.6 mm/15 mil) used as an insulation jacket. The insulation data are provided in Section 7.5 of this report. Figure 7-26 shows the E-at-B and NMR T2 data at various temperatures with a log scale. The correlation of NMR T2 with E-at-B is excellent and readily decipherable. Figure 7-27 shows the same data on a linear scale with all the data referred to 100°C by multiplying the aging times by the factors shown in the legend to achieve best fit at 50% remaining E-at-B. Figure 7-27 shows that the different aging temperatures did not result in significantly different aging patterns especially as the material is beginning to age significantly (below 150% retained E-at-B). At 50% remaining E-at-B, the NMR T2 has dropped to 3.5–4 msec from the original 10.9 msec. Figure 7-28 shows E-at-B versus edge modulus. Again, the correlation is good. Figure 7-29 shows the same data referred to 100°C. The correlation is strong, but the data are less well-behaved as the material becomes significantly aged (at and below 75–100% remaining E-at-B).

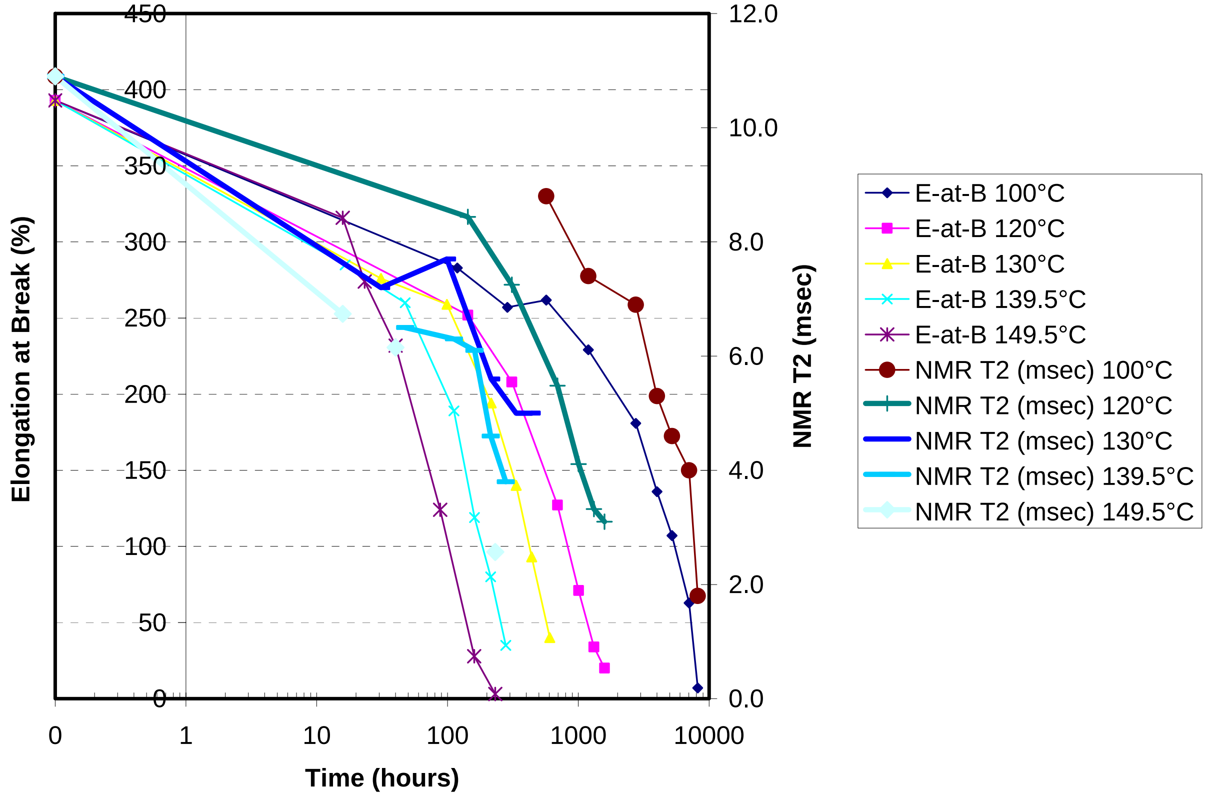
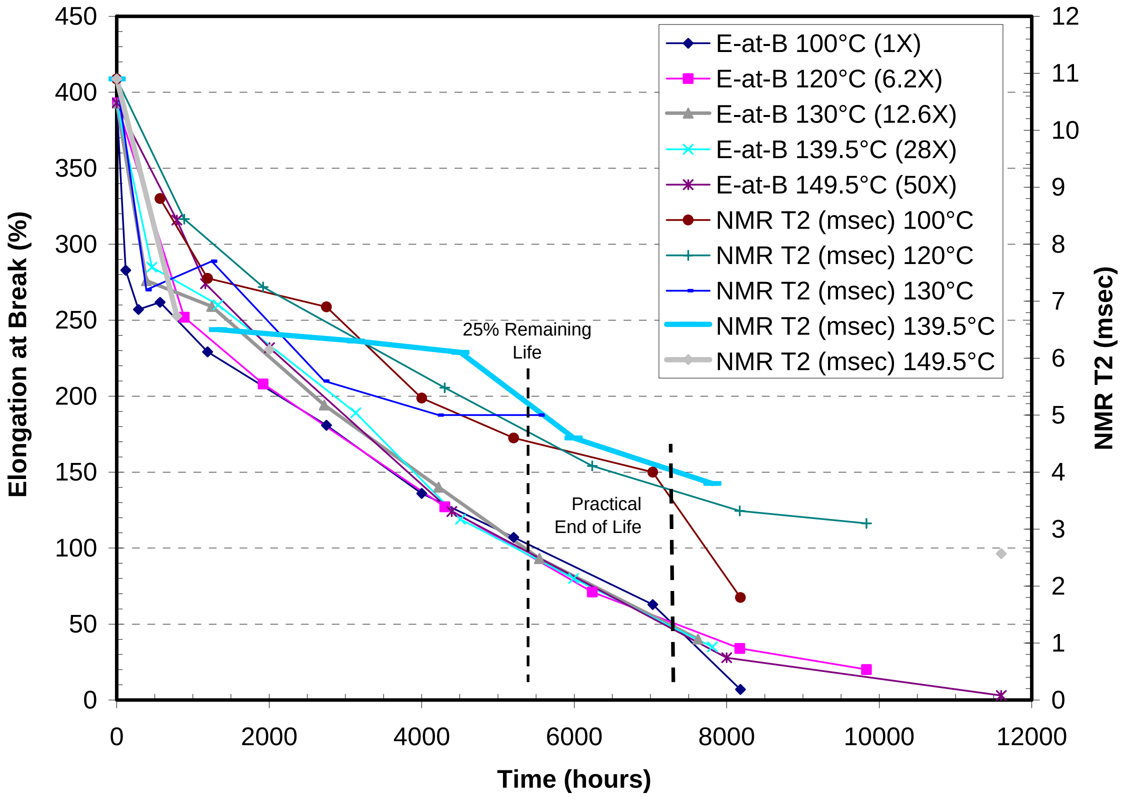


Figure 7-26
Anaconda CSPE E-at-B Versus NMR T2, Various Aging Temperatures



Note: Time multipliers (for example, 1X, 6.2X) are shown for each temperature to superpose to 100°C.

Figure 7-27
Anaconda CSPE E-at-B Versus NMR T2 with Aging Temperatures Superposed to 100°C

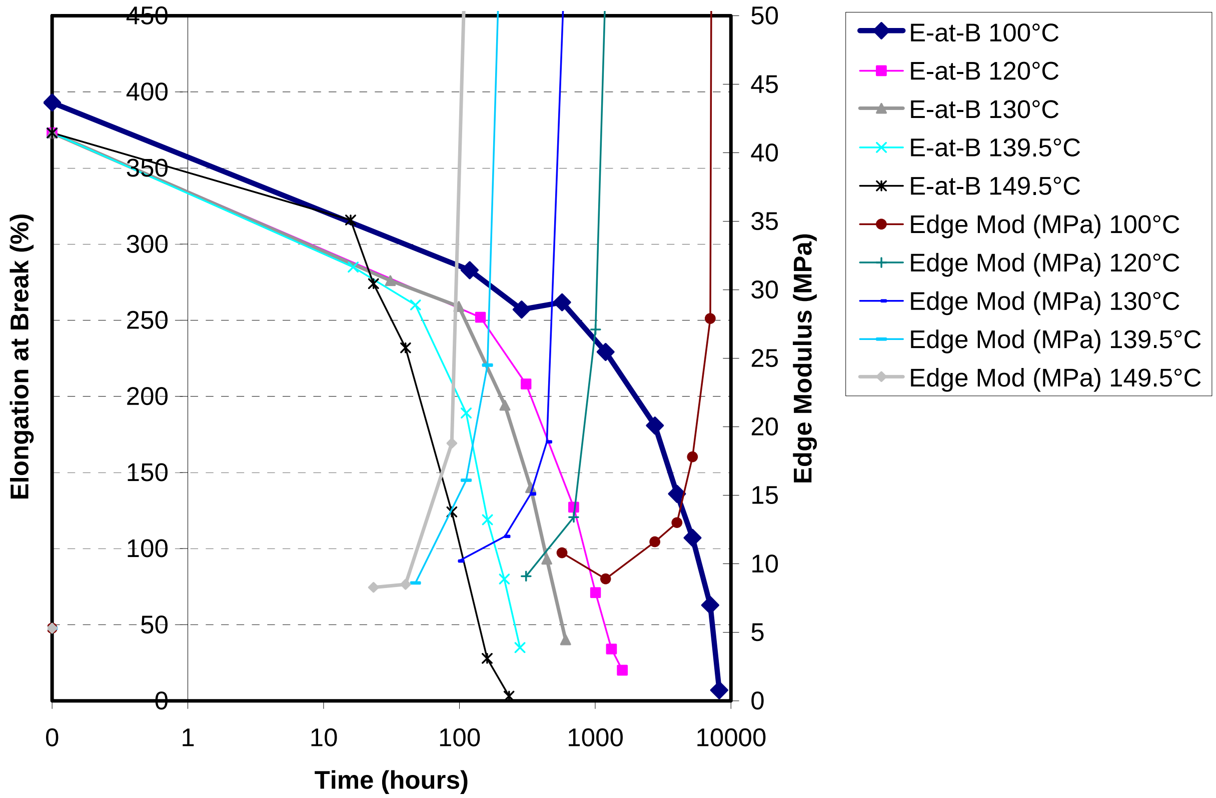


Figure 7-28
Anaconda CSPE E-at-B Versus Edge Modulus, Various Aging Temperatures

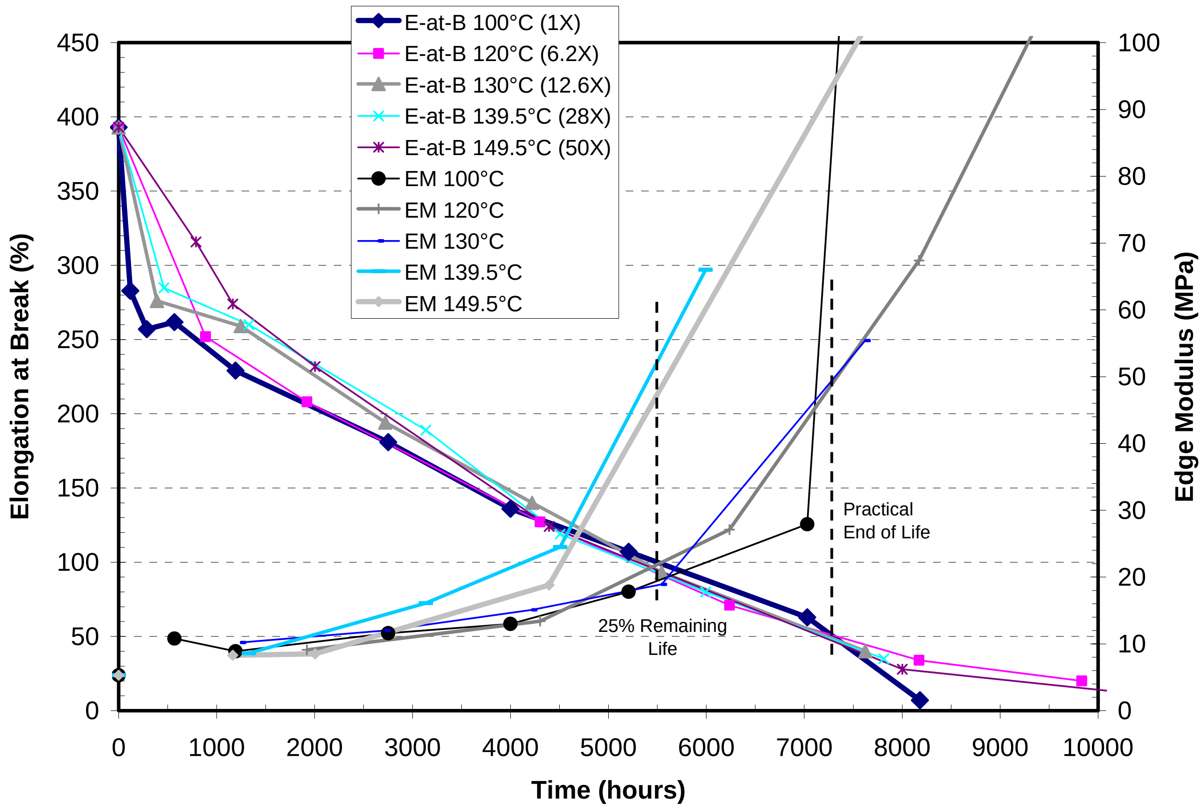


Figure 7-29
Anaconda CSPE E-at-B Versus Edge Modulus, Superposed to 100°C

BIW Overall Jacket

Figure 7-30 shows E-at-B at various temperatures referred to 100°C for the overall BIW CSPE jacket. There is a scatter in the data in the early stages of aging where different results occur for different test batches. However, after moderate degrees of aging, the data settle out and the plots become similar. Figure 7-31 shows superposed E-at-B along with density. The density data are not well-behaved, partly because the material may not be aging uniformly through its depth at higher thermal aging rates and the bulk density may increase less. However, the drop in density at higher degrees of aging is more disturbing and makes density measurement less useful for this material. Figure 7-32 shows that the correlation of E-at-B with edge modulus is good. At high levels of degradation, the correlation of E-at-B to edge modulus breaks down due to the rapid increase in the edge modulus. However, high edge modulus is definitely indicative of severe aging.

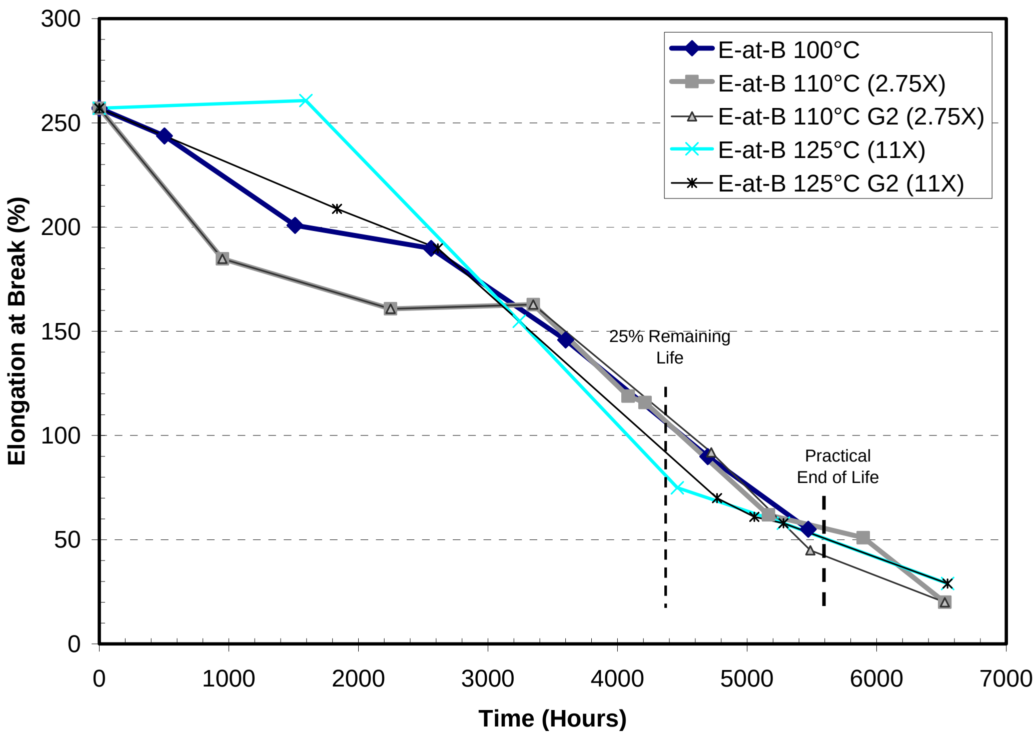


Figure 7-30
BIW Jacket E-at-B Under Thermal Aging, Superposed to 100°C

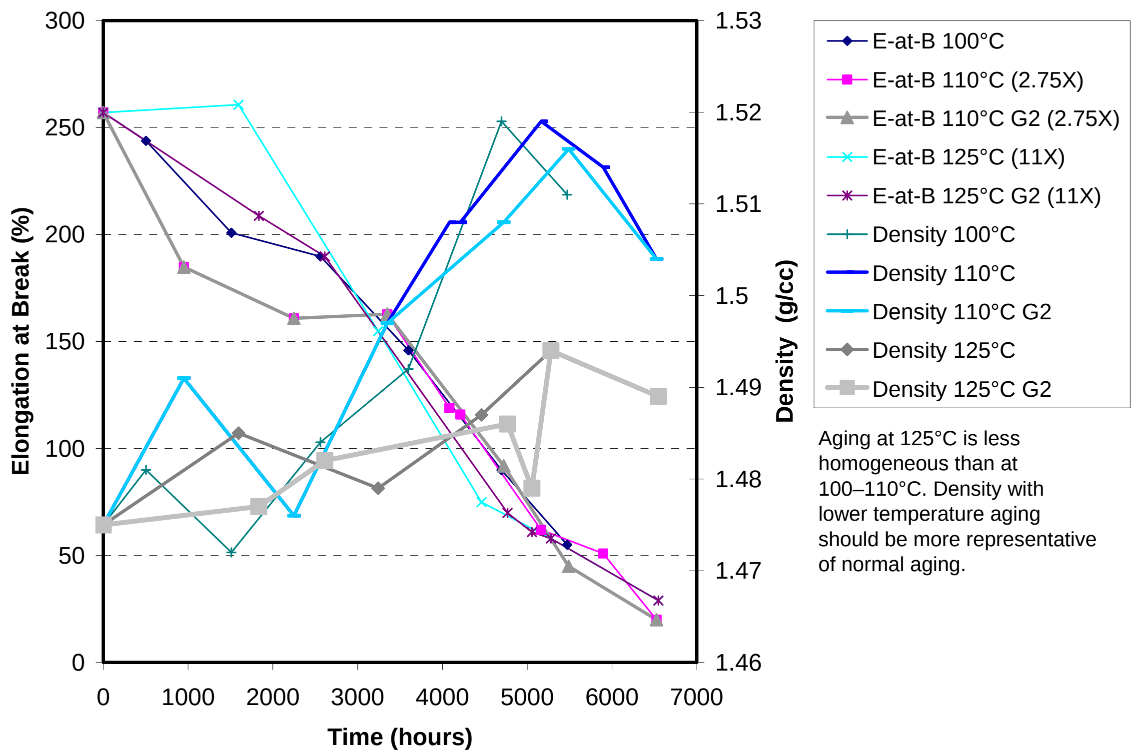


Figure 7-31
BIW Jacket E-at-B Versus Density, Superposed to 100°C

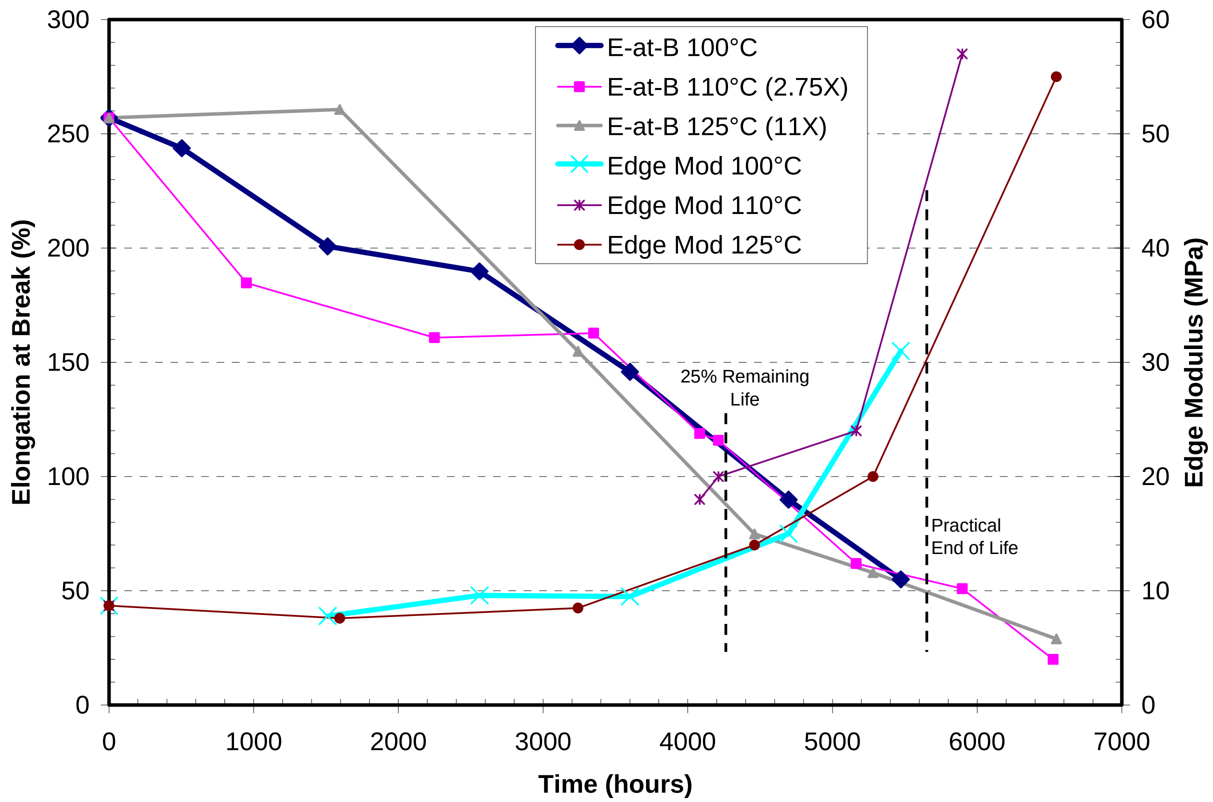


Figure 7-32
BIW Jacket E-at-B Versus Edge Modulus, Superposed to 100°C

Figure 7-33 shows the correlation between E-at-B and the uptake factor. The correlation is good, but resolution is limited. Below 50% remaining elongation, resolution is lost totally. Figure 7-33 provides the correlation between E-at-B and the uptake factor with the data superposed to 100°C. The uptake factor correlates well with E-at-B, but may suffer from a lack of resolution. Figure 7-34 shows the correlation between E-at-B and percent gel. While there is an obvious correlation, resolution is not ensured and, at higher levels of aging, there is no discrimination between degrees of degradation.

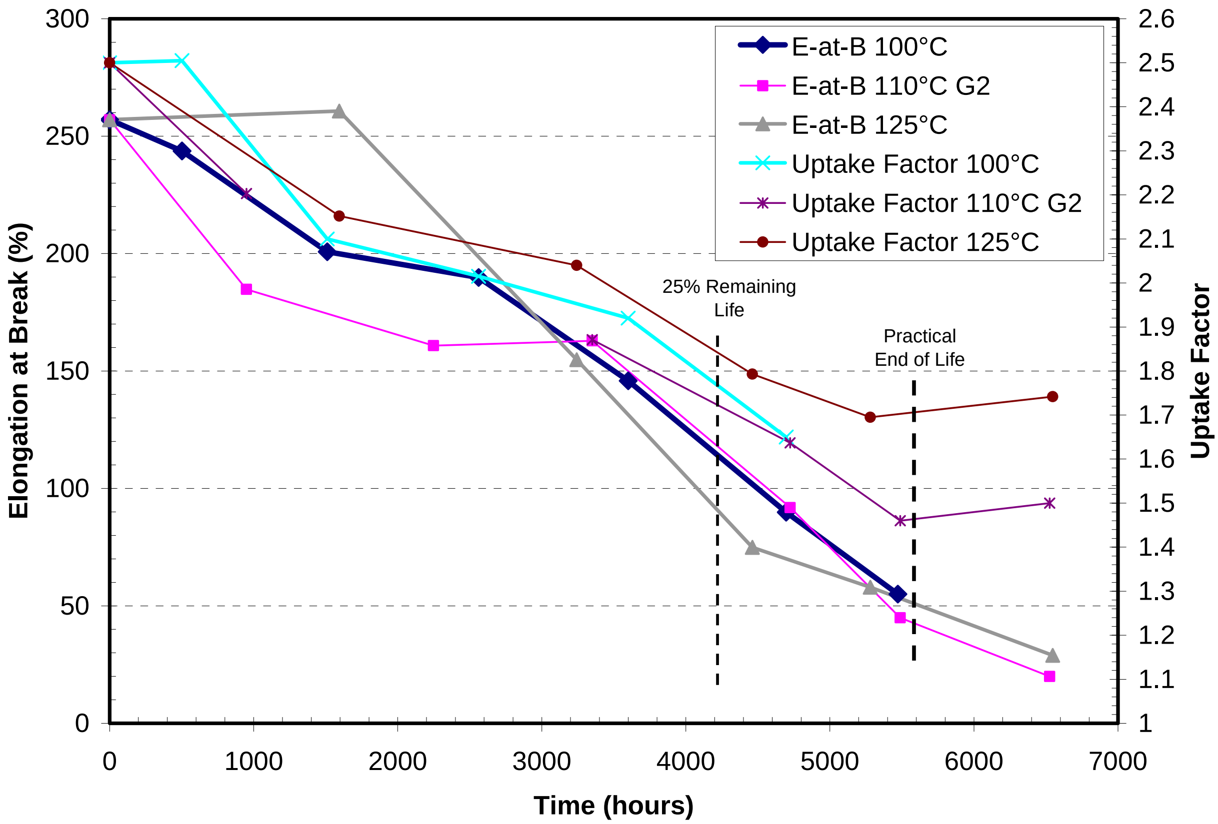


Figure 7-33
BIW Jacket E-at-B Versus Uptake Factor, Superposed to 100°C

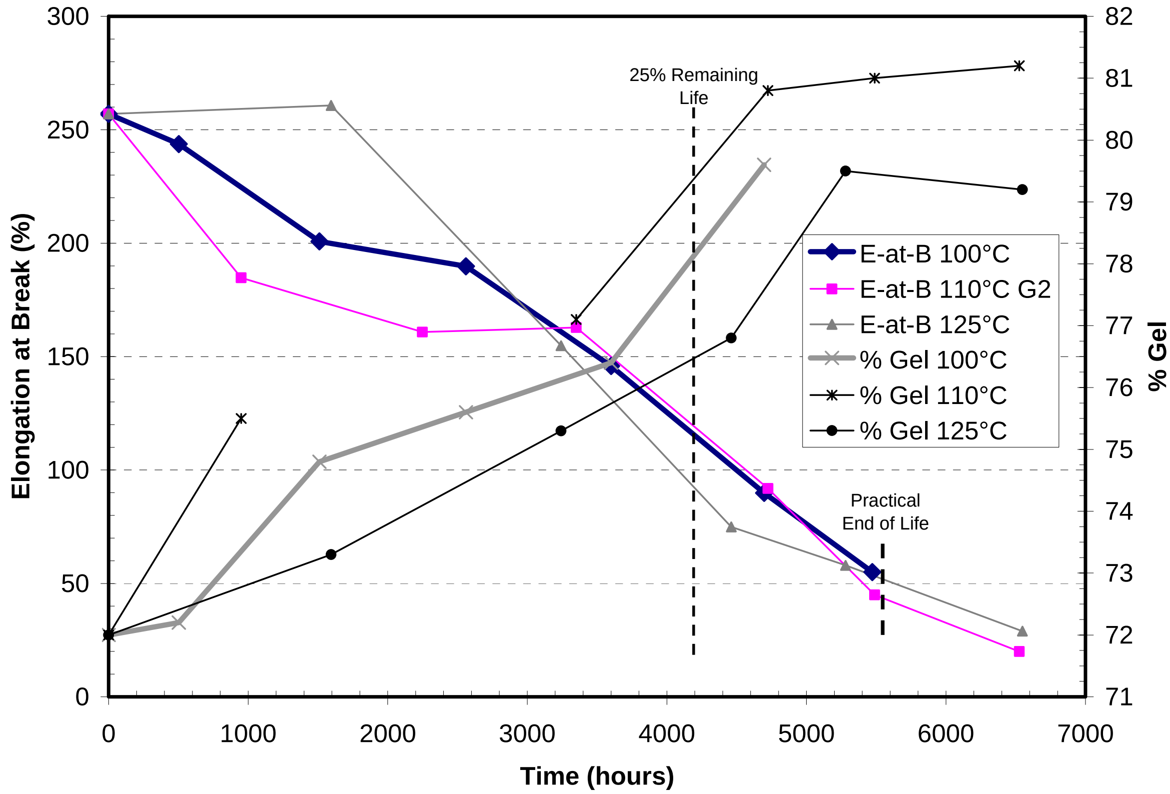


Figure 7-34
BIW Jacket E-at-B Versus % Gel, Superposed to 100°C

Brand Rex Jacket

Figure 7-35 shows E-at-B for a Brand Rex CSPE jacket. The reason for the variability of the data is not known. Figure 7-36 shows the 124°C curve superposed upon the 99°C curve. The variability of the 99°C curve limits any analysis that is possible.

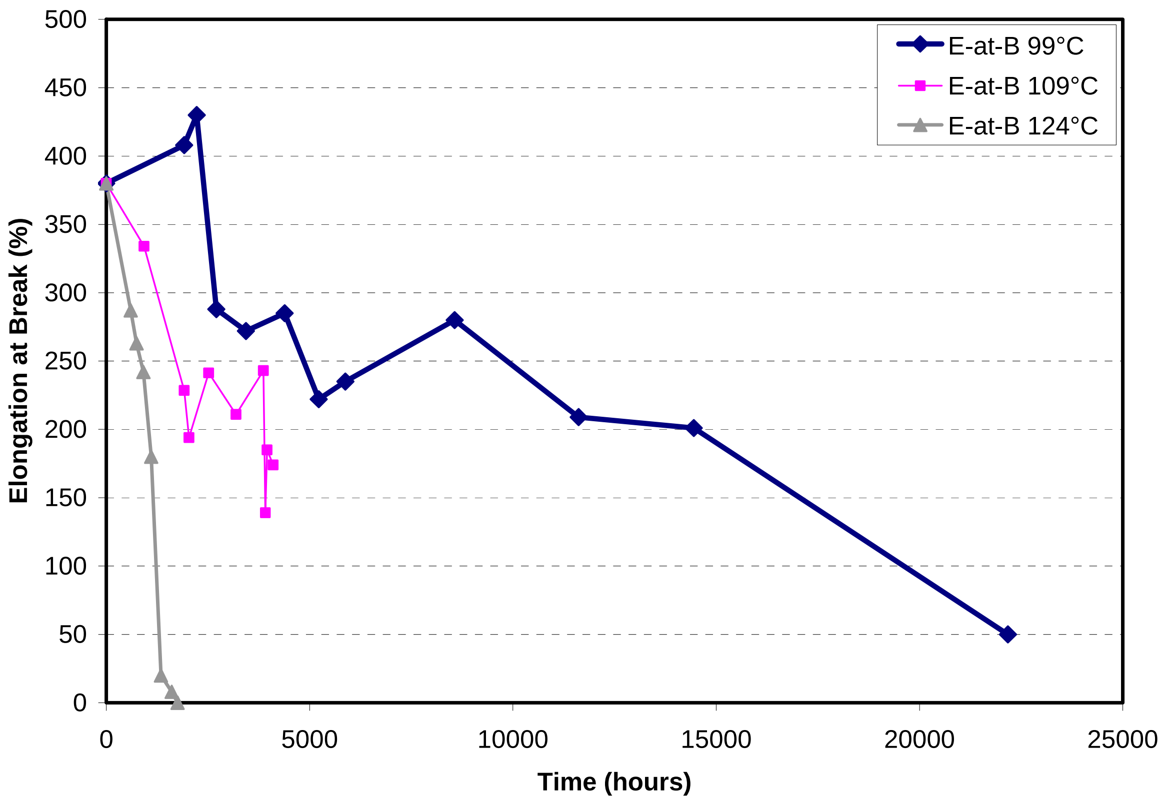


Figure 7-35
Brand Rex Jacket E-at-B, Various Aging Temperatures

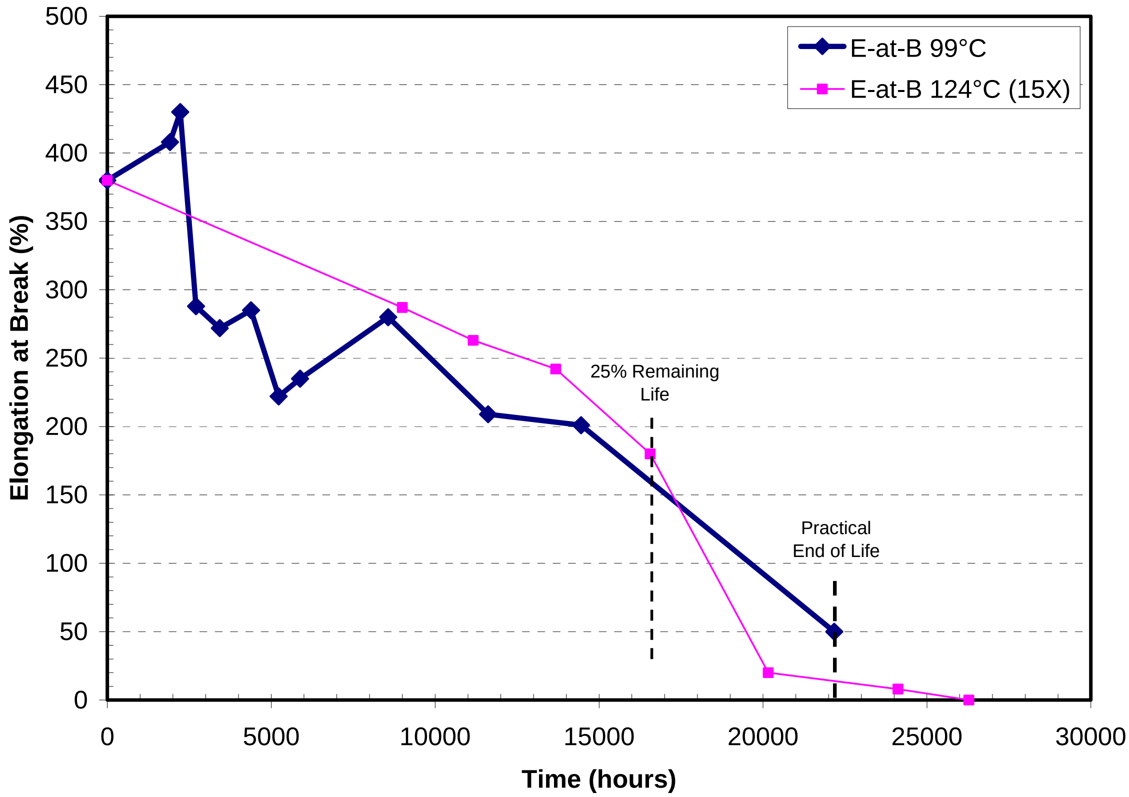


Figure 7-36
Brand Rex Jacket E-at-B, Various Temperatures Superposed

Kerite

Figure 7-37 shows the E-at-B related to numerous aging temperatures on a log scale. Figure 7-38 shows these data superposed to 91°C on a linear scale. The curves show agreement at all temperatures. Accordingly, there is little concern for changes in degradation at various aging rates in accelerated aging of this CSPE material.

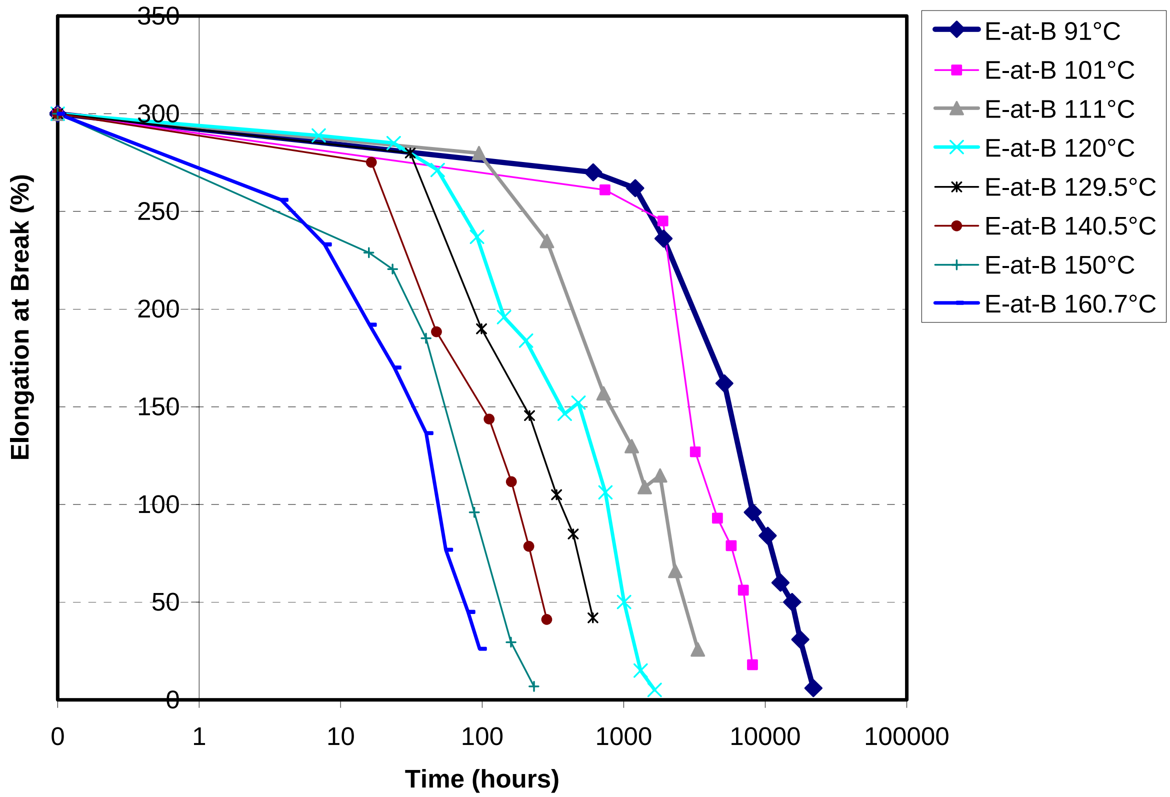


Figure 7-37
Kerite CSPE Outer Jacket E-at-B, Various Aging Temperatures

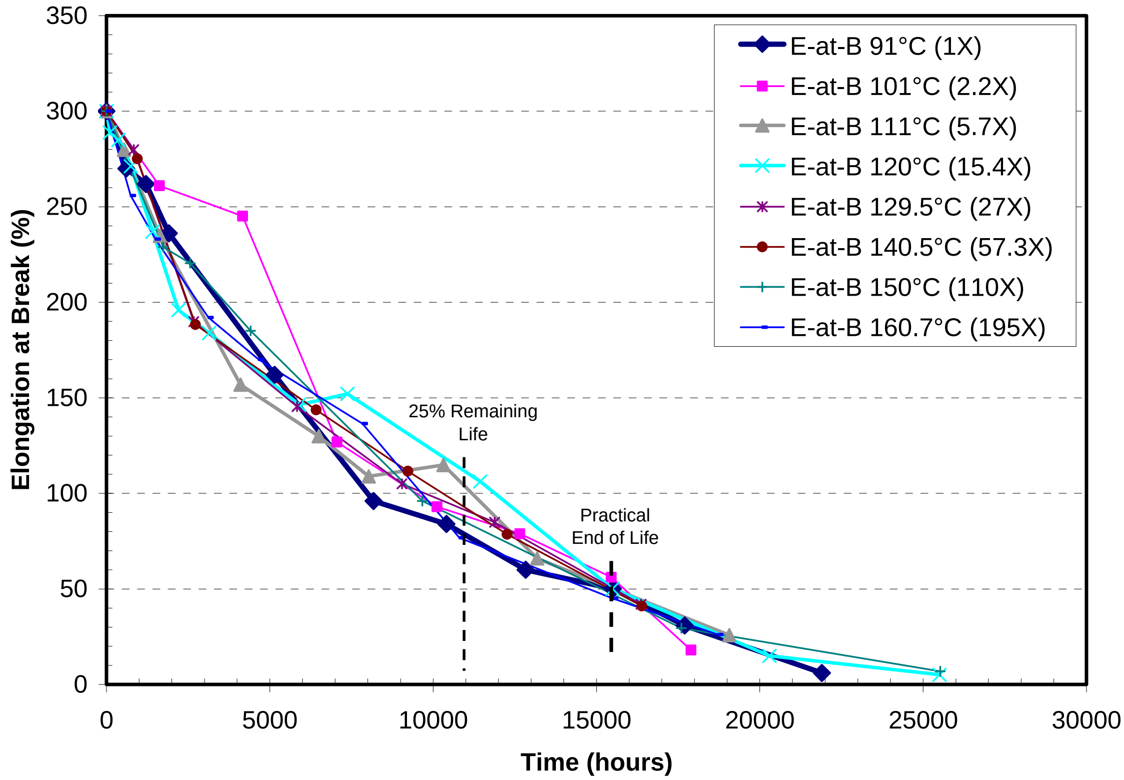


Figure 7-38
Kerite CSPE Outer Jacket E-at-B, Time Superposed to 91°C

Okonite Outer Jacket

Figure 7-39 shows indenter modulus for Okonite outer CSPE jackets of various thicknesses. Wall jackets of 45-mil thickness are used for control cables. Walls of 65-mil thickness are used as the jackets of 750 KCM single conductor insulations. Walls of 100-mil thickness are used as the outer jackets of 4/0 AWG, three-conductor cables. The plots for the 45-mil and 65-mil thicknesses, which would be the more commonly used jackets, are very similar. In this case, 42 N/mm has been taken as the modulus where 50% E-at-B (practical end of life) occurs based on CSPE failure in the CSPE/EPR. Based on that point, 25% remaining life occurs at 33 N/mm.

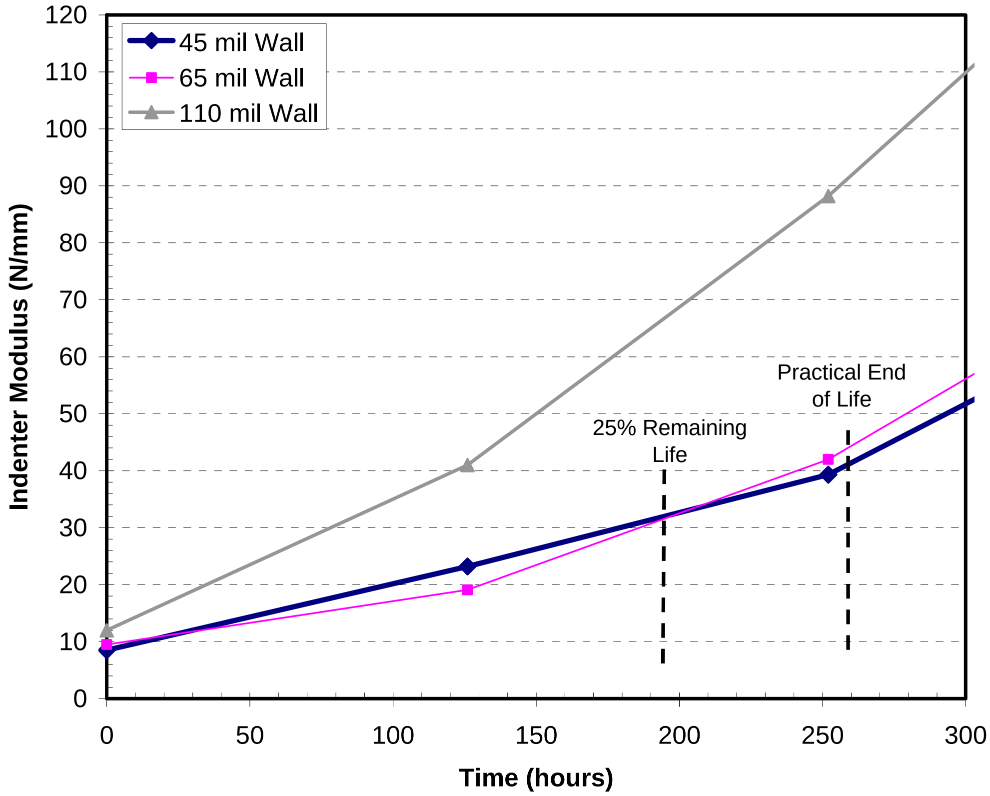


Figure 7-39
Okonite CSPE Outer Jacket, Indenter Modulus, 150°C Aging

Rockbestos CSPE Jacket

Figure 7-40 shows the E-at-B for a Rockbestos CSPE jacket at 100°C, 110°C, and 125°C. At 100°C, degradation to 50% remaining E-at-B took approximately 10,000 hours. Figure 7-41 shows E-at-B versus density at 110°C and 125°C superposed to 100°C. The density change shows a strong inverse correlation with E-at-B with reasonable resolution. Figure 7-42 shows E-at-B and edge modulus superposed to 100°C. Again, there is a strong inverse correlation with E-at-B and reasonable resolution through most of the aging. In severe aging, the edge modulus increases very quickly, reducing resolution in the correlation with E-at-B. Figure 7-43 shows E-at-B versus the uptake factor. There is a strong correlation between the two, but the scatter in the uptake factor data is high. Figure 7-44 shows E-at-B versus percent gel having an inverse correlation. Again, the scatter in the percent gel data is high.

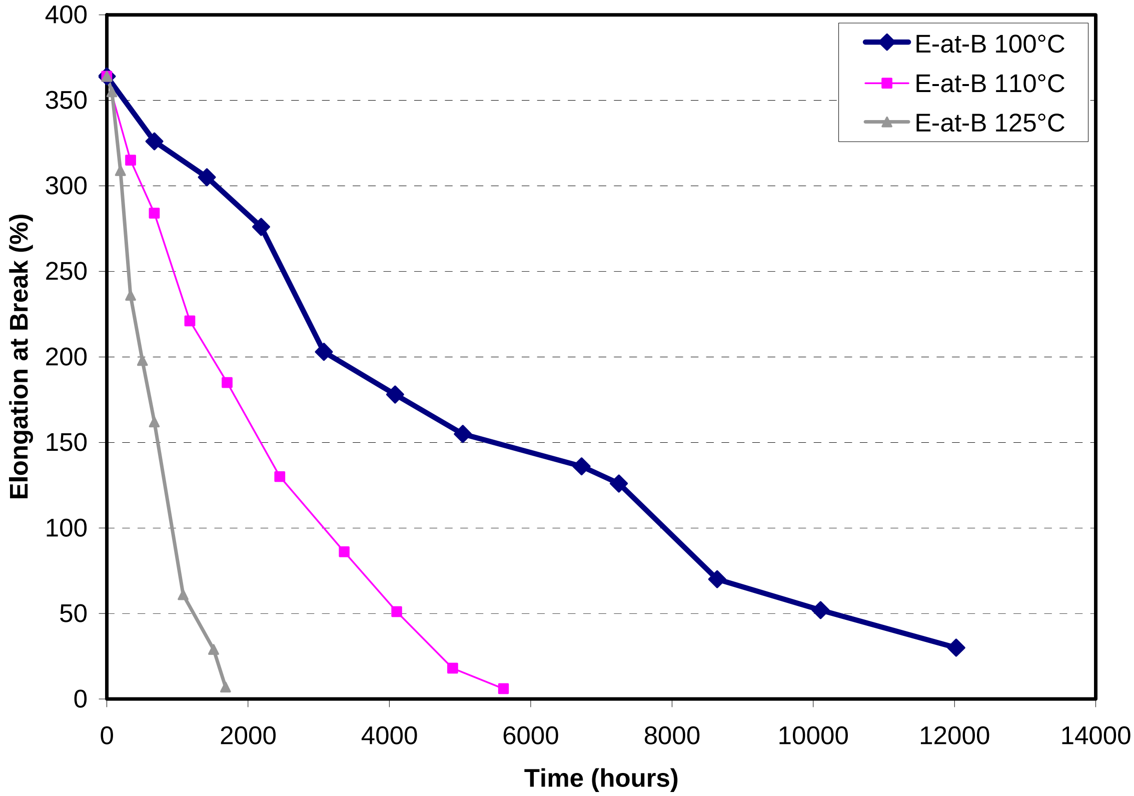


Figure 7-40
Rockbestos CSPE Jacket E-at-B, Various Aging Temperatures

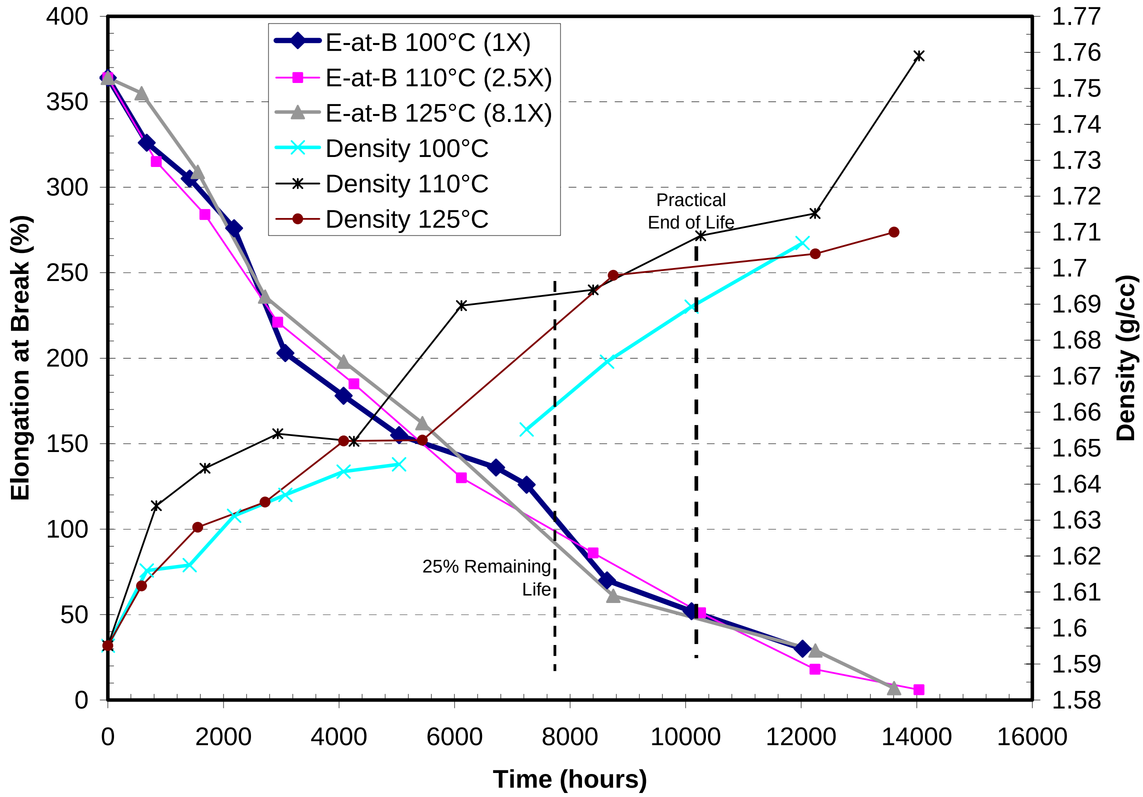


Figure 7-41
Rockbestos CSPE Jacket E-at-B Versus Density, Superposed to 100°C

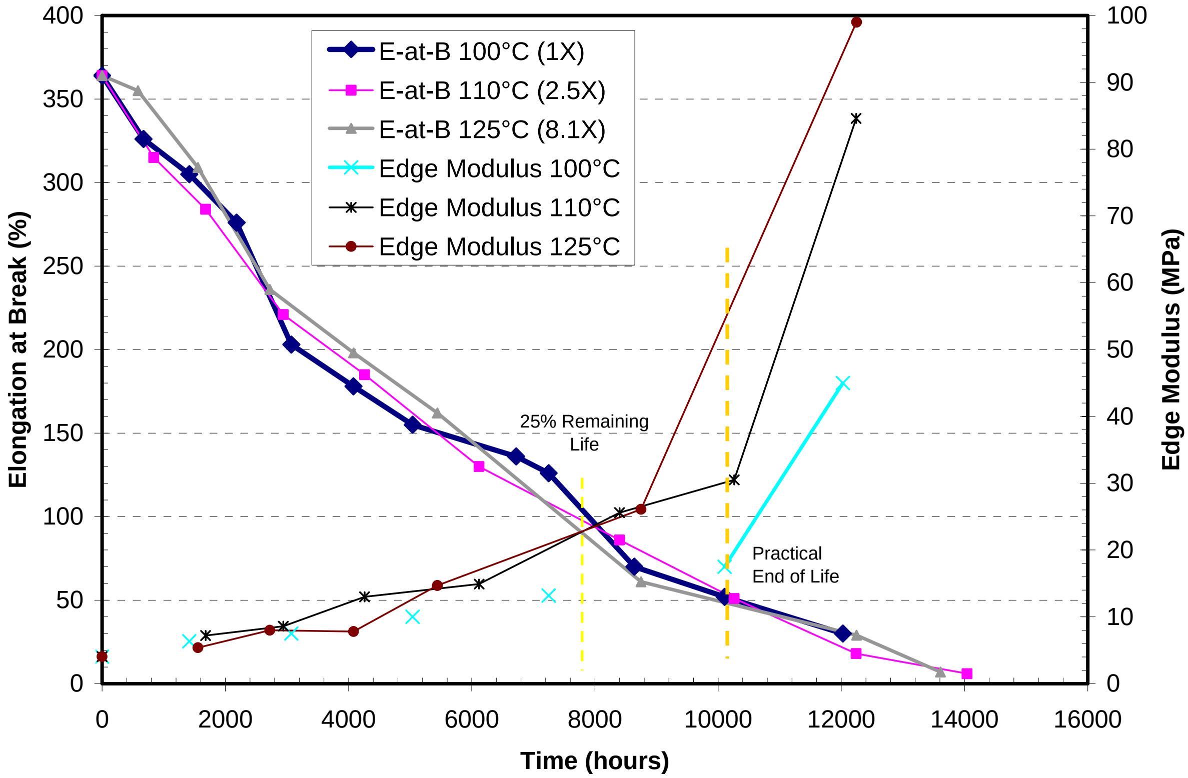


Figure 7-42
Rockbestos CSPE Jacket E-at-B Versus Edge Modulus, Superposed to 100°C

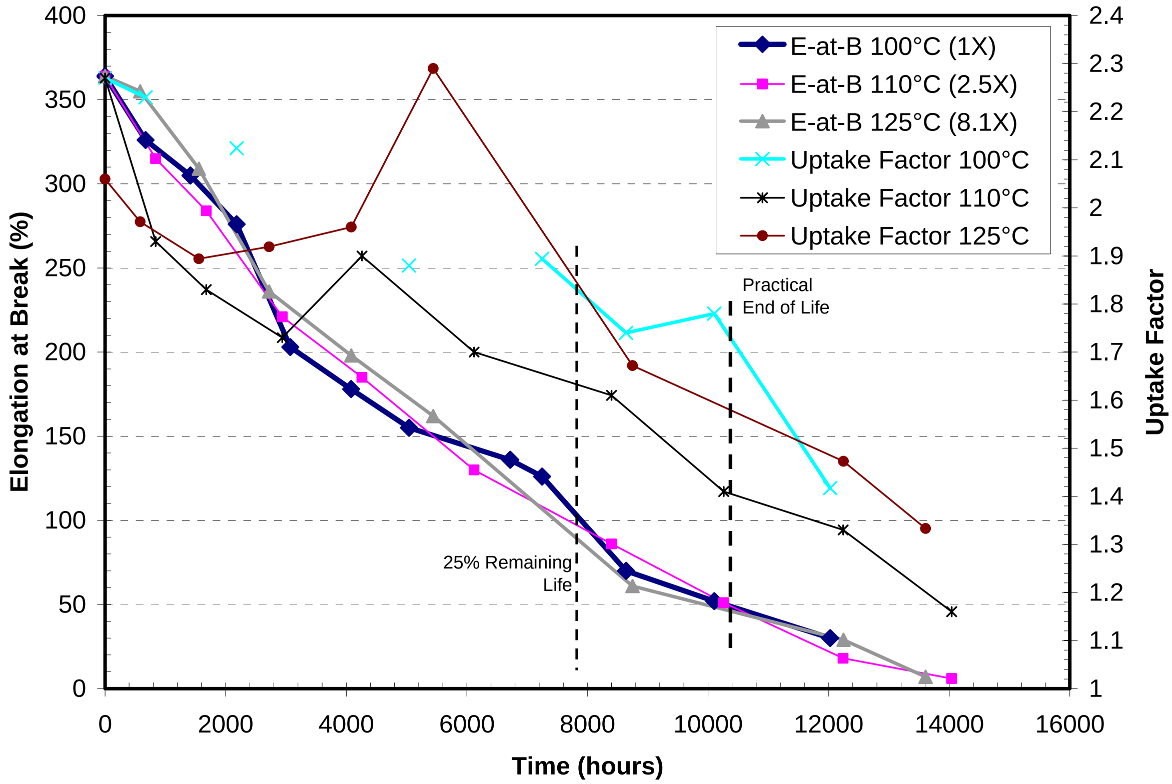


Figure 7-43
Rockbestos CSPE Jacket E-at-B Versus Uptake Factor, Superposed to 100°C

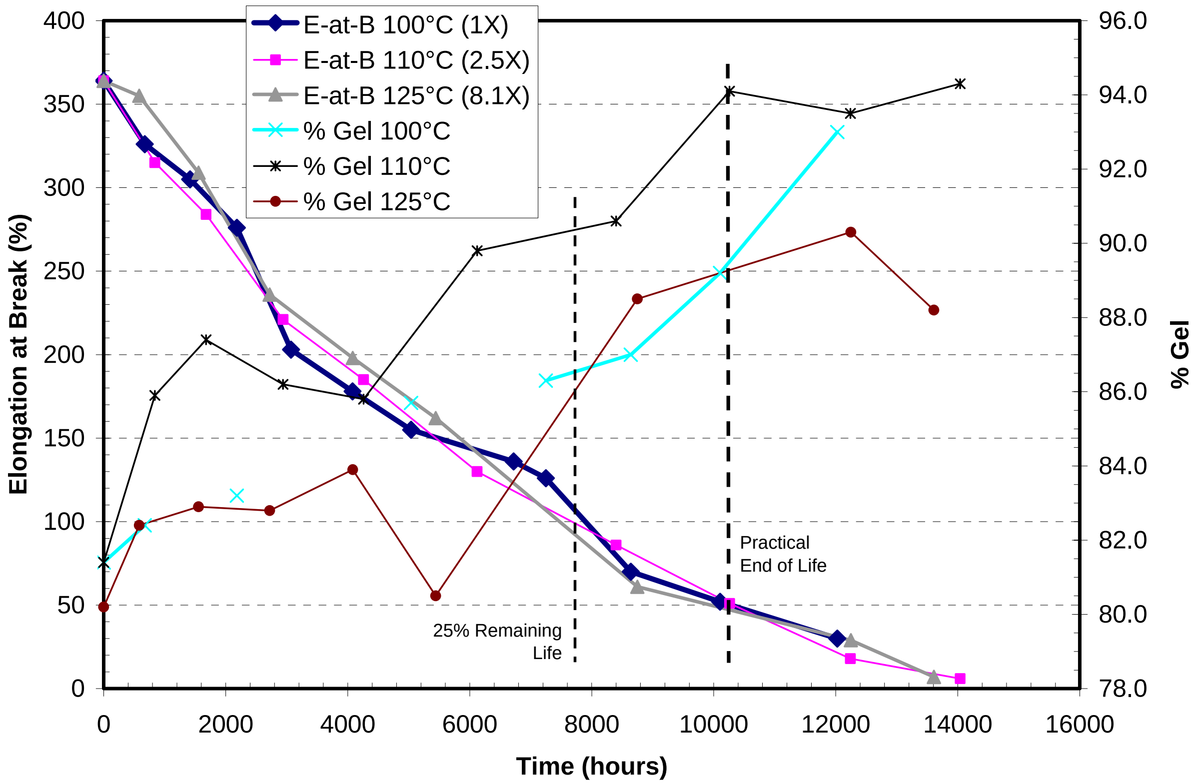


Figure 7-44
Rockbestos CSPE Jacket E-at-B Versus % Gel, Superposed to 100°C

Figure 7-45 shows the effect of simultaneous radiation and thermal aging versus thermal aging alone at 100°C. Under pure thermal aging, 50% E-at-B occurs at 10,000 hours. When 6.4 krd/hr irradiation is applied simultaneously, 50% E-at-B occurs at 3200 hours with a 20-Mrd dose.

Figure 7-46 shows indenter modulus versus aging at 142°C. At 50% E-at-B, the IM increases to 24 N/mm from 8 N/mm when unaged.

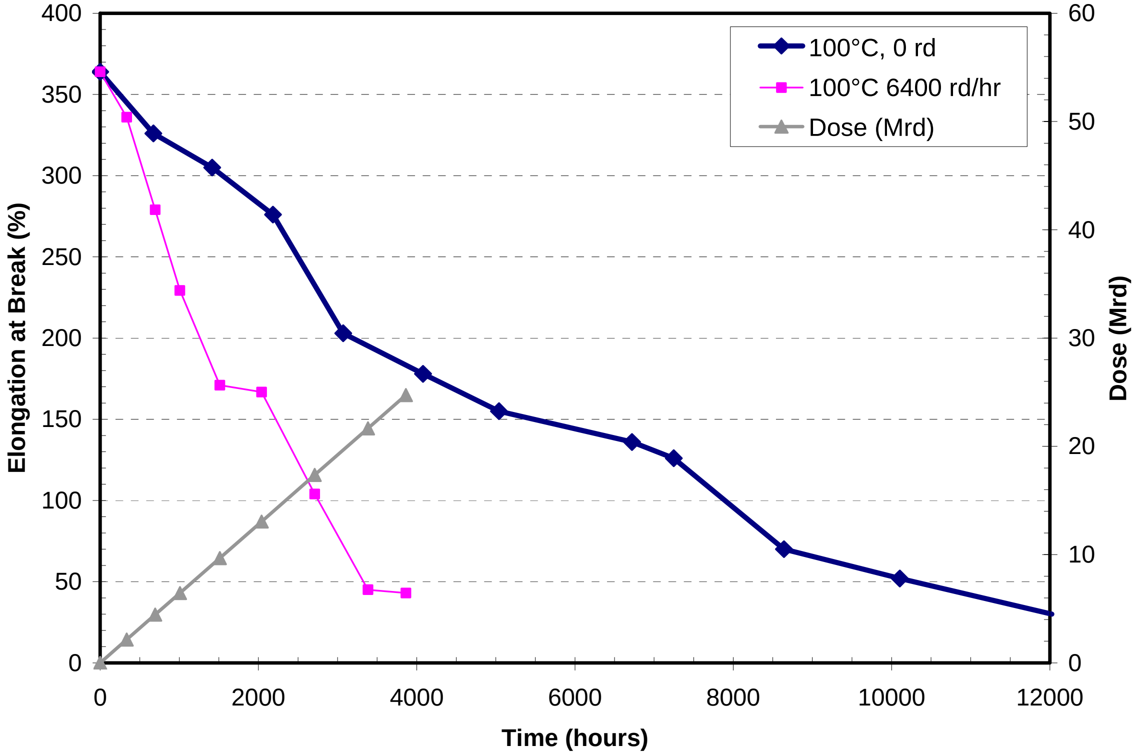


Figure 7-45
Rockbestos CSPE Jacket Effect of Radiation, 100°C, 6.4 krd/hr Aging

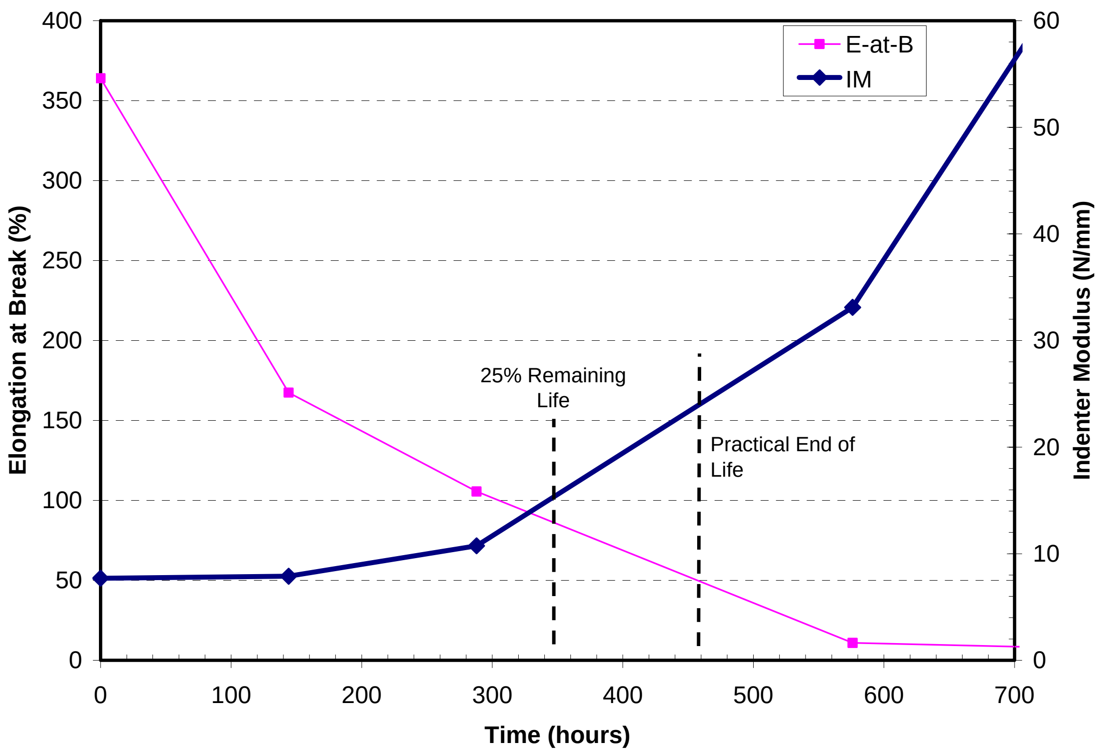


Figure 7-46
Rockbestos CSPE Jacket E-at-B Versus Indenter Modulus, 142°C Thermal Aging

Samuel Moore Dekoron Jacket

Figure 7-47 shows E-at-B for aging of the Dekoron CSPE jacket material at 100°C, 110°C, and 125°C. Ignoring the anomalies in the early portions of the 100°C and 125°C curves, the aging curves have similar shapes. Figure 7-48 shows the data superposed to 100°C with density data as well. The correlation of the E-at-B data with the density data is strong, although there is some scatter in the data. Figure 7-49 shows the correlation between E-at-B and uptake factor. There is a strong correlation and the resolution appears to be reasonably good. Figure 7-50 shows the correlation of E-at-B with percent gel. While there is a correlation, the variability of the results is a concern and the lack of resolution at advanced aging would limit the use of the test for this material. Figure 7-51 shows the correlation of E-at-B with edge modulus. The correlation is strong and the resolution is good until the point of very advanced aging.

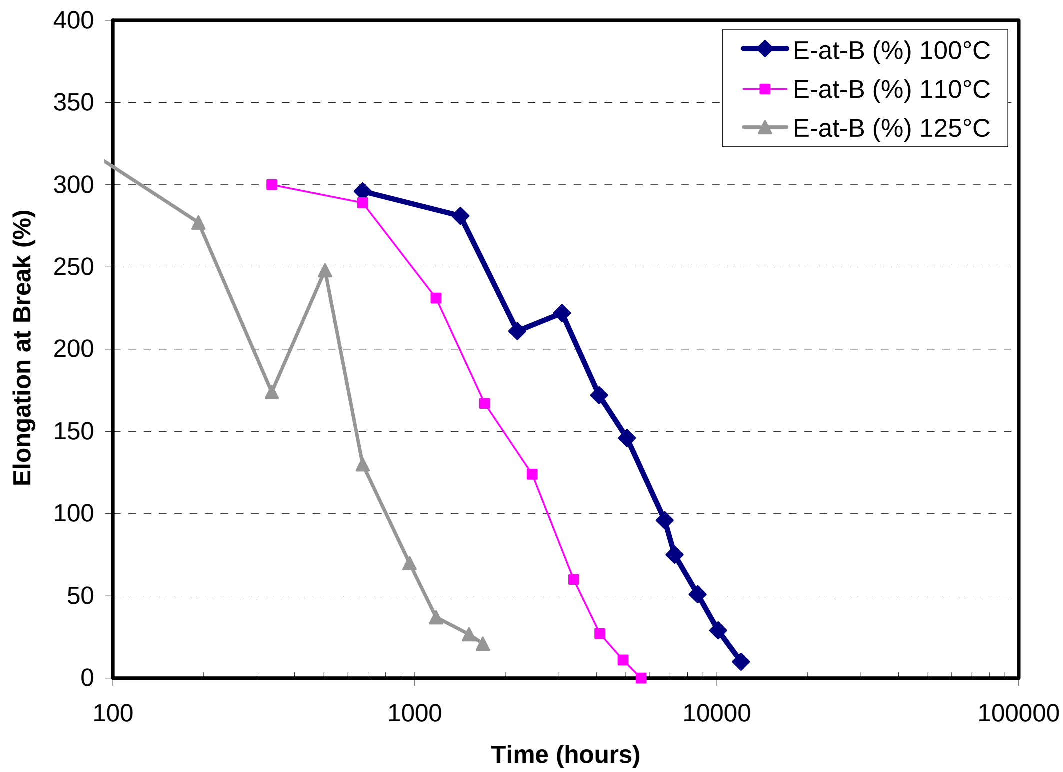


Figure 7-47
Samuel Moore Dekoron CSPE E-at-B, Various Aging Temperatures

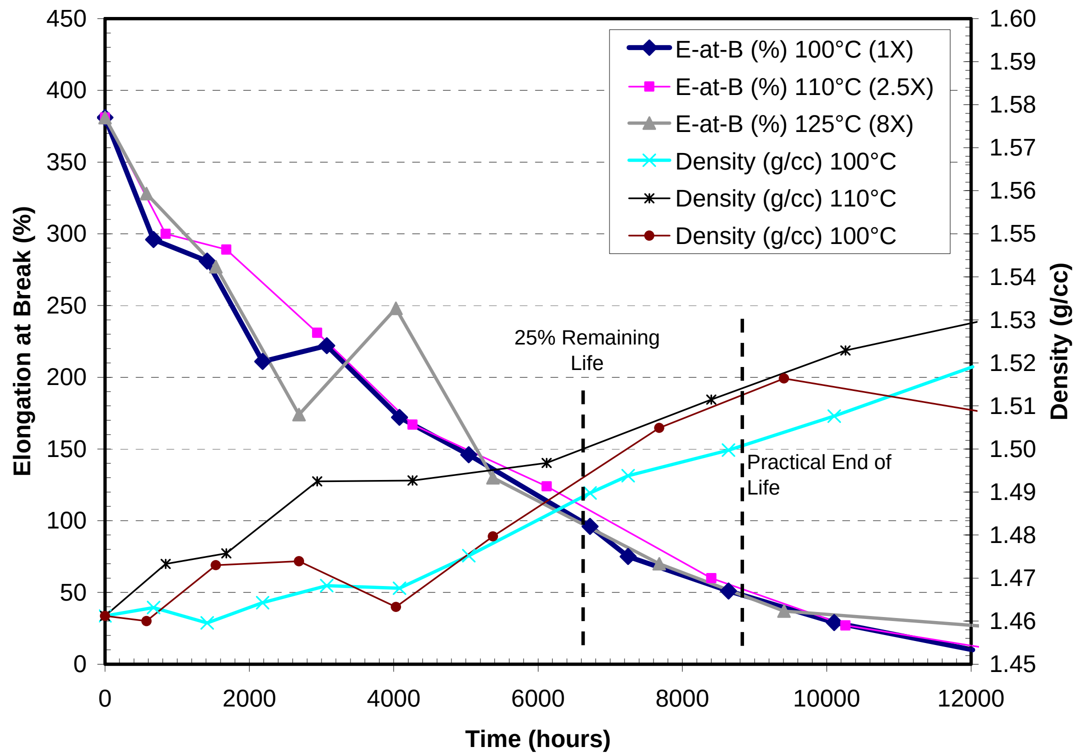


Figure 7-48
Samuel Moore Dekoron CSPE E-at-B Versus Density, Superposed to 100°C

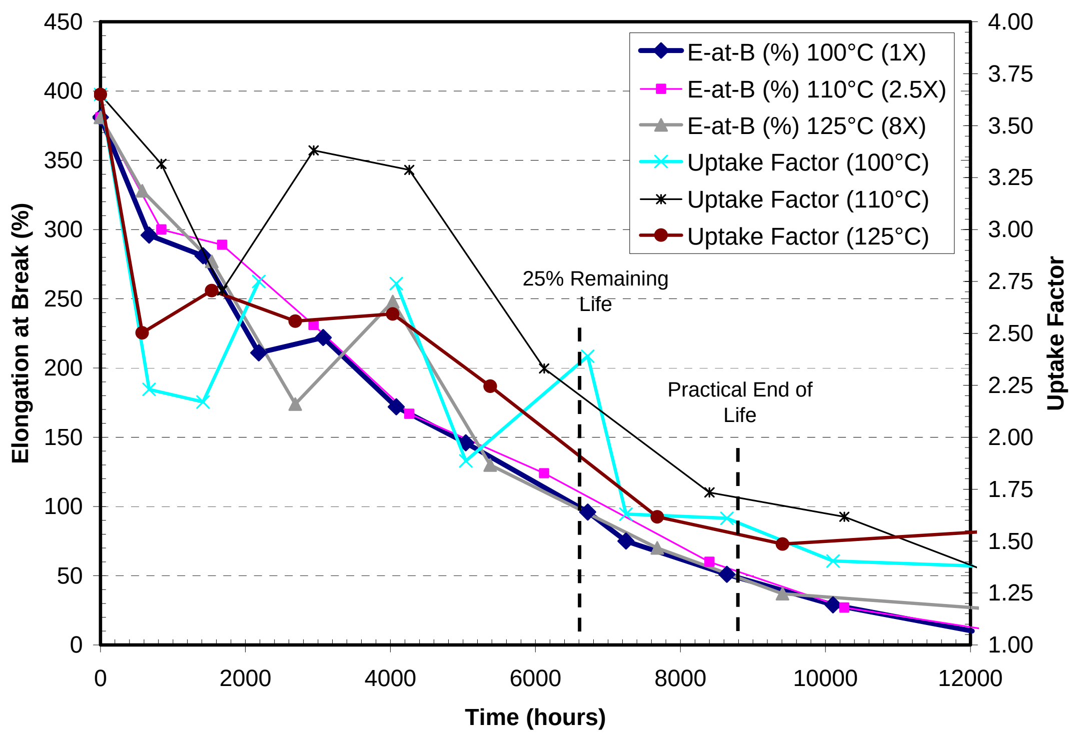


Figure 7-49
Samuel Moore Dekoron CSPE E-at-B Versus Uptake Factor, Superposed to 100°C

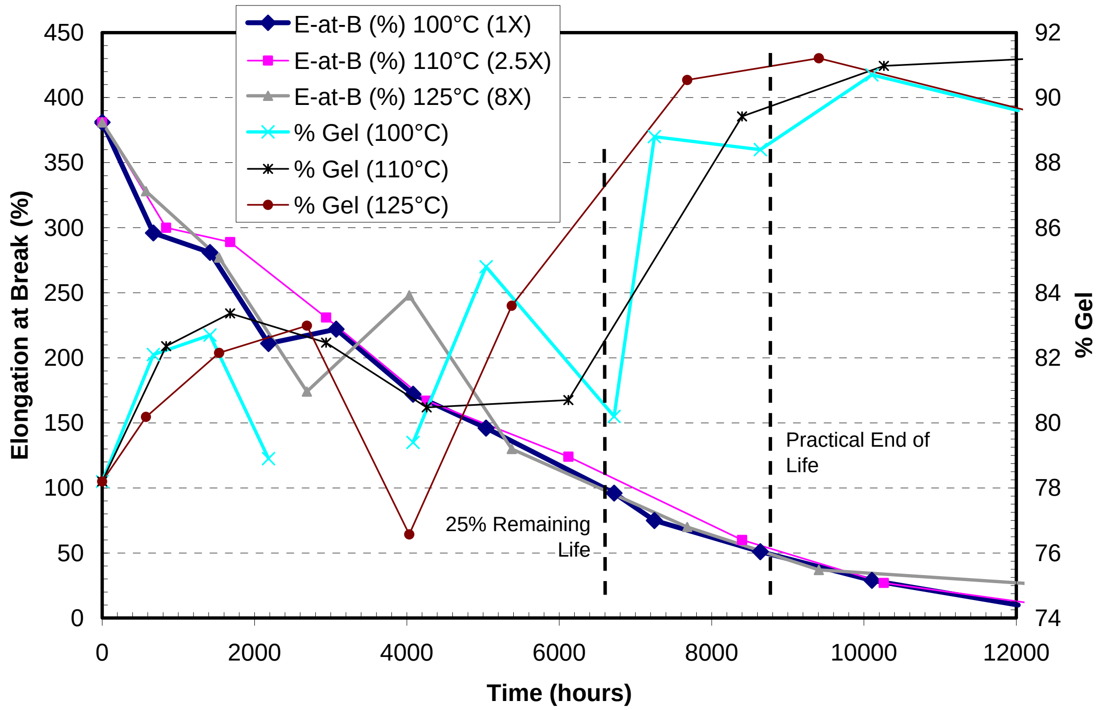


Figure 7-50
Samuel Moore Dekoron E-at-B Versus % Gel, Superposed to 90°C

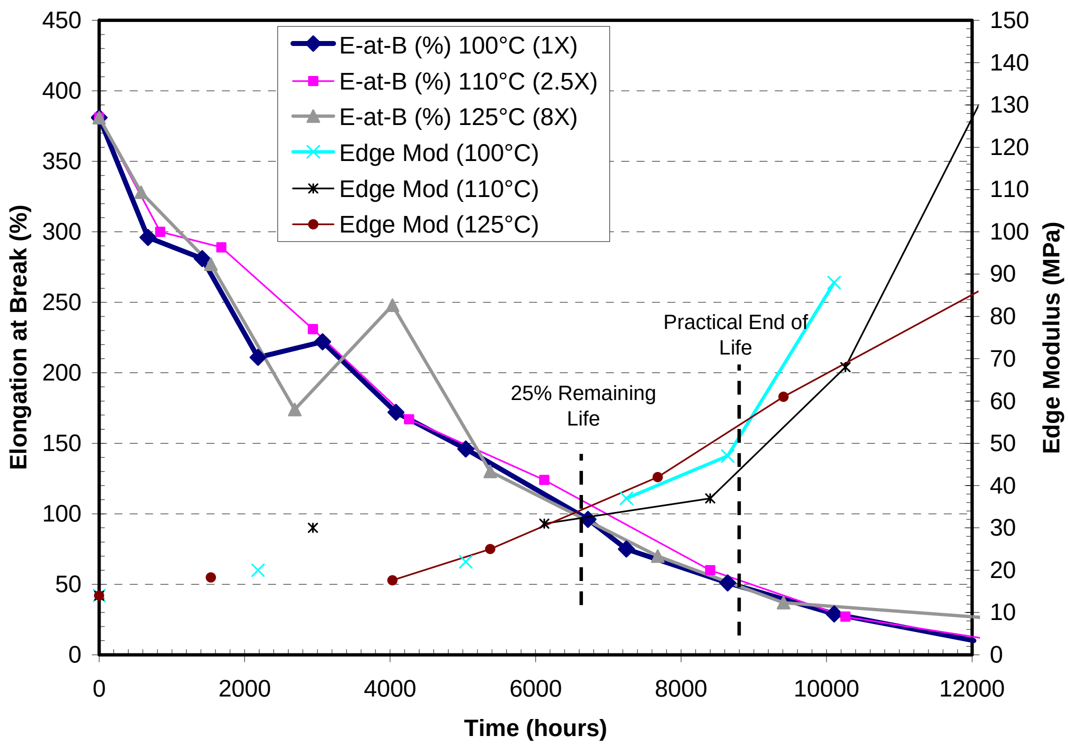


Figure 7-51
Samuel Moore Dekoron E-at-B Versus Edge Modulus, Superposed to 90°C

7.4 Composite CSPE/EPR Bonded Insulation

To provide fire retardancy to ethylene propylene rubber insulation not containing fire-retardant additives, a CSPE layer was placed over the insulation. Some manufacturers bonded the CSPE layer to the EPR layer, which resulted in a composite insulation that behaves differently from EPR insulation alone. When highly aged, the CSPE layer controls behavior in manipulation and LOCA exposure. The CSPE layer ages more rapidly than the EPR layer. Accordingly, a hardened CSPE layer will crack first when bent. In some cases, continued bending will cause the EPR elongation to be concentrated in the area within the root of the crack in the CSPE. This will cause the capability of the EPR to be exceeded and the crack will propagate through the EPR. Under LOCA conditions, CSPE that is highly aged at the surface will resist swelling of inner layers of CSPE and EPR, which can result in splitting through the CSPE and EPR. As discussed in Section 4, approximately 15% remaining E-at-B in the composite will preclude failure under LOCA conditions. The following discussion provides E-at-B and indenter modulus results for two common bonded CSPE/EPR insulations.

BIW Bostrad 7E Single

Figure 7-52 shows the comparison of E-at-B and indenter modulus for Bostrad 7E composite insulation when aged at 110°C. At 2700 hours, 50% E-at-B occurs. The corresponding IM is 42 N/mm. At 80% E-at-B and 32 N/mm IM, 25% remaining life occurs.

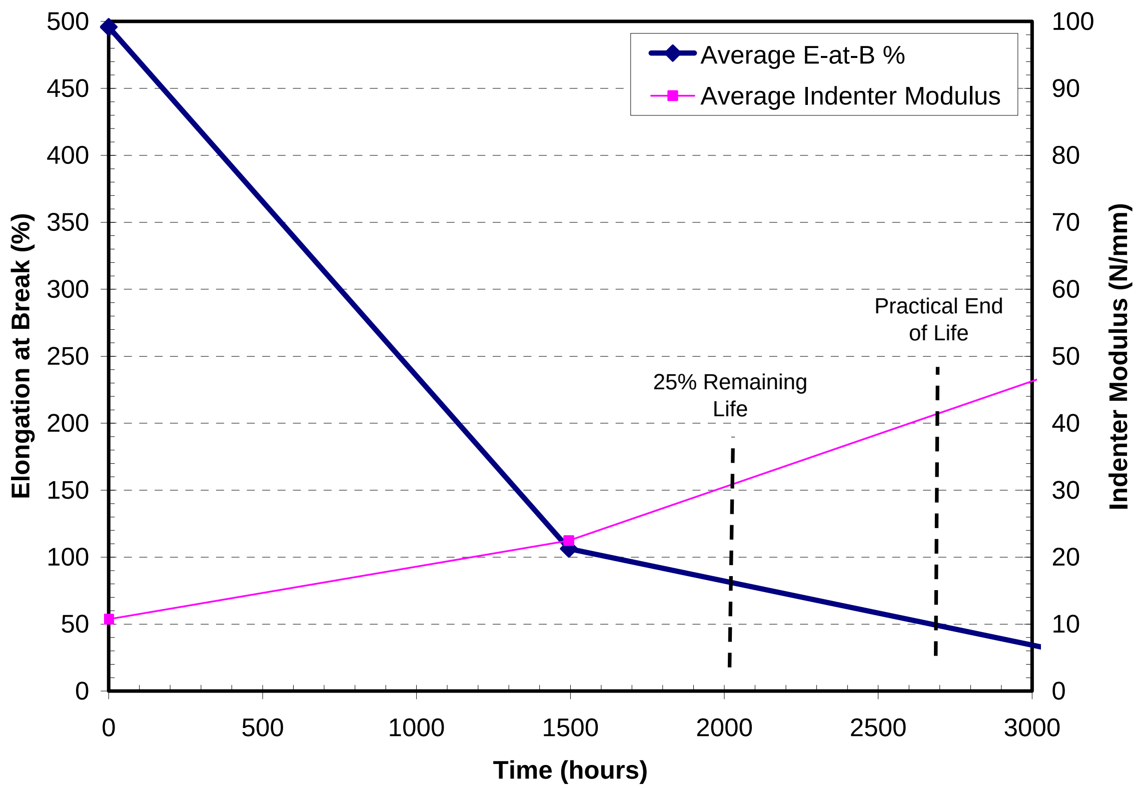


Figure 7-52
BIW Bostrad 7E CSPE/EPR E-at-B Versus Indenter Modulus, 110°C Aging

Okonite Okolon Singles

Figure 7-53 shows E-at-B versus IM for Okonite Okolon bonded CSPE/EPR composite insulation. The IM related to 50% E-at-B is 38 N/mm (0 rd dose condition). At 25% remaining life, the E-at-B is 120% and the IM is 20 N/mm. The plot provides information on unirradiated through five degrees of irradiation. With 2-Mrd irradiation, there is little effect on E-at-B. At mid-life, the effects of irradiation are noticeable. However, the plots reconverge at higher aging levels.

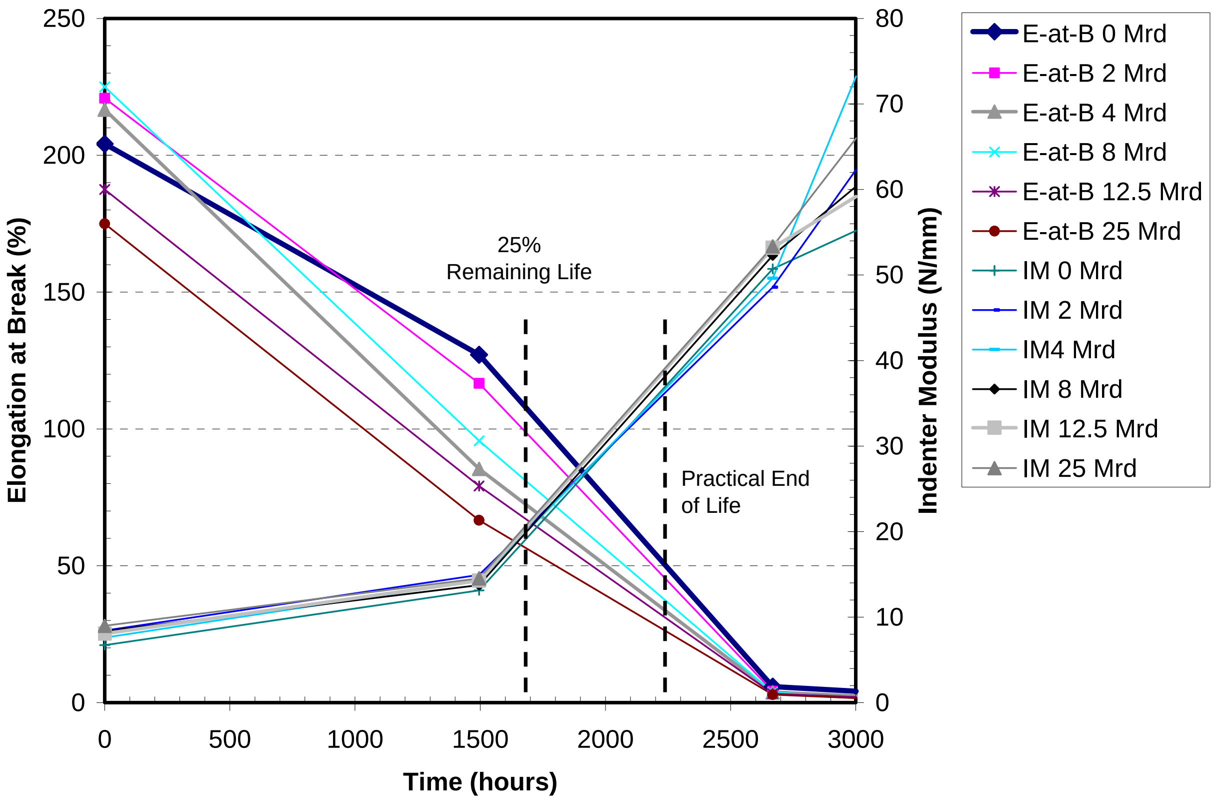


Figure 7-53
Okonite Okolon Single E-at-B Versus Indenter Modulus, 110°C Various Doses

7.5 Ethylene Propylene Rubber

EPR is a compounded rubber. Because different manufacturers use different compounds, their EPR characteristics may vary significantly. Overall, EPR used as cable insulation is relatively soft. Fire retardancy may be provided by either an additive (FR-EPR) or by bonding a neoprene or CSPE layer to the outer surface of the insulation. EPRs have relatively long thermal lives because they are heat-resistant, oxidation-resistant, and ozone-resistant. They are not oil-resistant.

Degradation Under Thermal Exposures

At 100°C, 50% E-at-B occurs at 13,000 hours for Anaconda FR-EPR.

Degradation Under Radiation Exposures

The data for radiation aging have not been evaluated for this report.

Manufacturer-Specific Aging Data

Anaconda

Figure 7-54 shows E-at-B for Anaconda Flameguard EPR when exposed to various aging temperatures from 100.9 to 170°C. The aging curves appear consistent at the various aging temperatures in this log scale plot. Figure 7-55 shows the same data superposed to 100.9°C. In this plot, a knee appears in the 150–170°C plots that does not exist in the lower temperature plots. The plots for the higher temperatures seem to indicate that the material is degrading less until quite late in life (10,000 superposed hours) and then dropping off suddenly. This behavior may be due to limited oxygen diffusion at the higher temperatures causing less damage through the depth of the material in the high rate aging.

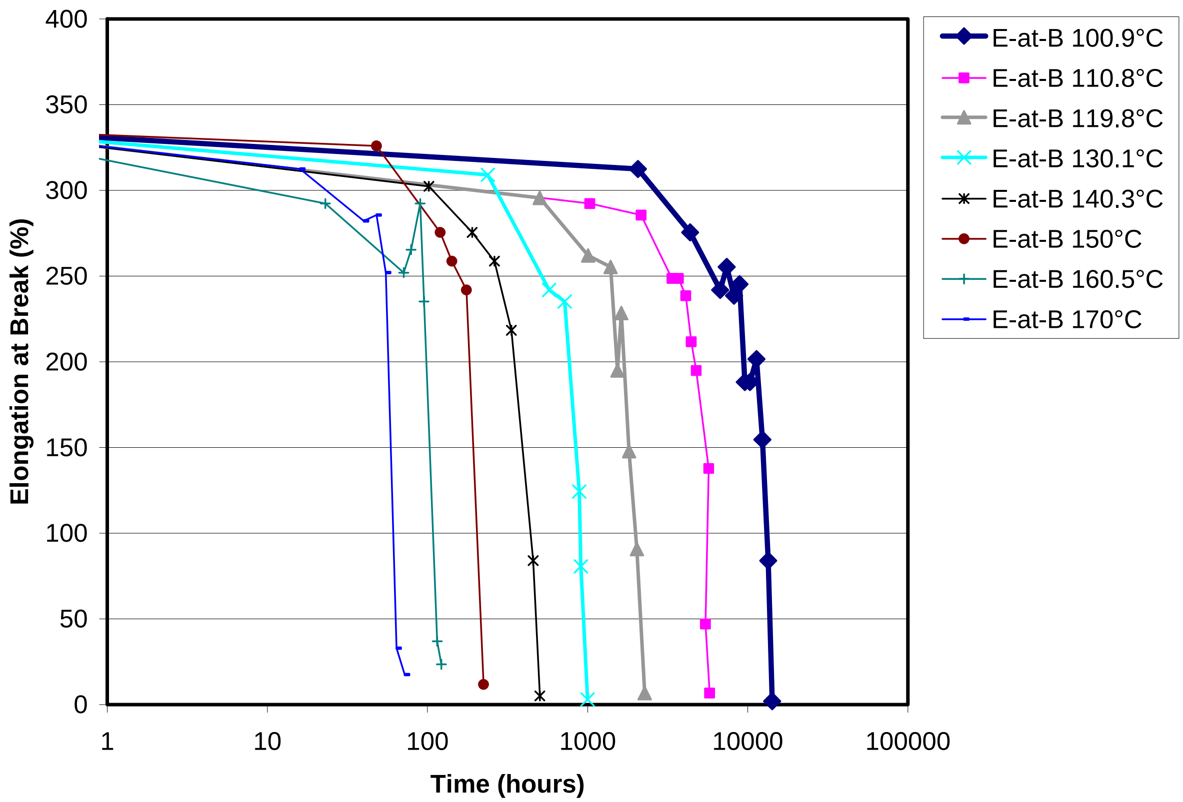


Figure 7-54
Anaconda Flameguard EPR E-at-B, Various Temperatures

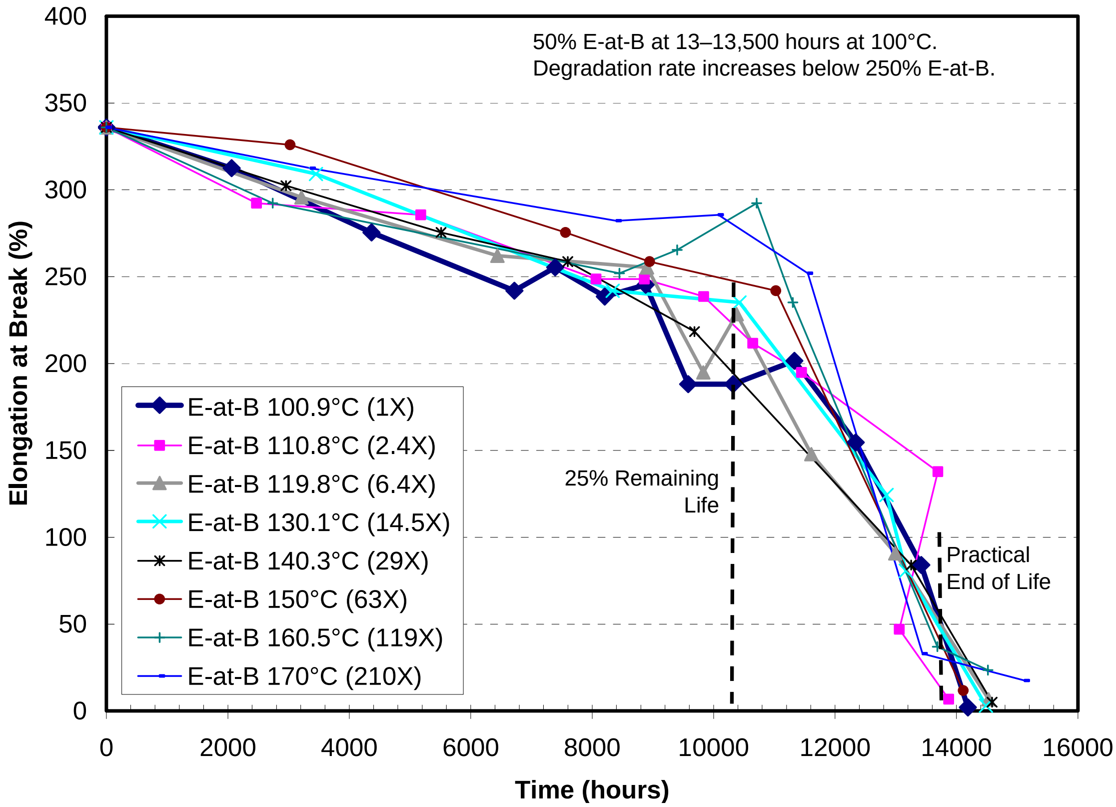


Figure 7-55
Anaconda Flameguard E-at-B, Superposed to 100.9°C

Okonite EPR

Figure 7-56 shows data for oxidation induction temperature evaluation of Okonite EPR that has been aged at 150°C and subsequently irradiated to 10 and 50 Mrd. The OITemp curve is shifted down by the application of 10 Mrd. It is shifted further by the application of 50 Mrd, but not by a proportional factor. The degradation from the additional 40 Mrd appears to be about equal to the first 10 Mrd through most of the curve. There is no more damage possible at high aging and, therefore, the increment appears smaller. Figure 7-57 shows oxidation induction time for the same conditions with two different types of specimens—small slivers or bulk. The results differ because of the amount of surface exposed during the test (slivers have more surface that reacts with oxygen in the test). The sliver results provide better resolution.

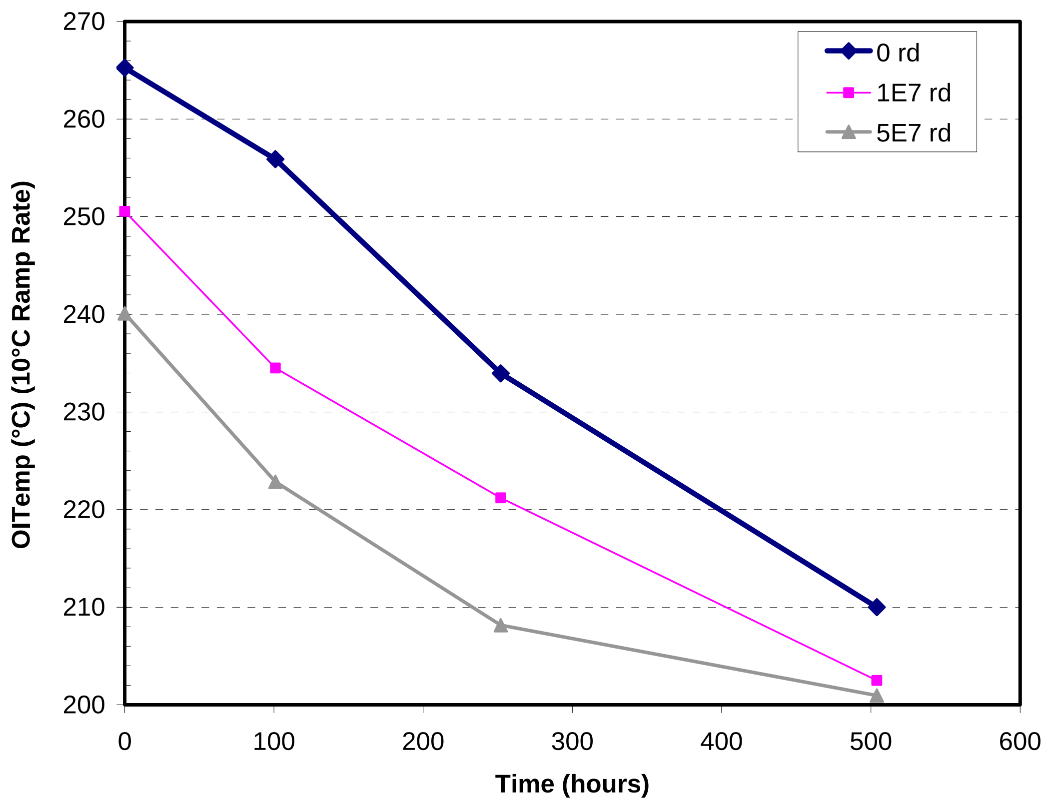


Figure 7-56
Okonite EPR Oxidation Induction Temperature, 150°C Aging

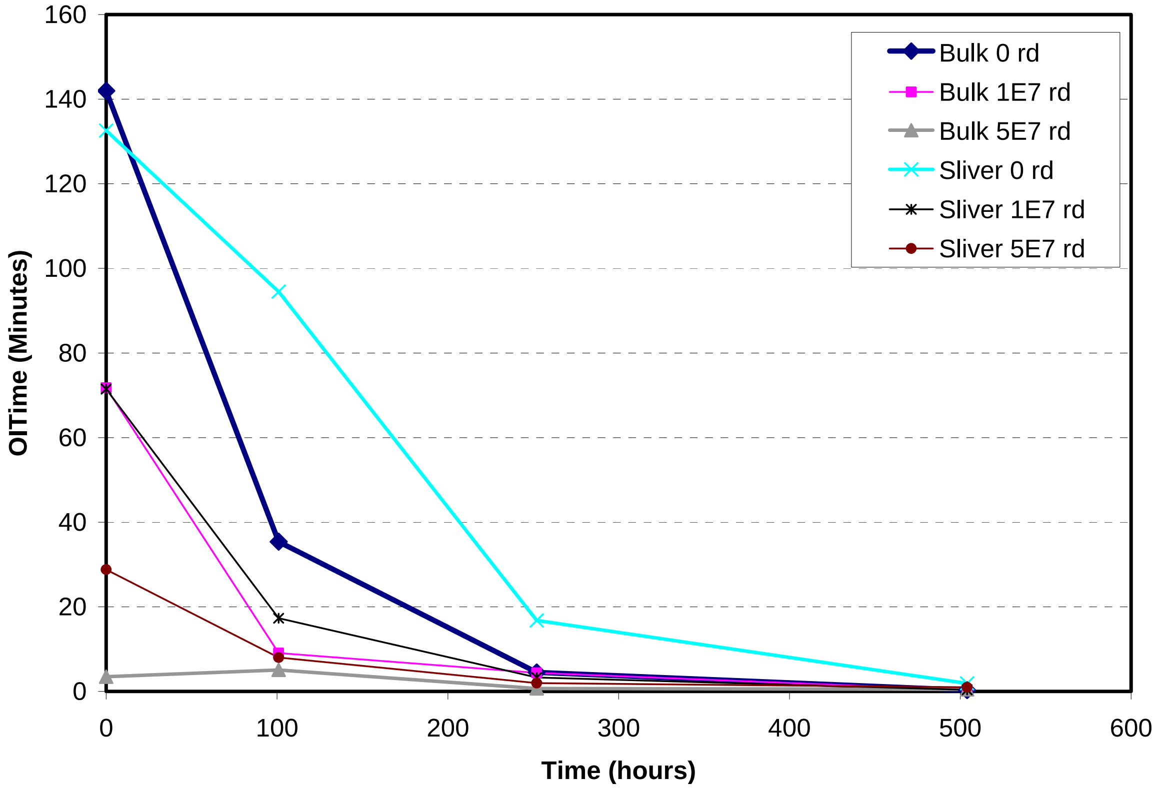


Figure 7-57
Okonite Oxidation Induction Time, 150°C Aging

7.6 Neoprene

Neoprene is a synthetic rubber that has similar mechanical properties and structure to those of natural rubber. It is resistant to oils, chemicals, sunlight, and ozone. It does not support combustion [8]. Neoprene was used as a cable jacket in many cables produced for nuclear plants during the 1970s to protect insulated conductors. It has also been used as an insulation jacket over CPR due to its fire-retardant qualities.

Degradation Under Thermal Exposures

Neoprene has a long life at temperatures in general plant areas (40–50°C/104–122°F). Neoprene ages relatively rapidly at higher temperatures and can be expected to age 3–10 times faster than CSPE at elevated temperatures. Neoprene hardens with age. When highly aged, neoprene shrinks and cracks spontaneously. Longitudinal and circumferential cracks can be expected. When used as an insulation jacket for fire retardance on EPR-insulated cables, the cracks in the aged neoprene have not been observed as propagating into the EPR layer. Such propagation is not expected due to the relatively weak bonding between the neoprene and EPR layers.

Degradation Under Radiation Exposures

Neoprene also hardens with irradiation.

Manufacturer-Specific Aging Data

Okonite Okoprene Jacket

Figure 7-58 shows E-at-B for an Okonite Okoprene jacket at various aging temperatures. At 70°C, 50% E-at-B occurs at 7000 hours. But at 101°C (an aging temperature comparable to that used for many of the other materials), 50% E-at-B occurs at 1100 hours. Figure 7-59 shows the same data superposed to 101°C. Similar E-at-B results occur for all temperatures from 70 to 140.6°C when superposed, indicating that degradation is similar no matter which aging temperature is used.

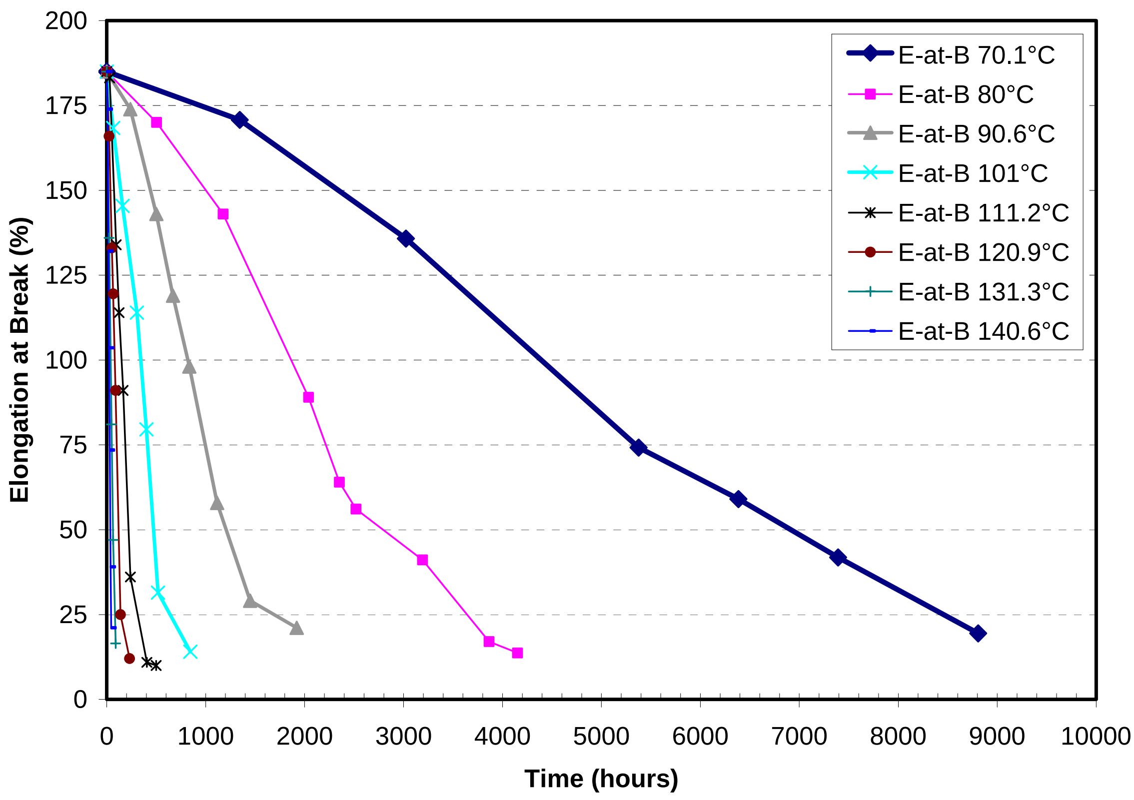


Figure 7-58
Okonite Jacket E-at-B, Various Temperatures

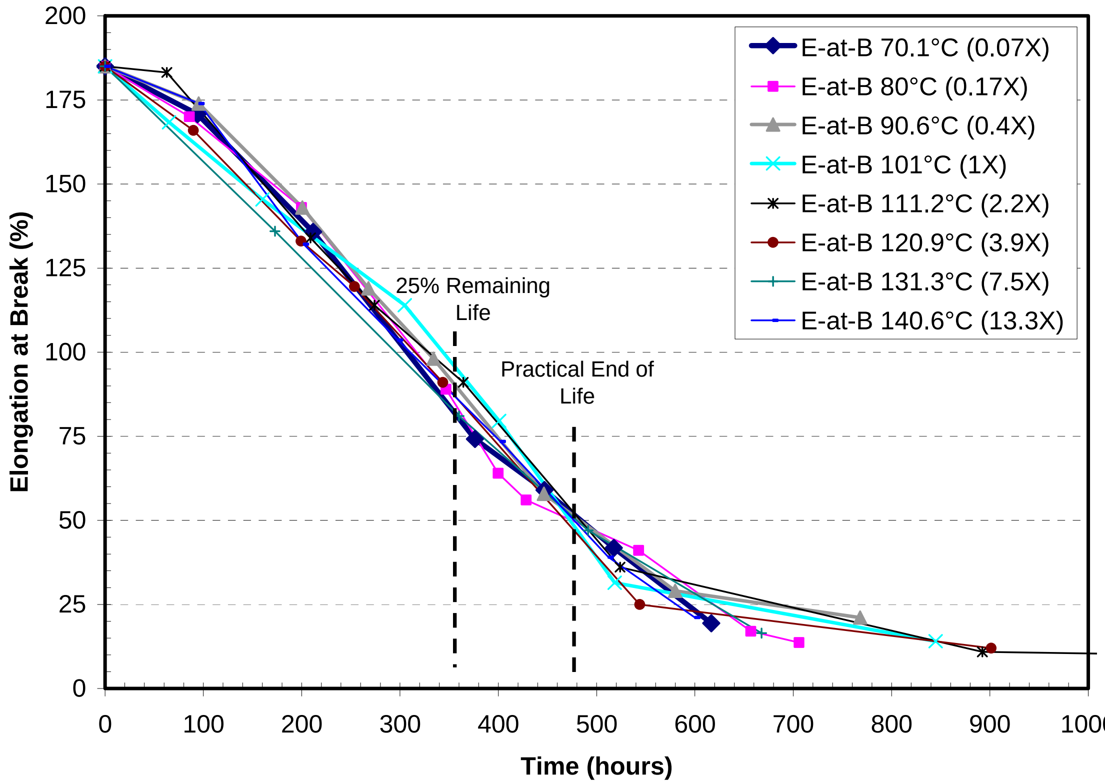


Figure 7-59
Okonite Neoprene Jacket E-at-B, Superposed to 101°C

Neoprene Jacket

Figure 7-60 provides E-at-B and IM for a neoprene jacket [9]. The manufacturer of the neoprene is not stated, but the approximate relationship of E-at-B with IM is provided. At the practical end of life the IM is 24 N/mm. At 25% remaining life, the IM is 16 N/mm.

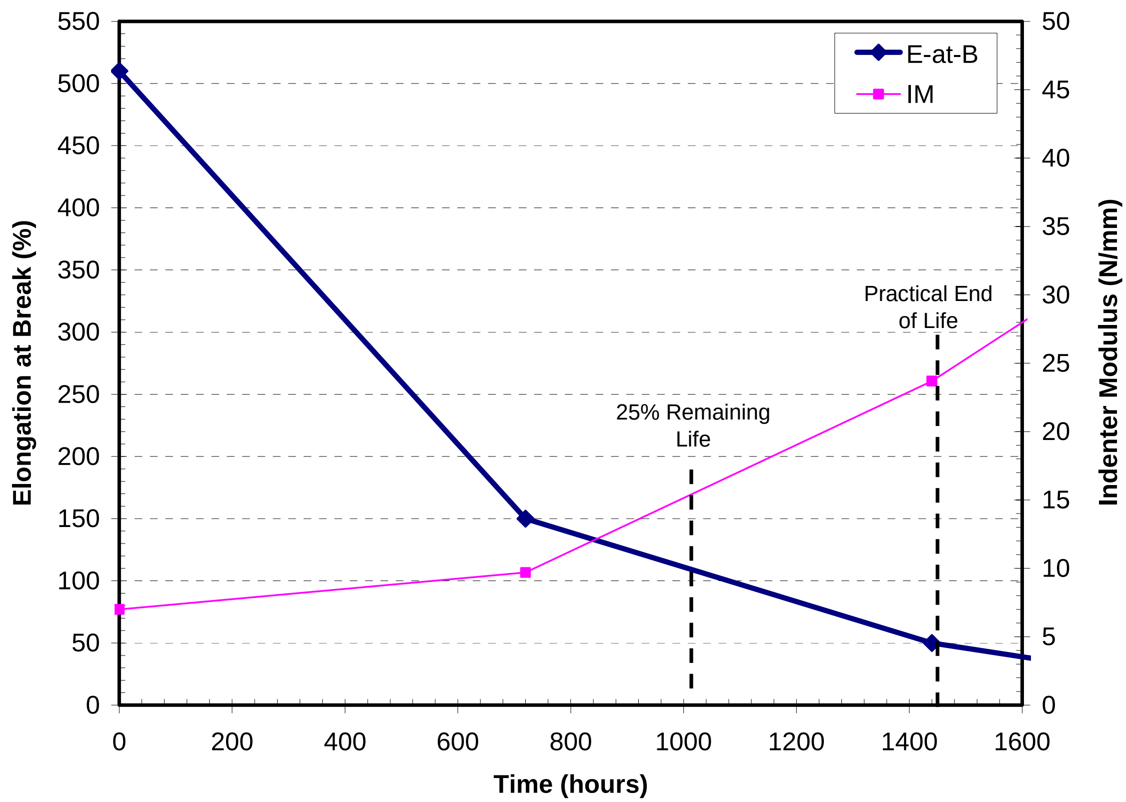


Figure 7-60
Neoprene Jacket E-at-B Versus Indenter Modulus, 110°C Thermal Aging

Rockbestos Neoprene

Figure 7-61 shows E-at-B at temperatures from 80 to 110°C for a Rockbestos neoprene jacket. Even at a low 80°C aging temperature, the material is relatively short-lived with 50% E-at-B occurring at 450 hours. Figure 7-62 shows the same plots superposed to 110°C. The plots align well and provide consistency of aging mechanism at these three aging temperatures. Figure 7-63 shows the correlation of E-at-B to NMR T2. The correlation is strong with a reasonable resolution. Figure 7-64 shows the correlation of E-at-B with edge modulus. There is a strong inverse correlation also having reasonable resolution. Figure 7-65 shows the correlation between E-at-B and the uptake factor. The correlation is strong with good resolution. Figure 7-66 shows the correlation between E-at-B and percent gel. While there is a rough correlation, the scatter is excessive.

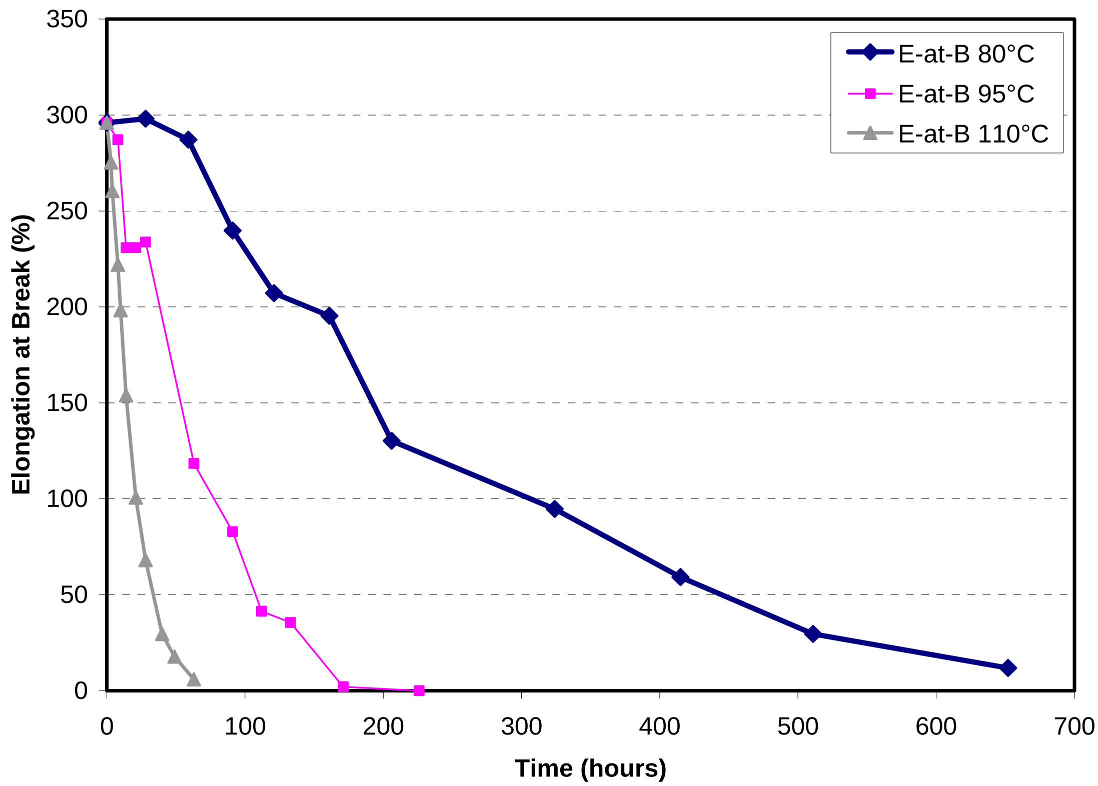


Figure 7-61
Rockbestos Neoprene Jacket E-at-B, Various Aging Temperatures

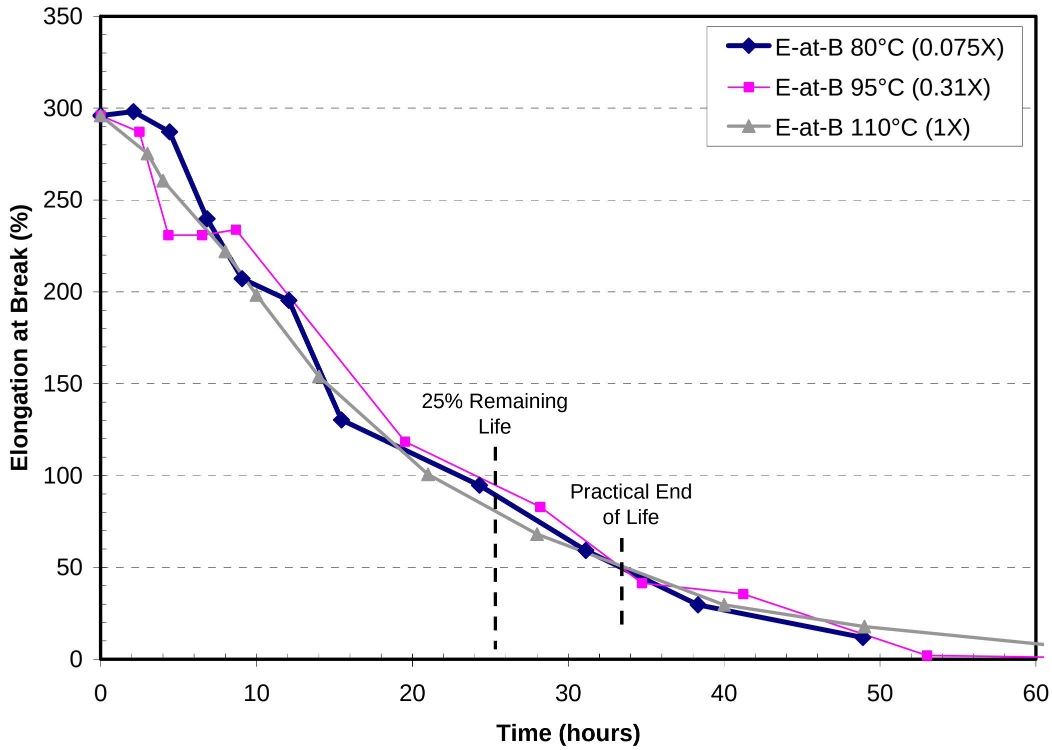


Figure 7-62
Rockbestos Neoprene Jacket E-at-B Superposed to 110°C

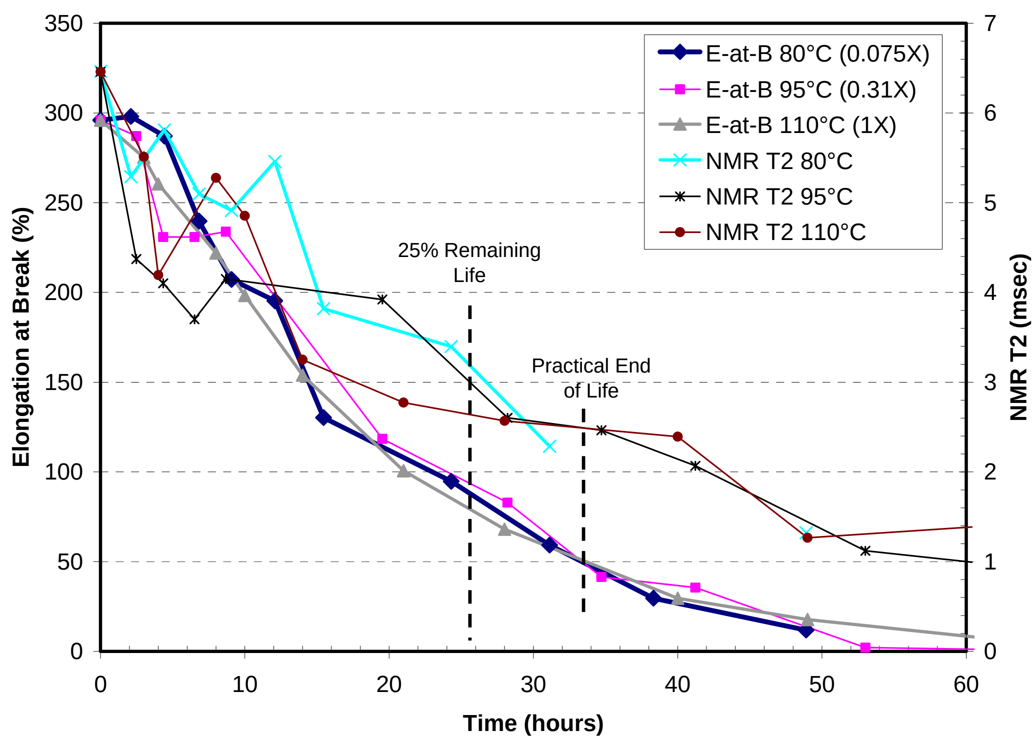


Figure 7-63
Rockbestos Neoprene Jacket E-at-B Versus NMR T2, Superposed to 110°C

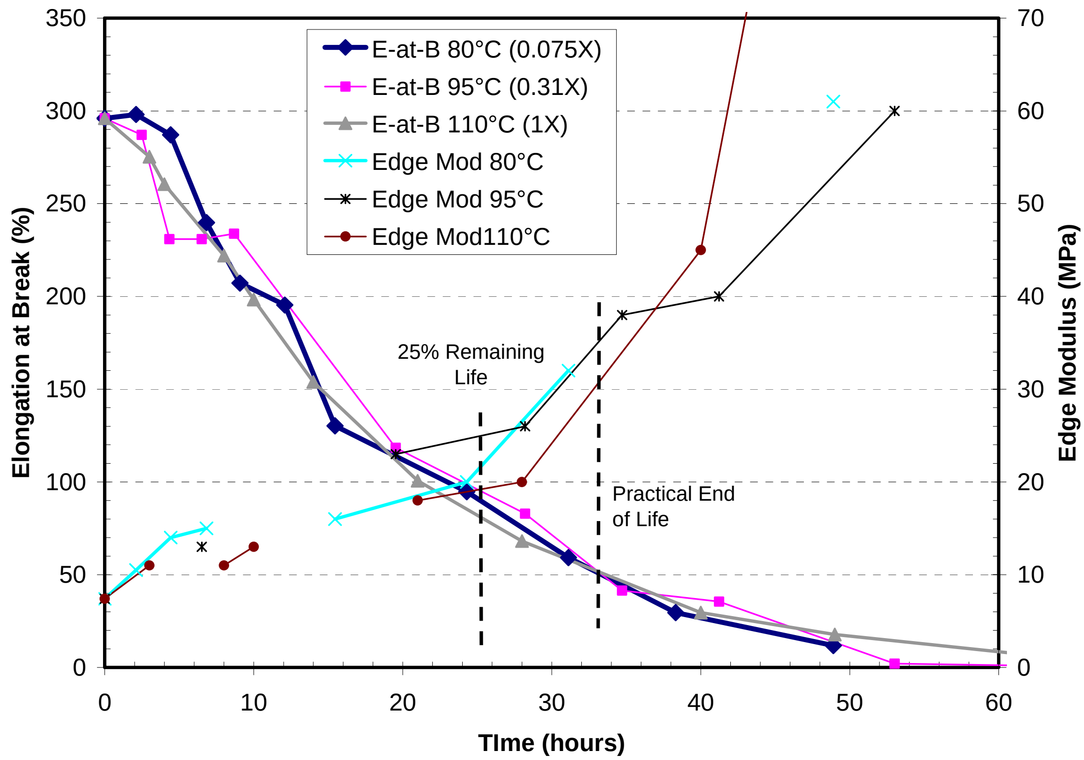


Figure 7-64
Rockbestos Neoprene Jacket E-at-B Versus Edge Modulus, Superposed to 110°C

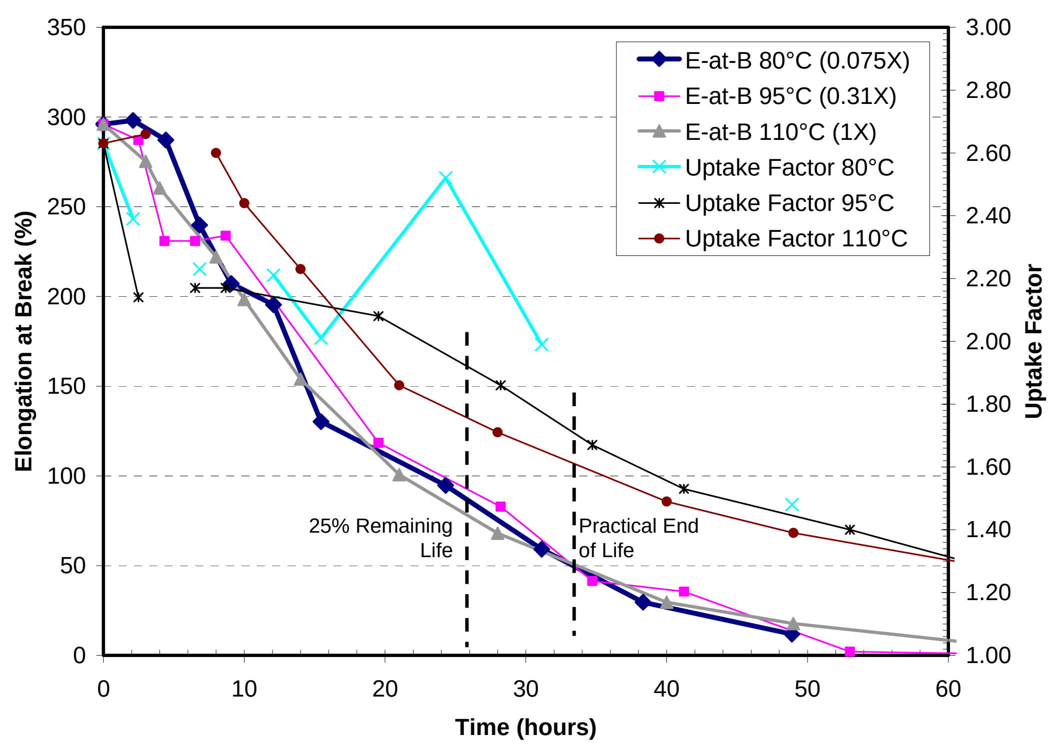


Figure 7-65
Rockbestos Neoprene Jacket E-at-B Versus Uptake Factor, Superposed to 110°C

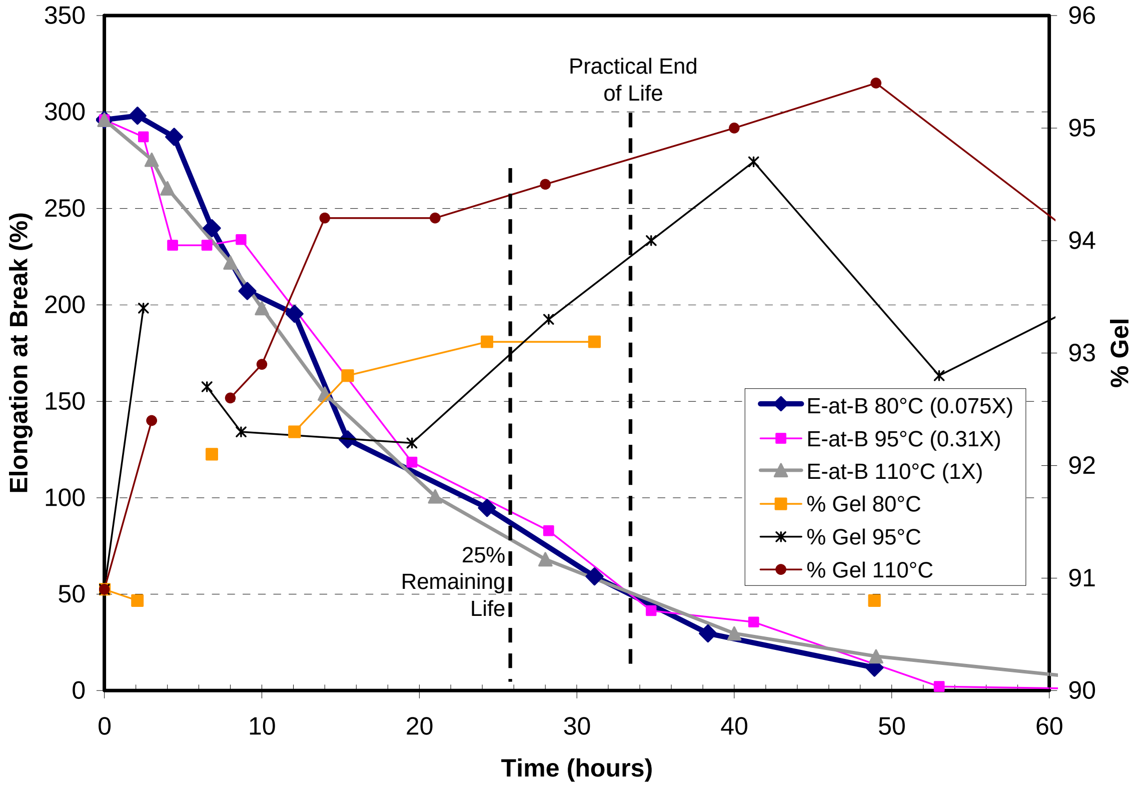


Figure 7-66
Rockbestos Neoprene Jacket E-at-B Versus % Gel, Superposed to 110°C

7.7 Silicone Rubber

Silicone rubber (SR) looks and feels like rubber. It is based on an arrangement of silicone and oxygen atoms rather than on a chain of carbon atoms. The structure gives a very flexible chain with weak interchain forces, which provides a small change in dynamic characteristics over a wide temperature range [10]. It is a non-crystalline material. Silicone rubber provides satisfactory service at high temperatures. It tends to have good E-at-B characteristics, but it is damaged more easily than other rubbers by compression or physical abuse. Asbestos and glass braids have been used as protective covers for SR insulations. When removing silicone rubber cables that were installed in the 1970s, care should be taken due to the high likelihood that they have asbestos braids. Cables that were installed later are likely to have glass braids.

Degradation Under Thermal Exposures

Silicone rubber insulations may be purchased for use in very high service temperatures. They have been environmentally qualified for temperatures up to 125°C.

Degradation Under Radiation Exposures

Some SR insulations lose elongation properties relatively rapidly under irradiation. Earlier versions from the 1970s tended to lose all elongation at 100 Mrd. Currently available versions of SR have been environmentally qualified successfully to 200 Mrd.

Manufacturer-Specific Aging Data

Rockbestos

Figure 7-67 shows E-at-B for Rockbestos Firewall II silicone rubber insulation when aged at 140°C. At 675 hours of aging, 190% E-at-B remains. Figure 7-68 shows the effects of radiation at various aging temperatures and dose rates. The behavior of this material at various aging temperatures and dose rates is confusing. At 41.5°C, aging is more severe than at 60.7°C with essentially the same dose rate (5.2–5.4 krd/hr). At 11.2–11.4 krd/hr, aging is slightly more severe at 115°C than at 100°C as would be expected. At 2.6 krd/hr and 110°C, the aging plot falls logically between higher and lower aging temperatures, but the total absorbed dose (8.8 Mrd) is lower than might be expected at 50% E-at-B. At the highest dose rate (17.6 krd) with a low aging temperature (100°C), 50% E-at-B occurs only at 450 hours. Figure 7-69 shows the aging plot in terms of absorbed dose. Interestingly, while these plots show variations in aging rates with various thermal and radiation stress rates, all curves seem to converge at 15–25% E-at-B where damage stabilizes until 30–40 Mrd is absorbed.

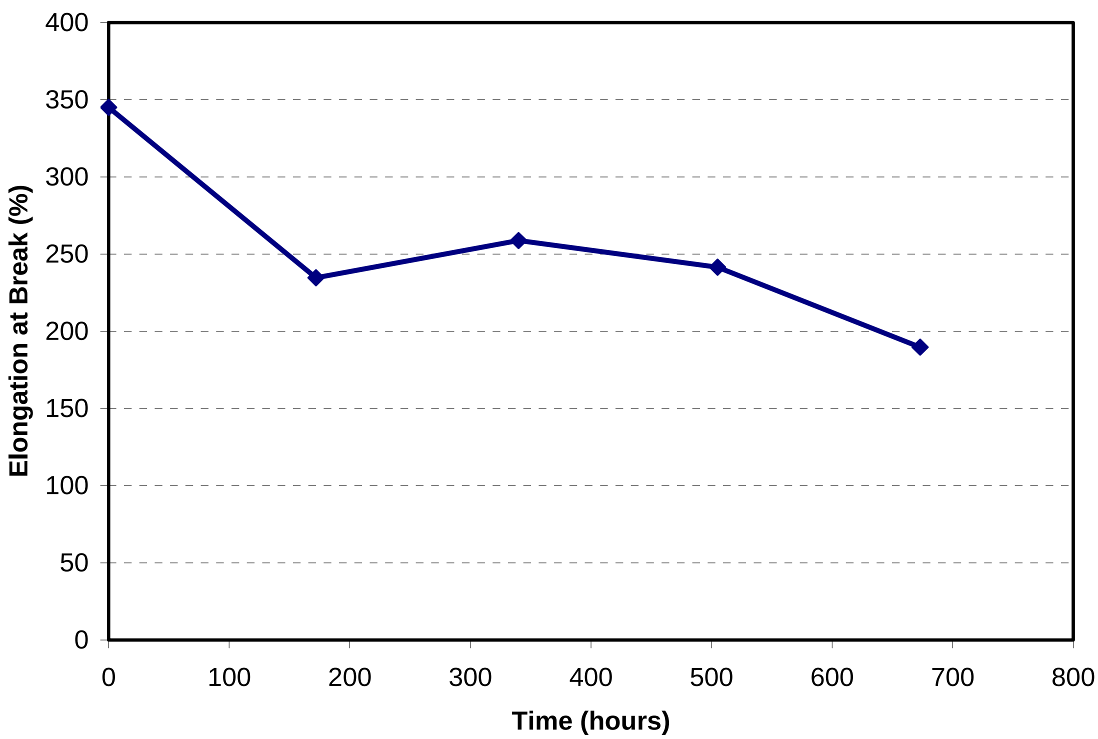


Figure 7-67
Rockbestos Silicone Rubber (FW-II) E-at-B, 140°C Aging

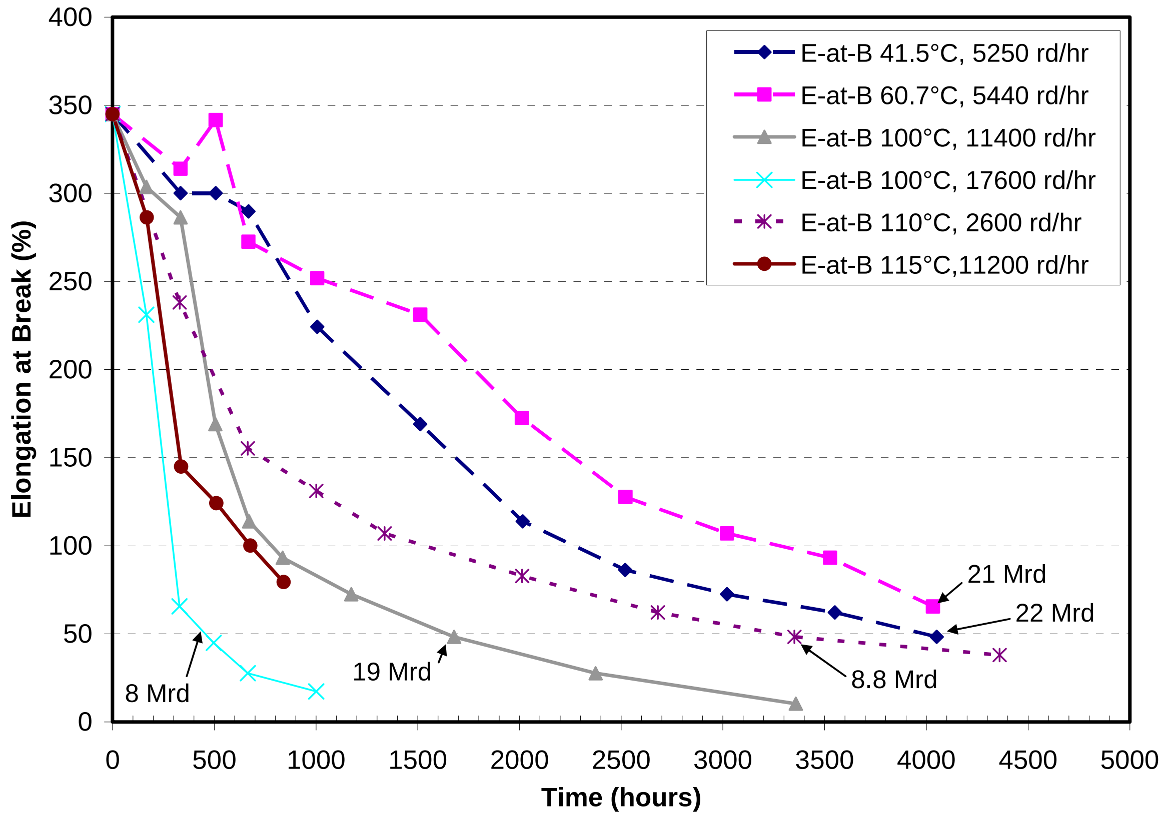


Figure 7-68
Rockbestos Silicone Rubber (FW-II) E-at-B, Various Aging Temperatures and Dose Rates

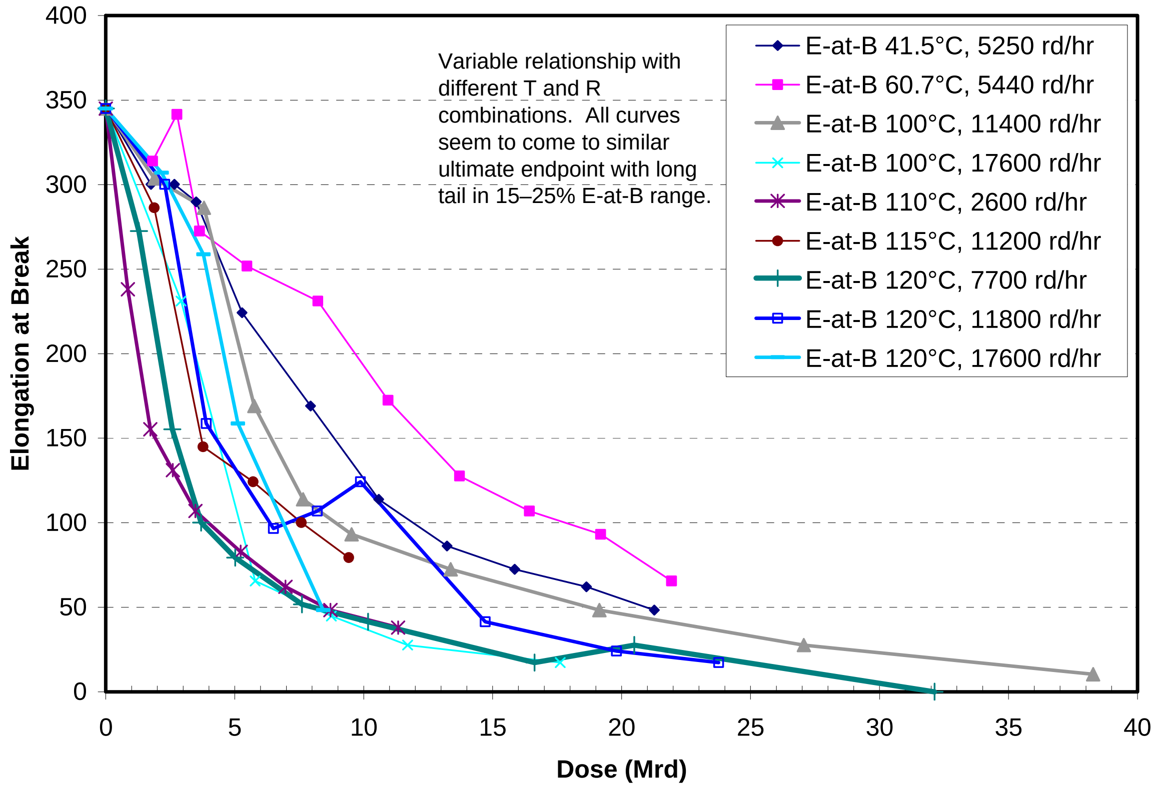


Figure 7-69
Rockbestos Silicone Rubber (FW-II) E-at-B, Various Aging Temperatures and Dose Rates by Dose

Figure 7-70 shows the correlation of E-at-B with density for Rockbestos silicone rubber when aged at 120°C and 7.7 krd/hr. Density appears to be a good measure of aging during the relatively long period of stability between 20–35% E-at-B. Figure 7-71 shows the correlation of E-at-B with the uptake factor under the same conditions. The correlation is strong until complete aging occurs where it breaks down. Figure 7-72 shows the correlation with percent gel, which provides a good correlation through complete degradation.

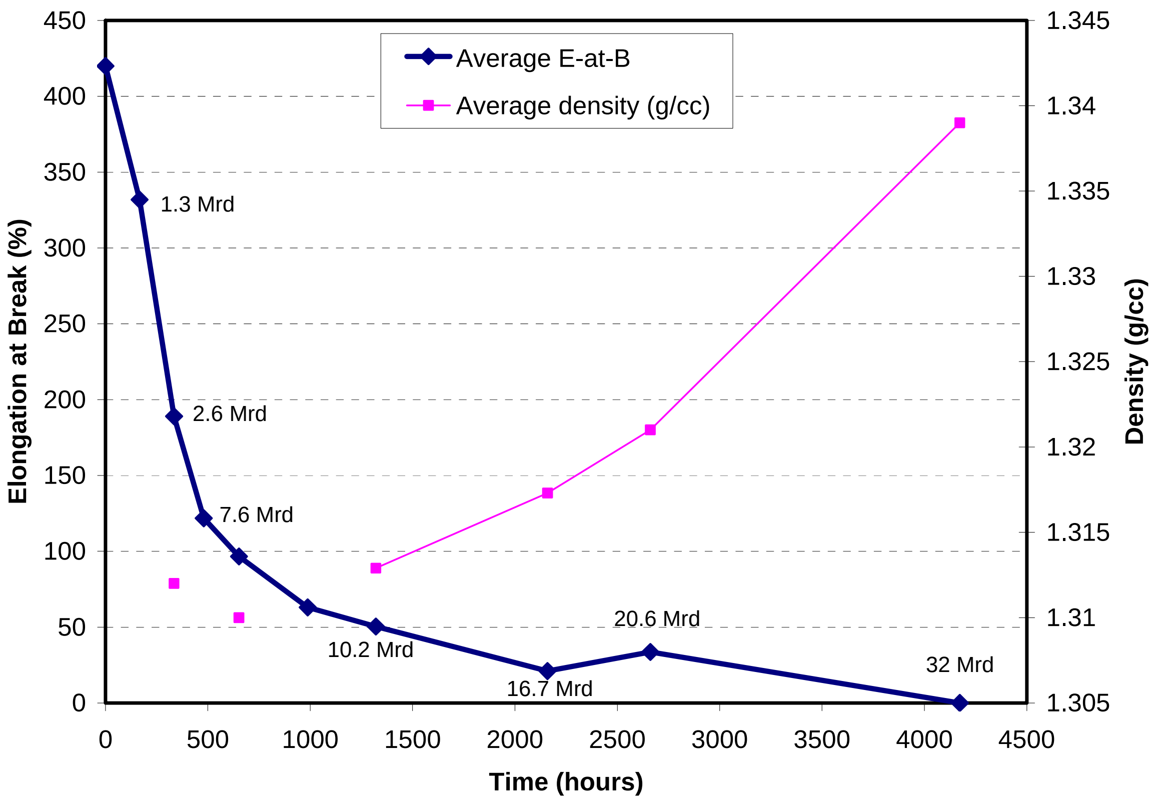


Figure 7-70
Rockbestos Silicone Rubber (FW II) E-at-B Versus Density, 120°C, 7700 rd/hr Aging

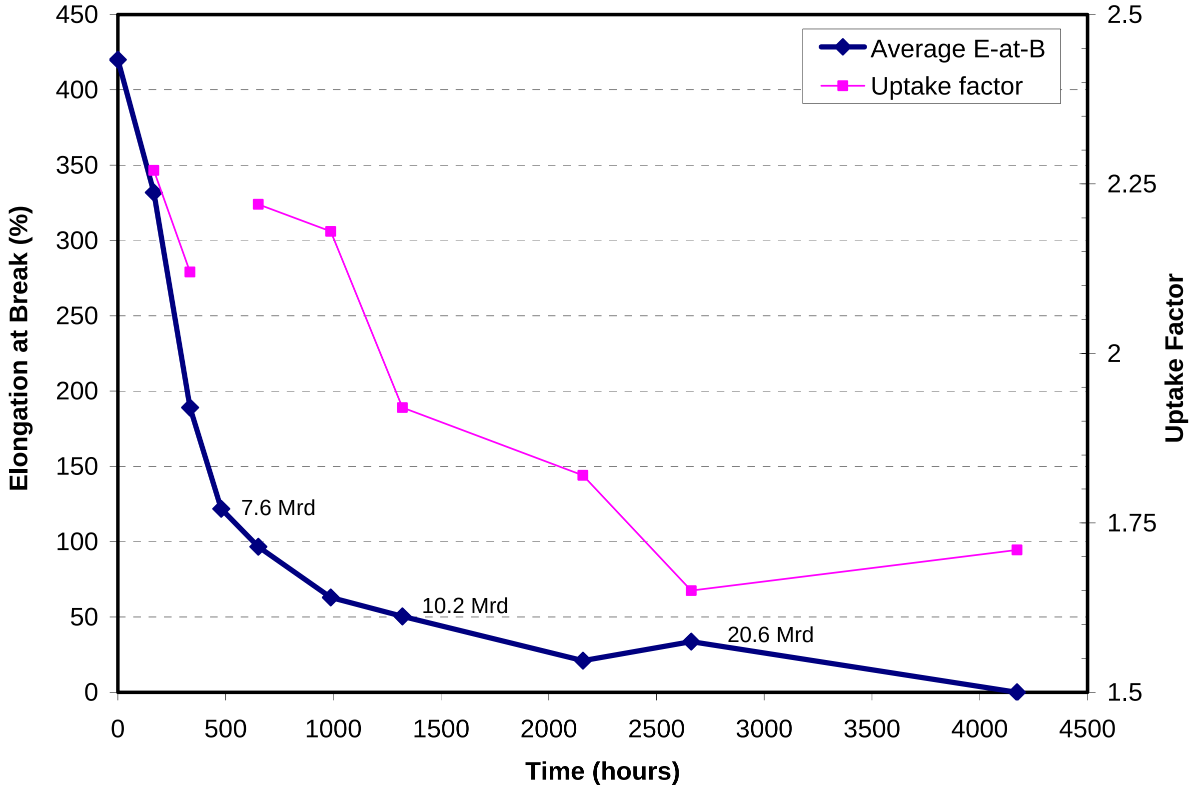


Figure 7-71
Rockbestos Silicone Rubber (FW II) E-at-B Versus Uptake Factor, 120°C, 7700 rd/hr Aging

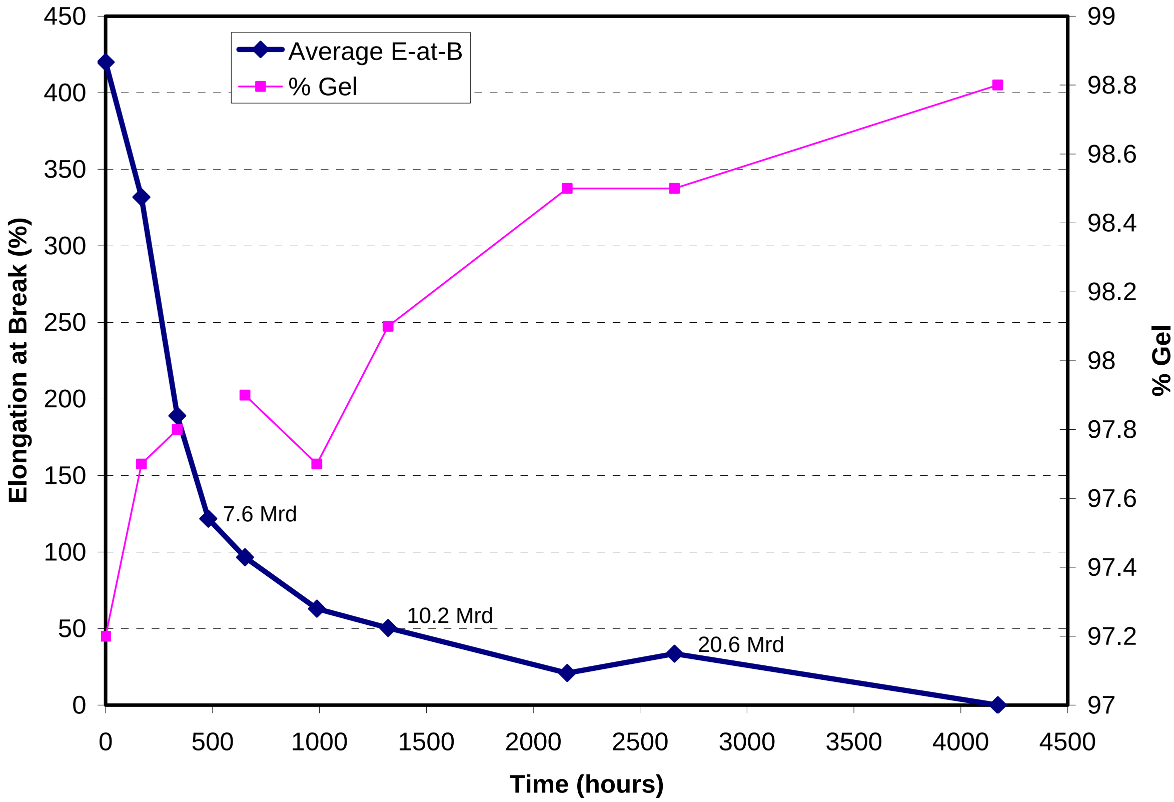


Figure 7-72
Rockbestos Silicone Rubber (FW II) E-at-B Versus % Gel, 120°C, 7700 rd/hr Aging

8 MATERIAL COMPARISONS

Thermal damage is expected to dominate aging for most nuclear applications. This section provides aging comparisons between common jacket and insulation materials used in nuclear applications. The discussion is general because there are variations in aging rates between specific manufacturers' formulations and compounds. This generalized discussion shows the approximate relationship in aging between the materials so that their basic capabilities may be understood. Because there is a large difference in capabilities and large differences in the aging regimen used in the various aging research programs, it is not possible to show all materials in one graph or under one aging regimen.

Figure 8-1 shows the relationship of a CSPE, an EPR, and an XLPE insulation aged at 150°C. While all XLPEs do not have the capability of the XLPE shown in this figure, it is obvious that XLPEs age slowly in comparison with CSPE and this EPR. The EPR ages more slowly than the CSPE (with the CSPE aging at least twice as fast through near end of life where convergence occurs in this case).

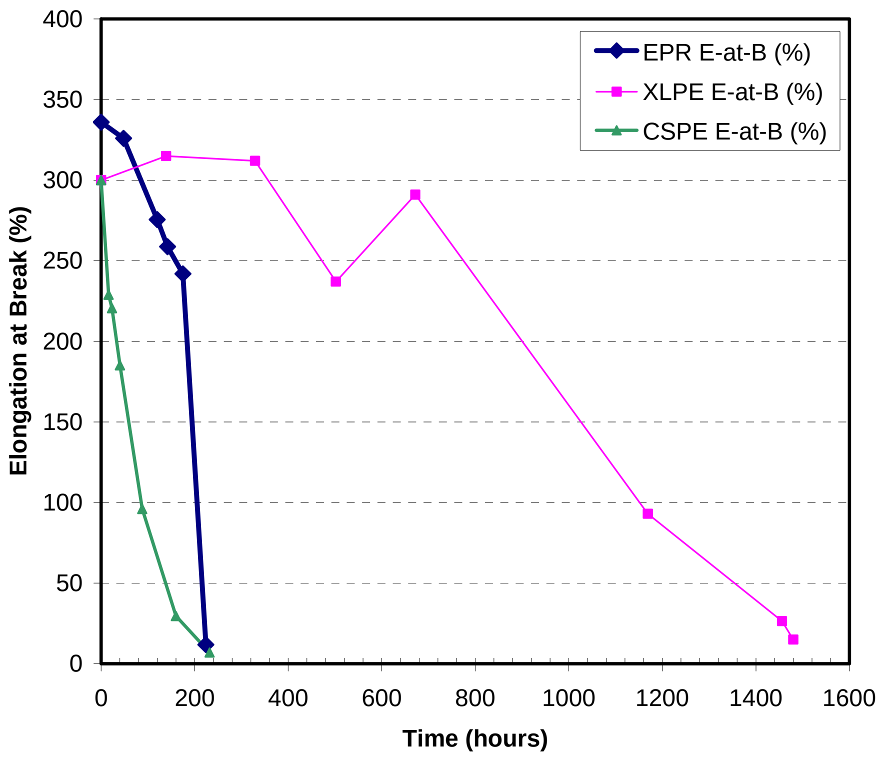


Figure 8-1
E-at-B Comparison of CSPE, EPR, and XLPE, 150°C Aging

Figure 8-2 compares XLPE, EPR, CSPE, and neoprene under 110°C aging. Because the XLPE has such a long life, little can be discerned about the aging of the other materials. Figure 8-3 shows the first 6000 hours of aging at 110°C for these materials. The EPR shows much slower aging until 5700 hours when there is a precipitous drop in capability. The CSPE ages much more slowly than the neoprene, with 50% E-at-B occurring at 2800 hours for the CSPE and at 800 hours for the neoprene.

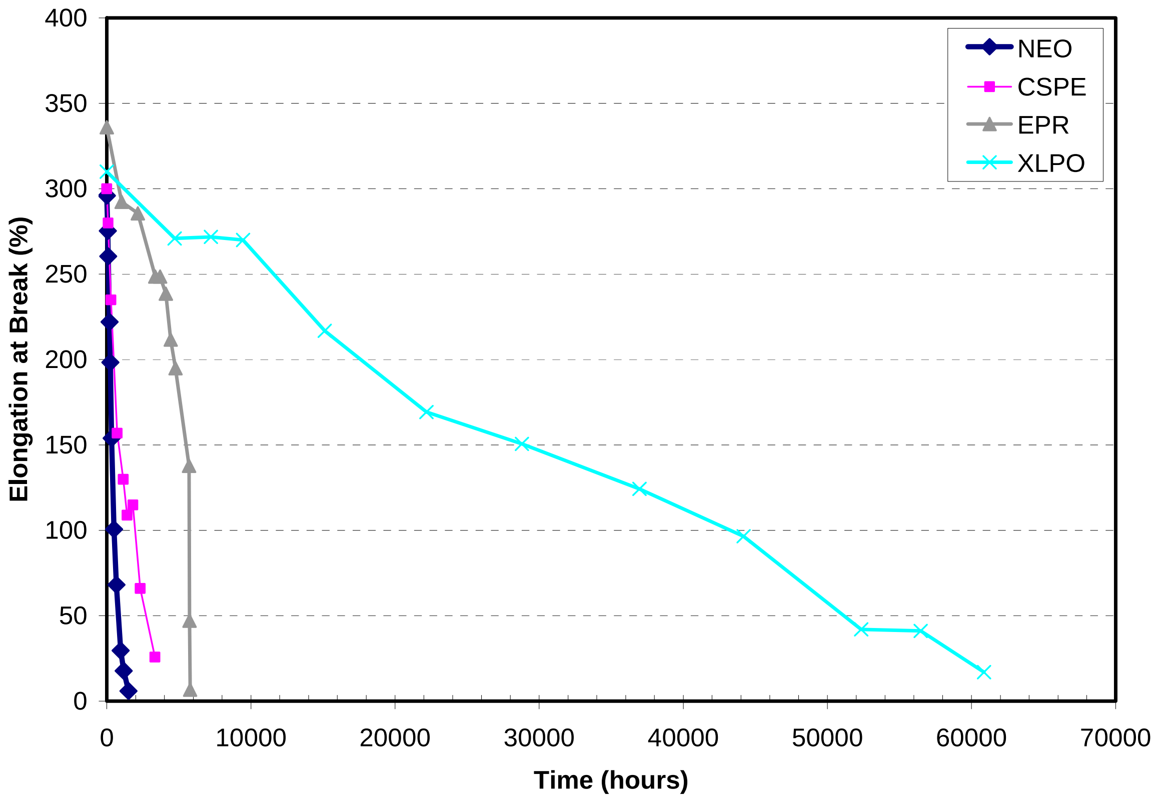


Figure 8-2
Comparison of Neoprene, CSPE, EPR, and XLPE, 110°C Aging

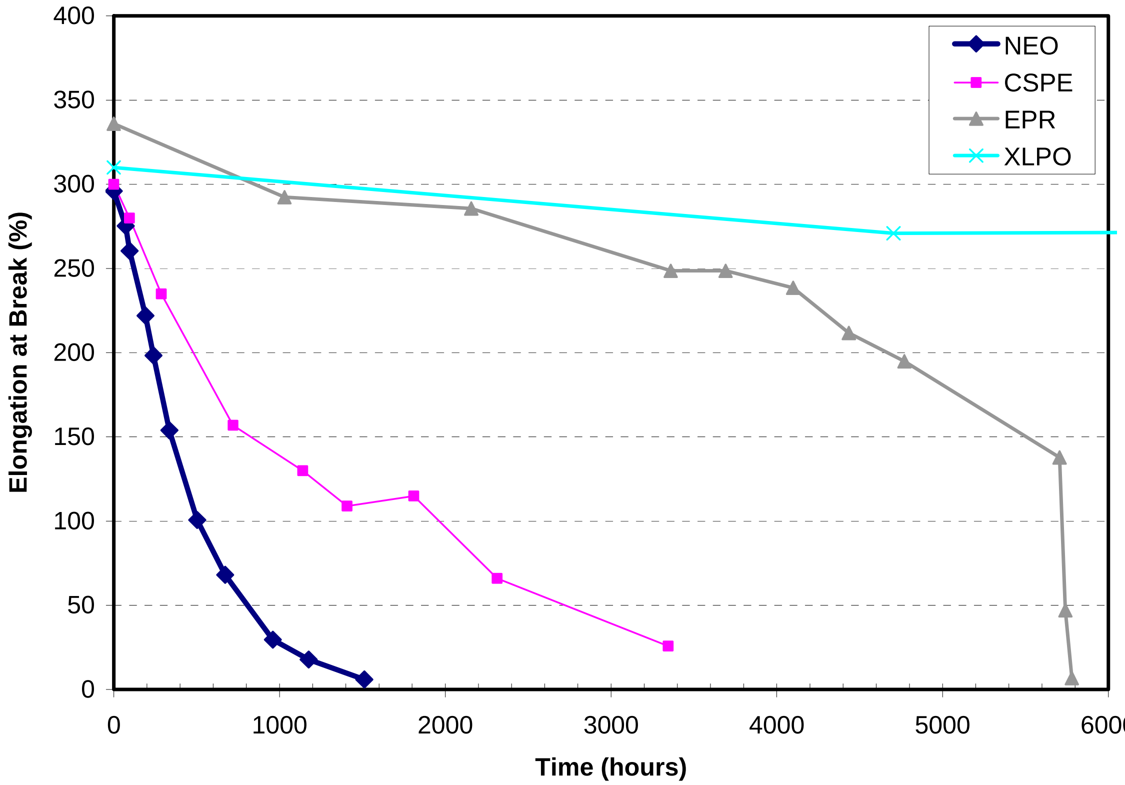


Figure 8-3
Comparison of Neoprene, CSPE, EPR, and XLPE to 6000 Hours at 110°C

Figure 8-4 presents a comparison that attempts to show the effects of irradiation on the capability of XLPE, EPR, and CSPE. Note that the dose rate applied to the XLPE is approximately one-third that of the other two materials. In comparison with Figure 8-3, the effect of simultaneous irradiation on the CSPE is limited. Instead of 50% E-at-B occurring at 800 hours, the projection of the plot indicates that it will occur at approximately 750 hours with a 35-Mrd dose. For EPR, 50% E-at-B occurs at 1100 hours instead of 5800 hours when 54 Mrd is applied. For XLPE, 150% elongation occurs at 2400 hours instead of 28,000 hours when 36 Mrd is applied. The effects of high normal dose rates (doses) is significant with regard to induced degradation. Fortunately, relatively few cables experience such high doses under normal operating conditions. No cables outside containment experience such doses, and few inside containment are exposed to such conditions.

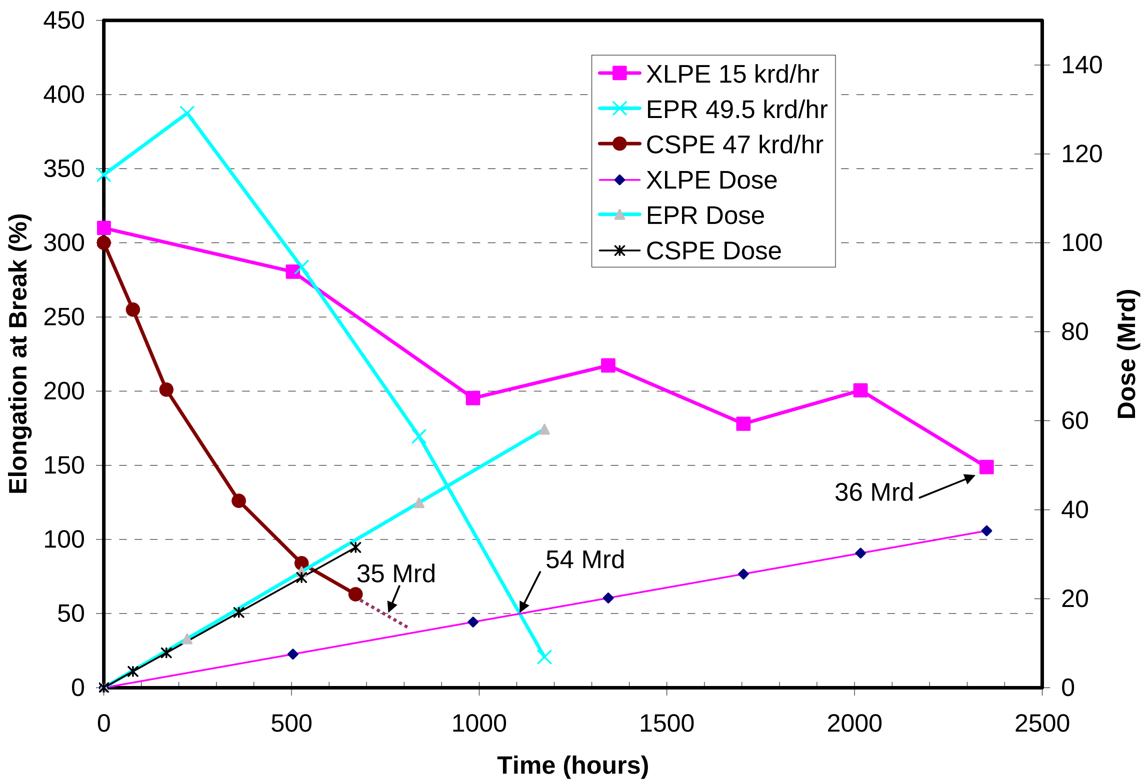


Figure 8-4
Comparison of CSPE, EPR, and XLPE with Irradiation at 110°C

9
PROPOSED USE OF ACCEPTANCE CRITERIA AND CONCLUSIONS

This report reduces a portion of the available cable polymer aging research data to a format directly usable in assessing the current condition and projected remaining life of installed cables. A basis has been presented for using 50% E-at-B as a conservative practical end of life for cables that may be manipulated during maintenance or subjected to LOCA exposure. A basis for cautious continued use beyond that point has also been presented.

A method for identifying remaining life based on limiting use to the 50% E-at-B practical end of life has been presented. The tables in Section 5 provide correlations between the results of various condition-monitoring methods and 25% remaining life of common cable insulation and jacket materials. The figures in Section 6 describe the aging profiles for the materials. With this information, it is possible to evaluate the condition of in-service cables that are located in adverse environments or that have severe service conditions due to ohmic heating of the conductor. The point of 25% remaining life has been identified as a reasonable point at which to identify aging so that planned replacement may be implemented.

The remaining life at any time may be determined from the figures in Section 6 and the period of service to the point of measurement by use of Equation 9-1.

$$P_R = P_S \times \left(\left[\frac{1}{1 - \frac{\%RL}{100}} \right] - 1 \right) \qquad \textbf{Eq. 9-1}$$

Where:

P_R = period of remaining life

P_S = period of service to point of measurement

$\%RL$ = % remaining life at time of measurement

The data indicate that measurements of the condition of cable jackets will provide an early warning of degradation before severe aging of the insulations occurs. This should hold true in all but the most egregious ohmic heating situations where conductor currents are at or exceed the rated ampacity of the cables.

This report covers the basic cable insulations and jackets used in nuclear plants with the exception of PVC. More data exist and are being generated than could be evaluated under the scope of this report. Use of this report by the industry will help determine whether further refinement in basic methodology is required. It will also help focus the need for additional data evaluation and generation.

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A
CAPSULE DISCUSSIONS OF CONDITION-MONITORING TECHNIQUES

A.1 Condition-Monitoring Techniques

A full discussion of available condition-monitoring techniques is beyond the scope of this report. The following capsule discussions are provided to help the reader gain a quick understanding of each technique and how it is used.

Density

The two existing approaches, the neutral buoyancy approach in a column of high-density solution and the Archimedes approach, are described here.

Neutral Buoyancy Approach

In this approach, columns of high-density solution are prepared that cover the range of possible densities of the material under test. Small pieces of the material under test are dropped into a column and the point at which the material reaches neutral buoyancy is measured. The density of the solution at that point is determined and assigned to the specimen [A-1].

Archimedes Approach

In the Archimedes approach [A-2], the sample (typically 50 mg) is weighed in air and then in isopropanol on a balance with a reproducibility of better than 10 micrograms. Equation A-1 applies.

$$\rho_{sample} = \left[W_{air} \div (W_{air} - W_{sol}\right] \times \rho_{sol} \qquad \textbf{Eq. A-1}$$

Where:

ρ_{sample} = density of the sample

ρ_{sol} = density of the solution

W_{air} = weight in air

W_{sol} = weight when supported in the solution

Edge Modulus

Edge modulus is a modulus measurement for MPa measured using the Modulus Profiling Technique [A-3].

Elongation at Break

Elongation at break (E-at-B) is a measured elongation for material between two grips moving apart at constant velocity. Elongation is measured by an attached extensometer or by a tracking separation of marks on the surface of the specimen. Elongation is provided as a percentage of the initial length between the marks or initial position of the extensometer. This is called *absolute elongation at break* and is used throughout this report. Dividing the absolute elongation by the initial elongation and multiplying by 100 provides the relative E-at-B in percentage. To preclude confusion, care must be taken to verify the reporting system (relative or absolute) that is being used.

Indenter Modulus

Indenter modulus (IM) is a measurement related to hardening of a polymer in which an instrumented probe is pressed against the wall of a polymer at a constant velocity until a set force is measured. The change in force divided by the change in position during compression of the polymer is the indenter modulus with units of N/mm [A-4].

Nuclear Magnetic Resonance T2

This is a proton nuclear magnetic resonance (NMR) spin-spin relaxation time for a sample swollen in an appropriately chosen deuterated solvent. The sample is placed in the solvent at approximately 70°C and subjected to the NMR test. Placing the sample in solution eliminates crystal structure from masking changes in cross-linking of polymer chains and provides greater resolution from unaged through aged specimens [A-5].

Oxidation Induction Temperature

Oxidation induction temperature is a test using a differential scanning calorimeter in which a small sample of material is continuously bathed in oxygen and energy is applied to increase the temperature at a uniform rate (for example, 10°C/min) [A-2]. The temperature at which an exothermic reaction occurs (that is, the temperature rises with significantly less energy applied to the specimen) is the OITemp and is indicative of the consumption of antioxidants in the material during aging.

Oxidation Induction Time

Oxidation induction time is a test using a differential scanning calorimeter in which a small sample of material is raised to a specific test temperature (for example, 200°C) while bathed in nitrogen. When test temperature is achieved, the nitrogen is replaced with oxygen. The time from the start of the flow of oxygen until an exothermic reaction occurs is the OITime [A-2]. This test is also indicative of the consumption of antioxidants in the material during aging.

Percent Gel and Uptake Factor

Solvent uptake measurements are performed by first exposing a known weight of sample (w_0) to refluxing p-xylene (a solvent) for a minimum of 24 hours [A-6]. The sample is recovered from the hot solvent and then quickly placed and sealed in a small container of known weight so that solvent evaporating from the sample is trapped in the sealed container. From the weight of the sealed container, the weight of the swollen rubber (w_s) is then determined. The final weight w_f of the remaining gel is determined after drying the swollen sample under vacuum. The solvent uptake factor is defined as the ratio of w_s to w_f. The percent gel is given by the ratio of w_f to w_0 as shown in Equation A-2.

$$\text{Uptake Factor} = w_s / w_f \qquad \% \text{ Gel} = 100 \text{ X } w_f / w_0 \qquad \textbf{Eq. A-2}$$

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