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Literature Review of Environmental Qualification of Safety-Related Electric Cables

Summary of Past Work

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ABSTRACT

This report summarizes the findings from a review of published documents dealing with research on the environmental qualification of safety-related electric cables used in nuclear power plants. Simulations of accelerated aging and accident conditions are important considerations in qualifying the cables. Significant research in these two areas has been performed in the United States and abroad. The results from studies in France, Germany, and Japan are described in this report. In recent years, the development of methods to monitor the condition of cables has received special attention. Tests involving chemical and physical examination of cable's insulation and jacket materials, and electrical measurements of the insulation properties of cables are discussed. Although there have been significant advances in many areas, there is no single method which can provide the necessary information about the condition of a cable currently in service. However, it is possible that further research may identify a combination of several methods that can adequately characterize the cable's condition.

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SUMMARY

The potential for renewing current operating licenses for older nuclear power plants has highlighted a need to review the methods used previously to qualify electric equipment. In many instances, electric equipment was qualified using different qualification criteria for different vintages of nuclear power plants. In particular, the technical bases for this rationale in the Environmental Qualification (EQ) has been questioned. In response, the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), initiated the EQ Research Program. Electric cable was chosen as the first electrical component for assessment.

Plants of different vintages used different EQ requirements endorsed by the NRC for qualifying Class 1E electric cables. These requirements were generalized in IEEE Standard 323-1974, endorsed by Regulatory Guide 1.89, Rev.1, and IEEE Standard 383-1974 (not endorsed by the NRC staff). The sources of uncertainty include pre-aging calculations, postulated loss-of-coolant accident (LOCA) simulations, and post-LOCA testing. The level of uncertainty increased further after recent findings on the impact of diffusion-limited oxidation at elevated conditions during pre-aging, failure of cables with bonded jacket during LOCA testing at Sandia National Laboratory (SNL), and the lack of an effective method of condition monitoring capable of either detecting the extent of degradation or estimating remaining qualified life. The primary goal of the EQ research program at Brookhaven National Laboratory (BNL) is to define the levels of conservatism, and to answer questions related to differences between the various methods used in the qualification process.

As a first step in developing the research plan, a public workshop, sponsored by RES, was held in November, 1993 to obtain input for formulating the EQ research program. Panels of industry EQ experts were convened to discuss technical issues related to: 1) pre-aging, 2) operating experience, 3) condition monitoring, and 4) testing. From the information obtained at these meetings, specific details on evaluating EQ requirements for cables were developed. A literature review was found to be necessary to assess the work completed which could be used to fully or partially resolve these concerns. This report summarizes the results of this literature review of researches performed by many organizations in the United States and abroad.

The studies reviewed are presented in three basic areas: 1) aging characterization, 2) LOCA testing, and 3) condition monitoring methods. The first two areas are directly related to the EQ process of cables for nuclear applications. Since 1975, significant studies of various aspects of EQ requirements were performed at SNL under NRC sponsorship. France and Japan also have carried out research to understand the effect of EQ requirements on their cables. CERN, a European research institution, has performed extensive studies on radiation aging of cable polymers. Compared to LOCA testing, aging studies on polymers used for cable insulation and jacket materials have received the majority of the attention both in the United States and in foreign countries having nuclear programs.

During the last decade, electric utilities and affiliated industries have expressed interest in research on the condition monitoring of cables. Thus, the Electric Power Research Institute (EPRI) sponsored several significant programs at universities, power plants, and within the cable industry. Cooperative programs with individual utilities, foreign agencies (specifically, Ontario Hydro, Canada), and the NRC were initiated to identify the most effective monitoring methods. Recently, Japan, Great Britain, and Sweden became involved in developing condition monitoring methods for cables in nuclear power plants. Despite these activities, an effective method has yet to be developed, and research is continuing.

In addition to the published literature, many proprietary studies were performed by the cable manufacturers on their products. These companies have the distinct advantage of knowing the actual composition and formulation of the compound used to construct their cables. However, due to the proprietary nature, this

information is not available in the public domain. For similar reasons, such studies performed in Great Britain and Germany were not readily available for this review.

The information presented in Vol. 1 of this report, particularly on aging and LOCA testing, is comprehensive and it is difficult to draw definitive conclusions on a particular issue. Therefore, an independent evaluation and analysis of the findings from the literature review was performed and results from this effort are presented in Vol. 2 of this report to highlight those issues which can be resolved without further research, and those which require additional data and research. Additionally, three appendices included in Vol. 2 describe results from the following independent studies: Appendix A on comparison of EQ requirements in other countries with nuclear programs; Appendix B on evaluation of the NUS/EPRI EQ database on cables; and Appendix C on evaluation of the INEL/NRC database on cables.

PREFACE

This effort includes a review of over four hundred published documents; approximately two hundred and sixty of which were found to be relevant to this study. The information in Vol.1 of this NUREG report is a summary of work presented in these publications. No original work was performed in this effort, and no credit is taken by the author of this report for the work cited. In some instances, direct quotes are taken from the referenced work; in others, the findings are paraphrased and the reference cited. Vol. 2 of this NUREG presents appendices, and an independent analysis of the literature as it relates to the issues of interest for this program.

Significant progress on characterizing aging behavior of polymers used in making cable jackets and insulations is achieved, and therefore, half of the referenced documents found in the literature are on this subject. Studies relating to LOCA testing are limited to those published by researchers in the United States, France, and Japan. Very limited advancement in the area of monitoring the condition of cables is found worldwide. Although twenty-three methods with the potential of detecting degradation in cables are presented, no single method or combination of several methods is identified which effectively can provide the necessary information to assess the condition of cables in nuclear power plants.

Results presented in this report are in both U.S. and metric systems. Since many findings are taken directly from published materials available, it is difficult to convert them into one set of measurement units throughout. However, the following key conversions may help the reader to compare results from different case studies presented:

Temperature:	1 °F	=	[(F-32) 5/9] °C
Pressure:	1 psi	=	6.89 kPa
Radiation:	1 Gy	=	100 rad
Energy:	1 eV/molecule	=	23.06 kcal/mole
Thickness:	1 mm	=	39.37 mil

Elongation-at-break is the physical parameter most researchers use in characterizing degradation in polymeric materials. Although many studies have included other measurements, the elongation measurement data is chosen to compare results from different studies. For a detailed understanding of the degradation process from variations in other monitoring parameters, the reader should consult the original publications. As appropriate, other condition monitoring parameters, such as insulation resistance, density, and tensile strength are presented in several cases.

All figures presented in this report are taken directly from the published literature. With exception to a few, results presented in most tables are extracted from published data in graphs or tables given for various case studies, materials, or methodologies. These summary tables are generated to provide comparisons of different qualification procedures, or behaviors in cable's insulation and jacket materials under different environmental or testing conditions. The sources of this information are cited in the text while discussing results of these tables.

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ACRONYMS

AWG	American Wire Gauge
ASTM	American Society for Testing and Materials
BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
CERN	European Organization for Nuclear Research
CFR	Code of Federal Regulations
CHEM	Chemical Spray
CLPE	Cross Linked Polyethylene
CLPO	Cross Linked Polyolefins
CM	Condition Monitoring
CP	Chloroprene
CPE	Chlorinated Polyethylene
CSPE	Chlorosulfonated Polyethylene (also known as Hypalon)
CT	Computed Tomography
DBA	Design Basis Accident
DBE	Design Basis Event
DED	Dose to Equivalent Damage
DF	Dissipation Factor
DLO	Diffusion-Limited Oxidation
DMA	Dynamic Mechanical Analysis
DOE	U.S. Department of Energy
DOR	NRC Division of Operating Reactors
DSC	Differential Scanning Calorimeter
EAB	Elongation at Break
ECAD	Electronic Characterization and Diagnostics
EPDM	Ethylene Propylene Diene Monomer
EPR	Ethylene Propylene Rubber
EPRI	Electric Power Research Institute
EQ	Environmental Qualification
ETFE	Ethylene Tetrafluroethylene Copolymer (also known as Tefzel)
FIRL	Franklin Institute Research Laboratories
FR	Fire Retardant
FRC	Franklin Research Center (previously known as FIRL)
FTIR	Fourier Transform Infrared Spectroscopy
HELB	High Energy Line Break
I&C	Instrumentation & Controls
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
INEL	Idaho National Engineering Laboratory
IR	Infrared (Insulation Resistance in Section 5.9)
JAERI	Japan Atomic Energy Research Institute
LDPE	Low Density Polyethylene
LOCA	Loss of Coolant Accident

ACRONYMS (CONTD.)

MI	Mineral Insulation
MSLB	Main Steam Line Break
NIR	Near Infrared Reflectance
NR	Neoprene Rubber
NRC	U.S. Nuclear Regulatory Commission
NRR	U.S. NRC Office of Nuclear Reactor Regulation
NTS	National Technical Systems
NUS	NUS Company
OIT	Oxygen Induction Time
PD	Partial Discharge
PE	Polyethylene
PF	Power Factor
PI	Polarization Index
PVC	Polyvinyl chloride
PWR	Pressurized Water Reactor
RES	U.S. NRC Office of Nuclear Regulatory Research
SBR	Styrene Butadiene Rubber
SNL	Sandia National Laboratory
SR	Silicone Rubber
SRP	Standard Review Plan
TDR	Time Domain Reflectometry
TDS	Time Domain Spectrometry
TED	Time to Equivalent Damage
TGA	Thermogravimetric Analysis
TID	Total Integrated Dose
TMA	Thermomechanical Analysis
TMI	Three Mile Island Nuclear Power Plant
TS	Tensile Strength
UConn	University of Connecticut, Storrs, CT
U of Tenn.	University of Tennessee, Knoxville, TN
U of Va.	University of Virginia, Charlottesville, VA
U.S.	United States
XLPE	Cross Linked Polyethylene

EXPLANATION OF TRADE NAMES

Trade Name	Polymer	Manufacturer
Bostrad 7	CSPE	BIW
Bostrad 7E	EPR	BIW
Dekorad	EPDM	Samuel Moore
Firewall III	XLPE	Rockbestos
Flamtrol	XLPE	Raychem
Hypalon	CSPE	Du Pont
Kapton	Polyimide	BIW
Neoprene	Chloroprene	Du Pont
Okoguard	EPR	Okonite
Okolon	CSPE	Okonite
Okonite-FMR	EPR	Okonite
Okoprene	Neoprene	Okonite
Okozel	ETFE	Okonite
Pyrotrol III	XLPE	Cerro
Tefzel	ETFE	Du Pont
Vulkene	XLPE	GE
X-Olene	XLPE	Okonite

1. INTRODUCTION

Nuclear power plants are designed and licensed to produce electricity safely and reliably for a minimum of 40 years. To achieve this, consideration is given to alleviating problems anticipated during the engineering design, manufacturing, and installation phases. In addition, there are testing and qualification programs, and inservice testing and inspections that monitor and maintain the plant's safety-related equipment under normal operational conditions. Operational misuse, which includes human errors of commission and omission, also is considered. Since an accident at a nuclear power plant can have catastrophic consequences, it is essential that the equipment designed for detecting and mitigating these accidents and their consequences remains operational throughout the life of the plant. Safety-related electric cables are important not only to normal operation of the reactor, but also to its safe shutdown during an accident.

An environmental qualification (EQ) procedure is one used to demonstrate that safety-related electric cables can perform their design functions when required during the service life of a nuclear power plant. With a number of such plants requiring operating licenses during late sixties and early seventies, IEEE Std 323-1971 (Ref. 1.1), a trial use standard, was the industry's initial equipment qualification standard applicable to electric equipment. It did not specifically address aging or life determination issues. The standard called for a systematic and disciplined program of analysis, testing, and quality assurance. It specified that qualification may be achieved through analysis, type testing, operating experience (suitably extrapolated and justified), or a combination of these methods. Then, the Nuclear Power Engineering Committee (NPEC) of the Institute of Electrical and Electronics Engineers (IEEE) formed a working group to develop guidelines for the industry for qualifying cables for a set of operating conditions (temperature and radiation) recognized by the design engineers. The outcome was the publication of the IEEE Guide P-383 (Ref. 1.2) for Type Test to qualify electrical cables and connections, an interim document which later was issued as a standard.

For qualifying safety-related electric cables, the requirements to account for degradation of the insulation and jacket materials, and to simulate the worst scenario of a postulated design-basis accident became generalized by the publication of IEEE Std 323-1974 (Ref. 1.3) and IEEE Std 383-1974 (Ref. 1.4) and endorsement of the former standard by Regulatory Guide 1.89, Rev. 1 (Ref. 1.5). One major difficulty in the requirements is that of correlating the accelerated aging portion of the qualification process with the calendar period of service life, especially when both thermal and radiation conditions are to be simultaneously simulated. Other issues include assessing the effect of pre-aging on accident simulation, test margins, and synergistic effects.

1.1 <u>Background</u>

Safety-related electric cables include low-voltage (< 1000 Volts) cables used to transmit electric power to the safety-related electrical equipment and instrumentation & control (I&C) devices, and to deliver signals (e.g., communication, data, and control) for performing safety functions in nuclear power plants. The Code of Federal Regulations (10CFR50.49) (Ref. 1.6) requires demonstration that safety-related equipment, including electric cables, meets its operability requirements throughout its qualified life. Specifically, 10CFR50.49(j) requires that "each item of electrical equipment important to safety ... (1) is qualified for its applications and (2) meets its specified performance requirements when it is subjected to the conditions predicted to be present when it must perform its safety function up to the end of its qualified life." Thus, the cable's operability is defined as its continued ability to support the safety functions of the connected equipment.

The nuclear safety-related cables must be able to support the function of safety-related equipment during normal operating conditions, anticipated operational occurrences, and design basis events (i.e., accidents including loss-of-coolant accident (LOCA), main steam line break (MSLB), and high energy line break (HELB)) for the entire time they are in service. The principal NRC documents providing guidance on the environmental qualification of electrical equipment, including cables, are (1) Division of Operating Reactors (DOR) Guidelines (Ref. 1.7), (2) NUREG-0588 (Ref. 1.8), (3) Standard Review Plan (SRP) Sections 3.10 and 3.11 (Ref. 1.9), and (4) Regulatory Guide 1.89, Rev. 1 (Ref. 1.5). The DOR guidelines generally apply to equipment installed in plants that became operational before 1980. The Category II criteria of NUREG-0588 apply to plants that became operational after 1980, and originally committed to the requirements of IEEE Std 323-1971. The Category I criteria of NUREG-0588, the Regulatory Guide 1.89, Rev.1, and the SRP meet the intent of 10CFR50.49 and principally apply to plants committed to the requirements of IEEE Std 323-1974, and to replacement equipment in all plants.

To familiarize readers with the differences in EQ requirements based on the NRC's regulations, the important elements in each of these documents are discussed below (Ref. 1.10)[1]:

10CFR50.49 - Environmental Qualification Rule: The EQ Rule was issued on January 21, 1983, and became effective on February 22, 1983. As defined by the rule, equipment important to safety includes (1) safety-related equipment required to remain functional during and following design basis events (DBEs)[2] to ensure the performance of required safety functions, (2) non-safety-related equipment whose failure during postulated DBEs could prevent the accomplishment of safety functions, and (3) accident monitoring instruments providing information on certain key variables (see Regulatory Guide 1.97: Post-Accident Monitoring Instrumentation). The scope of the EQ Rule does not include requirements for dynamic and seismic qualification of equipment important to safety, environmental qualification of mechanical equipment and important-to-safety electric equipment located in a mild environment (i.e., the general quality assurance and surveillance requirements contained in other regulations are sufficient to ensure adequate performance of electrical equipment located in mild environment), and protection of equipment important to safety against natural phenomena and external events. The following are important elements of the EQ Rule:

- A list of electric equipment to be qualified must be developed and maintained. This list is commonly referred to in the industry as the EQ master list.

- Documentation demonstrating qualification must be maintained in an auditable form for all installed equipment.

- The qualification file must identify the equipment's performance requirements, electrical characteristics, and environmental conditions existing during and following design basis events.

- The environmental conditions must address the most severe DBE during or following which the equipment must remain functional.

- The environmental conditions must include, as appropriate, temperature, pressure, humidity, chemical sprays, radiation, and submergence.

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[2] Design basis events include anticipated transients, design basis accidents, external events, and natural phenomena.

- Consideration must be given to all significant types of aging degradation affecting the equipment's functional capability.

- Synergistic effects must be considered if they are known to have a significant effect on the equipment's performance.

- Margins must be applied to account for unquantified uncertainties, such as the effects of production variations and inaccuracies in test instruments.

- Qualification must be established using tests (including partial tests), analysis, operating experience, or a combination of these techniques.

- Existing equipment qualified to previous NRC EQ criteria documents (i.e., DOR Guidelines and Category II of NUREG-0588) need not be requalified to the rule's requirements.

- Replacement equipment must be qualified to the rule's requirements unless "sound reasons to the contrary" can be demonstrated.

DOR Guidelines: The NRC IE Bulletin 79-01B Attachment 4, issued on June 8, 1979, "Guidelines for Evaluating Environmental Qualification of Class 1E Electrical Equipment in Operating Reactors," is commonly referred to as DOR Guidelines. The guidelines were clarified in three supplements: #1 - February 29, 1980; #2 - September 29, 1980; and #3 - October 24, 1980. The following highlights of this document are relevant to the scope of this study:

- LOCA in-containment temperatures of 340°F for 3 hours (BWR drywells), and for 6 hours (PWR ice condenser lower compartments) were suggested.

- Qualification for in-containment MSLB conditions could be based on LOCA conditions if the plant used single-failure-proof, automatically actuated containment spray systems.

- In-containment gamma radiation of 20 Mrads was acceptable for PWRs with dry containment designs.

- For the sensitive internals of equipment, if an in-containment beta dose of 200 Mrads could be attenuated via shielding to less than 10% of the required gamma dose, then qualification to the level of the gamma dose alone was acceptable.

- Qualification tests should be at least as long as the period from initiation of an accident until the temperature and pressure returned to essentially pre-accident levels. Shorter tests were acceptable if an analysis indicated there was no significant accelerated thermal aging during the untested period.

- Thermal or radiation aging of the materials was not necessary if they were not susceptible to significant aging mechanisms during normal operation.

- If a component failed during a test, the test should be considered inconclusive.

- Qualification for radiation during accidents and chemical sprays could be performed by analysis.

- A margin need not be applied to the required environmental conditions.

- Equipment should be qualified for a one-hour minimum operating time, as per supplement #2 of the Bulletin.

NUREG-0588: This document established two categories of environmental qualification based on the 1974 and 1971 versions of IEEE Std 323 (Category I: 1974 and Category II: 1971). For both versions, the NUREG describes acceptable qualification methods and provides guidance for establishing service environments, performance requirements, selecting qualification methods, the contents of licensing submittals, and documenting qualifications. Also, it notes that IEEE daughter standards, which address qualification of specific types of equipment (e.g., cables : IEEE Std 383, motors : IEEE Std 334) represent acceptable methods of establishing qualification. The highlights of this NUREG are given below:

- For Category I equipment in harsh environments, NRC generally will not accept analysis alone as a qualification method unless testing is impractical due to size of the equipment, or unless partial test data support the analytical assumptions and conclusions.

- The NUREG accepts the margins proposed by IEEE Std 323-1974 on accident test conditions. Although these margins must address inaccuracies in test equipment, additional margins to account for other qualification uncertainties need not be added if the accident conditions were developed using conservative NUREG guidance.

- Like the DOR Guidelines, the NUREG requires a one-hour minimum operating time-margin for equipment to perform its function within a short time into the event.

- The NUREG addresses aging, supports the use of the Arrhenius methodology, and suggests that qualified life for the equipment is developed.

- A manufacturer's Certificate of Conformance alone, without supporting data, is not sufficient for establishing qualification.

Standard Review Plan (SRP) NUREG-0800, 1981: Environmental qualification of electrical and mechanical equipment is discussed in Chapter 3.11, and seismic qualification in Chapter 3.10. Chapter 3.11 uses the information and methodology in IEEE Std 323-1974 and NUREG-0588. Although it draws little distinction between qualification of mechanical and electrical equipment, the methodology for the latter has not been applied to mechanical equipment in reactors that were in operation before May 1980. Chapter 3.10 on seismic and dynamic qualification addresses mechanical and electrical equipment and their supports.

Regulatory Guide 1.89, Rev.1: The Guide describes methods acceptable to the NRC staff for complying with 10CFR50.49. It generally endorses IEEE Std 323-1974 but cautions against using the test profiles in the Standard's Appendix A without verifying their plant-specific applicability. Most information in the Guide is based on NUREG-0588 Category I criteria, with one significant difference. Contrary to the NUREG, but consistent with the EQ rule (issued on January 21, 1983 and effective on February 22, 1983), the Guide permits ongoing qualification and revisions of qualified-life estimates, based on the results of periodic surveillance and testing programs. Below are the highlights of this guide:

- The guide notes that there are considerable uncertainties about the processes and environmental factors resulting in aging degradation. Further, due to these uncertainties, state-of-the-art preconditioning techniques cannot simulate all significant types of degradation.

- Based on the above observation, consideration should be given to the combination of test sample preconditioning and surveillance, periodic testing, and maintenance directed toward detecting those processes not amenable to preconditioning.

- For equipment exposed to low-level radiation, the guide states that such equipment generally should not be considered exempt from radiation qualification testing. However, it notes that exemption of organic materials may be readily justified for exposures below 10 krads for a service life of 40 years.

- The guide permits exceptions to the requirement for one-hour minimum operating time if they are justified. The justifications must address the following four considerations: the spectrum of pipe breaks, the need for the equipment later during recovery from an accident, the impact of equipment failures on safety function and operator information/actions, and the adequacy of the selected time margin.

- The guide notes that the synergistic effects known at the time of its publication were dose-rate effects and effects resulting from applying different sequences of accelerated aging radiation and temperature. Both effects were related to accelerated aging of equipment.

- The guide amplifies on the 10CFR50.49 requirements to upgrade the qualification of replacement equipment.

- Appendix B of the guide provides examples of non-safety-related equipment requiring environmental qualification based on plant-specific considerations.

Plants of various vintages are committed to differing NRC EQ requirements. The EQ rule implies that meeting the provisions of NUREG-0588 Category I (IEEE Std 323-1974 and Regulatory Guide 1.89, Rev.1) constitutes compliance with the rule. It requires that all new and replacement equipment in existing plants is qualified to its requirements unless there are sound reasons to the contrary. However, it does not mandate that any equipment previously qualified to lower standards (i.e., NUREG-0588 Category II or DOR Guidelines), must be re-qualified to the rule.

There are approximately 60 operating reactors that used the oldest EQ requirements, (i.e., DOR Guidelines), an additional 24 that used NUREG-0588, Category II requirements, and the remaining 24 that used NUREG-0588, Category I requirements and Regulatory Guide 1.89, Rev.1. Therefore, the EQ programs for the first two categories of reactor units are relaxed in areas such as qualification by testing, application of margins, and consideration of aging and synergistic effects. Specifically, some questions were raised recently about the survivability of cables qualified to these regulatory requirements under a postulated design-basis events (Ref. 1.11).

In support of initiatives on license renewal, Sandia National Laboratories (SNL) carried out tests to determine the effects of aging on typical electric cables used in nuclear power plants (Refs. 1.12 to 1.15). After accelerated aging, some environmentally qualified cables either failed (e.g., Okonite) or exhibited marginal insulation resistance during an accident simulation. Also, in the risk impact study (Ref. 1.16) Saltos has indicated that 18% of cables pre-aged to 20 years and subsequently exposed to a simulated design-basis accident failed. The percentage of failures increased to 23% for cables pre-aged to 40 years and to 32% for cables pre-aged to 60 years. According to Saltos, it is difficult to draw strong conclusions based on the small sample size and lack of unaged control samples; the SNL tests neither validate nor disprove the adequacy of current qualification practices and requirements.

The differences in EQ requirements, in conjunction with these preliminary results, highlight the uncertainties associated with qualification methodologies and the reliability of equipment that must function in harsh environments caused by accidents. A public workshop was hosted by the NRC in Rockville, Md., on November 15-16, 1993 to obtain technical inputs in the following areas: pre-aging; operating experience; condition monitoring; and EQ testing (Ref. 1.17). Based on discussions, the following questions related to EQ requirements were identified:

- What is the overall conservatism in the EQ process? Can cables currently in service survive an accident during their remaining design life?

- Is there evidence of degradation from field conditions (thermal and radiation hot spots, interfaces between cables and connections, long cable overhangs or other unusual physical constraints) that are different from design values, and therefore, not usually considered in aging simulations? Do existing pre-aging techniques based on the accelerated-aging methodology adequately simulate such actual in-plant environments?

- What in-situ inspections and condition monitoring methods effectively determine the state of the cables? What are the relevant indicators of degradation?

1.2 Purposes

Before performing exploratory research (involving laboratory testing of unaged and aged cables) to answer these questions, the purposes of this study are to review the available literature and databases and to determine the current state of knowledge on EQ requirements. This report covers the findings applicable to electric cables in the following three specific areas:

Aging Simulation Methods
LOCA[3] Simulation Methods
Condition Monitoring Methods.

The technical issues associated with these three areas are identified, and the results are discussed as presented by each study. Appendix A of this NUREG (see Vol. 2) provides the EQ requirements imposed by other countries, for comparison to the NRC requirements.

1.3 Approach

Since its inception in 1975, the Qualification Testing Evaluation (QTE) Program at SNL has produced numerous results on equipment qualification relating to many kinds of electrical equipment, including safety-related electric cables. NUREG/CR-4301 (Ref.1.18) summarizes the findings from SNL studies, and also related research performed elsewhere. The NUREG addresses specific issues encompassing three generic areas: accident simulation methods, aging simulation methods, and special topics related to equipment qualification. In each area, specific EQ-related issues are discussed. Surprisingly, the specific issues published in this document in 1986 are very similar to those discussed in the 1993 EQ workshop, and are still the main topics of this research. Therefore, for this review the findings described in this document in the areas

[3]Unless otherwise mentioned, "LOCA" represents an accident that envelopes postulated design basis accidents including LOCA, MSLB, and HELB. Such a profile is illustrated in Figure A1 of Reference 1.3.

of pre-aging and LOCA testing were used as the main source of information on earlier researches.

Hundreds of other published documents on cable insulation and jacket materials are available, both in the United States and abroad, including reports, technical papers, qualification documents, and conference proceedings. Also, there are ongoing programs, whose results to date are included in this review. Each published document was critically reviewed for its usefulness to this program. A database was created to collect all relevant information in any of the specific areas. This report summarizes the results from this review, and provides technical bases for future research.

This report is based entirely upon the literature published by others and does not encompass the author's own research. Because so many detailed documents had to be reviewed, and because the descriptions given in them often were particularly concise and apposite, in many cases, direct quotes are used in the text. In all such cases, the original study is cited. Similarly, the sources of the tables and figures are given. The summaries and conclusions from this review reflect the author's assessment and evaluation of this published data.

The EPRI/NUS EQ databank was accessed to obtain information on the status of the qualification on various cable types. In addition, the NRC/INEL database on EQ of electrical equipment was included in this evaluation. Appendix B (see Vol. 2) provides the results of the review of the NUS database. The evaluation of the INEL database is presented in Appendix C (see Vol. 2). Also, data from the utilities' qualification reports were searched to augment the results obtained from this literature review.

1.4 Scope

The scope of this report is limited to cables; cable interfaces, including splices, connectors, and electrical penetrations are not considered. Since a cable's insulation and jacket are weak links compared to the other components (i.e., conductor, shields, filler materials), the majority of discussions involve the degradation and qualification testing of these materials in the EQ process.

This report is not intended to supplant the reference documents; rather, it should be used as a guide to the issues important in the EQ research.

1.5 Organization of the Report

In Vol. 1 of this NUREG report, section 2 discusses different constructions of safety-related electric cables and the general polymeric materials used in their manufacture. Section 3 addresses cable-related published studies performed by the industries and the government agencies in the United States and abroad. The general EQ process that has been used by the industry also is summarized. Results from an assessment of several cable qualification reports performed by different cable manufacturers during early years (1970-1983) are discussed. The technical issues on pre-aging of cables in the EQ process are discussed in Section 4. Accident simulations are included in Section 5. Several testing methods are evaluated to monitor the conditions of cables in situ as well as in the laboratory; Section 6 summarizes the strengths and weaknesses in each of these methods. Finally, Section 7 gives the results and conclusions about the current state of research on pre-aging, LOCA testing, and condition monitoring.

Vol. 2 of this NUREG contains results from an analysis of the data presented in Vol. 1, and appendices describing findings from three independent studies as follows: Appendix A on comparison of EQ requirements in other countries with nuclear programs; Appendix B on evaluation of the NUS/EPRI EQ database on cables; and Appendix C on evaluation of the INEL/NRC database on cables.

1.6 References

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2. CABLE CONSTRUCTION AND MATERIALS

Electric cables are used for the transmission of power, communication, and control signal and data. The design process for cables includes selecting the conductor, insulation, shield, jacket, and armor material, and determining the size of the conductor required for the anticipated service requirements. Since cables are designed for a particular application, interchanging different types for different applications is not normally permitted. Although some special cable constructions, such as coaxial, triaxial, and mineral-insulated, are used in nuclear power plants, the predominant type is a low-voltage, unshielded, multi-conductor cable. The lack of a shield is a significant impediment to electrical testing of the insulation because there is no consistent ground plane (Ref. 2.1).

Electric cables use organic polymers extensively in the form of insulation and jacket over the conductors. The most commonly used insulation base materials include polyethylene, ethylene propylene rubber, and silicone rubber, and jacket materials include chlorosulfonated polyethylene, Neoprene/chloroprene, and polyvinylchloride (in older plants). In most cases, these polymers are crosslinked by radiation or heat (vulcanized). These polymers and other organic materials used in making cables typically are among the "weak links" so far as aging is concerned. This is especially the case in an oxygen environment where oxidative degradation can be induced by a number of different stresses including radiation and thermal. The degradation chemistry of commercial polymeric materials is further complicated by the presence of such additives as antioxidants, pigments, plasticizers, and fillers (Ref. 2.2).

A large amount of cable is used inside the containment of a nuclear power plant. A typical boiling water reactor (BWR) requires approximately 60 miles of power cable, 50 miles of control cable, and 250 miles of instrument cable. Similarly, almost 1000 miles of cable went into the containment building of Waterford III, a pressurized water reactor (PWR). A large fraction of these cables is safety related, and hence, the life assessment of cable systems is an important issue (Ref. 2.3).

2.1 Cable Construction

Three basic types of low-voltage cables are used for safety functions in nuclear power plants; power cables, control cables, and instrument cables (Ref. 2.4). There is no significant distinction between power and control cables; the designs and materials used for these two overlap. Instrument cables include thermocouple (single or multiple pairs), twisted shielded pair (single or multiple), coaxial, twinaxial, triaxial, and multiconductor with conductors arranged in concentric layers. Each cable consists of a metal conductor (single or multiple) sized to ensure proper current flow without significant losses due to resistance, and made up of strands to facilitate flexibility during installation. The insulation provides primary electrical isolation between the conductor and the external environment; shield and drain wires reduce electrical noise at the conductor for instrument cables; fillers enhance the roundness of multi-conductor cables; and jackets protect the cable from mechanical damage during installation. Cable materials, specifically the insulation and the jacket materials, are directly vulnerable to thermal and radiation aging and to self-heating. In addition, they are exposed to accident conditions (e.g., radiation, steam, temperature, pressure, moisture, chemical spray, and submergence).

Typically, cables are contained in raceways, usually metallic conduits or cable trays. Conduits are not generally sealed from the environment. Often cables in cable trays are sprayed with fire-protection coatings to protect them from external sources of fire or heat; this can therefore, prevent cables from dissipating internal heat, thus exposing them to higher than the design temperature. Jackets often are extruded over the metallic sheath to provide mechanical protection and isolate the shield. The low-voltage power cables are typically #12 AWG (American Wire Gauge) and larger, carrying continuous or intermittent currents at 600 Vac and lower. The current loads may cause an appreciable temperature increase in some power cables. The control cables are typically #12-#14 AWG single- and multi-conductor cables, and are used at 120-240 Vac or 125 Vdc, although some low-voltage digital signals also are used. The current levels in control cable applications normally are much lower than in power cables, rarely amounting to more than a few amperes. Finally, the instrument cables are shielded #14 AWG or smaller wires. They are used for milliamp or microamp, low-voltage, and thermocouple signals. In addition to low-level signal transmission, coaxial/triaxial cables often provide high-voltage power to neutron and radiation detectors.

Low-voltage power cable, shown in Figure 2.1, interconnects low-voltage electrical equipment, such as switchgear, motors, motor control centers, and batteries. These systems operate at nominal voltages of 600 V, 480 V, and 208 V three phase; 277 V, 240 V, and 120 V single phase; and 250 V and 125 Vdc.

Typical control cables, shown in Figure 2.2, are used to interconnect the control components of a system, such as solenoid operated valves, relays, limit switches, and control switches. They typically provide the feedback signal path for status indication, i.e., motor running, valve closed, or plant annunciation. The service voltage of control circuits and associated cables is generally 120 Vac, 125/250 Vdc, or occasionally 24/48 Vdc. Shielded control cables are used for protection against interference.

Figure 2.3 shows a typical instrument cable. Its function is to transmit low-level (milliampere or microampere), low-voltage (50 volts or less) analog or digital signals that are generated by sensors such as temperature detectors, pressure transmitters, vibration detectors, and fluid analyzers. In general, these cables are shielded to eliminate induced noise or spurious signals, and to minimize radio-frequency or electromagnetic interferences.

2.2 Cable Materials

There are three different environments within nuclear power plants (Ref. 2.1). Service conditions representative of normal plant operation (200 Mrads and 60°C) are used for specifications and in the design of nuclear cables, and envelop the great majority of plant conditions. The thermal rating of the insulation is 90°C. Most actual service conditions are bounded by 35°C-60°C ambient, and total integrated doses of 20-100 Mrads. In the vicinity of pressurizer electric heaters in a PWR, and in certain high elevations in the drywell of a BWR, components such as continuously energized solenoids experience radiation and high temperatures (200 Mrads and 75°C-100°C). The insulation rating for this condition is 125°C, 150°C, or higher. Conditions immediately adjacent to the reactor vessel are classified as high radiation and high temperature conditions (200,000 Mrads and 75°C-125°C). For this, the maximum rating for the insulation and conductor is 200°C. Typical instruments exposed to these conditions are neutron detectors, reactor head cabling, and other reactor instrumentation.

Conductor

Copper, particularly annealed copper, is the most widely used conductor material due to its relatively high electrical and thermal conductivity, good ductility and malleability, reasonable cost, and strength. A copper conductor is acceptable for use at continuous temperatures up to 300°F (150°C). It often is coated with tin, tin-lead alloy, pure lead, nickel, or silver at coating thickness of 50 micro-inches or less to minimize oxidation, enhance solderability, and allow operation at higher conductor temperatures. Tinned copper is favored for ease of making connections. Most cable conductors in nuclear power plants are made of copper and most of those are tinned.

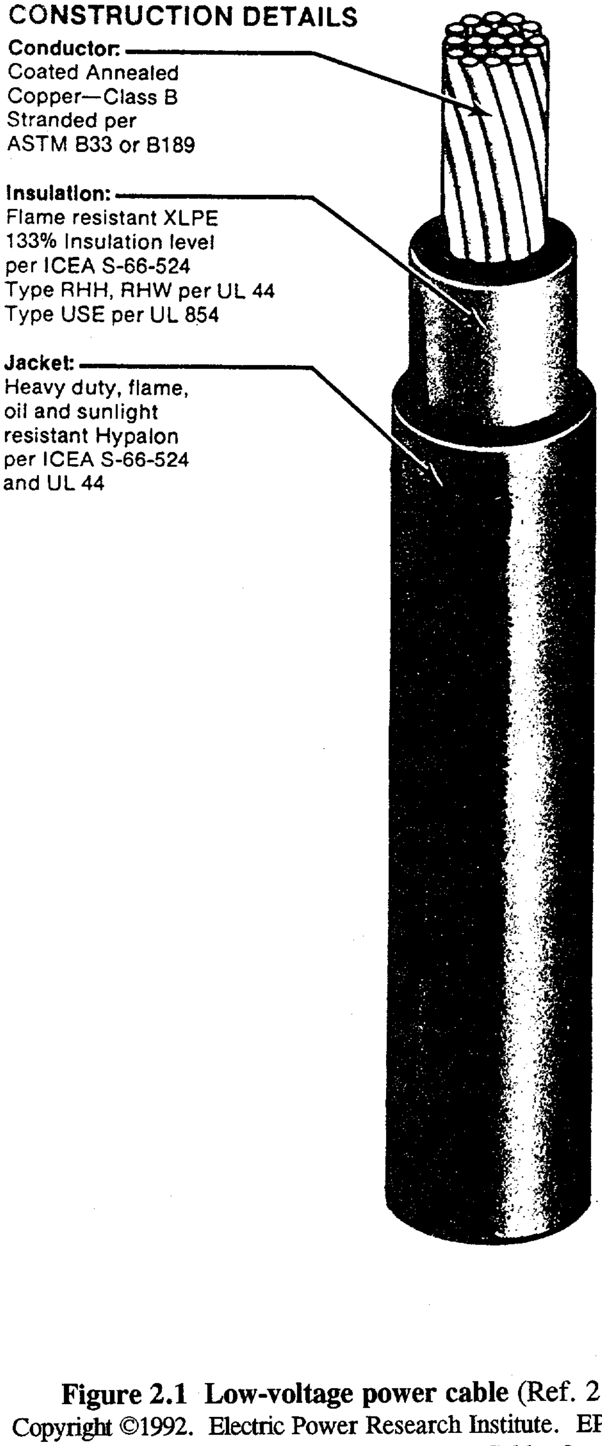

Figure 2.1 Low-voltage power cable (Ref. 2.1)
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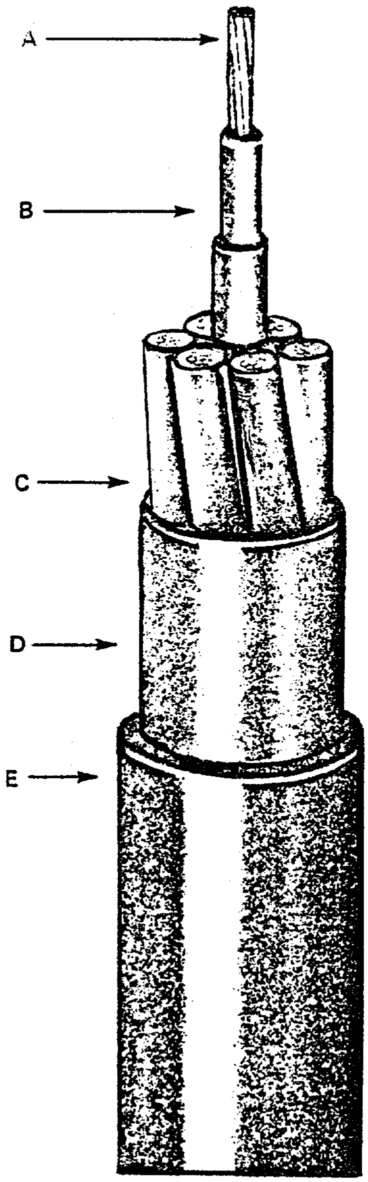
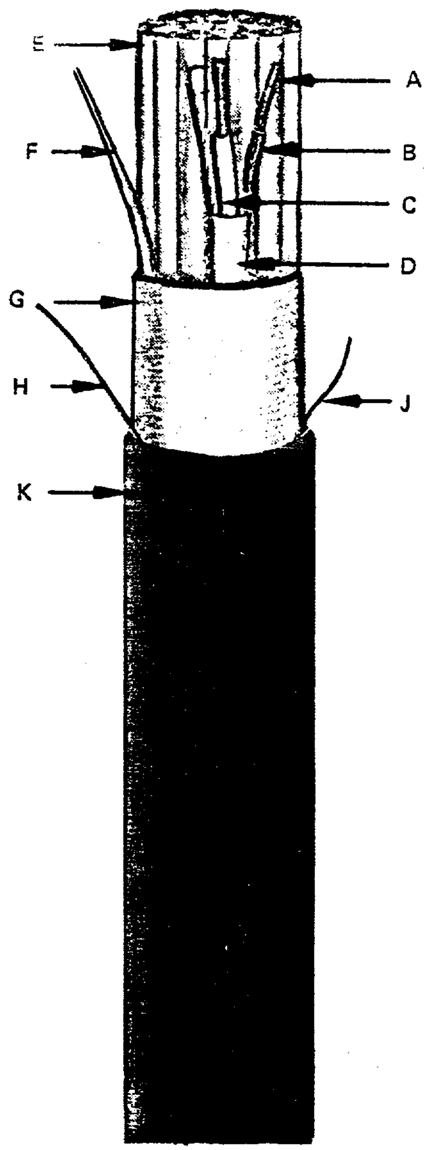


A. Coated Stranded Conductor
B. Insulation
#18 AWG & #16 AWG
#14 AWG through #9 AWG
C. Jacket
D. Extruded Belt or Cable Tape and Fillers
E. Outer Jacket

Figure 2.2 Control cable (Ref. 2.1)



A. Bare Stranded Copper Conductor
B. Insulation
C. Tinned Stranded Copper Group Drain Wire
D. Aluminum-Polymers Isolated Group Shield
E. Twisted, Shielded Pairs/Triads
F. Communication Wire
G. Aluminum-Polymers Cable Shield
H: Tinned Stranded Copper Cable Drain Wire
J: Rip Cord
K: Jacket

Figure 2.3 Instrumentation cable (Ref. 2.1)

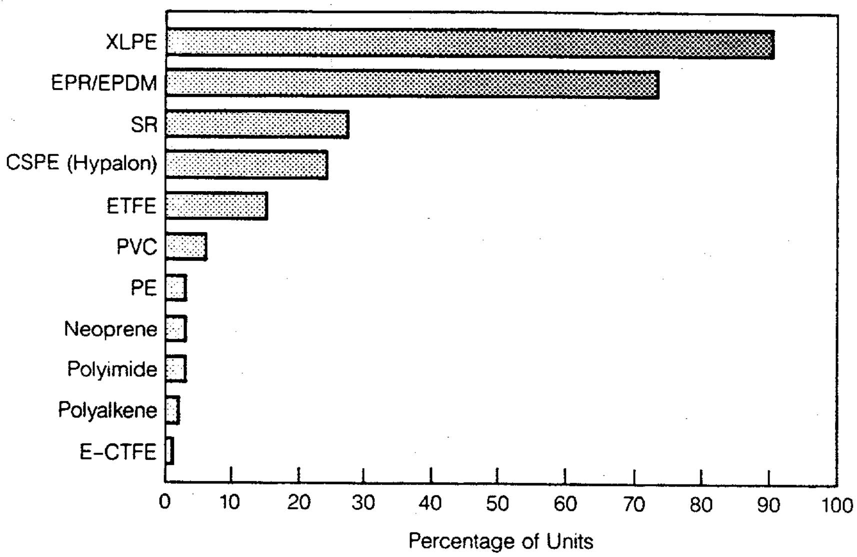


Figure 2.4 Cable-insulating and jacket materials inside containments of U.S. nuclear plants (Ref.2.5)

Insulation

The insulation used for nuclear safety-related cables is qualified for specific application, environment, and service conditions. As Figure 2.4 shows (Ref. 2.5), the principal polymeric cable-insulating materials include cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), silicone rubber (SR), and chlorosulfonated polyethylene (CSPE). These insulations, except SR, are rated for 90°C continuous conductor temperature, 130°C emergency temperature, and 250°C short-circuit maximum temperature. They are manufactured by mixing or "compounding" the raw polymer with selected chemicals, fillers, plasticizers, accelerators, and vulcanizing agents to enhance their electrical and physical properties.

SR compounds are the predominant insulators of cables used in high temperature environments; they retain good physical and electrical properties but have poor resistance to tears and abrasions. They are rated for continuous operation at 125°C-150°C. These cables often have coverings of abrasion- or fire-resistant asbestos glass braid or silicone glass braid.

Where both temperature and radiation are high, special cables are used; here, inorganic mineral insulation (MI) or polyimide film (trade name Kapton) typically is used. MI, having magnesium oxide, aluminum oxide or quartz insulation, requires a metallic watertight sheath because these insulations are hygroscopic and absorb moisture in humid environments. If unprotected, the insulation resistance would degrade severely, causing the cable to fail. Using a metallic sheath for protection (e.g., copper-bronze, stainless steel) results in a rather stiff cable that is difficult to install in a raceway.

Most cable insulations and jackets are manufactured by extruding and curing/vulcanizing the material blends directly onto the wire conductors. Kapton insulation cannot be extruded, but is manufactured in thin sheets precoated with a fluropolymer-type of adhesive. The sheets are spirally wrapped in multiple layers around the wire conductors and the adhesive fused at high temperatures. Although the capabilities of Kapton to withstand temperature and radiation may exceed 262°C and 10^7 Mrads, it is expensive and not as flexible as EPR or XLPE. It has a lower elongation-to-break, about 70% when it is new compared with 200-400% for rubbery insulation materials. Since steam and sodium hydroxide tend to degrade Kapton, it must be protected from direct exposure to LOCA sprays.

Neoprene and Hypalon have low insulation resistance (Ref. 2.4). The compounding additives used in manufacturing these polymers as insulation may have an adverse effect on the insulation resistance and on the rate of aging changes in the insulation resistance in wet and high thermal or radiation environments. Therefore, any highly filled compound is potentially susceptible to the problems of low insulation resistance when subjected to the steam/heat/radiation during an accident after an extended exposure to normal service conditions.

Shields

Shielding instrument cables is an effective way to reduce electrostatic noise in the instrumentation circuit and to ensure proper transmission of high frequency or pulse signals. Shielding also reduces information crosstalk between adjacent circuits. These cables use various types of shields, including braided copper wire and aluminized Mylar with a drain wire. Mechanically, the presence of a shield or tape barrier between a cable's inner conductor(s) and jacket may prevent cracks or other physical damage in the jacket from propagating into and through the conductor insulation.

Jackets

The jacket protects the cable's insulation from mechanical damage, chemical attack, and fire. The principal jacket materials include Neoprene, CSPE (commonly called Hypalon), and PVC (polyvinyl chloride); however, to minimize the release of halogens in the event of fire, PVC jackets are no longer used in the design of cables for nuclear plant service (Ref. 2.6). Hypalon has slightly better overall characteristics than Neoprene and shows good stability and excellent resistance to moisture. It also is better than Neoprene for the color coding specified by the NRC (Ref. 2.7). Special braids or compositions of asbestos, glass, or cross-linked polyolefins are used as coverings for cables used in high temperatures or high radiation.

Jackets of Hypalon, Neoprene, and PVC are extruded over the cable core. Cables with extruded jackets may not appear round and often, filler materials are used to round out the construction. For certain applications, metallic sheaths/armor are used. The insulated conductors are enclosed in a metallic covering of lead or aluminum, plain or galvanized steel tape, interlocked steel tape, or galvanized steel wire armor. In addition to mechanical protection, armored cables offer physical separation from other adjacent short-circuited cables.

In bonded jacket cables, the insulation and jacket are fused together and form a composite insulation. In this type of construction, the jacket and insulation cannot be easily separated and do not move relative to each other, as in unbonded jacket cables. This construction could affect the cable's failures, once the less resistive jacket materials begin to have cracks. Often during the aging process, initially unbonded jackets may effectively become bonded.

Among all the sub-components of low-voltage cables used inside the containment at nuclear power plants, the insulation and the jacket materials exhibit the most significant degradation. In most cases, by the time the electrical properties of the cable have deteriorated, the physical degradation to these two polymeric elements has occurred significantly.

2.3 Cable Manufacturers

There are approximately three dozen manufacturers in the United States who supply safety-related cables to nuclear power plants. For providing the necessary safety functions, the integrities of the conductor and cable insulation must be maintained. The conditions of jacket materials, fillers, and shield/drain wire are important in certain applications. Degradation of cables with age is primarily due to deterioration in physical and electrical properties of the insulation and jacket materials; the deterioration in one cable material can be quite different from that in another. For example, even the XLPE insulation produced by the same manufacturer, using similar formulations, raw materials, additives, and curing process can show very different deterioration characteristics because the manufacturer may use the same manufacturing procedure, but the formulations in the raw materials supplied by the chemical industry suppliers may have changed, altering the chemical composition of the cable materials. Therefore, the same manufacturer may not duplicate the cable previously supplied to a nuclear plant.

Table 2.1 shows the most commonly used cables for in-containment applications based on an industry database by EPRI (Ref. 2.8) and industry report (Ref. 2.9). Among insulating materials, XLPE and EPR/EPDM (ethylene propylene diene monomer) are dominant in normal service conditions, followed by SR and ETFE (ethylene-tetrafluoroethylene copolymer, also known as Tefzel) in high temperature service. The commonest jacket materials are Hypalon (CSPE), Neoprene, and PVC (only in older plants).

Table 2.1 Most Popular Cable Insulation Used Inside the Containment of U.S. Nuclear Power Plants (Ref. 2.9)

Cable Manufacturer (Material)	Number of Plants
Rockbestos Firewall III (XLPE)	61
Brand-Rex (XLPE)	30
Raychem Flametrol (XLPE)	23
Anaconda Y Flame-Guard FR (EPR)	35
Okonite FMR (EPR)	26
Samuel Moore Dekoron Dekorad (EPDM)	19
BIW Bostrad 7E (EPR)	19
Kerite HTK (EPR-like)	25
Rockbestos (Coax ,SR)	24
Kerite FR (SR)	13

Some manufacturers have either sold or closed their businesses. Consequently, it is difficult to develop a list with manufacturing details for tracing the original compositions of cable material. Also, as mentioned earlier, the chemical composition of cable insulation/jacket materials depends on the composition of the raw chemicals supplied by the chemical industry, the manufacturing processes, additives, and many other factors. Cable samples (aged or unaged) that can be obtained from the nuclear utilities may not be duplicated today, even by the same manufacturer. This poses problems in comparing the results from simulation studies on unaged cables with naturally aged cables. One solution may be to use similar or identical cables exposed to a controlled environment (e.g., control room) in the same plant as the unaged cable.

Manufacturers like BIW, Okonite, and Rockbestos, supplied cables of all types (including Tefzel, Kapton, and other frequently used XLPE, EPR, SR cables) to the nuclear power industry. There are another dozen manufacturers (e.g., General Cables, General Electric, Rome, Continental) who also manufactured and supplied specific types of safety-related cables to the power plants.

2.4 Summary

Electric cables are used extensively throughout nuclear power plants for power transmission, and control and communication of signals and data. Depending upon location and application, cables are exposed to a wide range of ambient conditions, including temperature, humidity, and radiation. As discussed in Section 1, one of the primary purposes of the EQ program is to ensure that electric cables continue to perform as designed throughout their service life.

The information presented in this Section provided an overview of cable design and fabrication:

a) the three general types of low voltage cables,
b) the general classes of polymer insulation, jacketing, and shielding for cables,
c) the common polymer material properties, and the application of certain polymer insulations for different plant conditions,
d) changes in polymer materials, and
e) the relative use of each type of insulation used in nuclear power plant containments.

Material properties for given polymer classes may vary, depending on improvements in the manufacturing process from batch to batch. It is important that these potential variations be understood and factored into any test designed. However, given the potential for wide variations, this may not always be possible or practical.

The information on cable design and manufacturing described in this Section will assist in predicting cable aging and survivability during accident conditions, as well as in interpreting previous aging and LOCA test results discussed in Sections 4 and 5.

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3. ENVIRONMENTAL QUALIFICATION AND RELATED RESEARCH ON CABLES

In EQ testing, cables are subjected to accelerated aging to simulate the design life of a nuclear power plant before being exposed to conditions of a design-basis event (Refs. 3.1-3.3). Because organic materials degrade significantly under certain environmental conditions (e.g., temperature, radiation), insulation and jacket materials can deteriorate considerably during their service life. Hence, the cable's reliability can be limited by the life of the insulating system. If properly installed and maintained, a qualified cable (i.e., one that successfully passed the EQ testing) should successfully withstand an accident, even at the end of its qualified life.

However, experimental pre-aging does not simulate the infrequent degradation resulting from physical damage, misapplication, local hot spots with temperature and radiation well beyond the design basis, and incorrect installation. Localized hot spots affect a portion of the cable's entire length, while design and installation errors affect a limited set of cables. In each case, corrective actions (e.g., repairs, or replacement when damaged) are included in the plant's maintenance program. The effects of such localized problems, even if undetected, generally should not pose a concern about common-mode failure, since redundancy built into the plant's design would assure its safety function. However, one study identified some aging-related cable failure modes and contributing factors that are potential sources of common-cause failures following a design-basis event or submersion event (Ref. 3.2). Both NRC and EPRI are sponsoring research to simulate some of these conditions in assessing naturally aged cables.

Significant research has been performed on EQ of cables, specifically on aging degradation of insulation and jacket materials. The effects of radiation and temperature conditions, accelerated aging methods, and the effect of insulation degradation on electrical properties have been studied extensively. However, for each aspect, the influences of a variety of factors has precluded reaching any definitive conclusion for a particular cable material. This section identifies EQ-related research performed on cables and cable materials, and briefly describes the typical EQ process adopted by the industry. Several cable qualification reports are assessed to better understand the differences and problems associated with various EQ requirements.

3.1 Environmental Qualification

During the 40-year license of a nuclear power plant, safety-related equipment, non-safety-related equipment whose failure during design-basis events could prevent safety functions, and accident-monitoring instruments providing information on certain key variables, are required to remain functional during and after an accident for a period identified in the license. Therefore, one of the basic requirements before accident testing is that the components are properly aged to simulate the actual in-plant conditions.

NRC's DOR Guidelines and NUREG-0588, Category II (IEEE Std 323-1971) do not require pre-aging tests for qualifying cables[1]. The former guidelines also do not require test margins (to account for uncertainties in the EQ process and manufacturing variations) and do not explicitly address consideration of synergistic effects from multiple stressors. Only 24 newer reactors have used NUREG-0588, Category I (IEEE Std 323-1974) which requires pre-aging and includes test margins and synergistic effects. Despite these differences in NRC regulations, the industry has said that most environmentally qualified cables in service in nuclear power plants have been subjected to some kind of pre-aging tests before the LOCA exposures (Ref. 3.4).

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[1] However, these documents require that an aging analysis be performed and that procedures be identified to account for significant aging mechanisms.

3.1.1 Pre-Aging

The environmental conditions simulated in the cable's pre-aging are thermal and radiation conditions inside the containment of a nuclear power plant. Other environmental factors (e.g., humidity, chemical attack) typically are considered benign compared to the effects of these two conditions, unless the integrities of the jacket and insulation already are compromised.

Appendix A (see Vol. 2) delineates a comparison of EQ requirements in several foreign countries including the United Kingdom (UK), France, Germany, and Japan. With regard to pre-aging, these countries use requirements and procedures given in the IEEE Std 323-1974 (Ref. 3.5) and IEEE Std 383-1974 (Ref. 3.6). Variations in their accelerated aging conditions to simulate the service life of cables in nuclear power plants (typically assumed 40 years) are summarized in Table 3.1 (Refs. 3.1 and 3.7-3.9). All use Arrhenius methodology to calculate oven conditions. For both thermal and radiation aging, air is introduced into the test chamber simulating the presence of oxygen inside the containment. Except for France and Japan, the irradiation temperature is not specified by other countries; ambient temperature probably is employed.

Table 3.1 Typical Thermal and Radiation Aging Conditions Used in Cable Qualification by Different Countries

Country	Thermal Aging	Radiation Aging
USA	7 days @ 150°C (air)	50 Mrad @ ≤ 1 Mrad/hr (T=ambient)
UK	15-40 days @ 115°C-135°C (air) (min. 10 days) (max. 150 °C)	20 Mrad @ 300 krad/hr (T=ambient)
France	40 days @ 135°C (air)	25 Mrad @ 50-150 krad/hr (T=70°C)
Germany	10 days @ 135°C (air)	5 Mrad @ 50 krad/hr (T=ambient)
Japan	7 days @ 121°C (air)	50 Mrad @ < 1 Mrad/hr (T=room)

Thermal Aging

The Arrhenius model is an accepted methodology for assessing time-temperature aging effects (Ref. 3.10) and is endorsed by the Regulatory Guide 1.89, Rev.1. For simulating accelerated aging, the Arrhenius equation is given by

$$\frac{t_s}{t_a} = e^{\left(\frac{\Phi}{k}\right)\left(\frac{1}{T_s} - \frac{1}{T_a}\right)}$$

where, Φ = activation energy (eV/molecule)
k = Boltzmann's Constant=8.617×10^{-5} eV/K-molecule
t_a = accelerated aging time
t_s = service time being simulated
T_a = oven aging temperature (K)
T_s = service temperature (K)

This equation is limited to the following assumptions: (a) degradation is caused by a single chemical reaction, (b) there may be differing activation energies in various temperature ranges for the same material, and (c) the parameters (i.e., aging time and temperature conditions) are derived by testing a population of material samples at various temperatures for a range of durations. Therefore, care should be exercised in extrapolating the time-temperature relationship to other temperature or time ranges where the material's aging characteristics are not well defined.

The estimation of activation energy of a polymer material varies with the chemical concentrations and engineering properties chosen. Typically, the estimate is derived from tests using tensile specimens aged at three temperatures, while the pre-aging is performed on actual cable samples. The Arrhenius method, used either to calculate the oven temperature for a specified test duration or to estimate the test duration for a specified oven temperature, employs these activation-energy values. A recent Swedish study (Ref. 3.11) gave a more accurate methodology to estimate the values for activation energy based on more parameters (e.g., elongation-at-break, indenter modulus, electrical parameters). Aging times of less than 100 hours are not permitted by the IEEE Std 323-74 (Ref. 3.5).

Radiation Aging

For most organic materials, the "equal dose/equal damage" model is employed in which the radiation effect is assumed to depend only on absorbed dose, and to be independent of dose rate or incident radiation type. Recent experiments showed that this model may not be conservative for some materials in certain configurations that are sensitive to the radiation dose rate. Also, like thermal aging effects, radiation exposure in different environments (e.g., vacuum, nitrogen, oxygen, or air) can affect both the type and magnitude of degradation. Specimens are irradiated by a gamma source, such as ^{60}Co to a dosage of up to 50 Mrad at a rate not greater than 1 Mrad per hour (Ref. 3.6). Typically, in-service doses ranging from 1-50 Mrad are combined with a LOCA dose, which ranges from 50-150 Mrad. This results in a maximum dose of 200 Mrad at a dose rate from 100 krad/hr to 1 Mrad/hr. Also, if more than one type of radiation is significant each can be applied sequentially.

Aging Sequence Effects

The effects of thermal and radiation aging on most materials generally do not depend on whether the aging is sequential (radiation followed by thermal, or thermal followed by radiation) or simultaneous. However, for conservatism, radiation aging should precede thermal aging for certain materials. The basic sequence followed in most qualification programs is thermal aging, irradiation to aging-plus-accident dose, seismic test and MSLB/LOCA testing (Ref. 3.5). On some cable specimens, Anaconda, Samuel Moore, and Raychem had qualified them using pre-aging with irradiation, followed by thermal aging. Also, ITT Suprenant, BIW, and Raychem have qualified some of their cables using simultaneous thermal and irradiation conditions during pre-aging (Refs. 3.13-3.45).

Synergistic Effects

Synergistic effects are those that result from two or more stresses acting together, rather than separately. The synergistic effect may produce more or less degradation, depending on their aging characteristics. Although there is very little information available on synergistic effects in accelerated aging for insulation materials, some of the jacket materials such as PVC exhibited significant synergistic effects, specifically under an oxygen environment. The two commonly known sources of synergistic effect on certain materials are dose-rate effects and aging sequence effects during accelerated aging simulations.

Effect of Oxygen

Cables in a plant are exposed to air which contains oxygen, except in containments that have inert atmospheres. During aging simulations, air is introduced into the test chamber at a partial pressure simulating atmospheric conditions and oxygen depletion does not occur. The effects of oxygen apparently are material-specific and may be significant. Research has indicated that the presence of oxygen during radiation aging at elevated temperatures significantly degraded certain cable materials (Refs. 3.1 and 3.2). For inert containments (typically for a BWR), the effect of oxygen should be considered accordingly.

3.1.2 LOCA Testing

The design basis environmental conditions are based on postulated accidents, such as LOCA, HELB, or MSLB. Depending on the location of the break and type of accident, cables can be exposed to a high radiation level, hot gases or vapors (e.g., steam), and a spray or jet of water, chemical solution, or other fluids. These environmental conditions differ markedly among various types of reactors, and also vary significantly between locations in the plant. Since the cables inside the containment are not limited to a particular location, the most severe conditions encompassing all possible design-basis accidents typically are considered for qualification. For cables, this is a combined profile from LOCA and MSLB conditions inside the containment (Ref. 3.5)[2].

After the specimens are aged for both thermal and radiation conditions, they are straightened and recoiled on mandrels with a diameter of approximately 20 times the cable's overall diameter and immersed in tap water at room temperature. While still immersed, the specimen's ability to withstand a potential of 80 V/mil ac or 240 V/mil dc for 5 minutes is tested (Ref. 3.6). Since both aging and accident radiation doses are typically applied together in the qualification program, the mandrel bend part testing is often excluded or modified by the test laboratories. However, cable specimens are mounted on 20 times cable diameter mandrel during thermal aging and the same mandrel is then exposed to both radiation and steam exposures.

Radiation Exposure

When thermal aging is complete, the cables are exposed to a total radiation dose equivalent to that expected during service (typically 50 Mrad) plus one LOCA exposure to radiation (typically 150 Mrad). The rate of exposure is approximately 1 Mrad/hr or less. Cobalt 60 typically is used as the radiation source.

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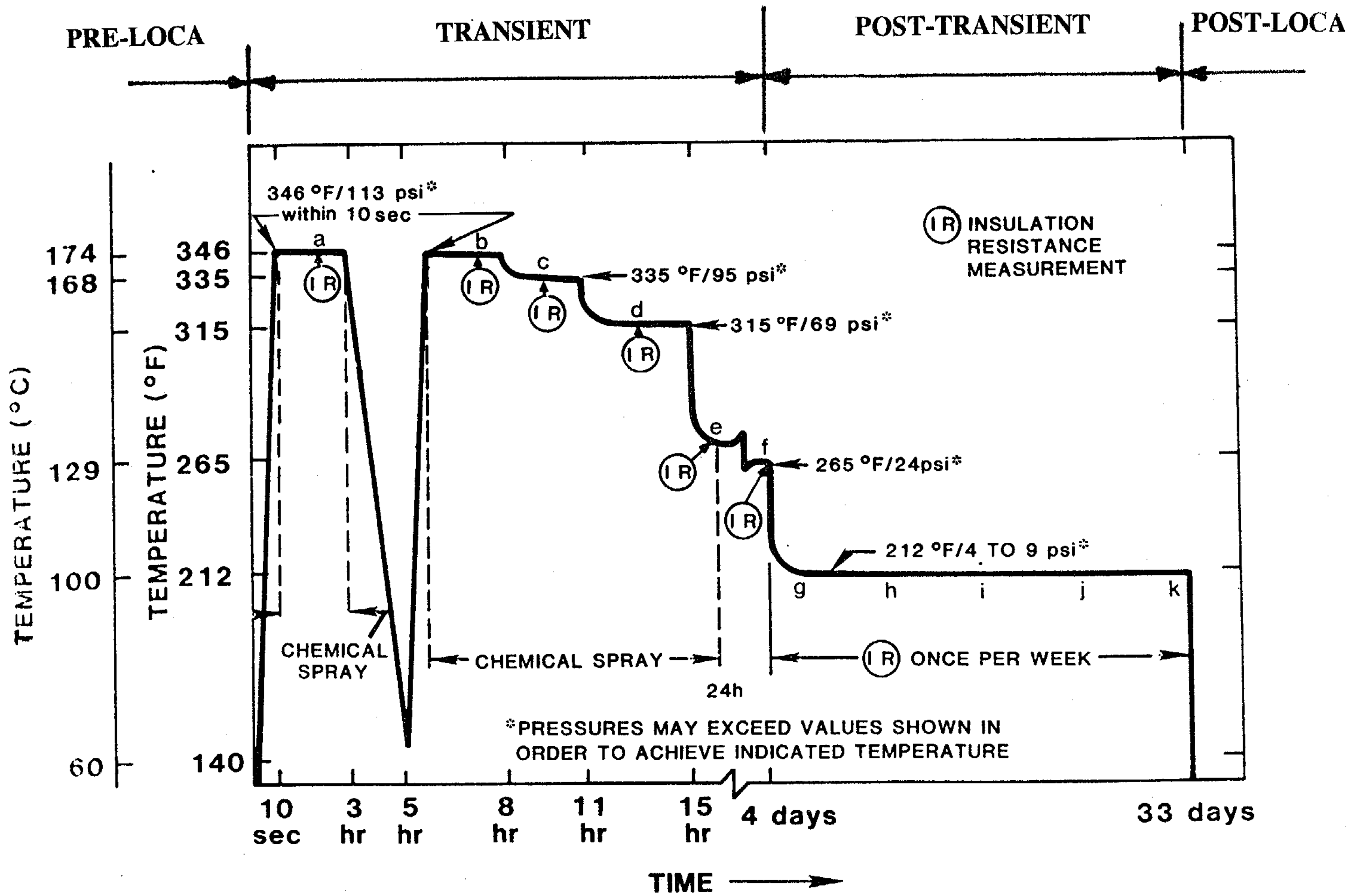
[2] For this report, LOCA transient duration is referred to first few days (Figure 3.1: 4 days) covering all transient peak conditions (double or single), Post-Transient duration is the period after these transient conditions to the end of LOCA testing with almost steady conditions in the LOCA chamber (Figure 3.1: 5-33 days), and Post-LOCA activities are those performed after the LOCA testing (Figure 3.1: after 33 days).



NOTE: TEMPERATURES TO BE WITHIN 5°F OF VALUES SHOWN

Figure 3.1 Typical temperature/pressure profile used in early steam/chemical spray exposure tests (Ref. 3.12)

Steam Exposure

The irradiated specimens are tested in a pressure vessel designed so that the specimens can be operated under load while simultaneously exposed to the pressure, temperature, humidity, and chemical spray of a DBE. Figure 3.1 illustrates a typical LOCA simulation profile used by SNL (Ref. 3.12). The LOCA environmental conditions differ markedly among different types of reactors, and also vary significantly from location to location in the plant. The profile shown in Figure 3.1 is a representative test chamber profile for a combined PWR/BWR test, and typically was used by cable manufacturers in early (1970s) qualification tests. If the actual conditions for an individual plant differ from this profile, the parameters should be adjusted accordingly. In later years, higher peak temperatures were used to simulate MSLB and the post-transient duration was shortened by (questionable) Arrhenius acceleration method. Although cables are expected to experience, at most, only one severe environmental transient from a LOCA during their qualified life, the cables typically have been exposed to two initial steam/chemical transients in the accident environment simulation, demonstrating margins. Typical margins for pressure, voltage, function time, and radiation are ±10% (whichever increases the test's severity). Note that for a BWR containment, deionized water spray instead of a boric solution spray can be used.

Post-LOCA Tests

After the LOCA simulation, the specimens are straightened and recoiled around a metal mandrel with a diameter approximately 40 times the overall diameter of the cable and immersed in tap water at room temperature. Then the specimens are tested for their ability to withstand a voltage potential of 80 V/mil ac or 240 V/mil dc for 5 minutes.

3.2 Review of Cable Qualification Test Reports

Test results presented in twenty-eight out of thirty-one qualification test reports (Ref. 3.13-3.40) received from NUS's EQDB files and five Okonite reports (Ref. 3.41-3.45) received from the Okonite Company (Dr. J.S. Lasky) are evaluated and findings are summarized here. Three NUS reports were excluded from this assessment: one that dealt with medium voltage cables subjected to moisture absorption tests, the second report analyzed the effect of beta radiation against gamma radiation, and the third report involved HELB testing of breakers and their terminal cables without performing radiation aging. However, the EQ tests performed on the medium voltage cables which were presented separately in another test report (Ref. 3.18) are included in this review.

This review is limited to the above thirty-three reports issued by several cable manufacturers. Table 3.2 summarizes the list of manufacturers and their cable types included in these EQ test reports. Very little information was available on the power plants for which these cables were qualified. Most reports used generic parameters for the aging and LOCA simulation conditions. A large fraction of tests were performed at Franklin Research Center in Philadelphia, followed by individual manufacturers, National Technical Systems, and Wyle. All used Isomedix for their radiation tests (both preaging and LOCA exposures), while Wyle used Georgia Tech for pre-aging and Isomedix for LOCA testing. Except for one test by Wyle (1989) and five Okonite reports (1987-88) received directly from the manufacturer, most other test reports were issued between 1969 and 1983. Many of them do not contain all necessary documentation required by regulation or standard practices, specifically in the areas of defining the objectives of the program and how these objectives were achieved based on the test results. This may be due to the difference in requirements between a test report and a qualification report. However, after the issuance of the EQ rule in 1983 many utilities conducted additional analyses or retested their cables to satisfy the regulatory requirements. Wyle was

Table 3.2 Manufacturer Test Reports and Cables Subjected to EQ Testing

Cable Manuf.	Report Year	Cable Appl.	Cable Materials	Aging Sequence	LOCA Profile	Test Results
Anaconda[1]	1969-79 and 1989	Power, Control, and Instrument	SR, EP, EPR, XLEPR, CSPE, and Glass tape	T-R and R-T (SR)	Soaking and SP	Analysis used for failed cables
BIW[2]	1975	Power	EPR, CSPE	T-R	DP	FRC:R+T & R+S
Cerro[3]	1974	Control and Instrument	FRXLPE, EPR, SR Neoprene, CSPE, and Asbestos braided	T-R	DP	Jackets embrittled
Eaton (Samuel Moore)	1978	n/a	XLPO, EPDM, and Hypalon	T-R and R-T	DP	Qualified
Essex	1980	n/a	EP, Hypalon	T-R	DP	Some failed during post-LOCA
General Electric	1980	n/a	XLPE	T-R	DP	Qualified
ITT Suprenant	1975-88	Control and Instrument	XLPE, XLN, Exane II Hypalon, and Exane(XLPO)	T+R and T-R	DP	Qualified
Okonite	1971-81 and 1987-88	n/a	Okonite, Okoguard, Okozel, Okoprene, and Okolon	T-R	DP	Qualified
Raychem	1972-75	Instrument	Alkane-imide and Flamtrol	R,R-T,T-R, and T+R	Soaking and SP	Qualified
Rockbestos	1977-89	Power, Control, and Instrument	XLPE, SR, and Asbestos braided	T-R and R-T	SP	Qualified

NOTES: n/a = not available, FR=Fire Retardant, SP=Single Peak, DP=Double Peak, T-R=Thermal followed by radiation, R-T=Radiation followed by thermal, T+R=Simultaneous thermal and radiation, R+S=Simultaneous radiation and steam profiles

1) SR, asbestos braided cables were qualified in 1989 with R-T aging sequence and single peak LOCA profile. All materials including SR were tested earlier (1969-79) with R-T aging sequence and LOCA by soaking and single peak profile.

2) FRC separately tested with simultaneous conditions (both R+T aging and R+S LOCA).

3) Merged with Rockbestos.

involved in conducting a large number of these tests for the utilities; none of these qualification and/or test reports were available at the time of this review.

Excluding a couple of reports, most contained an abbreviated description of cable specimens included in the test program, the aging simulation conditions, the LOCA simulation conditions, and condition monitoring tests that were conducted at the beginning (baseline), before and after aging simulation, before, during, and after LOCA simulation, and final qualification tests. Visual inspections, insulation resistance and sometimes functional tests at rated voltage and current were the principal CM techniques used to determine the cable's physical conditions. However, not all reports effectively assess these monitoring parameters in qualifying their cables. In some cases, ambiguity in test results, such as why the cables passed the functional tests during LOCA but failed final post-LOCA qualification tests, was not explained, nor why the cables then were claimed to be qualified for nuclear applications.

The review of these thirty-three test reports was made in the following four distinct areas:

QUALIFICATION
PLAN: Manufacturing data on cables
Installation data in power plants
Normal/abnormal plant environmental parameters used

	Accident conditions Condition monitoring methods used Other pertinent data relating to the test objectives
AGING SIMULATION:	Thermal aging conditions Radiation aging conditions Other design and environmental conditions Simulation processes adopted in the test program
LOCA SIMULATION:	LOCA profiles Test chamber conditions LOCA survivability and final qualification tests
CONDITION MONITORING:	Chemical measurements Physical measurements Electrical measurements

In each of these areas, information was sought from the test reports and each test program was assessed based on the availability of appropriate information, the relevance of this information to the test goals, and success in achieving these goals. Tables 3.3 and 3.4 summarize these results and compare them against an ideal case which represents an acceptable, fully qualified program if the tests were performed today based on the available technology. The table also discusses the merits and the demerits of the tests performed as compared to this ideal qualification process, and addresses improvements that can be achieved in the existing programs. The intent is to provide the reader a qualitative understanding of the EQ process.

Tests conducted in early years have very little information delineating test objectives, specimen preparation, or the test programs. Recent reports have good descriptions of the overall test program. The reasons for this may be due to the evolving process of the qualification requirements until 1975. Other reasons may include unavailability of a complete test report for this review due to the involvement of multiple laboratories. Almost all cables tested for accident simulation had undergone some sort of pre-aging, but of varying procedures from one test laboratory to another. The Arrhenius methodology and equal-dose-equal-damage models typically were used to simulate the 40-year life aging of cable specimens, but the limitations of these approaches were not discussed. Most used thermal aging followed by radiation, including the accident dose before exposing to accident steam and chemical environment. A couple of test programs adopted either simultaneous thermal and radiation aging or radiation aging followed by thermal in their simulations. All reached the conclusion that cables performed satisfactorily after being aged to the accelerated conditions. The effects of diffusion-limited oxidation and dose-rate effects were not assessed in any of these test programs.

There is a large variation in simulating LOCA conditions among these qualification test programs, as discussed in Table 3.2. Some early tests ranged from soaking cable specimens in boric acid solutions to single peak steam and chemical exposures. No consistency on the number of peaks, post-transient durations, and chemical spray durations was found. Except one, all performed radiation first before exposing the cables to a steam and chemical environment. Most reports used LOCA profiles similar to that given in IEEE Std 323-1974. During late eighties, Wyle has been using LOCA profiles with Arrhenius acceleration of the post-transient period. Passing the functional tests and/or insulation resistance tests was used to justify the final qualification of cables in the test program. Failures of cables have been reported after several days of post-transient conditions and were considered mostly as part of test anomalies. Recent tests used the post-LOCA mandrel bend and voltage-withstand test under warm water to pass cables for nuclear application.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

NOTE: Qualification Test Reports referred to in this table are manufacturers' test reports which utilities might have used to qualify their cables for nuclear applications. It is recognized that certain types of information discussed in this table typically are available in utility's qualification reports or other relevant documents. This comparison table addresses all aspects of an EQ test program that may or may not be available in these qualification documents. Here, the intent is to understand the evolving process that took place during the early years of EQ testing and how the older EQ requirements differ from an ideal case assumed by the author. Many cables qualified originally to older standards may have been re-qualified after the issuance of the EQ rule in 1983.

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
QUALIFICATION PLAN	Includes clear objectives of the test program and how to accomplish these goals. Should reference all industry and regulatory guidelines used in the test program.	Includes data on cable's manufacturing and installed condition, environmental parameters which can influence cable's degradation, accident conditions, condition monitoring techniques, and qualification criteria.	Most earlier reports have very little to almost no information delineating a test plan. Only reports after 1975, specifically FIRL and Wyle, have a good description of their test program. Separate test plan document or checklist may exist at test labs.	Lack of a test plan has caused large variations in test procedures performed by different labs. The test parameters were not chosen properly. Conclusions are sometimes not clearly stated.	A test plan articulating the test's objectives, procedures, and hypotheses (if any) is essential. Without a good test plan, it may impact significantly on the actual tests performed.
	MANUFACTURING DATA	-Conductor Specifications (size, tinned Cu) -Voltage/Current ratings -Insulation (material/thickness) -Jacket (polymer/thickness) -Construction details; shield, drain, solid/stranded, twisted, braided/bonded jacket -Insulation/jacket chemical composition and processing details (if possible)	Most reports provide a good description of cable construction data relating to insulation, jacket, and conductor specifications including their commercial names.	A few reports do not have enough details to determine what base polymer describes the insulation or the jacket material.	This information is critical for cables included in the test program and valuable for future evaluation and studies.
	INSTALLATION DATA	-Largest/shortest straight lengths -Bend geometries and locations -Large vertical overhangs and length -Cable trays, conduits, underground -Splices and their types -Abnormal mechanical stresses during installation (if known)	This information is not available in the qualification test reports. IEEE Std 383-1974 does not require this data to be included. However, utilities should document this information in qualification reports.	Lack of this information leads to an assumption that cables are qualified for general applications of all configurations. Note that reports reviewed were sponsored by cable manufacturers.	This will help justifying cables failed (certain specific test) during qualification for some specific applications.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

<table>
<tr><th colspan="3">ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT</th><th rowspan="2">STATUS OF QUALIFICATION TEST REPORTS</th><th rowspan="2">DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS</th><th rowspan="2">COMMENTS</th></tr>
<tr><th>DOCUMENTATION /MAJOR ACTIVITY</th><th>TECHNICAL DATA/ CATEGORY</th><th>SPECIFIC DATA/ RELEVANT INFORMATION</th></tr>
<tr><td>QUALIFICATION PLAN (Contd.)</td><td>NORMAL/ABNORMAL ENVIRONMENT DATA</td><td><table><tr><th></th><th>Normal/ <u>Design</u></th><th>Abnormal/ <u>Hot spots</u></th></tr><tr><td>-Temperature</td><td>X</td><td>X</td></tr><tr><td>-Radiation</td><td>X</td><td>X</td></tr><tr><td>-Humidity</td><td>X</td><td>X</td></tr><tr><td>-Fluid Leaks</td><td>n/a</td><td>X</td></tr></table></td><td>Only conditions typically mentioned are the oven conditions and the total integrated radiation dose. Very rarely is the required normal temperature of inside containment mentioned.</td><td>Without this data it is difficult to assess the actual qualification results for the plant environment. Hot spot data need further evaluation or study. Utility should identify these conditions.</td><td>Although it is difficult to include hot-spot conditions in the qualification program, this should be addressed and any detrimental effect from these conditions needs to be mitigated.</td></tr>
<tr><td></td><td>ACCIDENT ENVIRONMENT DATA</td><td>-Plant specific/generic test profiles
-steam conditions (peak T, P, H)
-number of peaks/rise time/dwells
-Chemical sprays and durations
-Radiation dose and dose rates
-Post-transient conditions/their durations
-Presence of Oxygen (or inert)</td><td>Early qualifications used innovative approaches to simulate accidents. Recent tests typically used IEEE Std 323-74 profile given in the appendix as a sample case.</td><td>Wide variations in defining accident conditions may need a closer evaluation against the actual plant data.</td><td>Cable failures during LOCA testing are reported to occur during post-transient conditions. Many cables that were severely degraded after LOCA, still passed the mandrel bend/voltage-withstand tests.</td></tr>
<tr><td></td><td>CONDITION MONITORING (CM) METHODS

VI= Visual Inspection
FT= Functional tests (V/A-Continuous)
IR= Insulation Resistance or Leakage Current(Periodic)
MB= Mandrel Bend (20X/40X)
HP= Voltage withstand (80Vac or 240Vdc/mil)
TP= Tensile Properties (Elongation/Strength)
SM= Submergence</td><td>Since no single CM test accurately characterizes degradation of a cable , no specific method(s) can be cited. However, with the knowledge of current technology the following is suggested.<table><tr><th></th><th>VI</th><th>FT</th><th>IR</th><th>MB</th><th>HP</th><th>TP</th><th>SM</th></tr><tr><td>Baseline</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr><tr><td>Pre-aging</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td>x</td><td></td></tr><tr><td>Dur Aging</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td>x</td><td></td></tr><tr><td>Post-aging</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr><tr><td>Dur LOCA</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td></td><td></td></tr><tr><td>Dur PostL</td><td>x</td><td>x</td><td>x</td><td></td><td></td><td>x</td><td></td></tr><tr><td>FINAL</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr></table></td><td>All CM methods (except TP) mentioned are used in various forms and at various times in the qualification process. No standard approach has been used. Post-1974 qualification reports used MB/HP/SM tests as required by IEEE Std 383-74. IR has been used by most tests. FT has been used by many during LOCA simulations. Often the VI results are implied (i.e., no mention means everything is OK).</td><td>Improper monitoring of cable degradation can provide random answers to the qualification process. No particular method used during pre-aging can assure the survivability during LOCA. Final conclusions should be based on these test data, and statistical approach (with multiple samples) should be used if there are random failures, even if the causes are identified as test anomalies.</td><td>This is one area which requires significant research, and methods characterizing the condition of cables both physically and electrically should be considered in the qualification process. An effective CM method should
-predict the physical and electrical conditions (i.e., the extent of degradation)
-correlate with age and predict remaining life
-predict LOCA survivability</td></tr>
</table>

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
QUALIFICATION PLAN (Contd.)	OTHER RELEVANT DATA	-Cable's commercial name (if any) -Cable application class/type(power, control, instrument) -Qualified life (i.e., 40 years) -Number of test samples (3-5 suggested) -Statistical averages/standard deviations -Industry/Regulatory standards or guides used in the qualification process -Qualification criteria/acceptability -Anomalies -Explanation of limitations (if any)	Early qualifications did not mention the standards/guides used; otherwise, all others used IEEE Std 323-74 and IEEE Std 383-74. No mention of the number of test samples used in the program. Typical qualified life used is 40 years. Justifications for cables failing CM tests were not always addressed.	Test sample information is critical to the qualification process. This is only used whenever a particular sample failed the test. Justifications and limitations on the test results should be explained.	This information is important for understanding and completeness of the test program and should be included in the test plan.
AGING SIMULATION	Includes qualification results relating to accelerated simulation methods and how it qualifies cables for a specific qualified life at conditions defined by the plant's service environment.	Includes calculation of oven conditions, air flow and other test setup conditions, instrumentation (thermal or humidity), radiation types, dose rates, synergistic effects, and condition assessments.	Most reports provide the oven temperature and duration, and total radiation dose used in the aging. Also, included are the test sequence and IR readings. All tests reviewed have considered pre-aging one way or another.	This kind of pass or fail data after aging provides very little information on the condition of cables and their survivability of a LOCA. No demonstration is provided to justify aging simulations with the actual normal conditions.	Trending of test parameters with the aging time can be very useful for understanding the degradation process. Also, a prediction model based on this degradation can provide assurance for the remaining life.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
AGING SIMULATION (Contd.)	THERMAL AGING	-Tests to determine values of activation energies of all temperature ranges of interest for all cable materials to be qualified. -Determine oven temperature condition (use IEEE Std 101-72 for regression line). Plot Arrhenius lines for the degradation level(s). -Extrapolation or interpolation of Arrhenius plots should be done within a straight line representing single degradation mechanism. -Air flow into the oven should be determined properly. -Instrumentation to monitor temperature, humidity (if any), and air flow should be included. -Conditions at the beginning and at the end (also intermediate time steps) should be documented and trends in the degradation should be assessed. -At high oven conditions, no heterogeneous degradation should occur across the insulation's thickness.	No test report has demonstrated that the degradation mechanism at oven temperature simulating normal plant conditions is the same, and therefore, Arrhenius plots are used. Almost all did not have any reference to the values or test results of activation energy used. Although most aging had used an oven temperature less than 150°C, some earlier tests used one as high as 210°C. All have used some sort of air flow conditions. Recent Okonite tests used actual field data to qualify 40-year life of cables otherwise qualified for <10 years using Arrhenius lines. Often unaged means not thermally aged.	Although cables qualified have undergone pre-aging before any exposure to an accident condition, differences in approaches (i.e., multiple thermal aging) indicate no uniform test procedure has been followed by the industry. Sometimes it was not clear what plant conditions were simulated in the accelerated aging tests. Data on activation energy used in the Arrhenius model should be experimentally demonstrated, since it can vary from one material to another and is sensitive to the life prediction.	With exception to defining limitations (i.e., temperature bands indicating single degradation process) in the Arrhenius method, most other technical approaches are sound and proper. However, details on the tests should be available.
	RADIATION AGING	-Cobalt 60 radiation source arrangements including dosimetry readings -Dose rates and TID used -Establish if the cable polymers are sensitive to dose rates and at what total dose does degradation become significant.	All radiation aging performed used Co 60 source at Isomedix. The dose rates used range from 300krad/hr to 1Mrad/hr. None studied the dose rate effects. One or two cases used electron beam sources for their radiation. Most cases use TID of 200 Mrad accounting for aging+LOCA.	For certain materials dose-rate effects can be significant. It was demonstrated that at 1-2krad/hr dose rate or less (at normal plant condition) this effect can be significant.	Beta radiation is typically simulated by an equivalent Gamma radiation. However, dose-rate effect on certain polymeric materials needs to be further addressed.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
AGING SIMULATION (Contd.)	OTHER CONDITIONS	-Effect of humidity -Effect of hot spots(abnormal conditions) -Effect of fluid(oil, water, or steam) leaks -Effect of mechanical stresses caused by installation/maintenance or vibration -Effect of additives (antioxidants, stabilizers, fillers, plasticizers) -Effect of cable constructions (bonded/braided jackets, multi-conductors) -Effect on special cable types(e.g., polyimides, mineral insulation)	No report has addressed the impact of these conditions on cable samples tested. One report used single conductor testing to qualify multi-conductor cables of the same material and construction.	Including these effects in the qualification process may be difficult. Many of these parameters relating to cable manufacturing are proprietary. Many other factors can be mitigated by improving the plant's QA/QC in the cable-handling programs.	Some assurance on the effect of these conditions may be warranted. A couple of studies on damaged cables could establish minimum threshold on cable thicknesses for a reliable performance.
	SIMULATION FACTORS	-Diffusion-limited oxidation (DLO) effects when high oven temperature or high dose rates are used. -Synergistic effects/Test sequences -Empirical prediction model -CM parameter(s) predicting survivability of LOCA simulations	Most reports used sequential testing (T-R used by many, R-T by others). One case used simultaneous (R+T) condition. Arrhenius model and equal-dose-equal-damage models were assumed in predicting cable life. No discussions on DLO effect. IR measurements are the only CM testing assuring the cable's performance.	Effects of DLO during accelerated aging need further evaluation. Synergistic effect due to radiation and thermal conditions for most cable materials may not be that critical. However, further study on this is warranted. Clough & Gillen model may need additional research. CM technique still remains to be addressed.	All these factors are important to simulating aging conditions at accelerated degradation rate. If the conditions of cable's polymers after aging and LOCA radiation are severely degraded, then many of these issues relating to DLO and synergism may be of no importance.
LOCA SIMULATION	Includes qualification results relating to cable's performance when exposed to simulated accident conditions anytime during the qualified life (i.e., 40 years) of a plant.	Includes defining the most severe accident conditions for the qualification program, simulating these conditions in performing LOCA testing, and establishing criteria to assure that cables can survive an accident even at the end of their qualified life and perform the necessary safety functions.	Many earlier simulations were innovative, ranging from soaking cables in boric solutions to a single peak steam profile exposure. Typically, radiation exposure during an accident was treated separately. Recent qualifications used test profiles similar to that given in the IEEE Std 323-1974.	The simulated conditions must represent the actual accident conditions of the plant for which the cables were being qualified. Often, this has not been explained clearly in the report. May be this is included in Utility's qualification report.	The reports reviewed are cable manufacturer's qualification test programs. The plant qualification reports must have compared their accident conditions with these generic profiles.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
LOCA SIMULATION (Contd.)	LOCA PROFILES	-Accident radiation condition (TID, dose rate) -Accident steam condition (P,T,&H) -Accident chemical spray (pH, duration) -Number of profile peaks (duration, steam & chem) -Post-transient conditions and durations -Total simulation period	LOCA radiation was typically combined with aging (200 Mrad) and applied to cables first before any steam test. Most early tests used single peak and chemical spray (with pH 7-8 for 24 hrs) during this peak. Post-transient exposures were at saturated steam conditions for 11days to 100 days.	Difficult to assess any deficiency in these simulations, since no plant-specific profile was compared with these generic models. However, many reports did not explain or justify the chosen profile.	No studies relating to a comparison or margins among various simulation parameters (single peak vrs double, post-transient durations, chemical spray conditions/durations, steam conditions) were found. This should be considered as research rather than qualification need.
	TEST CHAMBER CONDITIONS	-Radiation done separately or simultaneously with steam (dose rate at 1Mrad/hr). Dose rates should be higher for the first 4-days at peak conditions and lower for the remainder post-transient duration. -First peak reaches in 10-20 secs at about 350F/70-115psi and holds for 3 hrs; next 2hrs it comes down to initial conditions and the peak is repeated; after dwelling for 3 hrs at second peak it gradually reduces to 212F/0-10psi at the end of 4 days total; post-transient starts for another 26days; chemicals sprayed during two peak dwells. -Air supplied simulates containment conditions -Instrumentation and test arrangements	Except one, all tests performed radiation separately. The pressure, humidity, boric solution, rise time to peak conditions, and LOCA duration vary significantly among all tests. Peak temperature, saturated steam condition, and post-LOCA conditions remained similar in many cases.	There exists very little variations in TID of gamma radiation. No discussion is available on justifying the steam conditions, chemical solution, or air flow condition. Typical goal seems to just pass a "LOCA" test and then one can justify for any type of accident conditions. Margins of safety are not discussed, except using those described in IEEE Std 323-74 (10% on test parameters).	Unlike aging simulation, variations in test chamber conditions are not studied to determine safety margins available from one simulation to another.

Table 3.3 Comparison of Attributes for an Ideal Cable Qualification Test With Existing Requirements From Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
LOCA SIMULATION (Contd.)	LOCA SURVIVABILITY AND FINAL TESTING	-IR readings, visual inspection, and post-aging voltage withstand testing on 20X mandrel bend under water are performed both before and after LOCA radiation exposures -During LOCA, the cables are functionally tested and passed; IR readings remain within acceptable level; physical conditions remain good -During post-transient period while cables are exposed to a humid and hot containment conditions, IR readings, functional tests, and physical conditions are within acceptable level -After LOCA testing, cables are subject to IR, functional tests, voltage withstand test on 40X mandrel bend. Satisfactory performance on each of these tests is expected.	Most earlier tests included IR as the only test to qualify cables. Later, functional test and HiPot test were introduced. Tests performed after 1974 included all those tests required in the IEEE Std 383-74 standard. IR readings were taken daily (once or twice) or anytime there was a change in the test chamber conditions. Visual inspection was the only activity which evaluated the physical condition of cable's jacket and insulation materials.	When cable passed all tests, it was qualified for nuclear application. Then, it was the responsibility of the utility to compare conditions of their own plant with these generic cases and qualify their own Class 1E cables. When a cable specimen failed a test, it was further evaluated to determine the cause(s). Often it was due to pressure against mandrel, unusual bends, or located near a hot spot inside the test chamber. In most times, cables were claimed qualified because other specimens of the same kind passed or as long as functional tests were good. Sometimes no explanation was given.	Monitoring the condition of cables in a qualification program remains a challenging issue. There is no one technique available which can provide all necessary information to characterize the LOCA survivability of cables in power plants. Many earlier LOCA simulations were not rigorous enough to pass today's standard.

Table 3.4 Comparison of Condition Monitoring Methods with Those Used in Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
CONDITION MONITORING(CM) METHODS	A CM technique or combination of few CM techniques should be able to -correlate the degradation with dielectric properties -predict insulation aging from the degradation of jacket -predict LOCA survivability from the aging condition -determine the remaining life (empirical models)	Should have the following attributes (if possible): -non-intrusive -reproducible results -non-destructive -unaffected by environment -sensitive to degradation -applicable to wide range of materials -portable -cost-effective	The only test used for both aging and LOCA simulations was IR measurements. Visual inspection was the other way used to find any gross degradation.	Because there is no CM method effective for monitoring cable degradation, the LOCA survivability was not predicted from the IR readings after aging simulation.	Significant research in developing monitoring methods for cable degradation is warranted.
	CHEMICAL MEASUREMENTS	-Near infra-red (NIR) -Computed tomography -Sonic velocity -Fourier transform infra-red (FTIR) -Solubility measurements -Oxidation induction time/temperature -Plasticizer content -Differential scanning calorimetry (DSC) -ThermoMechanical analysis -ThermoGravimetric analysis (TGA)	None has been used in any of the test programs.	None of these methods are well developed for use. DSC, TGA, FTIR, and Solubility measurements can be good laboratory tools.	Most of these methods are in various developing stages. These methods may be good laboratory tools for developing other methods while monitoring the degradation of insulation or jacket polymers.
	PHYSICAL MEASUREMENTS	-Tensile properties (elongation/strength) -Indenter modulus -Torque tester -Flexure test (mandrel bend) -Polishing/profiling -Hardness -Density -Dynamic mechanical analysis	None has been used in any of the test reports. A few test programs measured elongation at the beginning and end of test, but the results were not used in the qualification. Mandrel bend was used while performing voltage withstand test.	Tensile tests are used by many studies as the benchmark for polymer degradation. Indenter has been used by some as plant monitoring tool. Some other tests are typically used as laboratory tools.	All these methods provide local information on the condition of cable polymers. They may be useful for research, but their use in plants may be difficult. However, elongation and indenter modulus can be used in the qualification.

Table 3.4 Comparison of Condition Monitoring Methods with Those Used in Qualification Test Reports

ATTRIBUTES FOR AN IDEAL CABLE QUALIFICATION TEST REPORT			STATUS OF QUALIFICATION TEST REPORTS	DISCUSSIONS ON THE QUALIFICATION TEST PROGRAMS	COMMENTS
DOCUMENTATION /MAJOR ACTIVITY	TECHNICAL DATA/ CATEGORY	SPECIFIC DATA/ RELEVANT INFORMATION			
CONDITION MONITORING METHODS (Contd.)	ELECTRICAL MEASUREMENTS	-Dc tests (IR,PI,Leakage) -Ac tests (transfer function, DF, PF) -Stepped voltage test (in air) -Partial discharge -Voltage withstand test (under water) -Time domain reflectometry -Dielectric loss	IR and voltage withstand tests were used in the qualification.	These tests provide some assurance that cables can function.	Need additional research.

Condition monitoring used in earlier test programs differed from CM used in more recent qualification tests. Still, none of these methods reports the level of degradation in the cable's insulation and jacket materials, nor its relationship with the LOCA survivability. Functional tests, insulation resistance, and voltage-withstand tests were performed to determine the state of the electrical behavior of cables. Significant research may be necessary to correlate these test parameters with the physical and chemical degradation of polymers used in constructing cables.

Finally, environmental qualification of cables has been an evolving process since the first commercial nuclear power plant (Dresden 1) came into operation in 1960. During the early sixties, cable manufacturers were continuously searching for improved answers to insulation problems against harsher conditions such as high temperature, radiation, steam/wet conditions, flame/fire, fungus, and high voltage gradients. General Electric came up with silicone rubber insulation which had demonstrated stability in electrical and physical properties over long intervals under wet and dry conditions (Ref. 3.46). Varied testing procedures had been evaluated to exhibit stability in electric strength. The significance of such inherent properties as resistance to corona, ozone, heat, fungus, flame and radiation had been demonstrated by tests. Normal service conditions were simulated by immersing cables in water at both room temperature and 70°C for over 10 years (125 months), high voltage tests were conducted to determine minimum insulation thicknesses, and abnormal conditions were considered using military standards on fungus resistance. Flame and fire resistance was accomplished by introducing halogen radicals to base polymer structures, and radiation resistance by introducing compounds based on a methylphenyl or methylphenylvinyl polymer. Steam resistance was measured by exposing to live steam conditions.

Similar to General Electric, Okonite (Ref. 3.47) qualified their cable products in accordance with IEEE Guide P 383 (Ref. 3.48) requirements for the moisture and steam tests, thermal aging, radiation exposure to aging and LOCA doses, and fire tests. The water immersion tests were conducted for over three years at 75°C and 90°C, long term thermal aging was accomplished in air oven at 135°C, 150°C, 165°C, and 180°C, a total dose of 200 Mrad was given after thermal aging, and finally specimens were subjected to LOCA conditions for a PWR and a BWR profile. Fire tests were conducted separately on cable trays and flame resistance tests also were performed on individual cable insulations. The study demonstrated the superiority in physical behavior of EPR and XLPE over butyl rubber at the time, but critics of the paper (Ref. 3.47) questioned the Arrhenius characteristics of cable materials at high oven temperatures.

Two Wyle reports (Refs. 3.49 and 3.50) for the Big Rock Point qualified butyl rubber/PVC and PE/PVC cables for outside containment area applications. Both EQ reports used similar approaches by comparing materials from qualification tests on similar materials. Since it is not necessarily true that identical cable materials with similar base polymer content would perform the same, this kind of similarity may require further attention with regard to its technical validity.

3.3 Sources of EQ Research

The first EQ research started in 1975 at Sandia National Laboratory (SNL), and was sponsored by the NRC's Office of Nuclear Regulatory Research after IEEE Std 323-1974 and IEEE Std 383-1974 were published. The goals of the program, Qualification Testing Evaluation Research, were to provide the NRC with technical information for creating, interpreting, and revising Regulatory Guides and Standards pertaining to EQ (Ref. 3.51). Specifically, the objectives of the program were: (1) to obtain data to confirm the suitability of current standards and regulatory guides for safety-related equipment; (2) to obtain data to improve the technical bases for modifying appropriate regulatory instruments; (3) to establish data-based and standardized test methodologies for qualifying equipment; and (4) to support the NRC licensing process with technical and expert advice. During the same period, utilities and cable manufacturers began environmental qualification of their cables for applications in nuclear power plants. As discussed, the Franklin Institute Research Laboratories (FIRL), Wyle Laboratories, National Technical Systems (NTS), and several other laboratories and cable manufacturers supported the efforts of the utilities with appropriate EQ tests and documentations. Also, the EPRI and NRC databases which contain information on EQ tests were considered part of this literature review.

Figure 3.2 shows the research on cables at various organizations in the United States and select foreign countries with active nuclear programs. In the United States, in addition to the NRC's efforts, the Department of Energy (DOE) has been conducting research at SNL on the aging degradation of polymers used in cable insulation. In parallel, EPRI and other industry organizations are sponsoring research in developing condition monitoring (CM) techniques which can assess the conditions of cable materials in a plant. During the last decade, several foreign countries including Canada, Japan, and France have aggressively developed their own EQ programs. Because of proprietary laws, most research in Great Britain and Germany is not published, while several other countries have just started EQ programs. CERN is primarily focussing on high radiation effects on cable materials. Recently, because of the global effects of nuclear accidents, IAEA has been developing standards and guidelines to monitor aging of insulation and jacket materials.

3.3.1 NRC-Sponsored Research

Major programs at SNL involved specific issues related to aging and LOCA simulations of cables in the EQ process. Recent studies involved potential effects of long-term aging for license renewal. Numerous NUREG reports and technical publications are available describing the research findings in the following areas:

Aging Simulation Studies:

Simulation of inside containment environment.
Use of Arrhenius methodology.
Radiation aging and dose rate effects.
Synergistic effects: sequential versus simultaneous simulations.
Effect of the presence of oxygen.
Effect of humidity and other environmental stressors.

LOCA Simulation Studies:

LOCA transient profile simulation: superheated/saturated/chemical spray.
Sequential and simultaneous radiation and steam exposures.
Effect of radiation types: gamma and beta.
Effect of the presence of oxygen.
Simulation of post-accident environment.
Effect of pre-aging on LOCA responses.
Effect of hydrogen burn.
Simulation of submergence.

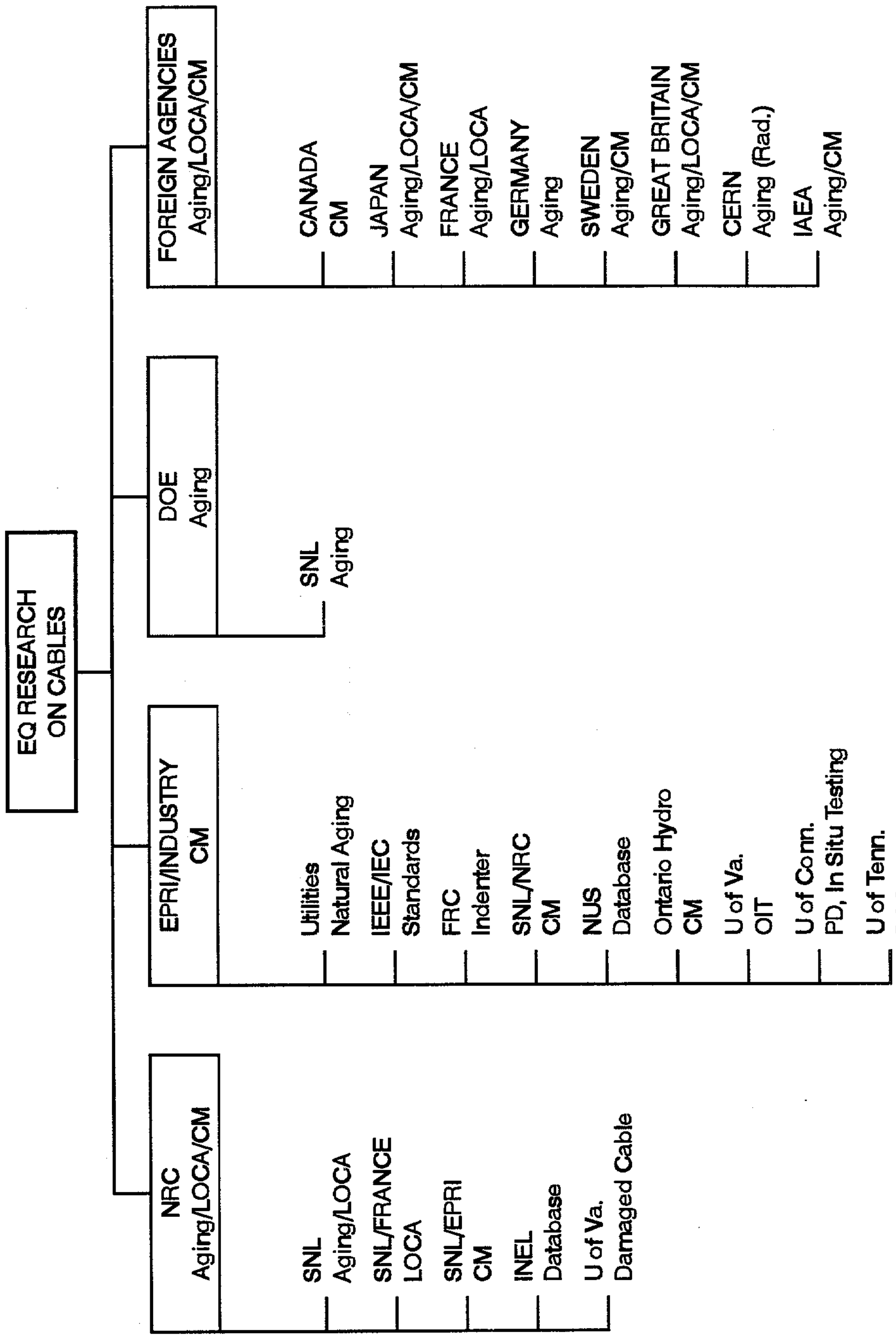


Figure 3.2 EQ research on cables

Additionally, in support of the license renewal of operating reactors, SNL has undertaken EQ tests on several types of cable to determine their survivability after a 60-year life inside the containment. These tests also include several CM techniques for assessing their usefulness in monitoring cable conditions as the plants age. Another study assesses the effects of high potential testing of aged and damaged cables under LOCA conditions. A similar study was conducted at the University of Virginia where finite-element analysis was used to determine the electric field at breakdown.

An EQ database, including data on cables, was developed at the Idaho National Engineering Laboratory (INEL) using information available from the SCEW (System Component Evaluation Worksheet) sheets submitted to NRC by each utility in response to IE Bulletins or in operating license submittals. Information on EQ of cables is present in this database, and could be useful in assessing the current status of a cable's qualification and its vulnerability to a design-basis accident (see Appendix C in Vol. 2).

In collaboration with EPRI, NRC sponsored research at SNL to investigate the effects of various ionization media around a cable while performing electrical breakdown tests. The objective was to define a continuous ground plane along the cable's length so that electrical tests could monitor its condition. This study augmented EPRI's effort at the University of Connecticut to use a partial-discharge test as a viable CM tool.

An extensive research effort in the LOCA testing area was undertaken at SNL in collaboration with the French nuclear agency on several types of cable material. Some results have been published in NUREG reports and are reviewed here.

3.3.2 EPRI-Sponsored Research

Since the first workshop on condition monitoring methods for cables in 1988, EPRI has sponsored research on developing effective CM methods for monitoring cables in nuclear power plants. The major effort, which is still continuing, involves Ontario Hydro and the University of Connecticut. Ontario Hydro has been assessing all kinds of tests including chemical, physical and electrical methods. This work is supported in collaboration with Canadian agencies, and other cable industries. The University of Connecticut is involved in two general areas: development of an electrical test method to monitor the cables in situ, and a comparison between naturally aged cables in several plants operated by EPRI's member utilities and cables subjected to accelerated aging. Both efforts are ongoing and interim findings are published as EPRI reports.

The University of Tennessee studied the use of a differential scanning calorimeter to extract the thermal history of cable materials based on their crystallinity behavior. The University of Virginia is working on developing an oxidation induction time (OIT) method for applying to cables in plants and expects that, based on the antioxidants remaining in the cable material, the life of a cable can be predicted. EPRI also has supported the Franklin Research Center in developing a method, known as Indenter Modulus, to assess the cable's condition based on the compression modulus of the jacket/insulation materials. At present, Ogden provides the sales and services on Indenter test equipment.

In parallel to NRC's effort at INEL, EPRI sponsored an EQ database at NUS, which provides member utilities with information that can help them qualifying safety-related (or Class 1E) equipment. Access to this database was obtained, and a separate evaluation is included as Appendix B (see Vol. 2) to this report.

As evident from presentations at the second EPRI workshop on CM methods in 1993, several utilities are closely monitoring the environmental conditions inside the containments. Locations chosen involve hot spot areas, and the proximity of cables important to plant safety. In addition, staff from both EPRI and individual utilities are involved in various standards activities sponsored by the IEEE, IEC, and other organizations in the United States and abroad that develop standards.

3.3.3 DOE-Sponsored Research

DOE has sponsored a decade of research at SNL on several cable materials. The effort was initiated when some PVC and PE cable materials used at the Savannah River K-reactor facility exhibited significant degradation following only 12 years of service. Moreover, this was unexpected because the radiation and temperatures inside the containment were not that severe. The study successfully identified the causes of this premature failure, which proved that cables exposed to low dose rate and the presence of air inside the containment degraded faster than expected. Since then, SNL has made similar studies on other cable materials and recently, developed a methodology involving a modified Arrhenius technique to include the effects of radiation dose-rate along with thermal degradation.

3.3.4 International Research

Great Britain, Germany, France, Canada, and Japan have been performing research on cables since the inception of their own nuclear programs. However, many of their studies are unpublished and are not available for review as with similar case studies performed by American cable manufacturers. Since such studies have the benefits of complete knowledge on the chemical composition and the manufacturing process, their results can be of significant advantage to any EQ research on cables. Nevertheless, several studies from France, Canada, Germany, Japan, and Sweden are available. CERN (European Organization for Nuclear Research) has been studying the effects of radiation on a variety of cable materials by using their particle accelerator facility. Recently, in response to the Chernobyl accident, international radiation experts under the auspices of the International Electrotechnical Commission (IEC) have been preparing standards to evaluate and monitor radiation damage of materials. Also, IAEA has sponsored research co-ordination meetings on the management of aging in containment instrumentation and control cables.

3.4 Summary

The foregoing has attempted to summarize significant EQ-related research on cables. The evaluation of this research will be accomplished in the dossiers, given in Vol. 2. The following provide some focus for issues that was given in this literature review:

Aging: (a) Using a high oven temperature for short durations of long-term aging in air may not accurately simulate degradation that occurs under normal temperatures. This difference may limit the use of the Arrhenius method. (b) Some insulations exhibit radiation dose-rate effects, and therefore, using high dose rates in simulation may not cause degradation similar to that occurring normally. (c) Synergistic effects due to thermal and radiation conditions and low dose rate are not clearly understood for commercial materials. (d) Other environmental parameters, such as humidity, may have caused random cable failures, as evident from operating experience. Although most failures were attributed to cable interfaces rather than to the cable itself, some studies on this aspect could be useful.

LOCA: (a) The presence of what is an appropriate amount of oxygen during an accident simulation should be determined. (b) The effect of post-transient condition duration on the cable's performance can be significant. Recent suggestions of accelerated simulation of this period require additional study, in conjunction with PRA evaluations which assume the safety equipment remains operational for a definite period after an accident. (c)The cable's responses to a single LOCA transient versus a double transient profile were not found in the literature. The margin available using double peak profiles needs to be established. (d) The severity of post-LOCA tests, including mandrel bend tests and voltage breakdown tests, should be assessed and their margins identified. (e)The ability of cables to perform when submerged after a DBE should be evaluated. Lessons learned from the TMI-2 indicate a large number of circuit failures when almost new cables were exposed to an 8 Mrad accidental dose. (f) The effect of pre-aging on subsequent LOCA testing in the EQ process is considered significant, as several studies have shown.

Other Issues: (a)Physical conditions (e.g., bends, long vertical overhangs), installations, and other mechanical stresses can affect cable's performance. (b)The effects of thermal and radiation hot spots, high humidity and vibration conditions, and water/steam/chemical impingements should be assessed. (c) There is no test to monitor the conditions of a cable's performance. Studies relating to developing test methods, correlating jacket degradation with insulation degradation, and understanding the behavior of jackets and insulation are needed. (d) For some cable insulation and jacket materials, the elongation after aging and accident radiation is practically the same, independent of the aging sequence (R-T, T-R, or R+T); therefore, for such materials, the choice of aging sequence probably has little effect on the outcome of the steam/chemical spray exposure.

Significant research on every aspect of the EQ testing on cables has been performed by NRC, EPRI, and the international community. An effort to coordinate and evaluate all the findings from these studies may provide the impetus for better understanding the behavior of cable materials. Once this is understood, the status of EQ issues facing the industry can be better assessed. Sections 4 and 5 assess issues relating to aging characterization and LOCA testing of cables, respectively.

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4. AGING CHARACTERIZATION OF CABLE MATERIALS

Cables may perform adequately even under the harsh conditions of a nuclear power plant when new, yet experience sufficient in-service aging degradation, specifically of the insulation and jacket materials, to possibly fail when the performance of a safety function is required. One objective of the environmental qualification of cables is to evaluate aging effects by either simulating them or assessing them by analysis, operating experience, or maintenance. It is imperative that aging stressors experienced by cables during their normal service life are identified, and the significant aging mechanisms caused by them are understood. Another purpose of an aging evaluation is to estimate a qualified life, after which cables must be replaced. The cable manufacturing industry, the electric power industry using the products, and the government agencies regulating this power industry all have undertaken significant research in this area (Refs. 4.1-4.3).

For the last two decades, researchers have faced the challenge of simulating the environmental and operational conditions of low-voltage electric cables located inside and outside the containment and predicting the degradation processes caused by these stressors (Ref. 4.3). This is even more difficult when each cable manufacturer uses proprietary formulations, including many additives to the base resins. These additives include antioxidants, flame retardants, coloring agents, fillers and curing agents, plasticizers, and other chemicals for thermal and radiation stability. They can affect the aging characteristics of the cable's insulation or jacket compounds. Furthermore, the thickness, geometry of the specimens, and fabrication procedures can affect the overall aging characteristics. Findings on degradation sensitivity of certain polymeric materials to dose rates in radiation aging, and synergistic effects due to combined radiation and thermal aging have complicated the simulating process even further.

Besides the United States, both the European countries (e.g., France, Great Britain, Germany, and Italy) and Japan have been studying radiation effects on polymers used in their cable products for the last one and half decades. Publications relating to these studies are discussed in this section, as appropriate. CERN (European Organization for Nuclear Research), a European facility sponsoring research on accelerator radiation of cable materials, has been irradiating many polymers either in a nuclear reactor, or with a ^{60}Co source, or in the CERN accelerators, at different dose rates and according to the recommendations of the International Electrotechnical Commission (IEC) standards. Schonbacher and Tavlet (Ref. 4.4) presented the results of these studies in the form of tables and graphs to show the effect of the absorbed dose on the measurable properties (e.g., tensile strength, elongation, and hardness). However, most of these insulation materials are available in Europe and not used in the U.S. nuclear plants.

Research in the U.S. has produced similar results on American cable products. Significant improvements in the construction and testing of cables used in nuclear power plants have been implemented by the industry (Ref. 4.5). Aging management guidelines have been developed to provide the nuclear utility industry an analysis of the potential degradation mechanisms and management programs for controlling them (Ref. 4.6). Industry standards have been written to guide the electrical industry in the designing of cables and their aging tests, when subjected to multiple stress conditions (Ref. 4.7).

This section reviews the results from the research on the thermal and radiation aging of insulation and jacket materials used in commercial cables. As a background, the environmental parameters inside the containment are described briefly, and various thermal- and radiation-induced aging mechanisms that cause the cable insulation and jacket materials to degrade are discussed in detail. These studies discuss both Arrhenius and non-Arrhenius degradation processes, the effect of the presence of air/oxygen, dose-rate effects at room and elevated temperatures, aging sequence, and synergistic effects including stressors other than thermal and radiation, methods of predicting cable life, and comparisons of the characteristics of naturally or long-term aged cables and cables after accelerated aging.

4.1 Environmental and Operational Conditions

One of the most important elements that affects aging degradation and hence, the environmental qualification of cables is the actual conditions to which cables are exposed during their service life. Most qualification programs assume the design parameters given in the plant's standard review plan or national standards and guides. However, in actuality, hot spots and other abnormal conditions exist that can accelerate the degradation of the cable's insulation and jacket materials. Here, plant conditions taken from various design source documents and from plant experiences are discussed. There is a difference in values summarized from different sources, but from knowing the differences, the conservatism available for particular cables can be derived.

To properly simulate the actual plant environment to which safety-related low-voltage cables are exposed, the conditions, such as temperature, radiation, and humidity, inside the primary containment are defined. Gillen, Salazar, and Frank (Ref. 4.8) obtained these parameters for all reactor designs in the United States:

PWRs:	49°C
	0.1 - 200 rad/hr (gamma plus neutron)
BWRs:	65°C
	40-60% relative humidity
	0.3 - 160 rad (carbon)/hr (gamma)
	0.1 - 50 rad (ethylene)/hr (neutron)

Johnson, Thome, and Craft (Ref. 4.9) also made a survey of electronics components in both PWR and BWR nuclear power plants on the in-containment environment:

Temperature:	1.	24°C - 66°C over an operating cycle.
		Generally 32°C - 38°C
	2.	49°C -54°C control rod drive area
	3.	To 94°C pressurizer shed
Humidity:		10 -100% relative humidity
Radiation:	Gamma Rates: .004 - 740 rad (tissue)/hr	
		(1 krad - 100 Mrad over 40 years)
	Neutron Rates: 4x10^{-6} - 0.54 rad (tissue)/hr	

EPRI's effort to compare the in-plant natural aging of cable specimens and small electrical equipment with accelerated aging simulation conditions is documented in a study by the University of Connecticut (Ref. 4.10). Fifteen specimen "bundles" were placed at each fifteen locations in eight plants; five of which were PWRs, and three were BWRs with inerted atmospheres. All of these bundles were placed in reactor containment areas except one located in the steam tunnel of a BWR. Estimated average temperatures ranged from 24°C to 66°C and 40-year doses ranged from 0.01 to 22 Mrads. It was claimed that some of these estimates of environments were based on conservative values used in the plant design.

Table 4.1 gives the normal environment inside the containment taken from IEEE Std 382-1980 (Ref. 4.11). As noted, these parameters differ significantly from plant to plant, as well as from location to location within a plant.

Table 4.1 Typical Normal Conditions Inside the Containment of a Nuclear Power Plant (Ref. 4.11)

Reprinted from IEEE Std 382-1980 *IEEE Standard for Qualification for Actuators for Power Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants*, Copyright © 1980 by the Institute of Electrical and Electronics Engineers, Inc. This document is an archived standard which has been superseded. The IEEE disclaims any responsibility or liability resulting from the placement and use in this publication. Information is reprinted with permission of the IEEE.

PWR	**Average**	**Maximum**	**Minimum**
Temperature (°F/°C)	112/45	135/57	40/5
Humidity (%RH)	80	100	10
Pressure (psig)	0	60*	0

BWR	**Containment**			**Drywell**		
	Avg	**Max**	**Min**	**Avg**	**Max**	**Min**
Temperature (°F/°C)	90/32	120/49	40/5	135/57	180/82	100/38
Humidity (%RH)	45	90	20	45	90	20
Pressure (psig)	~0	50*	~0	~0	50*	~0

*Under containment leak test. Varies from plant to plant.

In both BWR and PWR plants, the radiation exposure rates vary with location, and typical values range between 0.01 and 100 rad/hour for gamma-rays and 1 and $2x10^5$ n/cm^2 s for neutrons. In the areas where most cables are located (except those used for reactor instrument and monitoring) the gamma dose rate typically is 100 rad/hour, with negligible neutron exposure .

At the 1993 EPRI Workshop on Cable Condition Monitoring, McGuire (Ref. 4.12) described the polymer degradation program at the Perry Nuclear Power Plant. After five years exposure of cable samples to the plant environment, the average temperature and total integrated dose readings at five locations were:

Location	**Average Temperature °F/°C**	**Radiation @ 5 year Rads (Dose Rate)**
A	125/52	7.0E6 (~160 rads/hr)[1]
B	85/30	1.2E6 (~27 rads/hr)
C	140/60	4.7E5 (~11 rads/hr)
D	125/52	4.7E5 (~11 rads/hr)
E	78/26	21.9(0.0005 rads/hr)

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Participants at the NRC EQ Workshop (Ref. 4.13), expressed different opinions on defining the worst possible temperature and radiation levels inside the containment. Ceiling areas of the drywell at River Bend, cable

[1] It is interesting to note that the extrapolated 40-year dose at this location is 56 Mrad, which exceeds 50 Mrad aging.

vaults and reactor cavities at the Yankee plants, and other hot spot areas were reported to have higher temperatures and radiation levels than normal (i.e., as high as 235°F/113°C and 300 rad/hr)[2].

Other factors which can affect the operability of this class of cables include manufacturing defects, improper installation (e.g., excessive pulling tension, sharp corners), severity of electrical and mechanical loading (e.g., higher operating voltage, lack of ventilation), abnormal environment or operation (e.g., hot spots), and human errors (e.g., maintenance errors, crushing, insulation cuts). Standard procedures and guidelines (Ref. 4.14) can be used to minimize the effects of these factors, although complete elimination may not be possible. The thermal or electrical stresses caused by operating the low-voltage cables normally are not considered detrimental since they are factored in the cable's design with appropriate margins. However, poor installation practices can damage cables or cause conditions leading to faster degradation of the cable's materials.

4.2 Cable Degradation Mechanisms

Embrittlement of the polymers used in the construction of the insulation and the jacket is presumed to be responsible for most cable failures. Other factors affecting performance with age include changes in the inherent electrical properties of the insulation material, corrosion of conductor/shield, loss of fire-retardants from the insulation and jacket materials, corona discharges and voltage capacity breakdown of insulation materials, and formation of water and electrical trees in the insulation materials. For low-voltage applications, none of these factors are considered important enough to include in the qualification process. However, their potential effects are discussed.

Operating experience of low voltage cables used inside the containment indicates very little degradation in cable polymers. Rather, a large fraction of failures was attributed to cable connections and interfaces, and abuses or errors during installation and maintenance. This finding supports the need to concentrate on hot spots and weak links in any effort to increase plant safety.

Degradation of Insulation/Jacket Polymers (Refs. 4.15 - 4.18)

Providing that the physical and material integrities of the insulation and the jacket are not compromised, there is very little chance that the cable's performance will deteriorate. Performance is affected when the electrical characteristics, such as dielectric strength, and insulation resistance, are degraded due to changes in the physical and chemical properties of the insulation and the jacket materials. By the time a significant change in the electrical characteristics of the cable is found, the cable might already be well beyond the point where it needs replacing. The insulation and the jacket materials consist of organic polymers, whose degradation depends on the changes in their molecular structure. This subsection familiarizes the reader with terms later used in discussions of polymer degradation.

Polymers are broken down by heat, chemical attack, radiation, or a combination of these in a variety of degradation modes. Random bond breaking along the main chain(s) of the polymer molecules or at functional groups can occur from heat and radiation. Bond breaking produces two reactive free radical sites on the polymer chain which can then react along one of several path options:

- recombination of the broken bond,
- reaction at another location of the same polymer molecule (crosslinking),

[2] Extrapolation to 40 years yields a total dose of 100 Mrad.

- reaction of the polymer molecule with another (also crosslinking),
- reaction producing smaller molecules or polymer fragments, with a net decrease in polymer molecular weight (scission), or
- reaction with ambient air, specifically oxygen (oxidation).

Crosslinking reactions can propagate the free radicals in a chain reaction that can affect the main chain of the backbone as well as functional or side groups. Oxidation by direct reaction of the polymer molecule with air (oxygen) or oxidizing agents in solution can also result in chain scission. The latter mechanism does not leave free radical sites on the polymer chain.

Without radiation or other means of producing free radicals, the rate of oxidation at ambient temperatures is small. The free radical mechanism is more damaging because it is self-propagating unless quenched or inhibited by additives. Free radical initiation is most often associated with electromagnetic radiation (such as ultraviolet, x-ray, gamma), or particle radiation (alpha, beta, protons), although other means such as thermal or mechanical can produce them. The number of free radicals produced, and subsequent rates of reaction (crosslinking or scission) depend on the type of polymer, the use of additives, and the type of radiation.

The effects of scission and crosslinking combined with oxidation vary according to several factors, and are not easily predicted. Important factors include the type of polymer, the use of any additives (fire retardants, colorants, anti-oxidizers), and the environment (radiation field, temperature, atmosphere). Chain scission without oxidation results in a net decrease in polymer molecular weight and is evidenced by reduced tensile strength, hardness, and Young's modulus (increased elasticity). Crosslinking without oxidation usually results in increased tensile strength, hardness, and Young's modulus.

Oxidation generally reduces the molecular weight of the polymers and introduces oxygen containing functional groups. Oxidation often is characterized by brittleness and cracking. Dose-rate and diffusion-limited effects are associated with oxidation in a radiation environment.

Polymer degradation is the result of two main causes. The first is chemical degradation changing the chemical structure of the polymer sample. In a high temperature environment, the polymer deteriorates by reactions of the side groups, scission of main chain links, and recombination of radicals formed from bond breakage. Oxidation is the main cause of degradation in the ambient atmosphere, and is accelerated by increased temperatures and by ionizing radiation.

The second cause of degradation is associated with physical changes in the polymer. An example is changes in composition due to the diffusion of low-molecular-weight components, such as plasticizer or water, out of the amorphous regions.

Changes in Electrical Properties (Ref. 4.19)

The following are electrical properties which change with the age of the cable:

- dielectric strength (Volts/mil), or the maximum potential gradient a material can withstand without puncture,
- dc resistivity (megohms), or the resistance to passage of dc current,
- dielectric constant, which is a measure of a particular insulation geometry, and
- dissipation factor, or resistance to ac current.

The ac breakdown voltage of an insulation depends on the material's composition, degree of cure, voids, contaminants, and test temperature. For 60 hz breakdown voltages on most low voltage cables, the dielectric strength is well above 200 V/mil and impulse dielectric strength is above 400 V/mil. Typical dc potential used in testing the cable dielectric strength is 240 Vdc/mil. Since the voltage levels of the cables are well below these threshold values, the materials suffer little electrical stress from their normal operations.

The insulation resistance changes with the age of the cable, temperature, humidity, and its geometry (e.g., two conductor #12 AWG versus coaxial cable). Theoretically, high radiation dose-rates can decrease a cable's insulation resistance by supplying additional charge carriers; however, this effect is not as significant as the thermal effect. It is not uncommon for the insulation resistance values to decrease 6 or 7 orders of magnitude (e.g.,from 10^{13} to 10^{6} ohms/1000 ft) during peak LOCA conditions, and return to near pre-LOCA values at post-test ambient conditions. Instrument and control circuits (e.g., radiation or neutron monitoring systems) which are sensitive to extremely low current signal levels (e.g., 10^{-12} amps) require very high coaxial cable insulation resistance and impedance to transmit the detector signals properly.

For ac and pulse type applications (e.g., digital transmission circuits, neutron monitoring circuits), circuit parameters such as transfer function, ac resistance, and power factor depend on the dielectric constant and dissipation factor of the associated cables, and are important for instrument applications. There is evidence of change in these parameters with the age of cables, specifically for ac impedance of coaxial cables.

Conductor/Shield Corrosion (Ref. 4.19)

The integrity of the conductors for all types of cables is important for reliability, as is that of the copper braid shield of some coaxial and triaxial cables. Since most conductors used in nuclear plants are tinned, corrosion normally does not cause a problem unless the cable was sharply cut during installation or maintenance to expose the copper conductors to the reactor's environment. The only parts of the cable conductors subject to such degradation are the connection ends and splices. Corrosion of shields may not have any adverse impact on the cable's performance.

Loss of Fire Retardant (Ref. 4.19)

Cable insulations and jackets often include fire-retardant additives to reduce flammability. One of the most widely used types of fire-retardant additives is halogenated hydrocarbons (e.g., typically containing chlorine, and/or bromine), usually in combination with antimony oxides; the two work synergistically. Some types of polymers are intrinsically less flammable than others because they have chlorine substituents along the polymer chain (e.g., PVC, Hypalon, Neoprene).

Under thermal aging, fire-retardants can volatize, decreasing the protection of the fire retardants; this was observed for EPR and CSPE materials. Radiation aging had a substantially smaller effect on fire-retardant loss for EPR. No result on Hypalon has been reported.

Corona Degradation (Ref. 4.19)

Ionization of air at the surface, or inside voids of the insulation, can cause it to progressively deteriorate adjacent to the ionized air. After prolonged deterioration, the insulation may break down. Since high electrical-field strengths are necessary for ionizing air, this kind of degradation is not applicable to low voltage cables.

Water and Electrical Trees (Ref. 4.19)

Electrical trees are hollow microchannels with a tree-like pattern initiated at the foci of electrical stress within a polymer, and progressively causing its localized decomposition. The stress concentrations may be protrusions on an electrode surface or contaminants within the insulation. Electrical treeing requires an exposure of the insulation to a high electrical field although once formed, the trees may grow at lower voltages. For low voltage cables, electrical trees do not generally occur, and therefore, do not affect their reliability.

Operating Experience (Refs. 4.19 and 4.20)

Two separate searches of Licensee Event Reports (LERs) by others indicated that very few cables failed due to aging degradation of the insulation and jacket materials. One search, from mid-1980 to 1988, reported 63 events relating to inside containment cable failures and estimated a failure rate (including 88 events for outside containment cable failures) of $4x10^{-5}$/circuit demand (Ref. 4.20). The other search covered all LER submittals from 1968 to 1992 and reported 87 cable failure events (Ref. 4.19). These data were based on reviewing 2,657 LERs and excluding those events attributed to cable connections and interfaces, circuit design deficiencies, personnel errors, and unqualified cables. The following were the causes given for these events:

Cause Category	Number of Failures
Degraded	13
Mechanical	23
Misapplication	11
Nonspecific	40
	87

Roughly half of the failures (43) were in the first 6 years of operation, and many were due to mechanical damage (13) or cable misapplication (8). Most degraded cables are presumed to be attributed to thermal aging. No mention of radiation damage was made, although the maximum age range for some cables was 25-30 years old. Most mechanical damages may have been produced during installation or maintenance. These damages typically include nicked or pinched cable insulation or worn and damaged jackets (pulled or stepped over).

4.3 Accelerated Aging Simulations

To pre-age cables before simulating an accident exposure and to make long-term predictions about aging of their insulation and jacket materials exposed to the low-temperature and low-radiation dose-rate environments of nuclear power plants, experiments must be conducted under accelerated thermal and radiation conditions. Historically, aging simulations for cable materials have used a sequential exposure at an elevated temperature, followed by an accelerated radiation exposure. The elevated temperatures typically are chosen based on the Arrhenius method, while the accelerated radiation exposures are based on an "equal dose - equal damage" concept. Such aging simulation techniques are endorsed by the IEEE Std 323-1974 (Ref. 4.21) and accepted by the NRC Regulatory Guide 1.89 (Ref. 4.22).

Accelerated tests are widely used in an attempt to derive either qualitative or precise information about long-term responses of materials under a particular set of environmental stresses (Ref. 4.23). These simulation models assume that degradation rates can be raised by increasing the environmental stresses responsible for degradation. The simplistic application of these accelerated tests can yield highly misleading predictions. An understanding of the mechanisms underlying polymer degradation at different stress levels can facilitate the use of accelerated tests to reach meaningful conclusions. For example, a given material often exhibits major differences in degradation phenomena under different conditions of radiation dose rate, aging temperature, and oxygen environment (Ref. 4.24). Such differences can result in surface oxidation versus oxidation throughout the material, or cross-linking as the predominant molecular-level change versus chain scission. Extrapolating accelerated test data to determine the qualified life for cables can be difficult when multiple stresses influence the degradation process, and the synergistic effects of these stresses can be significant. Many times conservative activation energies were used to determine the thermal life using the Arrhenius equation. Thus, estimation of the qualified life is insufficient unless coupled with an adequate technical justification (Ref. 4.25).

4.3.1 Accelerated Thermal Aging

As temperature increases significantly above room temperature, the physical, mechanical, electrical, and chemical properties of insulation/jacket materials begin to change, affecting their hardness, brittleness, tensile strength, elongation, compressive strength, elastic modulus, insulation resistance, high-potential dielectric withstand strength, and other properties. Accelerated thermal aging is carried out at temperatures in the vicinity of 100°C-150°C for relatively short durations of about a month or less. The degradation must simulate the 40-year thermal condition of the plant (Ref. 4.26). As discussed in the previous section, actual qualification tests of cables during the seventies did not explicitly address the underlying degradation mechanism(s) for the insulation materials at this temperature range.

The Arrhenius technique usually is used for extrapolating the plant's temperature conditions to determine the oven conditions for accelerated aging; this approach was endorsed both by the IEEE Std 323-1974 (Ref. 4.21) and the NRC Regulatory Guide 1.89 (Ref. 4.22). Steffens (Ref. 4.27) indicated that to reduce expected errors in the rate of chemical reaction to 10%, temperatures must be limited to ±0.3% (i.e., for an oven condition at 250°C this variation is 0.75°C). Oven conditions can vary within the chamber by 5°C-7°C. The corresponding error in the reaction rate is almost 100%. This illustrates the practical problems faced in controlling the oven conditions. Since the Arrhenius equation presents the pseudo-first-order reactions to simplify the calculations and most thermal aging of polymers can be second-order, the presence of oxygen at a constant concentration in the oven chamber may dominate other reactants to exhibit a single degradation mechanism. He therefore suggests a high rate of ventilation to avoid stagnation within the oven chamber and the consequent variations in temperature. However, common industry practice assures that only the time above the required aging temperature is utilized, thus thermal aging is conservatively applied.

According to Clough & Gillen (Ref. 4.28), measurements of the thermo-oxidative stability of polymeric material at elevated temperatures can result in complicated assessment of temperature-dependent degradation. Phenomena which may dominate degradation at elevated temperatures may be unimportant at lower temperatures. The heterogeneous oxidation effects, caused by oxygen diffusion or other chemical reactions, would likely be of general importance for elevated temperature aging in the presence of air. These effects could strongly affect aging predictions.

Some earlier studies investigated the thermal aging effects on cables using PVC as the insulation as well as sheath. The degradation affecting this polymer is a complex physico-chemical process involving mainly the diffusion of the oxygen into the cable, the diffusion of plasticizers from the insulation and from the sheath into the surroundings, and thermo-oxidation of PVC involving dehydrochlorination, chain-breaking, and subsequent cross-linking of the macromolecules under temperature conditions varying in time and space (Ref. 4.29). This is followed by significant changes of some electrical and mechanical properties of the PVC compounds.

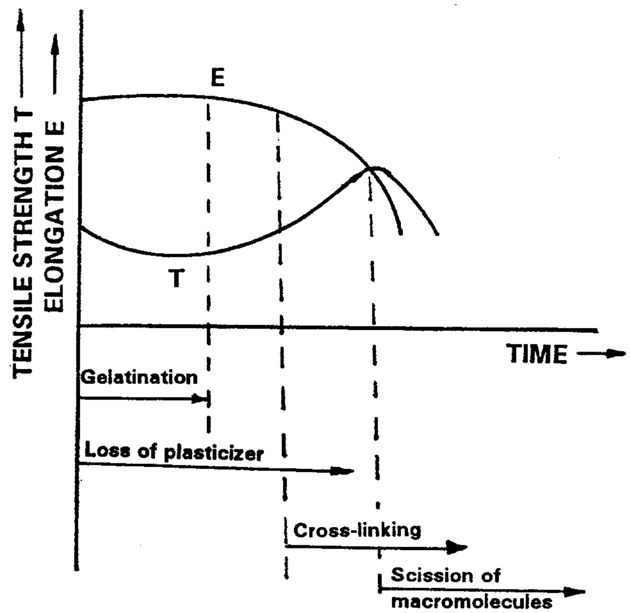

Figure 4.1 Changes of tensile strength and elongation during aging of PVC (Ref.4.29)

Figure 4.1 shows schematically the typical time curves of the tensile properties. At the beginning there is a slow decrease in tensile strength and increase in elongation, presumably due to gelatination. The next phase is marked by an increase of both the tensile properties and is probably due to loss of plasticizer. After reaching the peak, tensile strength decreases, indicating two opposing processes, e.g., crosslinking and chain-scission of the macro-molecules. Similar characteristics also were observed when this material was studied by using thermally stimulated current (TSC) technique (Ref. 4.30).

Marsal and Slaninka (Ref. 4.29) concluded that the elongation was the most sensitive indicator of the degree of deterioration and a decrease to about 50% of its original value seemed to indicate the end of life (i.e., occurrence of breakdown, formation of cracks specially in the sheath). Among electrical measurements, the changes in loss factor (tan δ) offered a better criterion for estimating the degree of deterioration than the insulation resistance, specifically above 90°C oven temperature. Higher temperatures accelerated degradation.

4.3.1.1 Arrhenius methodology

Gillen and Clough (Ref. 4.31) discussed the Arrhenius aging behavior of cross-linked polyolefins (CLPO or XLPO) insulation materials under various temperature conditions. Figure 4.2 illustrates isotherms between the aging duration and elongation ratio e/e_o (with e_o = 240%) for the CLPO-A material. Figure 4.3 shows the corresponding Arrhenius plots between time to equivalent damage (TED) and temperature for various elongation-ratio criteria. The slope of these lines corresponds to a 26.2 kcal/mole (1.136 eV/molecule) activation energy. This clearly indicates an acceleration of reaction rate without a change in mechanism caused by an increase in temperature within the range specified in the Figure. The data now can be shifted to an arbitrary reference temperature, T_{ref} (i.e., 45°C) by multiplying the TED appropriate to each aging temperature, T in K, by

$$a_T = \exp \{(E_a /k) (1/T_{ref} - 1/T)\} \qquad (4\text{-}1)$$

where E_a is the activation energy (eV/molecule),
k (=8.167 X 10^{-5} eV/K-molecule) is the Boltzmann's Constant.

The results of this shifting procedure, given in Figure 4.4, show an excellent superposition for temperatures from 90°C to 170°C. These results would predict a long lifetime for this material in a 45°C thermal-only environment.

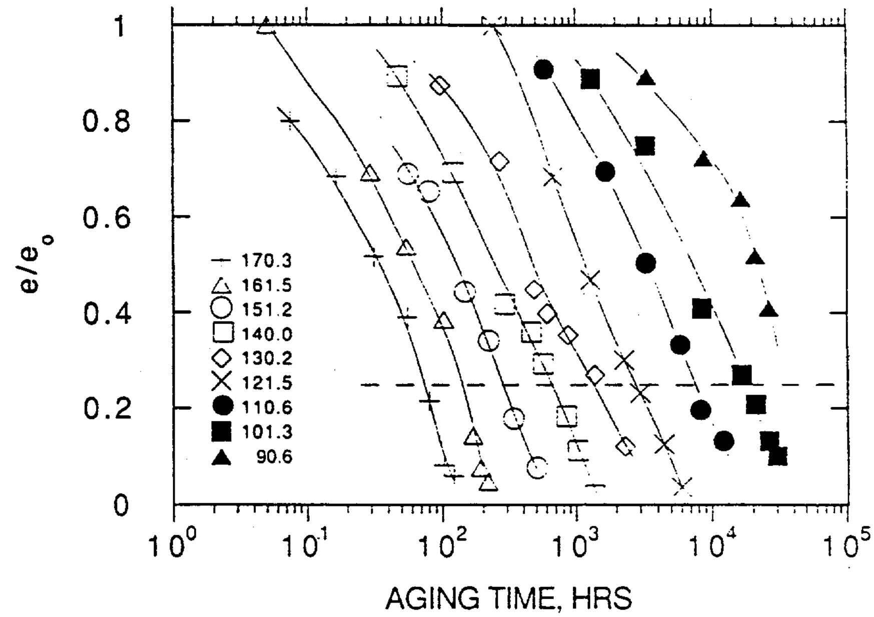

Figure 4.2 Ultimate tensile elongation versus aging time in air for CLPO-A (Ref. 4.31)

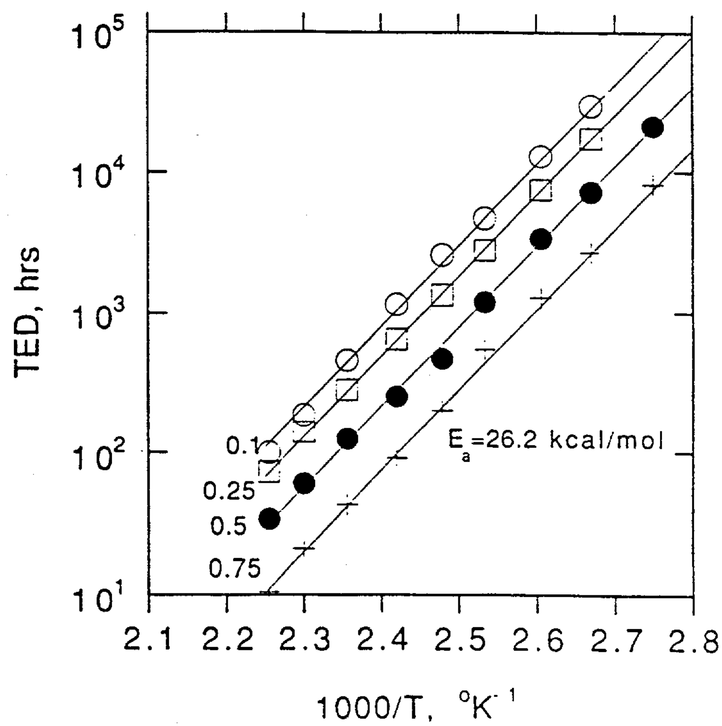

Figure 4.3 Arrhenius plot for thermal aging data for CLPO-A (Ref. 4.31)

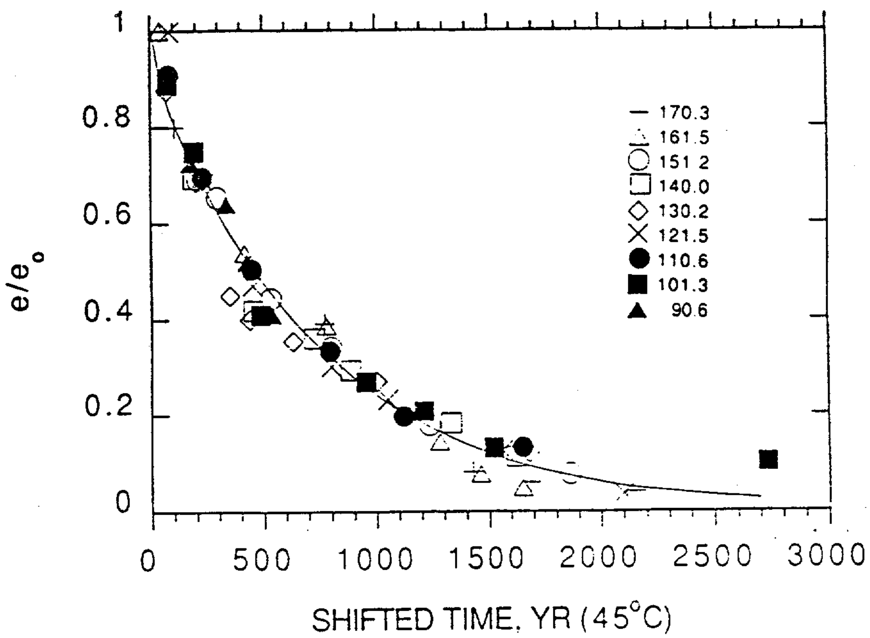

Figure 4.4 Time-temperature superposition at 45°C for CLPO-A from Fig. 4.1 (Ref.4.31)

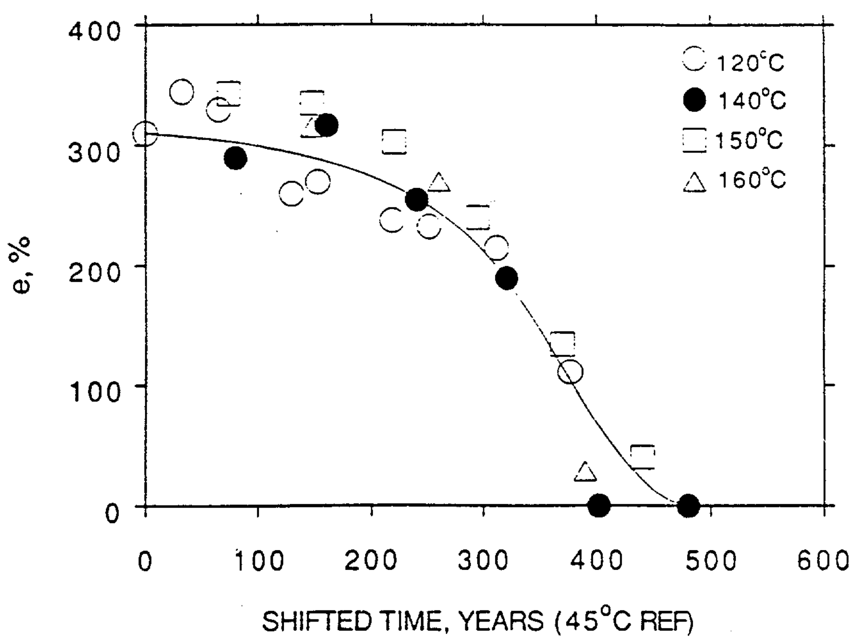

Figure 4.5 Time-temperature superposition at 45°C for CLPO-B (E_a=21 kcal/mol) (Ref. 4.31)

Figure 4.5 shows a similar time-temperature superposition curve using data from another cross-linked polyolefin (from a different manufacturer). These results are displayed as total elongation vs. shifted time, giving a different shaped curve, but a good correlation to the 45°C reference temperature.

Gillen and Mead (Ref. 4.32) described some of the data-analysis techniques necessary to apply the Arrhenius methodology to heat-aging studies, and discussed some major uncertainties of this technique, including the potential problems caused by competing reactions, material transitions (near the crystalline melting point), oxygen-diffusion effects, and sorption effects. Since these uncertainties can lead to changes in activation energy, the report recommended long-term exposures that minimize extrapolation, thereby minimizing any chances for significant changes in slope, and also using a large temperature range so that any non-Arrhenius behavior may be more easily ascertained. The two data-handling techniques suggested include straight and parallel Arrhenius plots shown in Figure 4.3, and the time-temperature superposition plot shown in Figure 4.4. The straight and parallel line plots indicate that activation energy is independent of the extent of material damage in this temperature range. The second method implicitly supports this same conclusion.

Linear Arrhenius behavior has been demonstrated in other aging studies for certain cable materials and within certain temperature ranges. Over the range 90°C to 140°C, Neoprene (chloroprene) exhibits this behavior, as shown in Figures 4.6 and 4.7 (Ref. 4.33). The single degradation mechanism later was shown to extend to 70°C (Ref. 4.34). Similar results for Hypalon (Ref. 4.35) are shown in Figure 4.8.

4.3.1.2 Heterogeneous degradation by multiple mechanisms

The Arrhenius methodology, as noted earlier, is not applicable when more than one mechanism causes aging degradation. Straight-line behavior, associated with a single degradation mechanism, generally reflects homogeneous changes in material properties. When more than one degradation mechanism occurs, the Arrhenius relationship becomes non-linear, because the different activation energies (E_a) for each mechanism must be included as additional factors in Equation 4-1. Mechanisms with lower activation energies predominate at lower temperatures. The presence of multiple mechanisms can also result in heterogeneous degradation of the material due to such factors as surface effects or diffusion-limited reactions.

An Arrhenius plot for an ethylene propylene rubber (EPR) material is shown in Figure 4.9 (Ref. 4.36) for temperatures from 100°C-170°C. Non-linear behavior appears in the data where relative elongation (e/e_o) equals 0.75. This was attributed to the presence of two degradation mechanisms: normal thermal degradation, and copper-catalyzed oxidation. The latter mechanism (which has a higher activation energy) greatly enhanced degradation near the inside of the insulation, where copper poisoning from the conductors had occurred.

Although Gillen and Clough (Ref. 4.36) may regard Figure 4.9 as clear evidence of non-Arrhenius behavior, cable manufacturers would regard the lines as quite straight. In fact, since cable manufacturers usually conduct their experiments at three points over a narrow temperature range, they are less likely to discover such behavior.

Several material profiling techniques (e.g., density, modulus, or hardness) were applied to identify heterogeneous degradation mechanisms, and characterize their effect. Figure 4.10 (Ref. 4.37) shows density profiling data for EPR samples which had been aged at 100°C. There is clear evidence for greatly enhanced oxidation near the inside of the insulation even before measurable changes in mechanical properties are observable. (In Figure 4.11, at 2062 and 7360 hours, the tensile properties have not changed significantly, while the heterogeneous oxidation is evident from Figure 4.10).

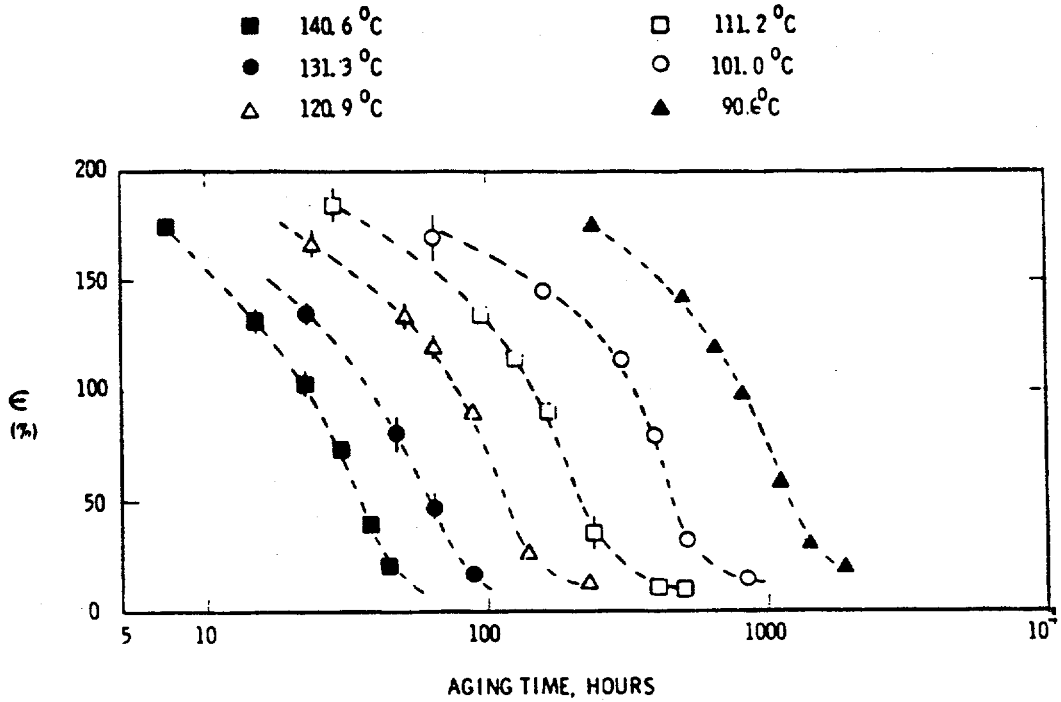

Figure 4.6 Ultimate tensile elongation versus aging time for chloroprene (Ref.4.33)

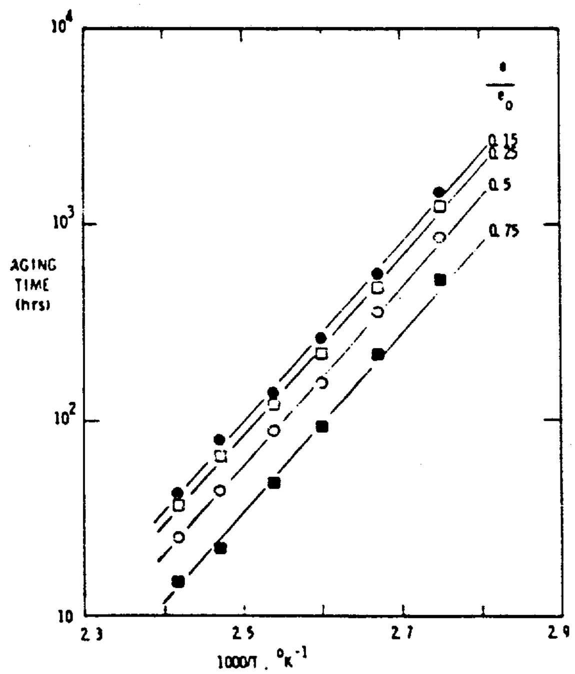

Figure 4.7 Arrhenius plot for chloroprene data (Ref. 4.33)

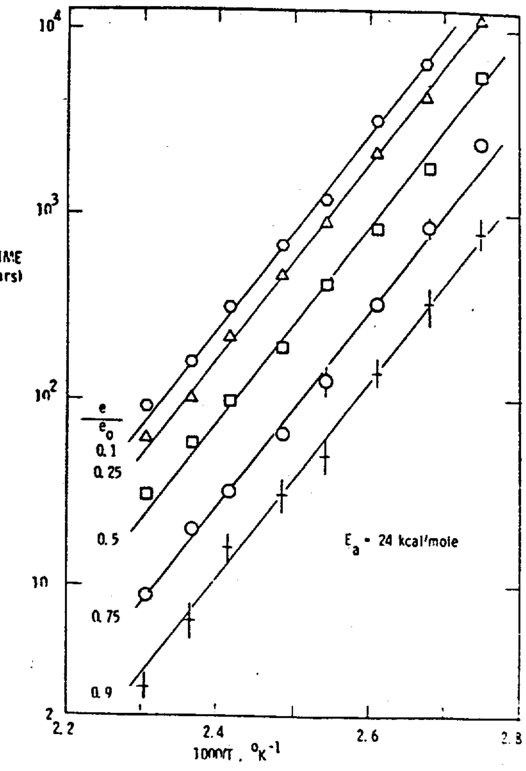

Figure 4.8 Arrhenius plots for Hypalon (Ref. 4.35)

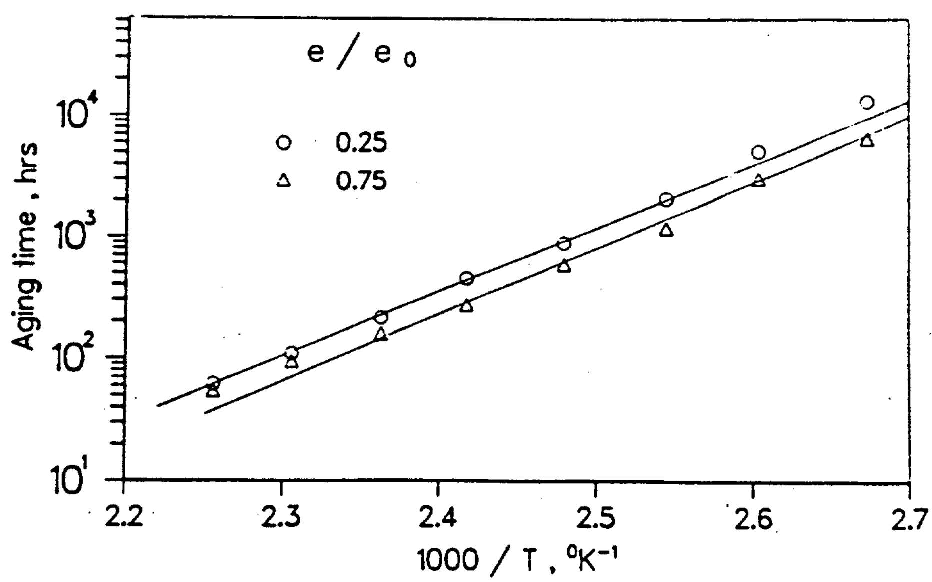

Figure 4.9 Arrhenius plots for thermal aging on EPR (Ref. 4.36)

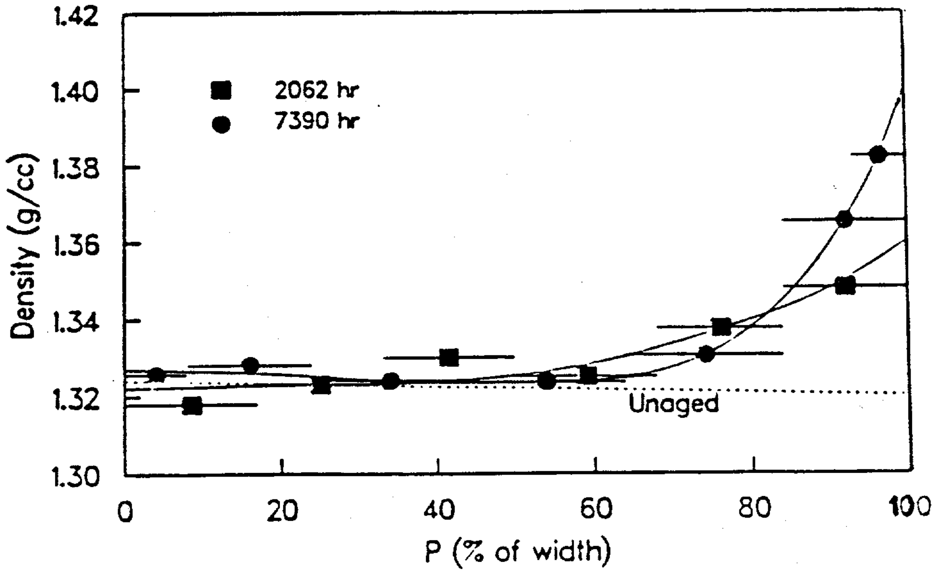

Figure 4.10 Density profiles for EPR heat-aged at 100°C (Ref.4.37)

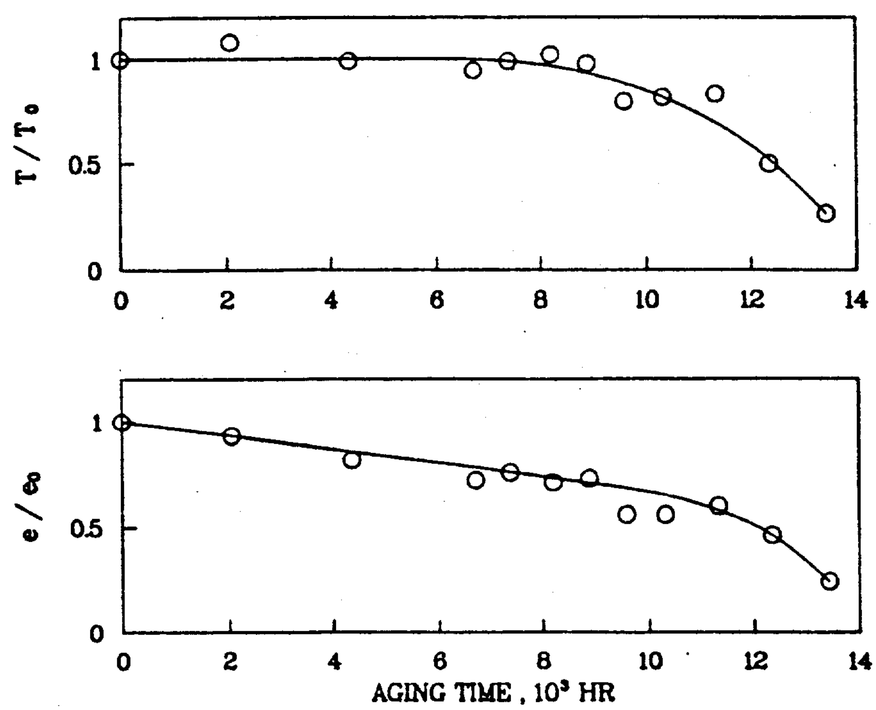

Figure 4.11 Changes in mechanical properties after heat-aging at 100°C for EPR (Ref. 4.37)

Heterogenous profiles of aged cable jacketing materials also were attributed to diffusion-limited oxidation. Figure 4.12 (Ref. 4.28) shows modulus profiles at different aging temperatures in the presence of air for Neoprene rubber (NR) and styrene-butadiene rubber (SBR). Clough and Gillen (Ref. 4.28) summarize these effects as follows: "At the lowest temperature, heterogeneous oxidation exhibits a latent onset. The material modulus at first rises in an approximately homogeneous manner. With ongoing degradation, the modulus in the surface region increases rapidly, whereas the rate of modulus change in the center region diminishes (or nearly stops). This "delayed" effect does not occur at higher temperatures; here, the heterogeneity is observed from the very beginning. As a result, the interior regions of the material aged at 150°C undergo much smaller change in modulus with aging." They further conclude: "The decreasing oxygen-permeability coefficient causes the oxidation to become limited to an ever-shrinking region near the surfaces. Oxygen continues to be consumed by degradation chemistry within the high-modulus, low-permeability surface regions, whereas these regions form a protective barrier which blocks further penetration of oxygen into the interior. As aging continues, the modulus of the interior may undergo no further changes."

Exposure of Neoprene or SBR samples to high temperatures under nitrogen gave only modest degradation, and did not exhibit the strongly heterogeneous modulus profiles found under air aging.

A study by Gillen, Clough, and Wise (Ref. 4.38) on a typical commercial nitrile rubber formulation found that the ultimate tensile-elongation data confirm Arrhenius behavior, even though the ultimate tensile-strength data from the same mechanical property testing was non-Arrhenius. The modulus profiling indicated that, for the highest temperature, heterogeneity in the modulus is evident immediately and becomes quite pronounced later on. For tests at lower temperatures, the importance of this effect at early aging times is less significant. When the edge modulus value is used, instead of the total modulus over the cross section, there was excellent superposition, indicating Arrhenius behavior. Their survey indicates the Arrhenius methodology must be applied with care, and should be supplemented with profiling measurements to evaluate heterogeneous oxidation effects on aging of specific polymers.

4.3.1.3 Interaction with other stresses and materials

As energy is added from the environment to the chemical structure such as a polymer chain, excited states, bond ruptures, and free radicals are generated (Ref. 4.39). Depending upon the complete structure of the molecule, these free radicals will recombine in different formations. Materials will either become cross-linked or degraded (by chain scission leading to shorter chain fragments). For certain materials under specific conditions these reactions will occur simultaneously in many structures. It is the net predominance of one over the other that is ultimately observed in the property changes in the materials. Although this study did not test actual cable polymer compounds, for certain basic polymers (e.g., polyvinyl, polytetrafluoroethylene, silicone) in the presence of both heat and radiation it was demonstrated that the kinetic balance of mechanisms were affected with a resulting equilibrium in the net change of the polymer structure. Once such equilibrium was reached, the corresponding physical or electrical properties did not change rapidly. For the polyvinyl sample, the thermal life doubled under combined heat and radiation while it decreased to 86% after sequential exposures to irradiation followed by thermal[3]. The thermal life for polytetrafluoroethylene became very short under combined or sequential environments. Similarly, reduced thermal life for PE and PVC materials used in cables also were observed under such combined environments (Ref. 4.40). These synergism effects were studied by many researchers in greater detail for cable materials, and are discussed later.

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[3] Note that this is an example of negative synergism, i.e., the degradation caused by combined heat and radiation was less than the degradation caused by applying heat and radiation sequentially.

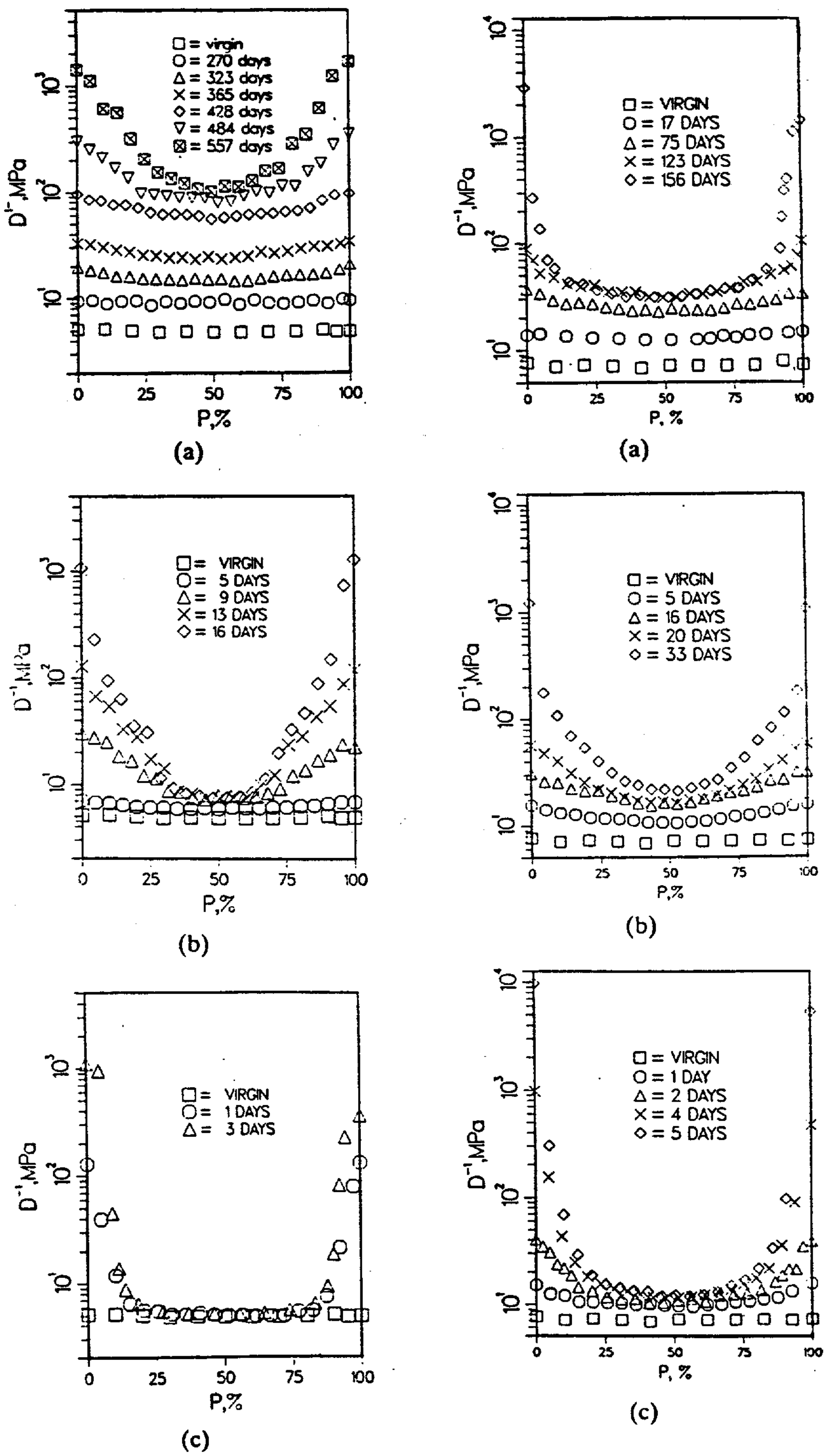


Figure 4.12 Modulus profiles for 2.2-mm thick samples of SBR (left) and NR (right) following thermal aging in air. (a)100°C; (b) 120°C; (c) 150°C. P=percentage of distance from one air-exposed surface to opposite air-exposed surface. (Ref. 4.28)

It is a conventional wisdom to assume that degradation rates can be raised by increasing environmental stress or stresses responsible for degradation. In a very recent study by Gillen and his co-workers (Ref. 4.41), this assumption was contradicted for an XLPO material. Under combined radiation plus thermal environments, this material mechanically degraded much faster at room temperature than at elevated temperatures. As shown in Figure 4.13, the degradation rate increases by more than a factor of two as the temperature drops below 60°C to 41°C and by another factor of two for a further decrease to 22°C. The results at temperatures of 60°C and higher are in accordance with normally expected behavior. The reasons for this anomalous behavior are still being studied by these researchers, although the present explanation involves competitive oxidative degradation and crystalline annealing processes at different temperatures.

Because of this phenomenon, predictions of equipment life in radiation ambients cannot be calculated easily from data obtained in a <u>limited</u> test program. Further, the more nearly the test conditions can be designed to simulate service environments, the greater the reliability that can be expected from the results.

Interaction of XLPO compounds with the copper conductor, apart from the crosslinking, was studied for an effective long-term stabilization against thermo-oxidative degradation (Ref. 4.42). It is well known that copper, unlike aluminum, has a strong catalytic effect on the thermo-oxidative degradation of polyolefins. The study demonstrated that commercial metal deactivators can improve thermo-oxidative stability. Figure 4.14 compares the temperature-dependent aging stability of XLPE with and without copper conductors, and with a number of different deactivators. The results clearly indicate the thermal life of cables with copper conductors is significantly reduced compared with those without them. Moreover, there is a significant difference in lifetimes and long-term stability with different chemicals used as metal deactivators.

The effects on the degradation characteristics of XLPE-insulated cables under thermal aging in combination with electrical stresses were studied in Italy (Refs. 4.43). Extremely long lives are detected at room temperature and an electrical field of lower than 10-11 kV/mm. For higher than room temperatures, the electrical threshold decreases as temperature rises and seems to disappear at temperatures above 100°C. However, a significant reduction of failure times is found, even at 60°C and 11 kV/mm, when both electrical and thermal stresses are applied. Also, the decrease in the electrical threshold values as temperature increases is a clear indication of the synergistic effect of multiple stresses. As shown in Figure 4.15, the thermal only line shows the typical Arrhenius linearity, but the lines with voltage superimposed are nonlinear. In fact, they exhibit a double curvature (i.e., first downward followed by upward) as the temperature decreases. This change in curvature occurs between 90°C and 110°C. In this temperature range, thermal aging for low voltages becomes more deleterious than electrical aging, i.e., thermal aging becomes more dominant.

Montanari and Motori (Ref. 4.44) discussed the changes in density, melting enthalpy, and dc electrical conductivity as a function of aging conditions under thermal and electrical stresses; they suggested that complex phenomena, like oxidation, recrystallization, charge injection, and trapping take place.

Recently, St. Lucie Unit 1 replaced all PVC-insulated wire contained in its nonsafety-related overcurrent protective relays with an XLPE-insulated wire after discovering that green substances from the internal wiring had coated the instantaneous trip units (Ref. 4.45). Laboratory analysis identified the green substance as copper chelate of the polyester plasticizer from the PVC insulation. It was hypothesized that overheating of the wiring could have caused the release of the plasticizer, which had decomposed at high temperature, oxidized, and interacted with the copper wire.

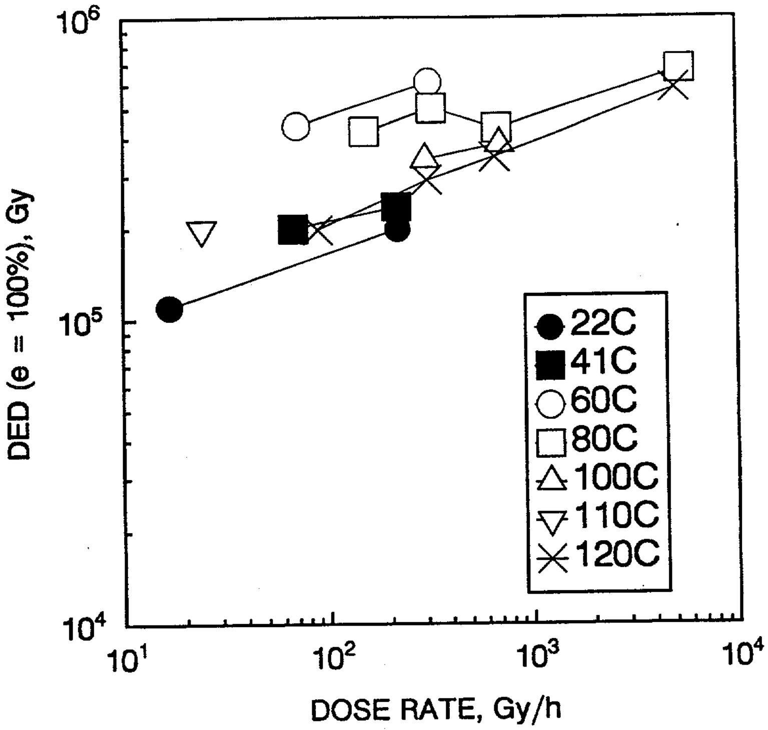
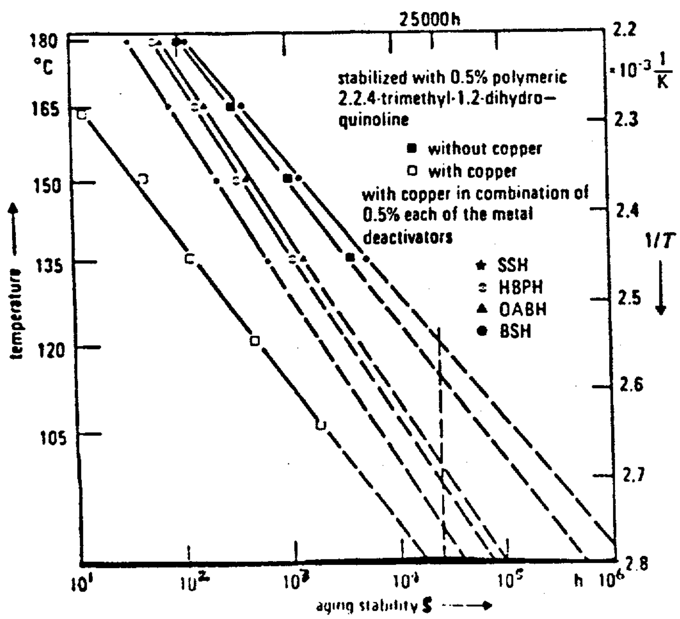


Figure 4.13 Radiation Dose required for elongation-at-break to 100% versus dose rate and temperature (Ref. 4.41)

Reprinted with permission from Dr. Kenneth T. Gillen, Sandia National Laboratory, Albuquerque, NM.



SSH = N-salicyloyl-N'-salicyliden-hydrazide

HBPH = N-N'-bis(4-hydroxy-3,5-di-tert. butylphenyl)propionylhydrazide

OABH = Oxalacid-bis-benzylidenhydrazide

BSH = Bis-salicyloylhydrazide

Figure 4.14 Comparison of temperature-dependence of XLPE in presence of copper (Ref. 4.42)

Reprinted with permission from Radiation Physics and Chemistry, Vol. 18, No. 5/6, pp 1217-1225, Kammel, G. and Knoch, G., *Thermal-Oxidative Aging of Radiation-Crosslinked XLPE Insulations in the Presence of Copper Conductor, A New Test Method and Results,* 1981, Elsevier Science Ltd., Oxford, England.

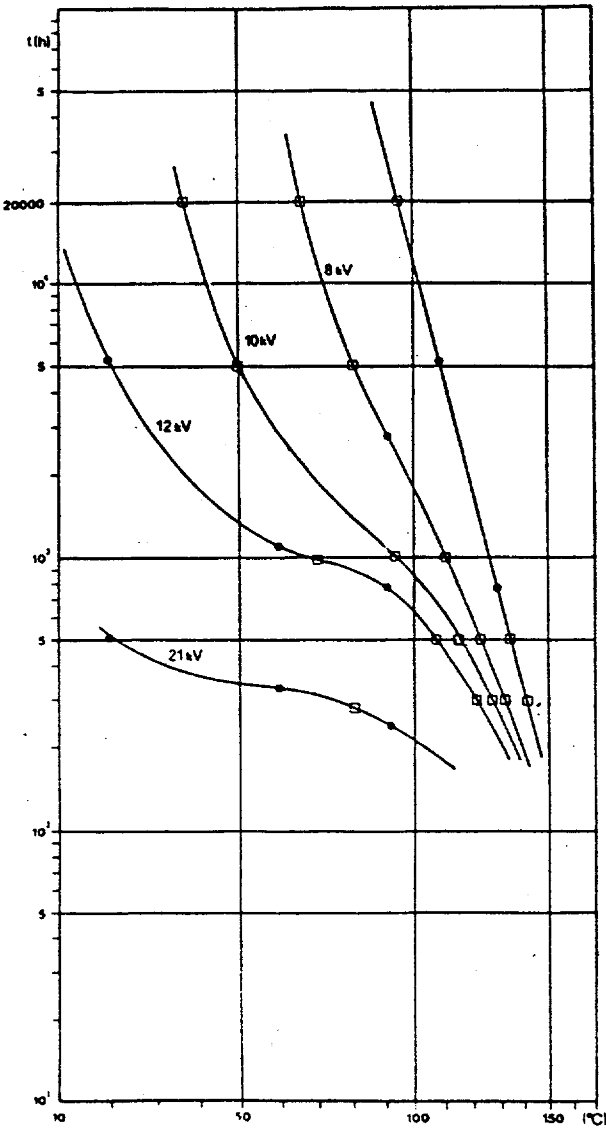


Figure 4.15 Thermal life curves at constant voltage for an XLPE (Ref. 4.43)
Reproduced with permission from Prof. G.C. Montanari, Italy.

4.3.2 Accelerated Radiation Aging

The principal source of radiation in a nuclear power plant is the fission products contained in the reactor fuel. There are four types of radiation: alpha, beta, gamma, and neutron. The effects of alpha and neutron radiation are not a concern for cables. Based on the U.S./French joint effort (Refs. 4.46- 4.49), beta- and gamma-ray induced damage in polymer base rubber materials may be correlated with the average absorbed radiation dose. These studies did not observe a difference between the effects of two types of ionizing irradiation, beta and gamma. Typically, gamma is the principal type of radiation used in environmental qualification.

Radiation changes the atomic and molecular structure of materials through processes such as excitation, ionization, cross-linking, and scission. The energy of a radiation source decreases as it travels through a material and releases energy. The dose absorbed by the material varies with the thickness of the material, and its absorption cross-section. The studies concluded that when the energy of the electrons is high enough with respect to the thickness of the material irradiated, their action on the materials is the same as that of the photons from ^{60}Co.

Accelerated radiation aging of cables for environmental qualification uses ^{60}Co sources for gamma radiation in air at a dose rate not greater than 1 Mrad/hr (Ref. 4.21). Typically, for a 40-year life of a nuclear power plant, a total integrated dose (TID) of 50 Mrad is accounted for in radiation aging. The concept of "equal dose - equal damage" is employed in which the radiation effect is assumed to depend only on absorbed dose and to be independent of dose rate. Recent experiments showed this model may not be conservative for specific materials in certain configurations that are sensitive to the dose rate. Also, similar to thermal-aging effects, radiation exposure in different environments (e.g., vacuum, nitrogen, oxygen, or air) can affect both the type and magnitude of degradation.

Schonbacher and Tavlet (Ref. 4.4) summarized radiation damage test data on commercial European cable insulation and jacket materials: EPR, PE, SR, polyurethanes, and copolymers based on PE. The materials were irradiated either in a nuclear reactor, or with a ^{60}Co source, or in the CERN accelerators, at different dose rates. The absorbed doses were between 1 kGy (100 krad) to 5 MGy (500 Mrad). Figure 4.16 presents the results on several organic materials from this compilation. Test results on elongation, tensile strength, and hardness are presented in tabular form. All tests were performed according to the recommendations given by the International Electrotechnical Commission (Ref. 4.50).

Japanese researchers conducted several studies to understand and characterize radiation-induced oxidation in pure polymers of PE and EPR in oxygen under pressure (Refs. 4.51-4.52). Seguchi and his co-workers presented the effects on swelling and gel fraction (Ref. 4.51), and on mechanical properties such as, tensile modulus, elongation, strength (Ref. 4.52) . Measurements of molecular weights for linear polymers, and of gel fraction and swelling ratio for crosslinked polymers were made to study the radiation effects. An increase in gel fraction and decrease in swelling ratio with dose indicated crosslinking for both PE and EPR when irradiated in vacuum.

However, when irradiated in oxygen a decrease in molecular weight with dose signified chain scisson. Crosslinked polymers were degraded through chain scission by radiation-induced oxidation. The results also indicated that the higher the initial crosslinking density of polymers, the less oxidative degradation was induced by irradiation. The presence of antioxidants in polymers effectively retarded the degradation by irradiation in oxygen.

Arakawa and his co-workers studied gas evolution and oxygen consumption (measured by chromatography) induced by irradiation of chlorine-containing polymers used for cable jackets; namely, PVC, chloroprene rubber, and CSPE (Ref. 4.53). The presence of oxygen increased evolution of HCL gas twofold for pure PVC. Gas evolution and oxygen consumption are retarded by the presence of plasticizer, vulcanizer, and stabilizers. Using measurements of both parameters, the effects of antioxidants and antirad agents on PE and EPR were studied (Ref. 4.54). The oxygen consumption of pure EPR is less than that of pure PE, but increases with increasing crystallinity. The pressure dependancy of oxygen is small for EPR and LDPE. Antioxidants were found effective in preventing secondary oxidation (i.e., chain reactions induced by peroxy radicals or oxidative products), but not effective against primary oxidation (i.e., active sites in the polymer chain). The antioxidant is consumed with increasing dose and therefore, higher concentrations are needed for high irradiation doses. The antirad, however, decreases oxidation by reducing the formation of active sites for free radicals.

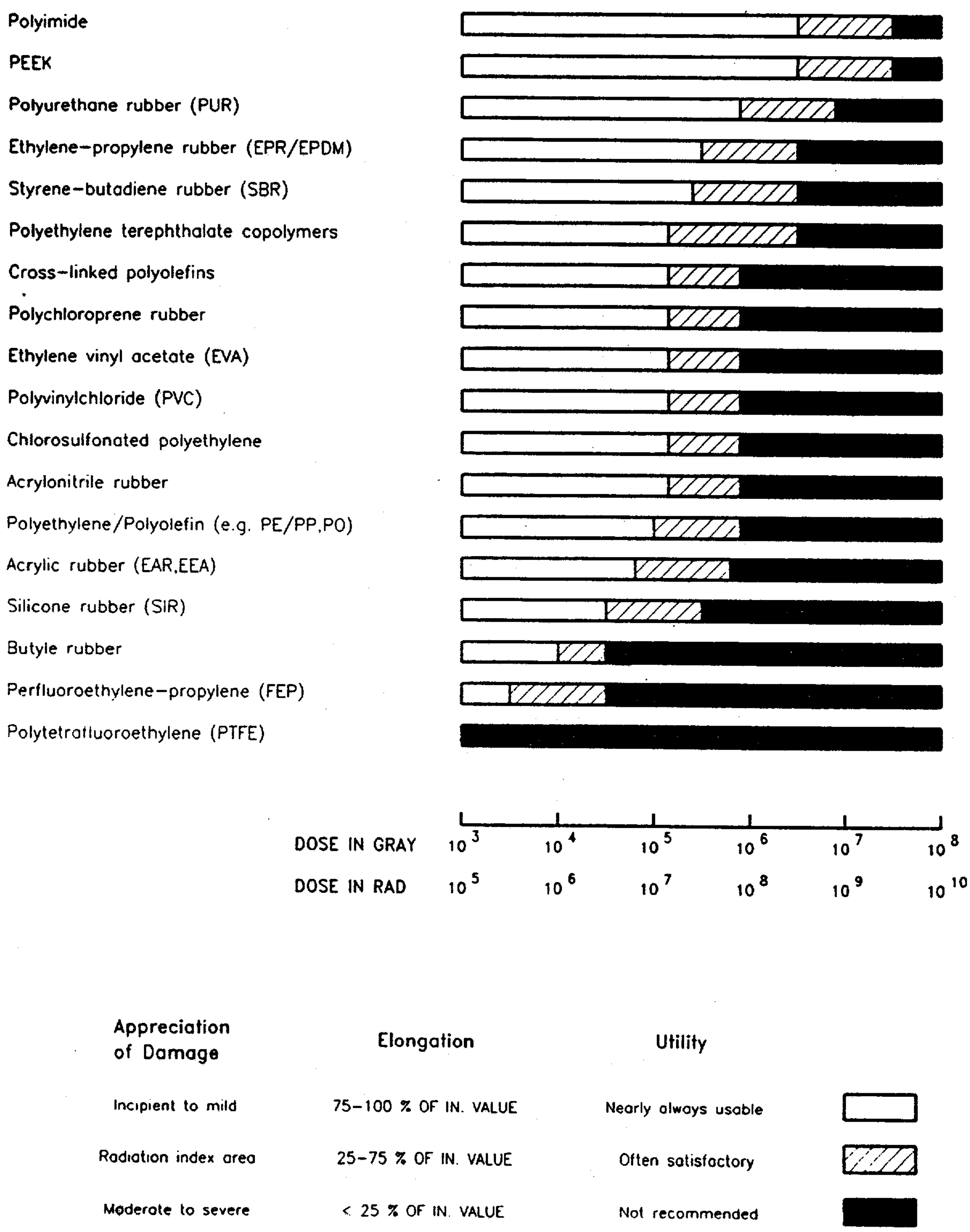


Figure 4.16 Classification of materials according to their radiation resistance (Ref. 4.4)
Reproduced with permission from Dr. Helmut Schonbacher, CERN, Switzerland.

CERN has published a large number of data on the radiation effects on cable materials used in its own facility during the last one and a half decades (Refs. 4.55-4.59). These studies include all types of commercial cable insulation and jacket materials (e.g., LDPE, XLPE, EPR/EPDM, SR, PVC, CSPE) available in Europe. In primary radiation effects, the energy absorbed by the electrons leads to excitation of the molecules, to the breaking of chemical bonds, and to ionization of atoms. This effect is virtually independent of the type of radiation, since the energy transferred is very small compared to the primary energy of the radiation. The secondary effects depend on the chemical composition of the polymer including additives and gases, temperature, local concentration of the radicals and free electrons, and on the accumulated dose. These conditions give rise to dose-rate effects. Hydrogen and halogen acids (if halogens are present), and carbon dioxide (if oxygen is present) are typical gaseous products found during irradiation. In the presence of oxygen, chain scission and degradation into low molecular weight products is the predominant effect, which is the cause of mechanical degradation. Therefore, whether or not a strong dose-rate effect is found depends on both the type of polymer and the concentration of oxygen and other additives (antioxidants, filler contents). The other parameter which influences this dose-rate effect is the thickness of certain polymer samples, which gives rise to heterogeneous oxidation for higher dose rates (>10 krad/hr).

4.3.2.1 Effects of radiation dose rate

Most cables qualified for nuclear power plants follow the requirements given in IEEE Std 383-1974 (Ref. 4.21) and therefore, are not tested for radiation dose-rate effects. Since the publication of this standard, significant studies to understand this dose rate effect have been performed, nationally and internationally. The underlying causes, as well as the characteristics of this behavior in cable polymers can be well established provided the composition of the base polymer and its additives and the environmental conditions are clearly defined. This becomes a problem when developing general conclusions on this behavior for commercial cable insulation and jacket materials whose compositions remain a trade secret in many countries. In spite of this set back, CERN has published radiation degradation characteristics of cable materials with varying compositions in each base polymer category. In addition, publications discussed in this section have assembled all available data in the world and presented generic behavior of certain cable materials used in their countries.

Degradation generally is considered independent of dose rate and dependent on the total integrated dose (TID), if an organic polymer is irradiated in an inert atmosphere or in vacuum. For certain materials, if the radiation takes place in air or oxygen environment, the degradation is more severe at lower dose rate. At very low dose rates, there is apparently a region where, for some polymers, the dose rate effect does not exist. On the other hand, at very high dose rates, irradiation in air or in the absence of oxygen gives similar results, since within the short time of irradiation, oxygen cannot diffuse into the interior of the (thicker) polymer. In the transition region between these two limits, irradiation causes either the formation of peroxy radicals or diffusion-limited oxidation which may give rise to dose-rate effects.

Dose-rate initially became a concern after the unexpected discovery of severely embrittled PE and PVC materials in the K-Reactor at Savannah River Site after only 12 years of service and exposure to a low dose rate (i.e., 25 rad/hr at ambient temperature of 43°C) for a total dose of 2.5 Mrad. Reference 4.60 discusses the findings from this study, and Figures 4.17 and 4.18 illustrate the aging behaviors of PE insulation and PVC jacket materials, respectively. Table 4.2 summarizes the tensile elongation data for various experimental conditions.

The combined effect of radiation and elevated temperature dramatically enhanced degradation compared with thermal effects alone or to radiation exposure at room temperature; this will be discussed further under synergistic effects. Radiation at room temperature followed by elevated temperature caused the severest degradation. Figure 4.19 shows the strong dose rate effects for PVC material when aged at 60°C. Similar trends also were observed for the PE insulation.

Table 4.2: Sequential Aging Experiments: Tensile Elongation Data (Ref. 4.60)

Experiment*	e/e_o	
	PVC (e_o=310%)	**PE(e_o=540%)**
Unaged Material	1.0 ±0.05	1.0 ±0.1
γ; no subsequent T	0.80±0.04	0.68±0.09
T (in air); γ (in air)	0.68±0.04	0.72±0.07
γ (in air); T (in air)	0.32±0.02	0.17±0.04
γ (in N_2); T (in air)	1.02±0.05	1.01±0.1
γ (in air); T (in N_2)	0.83±0.04	0.81±0.08

* γ:4.5 krad/hr for PE and 4 krad/hr for PVC - Both at 25°C for 83 days. T: 80°C for 83 days

The aging behaviors of the PE and PVC can be understood in terms of peroxide-mediated oxidative breakdown. Gamma radiation of polymers cleaves bonds giving free radicals, which, in the presence of oxygen, react by a chain mechanism to form oxidation products that include hydroperoxides. These are thermally labile, and yield more free radicals which can initiate new chain reactions with oxygen to give further oxidation, including the formation of more hydroperoxides. The free radicals produced can cause polymer chain scission and crosslinking.

Further confirmation of the importance of oxygen to degradation came from experiments performed in the simultaneous environment of radiation and elevated temperature, under an inert atmosphere of nitrogen. The degradation, as measured by tensile elongation, was much less extensive to non-existent (Table 4.2). Two sequential tests, one with irradiation at room temperature in nitrogen followed by elevated temperature in air, and the other with irradiation at room temperature in air followed by elevated temperature in nitrogen were performed in this study.

Gillen, Clough, and Jones (Ref. 4.61) studied the same PE and PVC cables from the Savannah River Site for different dose-rate effects. In addition, the study addressed the interaction effects among the four cable components (i.e., copper, PE, PVC, nylon) under combined environment of radiation (5 krad/hr) and elevated temperature (80°C). Although all four components showed substantial degradation based on tensile measurements, no significant differences in degradation rates were found for the PE and PVC materials when aged separately as opposed to intact cable sections. Figures 4.20 and 4.21 show the results from aging of these two materials for three different environments. The PE data is the average for the three insulation colors (white, red, black). Figures 4.22 and 4.23 show results under experimental conditions that differed only in the atmosphere used (air vs. nitrogen). Figures 4.24 and 4.25 also show similar plots for different dose rates at 43°C instead of 60°C. Another aging behavior exhibited by the PVC material in Figure 4.19 is the leveling out in tensile elongation in advanced stages of aging; elongation levels out at lower values as the dose rate is lowered. Finally, Figures 4.26 and 4.27 shows the trends due to the order of the sequential exposures.

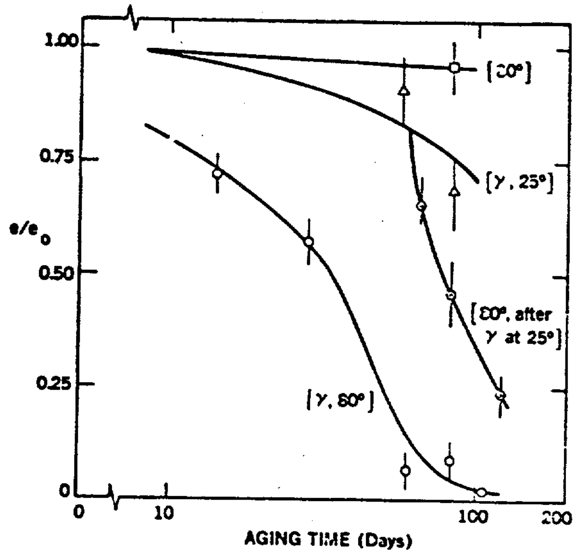


Figure 4.17 Aging of PE in various environments (Ref. 4.60)

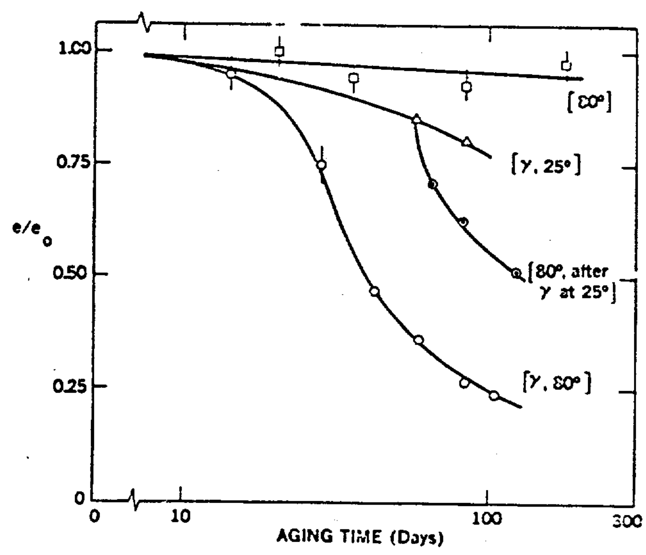


Figure 4.18 Aging of PVC in various environments (Ref. 4.60)

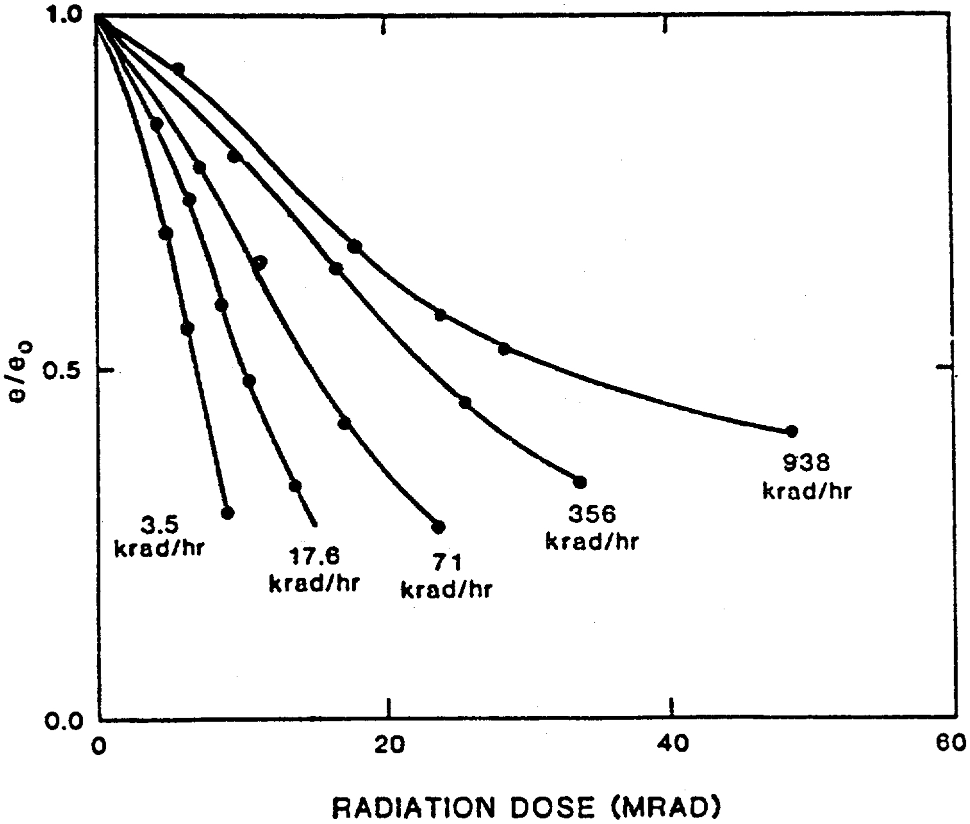


Figure 4.19 Aging of PVC at 60°C at a series of radiation dose rates (Ref. 4.60)

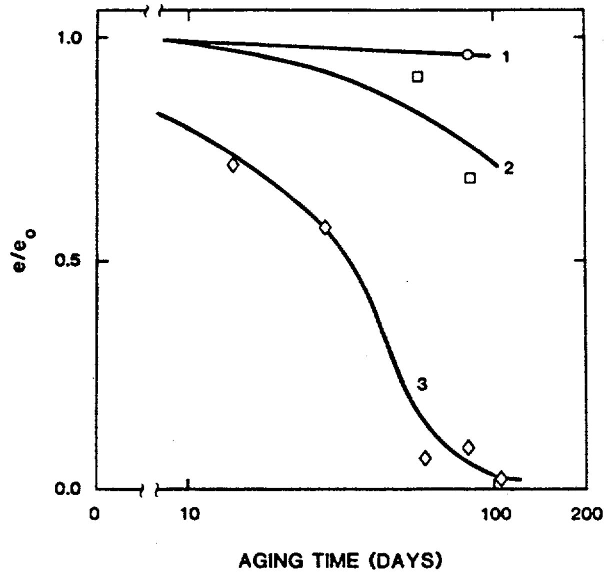


Figure 4.20 Tensile elongation for PE for (1) 80°C; (2) radiation 5 krad/hr at 25°C; (3) radiation 5 krad/hr at 80°C. (Ref. 4.61)

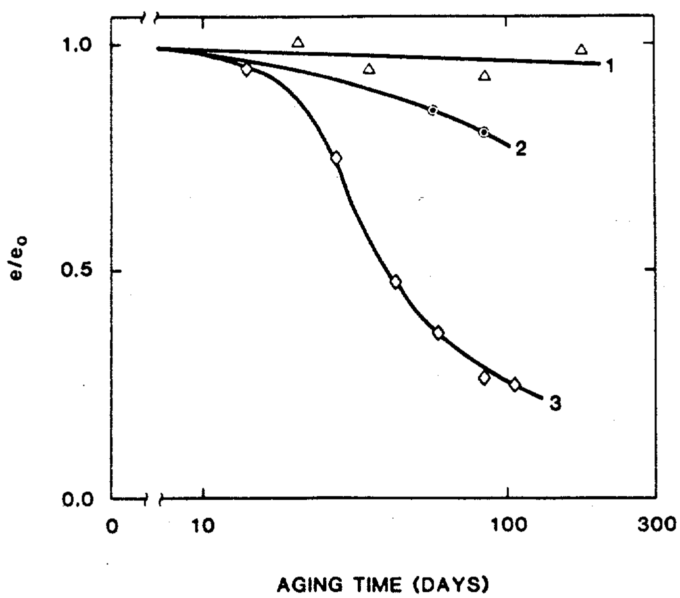


Figure 4.21 Tensile elongation for PVC for (1) 80°C; (2) radiation 4.4 krad/hr at 25°C; (3) radiation 4.4 krad/hr at 80°C. (Ref. 4.61)

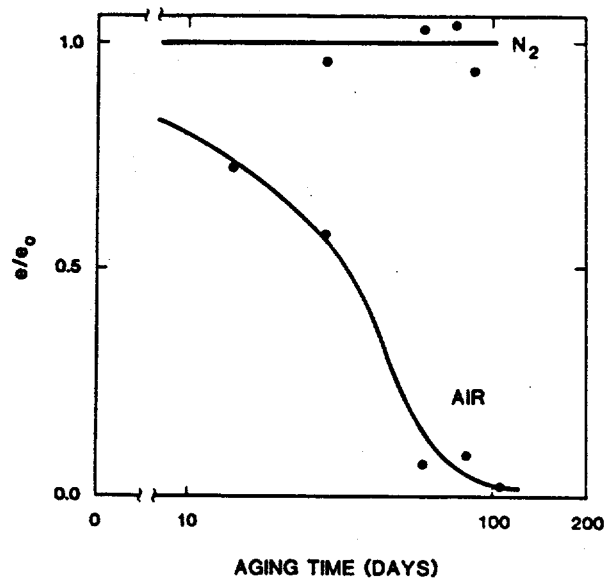


Figure 4.22 Tensile elongation for PE at 5 krad/hr, 80°C in air and nitrogen (Ref. 4.61)

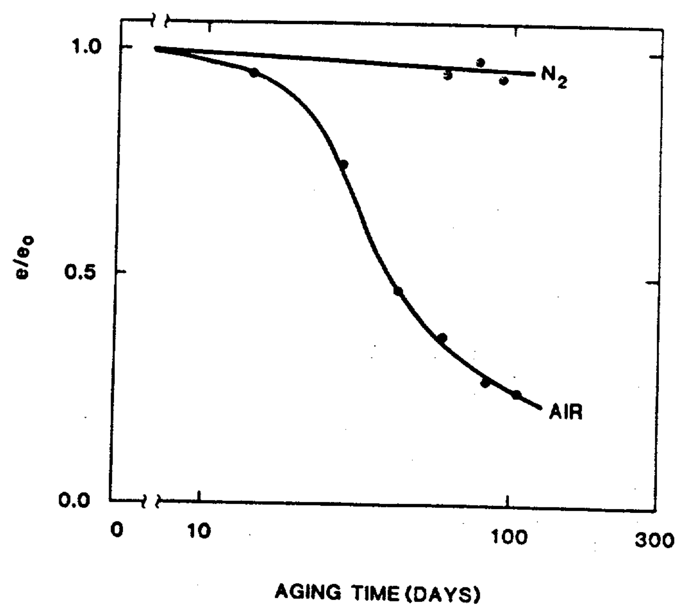


Figure 4.23 Tensile elongation for PVC at 4.4 krad/hr, 80°C in air and nitrogen (Ref.4.61)

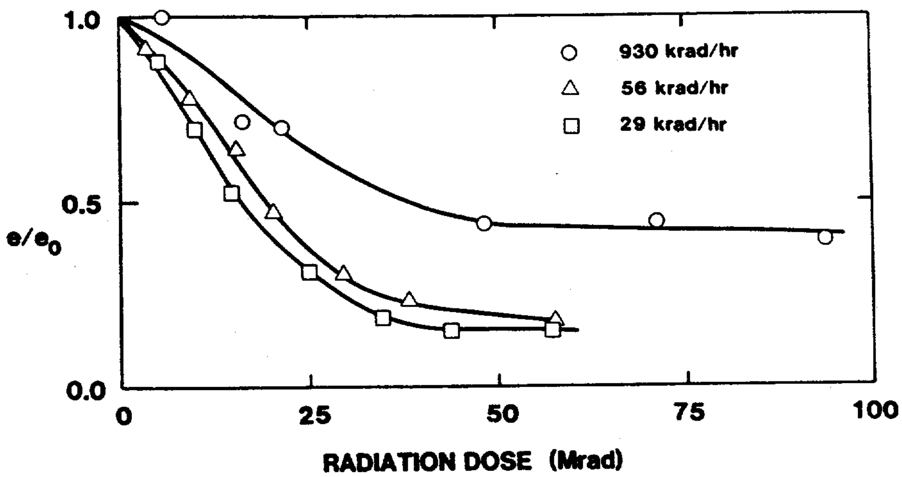


Figure 4.24 Tensile elongation for PVC at 43°C for three different dose rates (Ref. 4.61)

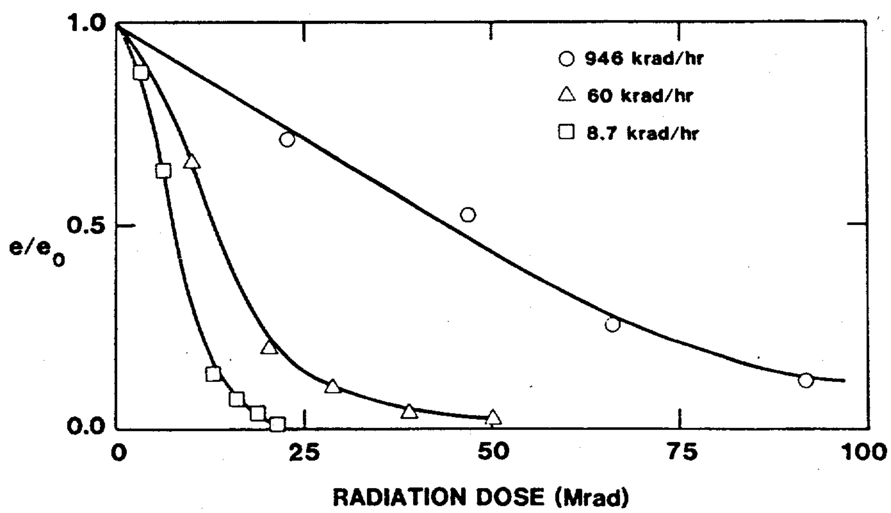


Figure 4.25 Tensile elongation for PE at 43°C for three different dose rates (Ref. 4.61)

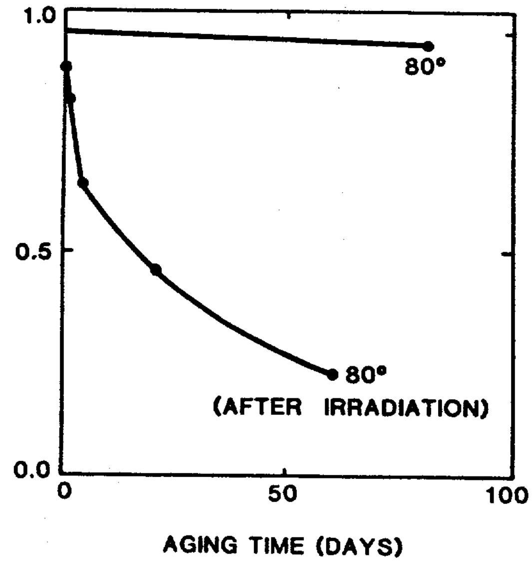


Figure 4.26 Tensile elongation for PE - effect of pre-irradiation at 5 krad/hr at 25°C in air for 83 days (Ref. 4.61)

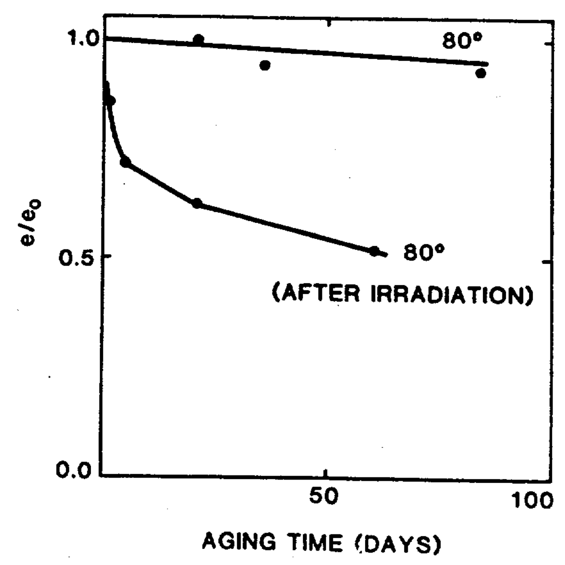


Figure 4.27 Tensile elongation for PVC - effect of pre-irradiation at 4.4 krad/hr at 25°C in air for 83 days (Ref. 4.61)

Irradiation at room temperature sensitizes the materials to subsequent thermal degradation. Rapid degradation with no induction period occurs upon exposing pre-irradiated samples of either PE or PVC to elevated temperatures. There was no substantial sensitization in the opposite case, namely exposure to elevated temperatures before radiation. However, a Japanese study (Ref. 4.62) indicated such thermal-sensitization in other types of materials. The PE insulation test found a color dependency, with black insulation more stable than red which, in turn, was more stable than white. The black insulation probably is more stable due to the carbon black which can act as an antioxidant. In naturally aged cable removed from containment, as well as in laboratory-aged samples, the nylon jacketing exhibited progressive yellowing and embrittlement of the PE. However, no quantitative measurements of nylon degradation were made.

Figures 4.28 - 4.31 show the dose-rate effects at room temperatures for XLPO, EPR, chloroprene, and chlorosulfonated polyethylene (CSPE) materials. Gillen and Clough (Ref. 4.63) summarize these effects: "In every case, as the radiation dose-rate in air is lowered, tensile strength shifts to lower values for a constant value of total radiation dose. Since crosslinking increases tensile strength and scission decreases it, these results can be interpreted as evidence that scission becomes more important relative to crosslinking as the radiation dose rate is lowered." The results from the case with irradiation in a nitrogen environment (Figures 4.28 and 4.29), implicated oxygen in the dose-rate effects, thus, scission is associated with oxidation.

The elongation results for EPR (Figure 4.29) imply that dose-rate effects exist for the entire dose-rate range investigated, but clear effects for the other three materials appear only at the lowest dose-rates tested. The relative lack of sensitivity of elongation to the changing competition between crosslinking and scission is due to the fact that both phenomena tend to lower this parameter. Solubility and swelling techniques were used to assess the relative importance of these two degradation mechanisms (Ref. 4.63).

Dose-rate effects are a definite factor in aging simulations. For PVC, this effect is severe and complex, and has been studied in great detail (Ref. 4.64). Figure 4.32 provides examples of the results of radiation aging for PVC material at two different dose rates. The trend in tensile strength, a drop followed by a rise, is an intrinsic aging behavior of PVC. As the material ages due to the influence of ionizing radiation, degradation is at first dominated by oxidative scission, and later, by cross-linking. The effect of nitrogen and thermo-oxidative behavior alone for this material is shown in Figure 4.33.

For XLPO, the tensile strength results in Figure 4.28 indicate the existence of the dose-rate effect, while the elongation results are more subtle and complicated. For the Hypalon material, the elongation data in Figure 4.31 barely indicate this effect, although it is more apparent from the tensile strength data. Again, comparisons of aging in air versus nitrogen indicate oxidation processes in the dose-rate effects. Several studies have indicated that oxidative scission becomes more important relative to crosslinking as the dose rate is lowered. In confirmation, the much larger carbonyl peaks seen by infrared spectroscopy under low dose rates for EPR are consistent with the expected increase in the extent of oxidative reactions.

According to Clough, Gillen, and Quintana (Ref. 4.65), the most obvious potential cause of dose-rate effects is physical, caused by diffusion-limited oxidation. In radiation environments, diffusion effects can be eliminated by using low dose rates. Using thinner samples also will reduce these effects, but this can create problems with commercial samples. The other possible cause involves chemical effects which include the hydroperoxide-mediated mechanism and the copper-catalyzed oxidation mechanism. The unfortunate aspect of chemical effects is that their disappearance cannot be guaranteed by aging at a low enough dose rate. When chemical effects are identified, this usually implies that both synergistic effects at low-temperature radiation plus elevated thermal environments, and sequential ordering effects are mechanistically dependent upon the same chemical reactions.

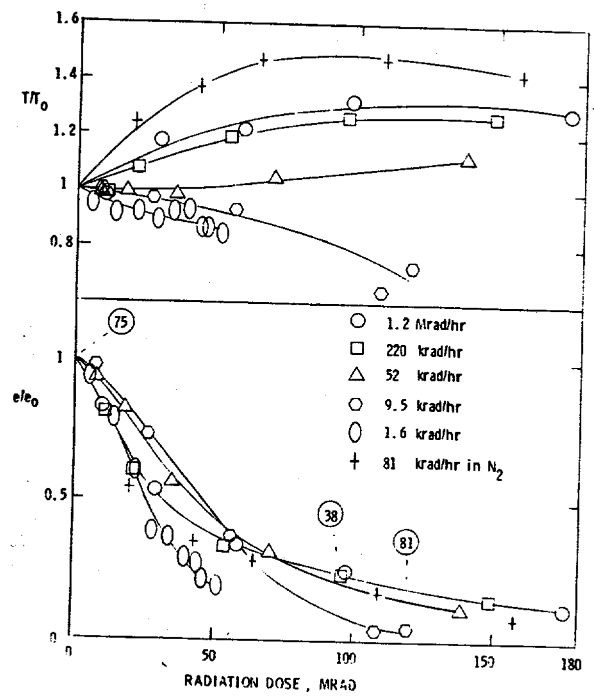


Figure 4.28 Aging of CLPO. Circled numbers indicate swelling ratios. (Ref. 4.63)

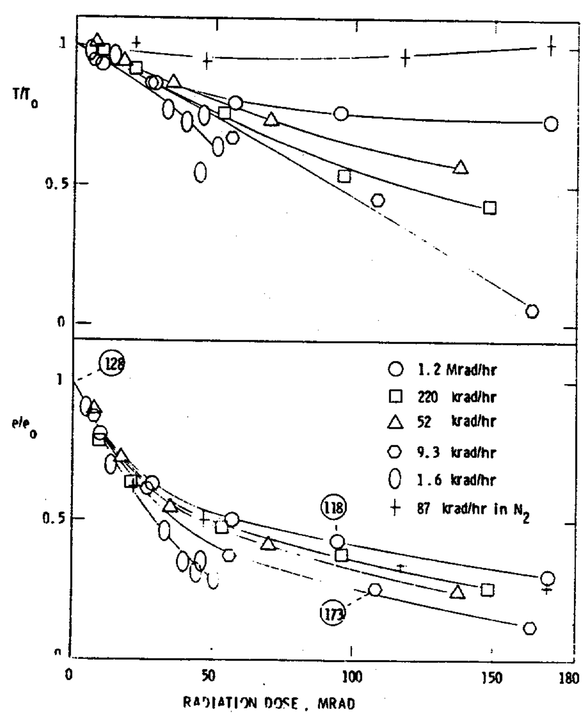


Figure 4.29 Aging of EPR. Circled numbers indicate swelling ratios. (Ref. 4.63)

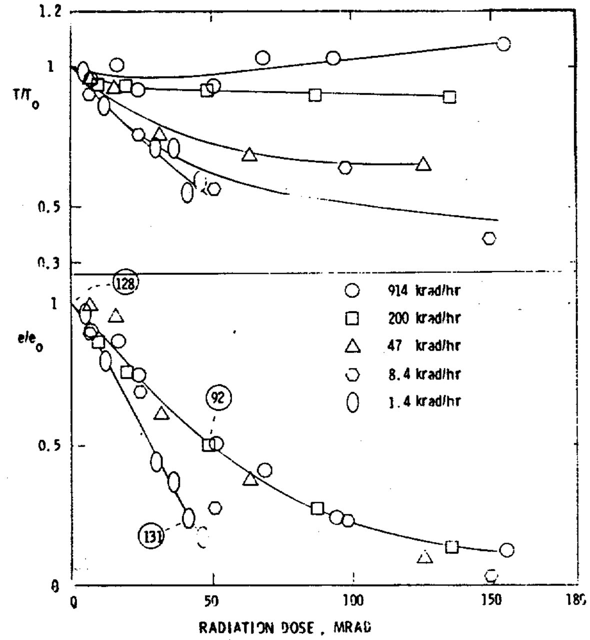


Figure 4.30 Aging of chloroprene. Circled numbers indicate swelling ratios. (Ref. 4.63)

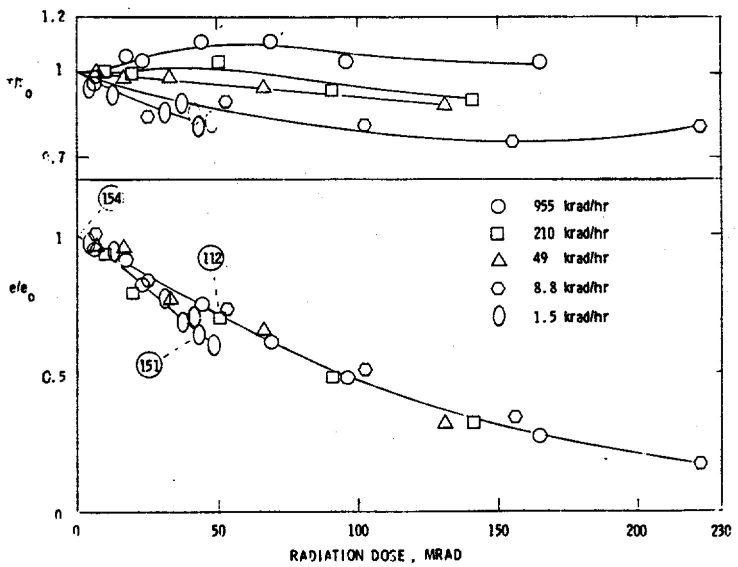


Figure 4.31 Aging of CSPE. Circled numbers indicate swelling ratios. (Ref. 4.63)

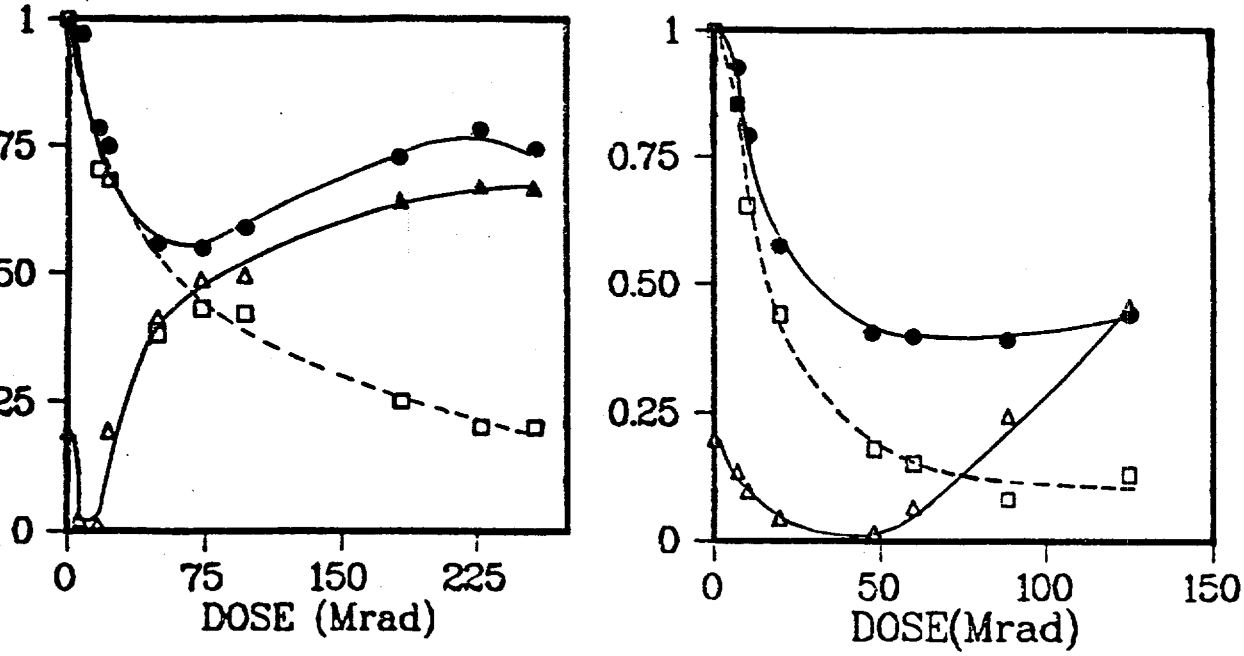


Figure 4.32 Radiation aging of PVC-I at 700 krad/hr (left) and 24 krad/hr (right), 43°C in air. Tensile strength (circles); elongation (squares); nonextractable fraction (triangles) (Ref. 4.64)

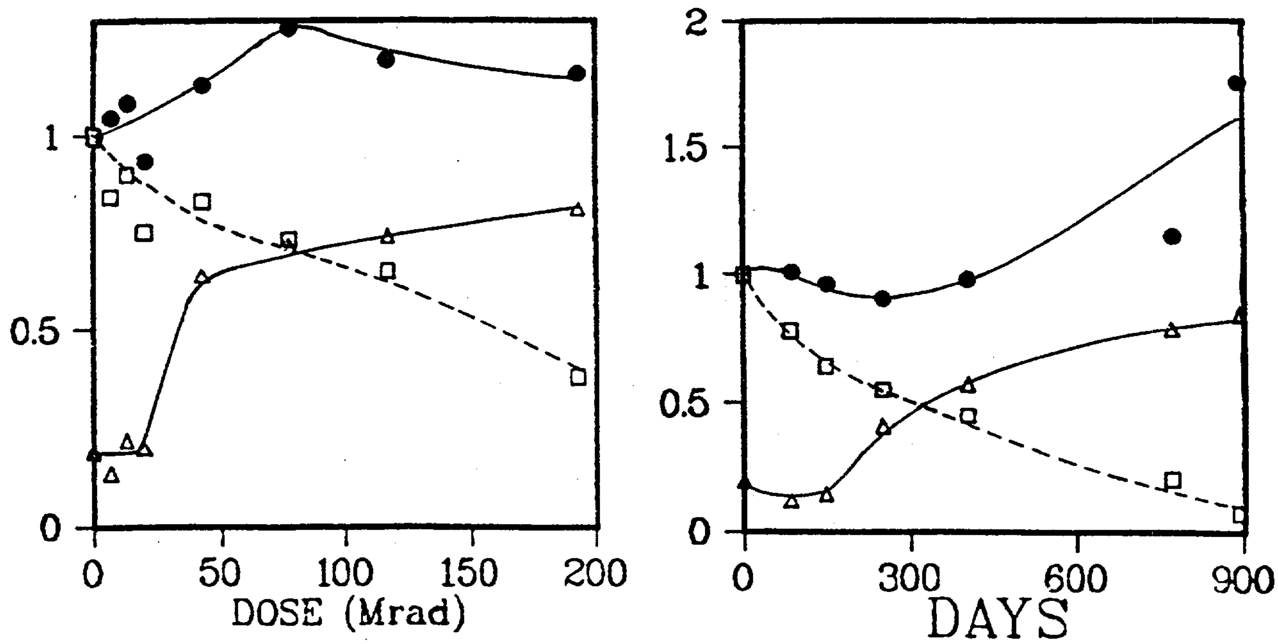


Figure 4.33 PVC-I: Radiation aging at 700 krad/hr in N_2 (left) and thermal aging at 110°C in air. Tensile strength (circles); elongation (squares); nonextractable fraction (triangles) (Ref. 4.64)

French researchers studied Hypalon and EPDM at very low dose rates of 10^{-5} to 10^{-4} Gy/s in a PWR nuclear power station and the results were compared with those previously obtained at higher dose rates of $5x10^{-4}$ to 1.4 Gy/s (Ref. 4.66). The oxygen consumption increased as the dose rate decreased, for a given dose. As the dose of irradiation was increased, this phenomenon became less pronounced. For Hypalon, the oxygen consumption was high at the beginning and then decreased at rates inversely proportional to the dose rate until negative values (oxygen desorption) were obtained.

The Harwell Laboratory of the United Kingdom Atomic Energy Authority has published data on halogen-free cable insulation materials exhibiting dose-rate effects (Ref. 4.67). Information presented is taken from several sources and is supplemented in some cases with work carried out at Harwell for the General Nuclear Safety Research Programme. Tables 4.3 and 4.4 summarize the results presented in this study. Table 4.3 lists the values obtained for the relative elongation at break (e/e_o) after 100 Mrad irradiation at different dose rates. Table 4.4 lists the doses required to reduce this relative elongation value to half ($e/e_o=0.5$) at two dose rates of 50 Gy/s (18 Mrad/hr) and 10^{-2} Gy/s (3.6 krad/hr). Based on the factors representing the ratio of the doses required for the same degradation at high dose rate (HDR) and low dose rate (LDR), the severity of dose rate effects seems to decrease in the following order: PE > EP copolymers > XLPE > XLPO.

Table 4.3 Elongation Ratio (e/e_o) After 100 Mrad Irradiation at Ambient Temperature (Ref. 4.67)

Base Polymer	Dose Rate (Gy/s)*	Elongation Ratio (e/e_o)
PE	50 0.05-0.66	0.10-0.45 0.016-0.027
XLPE	50 0.06-3.0	0.15-0.58 0.02-0.13
XLPO	50 0.0264-3.3	0.14-0.24 0.08-0.20
EP Copolymers	50 0.025-3.0	0.11-0.52 0.078-0.42

* 1 Gy/s = 0.36 Mrad/hr

Table 4.4 Comparison of Dose to Reduce Elongation Ratio to Half at High and Low Dose Rates (Ref. 4.67)

Base Polymer	Dose for $e/e_o=0.5$ at 50 Gy/s* (H in Mrad)	Dose for $e/e_o=0.5$ at 10^{-2} Gy/s* (L in Mrad)	Ratio H/L
PE	50	13	3.76
XLPE	95	52.5	1.81
XLPO	36.7	32.5	1.13
EP Copolymers	70	33	2.12

* 1 Gy/s = 0.36 Mrad/hr

In addition to work performed by Gillen and Clough at Sandia, Reynolds collected data on dose-rate effects on cable insulation polymers, namely, XLPE, EPR, and SR (Ref. 4.68). This work is presented in Figure 4.34a and 4.34b. The reference numbers and legends in Figure 4.34b are those references given in the publication and are applicable to both figures. Many results show dose-rate effects at high dose rates above 10-100 krad/hr where it is presumed that diffusion-limited oxidation governs the degradation process. However, at low dose rates which represent the actual plant environment conditions, many results show little to no dose-rate effects, except SNL's results for EPR, German and Japanese findings for XLPE, and the German for SR which have indicated some dose-rate effects.

Reynolds and his colleagues studied the same insulation materials in their own laboratory (Ref. 4.69). Two possible causes of the dose-rate effect were identified. First, diffusion-limited oxidation occurring at high dose rates and leading to heterogeneous oxidation across the thickness. This oxygen diffusion occurs more rapidly in amorphous than in crystalline polymers. XLPE being more crystalline than EPR, is vulnerable to dose-rate effects. Second, the formation of organic hydroperoxide causes oxidative degradation. This decomposes with time to form free radicals, which continue to react with oxygen and cause further degradation. This can occur slowly at room temperature at low dose rates. Both these phenomena being time-dependent cause dose-rate effects in polymer degradation. Figures 4.35 and 4.36 present the results. Based on Figure 4.35, no dose-rate effect was observed for EPR at lower doses, and a smaller effect was noted above 340 Gy/hr at higher doses. From both Figures 4.35 and 4.36, a dose-rate effect exists above 40 Gy/h for two out of three XLPE cable products, but there is no such effect in the lower range from 5-30 Gy/h.

CERN studied dose-rate effects for several types of polymers and the results for the PE, PVC, XLPE, and EPR are shown in Figure 4.37 (Ref. 4.55). The measured values fall within two solid lines for low dose rates and two dashed lines for high dose rates. Comparing the results, PE and PVC exhibit significant dependence on dose and dose-rates. Corresponding graphs for XLPE show a behavior similar to PE, but much better than PE in long-term tests above 1 MGy. Similarly, EPR values are higher than XLPE, and fall within the upper region of PVC. The dose-rate effect for some types of PE has been as high as a factor of 10 when irradiated at low dose rates (10 mGy/s) as opposed to high dose rates (50 Gy/s). The same applies to PVC, if tensile strength is the measurable parameter. For other types of PE and PVC, along with most EPR, the dose rate effect is considerably smaller, or even negligible. The limited studies performed on SR and CSPE indicate reverse dose-rate effect. The ratio of the elongation ratios at 100 Mrad irradiation for 60 mGy/s and 50 Gy/s dose rates are approximately 0.55 for both these materials. Because of the limitations on the number of samples studied, no general conclusion on SR and CSPE was drawn.

Wilski (Ref. 4.70) published an excellent compilation of data on radiation stability and dose-rate effects for several cable materials. Figures 4.38-4.43 present the results for the most commonly used insulation and jacket polymers. Each graph plots the "dose rates" against the "half value dose" representing the dose at which the elongation at break reaches half of its original value. For full details on the source, chemical degradation, and legends used, the reference document should be consulted. Since the purpose of this study is to obtain the overall radiation characteristics of cable's insulation and jacket polymers at different dose rates, these details are considered unnecessary for inclusion in these figures. All irradiations were carried out in air at room temperature; a few exceptions are indicated in the graphs. Elongation was always measured at room temperature. Solid lines connect measured points for samples irradiated in air, while broken lines connect measured points which were obtained for irradiated samples without air or oxygen. The paper contains data for several other thermoplastic polymeric materials which are considered unimportant for cables.

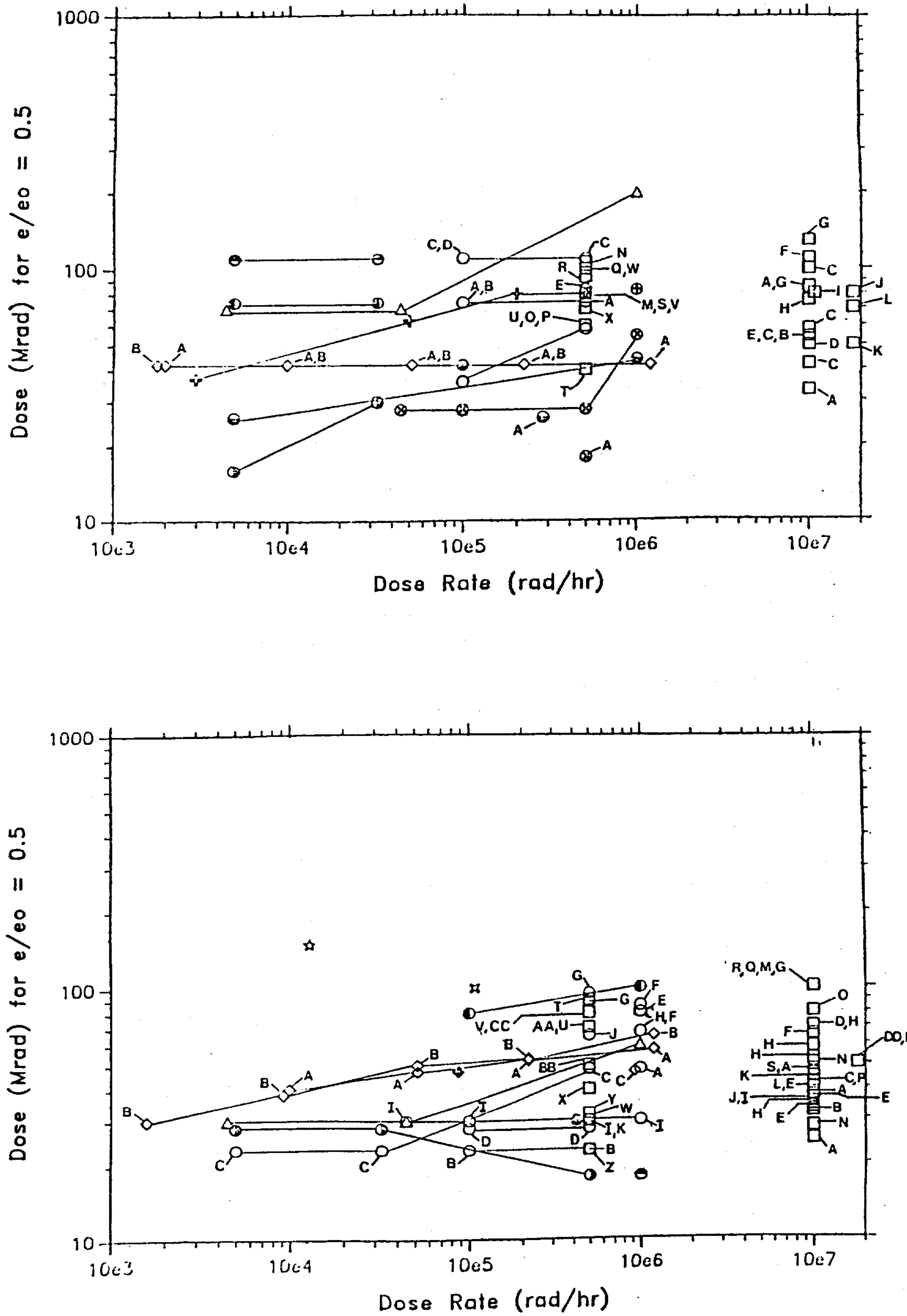


Figure 4.34a Dose rate effects in XLPE (top) and EPR (bottom) (Ref. 4.68)
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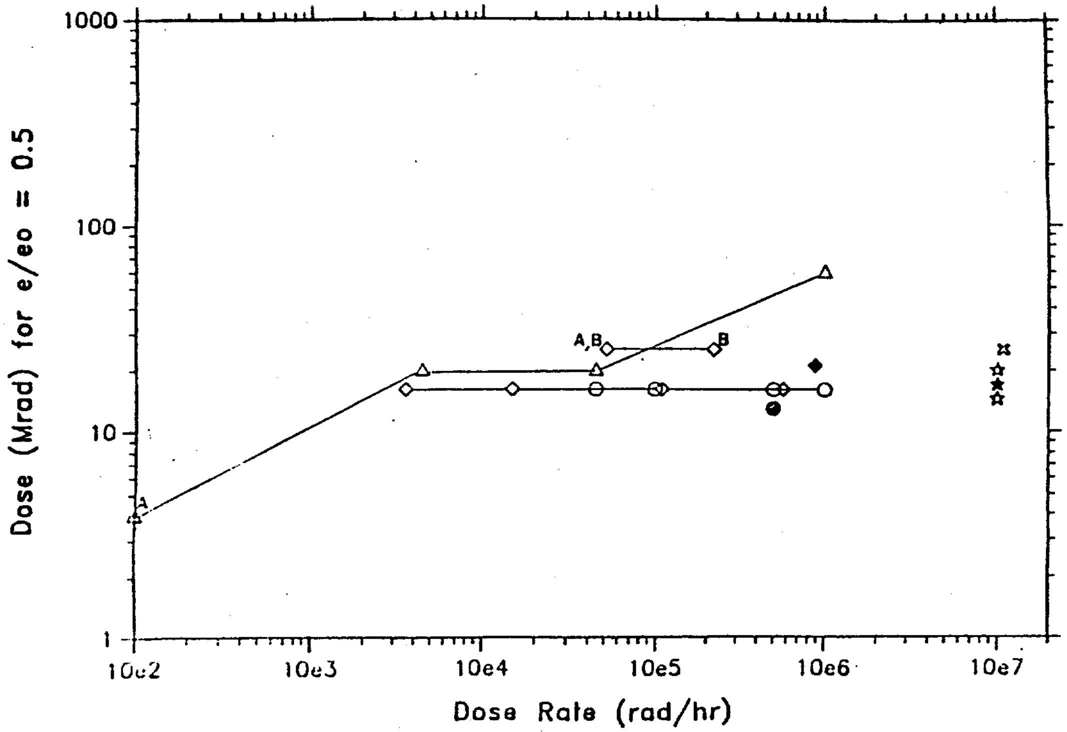

Material	Reference	Source	Year	Symbol	Atmosphere[a]	Temperature[b]	Comments
EPR	17	SNL	1978	◇A			0% and 70% relative humidity
	18		1981	◇B			
				◆	N_2		
	10	↓	1982	◇C		44.5°C	
	20	Japan	1981	○C, ◑			
				○B, D	O_2 (5 atm)		
				○A, ◓	Vacuum		
	22		1982	□T			Without flame retardant
				□U, V			With flame retardant
	24		1983	□W	Vacuum		No antioxidant
				□X, Y, Z	Vacuum		NBC, DPPD, I-1010 antioxidant
				□AA-CC			NBC, DPPD, I-1010 antioxidant
	25		1985	○F			
				○G	O_2		
	11		1985	○H, ◐			
				○J		70°C	
	12		1986	○I			
				○K		70°C	
		↓		●	O_2		
	27	Germany	1985	△			
	28	CERN	1975	□A-S			Different suppliers
	29		1982	×X		35-45°C	
	30		1983	□DD, EE			
	31	↓	1983	☆			
XLPE	17	SNL	1978	◇A			0% relative humidity
				◇B			70% relative humidity
	21	Japan	1981	◑, ◐, ◓			No antioxidant, I-1010, DPPD
				●, ○B, ○D	O_2 (1 atm)		No antioxidant, I-1010, DPPD
				○, ○A, ○C	O_2 (5 atm)		No antioxidant, I-1010, DPPD
	23		1982	◒			
				◒A	O_2 (10 atm)		
	24		1983	□M-X			Combinations of gas, pressure, and antioxidants
	25		1985	⊕			
				○E	O_2		
	12		1986	⊗			
		↓		⊗A		70°C	
	26	Germany	1982	+			
	27	↓	1985	△			
	29	CERN	1982	□I		32-45°C	
	30	↓	1983	□J-L		20-40°C	Different XLPE's
SIR	17	SNL	1978	◇A			0% relative humidity
				◇B			70% relative humidity
	10		1982	◆		44°C	
	19	↓	1985	◇		70°C	
	12	Japan	1986	○			
		↓		●		70°C	
	25	Germany	1985	△			
		↓		△A			e/e_o = 0.4 instead of 0.5
	28	CERN	1979	☆ ★			Different suppliers
	29	↓	1982	×		35-45°C	

a. Air unless specified otherwise
b. Room temperature unless specified otherwise

Figure 4.34b Dose rate effects in SR (top) and references and legends used (bottom) (Ref. 4.68)
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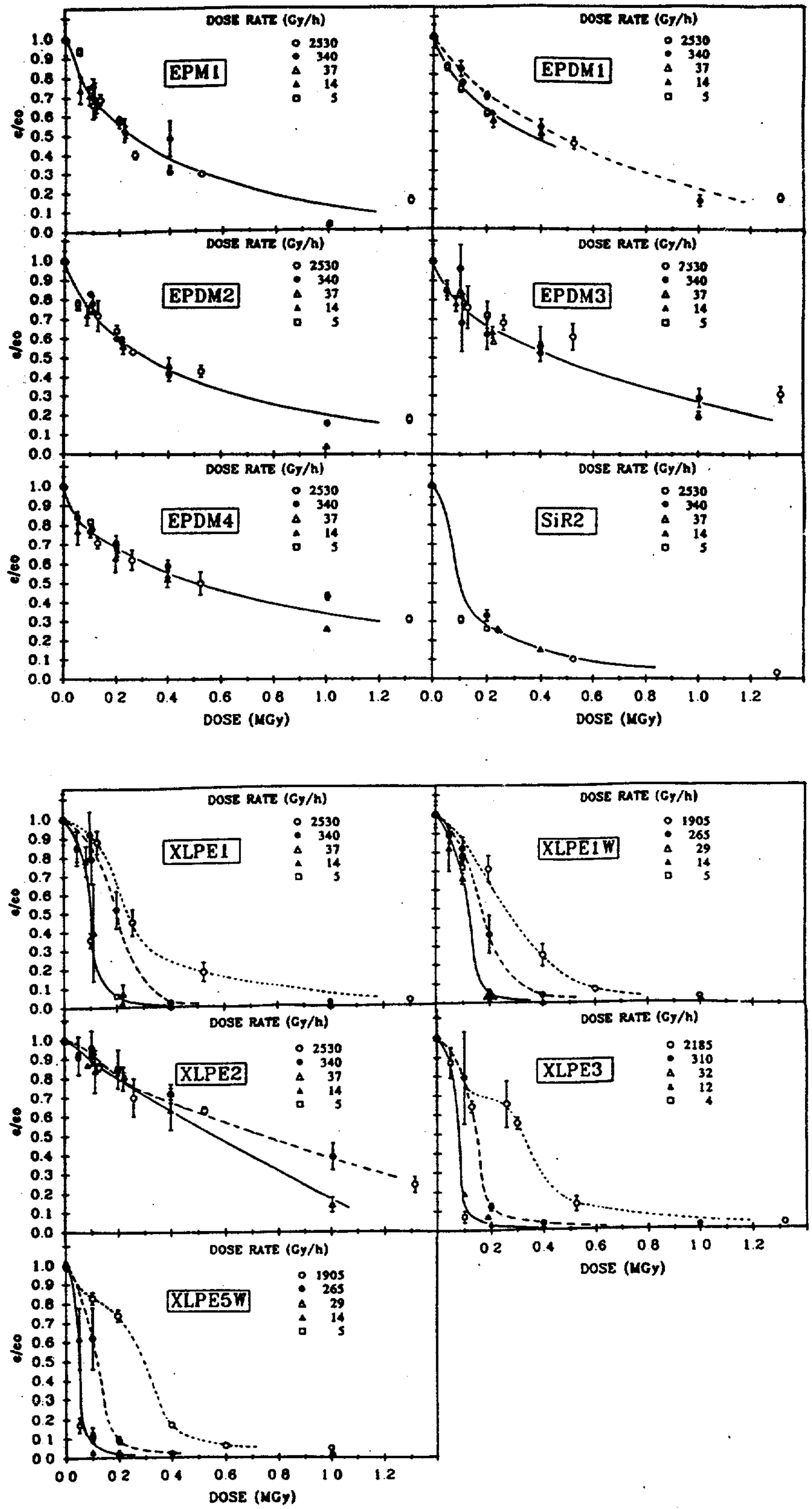
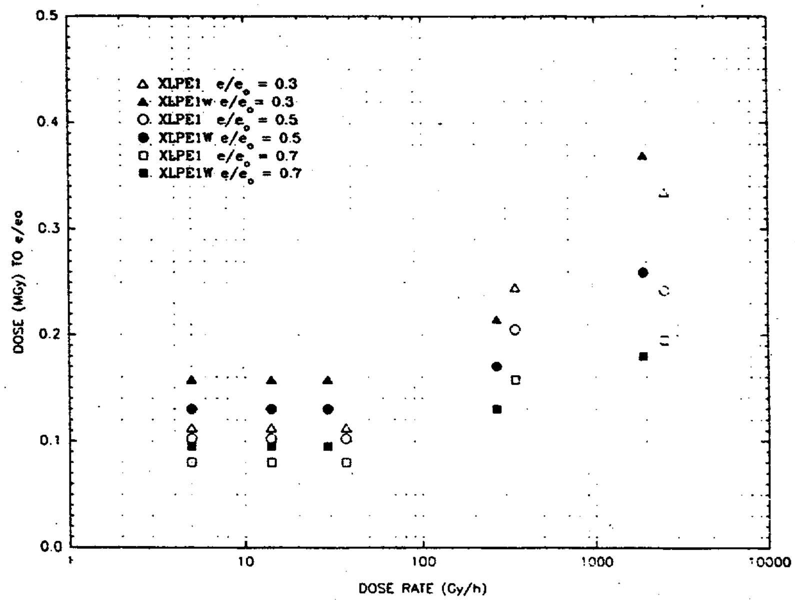


Figure 4.35 Relative elongation as functions of dose and dose rates for EPR, SR, XLPE (Ref. 4.69) Reprinted with permission from Radiation Physics and Chemistry, Vol. 45, No. 1, pp. 103-110, Reynolds, A.B., Bell, R.M., Bryson, N.M., et al., *Dose-Rate Effects on the Radiation-Induced Oxidation of Electric Cable Used in Nuclear Power Plants,* 1995, Elsevier Science Ltd., Oxford, England.



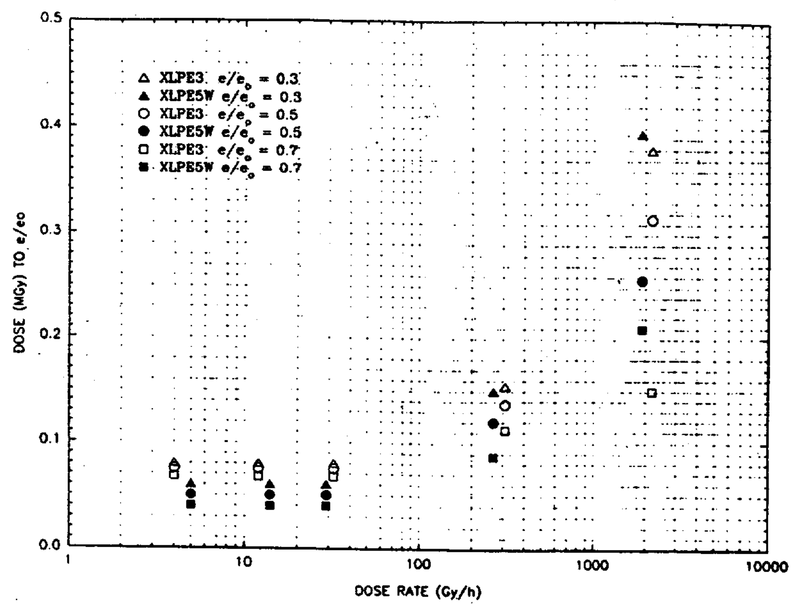


Figure 4.36 Dose to equivalent damage for two XLPE cable materials versus dose rate (Ref. 4.69) Reprinted with permission from Radiation Physics and Chemistry, Vol. 45, No. 1, pp. 103-110, Reynolds, A.B., Bell, R.M., Bryson, N.M., et al., *Dose-Rate Effects on the Radiation-Induced Oxidation of Electric Cable Used in Nuclear Power Plants,* 1995, Elsevier Science Ltd., Oxford, England.

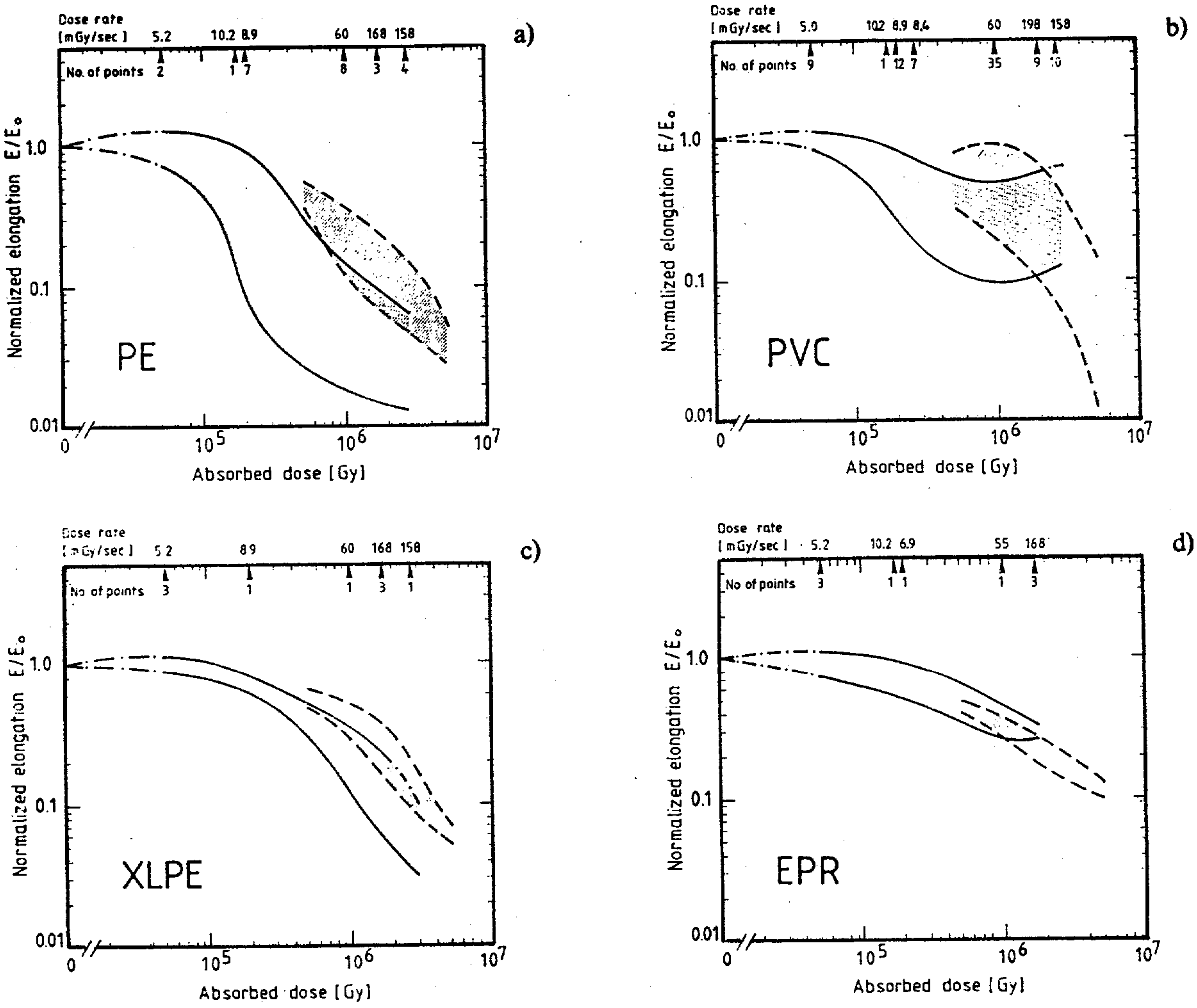


Figure 4.37 Relative elongation versus dose for PE, PVC, XLPE, and EPR.
Low dose rates: Data between solid lines. High dose rates: Data between dashed lines. (Ref. 4.55)
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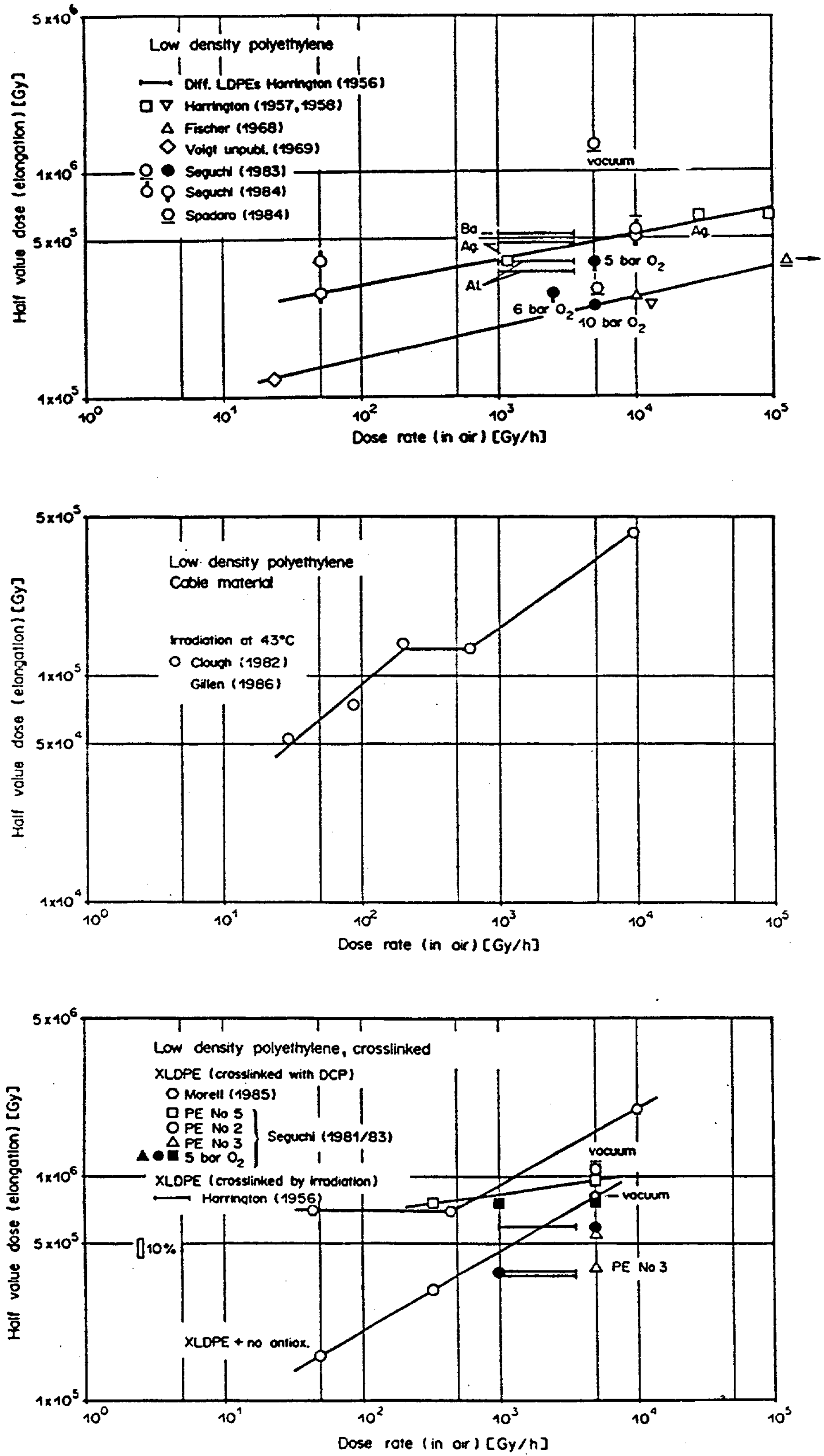

Figure 4.38 Half value dose (elongation) versus dose rate for LDPE (Ref. 4.70)
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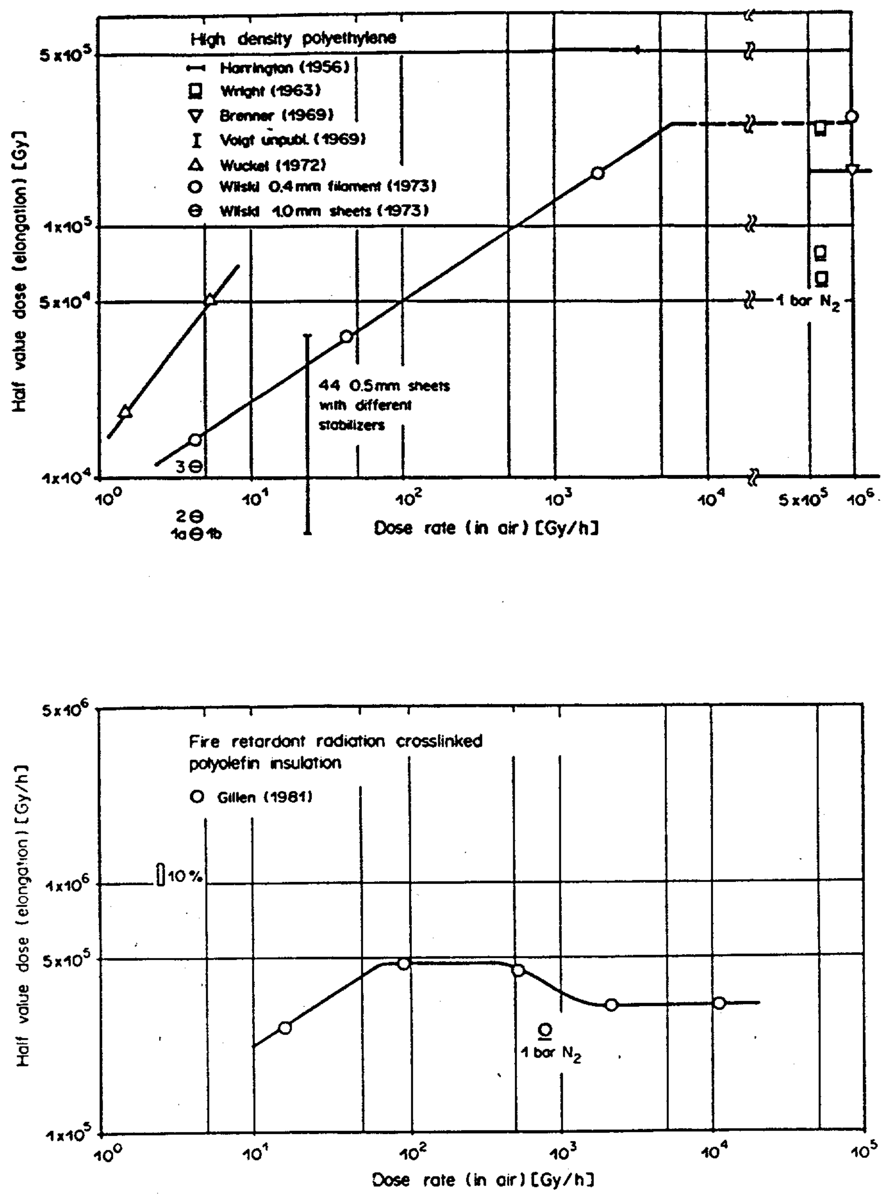

Figure 4.39 Half value dose (elongation) versus dose rate for HDPE and XLPE (Ref. 4.70)
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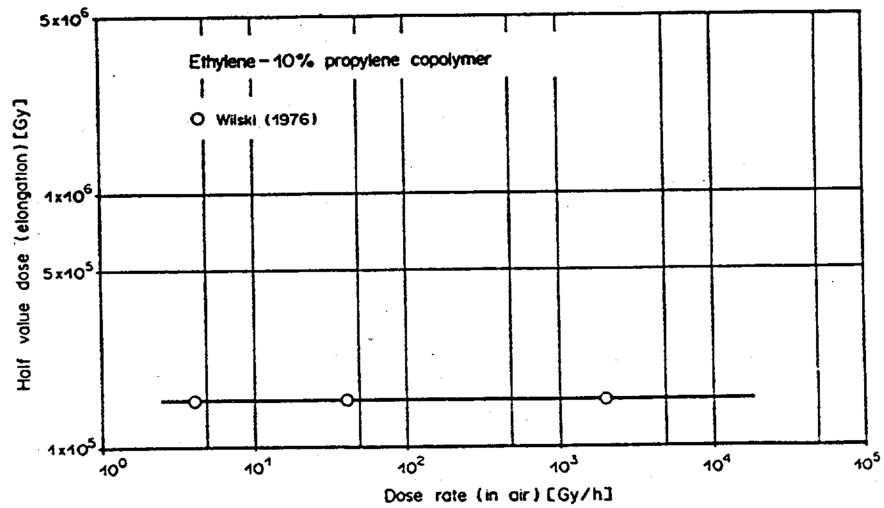

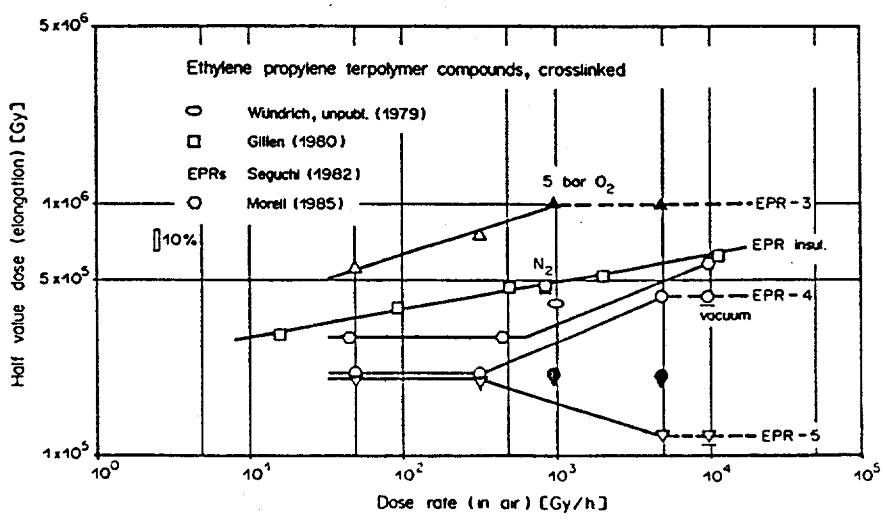

Figure 4.40 Half value dose (elongation) versus dose rate for EPR (Ref. 4.70)
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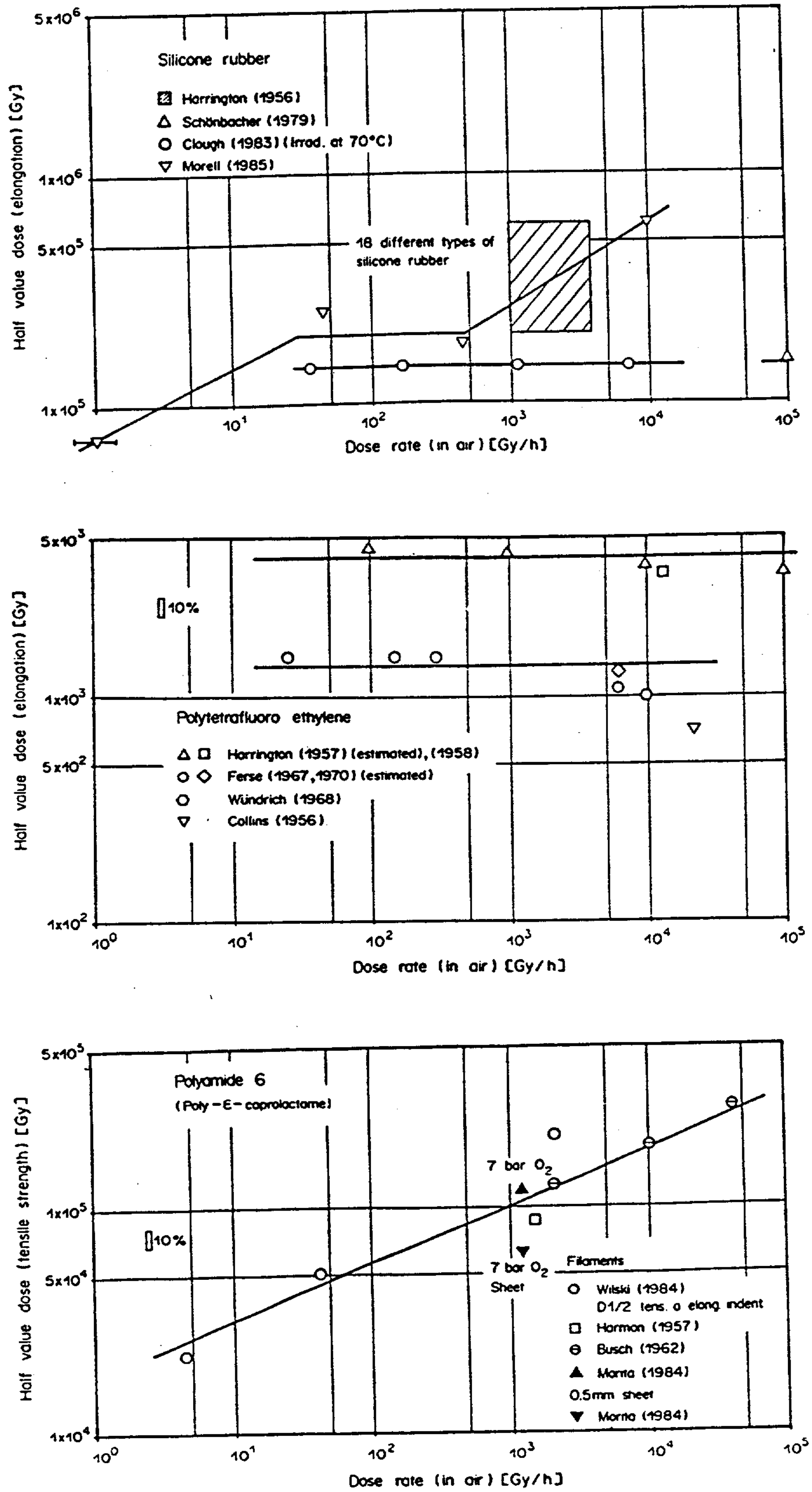

Figure 4.41 Half value dose (elongation) versus dose rate for SR, Teflon, Polyamide (Ref. 4.70)
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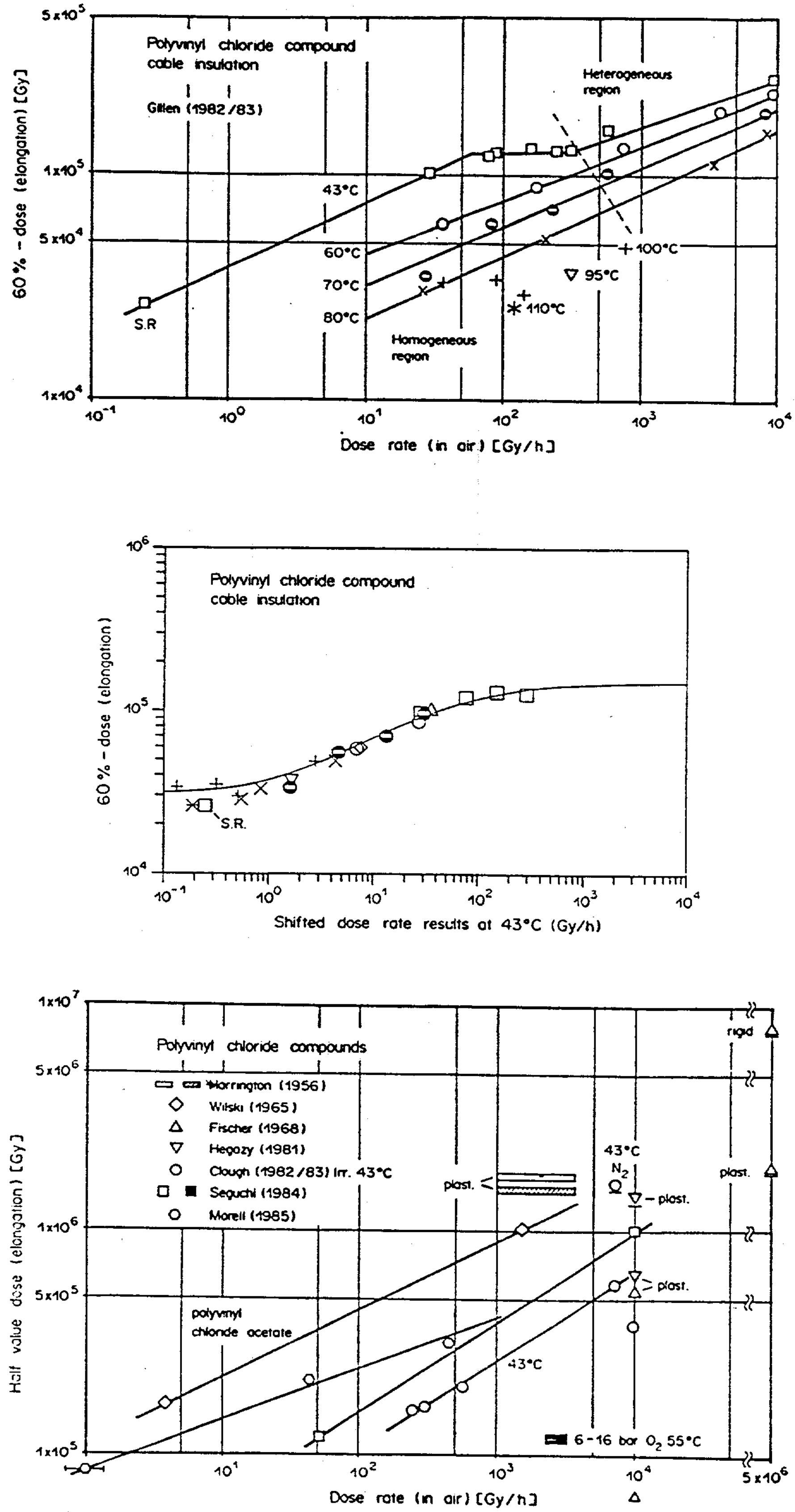

Figure 4.42 Half value dose (elongation) versus dose rate for PVC (Ref. 4.70)

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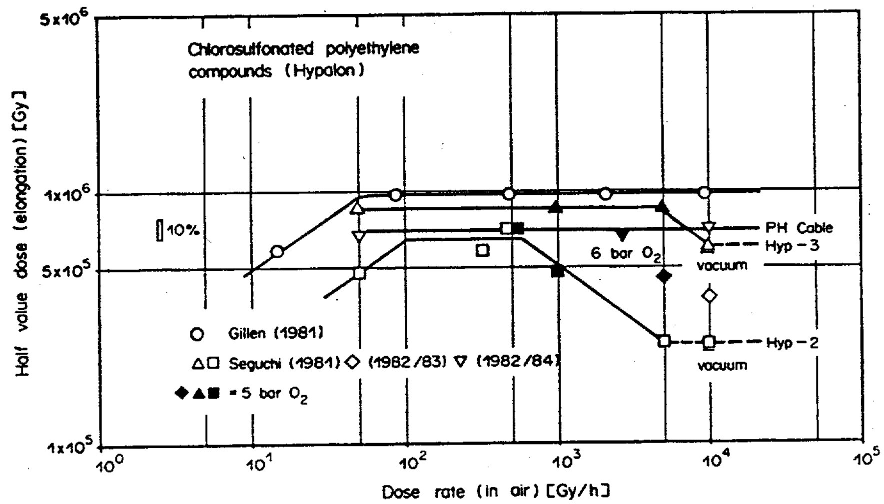


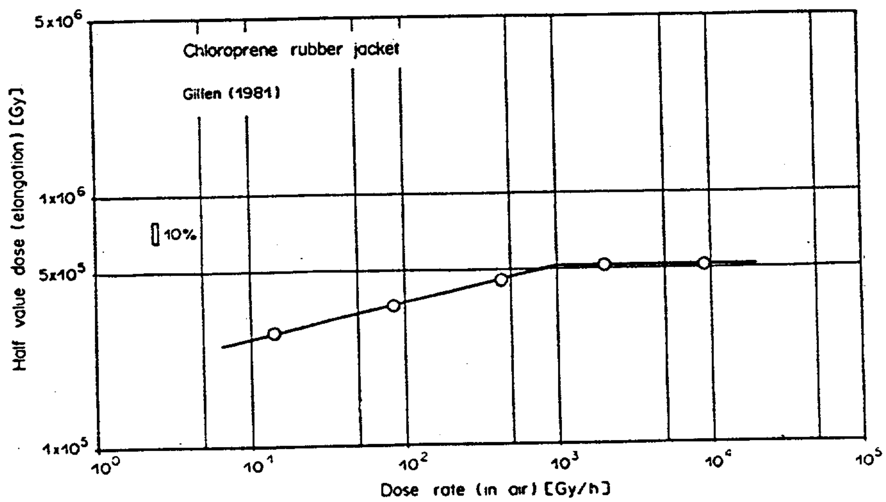


Figure 4.43 Half value dose (elongation) versus dose rate for CSPE and Chloroprene (Ref. 4.70) Reprinted with permission from Radiation Physics and Chemistry, Vol. 29, No. 1, pp. 1-14, Wilski, H., *The Radiation Induced Degradation of Polymers,* 1987, Elsevier Science Ltd., Oxford, England.

Based on the findings so far, the magnitude of dose-rate effects varies tremendously from one type of material to another, as well as from one degradation parameter to another. The use of any empirical "overdose" approach for accelerated aging has serious drawbacks, in that the dose chosen may substantially underestimate damage in the case of materials having very large dose-rate effects, while overestimating damage for materials having minor dose-rate effects. IEEE Std 775-1993 (Ref. 4.7) recommends one approach using the upper limits for an ambient-air radiation dose rate given in Table 4.5. An alternate approach employs theoretical analysis techniques to establish appropriate oxygen partial pressure, radiation dose rate, and radiation aging temperatures to ensure that homogeneous oxidation takes place throughout the insulation's thickness. This is further discussed in the following section.

Table 4.5 Critical Dose Rates for Thickness of Polymers in Which Radiation-Induced Oxidation Proceeds Throughout the Material (Ref. 4.7)

Polymer Material	Irradiation dose rate (Gy/h) in air at 25°C 0.5 mm	1.0 mm	1.5 mm	2.0mm
HDPE	50	13	5.8	3.2
LDPE	440	110	49	27
EPR	4800	1200	530	300
EPDM	2100	520	230	130
Hypalon	1200	300	130	75
Neoprene	520	130	58	32
Silicone*	35 000	8700	3900	2200
Silicone*	5100	1300	580	320
PVC	440	110	49	27

Source: Based on a presentation by Seguchi, T., Morita, Y., and Yoshida, K., "A Methodology of Accelerated Aging of Polymer Materials," 1985.
* No distinction is made between these two silicone materials.

4.3.2.2 Modeling dose rate effects

To extrapolate the results of accelerated aging in the presence of complications caused by physical and chemical dose rate effects, the aging of a material in combined radiation\thermal\air environments must be separated into two regions, each dominated by a different dose-rate mechanism. The first, which is operative at high dose rates, involves diffusion-limited oxidation (Ref. 4.65): this leads to heterogeneously oxidized samples. The second, which is important at low dose rates and enhanced by elevated temperatures, involves the thermally induced breakdown of intermediate peroxides formed by radiation. A metallographic polishing technique, together with results from oxygen consumption studies, can be used to determine the range of dose rates and temperatures over which oxygen diffusion-limited heterogeneous degradation is dominant (Ref. 4.71). In the remaining homogeneous degradation regime, a general kinetic model is derived.

The first requirement for determining the presence of dose-rate effects was to develop techniques to ascertain whether homogeneous or heterogeneous oxidation was taking place. Such techniques are required to select the accelerated aging conditions which assure homogeneous oxidation throughout the material, in agreement with the result anticipated for real-time aging. Three techniques were developed for identifying heterogeneous oxidation, which results from the physical diffusion-limited dose-rate effect; these are density profiling, relative hardness profiling, and cross-sectional polishing. Another useful technique is modulus profiling (Ref.4.72), already discussed in the thermal aging section referring to oxygen diffusion effects at elevated temperatures (Figure 4.12). Chemical dose-rate effects also can be determined using these techniques. Several examples illustrating the use of density profiling are presented here.

Figures 4.44 to 4.46 (Ref. 4.37) show the mechanical properties, overall density, and density profiles for a XLPE material at different dose rates. From Figure 4.44, it is clear that oxidation mechanisms are important for the degradation in air. Also, mechanical deterioration appears to be sensitive to dose rate above 70 krad/hr. The overall density changes in Figure 4.45 are linear with dose, implying that the responsible reactions are not time-dependent; in other words, the oxidation is not autocatalytic. Figure 4.46 shows that the oxidation is extremely heterogeneous with substantial oxidation near both the surfaces exposed to air under high dose-rate aging; essentially no oxidation occurred in the middle of the sample. As the dose rate is lowered, this effect is reduced, and thus provides unambiguous evidence that diffusion-limited oxidation is minimal under a 70 krad/hr dose rate. Furthermore, at the samples' surfaces, the density increase due to oxidation is approximately independent of dose rate. Since diffusion-limited effects are absent at these surfaces, this implies that chemical dose rate effects are minimal for this material over the range of dose rates studied.

Figures 4.47 and 4.48 show similar results for a low density polyethylene (LDPE). In contrast to XLPE, the dose-rate effects for this material are substantial, and give no indication of disappearing at low dose rates. The density profiles show that oxygen-diffusion-limited degradation is very important at the highest dose rates but becomes insignificant at the lowest. When the density at the outer edge is plotted for a constant TID (Figure 4.49), there is a factor of 6 increase in the density while the dose rate changes from 946 to 3 krad/hr. Since edge density is unaffected by diffusion, these results indicate that chemical dose-rate mechanisms are partly responsible for the breakdown for this material.

Figures 4.50 and 4.51 show representative density profiles for an EPR material (Refs. 4.36 and 4.73). At high dose-rates, diffusion-limited degradation is common during radiation aging simulations. As the dose rate is lowered, this mechanism disappears, as anticipated, but a second mechanism appears which is responsible for greatly enhanced oxidation at the inside of the insulation (adjacent to the copper conductor). It involves copper-catalyzed oxidation, which is often significant in high temperature aging studies.

If dose-rate effects are unimportant, aging simulations then can be carried out using the equal dose - equal damage assumption. When dose rate effects are found, they should be characterized sufficiently and modeled to verify complex degradation mechanisms and predict aging effects.

Chemical dose-rate effects occur whenever some chemical step in the kinetics underlying degradation occurs on a time scale comparable to the sample's exposure time. In a radiation environment at low to moderate temperature, the most common possibility of a chemical dose-rate effect involves the slow breakdown of intermediate hydroperoxide species that is expected to take hundreds to thousands of hours at the aging temperatures at a real-time environment. Reference 4.74 presents an example of chemical dose rate effects on a PVC jacket material. The kinetic model is based on (1) several consensus reactions used for oxidation chemistry, (2) unimolecular termination kinetics, and (3) rate-determining hydroperoxide-mediated branching reactions. Depending on the ratio of kinetic rate constants, the hydroperoxide concentration will either tend towards a limiting value, or continue increasing. For the former case, the dose-rate effects are predicted to disappear at very low dose rates, whereas for the latter they should become progressively more important as

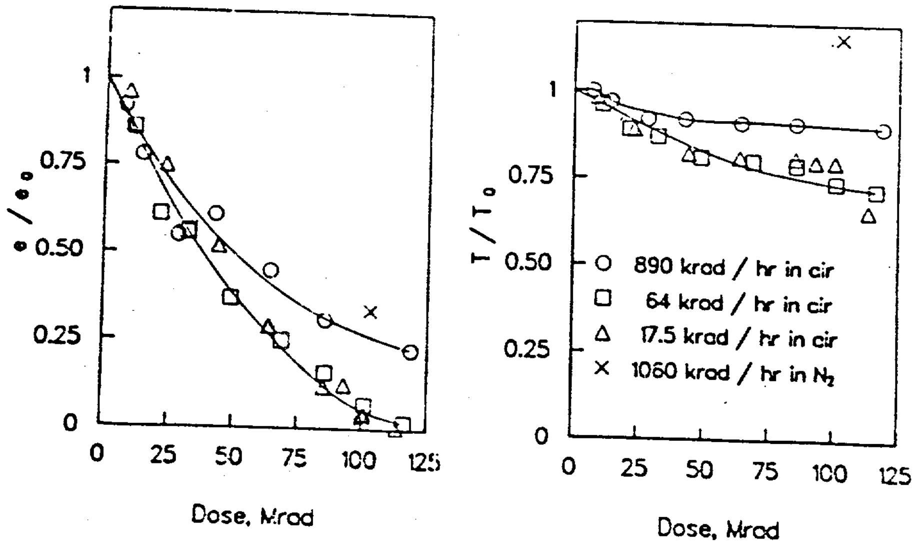


Figure 4.44 Radiation aging of chemically XLPE at 43°C (Ref. 4.37)

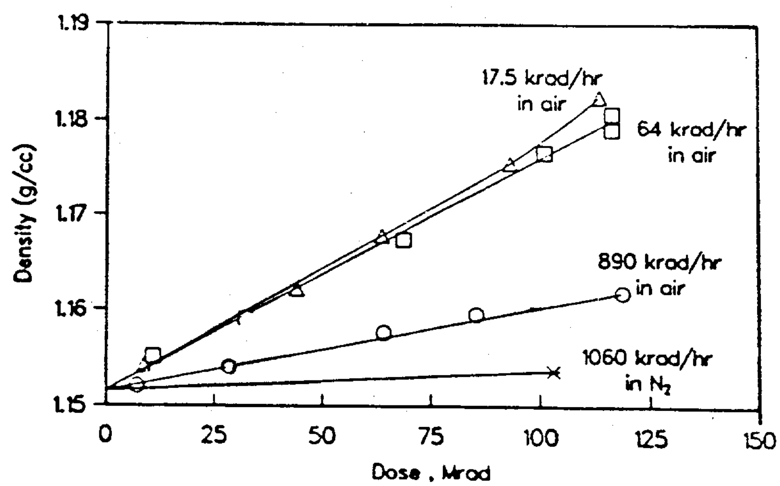


Figure 4.45 Overall density results for chemically XLPE (Ref. 4.37)

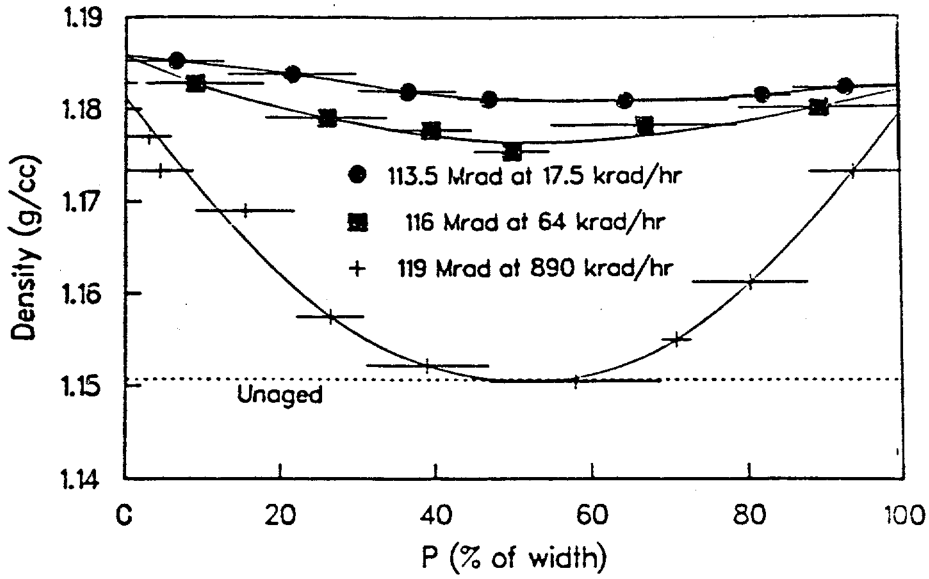


Figure 4.46 Density profiles for chemically XLPE (Ref. 4.37)

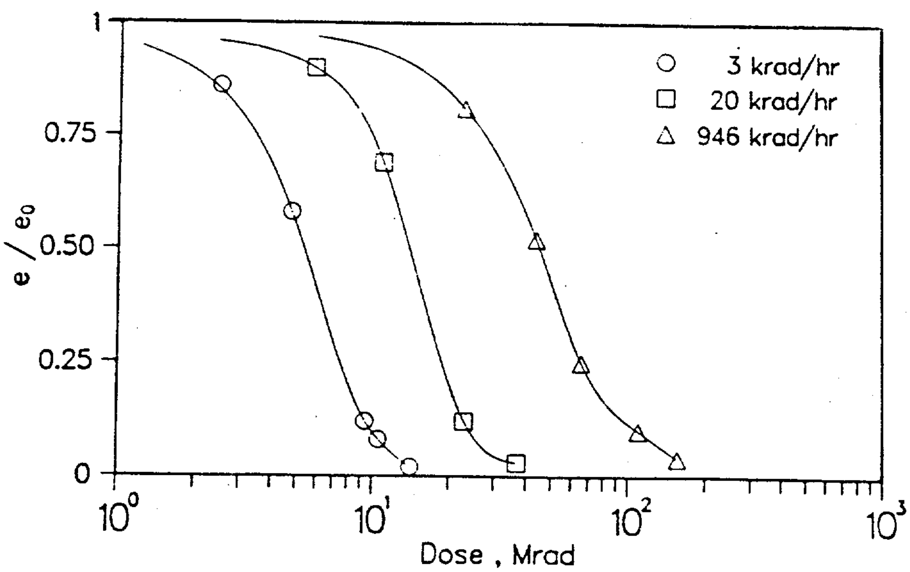


Figure 4.47 Tensile elongation for LDPE at 43°C (Ref. 4.37)

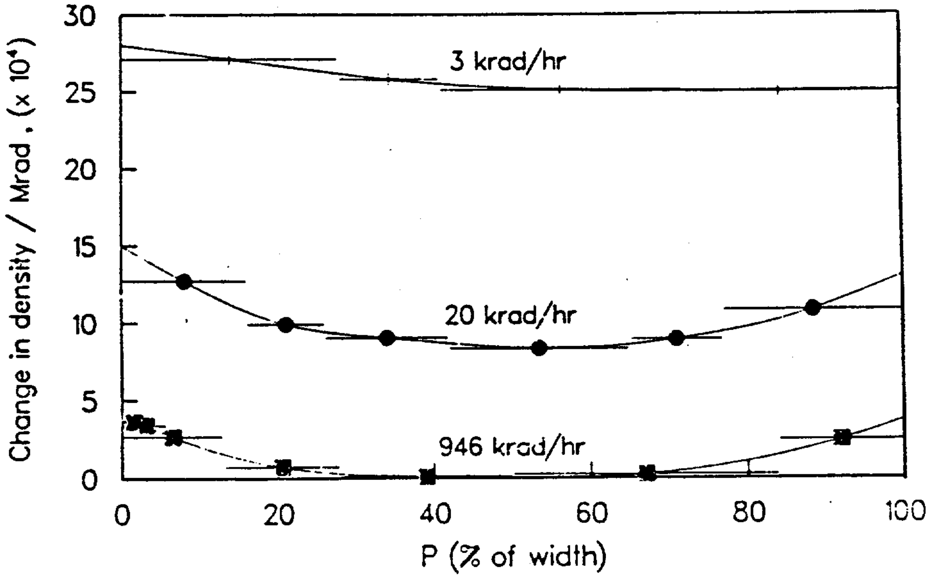


Figure 4.48 Density profiles for LDPE (Ref. 4.37)

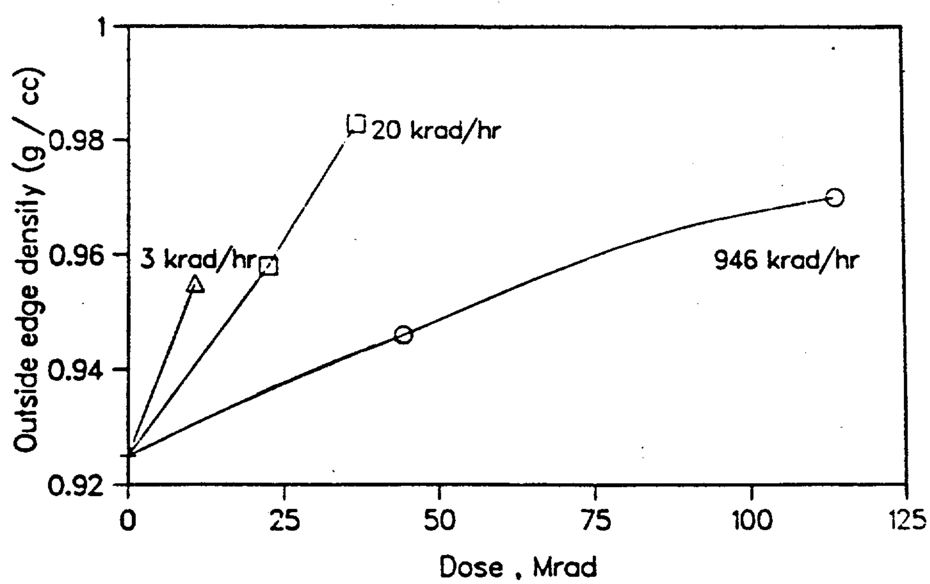


Figure 4.49 Density of outer edge of the LDPE material (Ref. 4.37)

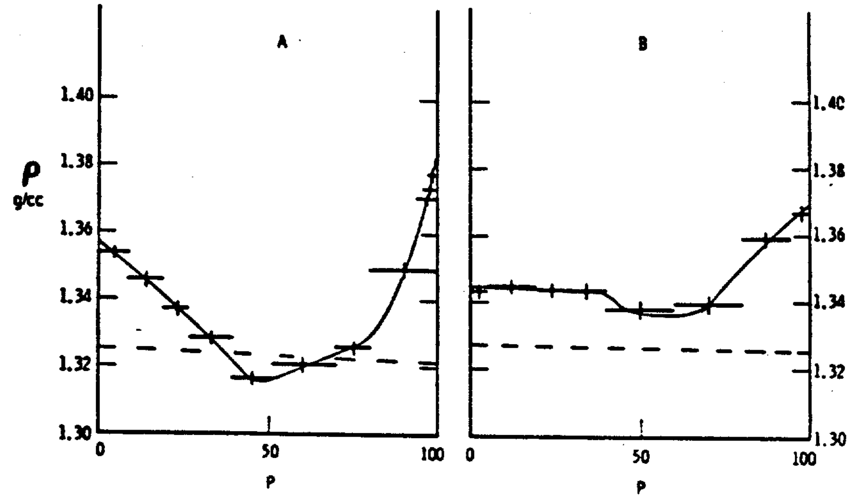


Figure 4.50 Density profiles for EPR; A: unaged (dashed), 172 Mrad at 1.2 Mrad/hr in air (solid); B: 117 Mrad at 87krad/hr in nitrogen (dashed), 150 Mrad at 220 krad/hr in air (solid) (Ref. 4.73)

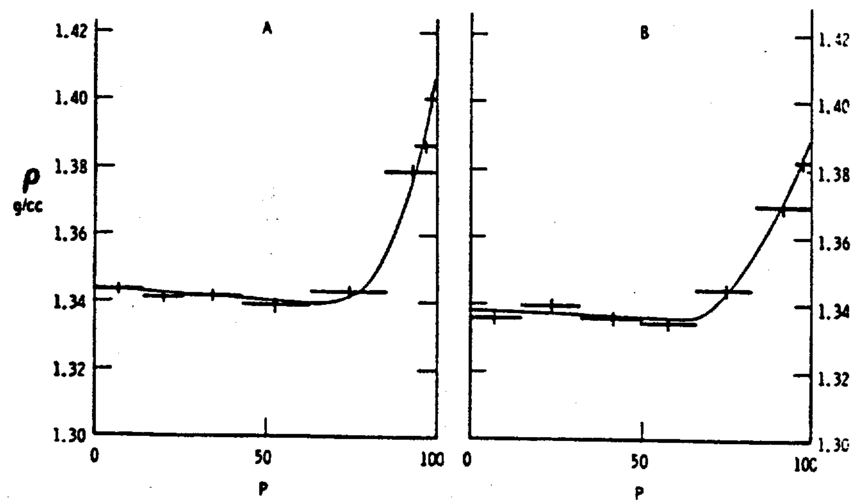


Figure 4.51 Density profiles for EPR. A: 135 Mrad at 52 krad/hr in air; B: 53 Mrad at 1.6 krad/hr in air (Ref. 4.73)

the dose rate is lowered. Kinetic analysis of sequential aging experiments gives an activation energy for the time-temperature component of the degradation mechanism. This allows a procedure for shifting the time-temperature-dose rate to a lower reference temperature.

French researchers Pinel and Gueguen (Ref. 4.75) and one of the IEC working group (Ref. 4.76) recently concluded that there were dose-rate effects in EPR with chain scission at a low-dose rate, and crosslinking at high-dose rates. Thermal aging shows an induction period, followed by thermo-oxidation. The activation energy of oxidation obtained in DSC (222 kJ/mol) compared with the value deduced from mechanical properties (55 kJ/mol), seems to demonstrate that degradation is not directly related to oxidation. The CSPE material mainly is broken down by crosslinking, regardless of the dose and dose-rate values. The thermal aging causes an important weight loss and a decrease of elongation at break. The good agreement between the activation energy deduced from mechanical properties (101 kJ/mol) and dehydrochlorination measurements (117 kJ/mol) indicates that degradation mainly is due to dehydrochlorination followed by crosslinking.

4.3.3 Simultaneous/Sequential Exposures and Synergistic Effects

Real-time aging of cables in nuclear power plants expose the polymers to a simultaneous combination of low-level stresses. Therefore, to simulate this ambient aging using accelerated aging exposures, several different approaches may be taken. If interactions (synergisms) occur between any two or more environments, the best approach would be to use appropriate combined accelerated simulations (Refs. 4.77 and 4.78). On the other hand, if synergistic effects are not important, sequential exposure to the environments might adequately simulate ambient aging. Also, sequential exposure might adequately simulate cases where synergistic effects are important, thereby eliminating the necessity for more complex and expensive tests. However, the order of the sequence becomes important when one environment sensitizes the material for higher degradation rates under the other. Most earlier cable-qualification tests employed sequential simulations with thermal first, followed by radiation; recently, the reverse sequence has been used in some (but not all) testing, and was accepted by IEEE standards.

Clough and Gillen in References 4.60 and 4.79 *(PE and PVC From Savannah River)* presented the results from four distinct combinations of radiation and thermal aging for these two materials. Figures 4.17 and 4.18, and Table 4.2 summarize the tensile-elongation data. The effects of simultaneously applying radiation and elevated temperature are severe when compared to either alone. For sequential tests, radiation followed by thermal stress degrades these materials more than the reverse sequence, but less than simultaneously. The mechanism responsible for aging is the thermally induced breakdown of relatively stable, intermediate peroxides.

Bustard (Ref. 4.80) presented tensile data from three different experiments on six different EPR materials. Five of the EPR materials (marked EPR-A,B,C,D,E) were representative of those used by manufacturers of safety-related electric cable. The sixth material, EPR-1483, originally was formulated for a fire-retardant aging study at SNL. For the EPR-A material, simultaneous exposures to radiation and elevated temperature stresses produced comparable tensile property degradation as the radiation-then-elevated temperature sequential exposures (see Table 4.6). Table 4.7 compares the behaviors of EPR-A and EPR-1483. The specimens of special EPR-1483 material exhibited neither an ordering effect nor a dependence on simultaneous versus sequential application. This material was separately tested for four aging conditions where the air circulation was not controlled well inside the oven. Although the sequence dependence like EPR-A still was not observed, the sequential thermal exposure followed by irradiation caused more degradation than its reverse. This sequential order yielded a similar degree of degradation that corresponded to simultaneous exposures (Table 4.8).

For EPR-D samples, a similar but much smaller ordering effect was observed. Tensile property degradation for the EPR-B, EPR-C, EPR-D and EPR-E specimens did not depend on the sequential ordering of radiation and temperature (Table 4.9). Simultaneous exposures produced more damage for the former two specimens than did sequential exposures for the same two stress levels. From these results and other studies on this material, the variables affecting this inconsistent behavior include the thickness and geometry of specimens, manufacturing techniques, material formulations, humidity levels, air-flow rates during exposures, oxygen replenishment during exposure, and the temperature.

Table 4.6 Relative Tensile Properties of EPR-A After Aging (Ref. 4.80)

Aging Method	Center of Chamber Dose Rate in EPR (krd/hr)	Center of Chamber Total Dose in EPR (Mrd)	Ultimate Tensile Strength T/T_o	Ultimate Tensile Elongation e/e_o
1. Unaged	0	0	1.00 ± .03 (8.7 ± 0.3 MPa)	1.00 ± .08 (360 ± 30%)
2. Simultaneous 30 day radiation and thermal exposures	60 ± 4	43 ± 3	~0.2*	< .03*
3. Sequential 28 day thermal then radiation exposures	65 ± 5	44 ± 3	0.85 ± .03	0.33 ± .04
4. Sequential 28 day radiation then thermal exposures	65 ± 5	44 ± 3	0.26 ± .07*	< .03*
5. Sequential 28 day thermal then 55 hour radiation exposures	850 ± 60	47 ± 3	0.99 ± .21	0.31 ± .04
6. Sequential 55 hour radiation then 28 day thermal exposures	850 ± 60	47 ± 3	0.21 ± .02	0.06 ± .03
7. Simultaneous 7 day radiation and thermal exposures	290 ± 20	49 ± 3	0.26 ± .02	0.03 ± .03

NOTES: (1) Errors reflect one standard deviation of three measurements.
(2) Insulation thickness is nominally 0.8 mm.
* Samples were extremely brittle and sometimes cracked in the pneumatic jaws used for the tensile measurements.

Table 4.7 Comparison of Aging Simulations for EPR-A and EPR-1483 (Ref. 4.80)

Aging Simulation Conditions	e/e_o	
	EPR-A(e_o=360%)	EPR-1483(e_o=340%)
Simultaneous R(43Mrad@60krad/hr)+T(30days@120°C)	<0.03	0.41
Simultaneous R(49Mrad@290krad/hr)+T(7days@139°C)	0.03	0.41
Sequential T(28days@120°C)-R(44Mrad@65krad/hr)	0.33	0.47
Sequential T(28days@120°C)-R(47Mrad@850krad/hr)	0.31	0.35
Sequential R(44Mrad@65krad/hr)-T(28days@120°C)	<0.03	0.41
Sequential R(47Mrad@850krad/hr)-T(28days@120°C)	0.06	0.32

Table 4.8 Degradation of EPR-1483 Without Well-Controlled Air Supply (Ref. 4.80)

Aging Simulation Conditions	e/e_o for EPR-1483
Radiation only in ambient (47Mrad@960krad/hr)	0.28
Sequential R(48Mrad@960krad/hr)-T(7days@136°C)	0.34
Sequential T(7days@136°C)-R(46Mrad@960krad/hr)	0.19
Simultaneous R(57Mrad@340krad/hr)+T(7days@136°C)	0.19

Table 4.9 Comparison of EPR Materials for Different Aging Simulations (Ref. 4.80)

Aging Simulation Conditions	e/e_o				
	EPR-A	EPR-B	EPR-C	EPR-D	EPR-E
Simultaneous R(44Mrad@260krad/hr*+ T(7days@139°C)	0.05	0.30	0.33	0.25	0.42
Sequential T(7days@139°C)- R(44Mrad@260krad/hr*)	0.36	0.45	0.43	0.33	0.29
Sequential R(44Mrad@260krad/hr*)- T(7days@139°C)	0.05	0.52	0.48	0.21	0.34

* For EPR-D and EPR-E, Radiation Dose was 55Mrad@330krad/hr.

Bustard and his colleagues (Ref. 4.81) presented the results from a joint U.S./French program investigating the influence of testing conditions on the polymers. Variables evaluated included aging sequence, irradiation temperature, oxygen presence during accident simulation, and simultaneous versus sequential accident and aging exposures. The U.S. samples included one radiation-crosslinked EPR-1, chemically crosslinked EPR-2, two XLPO-1&2, two Tefzel-1&2, one CSPE, and one CPE material. The French samples included one chemically crosslinked PE (PRC), two EPDM, one Hypalon, one VAMAC (acrylic PE), and EPR materials for cable insulation and jacket constructions. The test sequences were[4]:

For U.S. Samples:

A= R_{70}-120°C: A 16-day irradiation of ~25 Mrad at a dose rate of 65 krad/hr and 70°C followed by a 16-day thermal exposure at 120°C.
B= R_{27}-120°C: Same Sequence as A, but irradiation at 27°C.
C= 120°C-R_{70}: Reverse Sequence of A.
D= 120°C-R_{27}: Reverse Sequence of A, but irradiation at 27°C.
E= R_{120}: A 16-day simultaneous exposure to 120°C thermal and 65 krad/hr radiation.

For French Samples:

A= T-R_{70}: A 10-day thermal exposure followed by a 9- or 10-day irradiation at 115 krad/hr and 70°C.
B= R_{70}-T: Reverse Sequence of A.
C= T-R_{27}: Same Sequence as A, but irradiation at 27°C.
D= R_{27}-T: Reverse Sequence of A, but irradiation at 27°C.

Figures 4.52 to 4.58 illustrate the results from the U.S. studies. For CSPE, jacket degradation is more severe when the materials are exposed to radiation followed by thermal stress, and comparable when heated and irradiated simultaneously. There also is a noticeable temperature effect in these cases, in that aging at 120°C after irradiation at 70°C causes more degradation than after irradiation at 27°C. For CPE (Fig. 4.53), temperature differences do not have a significant effect, but the sequence of radiation and thermal aging condition causes more degradation when irradiation occurs first. As with CSPE, simultaneous radiation/thermal test conditions caused comparable loss in elongation-at-break. The ultimate tensile strength results for CPE (Figures 4.54 and 4.55) show more complex behavior. Figures 4.56 and 4.57 show elongation results for the two differently crosslinked EPR materials. For radiation-crosslinked EPR-1 (Figure 4.56), irradiation reduces both the ultimate tensile elongation and strength. Degradation is worse for radiation at lower temperatures, while the reverse is true for chemically crosslinked EPR-2 (Figure 4.57). Net degradation after 32 days of aging for both EPR-2 and XLPO-1 was the same for either aging sequence (e.g., A vs. C or B vs. C), as shown in Figures 4.57 and 4.58. Table 4.10 summarizes these results for two jacket and four insulation materials. Note the elongation data presented in this table are taken from the above figures, and therefore, represent approximate values.

Table 4.10 Comparison of Elongation Data for US Cable Materials (Ref. 4.81)

Aging Simulation Conditions		e/e_o					
		CSPE	**CPE**	**EPR-1**	**EPR-2**	**XLPO-1**	**XLPO-2**
	e_o=	**383%**	**357%**	**419%**	**223%**	**389%**	**336%**
A: Seq. R_{70} - T_{120}		0.05	0.15	0.7	0.4	0.7	0.75
B: Seq. R_{27} - T_{120}		0.25	0.15	0.6	0.5	0.75	0.85
C: Seq. T_{120} - R_{70}		0.45	0.28	0.65	0.5	0.7	0.7
D: Seq. T_{120} - R_{27}		0.45	0.28	0.55	0.4	0.75	0.75
E: Simult. R_{120}+T_{120}		0.15	0.25	0.75	0.35	0.6	0.65

Note: Methods of aging simulation are explained in the text above.

[4] X-Y indicates a sequential procedure with X followed by Y. X+Y indicates simultaneous procedure with X and Y together.

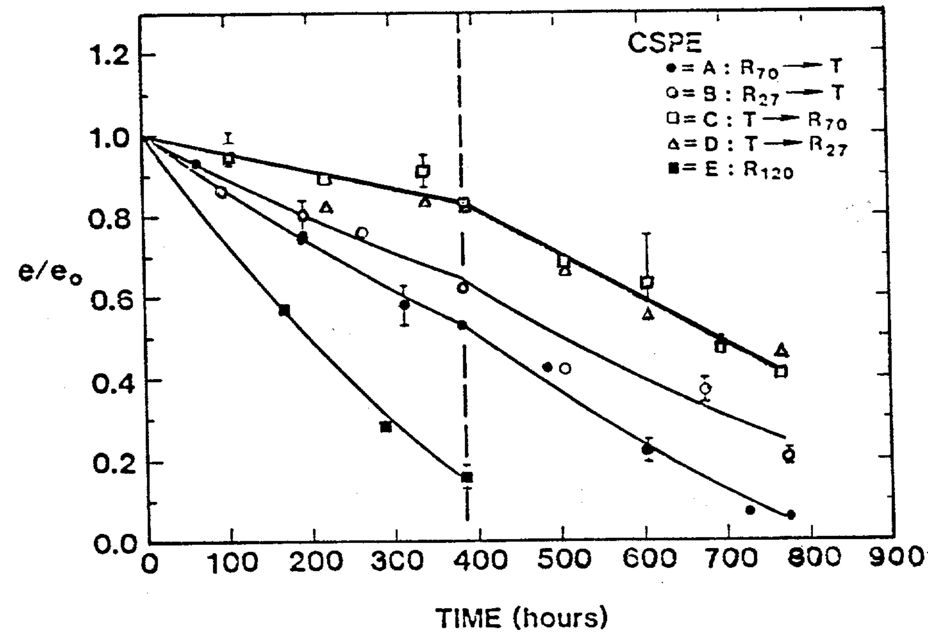


Figure 4.52 Tensile elongation of CSPE in various environments (Ref. 4.81)

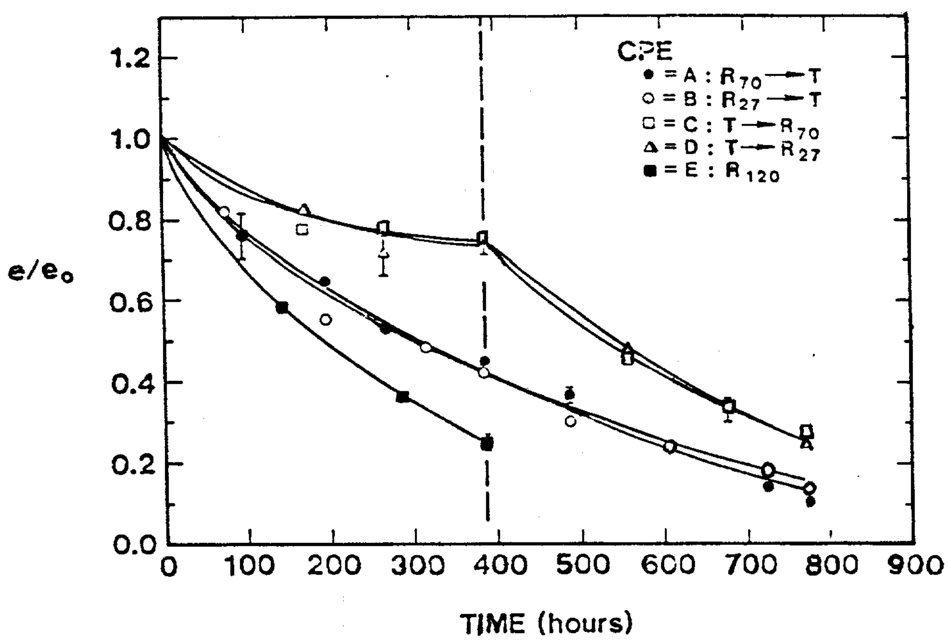


Figure 4.53 Tensile elongation of CPE in various environments (Ref. 4.81)

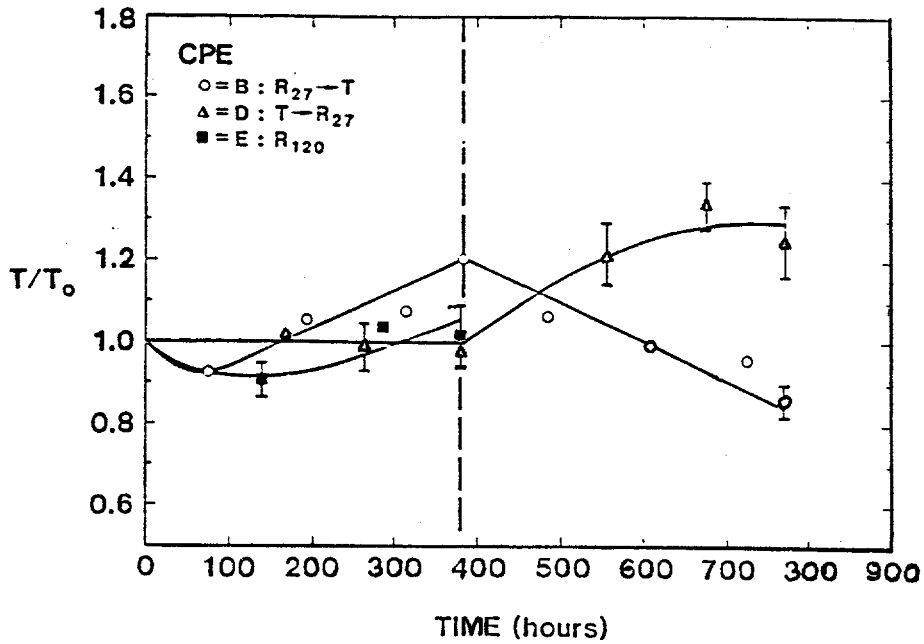


Figure 4.54 Tensile strength of CPE in various environments (Ref. 4.81)

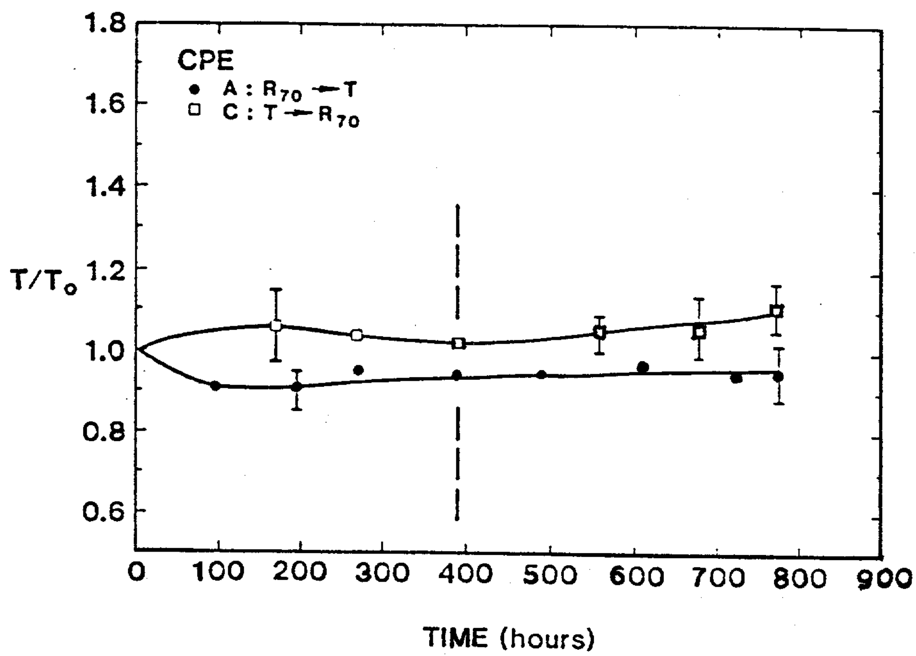


Figure 4.55 Tensile strength of CPE in various environments (Ref. 4.81)

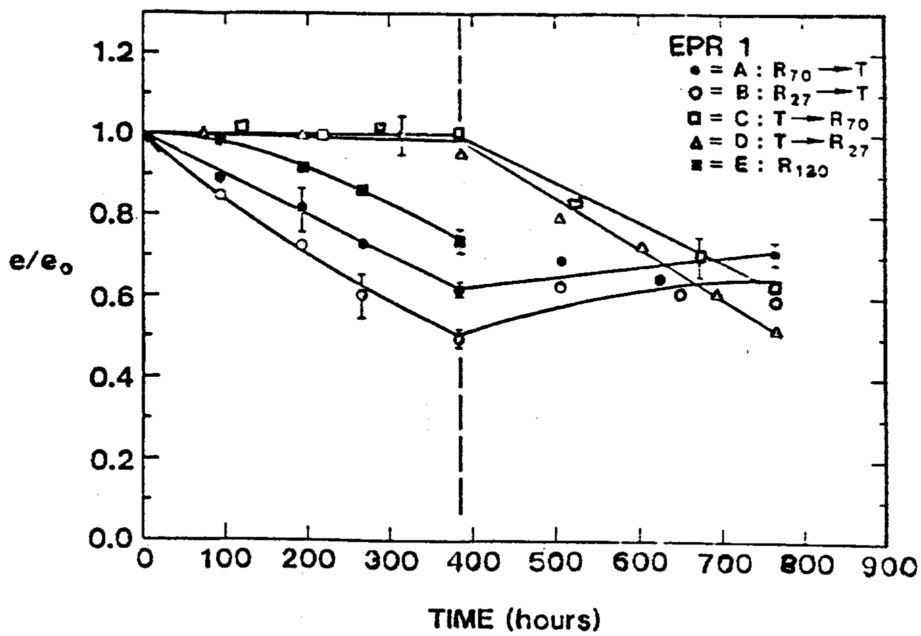


Figure 4.56 Tensile elongation of EPR-1 in various environments (Ref. 4.81)

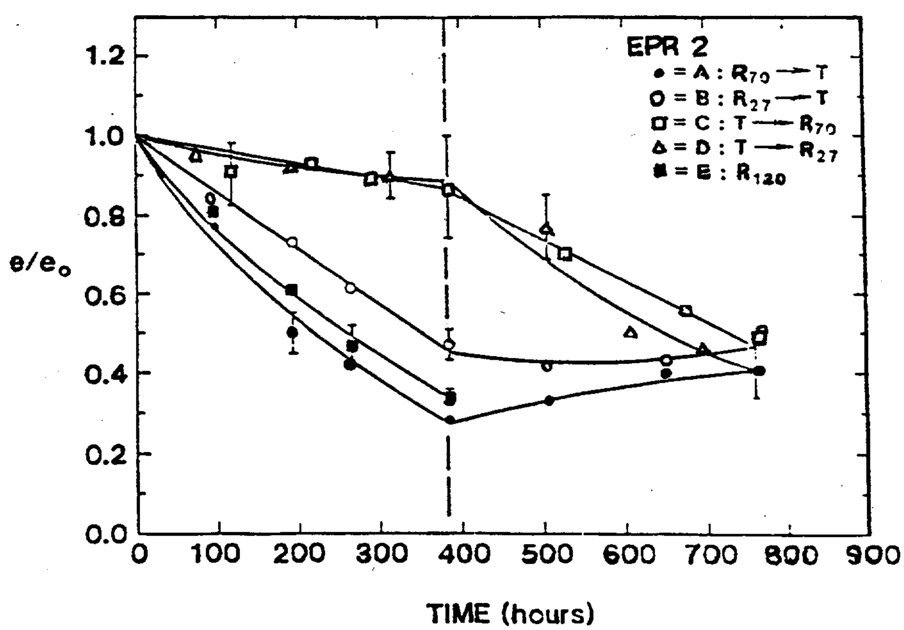


Figure 4.57 Tensile elongation of EPR-2 in various environments (Ref. 4.81)

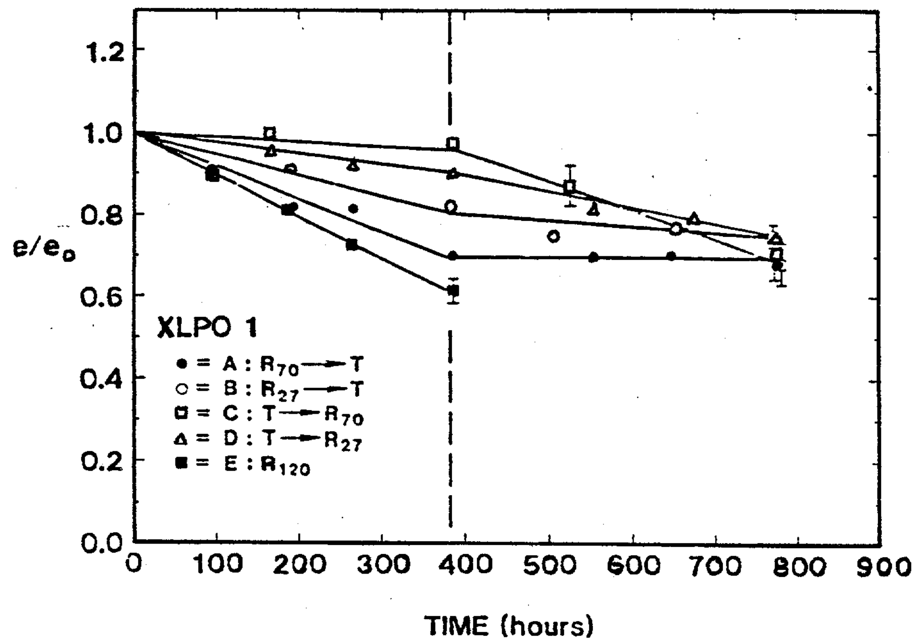


Figure 4.58 Tensile elongation of XLPO-1 in various environments (Ref. 4.81)

Although the report (Ref. 4.81) presents the French results, their details are not described here. However, the conclusions from both studies are discussed. Reference 4.82 presents some of these conclusions from the French studies. Irradiation followed by thermal exposure sequence was most severe on the elongation of CSPE, CPE, and EPDM and PRC only (French samples). In contrast, Tefzel 2 was more degraded by thermal stress followed by 70°C irradiation. LDPE and PVC materials were degraded more when radiation was followed by thermal. Except for the bend test on Tefzel, both for the tensile properties for CSPE, and tensile strength data for EPR-2 and EPDM (French) materials, the choice of irradiation temperature was secondary to the choice of aging sequence. For XLPO-1 and other compression materials (e.g., seal and gasket materials), tensile properties at completion of aging were only slightly affected by both the irradiation temperature and the order of the sequential exposures. Since studies discussed so far in this section were mainly concerned with empirical comparisons of aging procedures, the researchers made little attempt to probe the underlying mechanisms.

An Italian study on an EPR-like material with flame-retardant gave some interesting results (Ref. 4.83). The sequential aging tests yielded a more severe degradation when thermal aging followed radiation:

Doses in MGy (@2.8 kGy/hr)	0.5	1.0	2.0
Elongation Thermal-Radiation (%)	90	34	11
Elongation Radiation-Thermal (%)	43	8	3

The effect of copper wire inside the cable also was studied for two groups of samples: one group was thermally aged followed by irradiation, and the second group was irradiated to the same dose level. No significant differences were noted. The study also investigated radiation-induced free radicals in different environments using electron spin resonance (ESR) technique. It was demonstrated that below the total dose of 10 kGy oxidative degradation was insignificant, and beyond this, degradation increased as a function of the absorbed dose.

Table 4.11 Cable Degradation under Simultaneous Radiation and Thermal Exposures (Refs. 4.84-4.86)

Manufacturers/ Materials	Original Elongation e_o (%)	Mrad at Zero Elongation (e/e_o=0)*	Elongation e/e_o at 50 Mrad Exposure (%)
Brand Rex XLPE	320	130	15
Rockbestos Firewall III, XLPE	240	130	28
Samuel Moore Dekoran Polyset XLPO	350	10% @ 140	38
Raychem Flamtrol, XLPE	520	50	0
Anaconda, Flame-Guard FR-EP	230	5% @ 140	30
BIW Bostrad 7E, EPR	410	40	0
Samuel Moore Dek. Dekorad EPDM	340	5% @ 110	5
Okonite Okolon, EPR	300	30	0
Rockbestos Firewall, SR	450	40	0
Kerite FR Insulation	290	50	0
Brand Rex CSPE	330	25	0
Rockbestos Neoprene	210	13	0
Samuel Moore CSPE	360	40	0
Anaconda CPE	290	30	0
BIW CSPE	240	30	0
Kerite FR Jacket	300	40	0

* For several insulations, the data on Mrad at zero elongation was not available.

Elongation measurements on cables recently tested at SNL after 3, 6, and 9 months of simultaneous radiation and thermal aging showed significant degradation in both jacket and insulation materials (Refs. 4.84-4.86). This program included a large selection of cable materials used in nuclear power plants. The samples were subjected to an aging temperature of 95°C-100°C and a radiation dose rate of 9 krad/hr. Samples in the three-month chamber were exposed to a total dose of 20 Mrad simulating 20 years of service life. Similarly, the six-month simulation was made for a total dose of 40 Mrad simulating 40 years, and the nine-month simulation for a total dose of 60 Mrad simulating 60 years. Table 4.11 gives the results. The numbers are taken from the plots given in Appendix E of each report, and therefore are approximate values. It is evident that under the simulation conditions discussed above, all jacket materials (last 6 items in Table 4.11) lost all strength before reaching 40 Mrad exposure. With the exception of XLPE by Brand Rex, Rockbestos, and Samuel Moore, and EPR by Anaconda and Samuel Moore, most other insulation materials behaved similar to jacket materials by the time they were exposed to a total dose of 50 Mrad. On the other hand, by the time they were exposed to a total dose of 50 Mrad, all insulation materials had less than 50% relative elongation.

From the findings on thermal and radiation aging of commercial-grade cables, the following observations are made:

(1) For most materials, simultaneous simulation causes the severest degradation compared to any sequential methods. However, the next best simulation may be radiation followed by thermal aging. Which method simulates the actual service conditions best still remains to be determined. Moreover, the aging effects by simultaneous simulation using elevated environmental conditions may not necessarily reflect degradation under the actual service conditions which is at much lower stress levels.

(2) In general, the lower the radiation dose rate or higher the oven temperature, degradation of most cable materials increases. However, at too high a temperature or a dose rate, degradation across the thickness can be non-homogeneous indicating multiple degradation mechanisms. The threshold values at which the transition from homogeneous to heterogeneous degradation occurs for different cable materials are not well known. Also, one of the EPR materials (EPR-1, Ref. 4.81) exhibited more severe degradation during irradiation at 27°C than at 70°C.

(3) Normal plant conditions inside a containment are assumed to be much lower than the recommended 50 Mrad radiation dose, except hot spot locations. This suggests that 50 Mrad simulation may cover both normal and hot spot conditions. If this is the case, then most cables in hot spot area will degrade significantly by the end of their qualified life.

(4) Moreover, since the end conditions using any simulation method exhibit close to zero elongation after being exposed to 50-100 Mrad radiation, the choice of these aging simulation methods becomes a non-issue.

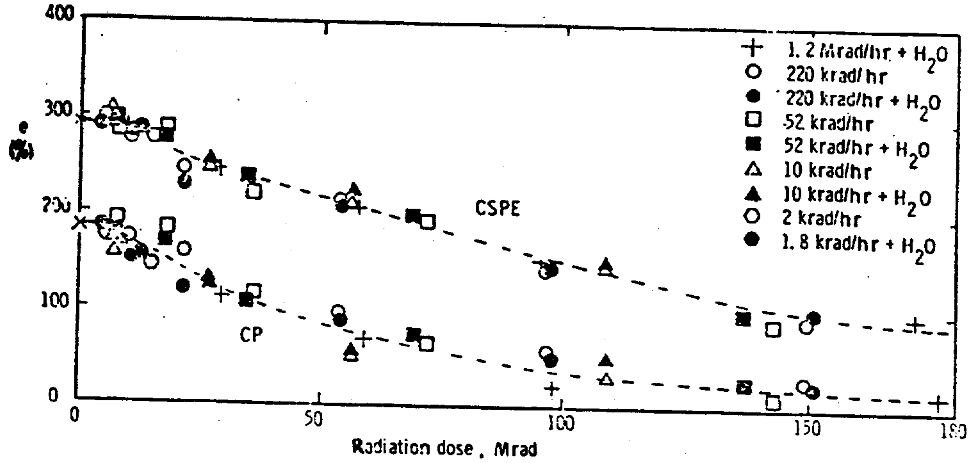
4.3.4 Effect of Other Conditions During Aging Simulations

Cables in nuclear power plants are not only exposed to thermal and radiation environments during their normal design life, but also to mechanical-stress loading due to overhanging, stretching, or bending, humid atmospheres (from nearby steam or water leaks), the presence of oxygen, and other deleterious conditions. Degradation in the cable's insulation and jacket materials containing chemical additives (e.g., antioxidants, antirad, fire-retardants) designed to enhance thermal and radiation stability or to enhance other cable properties are discussed, and reviews of special kinds of polymer materials, such as polyimides, are presented.

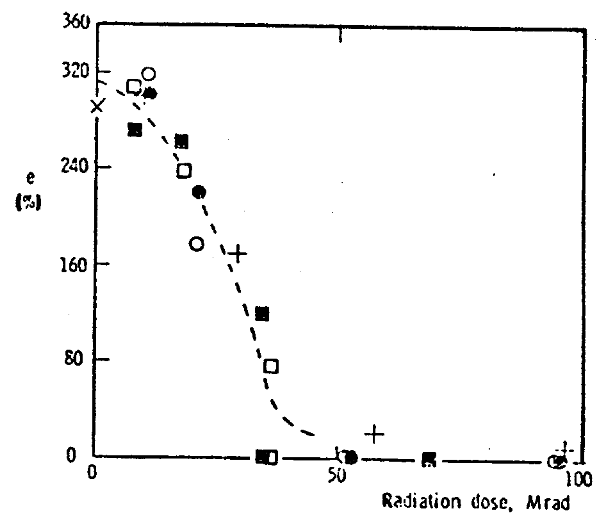
4.3.4.1 Effects of humidity

Gillen and Salazar (Ref. 4.87) described the effects of humidity on aging of several cable materials including XLPO, EPR, Tefzel, CSPE (both insulation and jacket), and chloroprene jacket materials from two manufacturers. In addition, a silicone insulation material was tested. The materials were aged at 5 dose rates ranging from 2 krad/hr to 1.2 Mrad/hr. The two aging chambers used were identical except that dry air (0% relative humidity) was circulated through one, and humid air (~70% relative humidity) through the other. Figures 4.59 and 4.60 summarize the radiations at room temperature on these materials. The authors concluded that humidity is not a significant environmental stress. Except for EPR, and to some extent for the Tefzel and XLPE materials, the dose rate effect was not significant.

Since there were no effects of humidity on most cable materials at room temperature for various dose rates, these researchers never considered it necessary to understand this effect during accelerated thermal aging.



(A)



(B)

Figure 4.59 Ultimate elongation; radiation aging under dry air and 70% humidity (A) for CSPE & CP; (B) for Tefzel (Ref. 4.87)

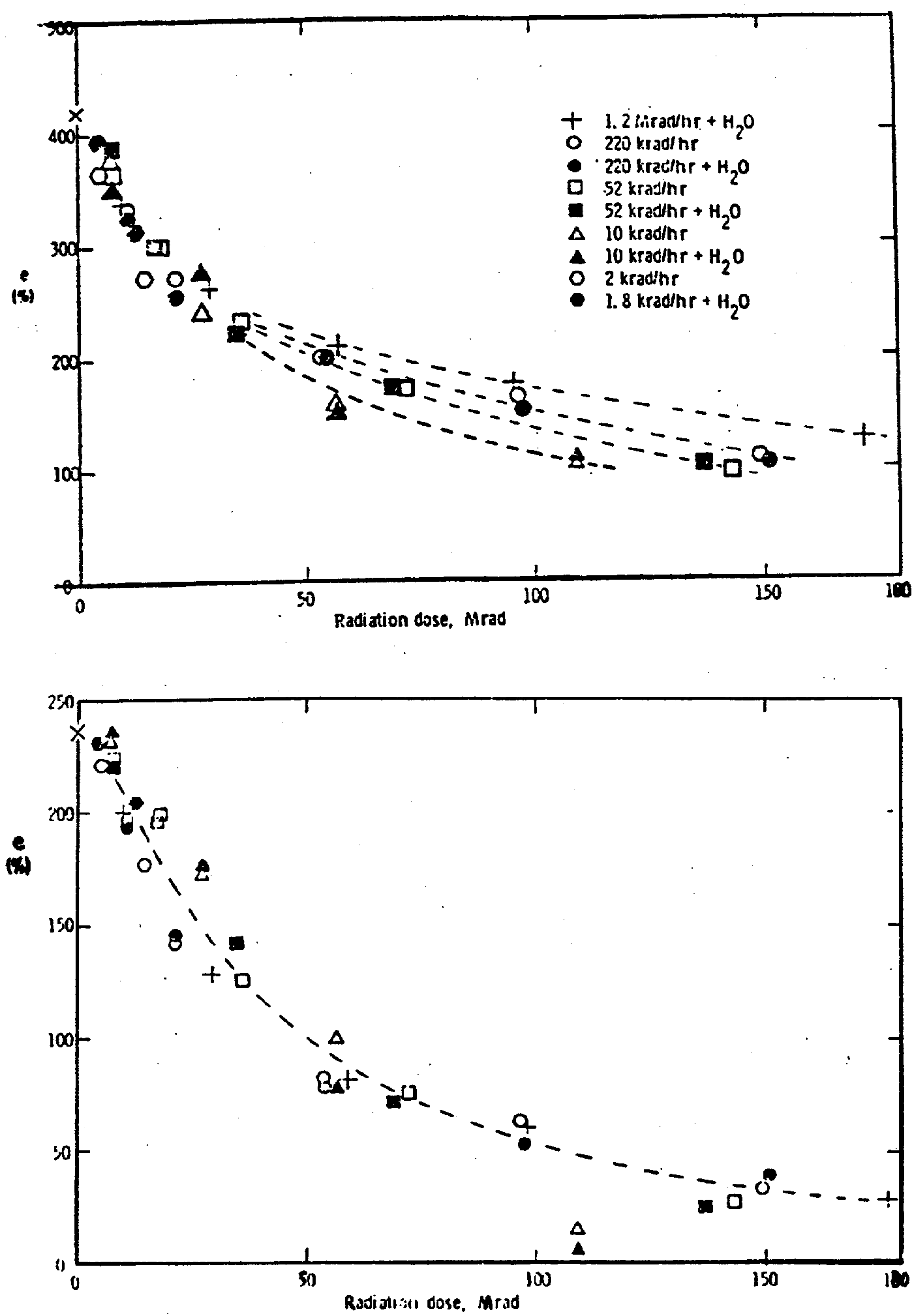


Figure 4.60 Ultimate elongation; radiation aging under dry air and 70% humidity upper: EPR; lower: XLPE (Ref. 4.87)

The only insulation material susceptible to hydrolysis under hot and moist conditions is a polyimide film - known as "Kapton"; this is discussed in detail later in Section 4.4.

This study based its conclusions on a test using relative humidity up to 70% at room temperature, which may be too limited to support generalized conclusions. Condensation is known to be a significant factor in many instances, specifically at cable interfaces such as terminal blocks, penetrations, and splices.

A recent EPRI study by Toman, Morris, and Holzman on both low- and medium-voltage cables is described in Reference 4.88. Unlike medium-voltage cables where water treeing was found to be one of the degradation mechanisms, there was little or no operating experience data on low-voltage cables indicating moisture-related degradation or failure. The report presents only two types of events that were presumed to be moisture-related. One relates to degradation of old, natural rubber cables experiencing prolonged immersion in water-filled conduits and low insulation-resistance readings prompted the investigation. The second relates to degraded noise-immunity for thermocouple and closed-circuit television circuits experiencing periodic immersion in water. In this case, the jacket was degraded while the insulation was unaffected.

4.3.4.2 Effects of the presence of oxygen

The effects of oxygen on aging fall into two broad classifications - physical effects and chemical effects. Physical effects are caused by oxygen diffusion-limited degradation, a mechanism which has been observed in various air-aging environments including heat and radiation. The oxidation processes in a material use up dissolved oxygen faster than it can be replenished from the surrounding atmosphere which leads to a more heavily oxidized material near the sample's surfaces, and reduced or depleted oxidation in the sample's interior. Accelerated aging often results in heterogeneously oxidized samples, whereas the long times appropriate to real-time aging allow sufficient time for diffusion to occur, and therefore, lead to homogeneous oxidation. Chemical effects refer to the multitude of new chemical reactions involving oxygen and oxidation products which occur when oxygen is present in the material. Several studies involving the effects of oxygen on the aging degradation of polymers in various simulations were discussed earlier in this Section.

The work of JAERI using high-pressure oxygen conditions for aging studies on polymers is of particular interest. Papers by Seguchi, et al. (Refs. 4.89 and 4.90) proposed that oxygen-diffusion effects can be eliminated under higher dose-rate conditions for a given material and material geometry, thereby, cutting the time necessary to simulate radiation aging. Figure 4.61 (Ref. 4.34) illustrates JAERI results for an EPR material irradiated under different oxygen pressures. Elongation properties are similar for 1 Mrad/hr exposures with ambient air or a vacuum. Degradation is more substantial for a 5 krad/hr exposure with ambient air pressures. By increasing the oxygen pressure to 5 atmospheres, 0.1 and 0.5 Mrad/hr exposures also produced more severe degradation, supporting the conclusion that increased oxygen pressure eliminates oxidation dose-rate effects in accelerated aging simulations.

4.3.4.3 Effects of fire-retardant additives

Salazar, Bouchard, and Furgal (Ref. 4.91) presented the results on the flammability characteristics of EPR and CSPE containing fire-retardant additives, aged in different thermal and radiation environments. The fire-retarding agents did not reduce rubber flammability when exposed to a full-scale fire but in some cases, contributed to it. In addition, for full-scale fires, the energy required to ignite CSPE was lower than that required by EPR, a complete reversal of that observed in small-scale "match" tests. The effects of aging on tensile elongation indicated that fire-retardant additives have a negligible influence on the degradation of these materials.

Polymers containing halocarbons or halocarbon-antimony-oxide-based fire retardants can lose appreciable amounts of both halogen and antimony through volatilization during thermal aging. This occurs when halogen is contained in a low molecular weight additive in the formulation (as in EPR), or when halogen is a part of the base polymer resin (as with Hypalon). Fire-retardant loss appears to strongly depend upon the molecular structure of the halocarbon in terms of its ability to undergo intra-molecular loss of HCL. The HCL generated can react readily with Sb_2O_3 to produce volatile $SbCl_3$. From Reference 4.92, Figures 4.62 and 4.63 show data for EPR-V samples aged at different temperatures under thermal conditions or simultaneous thermal and radiation at 5 krad/hr. Comparisons show that radiation did not appreciably affect the rate of fire-retardant loss.

Oxygen-index flammability tests indicated modest increases in the flammability of EPR with fire-retardant loss on aging. Hypalon formulations became markedly less flammable on aging; this behavior appeared to be associated with the loss of flammable, volatile additives from the polymer.

Using the loss-rate data on the EPR formulation which lost fire retardants most rapidly, Arrhenius extrapolation indicated that the loss should be important only at very significantly elevated temperatures; for example, a loss of 25% of the initial antimony content would require approx. 120 years at 60°C, and approx. 3,000 years at 40°C. The aging data for Hypalon was not amenable to an Arrhenius treatment, though fire-retardant loss rates under the accelerated conditions employed in this study were about the same as those of EPR. Thus, the loss of antimony-halocarbon fire retardants due to aging under the ambient conditions of nuclear power plants should not be significant.

4.3.4.4 Effects of thermal aging on flammability

Both Rockbestos FIREWALL III and BIW BOSTRAD 7E cables were tested to study the effect of thermal aging on their flammability when exposed to external fire sources (Refs. 4.93 and 4.94). Four large-scale flammability tests were performed on unaged and accelerated thermally-aged samples and, in all cases, the fire consumed virtually all of the combustible jacket and insulation materials. Four parameters measured for fire intensity in this assessment included peak fire heat release rate, peak rate of fire growth, total heat released, and near fire temperatures.

Based on these results, material flammability did not increase for the two cable products, and in fact, was reduced as a result of material aging. The reason is that the aging process tends to drive off some of the more volatile constituents existing in the polymers during manufacturing. Since these volatile compounds are released first during a fire and support the combustion process, the flammability of the aged materials is correspondingly reduced. The authors expect similar behavior from other cable products typically used in nuclear power plants.

4.3.4.5 Effects of flame-retardant coatings on cable aging

Flame-retardant coating and fire barriers are used in nuclear power plants to prevent fire propagation from a high concentration of electrical and telecommunication cables which can be a source of fire under severe fire conditions. Fire-protective coatings can be one of the most economical means of preventing flame spreading along a group of, or single cables. The coatings are applied in the field along the entire cable run, or only at critical locations. The adequacy of several protective coatings was tested and their relative effectiveness was demonstrated in two studies (Refs. 4.95 and 4.96).

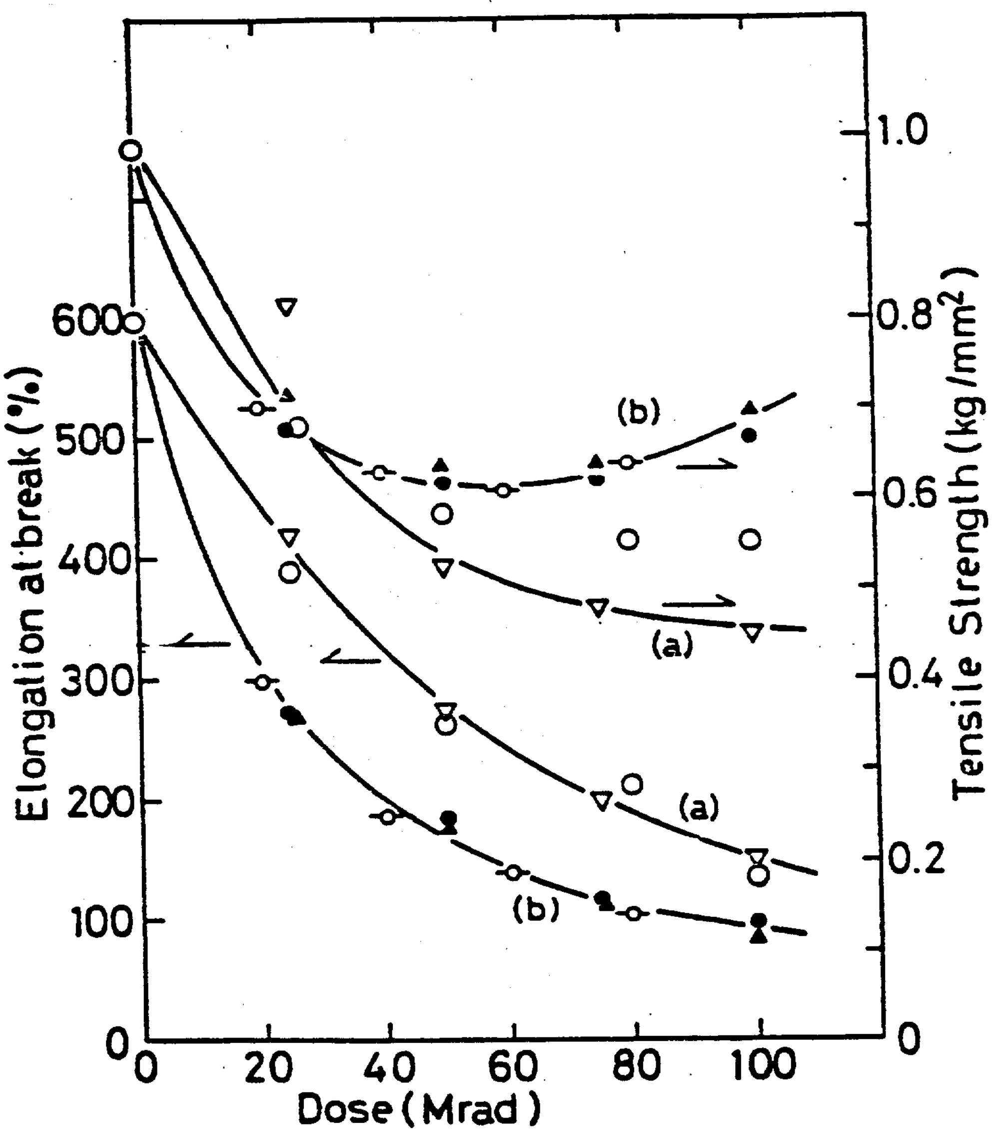
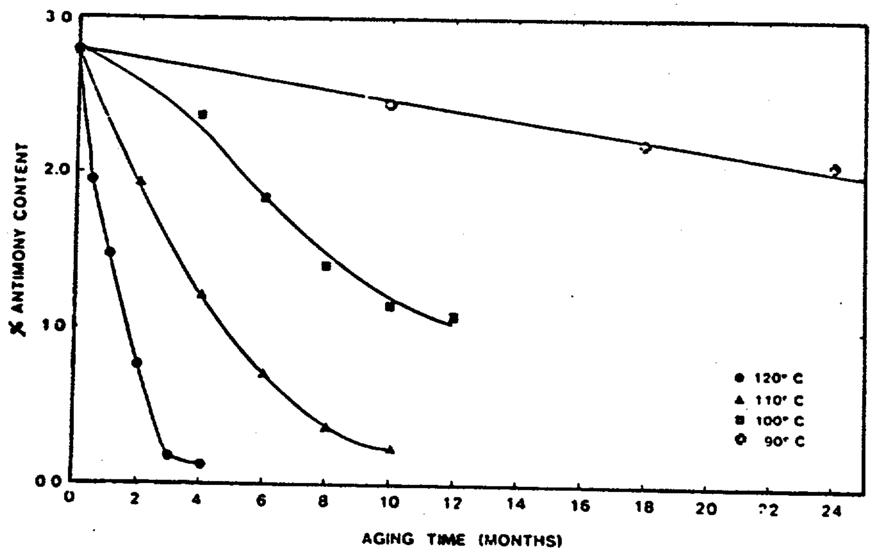


Figure 4.61 Tensile properties for EPR irradiated at various conditions at room temperature. Open triangle: In vacuum with 1 Mrad/hr; open circle: In air with 1 Mrad/hr; open circle with bar: In air with 5 krad/hr; solid circle: In oxygen 5 atm with 0.5 Mrad/hr; solid triangle: In oxygen 5 atm with 0.1 Mrad/hr. (Ref. 4.34)



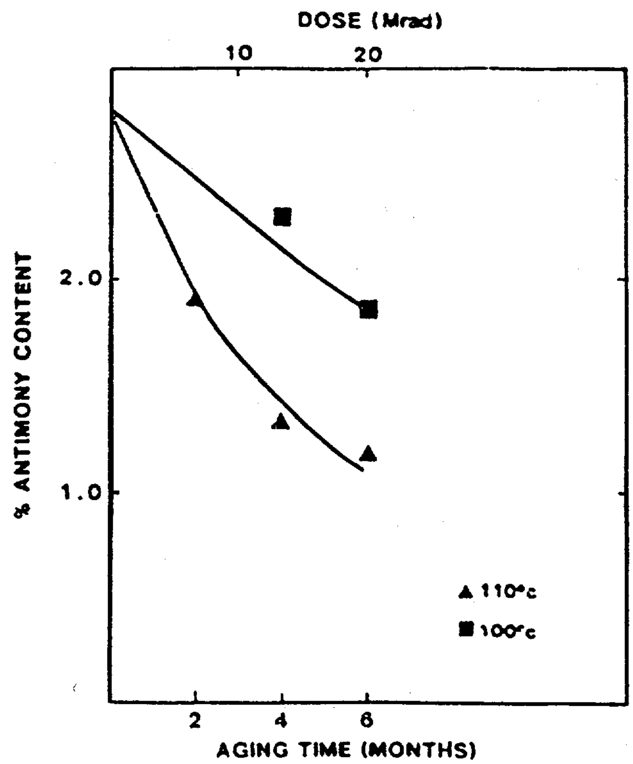
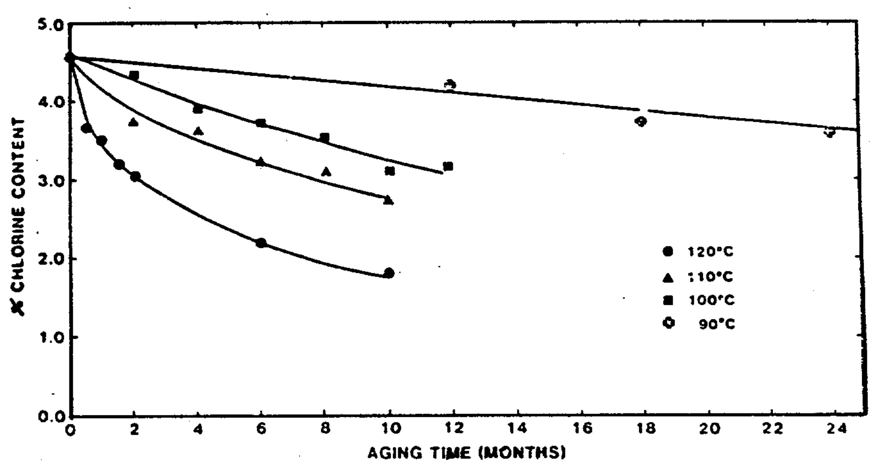


Figure 4.62 Antimony content (weight percent) on fire-retarded EPR-V; Upper: thermal aging only; lower: thermal plus radiation at 5 krad/hr (Ref. 4.92)



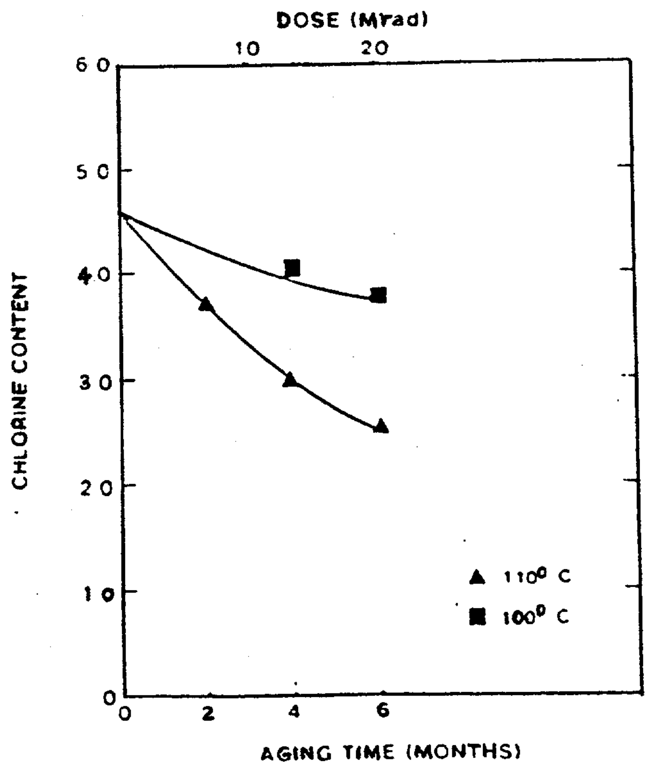


Figure 4.63 Chlorine content (weight percent) on fire-retarded EPR-V; Upper: thermal aging only; lower: thermal plus radiation at 5 krad/hr (Ref. 4.92)

Although no specific study relating to aging effects on cable polymers due to the presence of these coatings was found, the dissipation of internal heat generated in power cables can be affected, thus exposing them to temperatures in excess of design conditions. Also, these coatings can absorb moisture, which could keep cables wet and accelerate degradation. These factors often are factored in the original formulation and design of cables and hence discredited for their impacts on life assessments.

4.3.4.6 Effects of antioxidants additives

Reynolds, Ray, and Wlodkowski (Ref. 4.97) document a study performed at the University of Virginia, the objective of which was to determine if particular antioxidants, originally added by the manufacturers for thermal stability, could be effective for stabilization against radiation aging, and combined thermal and radiation aging. Samples were irradiated to 17.5, 50, and 100 Mrad. Some samples were irradiated to 200 Mrad, but the elongations were too low (<0.03) to be measured accurately.

Figure 4.64 shows the results for several antioxidants used in making EPDM and XLPE cable materials; all conferred significant stability against radiation aging. Thus, antioxidants which are effective for thermal stability also are effective for radiation stability. No particular antioxidant was especially superior to the others.

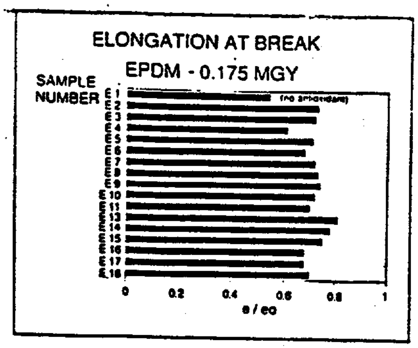
To the extent measured in this study, degradation from radiation aging and thermal aging could be superposed. Whether aging is synergistic, as determined by sequencing of aging versus simultaneous aging, was not determined.

4.3.4.7 Effects of mechanical stresses

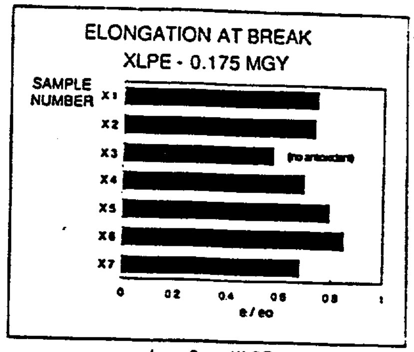
Electric cables potentially are subject to two failure mechanisms caused by mechanical stress (Ref. 4.98). First, if the cable is stretched by an applied force (or by its weight) over an edge with small curvature, the metal wires will gradually creep through the soft polymeric insulation resulting in metallic contact between cable wires or a wire and the cable support, short-circuiting the cable (creep short-circuit). Second, the polymeric materials embrittled by aging may crack under mechanical stress; during a subsequent accident (steam and spray), strong leakage currents or short-circuits may occur. Reference 4.99 summarizes the short-term and long-term research results on EPR and Hypalon cable materials.

The main parameter for creep effects is the average stress at the closest proximity between the cable wire and its (metallic) support. This stress is determined essentially by the wire's radius, the support's curvature, and the weight of the overhanging cable part. With increasing time two phenomena decrease the likelihood of creep shortout. First, the strands will position themselves so that the effective support areas increase. Second, plastic bending of the wire further increases the effective support area. With this, the effective stress decreases and creep slows down.

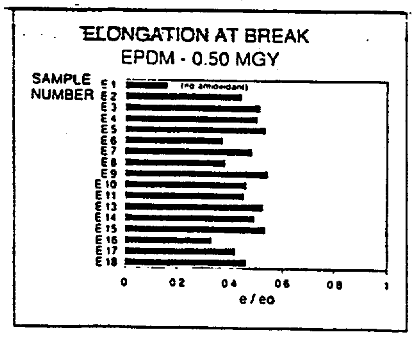
For realistic geometries, creep short-circuit is observed only at very high temperatures ($>175°C$) in combination with high stress (>500 psi) where failure will occur quickly within hours or days. Temperature and radiation hardening slow down creeping with increasing exposure time, and the mitigating phenomena described above come into play. The critical stress (~500 psi) causes different lengths of critical overhang for different cable gauge sizes; a scaling equation presented in the report can be used to estimate the critical stress.



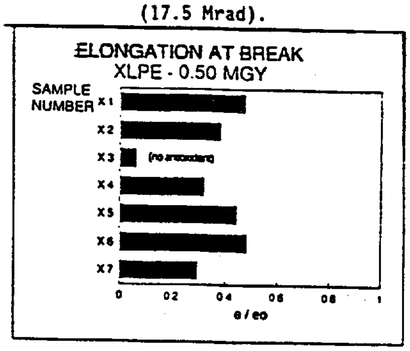
e/e_0 for EPDM at 0.175 MGy (17.5 Mrad).



e/e_0 for XLPE at 0.175 MGy (17.5 Mrad).



e/e_0 for EPDM at 0.50 MGy (50 Mrad).



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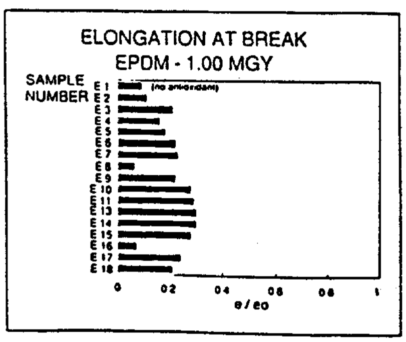
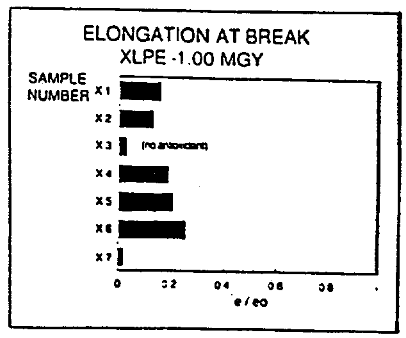


e/e_0 for EPDM at 1.00 MGy (100 Mrad).



e/e_0 for XLPE at 1.00 MGy (100 Mrad).

Figure 4.64 Elongation data for EPDM & XLPE for different antioxidants (Ref.4.97) Copyright © 1991. Electric Power Research Institute. EPRI NP-7140. *Effect of Antioxidants on Aging of Nuclear Plant Cable Insulation.* Reprinted with Permission.

Crack failure differs from the above cases because it requires the presence of a contaminating liquid or condensate. The two most important situations investigated were cracking of undisturbed cables in (long) conduits, and cracking due to bending during maintenance. In both cases, the appearance of cracks correlates well with the polymers reaching a certain critical strain-to-break factor (e.g., $e/e_0 \sim 0.02$). For example, "through" cracks, i.e., cracks extending all the way to the conductor will, under no outside stress, appear in 5 days at 200°C, and in about a year at 125°C. When bending stresses are applied after cooling, the corresponding times are only half as large. If the temperature does not exceed 100°C, through cracks under no outside stress will not appear in 5 years. However, even a few days exposure to very high temperatures (200°C) will produce unacceptable cracking.

Briefly, creep short-circuit is mitigated by radiation that enhances embrittlement[5]; for cracking, strain-to-break curves measured under radiation must be used to validate the prediction model. However, the essential fact is that situations of concern occur only at high environmental stress, i.e., high temperature and bending. During the life of a reactor, such situations are rare and brief, much shorter than the reported aging and measurement times.

4.4 Aging of Polyimide Insulated Cables

Toman and Lindsay (Ref. 4.100) evaluated the appropriateness of using polyimide film ("Kapton") insulated wire in nuclear power plants, especially for accident conditions. The predominant use of this insulation is component leads, mostly in electrical penetration assemblies, electrical component seal assemblies, and instrument and solenoid leads. This insulation has a wrapped-film structure with "Teflon" adhesive between the layers. Kapton insulations are excellent for dry, high temperature applications. Kapton film is flame resistant, radiation resistant, and highly chemical resistant, except to highly caustic liquids.

When exposed to strains greater than 5-6% and elevated temperature in the presence of water, steam, or caustic spray, Kapton will degrade significantly. Under hot and moist conditions, Kapton is susceptible to hydrolysis (Ref. 4.101). Deterioration of the Kapton film may cause cracking, resulting in shorting or low insulation resistance in the presence of water or condensation.

Teflon has well-known lower-than-average resistance to irradiation, (losing half of its original elongation at break when irradiated to 0.35 Mrad). Failure of the adhesive may allow the film layers to unravel and separate. If full unraveling does not occur (i.e., the film stays in place mechanically due to spiral wraps), shorting or low insulation may still occur if the insulation wire is wet.

Based on operating experience, the failure mechanism of arc tracking followed by propagating electrical arcing (which was found in naval aircrafts) is not a significant concern for nuclear power plants. The required conditions would be rare, and circuit fusing would prevent sustained arcing. Ref. 4.100 lists several precautions which can alleviate the degradation of Kapton in nuclear power plants; namely, the insulated wire should not remain flexed beyond the minimum bend radius, the insulation should be handled carefully to avoid inflicting inadvertent damage, after irradiation beyond tens of Mrads the insulation should not be exposed to direct spray in accidents, and the insulation should be protected from wetting caused by flooding, steam, and chemical spray.

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[5] Embrittlement, however, increases the probability of cable failure under accident conditions.

Problems related to Kapton-insulated wire are attributed to mechanical nicking or gouging, chemical attack by strong alkaline solution, and hydrolytic degradation under high temperature, moisture and mechanical strain (Ref. 4.102). This NRC Information Notice has outlined the conditions that may breach the integrity of Kapton insulation in a nuclear power plant. The notice also warns against excessively handling these wires during maintenance. Common application of this product includes electrical penetration assemblies and cable entrance seals. The Notice discusses that the performance of numerous Kapton-insulated wires degraded considerably after only one year in a quite mild environment. Mechanical damage combined with exposure to condensation of moist salty air produced unacceptable degradation of its electrical insulation properties. Although Kapton-insulated pigtails have successfully passed EQ tests, the test specimens are believed to have been free from nicks in the insulation; further mishandling of test samples of pigtails is often considered as a test anomaly.

Even though SNL took special efforts to avoid mechanical damage of Kapton, this material had the highest failure rate of all the cables tested (Ref. 4.86). It is suggested that additional research on Kapton, such as inspection of naturally aged cables, be performed to assess the adequacy of Ref. 4.100 and follow-up of results in Ref. 4.86.

4.5 Life-Prediction Method Using Accelerated Aging Test Data

The commonest methods for estimating the embrittlement of a cable are to use the Arrhenius equation for predicting its performance in a thermal environment, and the equal dose - equal damage assumption for predicting its performance in a radiation environment. Thermal aging studies often generate isothermal, time-dependent degradation data at several temperatures. Time-temperature superposition assumes that raising the temperature by a certain amount increases the degradation rate by a constant multiplicative factor (a_T, using the Arrhenius relationship) which is independent of the extent of degradation. When the data is shifted to a single reference temperature, excellent time-temperature superposition over a large range of test temperatures demonstrates the validity of the above assumptions. Sometimes, it is found that the complicated chemistry underlying the causes of degradation may result in a non-linear Arrhenius temperature-dependence due to competition between processes with differing activation energies. Likewise, linear Arrhenius behavior should not be expected when a physical transition of the polymer, such as the glass-transition or crystalline-melting temperature, occurs within the temperature range of the accelerated experiments or the temperature range of the extrapolation. Since most accelerated aging tests are conducted at a temperature beyond melting transition condition for <u>some</u> semi-crystalline polymer, no clear solution to this extrapolation issue is yet available.

An earlier Japanese study developed the thermo-equivalent dose rate for the chloroprene rubber (Ref. 4.103). Since both heat and radiation can cause chain scission in polymers, the rate of degradation (or chain scission) at any dose rate may correspond to the scisson rate at a certain temperature. Chemical stress relaxation which corresponds to polymer chain scission of chloroprene rubber was measured under the combined environment of heat and radiation. Raising the temperature 10°C from the reference condition corresponded to an increased dose rate of 45 krad/hr. This method of estimating the equivalent damage is valid even though there is a synergistic relationship between heat and radiation on the polymer chain scission.

Several other studies predicted polymer degradation based on changes in other chemical process parameters with the change in environmental parameters (Refs. 4.104-4.108). A non-empirical method was used to predict the life of PE by measuring the thickness of the oxidized zone versus carbonyl index (Ref. 4.104). The paper identified two kinetic regimes; a homogeneous zone corresponding to high dose rates, where elongation-at-break is governed by the macromolecular structure (i.e., chain length or crosslinking density) and a heterogeneous zone corresponding to low dose rates, where cracks are initiated and propagated. For the PE material tested, the transition dose rate for a 10 Mrad radiation was approximately 250 krad/h. These results should not be compared with those reported earlier on diffusion-limited oxidation effects, which is a physical process.

A fundamental relation is developed for polyimide-insulated wire based on chemical-thermodynamic multifactor stress aging (Ref. 4.105). The stresses are water, temperature, and mechanical strain. The relations developed are very complex and were verified with extensive test data and empirical field experience. Another study by Campbell and Bruning (Ref. 4.106), describes a geometrical approach to determine the combined stress endurance limits for an XLPE insulation subjected to both thermal and electrical stress. This method uses experimental data from thermal alone, electrical stress alone, and combined thermal and electrical tests. Geometric models then are developed, based on these results.

Life estimation of EPR was studied in Japan by monitoring the amount of gas evolution and oxygen consumption during radiation and thermal aging (Ref. 4.107); parameters increased with radiation and thermal aging. A relationship was developed between these two parameters and the elongation at break for the EPR. Finally, the radiation dose and aging temperature were found to have little influence on these relationships. Another Japanese study at JAERI derived degradation kinetics from the accelerated radiation and thermal aging for predicting the life of an organic material (Ref. 4.108). These kinetics are based on the polymer oxidation mechanism by radiation, thermal, and radiation-thermal combined aging. Figures 4.65-4.67 illustrate some of these results for an EPR material.

CERN developed a method to estimate the long-term degradation, and hence the lifetime of cables used in its facility (Ref. 4.109). The formula suggested is given by:

$$DED = K\,(DR)^n$$

where, DED is the dose-equivalent damage (end-point criterion),
DR is the dose rate,
K is the dose at which the end-point criterion is reached after irradiation at the rate of 1 Gy/hr,
n is the dose-rate effect factor ($0 < n < 1$).

K and n are material constants to be determined from tests. By taking the $\log_{10}$ of the formula, we obtain:

$$\log(DED) = RI(DR) = \log K + n \log(DR)$$
$$= RI(1\ Gy/hr) + n \log(DR)$$

where, RI is the radiation index and defined as the logarithm (base 10) of the dose (in Gy) at which the end-point criterion is reached after irradiation at a given dose rate. Thus, log K is the RI at 1 Gy/hr.

The corresponding time-equivalent damage (TED) is the time it takes to reach the end-point criterion, given by the following expression:

$$TED = DED/DR$$
$$= K\,(DR)^{n-1}$$

This method was suitable for all materials tested. The value of n varies between zero for materials that are insensitive to dose-rate effects, and 0.3 for those very sensitive to oxygen degradation. Figure 4.68 illustrates the results for an XLPE material.

EDF in France developed a kinetic model for combined radiation and thermal environment to extrapolate the accelerated aging data for predicting the life of the materials under low dose rate and low temperature conditions (Ref. 4.110). The model takes into account the physio-chemical changes versus time and environment constraints. The model has several complex mathematical derivatives and requires six parameters on each material, which may require material tests for a minimum of eight different conditions of aging. Pinel and Boutaud (Ref. 4.111) presented the application of this model to an EPR insulating material.

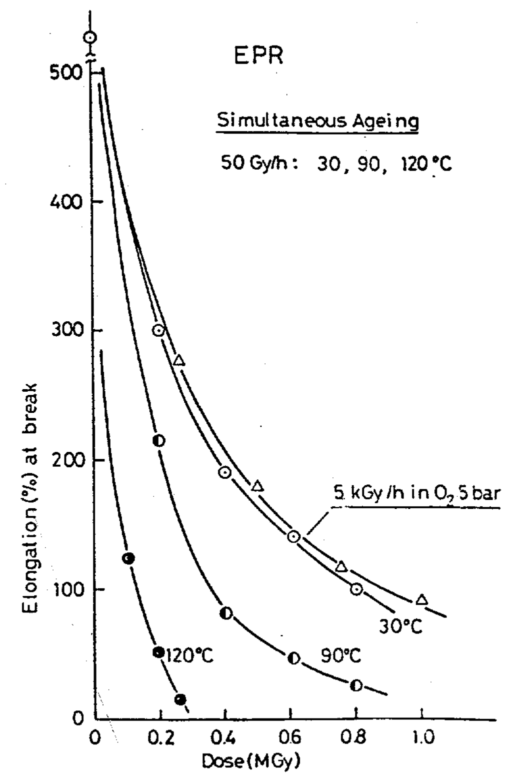

Figure 4.65 Simultaneous aging of EPR at 50 Gy/h and 30, 90, 120°C (Ref. 4.108)
Reproduced with permission from Dr. Tadao Seguchi, JAERI, Japan.

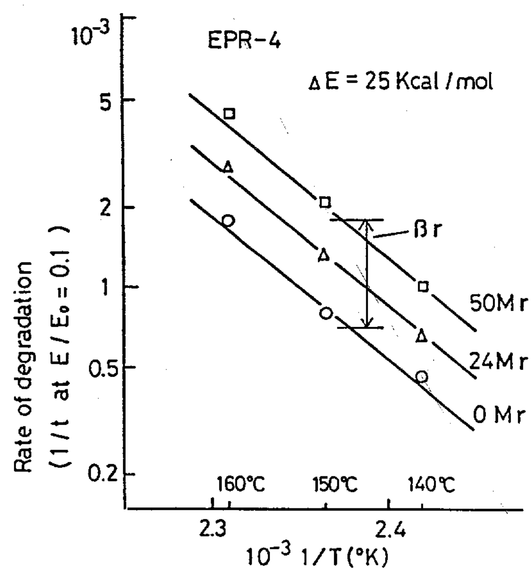

Figure 4.66 Arrhenius plots at different aging conditions for EPR-4 (Ref. 4.108)
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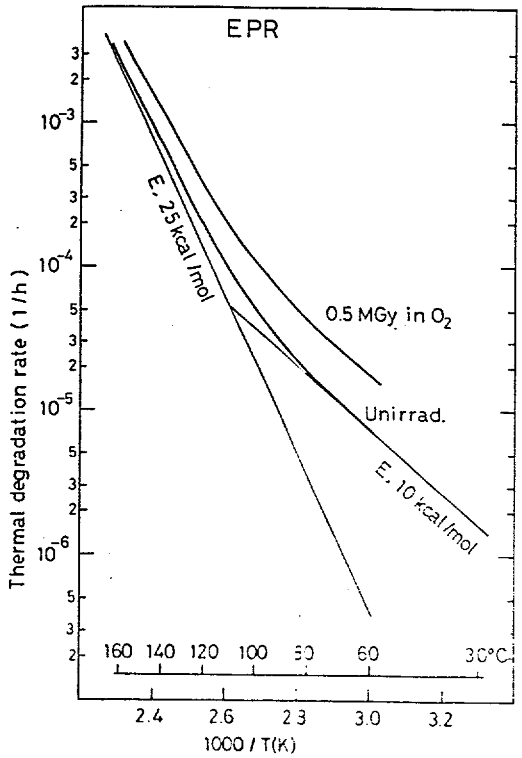

Figure 4.67 Arrhenius plots for combined aging conditions for EPR (Ref. 4.108)
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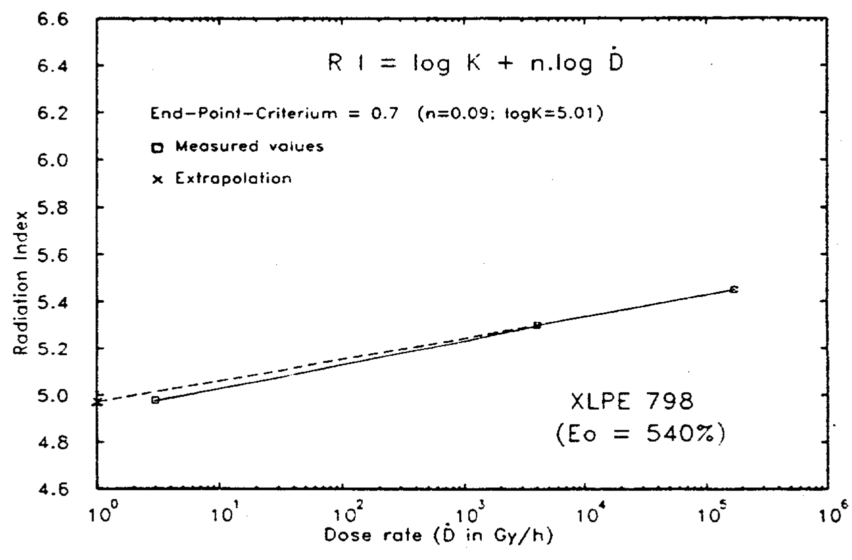

Figure 4.68 Examples of long-term aging and extrapolation for XLPE (Ref. 4.109)
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The testing part of this study involved thermal only aging tests at several temperature conditions, irradiation only at several dose rates and total dose conditions in ambient temperature environment, and simultaneous thermal and irradiation tests at one dose rate, but at several total doses and temperatures. The duration of these tests ranged from several days to several months (2 years). Data on elongation at break versus time, temperature, and irradiation was obtained. The conclusion of this study suggests the degradation of the EPR considered is predicted to be low in a nuclear power plant environment, even after 50 years of service life.

Gillen and Clough (Refs. 4.112-4.114) developed a superposition of the time-temperature-dose rate which represents an extension of the empirical approach of time-temperature superposition to combined radiation plus thermal environments. One basic assumption in this method is that at low enough dose rates, the combined-environment curves, in Figure 4.69, must approach thermal-only isochrones (the straight lines with unit slope whose starting point corresponds to the product of the dose rate on the abscissa and the thermal life from the time-temperature superposition results). As shown, the horizontal dashed line represents the "isodose" condition, and its intersection points with the combined environment curves represent the temperature and dose rate conditions which yield equivalent degradation after the same total dose. The Figure presents all data for a particular degradation level, e.g., 100% absolute elongation. Since the time to a constant total dose is inversely proportional to the dose rate, for each point, the ratio of the times appropriate to their respective temperatures is exactly equal to the inverse of the ratio of their respective dose rates. In other words, the functional relationship between time and temperature for combined radiation plus thermal environments under isodose conditions is empirically the same between inverse dose rate and temperature.

Analogous to time-temperature superposition, when this isodose relationship between time and temperature is determined, it can be extrapolated to a lower temperature under the same isodose condition. Thus, the experimental data at various isodose conditions can be shifted to lower temperature conditions, as illustrated in Figure 4.69.

This empirical relationship between time and temperature may be complex, depending on the isodose level and on the particular value of DED (dose-to-equivalent damage) chosen for analysis. Extrapolating results in such a situation requires extreme caution, analogous to attempting an extrapolation of a non-Arrhenius, damage-level dependent relationship derived from thermal-only aging experiments. Confident extrapolation involves a simple relationship independent of both the level of degradation and the isodose value. To simplify the matter, the approach assumes that an Arrhenius expression relates time and temperature under isodose conditions and that the appropriate value of the activation energy is independent both of the isodose level and the damage level selected.

Gillen and Clough (Ref. 4.112) state that assuming equivalent data scatter, it should be noted that "the uncertainties in the derived values of the activation energies using time-temperature-dose rate superposition are usually higher than those derived from time-temperature superposition of thermal-only data. The uncertainty in E_a for the combined environment method increases as the dose-rate effect decreases" (i.e., horizontal shift at the same DED is rare). Small to moderate dose-rate effects, coupled with large amounts of scatter in the raw data, can result in large uncertainties in activation energy. In addition, superposition of the time-temperature-dose rate may not always be appropriate for cases where accelerated data are taken, or extrapolation attempted, across a thermal transition of a polymer. This point is discussed further later.

Figure 4.70 gives the dose required for relative elongation (e/e_o) to reach 0.6 (i.e., equivalent absolute elongation of 204%) of a Hypalon-B material versus the dose rate and temperature (numbers by the data point in °C) of the combined-environment experiments. The results indicate that either raising the temperature or

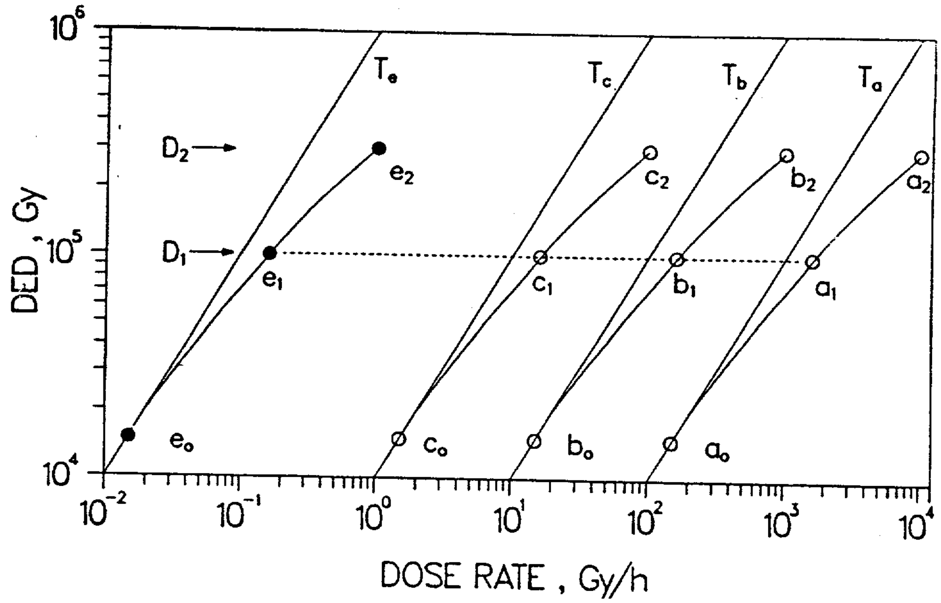

Figure 4.69 Hypothetical DED versus dose rate curves under isothermal conditions (Ref. 4.112)

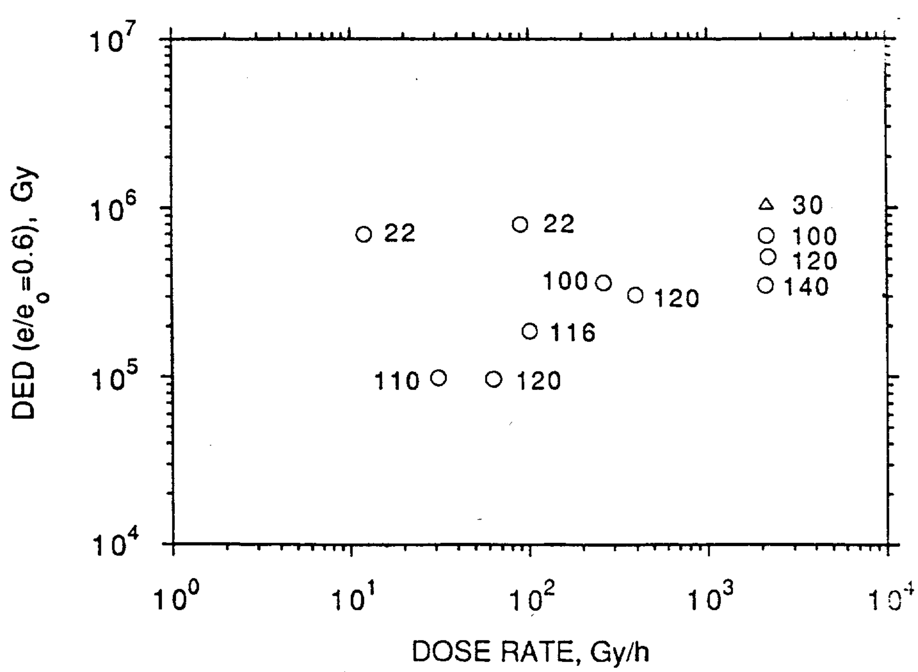

Figure 4.70 Combined thermal and radiation aging data for Hypalon-B (Ref. 4.112)

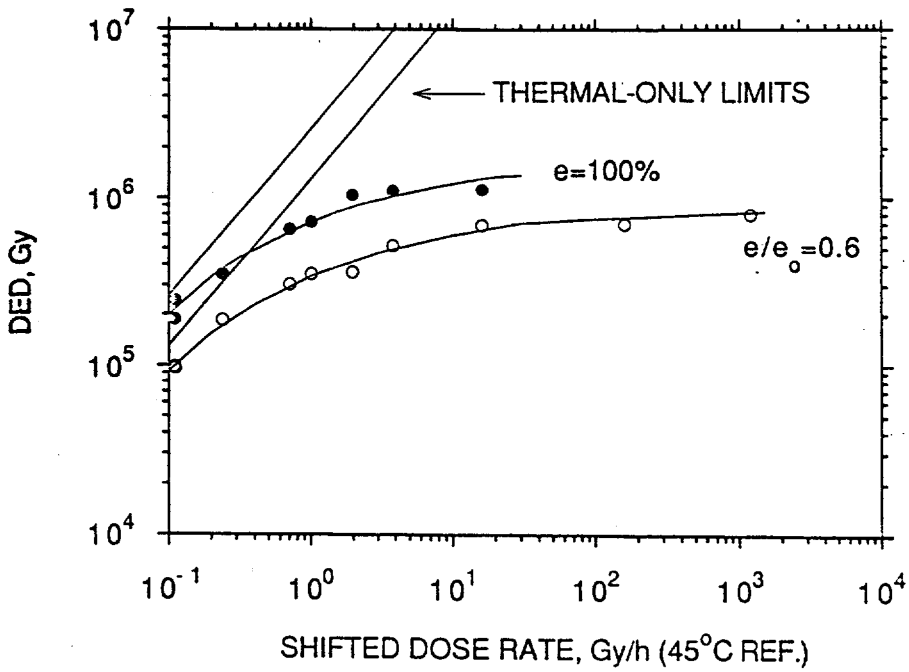

Figure 4.71 Predictions for Hypalon-B (DED vs dose rate) (Ref. 4.112)

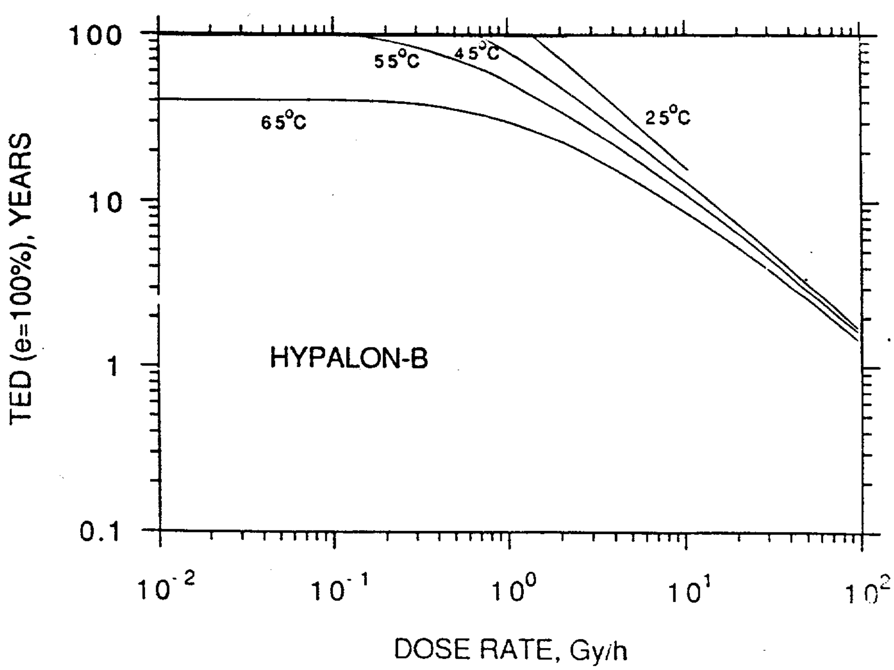

Figure 4.72 Predictions for Hypalon-B (TED vs dose rate) (Ref. 4.112)

lowering the dose rate increases the degradation rate per unit dose, implying that dose-rate effects are present. One requirement, before these data can be analyzed by the above methodology, is to eliminate from the analysis any data points which are taken on samples aged under diffusion-limited oxidation conditions. This can be done by determining which samples are heterogeneously oxidized either by direct experimental profiling techniques discussed earlier or through the use of theoretical expressions discussed in Reference 4.31. Thus, the 30°C data was believed to have such degradation and was discarded from the model.

Based on the results of thermal-only superposition an activation energy of 21 ± 2 kcal/mol was used to shift the combined environment data. Figure 4.71 shows the resulting superposed predictions for this Hypalon-B material. The curves now allow predictions to be made for very low dose-rate conditions, such as might occur during ambient aging in a nuclear power plant operations. At .1 Gy/hr plus 45°C, for instance, the top curve predicts that the elongation of this Hypalon insulation will drop to 100% absolute after ~230 years.

Although this prediction is limited to one isothermal condition (i.e., 45°C), modelling allows the results to be easily transformed to other temperatures. Further, the data can be manipulated to plot the time required for the elongation to drop to a specified value (e.g., the time to equivalent damage or TED) versus dose rate and temperature, as shown in Figure 4.72. This analysis applies to homogeneously oxidized material and should not be extended to high dose rates where diffusion-limited oxidation effects can occur. When the curves level out (slope of zero) at low dose rates (e.g., the 65°C curve), this reflects the transition to thermal-only domination of degradation, and no dose-rate effects exist.

Table 4.12 summarizes several of the studies performed by Gillen and Clough (Ref. 4.112). The last column, which gives the approximate ratios between the first and third conditions, shows the potential impact of dose-rate effects. Since the importance of diffusion depends on geometry (e.g., sample thickness), the high dose rates in Column I apply to materials of <1.5mm thickness.

Table 4.12 Summary of Expected Dose-Rate Effects (Ref. 4.112)

Material	Activation Energy (kcal/mol)	Predicted/Expected Dose to 100% Absolute Elongation (Gyx10^6) at 10 kGy/hr plus 45°C I	at 100 Gy/hr plus 45°C II	at .1 Gy/hr plus 45°C III	I/III
CLPE	21	1.0	0.7	0.7*	1.4
Hypalon-B	21	2.5	1.5	0.2	13
Hypalon-C	25	1.3	0.75	0.08	16
Hypalon-A	24	1.4	0.87	0.08	18
ETFE-B	21	0.3	0.11	0.11*	2.7
ETFE-A	21	0.2	0.08	0.08*	2.5
PVC	23	1.4	0.19	0.052	27
Silicone	21	0.3	0.2	0.046	7
LDPE	16	0.8	0.12	0.01	80
Neoprene	21	0.44	0.25	0.0044	100

* Horizontal Extrapolation - assumes no chemical dose-rate effect

The prediction methodology was applied further on three CLPO and two EPR materials (Reference 4.31). The technique was found to be applicable to one CLPO-C and one EPR-A material, allowing predictions be made for these materials under low dose-rate, low temperature conditions. For other materials, at low temperatures a decrease in temperature at a constant radiation dose-rate increases the degradation rate of their mechanical properties. Since these results contradict the fundamental assumption underlying superpositioning of the time-temperature-dose rate, this methodology cannot be applied to such data. Further investigations revealed that such anomalous results might be expected when attempting to model data taken across the crystalline melting region of semicrystalline materials, such as CLPO and EPR.

4.6 Comparison Between Natural and Accelerated Aging of Cables

The basic assumption in the current requirements for environmental qualification is that accelerated pre-aging will result in the cable materials being in the same state as if they had aged naturally during their qualified life. Proof that accelerated-aging methods are valid can only come through comparisons with naturally aged materials. The pre-aging of cable materials generally includes radiation and thermal aging before any accident simulations. The sensitivity of cable materials to accident tests is strongly influenced by pre-aging because the aging degradation of organic materials during normal service life can be severe.

In the early eighties, researchers at Sandia investigated the deterioration of PE and PVC cable materials taken from inside the containment of the Savannah River Nuclear Reactor (Ref. 4.61). Radiation dosimetry and temperature mapping of the containment indicated that the maximum dose experienced by the materials was only 2.5 Mrad at an average operating temperature of 43°C. Figure 4.73 illustrates the model's predictions for PVC tensile strength and compares these results to naturally aged samples taken from Savannah River (S.R.). An excellent correlation was obtained. Similar results were noted for PE.

Shaw (Ref. 4.115) discussed a program at the University of Connecticut, sponsored by EPRI since 1985. Several utilities have participated in this effort supplying Class 1E low-voltage cables as well as participating in the in-plant natural aging program at their own facilities. The report outlines methods for monitoring the radiation and temperature levels at each site, and plans for removing and testing the physical properties of the specimens. Tentative procedures for the accelerated aging and testing identical specimens also are outlined for comparison with the results from naturally aged samples.

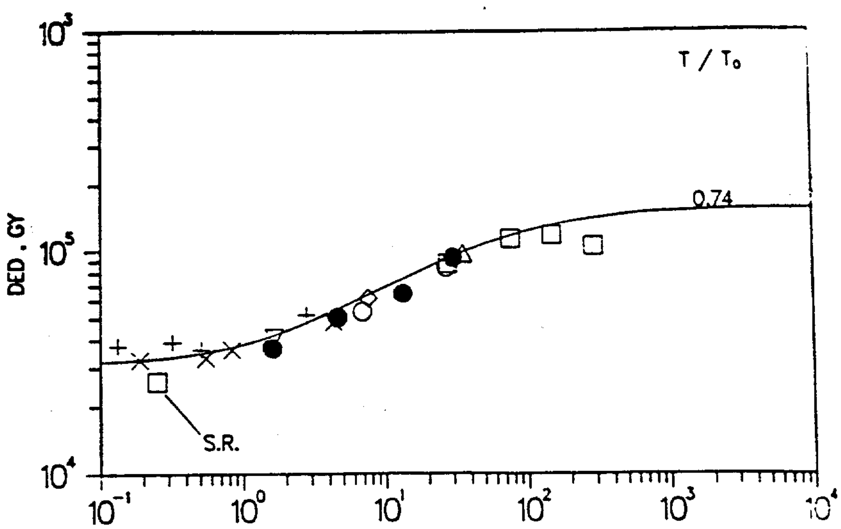

Figure 4.73 Aging prediction and comparison with Savannah River PVC sample (Ref. 4.61)

In predicting the insulation life from the accelerated aging data, Gillen and Clough (Ref. 4.112) demonstrated the validity of their time-temperature-dose rate model by using data on naturally aged material from the Hanford N-Reactor on Hypalon, and from Siemens studies on several other insulation materials.

Rost, Bleier, and Becker (Ref. 4.116) presented the results from a long-term study by Siemens in Germany. They included cable materials such as XLPE, EPR, SR, ETFE, EVA (Jacket), PVC for both long-term (9 years) natural aging in the containment of a PWR at a dose rate of 0.7 Gy/hr(50°C) and long-term accelerated aging in a cobalt source at dose rates ranging from 0.5-1.3 Gy/hr(room temperature). They also included short-term irradiation at dose rates from 40 Gy/hr to 10 kGy/hr. The study started in 1979 and the findings discussed here are results from mechanical, electrical, and LOCA tests performed on samples in 1988. Tables 4.13 and 4.14 summarize the elongation data on radiation aging and LOCA testing.

Table 4.13 Half-Value ($e/e_o=0.5$) Doses for Irradiation Test Results on European Materials (Ref. 4.116)

Cable Materials	Half-Value Dose in kGy				
	Short-Term Tests			Long-Term Tests	
	10,000 Gy/hr	400-500 Gy/hr	40-50 Gy/hr	0.7 (50°C) Gy/hr	0.5-1.3 Gy/hr
XLPE(I)*	2000	600	600	42(~0%)**	54(~0%)
EPR(I)	600	150-250	130-250	40, 42(15-20%)	60, 54(15-20%)
SR(J)	550-600	160-170	160-180	40-45	50, 54(35%)
ETFE(I)	400	150-170	150-170	45, 42(0%,20%)	54(0%,10%)
EVA(J)	700-1700	650-1700	450-1600	50, 42(15%,25%)	60, 54(15%,25%)
PVC	>2000	300	200	30	50

** Values inside bracket represent percentage of *decrease in elongation ratio* from $e/e_o=1.0$ (i.e., 0% decrease means no change).

* I = Insulation Material; J = Jacket Material.

Table 4.14 Final Aging Test Results on LOCA Responses (Ref. 4.116)

Cable Materials	Dose Rate Effects*	Short-Term Test Dose(kGy)	Long-Term Test Dose(kGy)	LOCA Responses**
XLPE	Insignificant	1000 ($e/e_o=0\%$)	55 ($e/e_o=105\%$)	No deterioration
EPR	Moderate	1000 ($e/e_o=10\%$)	40 ($e/e_o=80\%$)	No deterioration
SR	Moderate	2300 ($e/e_o=30\%$)	30 ($e/e_o=85\%$)	No deterioration
ETFE	Moderate	500 ($e/e_o=0\%$)	55 ($e/e_o=40\%$)	Significant
EVA	Moderate	250 ($e/e_o=0\%$)	40 ($e/e_o=60\%$)	No deterioration
PVC	Significant	Not available	Not available	Not available

* Insignificant = Marginal; Moderate = one order of magnitude; Significant = two orders of magnitude.

** No deterioration = No change in mechanical and electrical properties; Significant = elongation ratio changed from 95% before LOCA (i.e., after being exposed to >20 kGy irradiation) to 0-35% after LOCA steam exposure. Note that LOCA here is a 24 hours test in saturated steam condition (peak temperature 160°C).

Based on this study of 9 years of exposure under a realistic containment environment, the authors concluded the following: (1) For 50 kGy (5 Mrad) exposure or less, most cable materials exhibited no dose-rate effects. (2) XLPE/EVA (I&C) and EPR/EVA (power) materials are suitable for nuclear applications. (3) For irradiation above 50 kGy (5 Mrad), dose rate effects on all materials should be determined before qualification. (4) ETFE did not insure survival during a LOCA, specifically once exposed to 20 kGy of radiation. For this material, periodic replacement was recommended.

Radiation aging experiences at CERN are reported in References 4.117 and 4.118. The cable examined in Reference 4.117 includes EPR-insulated, PVC-jacketed 3.6/6 kV power cable, consisting of four aluminum conductors, each insulated with 3 mm EPR. These four conductors are held together by a wrapping of fabric, filled with soft plastic, and the outer sheath made from 2.5 mm flame-retardant PVC. Both materials are charged with calcinated clay and contain antimony trioxide; the EPR also contains aluminum trioxide. The cable was manufactured in 1975 and was installed in 1976 in the pulse magnets of the CERN SPS neutrino facility. It remained in service till 1980 in high-level radiation areas (< 1 MGy/year or 114 Gy/hr and 30°C) exposed to a combined effect of cyclic electric, mechanical, and thermal transient stresses under pulsed operation. For accelerated-aging tests, samples from non-irradiated cable were sent to a nuclear reactor where they were irradiated at a dose rate of 100 kGy/hr in air at about 35°C representing an accelerated factor of 1000-5000 with respect to actual service conditions.

Figure 4.74 presents the results of the absolute elongation (E), hardness (H), and tensile strength (R) as a function of dose for the EPR and PVC materials. The triangles and circles represent service conditions, while the squares are the results of short-term reactor irradiation. From the elongation at break data, the 50% reduction is found at the following dose levels:

Aging Method	EPR-Insulation	PVC-Sheath
Actual Service Exposure	1.0 MGy	1.2 MGy
Accelerated Exposure	0.5 MGy	1.3 MGy
Ratio (Accelerated/Actual)	0.5[6]	~1.0

Comparing the data, the PVC is initially less damaged under accelerated conditions but then, the degradation becomes significantly larger at dose levels beyond 2 MGy. For the EPR, this behavior is less pronounced. The results for the PVC also indicate that there is a dose-rate effect of a factor of 2 to 3 between accelerated irradiation (100 kGy/hr) and service condition (~130 Gy/hr) below 1 MGy dose. The study also did not establish a correlation between mechanical and electrical degradation of the cable.

Schonbacher studied cables taken from the Intersecting Storage Rings at CERN, which operated from 1971 to 1984 (Ref. 4.118). These cables were exposed to doses between 10 Gy to 50 kGy for 45,000 hours of service life. The materials of interest include EPR, PE, and PVC. There was no evidence of radiation degradation below doses of 10 kGy and dose rates below 0.1 mGy/s (0.36 Gy/hr). Polyolefin-based insulations (PE) were sensitive to oxygen-induced dose-rate effects. A dose limit of 100 kGy at dose rate of 1-10 mGy/s (3.6-36 Gy/hr) was set for using PE as cable insulation. EPR did not show very pronounced dose-rate effects. For this material, the dose limit, above which dose-rate effects are significant, was set between 0.5-1.0 MGy.

[6] Note that EPR appears to degrade more rapidly at high dose rate than at low dose rate, which is opposite to the behavior of many other materials.

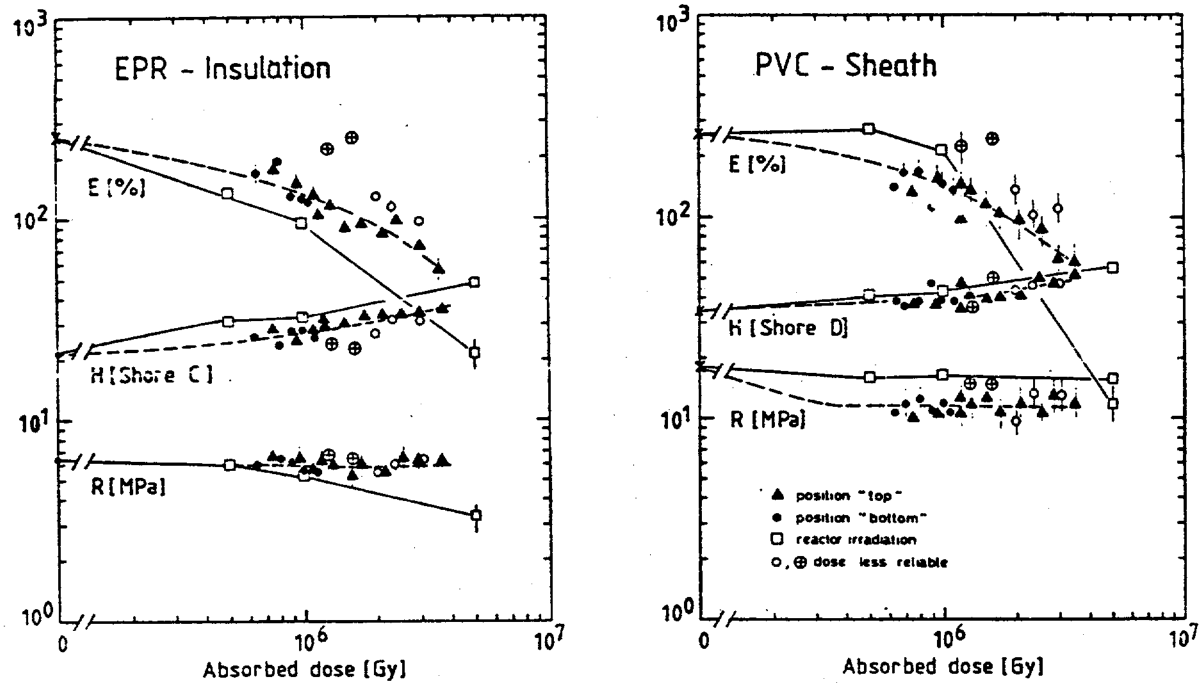

Figure 4.74 Comparison of EPR and PVC subjected to service and reactor irradiation (Ref. 4.117)
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A joint research effort between U.S. and France compared long-term and short-term aging of several cable materials since 1988 (Ref. 4.119). The U.S. test program (sponsored by NRC and performed at SNL) was known as the U.S.-French Cooperative Research Program on Long-Term Cable Aging Degradation, and the French test program (sponsored by CEA and performed at Osiris research center and CIS bio international's irradiation facilities) was known as VEILLE program, a French acronym for the long-term irradiation aging of electrical cables. Although both U.S. and French specimens were tested in both U.S. and French facilities, the focus here is on the U.S. cables.

The U.S. cable specimens included EPR cables with flame-retardant EPDM insulation and Hypalon jacket manufactured by Samuel Moore (Dekoron 2/C 16 AWG 600V) and XLPO cables with XLPE insulation and Hypalon jacket manufactured by Rockbestos (Firewall III 3/C 12 AWG 600V). Similar cable materials were used for the French samples. At SNL, specimens were irradiated with 20 Mrad at a dose rate of 10 krad/hr and a temperature of 40°C. Then they were exposed to LOCA conditions consisting of accident irradiation of 60 Mrad at a dose rate of 90 krad/hr and a temperature of 70°C, followed by a single peak saturated steam exposure for 4 days (peak temperature 159°C) and another 10-day post-transient period (temperature 100°C). In France, specimens were irradiated in Kronos facility (CIS bio) to a range of total doses (1.4-21 Mrad) at dose rates of 0.5, 1.0, and 2.0 krad/hr at both 40 and 70°C. In the Evocable facility (Osiris), specimens were irradiated at a dose rate of 0.2 krad/hr and 40°C for a total dose of 1.4-5.6 Mrad. In parallel, samples were thermally aged for up to 5 years at 70±2°C in ventilated ovens. All irradiated samples along with some unaged samples were exposed to LOCA conditions consisting of an accident dose of 60 Mrad at a dose rate of 80 krad/hr and 70°C, followed by a single peak saturated steam exposure for 4 days (peak temperature 156°C) and another post-transient period of 10 days at 100°C.

Table 4.15 Results from U.S.-French Long-Term Study (Ref. 4.119)

Cable Material	Material Density(F)[a]	Aging				LOCA		Remarks
		Thermal(F)	Radiation(US)	Radiation(F)	Synergism(F)	Radiation	Steam	
US-XLPO(I)	Decreased-Aging Increased-Acc. Rad. Decreased-Steam	No change in elongation.	e/e_o=.55@20Mrad.	Not conclusive Data unreliable	Not determined	US e/e_o<.20	US e/e_o>.35	Polypropylene filler melted and fused to jacket after LOCA.
French-PE(I)	Increased-Aging Increased-Acc. Rad. Decreased-Steam	Relatively constant.	No US results	e/e_o=0@2.8Mrad.	Not determined. Degradation solely by irradiation.	Insulation material completely degraded after steam.		Braided jacket not easily removable(US).
French-PE(J)	Increased-Aging Increased-Acc. Rad. Decreased-Steam	Relatively constant.	Waxy@8.4Mrad. e/e_o=0@20Mrad.	e/e_o=0@5.6Mrad.	Not determined. Degradation solely by irradiation.[b]	Completely brittle after LOCA.		US samples appeared to have melted. Sudden change in e/e_o to zero after 10 Mrad (F).
US-EPR(I)	Increased-Aging Increased-Acc. Rad. Unchanged-Steam	Slight decrease in e/e_o.	e/e_o=.55@20Mrad.	No dose-rate effect. e/e_odecreases with dose.	No synergistic effect. Inverse temp effect seen.[c]	US e/e_o=.3-.6	US e/e_o slightly improved (except two specimens).	After LOCA, French samples stuck to the conductors.
French-EPR(I)	Unchanged-Aging Increased-Acc. Rad. Unchanged-Steam	Slight decrease in e/e_o.	e/e_o=.55@20Mrad.	No dose-rate effect.	No synergistic effect. Inverse temperature effect seen.[c]	US e/e_o=.25-.3 French found e/e_o<.5 and can be handled without damage.	US e/e_o slightly improved.	Inverse temperature effect presumably due to structural changes in 40-70°C range.
US(EPR)Hyp.(J)	Increased-Aging Decreased-Acc.Rad. Increased-Steam	e/e_o=.45 after 5 years @70°C.	e/e_o=.6@20Mrad.	Dose-rate effect exists and significant at higher temperature.	Reverse synergistic effect seen.[d]	US e/e_o decreased 35-60% of the pre-LOCA values after accident irradiation and further down after steam for all three Hypalons. Aging exposure affects LOCA		e/e_o<50% absolute after LOCA steam.
US(XLPO)Hyp.(J)	Not available	e/e_o=.45 after 5 years @70°C.	e/e_o=.9@20Mrad.	Dose-rate effect insignificant at 40°C but significant at 70°C.	Synergistic effect exists.	performance (F). Note, all three Hypalon formulations were different. In fact, US(EPR)Hyp. was less dense than other two. Specimens pre-aged with lower		Crosslinking effects during irradiation. Dose-rate effect seen at 100 Gy/hr.
French(EPR)Hyp.(J)	Not available	e/e_o=.7 after 5 years @70°C.	e/e_o=.7@20Mrad.	For dose rates5 &10 Gy/hr, e/e_oincreased with temp.increase. At dose rate 20Gy/hr temp had no effect and had reverse dose rate effect.	Synergistic effect exists.	dose rates had more degradation after LOCA than those with high dose rates.		At 40°C no dose-rate effect seen at 2,5,20 Gy/hr. But at 20Gy/hr reverse dose rate effect seen (F). At 70°C, dose rate effect observed.

NOTES: (I)=Insulation Material; (J)=Jacket Material; (F)=French results; (US)=US results

a French study: the density of all jackets and insulations remained relatively constant during radiation aging. Densities for all jackets and French EPR did not change even after LOCA.

b This material behaved reverse dose rate+thermal effect. As temperature increases from 40 to 70°C and dose-rate decreases, e/e_o improves.

c This material irradiated @ 20 Gy/hr is more degraded during irradiation @ 40°C than 70°C. Similar behavior was noted earlier at SNL. This may be due to semi-crystalline nature of EPR.

d The thermal effect plus radiation effect is more degrading than a combined environment.

Table 4.15 summarizes results from studies performed both in US and France. Although many findings are known as the individual material characteristics, there are several interesting results that might raise additional questions on their aging behaviors and LOCA responses. The Rockbestos XLPO insulation material had polypropylene fillers which melted and fused to the Hypalon jacket after experiencing a total dose of 80 Mrad irradiation and LOCA steam test. There were problems in separating the jacket of braided jacket cables (French PE) from their insulations after aging. The insulation of Samuel Moore EPR cables stuck to conductors after LOCA exposures. All three Hypalons, including two US and one French materials, behaved more or less same.

All insulation materials (US XLPE and US EPR) had slight or no decrease in elongations after being exposed to 5 years at 70°C in well-ventilated ovens. This behavior may be due to the presence of antioxidants and until these additives are depleted the thermal effect on the insulation material can be negligible. Also, at lower aging temperatures, the materials are probably still inside their induction periods, beyond which the degradation can be significant. If this is true, then this induction period is a strong function of the aging temperature and therefore, it will be difficult to establish its duration for cables experiencing lower service temperatures inside the plant without performing very long thermal aging experiments. The jacket materials (Hypalons) had lost half of their relative elongation value at the end of 5-year thermal aging.

On the other hand, radiation aging caused both US insulation materials to lose half of their elongation after an exposure of 20 Mrad irradiation at 10 krad/hr dose rate. But under lower dose rates (0.2-2.0 krad/hr) the XLPO insulation specimens yielded unreliable data (e.g., one group showing less sensitivity to irradiation and slight degradation after 21 Mrad exposure, while the other group showed significant degradation to very low elongation-at-break). The French specimens from this material could not be tested after LOCA tests since the polypropylene filler material had melted and fused the insulation and jacket material. The EPR insulation material also lost half of its elongation after 20 Mrad irradiation at 10 krad/hr dose rate. No specific dose rate effect was noted from the French testing. In fact, the degradation increased with the increase in total dose irrespective of the dose rate. The French specimens again stuck to the conductors after LOCA steam exposure. Therefore, no post-LOCA measurements on the US insulation samples were performed in French studies. However, US studies on US insulation materials indicated significant degradation after LOCA irradiation of additional 60 Mrad; e/e_0 was reduced to less than 0.20 for XLPO and to 0.30-0.60 for EPR. Both materials showed slight improvement in their elongation properties after steam exposure.

Both US and French EPDM/EPR samples exhibited an "inverse temperature effect" under combined environment. Samples irradiated at 20 Gy/hr were more degraded during irradiation at 40°C than during irradiation at 70°C. Similar behavior also was noted by SNL researchers for XLPO (Ref. 4.41) and EPR (Ref. 4.81) from their earlier studies. It was proposed that these findings reflected the semi-crystalline nature of these materials and the fact that they undergo crystalline melting and reforming over a broad temperature range from roughly room temperature up to at least 100°C. Additionally, the US EPR/EPDM insulation exhibited no synergistic effect, but rather yielded lower degradation values under a combined environment than from adding individual contributions from each environmental condition (e.g., temperature, radiation).

The US jacket materials (Hypalon) degraded with increased dose and had a strong dose-rate effect. Some of them exhibited a weaker dose-rate effect at lower temperature, which became significant as the temperature was raised. After 20 Mrad irradiation, the e/e_0 remained around 0.50 or above at 40°C and ranged from 0.15-0.45 at 70°C. Table 4.16 presents the dose-rate effects of some of these materials subjected to a total dose of 21 Mrad at 70°C. The Rockbestos Hypalon showed synergistic effects under a combined thermal and radiation environment while Samuel Moore Hypalon indicated a reverse synergistic effect. For both materials, including the French Hypalon material, their elongation properties decreased by a further 35-60% of their pre-LOCA values after accident irradiation, and fell to a range of 0-50% absolute elongation after steam exposure. The level of degradation during LOCA conditions depended on the aging conditions before the LOCA and specimens pre-aged with lower dose-rates had more degradation after LOCA than those with high dose rates.

Table 4.16 Dose-Rate Effect of Cable Materials When Subjected to Irradiation of 21 Mrad at 70°C (Ref. 4.119)

Cable	e/e_o at Different Dose Rates			
Material	**5 Gy/hr**	**10 Gy/hr**	**20 Gy/hr**	**100 Gy/hr(US)***
US EPR-EPDM	0.51	0.57	0.57	0.55
US EPR-Hypalon (Samuel Moore)	0.19	0.35	0.49	0.60
US XLPO-Hypalon (Rockbestos)	0.16	0.50	0.56	0.90
French EPR-Hypalon	0.39	0.43	0.48	0.70

* US results taken from graphs in the report at 20 Mrad irradiation at 40°C are approximate values.

McGuire (Ref. 4.12) presented the natural aging results for several safety-related cables inside the containment of Perry Nuclear Power Plant. In section 4.1, the actual plant conditions at five selected locations were discussed. Cable samples, each 13 ft long, were laid in cable trays at these specific locations. The cables were not energized to emulate most safety-related cables which remain de-energized during normal operation of the plant. Except for the medium voltage (5 kV) Anaconda cable, all other specimens are low voltage (600Vac). Details on the cable types and materials, and corresponding tensile property changes for each environmental condition are summarized in Table 4.17. After 5 years exposure to reactor environment conditions, dielectric withstand testing registered less than 1 mA of leakage current for all samples except Anaconda cable which had 4 mA. In all cases, the insulation resistance was greater than 10^{11} ohms.

Table 4.17 Insulation Properties After 5 Years of Natural Aging (Ref. 4.12)

Environment	**Percentage Change in Tensile Strength (T) and Elongation (E)**											
Thermal/ Radiation (°F/Mrad)	**Anaconda EPR MV-Power**		**Brand Rex XLPE Instrument**		**Rockbestos XLPO Power & Control**		**Rockbestos LD-XLPO Instrument**		**Rockbestos XLPO Inst. & TC**		**SamuelMoore XLPO Thermo Couple**	
	T	**E**	**T**	**E**	**T**	**E**	**T**	**E**	**T**	**E**	**T**	**E**
A:125/7.0	+1.7	-27.5	-12.6	-2.8	+1.9	-33.3	n/a		-4.9	-13.7	-3.4	-13.7
B:85/1.2	-13.3	-29.0	-1.6	-3.0	-5.5	+5.6	n/a		-6.5	-14.5	-2.5	-8.4
C:140/0.47	-2.3	-21.2	-4.0	-5.1	+4.9	-14.4	n/a		-2.5	-8.3	-4.8	-11.9
D:125/0.47	-2.5	-26.7	-1.5	-6.2	+3.9	-7.8	n/a		-0.9	-7.5	-1.9	-10.4
E:78/0.000022	-3.5	-14.1	-1.9	-2.5	+4.7	0.0	n/a		-0.3	-1.8	-1.7	-10.7

NOTES: n/a = not available; "+" indicates increase and "-" indicates decrease from the original values

The five different environmental conditions in Table 4.17, designated by A to E, represent five locations inside the containment of Perry Nuclear Power Plant. Location A can be considered as a radiation hot spot location, while other locations from B-E represent normal plant conditions. Therefore, the following conclusions can be drawn from these results: (1) Radiation hot spots can degrade cable insulations faster than normal plant conditions, (2) The EPR insulation degraded faster than all XLPO/XLPE insulations considered (except at location A), (3) Comparing locations C and D, both Anaconda EPR and Brand Rex XLPE degraded more under 125°F than 140°F while the radiation exposure remained the same.

4.7 Summary

Sandia National Laboratory (SNL) has performed significant studies on aging degradation of cable insulation and jacket materials. In addition, SNL has developed a technical basis for simulating the environmental conditions and provided guidelines for pre-aging requirements in the EQ process. Also, SNL collaborated with France, in the VEILLE program, to further study the effect of long-term aging on cables from U.S. and French manufacturers.

Under the sponsorship of DOE, SNL studied the aging behavior of cable materials using small samples. Using the test data under thermal and radiation conditions, an analytical model was developed (a modified Arrhenius model) to predict the remaining life of aged cable. Differences in aging characteristics between elevated (temperature and dose rate) conditions and actual plant conditions (i.e., low temperature and dose rate) were identified, and suggestions discussed to alleviate inadequacies in aging predictions in the EQ process.

In addition to the United States, Japan, Great Britain, Canada, and Sweden have developed similar programs for their own cable products; though only a few of the results have been published. Researchers at CERN studied extensively radiation effects on cable materials. Similar to the EPRI program with the University of Connecticut, Germany developed a long-range program where cables are aged in an actual plant environment.

All aspects of pre-aging requirements in the EQ process appear to have been studied by SNL. Two decades of research have given some insights into aging degradation and accelerated test limitations, but the practical applications of the research findings to qualification remains questionable and will be evaluated in the dossiers (see Vol. 2). This may be due to a variety of reasons, including the variations in cable materials from one manufacturer to another, lack of adequate data on material formulation and processing, and inadequate information on naturally aged materials. Several issues relating to the effects of humidity, oxygen, fire retardants, antioxidants, and mechanical stresses are better understood from laboratory experiments. How these results correlate to actual cables in the nuclear plant environment needs to be studied using cable samples from plants.

Pre-aging requirements which account for synergistic effects and the determination of elevated conditions for accelerated aging are issues which warrant further study. Since each cable material has its unique aging behavior when exposed to the conditions necessary for qualification, one general consensus or methodology may not apply to all products. At the same time, to cover all possible cable materials to develop criteria, the program must be encompassing. Therefore, the results from all studies already completed by SNL, France and Japan should be assimilated and evaluated with the ongoing research.

For certain materials, total degradation after LOCA radiation and before LOCA steam exposure far exceeds the degradation during pre-aging. In fact, after being exposed to a total dose of 200 Mrad required for both pre-aging and accident radiation most cable materials become very brittle (i.e., almost zero elongation-at-break). In such cases, it might not matter which pre-aging procedure (i.e., sequence, synergistic, or other simulation factors) was used in qualification. The dose-rate effect of radiation on certain materials should be established before any irradiation is performed, and it seems to be prudent to measure the tensile properties of the insulation materials at each juncture of a qualification test program.

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5. LOSS OF COOLANT ACCIDENT (LOCA) TESTING OF CABLES

During the design life of a nuclear power plant, cables used to operate safety-related equipment must be capable of delivering electric power, controlling equipment, and transmitting data to prevent and mitigate the consequences of an accident. To ensure this, the environmental qualification process simulates the postulated accident environments, which include simultaneous exposure to radiation, steam, thermal, and possibly, chemical sprays (PWR) or deionized water sprays (BWR). The cables are generally pre-aged or pre-conditioned, in most cases, to an equivalent age of 40 years (i.e., the original license period of a nuclear power plant) before their exposure to these accident conditions. IEEE Std 323-1974 (Ref. 5.1) describes the principles, procedures, and methods for qualifying Class 1E equipment, such as cables. Its daughter standard, IEEE Std 383-1974 (Ref. 5.2) delineates specific details on qualification parameters applicable to cables. The IEEE Std 323-1974 is endorsed by the NRC in Regulatory Guide 1.89, Rev. 1 (Ref. 5.3) and its guidance meets the requirements of 10CFR50.49 (Ref. 5.4). The Regulatory Guide recognizes that qualification may be accomplished in several ways, i.e., through type testing, operating experience, analysis, or a combination of these methods. Most cable qualifications are type tested, by subjecting the cables to the environments and operating conditions for which they are designed.

Qualification by testing is satisfied only when the cables to be tested are aged (except those qualified to older requirements, DOR Guideline, NUREG-0588/Category II), subjected to potential environmental influences, and operated under post-accident conditions to provide reasonable assurance that they can perform their intended functions for a specified time. One of the practical difficulties encountered in early development of the qualification process was to apply all test environments simultaneously. In particular, radiation testing usually was done sequentially and separately from the other environments. A typical qualification test consisted of the following sequence:

- thermal aging equivalent to a 40-year service life
- gamma radiation which simulates the effect of 40-year ambient radiation plus that released by the accident (e.g., typically a LOCA event)
- steam/chemical-spray exposure which simulates the non-radiation portions of a LOCA.

Such tests are referred to as sequential-exposure tests, or simply, sequential tests. In a few cases, simultaneous-exposure tests were conducted which consisted of the following exposures:

- combined accelerated thermal and radiation aging
- combined radiation-, steam-, and chemical spray-exposure simulating a LOCA.

Although the sequential test is not as realistic as the simultaneous test, intuitively it is conservative, primarily because the cables are thought to be more degraded (after exposure to radiation) when they are exposed to severe thermal transients and high temperatures of the steam/chemical-spray exposure than they are in a simultaneous test at the start of the combined exposure. Because sequential tests are intuitively conservative and are substantially less expensive than simultaneous tests, most qualification programs have been sequential[1]. In addition to these qualification tests, SNL has built facilities to perform EQ-related research where any combination of sequential and simultaneous procedures are simulated to verify these contentions.

Since its inception in 1975, the Qualification Testing Evaluation (QTE) Program at SNL has outlined and performed research on a number of broad issues in the EQ process, including both aging and accident

[1]According to Dr. S.P. Carfagno, Franklin Research Center (FRC) performed several simultaneous simulation tests for cable manufacturers (i.e., Anaconda, Kerite, Boston Cables, Rockbestos, Okonite). Tests were conducted at a special test facility built by FRC at Isomedix.

simulation methods (Ref. 5.5). Recently, the EQ-Risk Scoping Study used the probabilistic risk assessment (PRA) techniques to assess the impact of various EQ requirements on plant risk and to identify any needed modifications to the current EQ practices to reduce the risk or its uncertainties stemming from lacking of qualification of safety-related equipment (Ref. 5.6). The study suggested that (1) EQ should focus on assuring equipment's operability for the first few days of the accident rather than over a long term, (2) operability of the equipment during steam conditions is more important than during irradiation[2], (3) the equipment's reliability might increase the estimates of core damage frequency, and (4) instrumentation and control devices for accident management and plant status indicators are important, although it is difficult to assess their impact from the PRA techniques. To date, PRA techniques have not played a role in EQ. Therefore, the uncertainties and the differences among various test conditions and parameters associated with the qualification for accident conditions are discussed in this section.

Table 5.1 summarizes typical EQ requirements for the qualification of electric cables in several countries including the United States[3], for both aging and accident simulation requirements. Some details on test durations, chemical sprays, and post-design basis are not available. Nevertheless, this comparison of requirements in different countries with nuclear programs provides a basis for the results presented in this literature review which includes studies from the U.S. and abroad. Significant differences exist in the total radiation doses and dose rates used during both aging and accident irradiation. Some irradiations were performed at room temperature and others at elevated temperatures. Based on the information presented in the previous section, irradiation at elevated temperatures can degrade certain organic materials significantly when compared to irradiation at room conditions. Another area with large variations is in the definition of the accident steam conditions (e.g., pressure and temperature profiles) and their durations. Since these accident conditions are specific to the design of a plant, such variation from plant to plant, and hence, from country to country can be possible. However, the variation in the duration of an accident transient for different countries is noteworthy.

As indicated in Table 5.1, the total radiation doses used in qualification testing vary from as low as 4Mrad to 50Mrad for aging, and 20Mrad to 150Mrad for accidents (except for Spain where the LOCA radiation values are uncertain). Results from one nuclear power plant (Ref. 4.12) presented in the previous section indicated that with the exception of hot spots, the majority of cables inside the containment are exposed to an TID of 10 Mrad during 40 years of design life. Also, based on results from the TMI accident discussed in this section, the TID absorbed by cables during that accident was less than 12 Mrad. This disparity between actual plant data and typical qualification values, specifically in U.S., may need further examination of the current EQ requirements.

In early years, most of the industry's qualification as well as research tests, were conducted at the Franklin Institute Research Laboratories (FIRL), Philadelphia. Over the last two decades, significant research was carried out at Sandia National Laboratory (SNL) sponsored by the NRC (Ref. 5.7). The following four major facilities were built to simulate the environmental qualification conditions: Low-Intensity Cobalt Array (LICA), High-Intensity Adjustable Cobalt Array (HIACA), I-Steam, and V-Steam with transient superheat capability.

[2] Note that LOCA testing results have indicated radiation causing more degradation than steam exposure. In fact, for certain insulation materials, steam conditions had enhanced cable's elongation properties. However, most cable failures were reported during the saturated steam exposure (i.e., post-transient duration) of the LOCA testing.

[3]Personal communication with Mr. D.J. Stonkus of DJS Associates.

Table 5.1 Typical EQ Requirements for Cables Used in Different Countries (Mr. D.J. Stonkus)

Country	Aging Simulation			LOCA Simulation						Post-Design Basis
	Thermal	Radiation	Comments	Radiation	Steam Conditions (extremes)	Chemical Spray	Durations (Hours)		Comments	
							Transient	Post-Transient		
USA	168 hrs @150°C(air)	50 Mrad @≤1Mrad/hr	Irradiation at room temp.	150 Mrad @≤1Mrad/hr (room temp.)	174°C@880kPa 100°C@100kPa	Boron Sol. pH 10.5	96	624	Total 30-day LOCA test	93°C @ 100% RH for 100 days
UK	240 hrs @150°C(air)	20 Mrad @≤0.3Mrad/hr	Irradiation at 90°C	30 Mrad @≤0.3Mrad/hr (90°C)	200°C@490kPa 50°C@100kPa	Boron Sol. pH 8.5	22.4+	n/a	none	100°C @215kPa Duration based on activation energy
France	950 hrs @135°C(air)	25 Mrad @0.05-0.15Mrad/hr	Irradiation at 70°C	60 Mrad @0.15-0.75Mrad/hr (70°C)	157°C@560kPa	Yes	96	n/a	none	n/a
Germany	240 hrs @135°C(air)	5 Mrad @0.05Mrad/hr	none	20 Mrad @0.05Mrad/hr	180°C to 100°C 50°C	Yes	241	n/a	none	400 hours
Japan	168 hrs @121°C(air)	50 Mrad @≤1Mrad/hr	Irradiation at room temp.	150 Mrad @≤1Mrad/hr	150°C	Yes	n/a	n/a	none	n/a
Canada	31years life based on Arrhenius	20 Mrad @≤1Mrad/hr	none	30 Mrad @≤1Mrad/hr (room temp.)	115°C@196kPa 65-40°C	Boric acid pH 10	12	n/a	Negative steam press. for 6 hours	90days @40°C and 100% RH
Italy	n/a	35 Mrad	Irradiation at 57°C	18Mrad γ and 27Mrad β	130°C@280kPa 80°C@100kPa	Yes	12	n/a	none	100 days @ 50°C
Belgium	40years life @90°C based on Arrhenius	50 Mrad @≤1Mrad/hr	Irradiation at 30°C	150 Mrad @≤1Mrad/hr (30°C)	180°C@1000kPa 120°C@100kPa	Boron Sol. pH 10.5-11	504*	n/a	none	1 year @ 70°C
Spain	n/a	n/a	none	5380 Mrad γ &714 Mrad β (?)	165°C 57°C	n/a	24	100 days*	Total radiation 175-350 Mrad(?)	n/a
Brazil	n/a	4 Mrad @≤1Mrad/hr	none	200 Mrad	149°C@467kPa 122°C@215kPa	Boric acid pH 8-8.5	240*	n/a	none	n/a

NOTES: * Presumably these numbers represent total LOCA duration including transient and post-transient durations. n/a = not available
Accident radiation doses for Spain are uncertain.

In addition to verifying industry's claims on the current qualification requirements, the goals of this research were to understand the effects of each of the environmental conditions and any of their synergistic effects. Additional studies were carried out on oxygen effects, post-accident environments and their durations, sensitivity to aging methods, post-accident tests, and comparisons were made with actual accidents (e.g., TMI).

5.1 Simultaneous/Sequential Exposures

Bonzon (Ref. 5.8) reported test results on nine generic LOCA type tests conducted on electric cables, cable-connector assemblies, and cable field-splice assemblies, including sequential and simultaneous exposures to LOCA radiation, steam, and chemical sprays. For all tests, saturated steam conditions (without air) were employed. The materials tested were EPR/CSPE, XLPE/XLPE, Neoprene/Neoprene, and XLPE/no jacket. The cables showed no obvious synergistic effects in either the electrical or material properties. Some of the conclusions from this study were: (1) elongation is an inverse function of total radiation dose, (2) radiation is a principal mechanism of damage in the LOCA type test environment[4], (3) there is no correlation between the extent of damage and the type of test (sequential or simultaneous), (4) in terms of elongation, all cables failed at the bend area, (5) although all cables failed at the bend area, visual examination would not necessarily reveal the failure or the relative failure, and (6) there was no significant difference in the response of the cable types tested.

Tensile specimens of two compounds of typical radiation-crosslinked, highly flame-retardant polyolefins were tested under sequential and simultaneous conditions; Table 5.2 summarizes the results. One general comment that can be made is that the effect of aging is apparent, and the pre-aged samples are more severely degraded than those that were not pre-aged by the manufacturers. It may be noted that the radiation doses were low by comparison with the values used in typical cable qualification programs.

The compound B data shows that increasingly severe degradation correlates well with the increasingly severe environment or environments. The normalized elongations are almost identical from both environment conditions, indicating no synergisms exist.

The NUREG also reported on FIRL's study (Ref. 5.9) of their own 1969-1977 historical data to determine the synergistic effects resulting from simultaneous applications of radiation, steam, and chemical spray during qualification of safety-related electric cable. Among the 49 test programs examined, only a single pair of tests (one sequential and one simultaneous) met certain basic requirements for synergistic comparison; i.e., that the cable specimens and the accident test profiles are essentially the same in both tests. The cables were multiconductor 600 Vac control cables with primary insulations of flame-resistant XLPE, EPR, and SR. The outer jackets consisted of flame-resistant Neoprene and silicone-saturated asbestos.

All of the cables in the sequential test exposure maintained their electrical load during the 30-day steam and chemical-spray exposure, whereas in the simultaneous test, none maintained their loads beyond 13 days. Two of the three cables used in the simultaneous test program failed before the LOCA exposure. An analysis of these two tests revealed significant differences in cable handling, thermal aging conditions, and gamma-irradiation dose rates. These differences might account for the fact that all three cables in the simultaneous test failed, whereas none failed in the sequential test. Because of these uncertainties, this comparison was not regarded by the authors as a clear source of information on synergisms.

[4] see footnote #2 on page 5-2.

Table 5.2 Comparison of Sequential and Simultaneous LOCA Test Data on Two Compounds (A and B) of Radiation-XLPO Insulation Samples (Ref. 5.8)

Conditioning Sequence	Radiation Dose Range (Mrads)	e/e_o							
		Sequential				Simultaneous			
		A	P-A	B	P-B	A	P-A	B	P-B
Aging	-	.39	.58	.94	.59				
Aging	5-8.5					.58	.57	.92	.58
Aging+LOCA	-	.59	.47	.40	.19				
Aging+LOCA	20.5-38.5					.46	.38	.26	.30
Aging+Radiation	38-95	.16	.14	.46	.31				
Aging	10.5-18.5					.70	.43	.83	.58
Age+Rad.+LOCA	38-95	.30	.24	.27	.13				
Aging+LOCA	45.5-78.5					.30	.26	.21	.24
Radiation	12-31	.86	.48	.92	.47				
Radiation+LOCA	12-31	.55	.32	.38	.18				
LOCA	15.5-30					.53	.36	.30	.21
LOCA	-	.81	.39	.44	.27				
LOCA	35-60					.38	.26	.28	.24

Notes:

1. Initial percent ultimate elongation for A and B was 530% and 468%, respectively
2. Radiation dose varies from top(1st figure) to bottom (2nd figure) of sample
3. All values are the average of 3 tests
4. P-A/P-B: Pre-aged samples received additional thermal aging of 168 hrs at 175°C
5. Sequential:Thermal 130°C/5 days-Ambient Radiation at 1 Mrad/h (Aging+Accident) -LOCA(Steam+Chemical)
   Simultaneous:(Thermal(130°C/5days)+Radiation at .2 Mrad/h) - (Accident Rad.+ (LOCA) Steam +Chem.)

Bustard (Ref. 5.10) discussed the electrical and mechanical properties of seven commercial EPR materials subjected to three simulations of pre-aging and accident conditions. One set of cables and separate tensile specimens underwent accelerated thermal aging (140°C for 168 hours), then irradiation to a combined aging and LOCA total dose of ~160-170 Mrad (at ~.75 Mrad/hr), and then steam exposure (saturated) for 4 days with 17 additional post-transient days. For a second and third set of cables and separate tensile specimens, simultaneous applications of elevated temperature (~140°C for 168 hours) and radiation (~40-45 Mrad at .35 Mrad/hr) were used for pre-aging, followed by simultaneous exposure of accident radiation (.8 Mrad/hr for

Mrad/hr) were used for pre-aging, followed by simultaneous exposure of accident radiation (.8 Mrad/hr for 4 days followed by much lower dose rates for the remaining 17 days of post-transient exposure; total accident dose of ~105-115 Mrads), and steam exposures to simulate accident environments. In all three simulations, saturated steam conditions (without air) were employed but no chemical sprays. The cable samples included both single and multiconductor specimens. Reference 5.11 summarizes the results from three similar sets of accident simulation tests applied to three commercial XLPO insulation materials.

Except for the EPR-D cables, leakage currents were comparable (0.6-1.9 mA) for simultaneous and sequential testing. For multiconductor EPR-D cables, there was a significant difference in leakage current between sequential (1.2 mA) and simultaneous exposures (#1:180-750 mA; #2:150-550 mA). Surprisingly, the electrical properties for EPR-D single conductors remained small (< 1.0 mA) for all LOCA conditions. Periodic measurements of insulation resistance (Figure 5.1) throughout the LOCA simulation indicated that electrical degradation of the EPR-D multiconductor began several days after the start of the simultaneous LOCA simulation. EPR-D insulation also exhibited substantial dimensional swelling, more, in fact, than any of the EPR or XLPO materials. The dimensional swelling was more severe with simultaneous exposure.

Bustard (Ref. 5.10) suggested that the substantial absorption of moisture and dimensional changes produced mechanically damaged the EPR-D multiconductors leading to their electrical degradation. It was hypothesized that dimensional swelling of the insulation caused buildup of stresses within the multiconductor geometry. When the jacket split to relieve the stress, the sudden release of constrictive force on the insulation may have caused it to crack or breakup. Alternatively, sections of the insulation which adhered to the jacket during splitting were pulled away from the conductor. Bare copper conductors, observed at the completion of simultaneous testing are suggestive of such a process. The report also presents two additional hypotheses which are less acceptable. One relates to chemical interactions of the jacket and insulation such as evolution of HCL from the jacket and its interaction with the EPR-D insulation. The other relates to dimensional swelling of the EPR-D single conductors spirally wound around each other in a multiconductor geometry, resulting in the buildup of stresses.

Table 5.3 shows data on the tensile property for EPR-A after aging and sequential LOCA irradiation testing for a variety of aging sequences (compare, Table 4.6). Those samples which degraded significantly after aging simulations, also degraded significantly after the LOCA steam exposure. Table 5.4 shows the wide variation in the tensile properties of different EPR samples. Also, the tensile properties do not predict electrical degradation for multiconductor cables (see EPR-D data). Sequentially exposed EPR-D multiconductors performed substantially better electrically than did simultaneously exposed ones, even though the former's insulation tensile properties were equally degraded by the end of test.

Table 5.5 gives the results from the same study for the EPR-1483 material. There were six different aging simulations (as defined in Table 4.6) followed by three distinct LOCA conditions; steam only, sequential radiation followed by steam, and finally, simultaneous radiation and steam. This particular material degraded to a range of 0.32-0.47 in its elongation at break values after aging, suggesting that there is very little effect on aging degradation under various simulation procedures. On the other hand, the LOCA responses to these pre-aged specimens vary significantly from one LOCA simulation to another. In regard to their relative variations in elongation data after different aging simulations, all aged specimens under each LOCA conditions responded similarly. However, the increase in weights during each LOCA simulation shows significant variation from one pre-aged specimen to another. Samples aged simultaneously have significantly higher weight increases than those exposed to sequential aging conditions.

Based on the test results on EPR cables, the report concluded that single conductor specimens should not be used to establish qualification for multiconductors. Both jacket-insulation interactions and the helicity of multiconductor geometries need to be considered in a qualification program. Since there is a large variation in EPR behavior, generic EPR responses should be avoided. The qualification tests should correlate test conditions to actual installed conditions (e.g., bends). Also, no final conclusion on the simulation technique (simultaneous or sequential) could be made for this material.

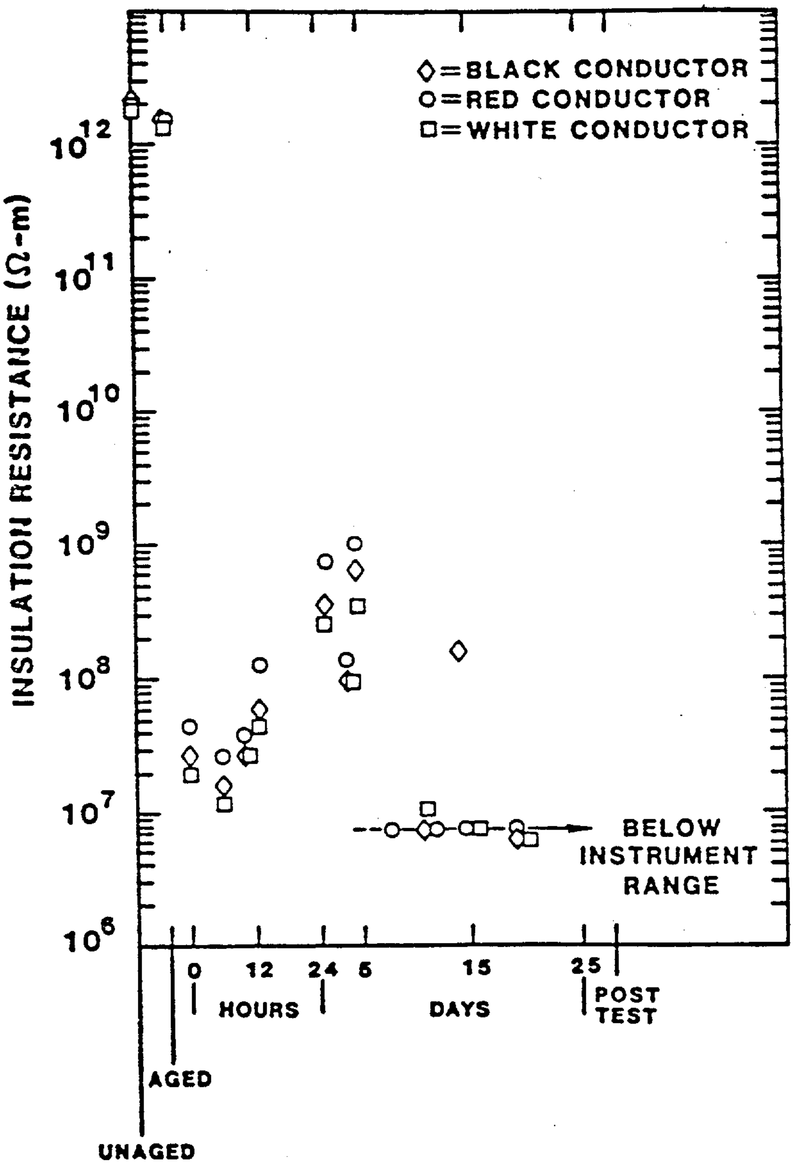

Figure 5.1 Insulation resistance for EPR-D multiconductor cable #2 during simultaneous test #2 (Ref. 5.10)

Table 5.3 Relative Tensile Properties of EPR-A after Aging and Sequential LOCA Irradiation (Ref. 5.10)

Aging Method	After Aging: Ultimate Tensile Elongation e/e_o	After Aging: Ultimate Tensile Strength T/T_o	After Sequential Accident Irradiation: Ultimate Tensile Elongation e/e_o	After Sequential Accident Irradiation: Ultimate Tensile Strength T/T_o
Unaged	$1.00 \pm .08$ ($360 \pm 30\%$)	$1.00 \pm .03$ (8.7 ± 0.3 MPa)	$.32 \pm .04$	$.65 \pm .03$
4 d T + R	$0.88 \pm .08$	$0.98 \pm .06$	$.26 \pm .03$	$.61 \pm .05$
30 T + R	< .03*	~ 0.2*	**	**
28 d T → 28 d R	$0.33 \pm .04$	$0.85 \pm .03$	$.18 \pm .03$	$.59 \pm .14$
28 d R → 28 d T **	< .03*	$0.26 \pm .07$*		**
28 d T → 55 h R	$0.31 \pm .04$	$0.99 \pm .21$	$.19 \pm .04$	$.64 \pm .06$
55 h R → 28 d T	$0.06 \pm .03$	$0.21 \pm .02$	~ .03	$.18 \pm .01$
7 d T + R	$0.03 \pm .03$	$0.26 \pm .02$	~ .03*	< .36*

NOTES:
(1) Errors reflect one standard deviation of three measurements.
(2) Insulation thickness is nominally 0.8 mm.
* Samples were extremely brittle and sometimes cracked in the pneumatic jaws used for the tensile measurements.
** Samples were too brittle to measure.

Table 5.4 Tensile Properties of EPR After Aging and LOCA exposures (Ref. 5.10)

	e/e_o			
	Sequential Test		Simultaneous Test #1	
Material	After Aging	After LOCA	After Aging	After LOCA
EPR-A	.29±.03	Uncertain	.05±.03	Uncertain
EPR-B	.37±.06	.20±.04	.28±.08	.14±.03
EPR-C	.38±.05	.13±.03	.58±.16	.15±.03
EPR-D	.41±.04	.06±.04	.19±.02	.13±.02
EPR-E	.34±.04	.05±.01	.49±.07	.19±.03

Table 5.5 LOCA Responses for EPR-1483 Material (Ref. 5.10)

Aging Conditions	After Aging	Steam Only			Sequential R-S			Simultaneous R+S		
	(e/e_o)	After 4 days (e/e_o)	After LOCA (e/e_o)	Weight Increase (%)	After 4 days (e/e_o)	After LOCA (e/e_o)	Weight Increase (%)	After 4 days (e/e_o)	After LOCA (e/e_o)	Weight Increase (%)
Unaged	1.00	0.96	1.02	-1	0.14	0.16	34	0.27	0.16	17
30d T + R	0.41	0.43	0.42	55	0.12	0.11	66	0.21	0.16	45
7d T + R	0.41	0.36	0.32	46	0.11	0.09	53	0.21	0.08	67
28d T-R(LDR)	0.47	0.42	0.44	5	0.11	...	...	0.23	0.16	22
28d T-R(HDR)	0.35	0.40	0.38	8	0.12	0.11	55	0.21	0.14	24
28d R-T(LDR)	0.41	0.43	0.46	12	0.12	0.11	63	0.22	0.16	30
28d R-T(HDR)	0.32	0.31	0.41	10	0.09	0.12	58	0.18	0.13	30

NOTES: LDR=Low dose rate (0.065Mrad/hr); HDR=High dose rate (0.85Mrad/hr); Aging+LOCA Radiation=175Mrad.
After 4 days=Post-transient; After LOCA=Post-LOCA; Weights were measured after LOCA.
7day T+R was performed at 0.29Mrad/hr and 139°C; 30d T+R was performed at 0.06Mrad/hr and 120°C. All other thermal aging was performed at 120°C.

Bustard (Ref. 5.11) presented the results for XLPO material from similar tests to those performed on EPR samples. XLPO-B was tested for all three test procedures (one sequential test, two simultaneous tests). XLPO-A and XLPO-C were tested for one of the simultaneous test program, in which both multiconductor and single conductor specimens were included for A and B, and multiconductor specimens for C. All thermal aging was done for 7 days at 139°C. An aging radiation dose of ~40Mrad and accident dose of ~110Mrad, with a total dose of approximately 150Mrad, were used. The LOCA included a 21-day exposure to saturated steam with 4 days of transient and 17 days of post-transient period; chemical spray was not used. XLPO-A and XLPO-C also were tested by the manufacturer for sequential conditions, including 7-day thermal aging conditions for XLPO-A at 150°C and that for XLPO-C at 136°C. Both were exposed to a total radiation dose of 200 Mrad before they were LOCA-tested for 30-day saturated steam conditions.

Bustard concluded that the electrical properties for XLPO-A and XLPO-B cables did not depend on whether single conductor or multiconductor was tested. The results for XLPO-B, which was exposed to all three test methods (aging and accident conditions for all three test methods were almost the same), indicated that there was no significant difference in the insulation resistance values between the three and that the testing technique did not impact the leakage current during post-test measurements. The electrical performances of XLPO-C during the simultaneous test and the sequential test performed by the manufacturers (with higher radiation doses and temperatures) were comparable.

Table 5.6 LOCA Responses for XLPO Materials (Ref. 5.11)

Material Specimens	Unaged Samples			Aged Samples			
	4d LOCA (e/e_o)	16d LOCA (e/e_o)	Weight Gain (%)	Aging (e/e_o)	4d LOCA (e/e_o)	16d LOCA (e/e_o)	Weight Gain (%)
XLPO-A	0.30	0.23	10	0.58	0.25	0.16(60%)*	15
XLPO-B	0.50	0.41	32	0.79	0.42	0.30(96%)*	58
XLPO-C	0.47	0.30	37	0.64	0.29	0.17(56%)*	25

* Values within bracket are absolute values of corresponding elongation at break.

Table 5.6 summarizes results from the simultaneous test sequence #2 for the three different XLPO materials. Aged samples absorbed more moisture than unaged samples except XLPO-C. It was suggested that XLPO-C underwent additional crosslinking during LOCA with a resultant reduction in moisture absorption. The weight and dimensional changes for these materials are substantially less than that observed for EPR-D whose jacket for multiconductor samples opened, presumably due to excessive dimensional changes during LOCA conditions.

Visually, the CSPE jacket on XLPO-C cables appeared substantially degraded by the simultaneous #2 test, consistent with the results from the previous study on EPR cables with an CSPE jacket. On the other hand, the CSPE jacket on XLPO-A showed no evidence of degradation after the same LOCA test. Thus, the degradation of this jacket material depends strongly on the specific manufacturer and cable product. Based on the manufacturer's data for XLPO-A and XLPO-C, sequential testing more severely degraded this jacket material than did simultaneous testing. Longitudinal and circumferential cracks were reported, as well as complete loss of the jacket from parts of the cable. The manufacturer's test was to high steam temperature (196°C versus 171°C) and the effect of this LOCA peak temperature has not been reported.

XLPO-B's Neoprene jacket also was substantially degraded by simultaneous test exposures compared with sequential testing. This was further verified by the Japanese tests (Refs. 5.12-5.14), discussed later, where more tensile degradation was observed for simultaneous than for sequential exposures.

The aging results in Reference 4.81 (see Section 4.3.3) were extended to include the influence of accident irradiation, steam, and chemical spray exposures on the behavior of pre-aged polymer samples. Both U.S. and French samples were tested at the French laboratories and the results were reported in Reference 5.15. The purpose of these tests was to observe the effect of the following factors on cable insulation materials during accident simulations: (1) the aging simulation method, (2) the order of accident simulation phases, (3) the comparison of reference accident simultaneous or sequential simulation, (4) the temperature during accident-phase irradiation and, (5) the presence or absence of oxygen during the accident simulations.

The following four accident simulations were performed on each of the five groups of pre-aged French samples (A,B,C,D, Unaged: as explained in Section 4.3.3):

> L1=R70-LOCA(air): Accident irradiation at 70°C, followed by thermodynamic and post-accident exposures with air.
> L2=LOCA(air)-R70: Reverse of L1.
> L3=R+LOCA(air): Simultaneous accident irradiation and thermodynamic exposures with air followed by a post-accident exposure with air.
> L4=R28-LOCA(air): Same as L1, except accident irradiation at 28°C instead of 70°C.

Experimentally, the LOCA simulation included both a thermodynamic (steam and chemical spray) and post-accident exposures. Results on French materials are not presented in this section; however, the reference documents give details.

For U.S. samples pre-aged by the six methods (A,B,C,D,E,and F=Unaged: as explained in Section 4.3.3), the accident simulation cycles were as follows:

> L5=R70-Steam(air): Same as L1.
> L6=R70-Steam(N_2): Same as L5, but air was replaced by nitrogen.
> L7=R28-Steam(air): Same as L4.
> L8=R28-Steam(N_2): Same as L7, but air was replaced by nitrogen.
> L9=R+Steam(air): Same as L3.
> L10=R+Steam(N_2): Same as L9, but air was replaced by nitrogen.

Experimentally, the LOCA simulation included both thermodynamic (steam and chemical spray) and post-accident exposures. The terminology LOCA(air) and Steam(air) refer to similar accident simulations. The average dose rate used in the French test program was approximately 300 krad/hr, and the irradiation time was calculated to obtain a maximum of 60 Mrad at the midpoint of each oven and each container. The vapor temperature, pressure, and chemical spray profiles were recommended by French nuclear safety organizations. Each test was comprised of two thermodynamic transients, followed by exposures to temperature, pressure, and chemical spray. During the second thermodynamic exposure, beginning 220 seconds after the start of the test, the sample were sprayed with borated solution (H_3BO_3=15 g/l and NaOH=6 g/l) at pH 9.25; the spray rate was 6.1 liters/min per square meter of horizontal section of the chamber, and lasted for 24 hours. After the LOCA exposure was over, the samples were exposed to 100°C and ~100% relative humidity for ten days.

Figures 5.2 to 5.13 show the results from this test program for the U.S. samples only. The report has similar plots for the French materials. The tensile elongation plots are normalized by their unaged values which allows an evaluation of the most conservative combinations of aging and accident simulation techniques. Plots indicating "accident effect only" have the tensile elongation value normalized by their after-aging values to illustrate the accident method's contribution to the degradation of mechanical property. Since the tensile properties alone may not indicate the severity of degradation in the insulation materials after the LOCA exposures, the moisture-absorption data (i.e., weight gain) also are plotted. For all these plots, the aging technique employed is displayed in the X-axis and the measurement location in the test sequence is indicated by the plotting symbols.

CSPE

Figures 5.2-5.4 present the test results for the U.S. CSPE material. Figure 4.52 in section 4 shows the aging results from different combinations of the environmental conditions. Figure 5.2 shows that there is not a large difference in results between alternative accident-exposure techniques. The influence of the aging technique is more pronounced; the R70-T and the R120 aging exposures lead to the most severe degradation. Since after the R70-T aging sequence, elongation already was substantially degraded (to 6% of the original value), the large scatter in additional degradation due to different accident simulation strategies is shown in Figure 5.3. Figure 5.4 shows the weight gains up to 35% for certain CSPE samples. *For this material, the R70-T aging sequence followed by any accident sequence is considered appropriate.*

For the French material, the R+LOCA(air) exposure was less damaging than all the sequential aging and accident techniques. *Hence, any sequential accident exposure qualification procedure is appropriate.*

CPE

Figure 4.53 shows the tensile properties for different aging sequences. The two R-T sequences reduced the ultimate tensile elongation to approximately 10-15% of its original value. After the accident exposures, most CPE samples had a value less than or equal to 0.1. Samples pre-conditioned by R120, T-R70, R27-T, and T-R27 yielded similar elongation values (see Figure 5.5). Moisture-absorption data is shown in Figure 5.6; the weight gains generally appear to be independent of the preaging technique used before the start of the accident simulations. *For this material, the R70-T aging technique followed by any accident simulation is considered appropriate.*

EPR

Two U.S. and three French samples were tested in this program. Figures 5.7 - 5.9 show the results for one U.S. EPR-1 material. Each material underwent a different combination of aging and accident simulation procedures. However, the R-T aging sequence satisfied all five materials. For French materials, the R70-LOCA (air) simulation approached the R+LOCA(air) results best. For U.S. materials, the use of a nitrogen atmosphere during the accident simulation was found to be less conservative, unless the containment is inerted. Also, the R120 and T-R27 aging techniques would be less conservative than the other three aging techniques. *Although each sample of this material had a different simulation scenario, a R-T aging sequence followed by the R70-LOCA (air) accident simulation is the preferred combination.*

XLPO

Two U.S. and one French samples are represented this material; Figures 5.10 - 5.12 show the results for one U.S. sample. The U.S. materials were irradiation cross-linked, while the French material was chemically cross-linked. The effect of alternative accident simulation techniques on the two U.S. materials is vastly different than that for the French material. However, the choice of aging simulation is less important than the choice of accident simulation. *For both U.S. materials, any sequential simulation is appropriate. For French material, any aging simulation followed by the R70-LOCA(air) accident simulation is preferred.*

Tefzel

Two U.S. samples were included in this category. Figure 5.13 shows the weight loss for one of these materials. A similar trend also was observed for the other samples. For each combination of aging and accident simulations, four samples were successively wrapped around tubes of smaller diameter until insulation cracking or breakage was observed visually. Both materials were more degraded when oxygen was present during simultaneous LOCA simulations (R+Steam). *If sequential qualification procedures are employed, then it is desirable to perform the aging and accident irradiation at elevated temperatures (i.e., 70°C). The aging sequence should be R70-T. Any accident simulation consistent with these constraints is acceptable.*

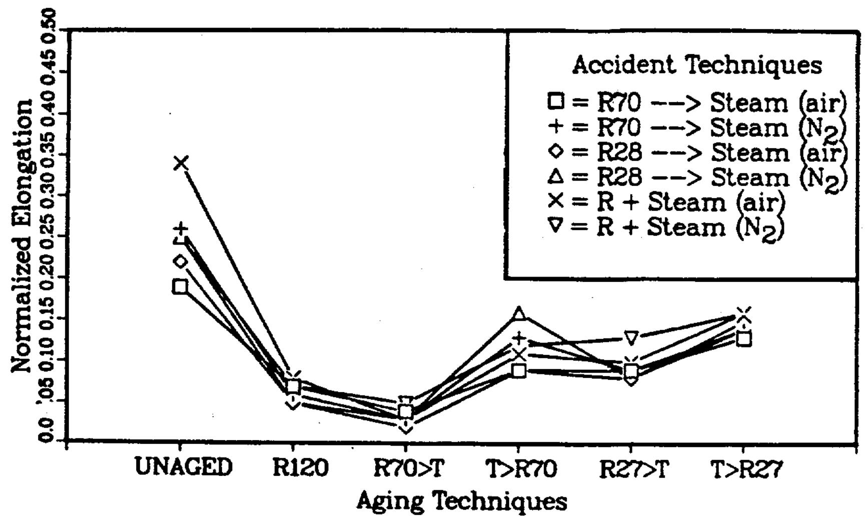

Figure 5.2 Ultimate tensile elongation of CSPE (Ref. 5.15)

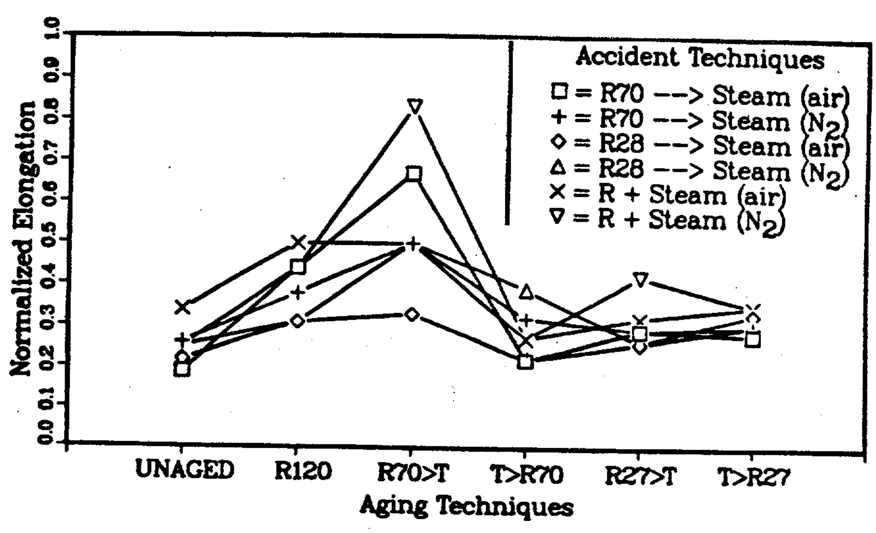

Figure 5.3 Ultimate tensile elongation of CSPE (accident effect only) (Ref. 5.15)

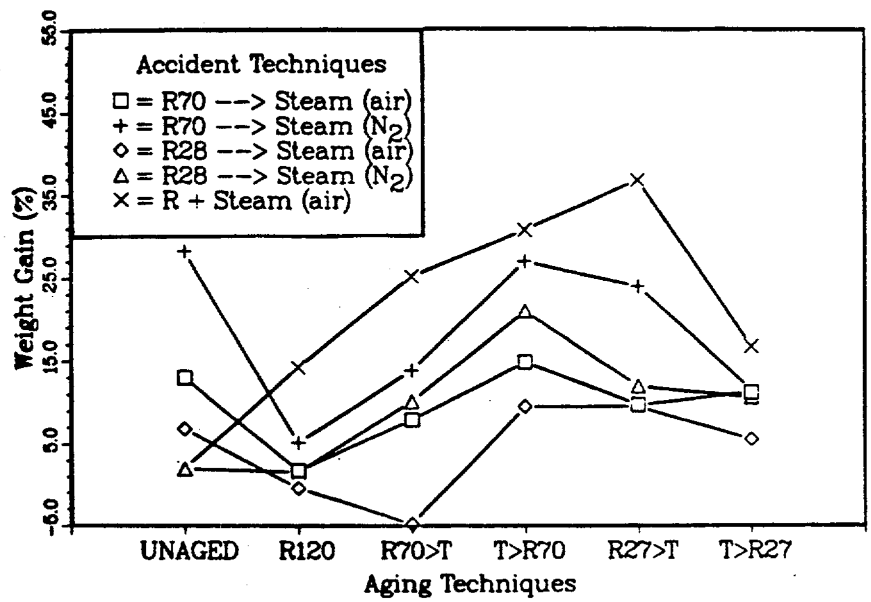

Figure 5.4 **Weight gain of CSPE** (Ref. 5.15)

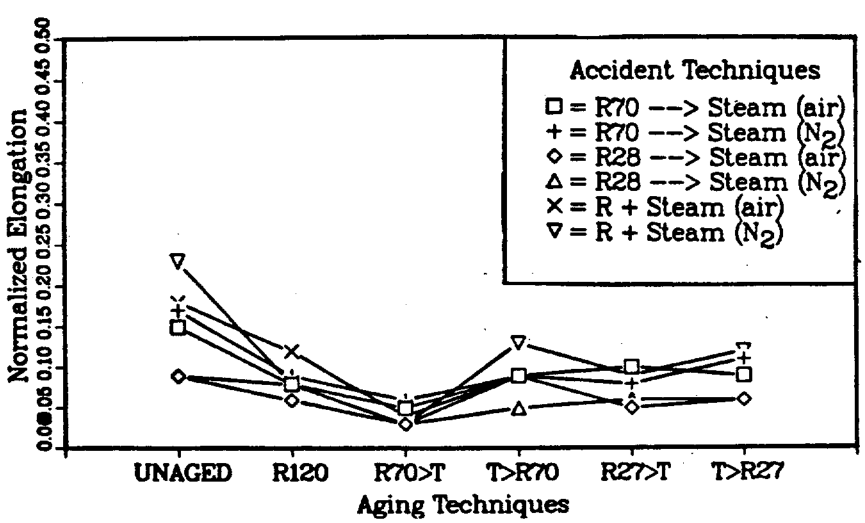

Figure 5.5 **Ultimate tensile elongation of CPE** (Ref. 5.15)

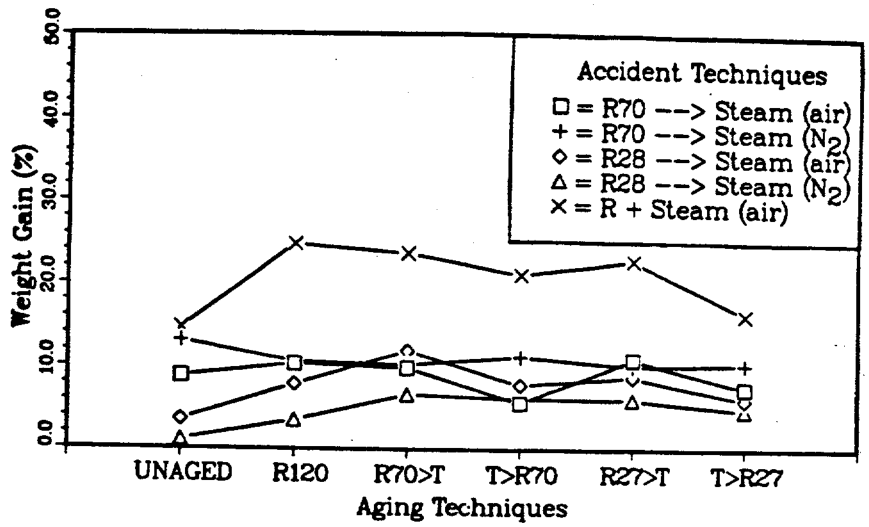

Figure 5.6 Weight gain of CPE (Ref. 5.15)

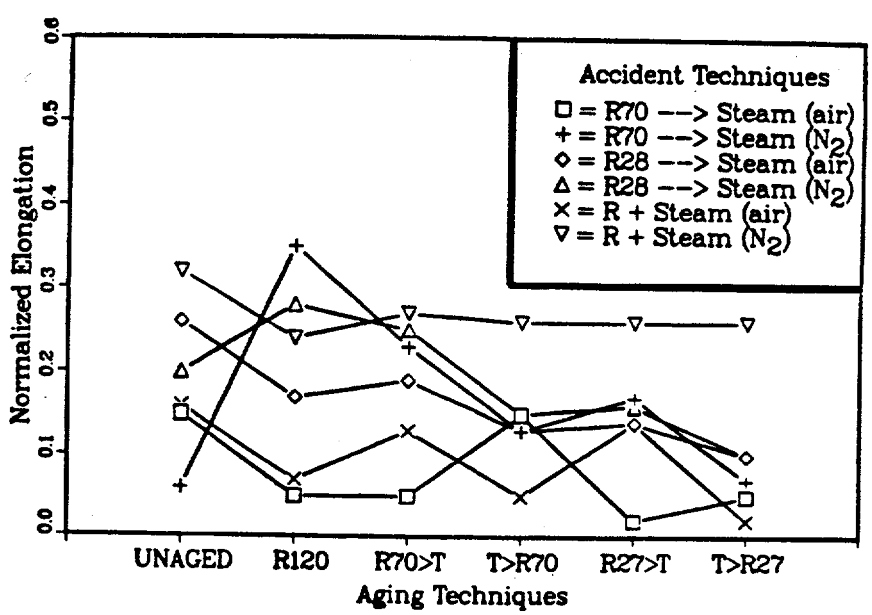

Figure 5.7 Ultimate tensile elongation of EPR-1 (Ref. 5.15)

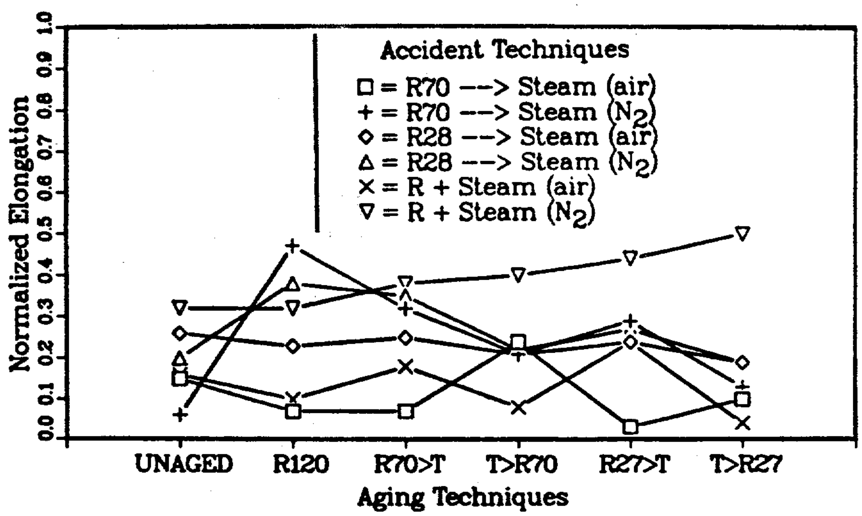

Figure 5.8 Ultimate tensile elongation of EPR-1 (accident effect only) (Ref. 5.15)

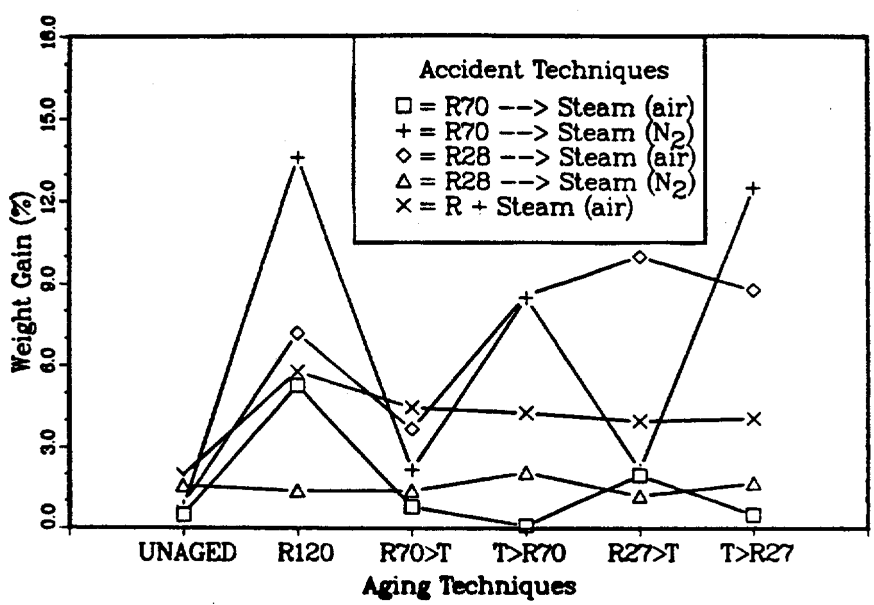

Figure 5.9 Weight gain of EPR-1 (Ref. 5.15)

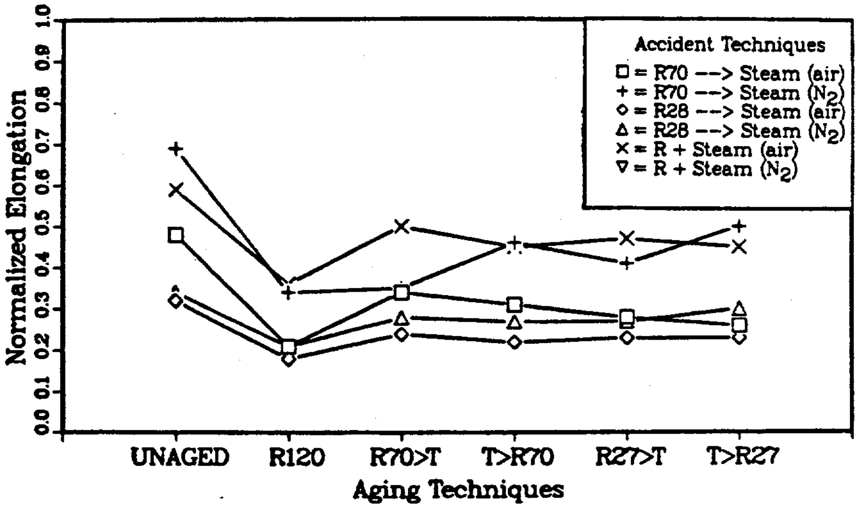

Figure 5.10 Ultimate tensile elongation of XLPO-1 (Ref. 5.15)

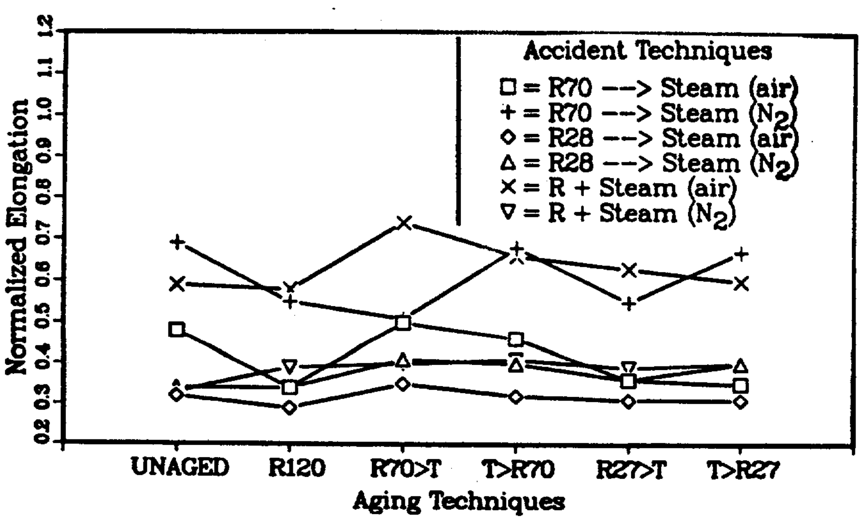

Figure 5.11 Ultimate tensile elongation of XLPO-1 (accident effect only) (Ref. 5.15)

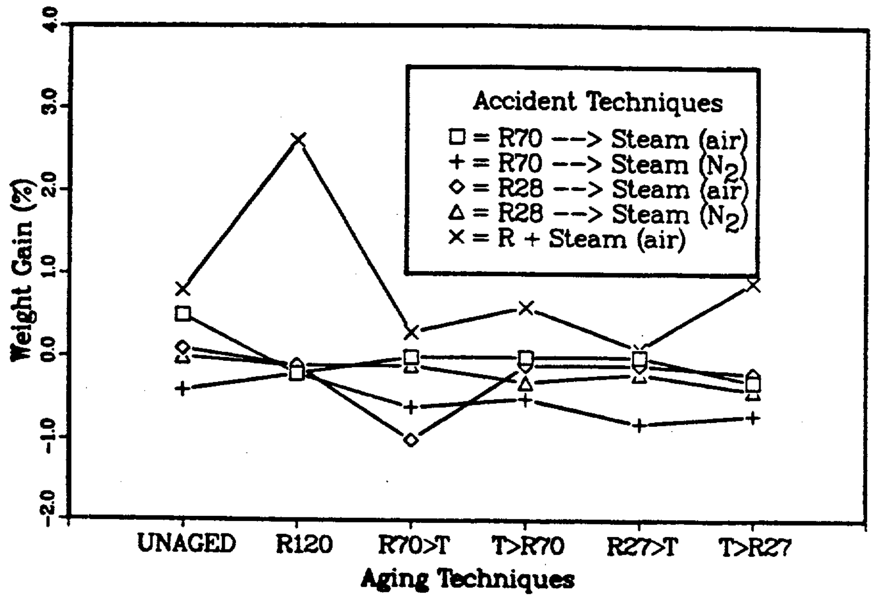

Figure 5.12 Weight gain of XLPO-1 (Ref. 5.15)

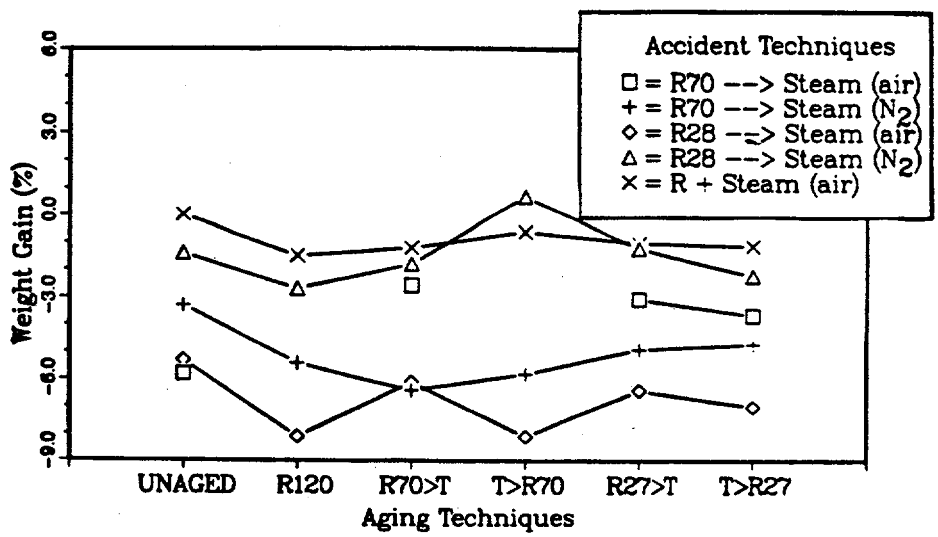

Figure 5.13 Weight gain of Tefzel-1 (Ref. 5.15)

Summarizing the results in this program, cable materials were subjected to a thermal aging, radiation aging of 25Mrad @0.1Mrad/hr and 70°C, accident radiation of an additional 60Mrad @0.3Mrad/hr and 70°C, 4-day LOCA transient at saturated steam condition and chemical spray, and 10 days of post-transient period at 100°C and 95% humidity. U.S. materials were aged in six different procedures in addition to unaged samples(see Section 4.3.3) and exposed to six different accident conditions (L5 to L10 discussed earlier). Based on the results presented from all possible combinations of the aging and accident sequences, the following observations are made:

(1) Two XLPO insulation materials behaved differently and both still possessed at least 70% of elongation (absolute) at the end of testing. One material exhibited a small weight loss (<1%) during steam exposure, while the other had weight gain of 2-6%. In sequential accident simulations, the elongation values improved from their post-radiation conditions after being exposed to steam. The results from sequential tests were more severe than from simultaneous tests.

(2) Two EPR insulation materials behaved differently. One material exhibited weight gain of 1-12% during steam exposure, while the other gained 8-50%. Both materials had a remaining elongation of 7-150%(absolute), with a large number of cases exhibiting less than 50%(absolute) at the end of testing. The elongation values did not improve, in general, during steam exposure from their post-radiation conditions. Both sequential and simultaneous simulations yielded almost similar results.

(3) For the CSPE jacket material, the weight changes ranged from -5% to 37%, while the remaining elongation values after testing were below 50%(absolute) excepting unaged samples which possessed about 100%(absolute) or larger. No particular difference was noted between all possible different aging and accident simulations. No significant change in elongation occurred during steam exposure.

(4) The results for CPE were more or less similar to those responses observed for CSPE.

Bonzon and his colleagues (Ref. 5.7) discussed several Japanese studies. The tensile properties for two EPR materials were monitored in simultaneous, sequential (150 Mrad - Steam/Chemical), and reverse- sequential tests (Ref. 5.12); there was very little difference between the results. However, the sequential method was most destructive and the simultaneous method was intermediate between the sequential and the reverse-sequential methods. Reference 5.7 indicated that one Japanese manufacturer's study compared the tensile properties of a flame-resistant EPR with Hypalon jacket and concluded that there was no synergistic effect. In Reference 5.13, both BWR and PWR LOCA conditions were simulated with and without air. The total accident radiation doses were 150 Mrad for PWR and 26 Mrad for BWR. Pre-aging for all specimens was a sequential exposure to high temperatures (7 days at 121°C) followed by irradiation (50 Mrad). When air was not included during the PWR accident simulations, sequential techniques seemed appropriate for most materials including EPR and XLPE. However, when air was present, simultaneous techniques were more damaging. In BWR simulations, the radiation dose was not sufficient enough to promote oxidative degradation. Similar observations were presented in Reference 5.14. For both Hypalon and EPR materials, the ultimate tensile elongation was dominated by the total radiation dose and affected only slightly by the test sequence. However, the ultimate tensile strength for both materials was affected considerably by the test sequence. Simultaneous tests with air was the most degrading, and without air the least.

5.2 Effect of Superheated and Saturated Steam Conditions

Bennett, Clair, and Gilmore (Ref. 5.16) discussed the results of a superheated steam test conducted on three different EPR cable products. Unaged and simultaneously aged (282°F for 168 hours and 40 Mrad, 40 year equivalent) cable specimens were tested in a simultaneous radiation and steam environment. The cables were energized at 480 V and 0.6 A throughout the exposure, and insulation resistance was measured periodically.

They compared the results obtained by Bustard (Ref. 5.10), in which similar cable products were tested under saturated steam. The cables were exposed to the same IEEE Std 323-1974 (Ref. 5.1) temperature profiles in both tests (340°F peak), but the chamber pressure was maintained at 77 psia for the two peaks and the first 320°F plateau during the superheat test. Cable specimens included single conductors and multiconductors; however, only one cable set was the same for both tests. The report summarizes the following comparisons of results:

(1) Single conductor cables exhibited high IR readings and low leakage currents in both tests.
(2) Both tests showed the following results for the multiconductor cables:
    - the jacket had a longitudinal split;
    - the exposed gap in the jacket was approximately 0.6 cm wide;
    - bare conductors were visible;
    - the circumference of the jacket increased during the test, although the increase was not large enough to contain the bundle of conductors;
    - the cables had large leakage currents after one minute at the following voltages:

Saturated Steam	Superheated Steam	
600 V: 180-750 mA	600 V:	2 mA
	1200 V:	5 mA
	1800 V:	750 mA

    - the values for insulation resistance followed the same pattern throughout the tests except that in the superheated-steam test the readings were below the instrument's range at 19-21 days, whereas in the saturated-steam test, the readings were below the instrument's range at approximately 8, 12, and 18 days into the accident.

The report concluded that (1) the results from single conductor cable tests may not be conservative for qualifying multiconductor cables; (2) superheat has little effect on cables other than slightly delaying the time of failure; and (3) the differences between the electrical degradation of single and multiconductor cables do not appear to be generic to all cables.

5.3 Effect of Radiation Dose-Rates During Accident Simulations

Bustard (Refs. 5.10 and 5.11) discussed the effects of LOCA simulation procedures on EPR and XLPO insulation materials, respectively. The test series include both sequential and simultaneous aging and LOCA radiation exposures in the range of 0.08 - 0.7 Mrad(air)/hr. Material degradation was monitored twice during a saturated-steam LOCA simulation. Some samples were removed after a 4-day LOCA exposure that included a simultaneous exposure to radiation (~65 Mrad at ~0.68 Mrad/hr); the remainder of the samples were tested after another 12-17 days of exposure that included simultaneous exposures to an additional 44 Mrads at lower dose rates (~0.2 and ~0.08 Mrad/hr). Examination of the two sets of data (Table 5.7), allows a qualitative assessment of the importance of the low dose-rate "tail" of the LOCA exposure to material degradation.

Ito and his co-workers (Ref. 5.17) reported a test of electric cable materials conducted to simulate post-LOCA conditions on an accelerated basis. A three-month, 55 krad/hr test was compared against a one-week, 925 krad/hr test, both with and without oxygen present; Table 5.8 summarizes some of these results. Degradation at low dose rates used in 3-month testing were higher than at high dose rates in one week. These results should be taken as a qualitative indication of accident dose-rate effects on the materials tested, since other factors (such as presence of oxygen) may not have had an effect. The effect of oxygen was significant during the three-month LOCA simulation.

Table 5.7 Comparison of Tensile Elongation and Weight Gain for EPR and XLPO (Refs. 5.10 and 5.11)

Material	4-day LOCA Exposure		21-day LOCA Exposure	
	e/e_o	%Wt. Gain	e/e_o	%Wt. Gain
A: Properties for EPR During Simultaneous Test #1				
EPR-B	0.17	0	0.14	-1
EPR-C	0.21	9	0.15	23
EPR-D	0.13	120	0.13	173
EPR-E	0.27	N/A	0.19	N/A
B: Properties for EPR and XLPO During Simultaneous Test #2				
EPR-D (Unaged)	0.33	16	0.25	23
(Aged)	0.16	144	0.18	172
EPR-F (Unaged)	0.28	8	0.10	20
(Aged)	0.22	59	0.10	94
XLPO-A(Unaged)	0.30	4	0.23	10
(Aged)	0.25	9	0.16	15
XLPO-B(Unaged)	0.50	15	0.41	32
(Aged)	0.42	33	0.30	58
XLPO-C(Unaged)	0.47	26	0.30	37
(Aged)	0.29	14	0.17	25

Table 5.8 Rate of Decrease (K) in Ultimate Elongation Under LOCA (1/100 Mrad) (Ref. 5.17)

Sample	Non Air		Air 0.05MPa	
	One Week	Three Months	One Week	Three Months
EPR-A	0.40	0.40	0.83	1.57
EPR-B	0.46	0.46	0.74	1.46
CSPE-A	0.56	1.00	0.77	1.60
CSPE-B	0.80	1.11	1.09	2.14

Decay curves are taken as Maxwellian (i.e. $e_t/e_o=\exp(-Kt)$ where K is rate of decrease and similar to activation energy for a total irradiation of 100 Mrad.

Kusama and his colleagues (Ref. 5.18) studied five different Japanese cable materials irradiated at different dose rates and steam/spray at different temperatures. Figure 5.14 illustrates radiation effects at different dose rates on the elongation at break values for these materials. All had lost their elongation by the end of 2MGy (200Mrad) radiation dose. The XLPE and, to some extent, Hypalon exhibited some dose rate effects. However, when these aged specimens (with 1.5 MGy irradiation) were exposed to steam/spray conditions at 120°C, the LOCA responses for each of these materials were quite different, as shown in Figure 5.15.

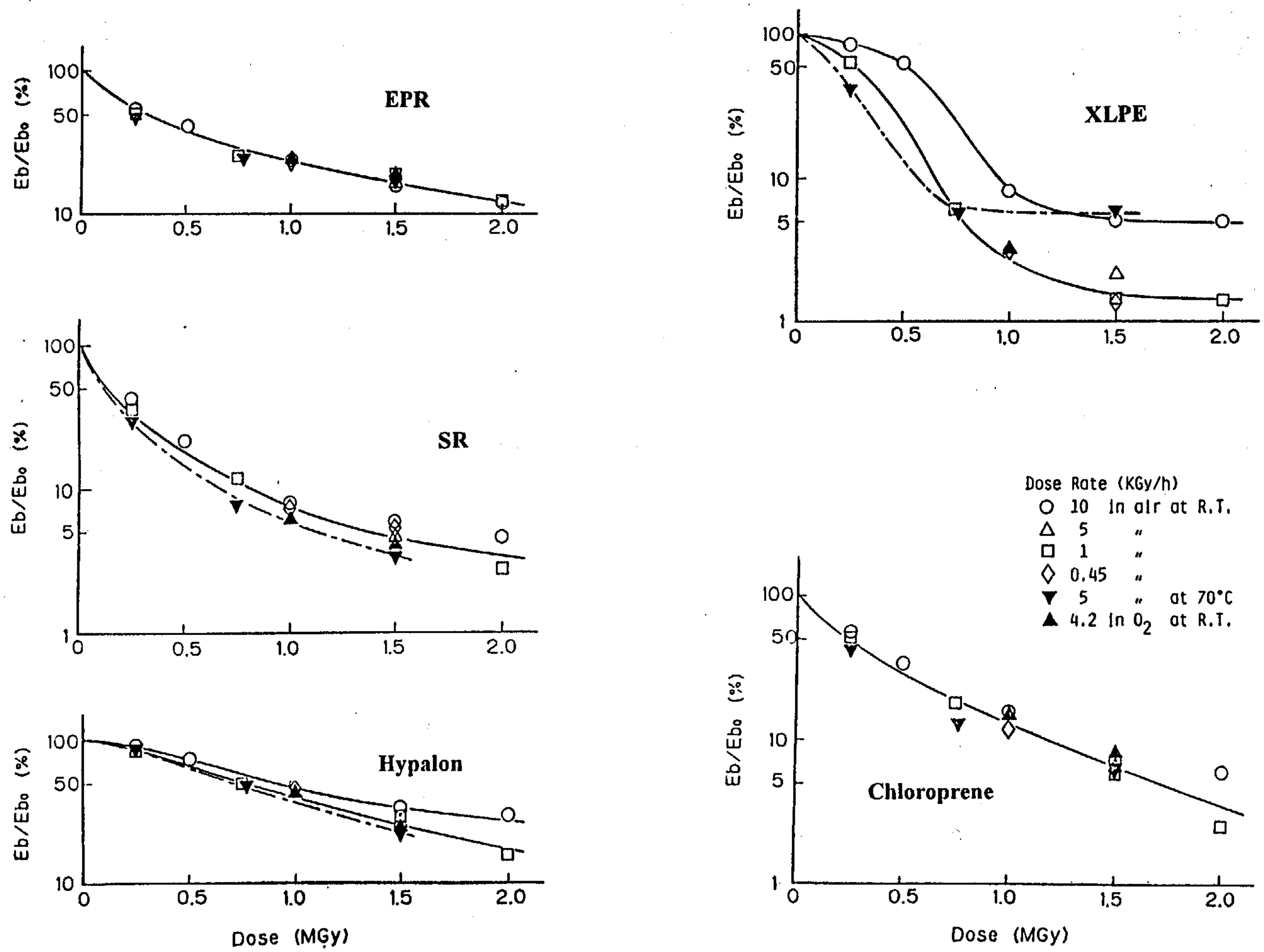

Figure 5.14 Elongation at break during irradiation for Japanese Cable Materials (Ref. 5.18)

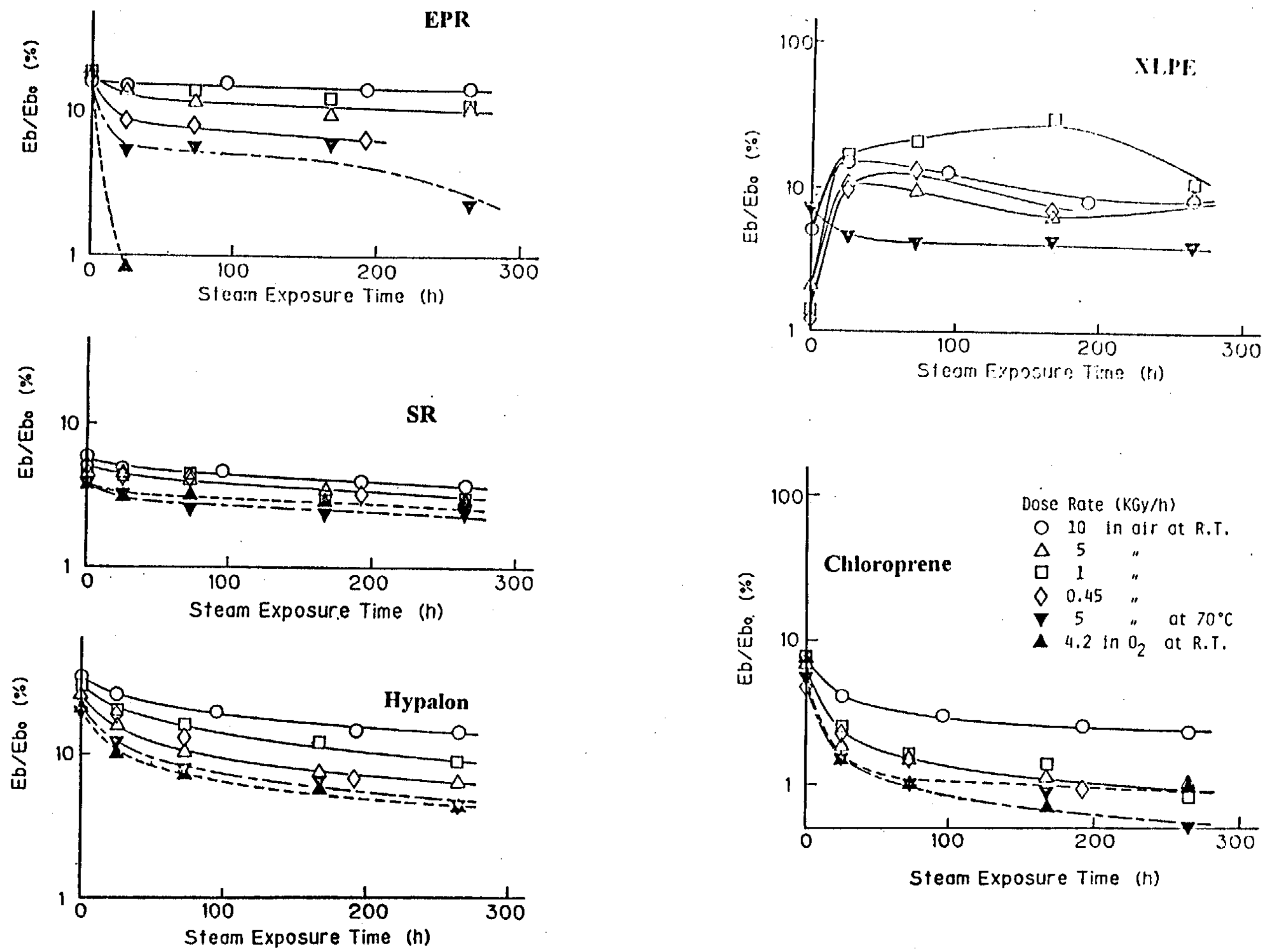

Figure 5.15 Effect of radiation aging on steam/spray exposure for Japanese materials (Ref. 5.18)

For EPR, specimens irradiated at low dose rates degraded significantly more than those at high dose rates. In the case of XLPE, which indicated dose-rate effects during irradiation, degradation during steam exposure was not significant; instead elongation improved. The results for SR indicated no significant dose-rate effect during steam exposure. Both Hypalon and chloroprene jacket materials exhibited a large decrease in elongation with some dose-rate effects. All materials aged at elevated temperatures and in a pressurized oxygen environment underwent significant loss in elongation when compared to those irradiated in non-oxidative conditions.

The volume resistivity of EPR and XLPE decreased remarkably when the samples were irradiated at lower dose rates; EPR showed a more significant decrease. It was hypothesized that unstable oxidized species formed during irradiation did not affect the tensile properties, but decomposed during steam exposure promoting mechanical degradation. Formation of these species depends on oxygen diffusion during irradiation and at low dose rates, this diffusion through samples can be significant. This diffusion process also can be enhanced at high temperature or in pressurized oxygen. Higher water absorption on these oxidized samples was observed during steam exposure, as well.

Figure 5.16 shows the effect of steam temperature on tensile properties and water sorption for Hypalon and EPR. Samples irradiated to 1.5MGy with a dose rate of 10kGy/hr were exposed to steam conditions at 120°C, 140°C, and 160°C for 264 hours. Both electrical and mechanical properties degrade significantly with the increase in steam temperature, especially in air-containing environment. The decrease in volume resistivity was presumed to be due to water molecules absorbed in the material and the process was further promoted in an elevated temperature and air-containing environment. In case of SR, this effect was not noted; however, a larger decrease in elongation at a higher steam temperature was assumed to be caused by hydrolysis of the material in the presence of chemical spray.

5.4 Effects of Beta and Gamma Radiation During LOCA Exposures

Bonzon (Ref. 5.19) was the first to define the radiation exposure during a LOCA event and his study had three significant results: (1) A definition of the expected magnitudes of combined gamma and beta dose and rates for a typical PWR containment; typical values of initial dose rate are 3.5 and 70 Mrad/hr, and of 30-day dose are 50 and 300 Mrad, respectively; (2) The beta dose and rate are about six times greater than the corresponding gamma values; (3) The gamma and beta spectra exhibit a changing energy with time, not typical of mono- or fixed-energy simulators. For both, the spectra are initially "hard", then "soften" until a minimum at about 4 days post-LOCA, then "reharden".

Leadon and Lurie (Ref. 5.20) identified five different failure mechanisms caused by the radiation exposure: (a) The failure mechanism is basically chemical, resulting in crosslinking and then chain scission, accompanied by evolution of gas. This occurs generally in low-dose rate and high dose environments. Gas evolution can result in bubble formation on the cable materials. (b) Radiation-induced heat can cause deterioration of cable polymers and their bondings. Synergistic effects could be important. (c) Non-uniform charge distributions in insulation can result from either incident gamma rays or electrons. (d) High incident dose rate can cause transient electrical signals in the cable. (e) Discharge of trapped electrons can cause transient electrical signals and noise in the cable. An evaluation by the authors on nuclear power plant cables concluded that chemical and mechanical deterioration of the insulation, exacerbated by a large temperature rise, would be the most significant. These damages depend on the total dose and hence, can be adequately caused by nearly any type of radiation source.

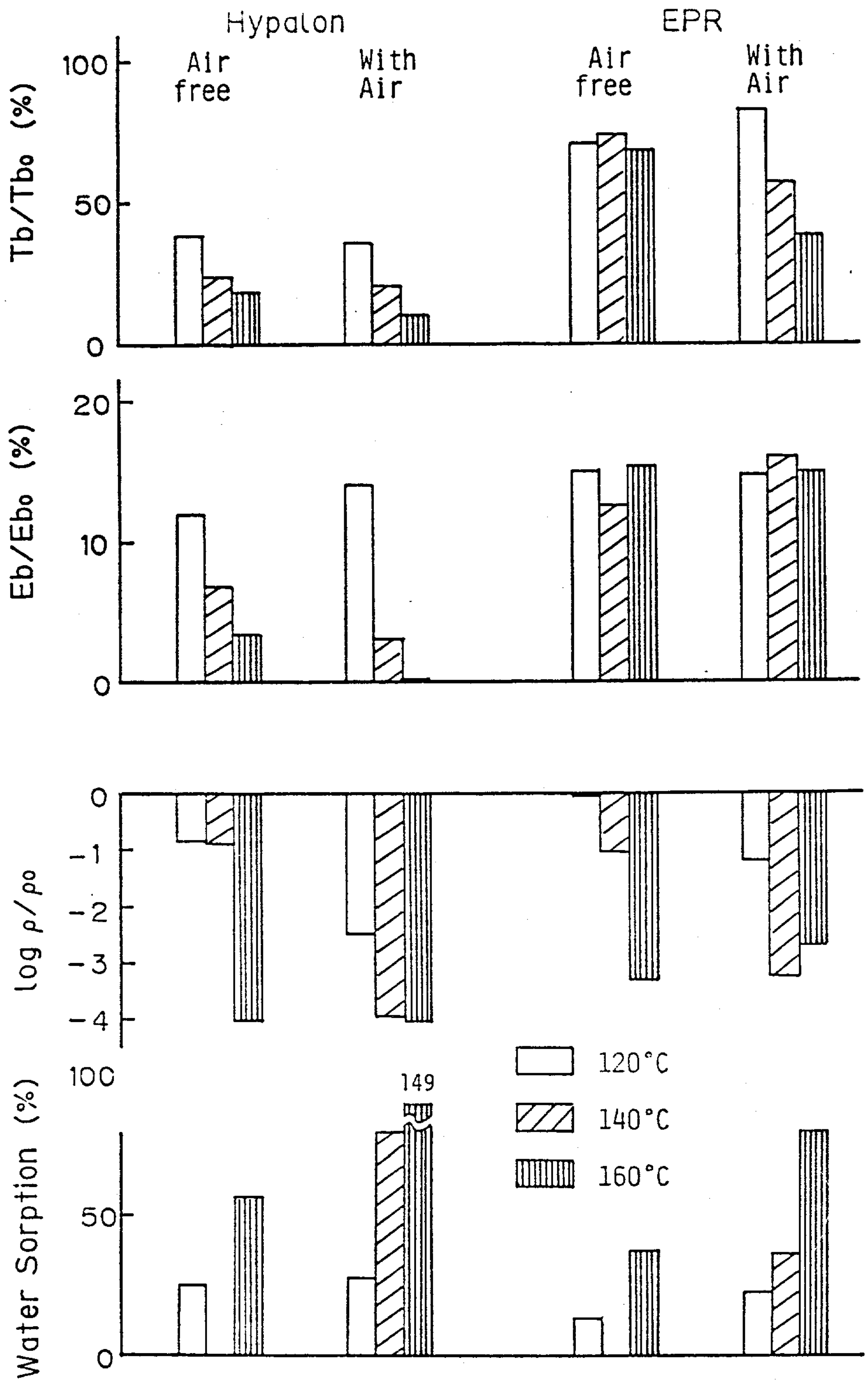

Figure 5.16 Effect of steam temperature on irradiated Japanese cables (Ref. 5.18)

Buckalew and his co-workers (Ref. 5.21) investigated charge breakdown from beta irradiations of EPR insulation material slabs and typical electric cables. Under certain conditions, charge accumulated and spontaneous breakdown occurred during irradiation in a vacuum; however, there was no evidence of breakdown during ambient air exposures. It was concluded that buildup and breakdown of electron charge is not apt to occur in EPR insulation exposed to electrons from a LOCA radiation environment, provided that the insulation is in contact with an ionized medium.

They were concerned with the adequacy of isotopic photon sources (e.g., ^{60}Co) to simulate the combined beta-gamma radiation environment accompanying a LOCA. A multi-year NRC/French/SNL cooperative test program was initiated, including a study of any synergistic effects associated with a mixed beta/gamma radiation field. They discussed the first results obtained by the complementary beta-gamma equivalence test program at Sandia (Ref. 5.22). These tests attempted to identify the degree to which factors, such as (1) differences in energy deposition profiles between electrons and photons, (2) differences in energy deposition for each particle type, and (3) differences in radiation-induced damage mechanisms (e.g., cross-linking, charge build-up/breakdown) might influence the dose-damage equivalence in certain organic materials.

These tests considered one EPR formulation in slabs of three different thicknesses (1, 1.5, and 2 mm), exposed to ^{60}Co or accelerated electrons at energies ranging between 0.235 and 0.85 MeV. In each case, the samples were irradiated at 2 Mrad/hr to 10 Mrad/hr. Analyses of the radiation-exposure data (tensile elongation and strength) suggest that the observed damage is a slowly varying function of absorbed energy and independent of particle type, within experimental uncertainty. Absorbed energy, particle energy, and surface dose are all interrelated parameters, and the data analysis on the basis of these parameters yields similar results. Data on material thickness indicates that, for the energies and thicknesses considered, the distribution of energy deposition within the sample is not significant; rather, damage is a function only of the total energy absorbed.

They provided the results of the U.S./French research program which investigated the relationship between the damage from beta and gamma radiation in polymer base materials used for cable insulations and jackets (Ref. 5.23). The results obtained for the thinner slab-geometry specimens reinforced the conclusions of the earlier studies, namely, that beta- and gamma-ray induced damage could be related on the basis of average absorbed radiation dose. However, data from thicker (4 and 6 mm) slabs were in disagreement, and displayed some effects of the material's thickness on its response. However, the preponderance of the results predict an equivalence between beta and gamma radiation damage on the basis of radiation-absorbed dose.

The results obtained for the EPR and Hypalon materials in a cylindrical cable geometry were similar to those obtained for the EPR materials in a slab configuration. Again, some slight deviations in the data were observed. However, the preponderance of data for cylindrical specimens indicate that electron beams and cobalt gamma-ray induced damage can be related on the basis of average absorbed radiation dose. Thus, it appears possible to qualify materials for beta radiation damage by exposing them in gamma ray irradiators. The study concludes that the results also can be used to estimate radiation damage to polymers exposed to the large beta dose rates associated with the release of fission products into a containment during accidents.

They concluded that ^{60}Co irradiators represent a conservative method of simulating the LOCA environment which is a mixture of both beta and gamma radiations (Ref. 5.24). Results for a cable with EPR insulation and Hypalon jacket predicted that conventional LOCA radiation simulation testing of jacketed cable components would overstress the jacket and insulation materials by factors of two and five, respectively. Shielding of the insulation (EPR) by the Hypalon jacket and enhancement of the EPR gamma dose by reflection from copper conductor also were noted. They considered that this conclusion may not be appropriate for radiation exposure of 1000 Mrad level.

5.5 Effect of the Presence of Oxygen During LOCA Exposures

The effects of oxygen on polymer materials were discussed in Reference 5.15, and Figures 5.2-5.13 illustrate the results with air and nitrogen environments for various simultaneous and sequential tests. For some materials, the presence of oxygen during accident simulations enhanced the degradation of tensile properties. For EPR materials, the tensile elongation was more degraded by LOCA simulations that included oxygen than those that did not. Oxygen also was important to the degradation of Tefzel materials for some aging and accident simulation techniques. For example, simultaneous steam, chemical spray, and radiation exposures typically were more degrading if there was an overpressure of oxygen rather than an overpressure of nitrogen. The presence of oxygen was not important for CSPE and CPE samples. For XLPO materials, a simultaneous accident simulation with oxygen typically was the least degrading. The report concluded that the presence or absence of air during accident simulations can influence the degree of degradation in some materials.

Gillen and his colleagues (Ref. 5.25) presented the results of the cooperative U.S.-French test program where nine materials commonly used as electric cable insulations and jackets were monitored in terms of mechanical properties, weight increases, solubility measurements, and infrared spectroscopy. Three different LOCA simulation tests were employed. In addition to a steam environment, the three simulations used 0% oxygen (L-0: containing nitrogen), 10% oxygen (L-10), and air (L-21: 21% oxygen) with constant gas pressures. Figures 5.17 - 5.24 illustrate the ultimate tensile properties for the different polymer materials. In each Figure, the circles give the results measured at Sandia, and the triangles denote those obtained from CEA-ORIS-STBR, France. The numbers on the abscissa refer to four aging conditions: (1) unaged; (2) 21 Mrad at 880 krad/hr; (3) 45 Mrad at 880 krad/hr; and (4) 23 Mrad at 24 krad/hr.

The chloroprene material, shown in Figure 5.17, appeared to suffer significantly more damage in LOCA simulations containing oxygen, a conclusion which was valid even for samples which were not aged. EPR (see Figure 5.18) also had substantially decreased tensile properties when oxygen was included; solubility, swelling ratio, and FTIR results indicated that increased oxidative scission enhanced the degradation. On the other hand, for a PVC material, the damage may become more severe as the oxygen content is lowered, as shown in Figure 5.19 (slightly greater mechanical damage, substantially greater swelling). Thus, a LOCA simulation without oxygen may underestimate the changes which occur in some materials, while overestimating the changes in others.

These results have important implications for material qualification testing relative to a LOCA. Since very low leak rates are designed into containment, it appears that the original oxygen content in the air is largely trapped in the containment area for the duration of the accident. Since there is no mechanism for replenishing oxygen, its concentration might decrease as the accident progresses due to leakage and its reaction with the material in containment. Therefore, it is important to estimate the time-dependent oxygen concentration during a LOCA more precisely, and to use it as a guide to the proper oxygen concentration to use in LOCA simulations.

For EPR insulation, which previously showed dose-rate effects during aging, evidence was found for dose-rate-induced effects being further amplified during the LOCA simulation. Another finding includes the widely varying responses of different materials to the aging and LOCA simulation sequences in terms of the kind and magnitude of the induced degradation. PVC and chloroprene exhibited huge steam-induced swelling. CLPO (Figure 5.20) and Silicone (Figure 5.22) were degraded by aging, but showed little or no further deterioration in a subsequent LOCA simulation. Tefzel (Figure 5.23), chloroprene, and PVC showed moderate to significant aging-related degradation, which was strongly amplified by the subsequent LOCA simulation.

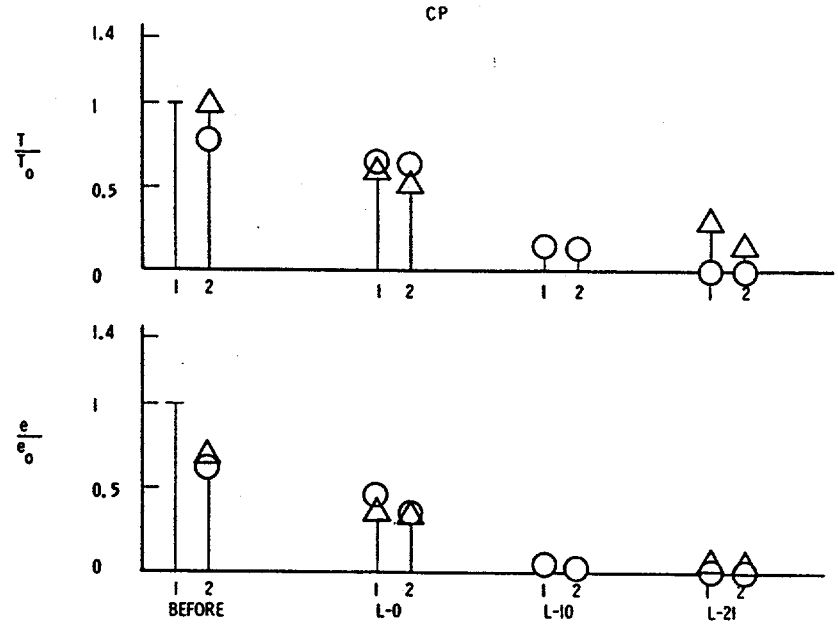

Figure 5.17 Tensile property results for CP (Ref. 5.25)

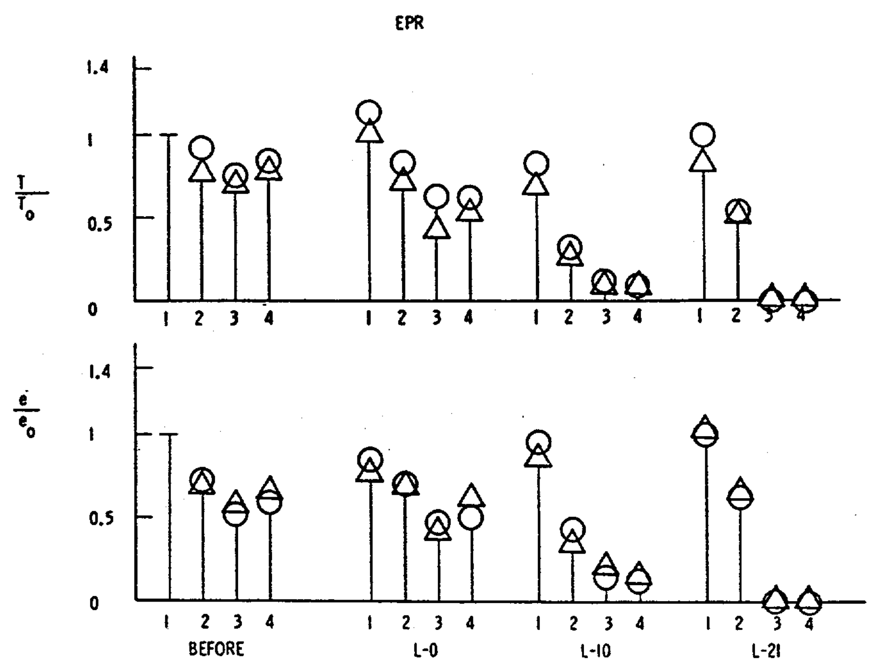

Figure 5.18 Tensile property results for EPR (Ref. 5.25)

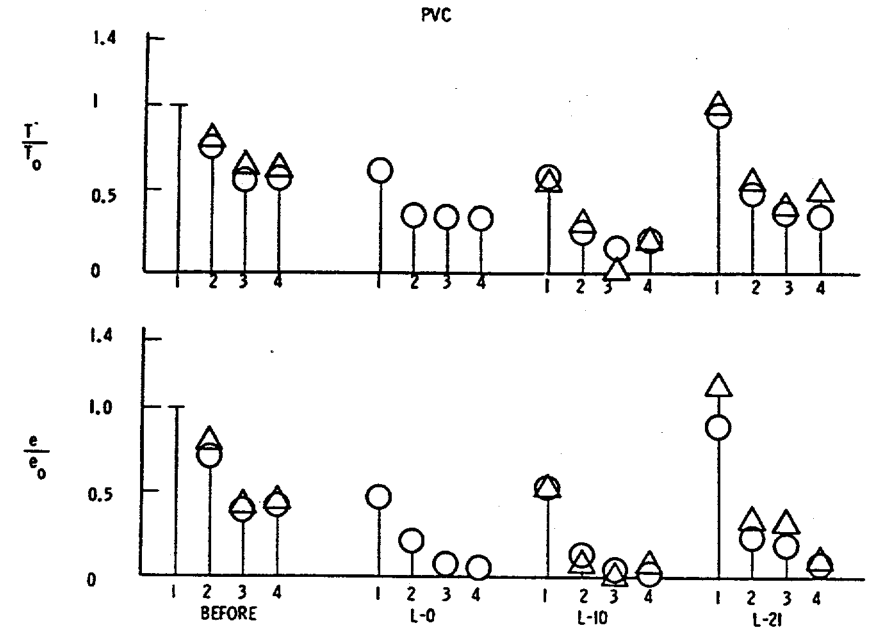

Figure 5.19 Tensile property results for PVC (Ref. 5.25)

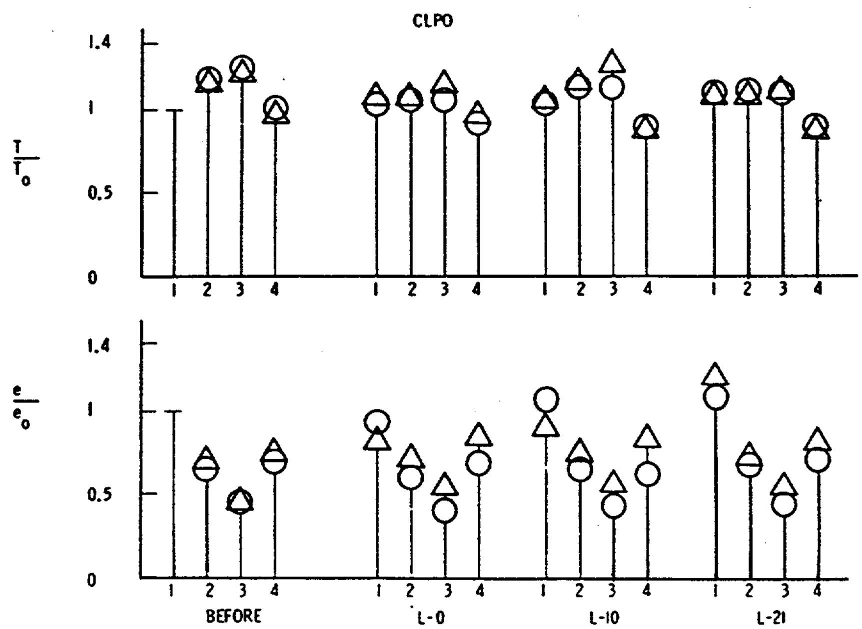

Figure 5.20 Tensile property results for CLPO (Ref. 5.25)

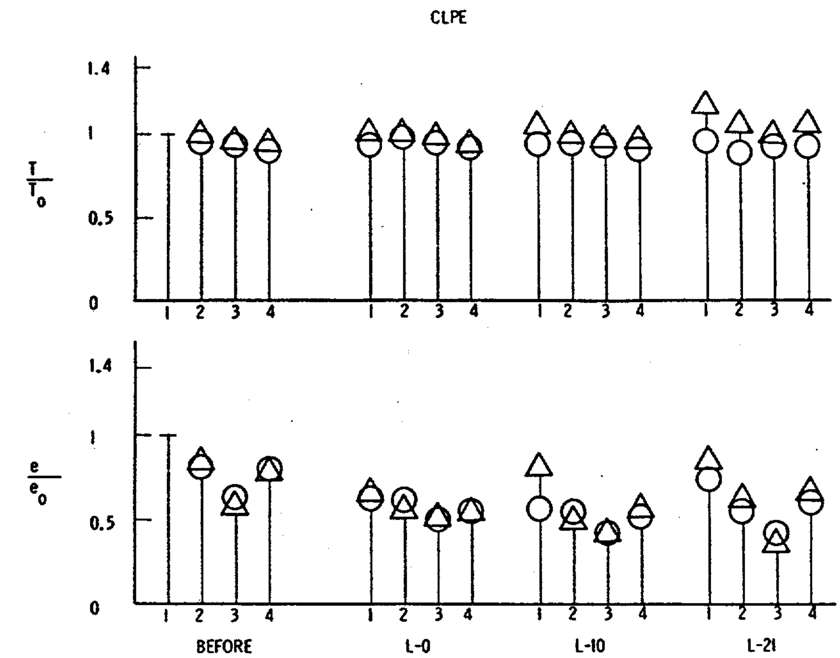

Figure 5.21 Tensile property results for CLPE (Ref. 5.25)

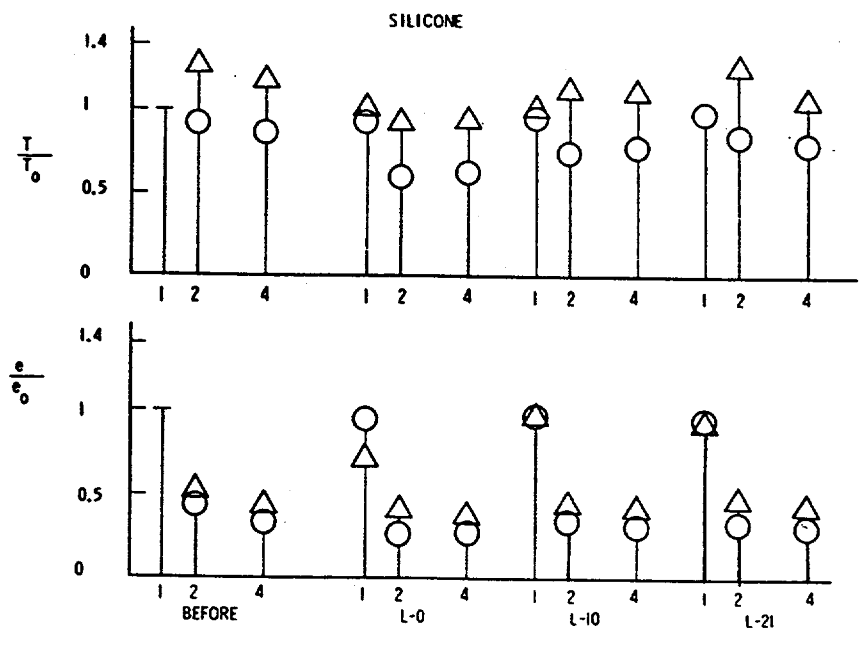

Figure 5.22 Tensile property results for silicone (Ref. 5.25)

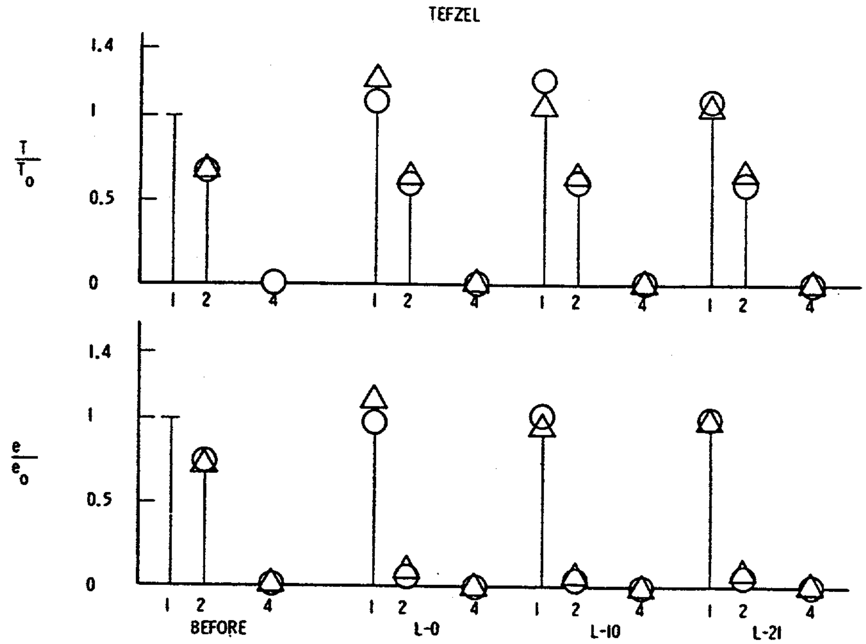

Figure 5.23 Tensile property results for Tefzel (Ref. 5.25)

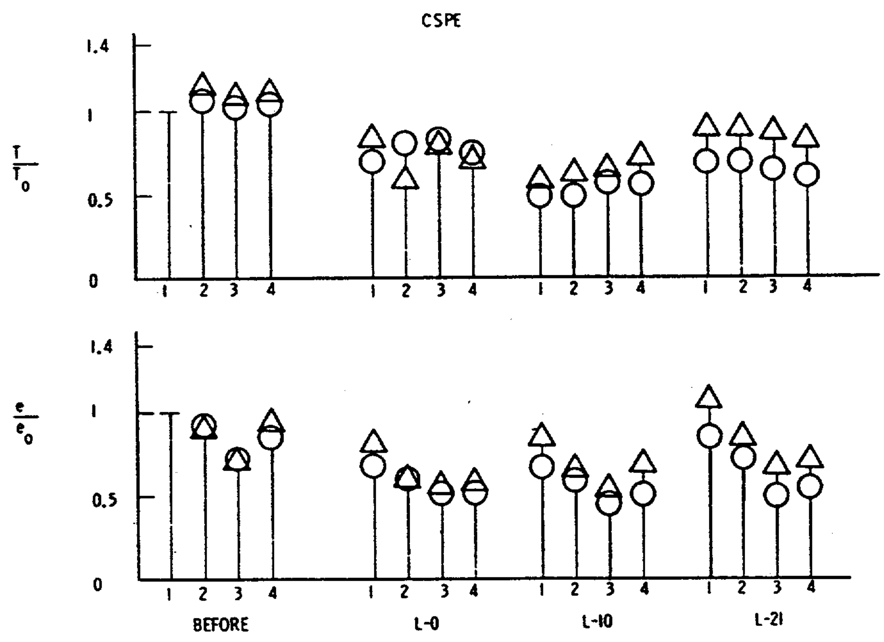

Figure 5.24 Tensile property results for CSPE (Ref. 5.25)

Materials, such as Tefzel, EPR, and PVC exhibited substantial degradation from the combination of aging and LOCA simulation, yet showed little or no damage when unaged samples were exposed to the LOCA simulation. Tefzel, chloroprene, and PVC were badly degraded (i.e., tensile values reduced to near zero) after exposure to the various aging and LOCA simulation sequences. Finally, CLPE (Figure 5.21), CSPE (Figure 5.24), and CLPO exhibited only modest damage in all the tests.

Based on the results presented, the effects of various pre-conditions and conditions during LOCA simulation on material responses were evaluated; this qualitative assessment is shown in Table 5.9. Because of the different behavior of cable insulation and jacket materials, the researchers suggested using thermal ovens in screening the importance of aging conditions on a material's response to LOCA. This sequential procedure could offer a relatively easy method for choosing materials and optimizing material formulations for applications to electric cables.

The results from Japanese studies discussed in some of the earlier sections indicate that oxygen may have some effects during LOCA simulations. Reference 5.13 presents data on volume resistivity for EPR, Hypalon, and Neoprene both with and without air in the steam, showing that it was degraded by 2 to 3 orders of magnitude in air-containing simulations, but only by 0-2 orders of magnitude when air was absent (see Figure 5.43). A relationship between swelling of materials and decrease in volume resistivity reveals that materials which show a larger drop in volume resistivity swelled easily under LOCA conditions, especially with air. Reference 5.14 concluded that the tensile properties for Hypalon were slightly degraded by simulations containing air, but reached no clear conclusion about EPR.

Ito (Ref. 5.17) compared the behavior of cable's EPR insulation and Hypalon jacket materials to the electrical performance of cables. Insulation resistance did not exhibit large effects, as indicated by the tensile and volume resistivity properties. Figures 5.25 and 5.26 demonstrate that differences in insulation resistance between air and non-air LOCA simulations are small. When the results of slab specimens were compared, it was found that the cable's jacket apparently reduced the oxygen available for interacting with the insulation.

5.6 Effect of Chemical Spray During LOCA Simulations

The chemical spray commonly used in qualification tests consists of 0.28 molar boric acid, 0.064 molar sodium thiosulfate, and sodium hydroxide added to obtain a pH between 10 and 11 at 77°C (IEEE Std 323-1974, Table A1). Chemical spray, deposited on the surface, affects the properties of electrical insulators. Most LOCA simulations at Sandia did not include chemical sprays. Some French studies and practically all qualification tests by the Franklin Research Center did include chemical sprays, but did not address specific effects due to their presence[5].

Yagi and his co-workers (Ref. 5.26) considered eight elastomer formulations exposed to boiling spray solutions (water and IEEE Std 323-1974 solution). Figures 5.27 and 5.28 summarize the results for the Hypalon and EPR materials. The study found that (1) all eight elastomers showed remarkable swelling with an increase of radiation dose when they were irradiated in air, (2) swelling in boiling water was about twice that in chemical solution, and (3) some types of Neoprene and Hypalon showed maximum swelling at a particular

[5] In a test program on the effect of different sprays on coating materials, the Franklin Research Center found that demineralized water sprays produced much more damage than three different chemical sprays; and there was very little difference among the effects of different chemical sprays (Personal communication with Dr. S.P. Carfagno).

Table 5.9 Material Behaviors under Radiation Aging and LOCA Simulations (Ref. 5.25)

Material	Original E(%)	Original T(MPa)	Weight Changes Due to LOCA	Dose Rate Effect (Aging)	Effect of Oxygen During LOCA	Effect of Pre-Aging on LOCA Responses	Comments
CLPE (Chem XL)	350	16.2	Insignificant	Insignificant	Insignificant	Insignificant(E), None(T)	Some minor pre-aging and LOCA effects exist
Tefzel	290	54	Insignificant	Very Significant	None	Very Significant(E), None(T)	Excellent thermal properties, but sensitive to radiation. After LOCA, samples were extremely brittle.
Silicone	430	7.6	Insignificant	Insignificant	None	Very Significant(E), Insignificant(T)	Major elongation changes occurred due to aging rather than LOCA.
EPR-S (molded)	360	12.2	Insignificant	Insignificant	None	None(E), Insignificant(T)	L10 was not performed.
CLPO(Rad XL,FR)	240	13.7	Significant	Insignificant	None	None	Radiation aging caused significant decrease in elongation. LOCA had no effect.
CSPE	300	24.4	Significant	Insignificant	Insignificant	Insignificant	L10 was run 5 months after other two LOCA tests.
PVC	300	20	Very Significant	Insignificant(T) Significant(E)	Mixed	Very Significant(E), Significant(T)	Because of large dimensional changes, samples were constrained during LOCA tests, giving inconsistent responses.
CP (Chloroprene)	185	11	Very Significant	N/A	Very Significant	Not Conclusive	Presence of oxygen caused significant degradation.
EPR	340	6.9	Significant	Insignificant	Very Significant	Insignificant	Carbonyl species (esters, acids, ketones, aldehydes) were found on aged samples.

NOTES: AGING: No Thermal; Lot 1: Unaged; Lot 2: 21Mrad @ 880 krad/hr 24hrs @44°C; Lot 3: 45Mrad @ 880 krad/hr 50.5hrs @ 44°C; Lot 4: 23Mrad @24 krad/hr 958 hrs @26°C (CLPE: 622hrs@26°C)

LOCA: No Chemical Spray; L0: Nitrogen Environment; L10: 10% Oxygen Environment; L21: Air Environment

Insignificant = Minor Changes; Significant = Moderate changes; Very Significant = Large changes; N/A = Not applicable; Mixed = Changes involve both large and minor changes under certain conditions; None = No noticeable change

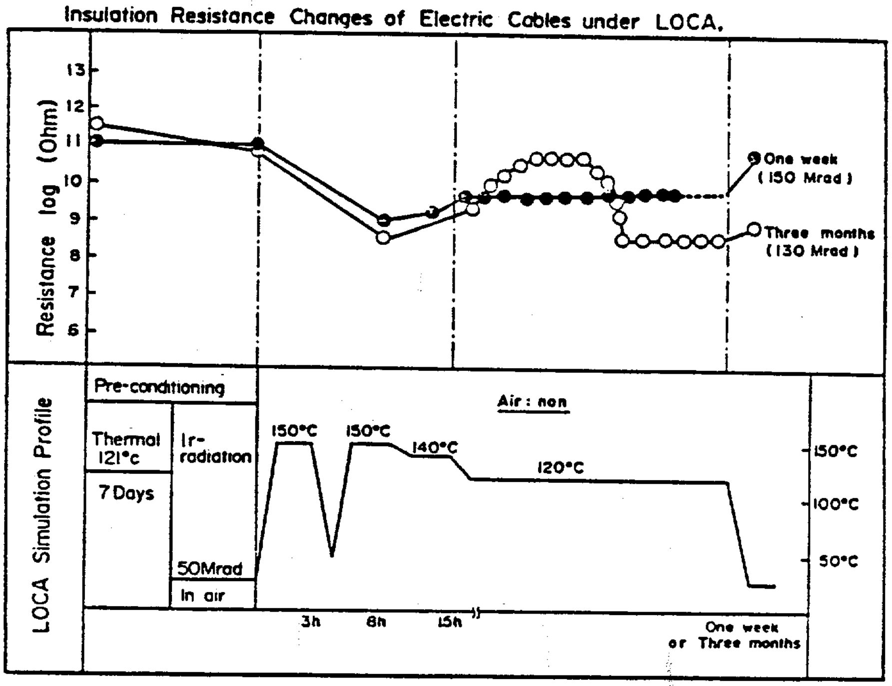

Figure 5.25 Electrical cable performance during a non-air LOCA exposure (Ref. 5.14)

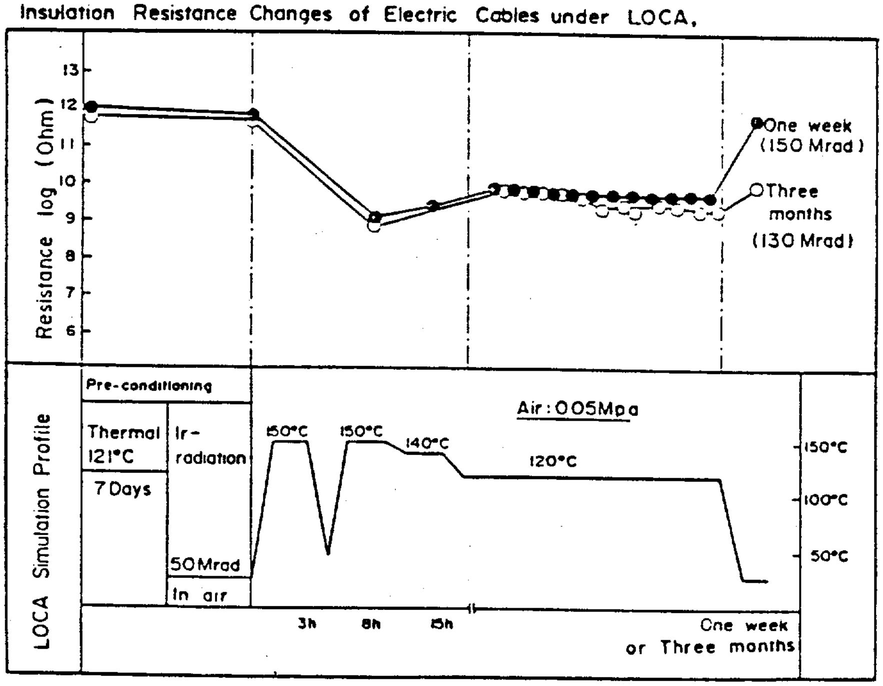

Figure 5.26 Electrical cable performance during an air LOCA exposure (Ref. 5.14)

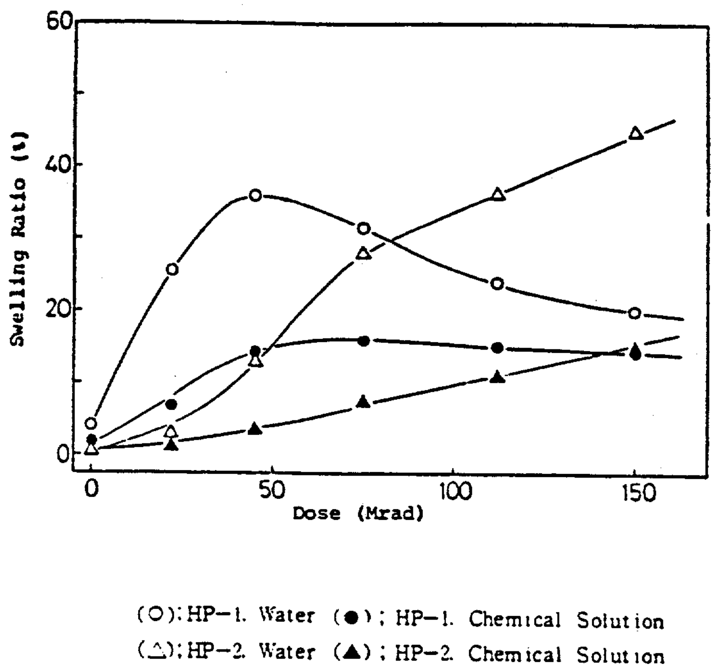

Figure 5.27 Comparison of swelling behavior of Hypalon in water and in chemical solution (Ref. 5.26)
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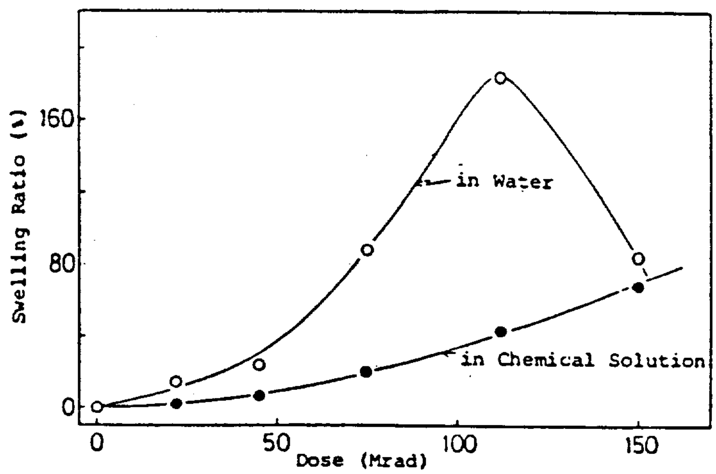

Figure 5.28 Comparison of swelling behavior of EPR in water and chemical solution (Ref. 5.26)
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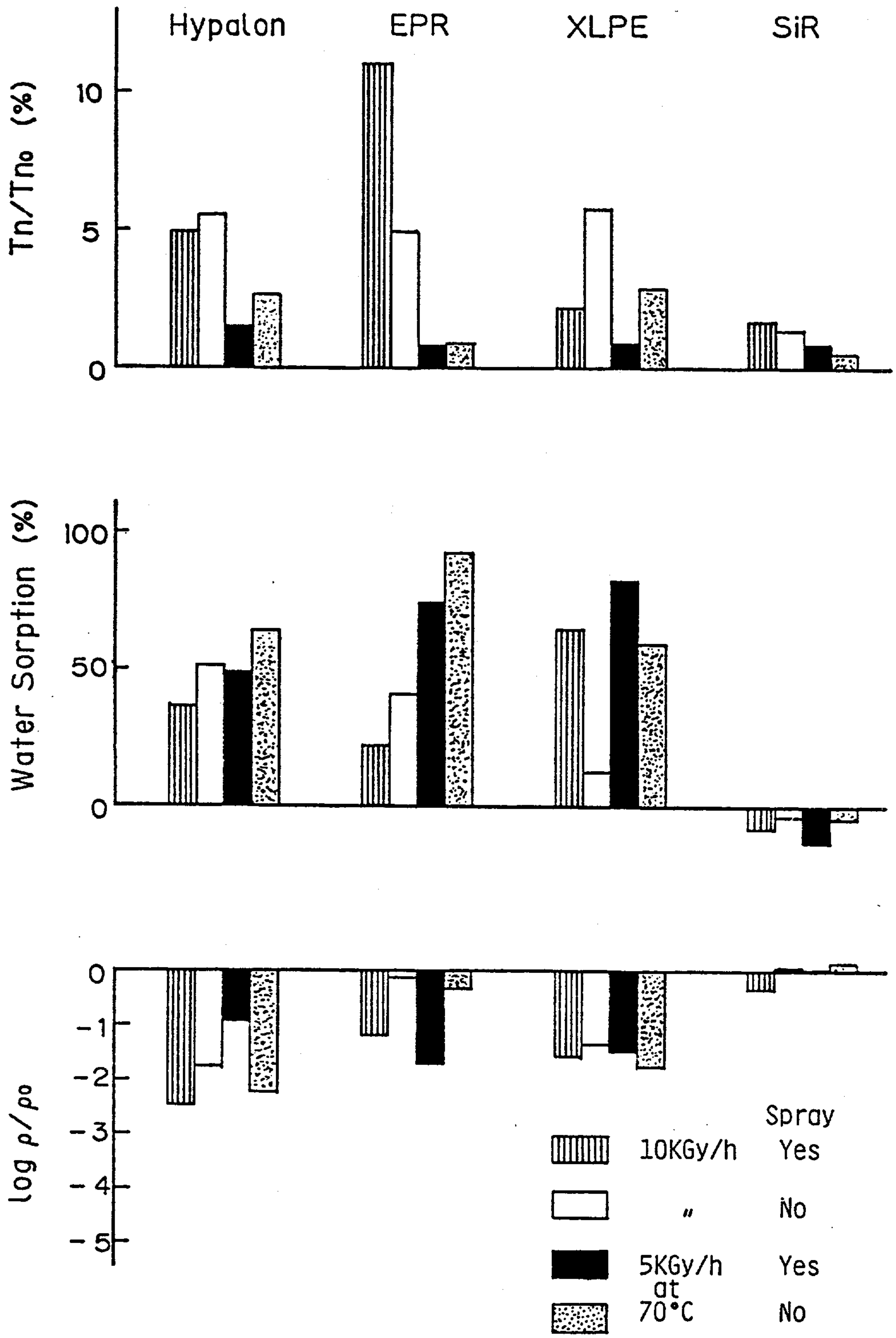


Figure 5.29 Effect of chemical spray on Japanese materials (Ref. 5.18)

dose, above which the swelling ratio decreased with dose. Reference 5.18 gives the results for material responses to spray conditions shown in Figure 5.29. Spray promoted degradation of Hypalon and XLPE, while SR showed no such influence. On the other hand, spray did not affect the electrical degradation of XLPE and SR, but enhanced that of EPR. The resistivity of Hypalon degraded when irradiated at elevated temperature. Chloroprene samples degraded severely after steam/spray exposure, and therefore, the effect of spray was not evaluated further.

5.7 Effect of Acceleration of Post-Transient Environments

The qualification of safety-related equipment must demonstrate that the equipment can perform its safety function during normal operations, and for the duration of a design basis event. A post-transient environment is defined as the fully saturated steam condition with 100% relative humidity at ~100°C; this simulates the conditions and durations of the inside containment after design-basis event transients. To reduce the cost and time, it is common industry practice to time-compress the post-transient environment simulation. The results by Gillen and his co-workers (Ref. 5.25) on the effects of various concentrations of oxygen during LOCA simulations have the potential for post-transient acceleration. Table 5.10 compares the 10% oxygen LOCA simulation (L-10) tests with air oven tests consisting of 96 hours exposure at 145°C. The temperatures during the LOCA simulations ranged from 171°C at the beginning and dropped off to 121°C after 4 days. Many materials exhibited comparable degradation during both tests, which suggests that similar degradation mechanisms may be involved. Hence, they suggested that this may provide a basis for post-transient acceleration.

Table 5.10 Sequential Screening Comparisons (Ref. 5.25)

Material	Aging Condition	e/e_o Air Oven	e/e_o L-10
CLPE	1	0.65	0.68
	3	0.05	0.42
	4	0.56	0.53
Tefzel	1	0.92	1.02
	4	0	0.04
Silicone	1	0.93	0.96
	2	0.24	0.38
	4	0.17	0.38
CLPO	1	0.79	0.98
	2	0.33	0.70
	3	0.24	0.49
	4	0.26	0.72
CSPE	1	0.40	0.74
	2	0.27	0.61
	3	0.19	0.48
	4	0.15	0.58
PVC	1	0.57	0.53
	2	0.18	0.09
	4	0.04	0.03
CP	1	0.01	0.05
	2	0.01	0.03
EPR	1	0.77	0.89
	2	0.49	0.38
	3	0.12	0.17
	4	0.14	0.12

Aging: 1-Unaged; 2-21 Mrad at 880 krad/hr; 3-45 Mrad at 880 krad/hr; 4-23 Mrad at 24 krad/hr

Ito and his colleagues (Ref. 5.17) discussed a limited Japanese experiment on this subject; the results are given in Table 5.8. They claimed that oxygen partial pressure should be included in the LOCA simulation if the samples are sensitive to the presence of oxygen. They had observed some differences in material and electrical properties during post-transient acceleration experiments.

Okada and his co-workers (Ref. 5.27) studied Hypalon and EPR subjected to LOCA testing. Simultaneous exposure of radiation and steam/chemical spray was performed in two distinct cases: one for a week at a high dose rate of 10 kGy/hr up to 1.5MGy (Sim-A and Sim-C) and the other for three months at a dose rate of 0.6kGy/hr up to 1.4MGy (Sim-B and Sim-D). Both were performed in air-free (Sim-A and Sim-B) and air-containing steam conditions (Sim-C and Sim-D). Sequential tests included irradiation performed first in air at high dose rate of 10kGy/hr and room temperature (Seq-a and Seq-b). Low dose rate conditions included dose rate of 1kGy/hr at room temperature in air, dose rate of 5kGy/hr at 70°C in air, and dose rate of 4.2kGy/hr at room temperature in pressurized oxygen (0.5MPa). Both groups were irradiated up to 1.5 MGy. Steam/chemical spray followed irradiation and several other variables such as steam temperature and oxygen pressure were changed to evaluate their effects on the mechanical and electrical properties of the two cable polymers.

Figures 5.30 and 5.31 illustrate the results for Hypalon and EPR materials, respectively. Both materials under one week LOCA simulations degraded less than those simulated for three month exposures. The Hypalon was more sensitive to presence of oxygen than EPR. Compared with sequential simulations, the degradation in both materials was less severe than simultaneous conditions (except Sim-A). Therefore, accelerating the simulation of the post-transient duration to a shorter period may underestimate the material's responses to LOCA conditions.

5.8 Effect of Aging Methods on LOCA Simulations

An important question is which combination of alternative sequential aging and accident simulations closely represent the real-time degradation of cable materials in the containment of a nuclear power plant in normal and accident environments. Most studies discussed have addressed various aspects of this question including the relationship between the aging simulation and the accident simulation techniques, synergistic and sequencing effects in various combinations of these techniques, and the importance of the aging pre-conditioning to the subsequent performance of cables during accident simulation. Results from the U.S.-French test program in Reference 5.25, test results on EPR and XLPO materials given in References 5.10 and 5.11, respectively, and accident simulation results in Reference 5.15 concluded that choice of aging simulation method does affect the cable's behavior during an accident simulation.

Reference 5.25 gives the results of a U.S.-French test program in which the mechanical properties, weight increases, solubility measurements, and changes in infrared spectroscopy of nine different materials were monitored. Three different LOCA simulations and four different aging simulations were employed. For the LOCA simulations, the only planned difference among the three tests was the composition of the overpressure gas. The study noted that aging conditions are a parameter that helps define the material's response during subsequent LOCA simulations. Table 5.11 has the data on weight change for a PVC material. The moisture absorbed during the LOCA simulation depended strongly on the aging technique (total dose and dose rate).

EPR-1483 (Ref. 5.10) is similar in composition to EPR-A and EPR-B discussed earlier, and is qualified for control and instrument cables in nuclear facilities. This material also was exposed to the eight different aging techniques (given in Table 5.3 for EPR-A), followed by the three accident simulations. After the 21-day

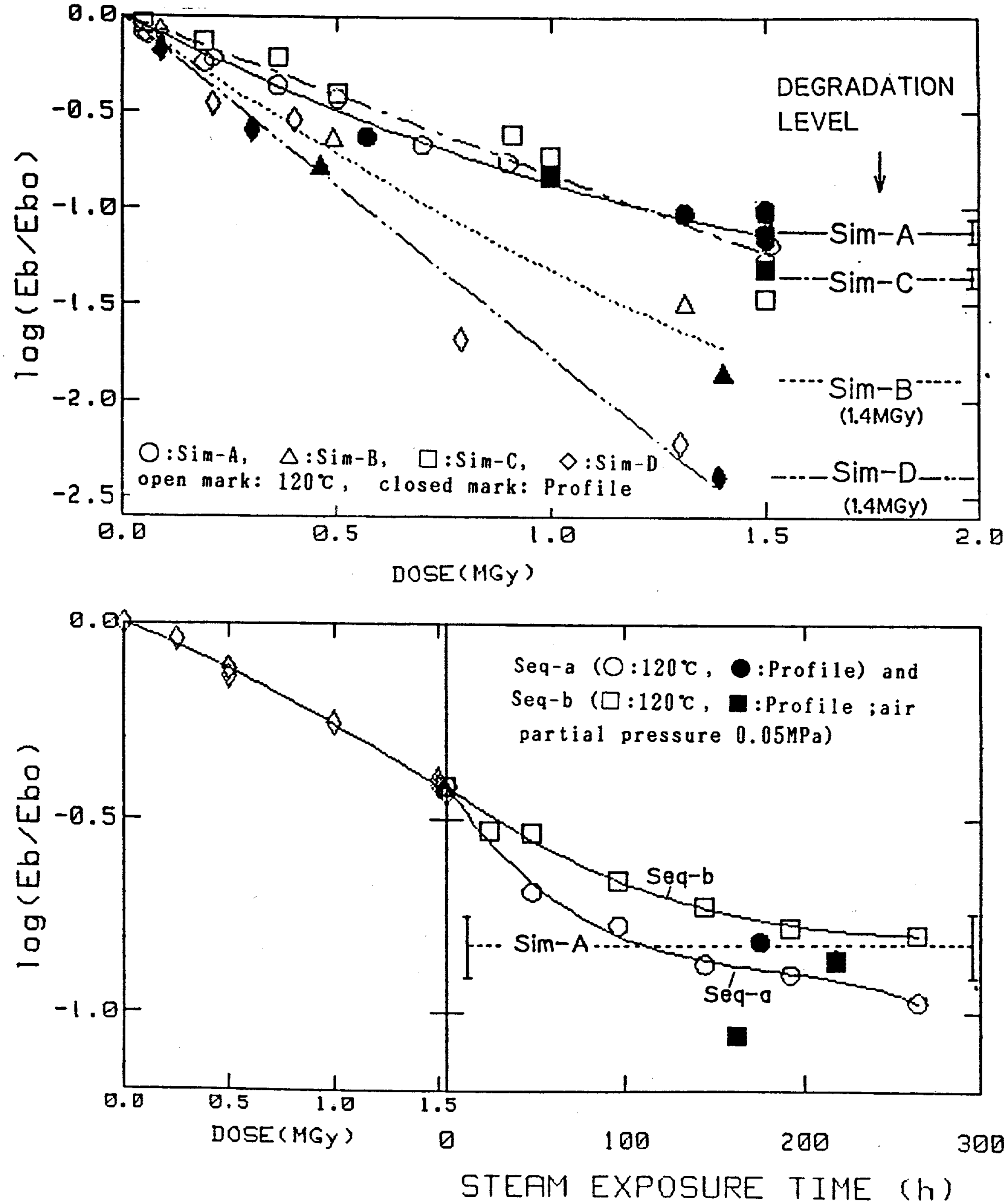


Figure 5.30 LOCA simulations for Hypalon (Ref. 5.27)

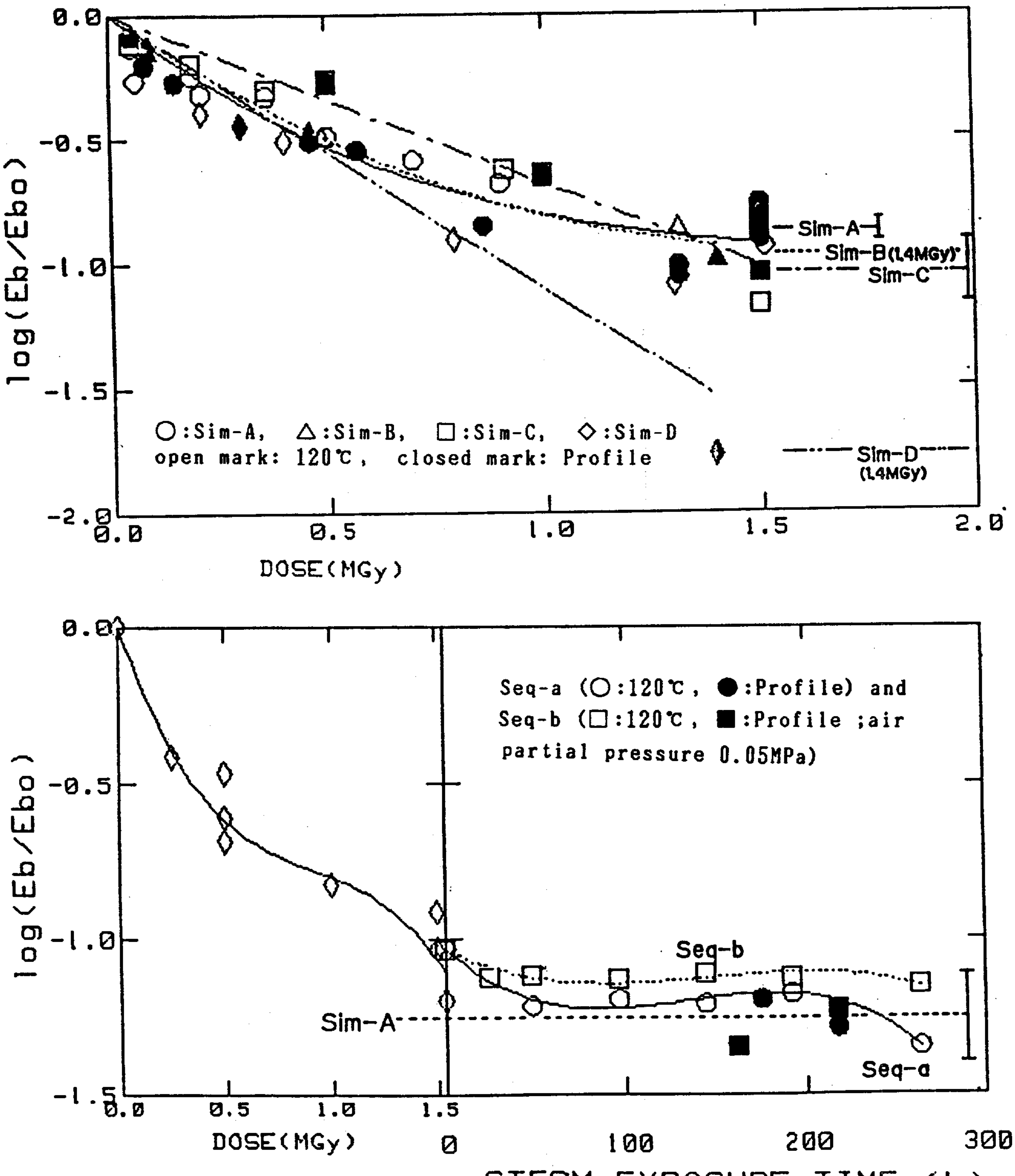


Figure 5.31 LOCA simulations for EPR (Ref. 5.27)

LOCA exposures, its tensile properties, weight changes, and dimensional changes were measured (Figures 5.32 - 5.34). There was not a large variation caused by alternative sequential aging techniques nor by dose-rate effects. Rather, differences between the simultaneous and sequential aging techniques were more important; the former caused more degradation during accident simulations than did the latter. Moreover, the degradation in tensile strength caused by simultaneous aging was amplified by subsequent LOCA exposures. However, thermal aging at 139°C instead of 120°C might have been the reason for such increased degradation for simultaneous aging. The data also illustrates the importance of aging to total material degradation. For example, specimens unaged before LOCA exposures tended to gain less weight and less volume than did aged ones.

Table 5.11 Weight Change Due to LOCA Simulation for a PVC Material (Ref. 5.25)

LOCA Test	Aging*	Percentage Weight Change After		
%Oxygen	Method	6 Hour	1500 Hour	5000 Hour
0	1	93	14	-4
	2	220	50	-1
	3	347	46	-4
	4	330	62	-7
10	1	53	-2	N/A
	2	150	-4	N/A
	3	360	-3	N/A
	4	230	-4	N/A
21	1	0	-1	-1
	2	18	0	-2
	3	39	4	-2
	4	35	4	-3

* Aging: 1-Unaged; 2-21 Mrad at 880 krad/hr; 3-45 Mrad at 880 krad/hr; 4-23 Mrad at 24 krad/hr
N/A=Not Applicable

Table 5.12 Effect of Accelerated Age on EPR Moisture Absorption (Ref. 5.10)

Material	Accelerated Age	Moisture Absorption (% Weight Increase)
EPR-D	Unaged	16
	40-year Equiv.*	172
EPR-F	Unaged	20
	40-year Equiv.*	94
Japanese EPR-5	Unaged	49
	40-year Equiv.*	77
EPR-1483	Unaged	17
	5-year Equiv.**	22
	40-year Equiv.***	67

* 7-day 139°C with simultaneous irradiation for 6 days to 40 Mrad.
** A 94-day simultaneous exposure to 120°C and 4.9 Mrad Irradiation.
*** A 30-day simultaneous exposure to 120°C and 39 Mrad Irradiation.

Unlike EPR-A and EPR-1483, unaged and simultaneously aged specimens of other EPR materials were exposed to the simultaneous accident simulations. Table 5.12 shows that accelerated aging was important to subsequent moisture-absorption during simultaneous steam and irradiation LOCA simulations. A higher weight increase in some EPR material might have been due to pre-aging at 139°C.

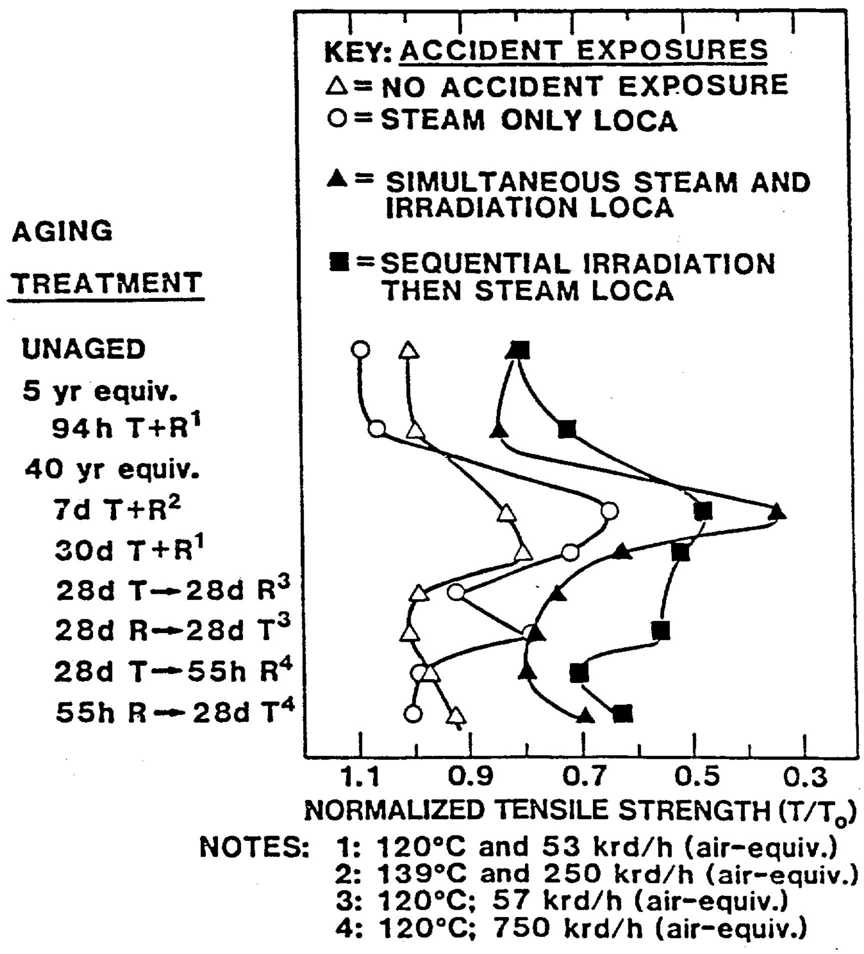


Figure 5.32 Effect of aging and accident techniques on normalized tensile strength of EPR-1483 (Ref. 5.10)

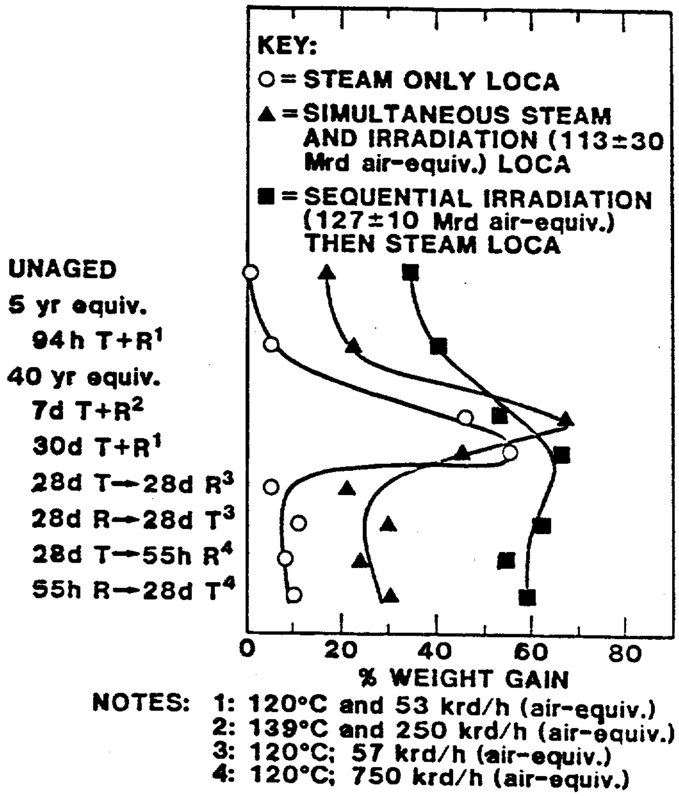


Figure 5.33 Effect of aging and accident techniques on percentage weight gain of EPR-1483 (Ref. 5.10)

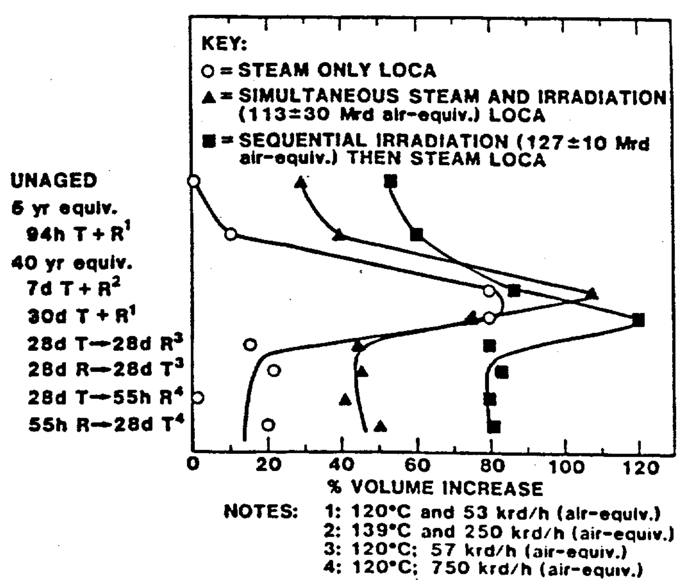


Figure 5.34 Effect of aging and accident techniques on percentage volume change of EPR-1483 (Ref. 5.10)

In Reference 5.11, none of the XLPO products exhibited as much degradation as some of the EPR products. XLPO-A and XLPO-B experienced the same effects from aging as did the EPR products; namely, there were larger increases in weight and dimensions for the aged specimens than the unaged ones. In contrast, unaged XLPO-C absorbed more moisture than did aged material. The ultimate tensile strength was enhanced by aging, suggesting additional crosslinking of the polymer matrix; this might explain the reduced moisture-absorption of the aged compared to the unaged specimens.

One of the goals of the accident simulation studies discussed in Reference 5.15 was to evaluate whether some combinations of alternative aging and accident simulation techniques were better suited for qualification than others. As shown in Figures 5.2 to 5.13, for some materials, the effects of the accident simulation technique were sensitive to the aging method, but for others, the aging method had very little impact on material properties subsequently (e.g., EPR and XLPO-2).

The study examined whether age pre-conditioning techniques might reduce synergistic and sequencing effects during accident simulations. Section 5.1 identifies the appropriate sequential simulation procedures for each material included in the test program. These sequential techniques produced deteriorations similar to those achieved during simultaneous irradiation and LOCA (with air) accident simulations except for a fire-retardant French EPDM material (EPDM-8219). The study considered the simultaneous accident simulation to be the best representation of postulated design-basis accident conditions. For several materials, irradiation followed by thermal exposure is the most appropriate technique for age pre-conditioning.

References 5.28 and 5.29 give tensile data for two chemically cross-linked polyolefin insulations. Both materials were exposed to three different aging exposures:

1. A high dose rate (865 krad/hr) irradiation to a total dose of 42.5 Mrad followed by thermal aging for 240 hours at 150°C.
2. Reverse of 1.
3. Same as 1, but the dose rate was 48 krad/hr.

After aging, the specimens were further irradiated at 865 krad/hr dose rate, in increments of 50 Mrad, up to a total dose of 200 Mrad. Figures 5.35 and 5.36 present the results for one of the materials. The effects of alternative aging techniques is clearly evident at completion of the aging exposures. However, after the accident irradiations, the insulations had very little remaining life and all three groups approached the same level of mechanical degradation[6]. The results for the other material are shown in Figures 5.37 and 5.38; this material exhibited similar behavior, but showed much more variability.

The Japanese studies described in Ref. 5.13 include tensile properties and volume resistivity data after both PWR and BWR LOCA testing (with and without air) for several polymers. Both pre-aged and unaged specimens were tested. Pre-aging for all specimens was a sequential exposure of thermal aging followed by irradiation (50 Mrad). The total accident radiation-exposure for PWR conditions was 150 Mrad, while that for the BWR was 26 Mrad. Simultaneous and sequential accident simulations were employed. Figures 5.39 to 5.42 compare the mechanical properties for different materials. Not unexpectedly, the effect of aging is more noticeable for the BWR simulations because there the accident irradiation is approximately half that of the aging irradiation, while for the PWR accident, irradiation is three times the aging irradiation.

[6] This finding tends to diminish the importance of differences among different methods of accelerated aging, because it indicates that the condition of cable insulation before the steam/chemical spray portion of the LOCA simulation might be nearly independent of the aging method.

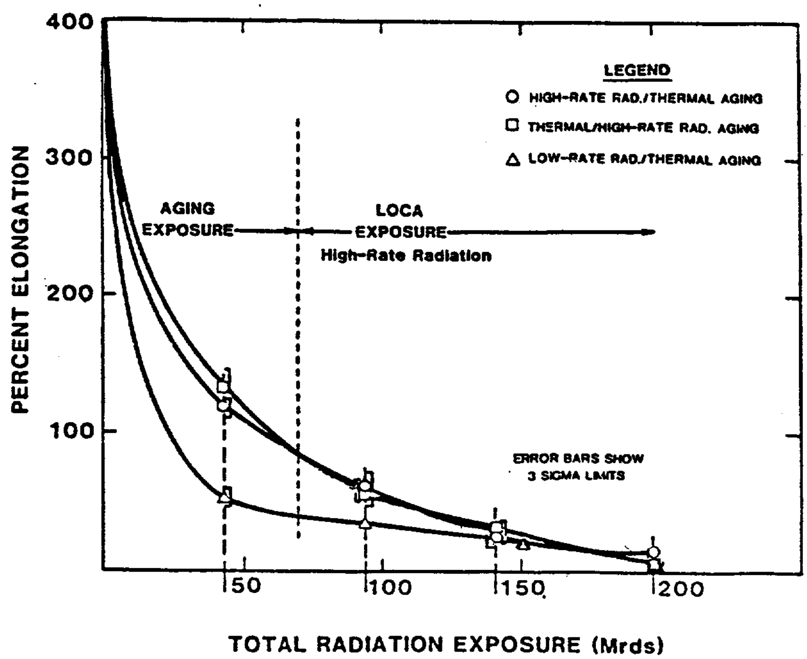


Figure 5.35 Elongation vs. radiation exposure for XLPO (Ref. 5.29)

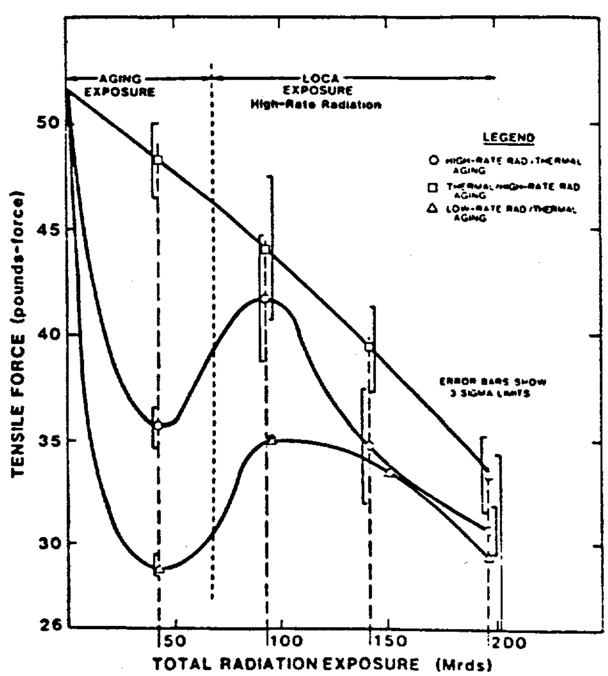


Figure 5.36 Tensile force vs. radiation exposure for XLPO (Ref. 5.29)

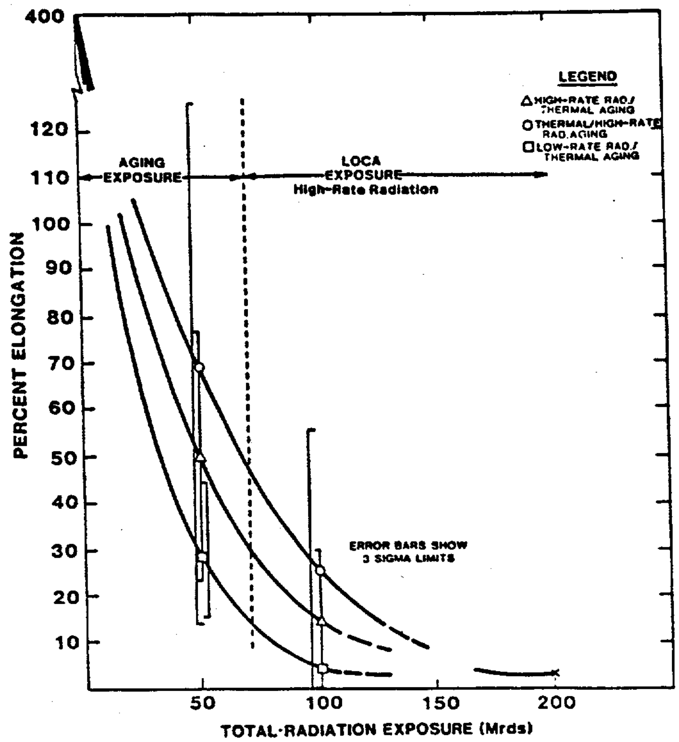


Figure 5.37 Elongation vs. radiation exposure for XLPO (Ref. 5.28)

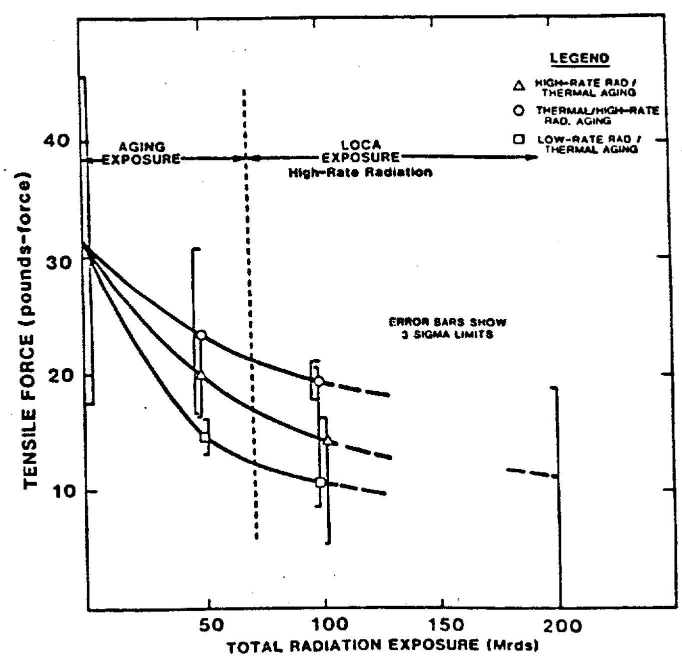


Figure 5.38 Tensile force vs. radiation exposure for XLPO (Ref. 5.28)

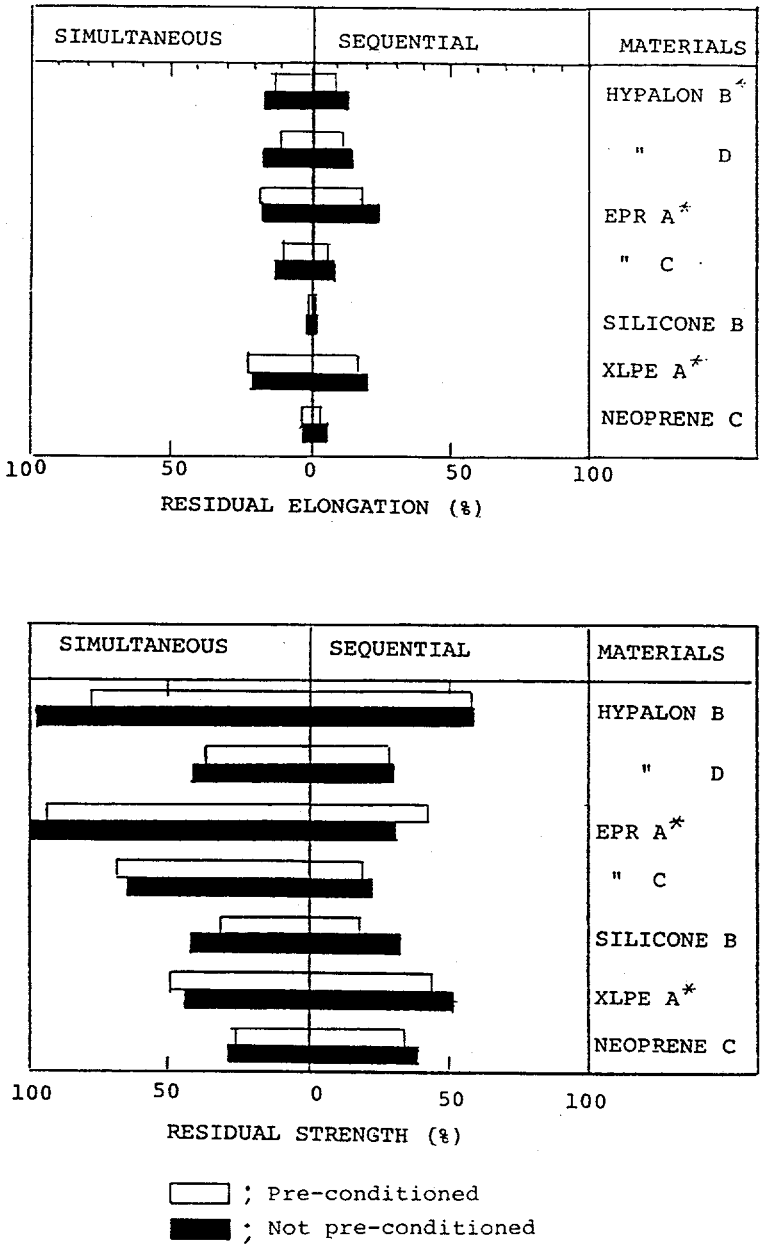


Figure 5.39 Comparison of mechanical properties after simultaneous and sequential LOCA testing (PWR Conditions) (Ref. 5.13)

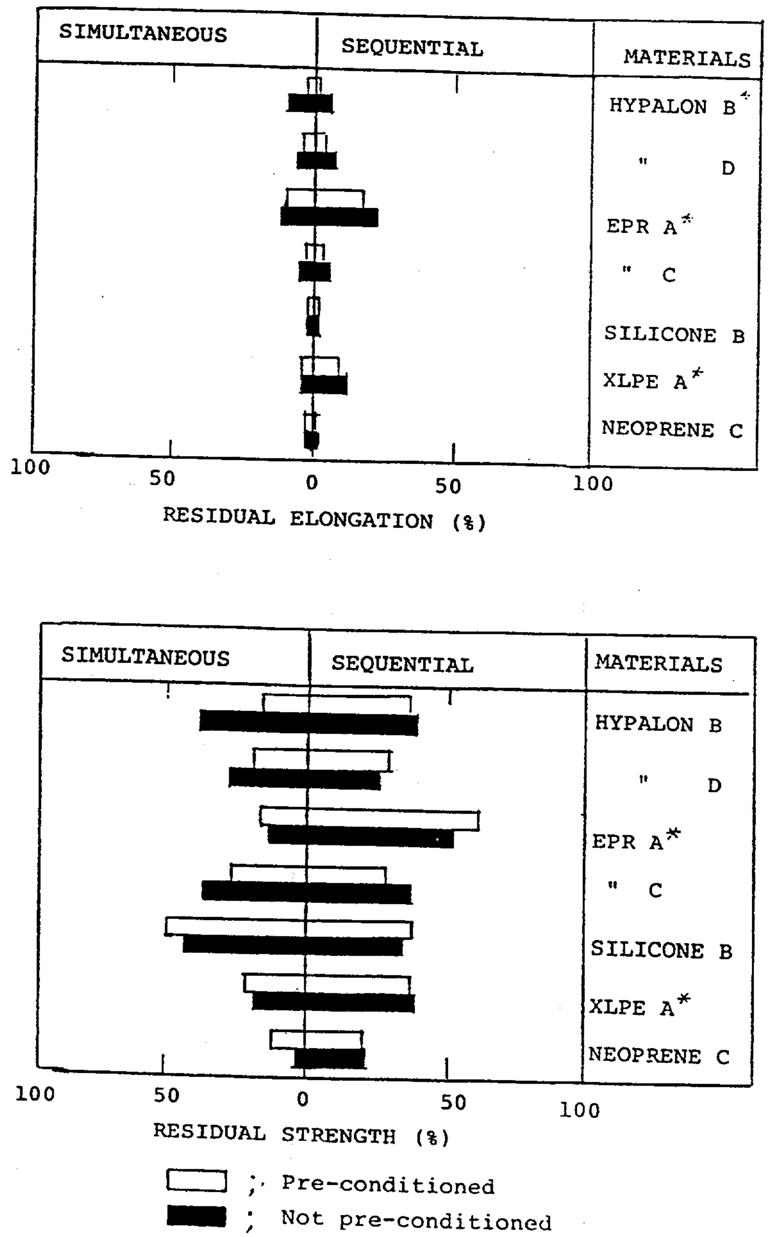
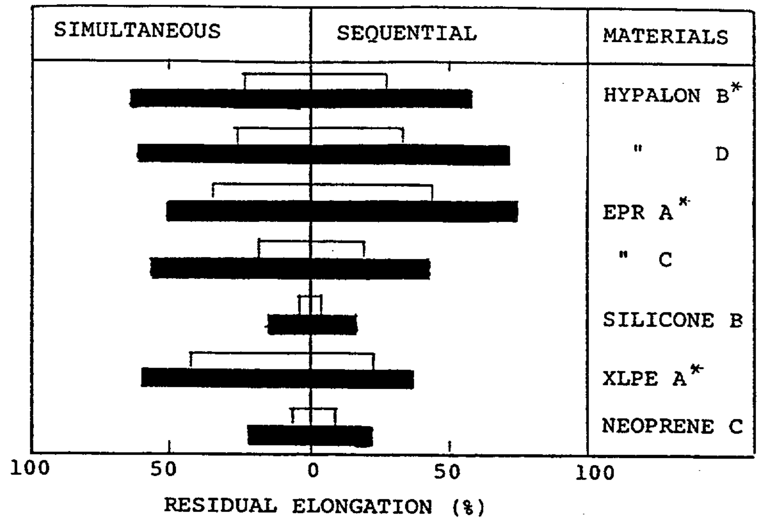


Figure 5.40 Comparison of mechanical properties after simultaneous and Sequential LOCA testing (PWR conditions containing air) (Ref. 5.13)



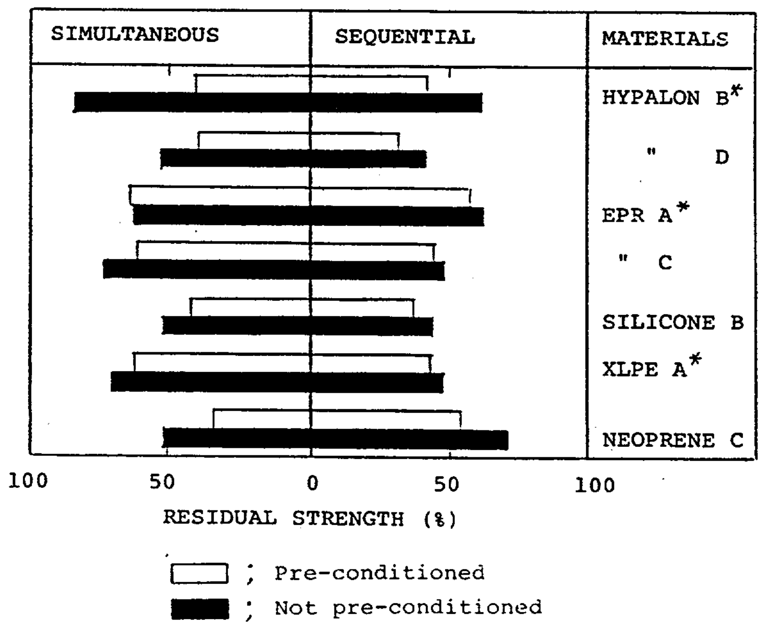


Figure 5.41 Comparison of mechanical properties after simultaneous and sequential LOCA testing (BWR conditions) (Ref. 5.13)

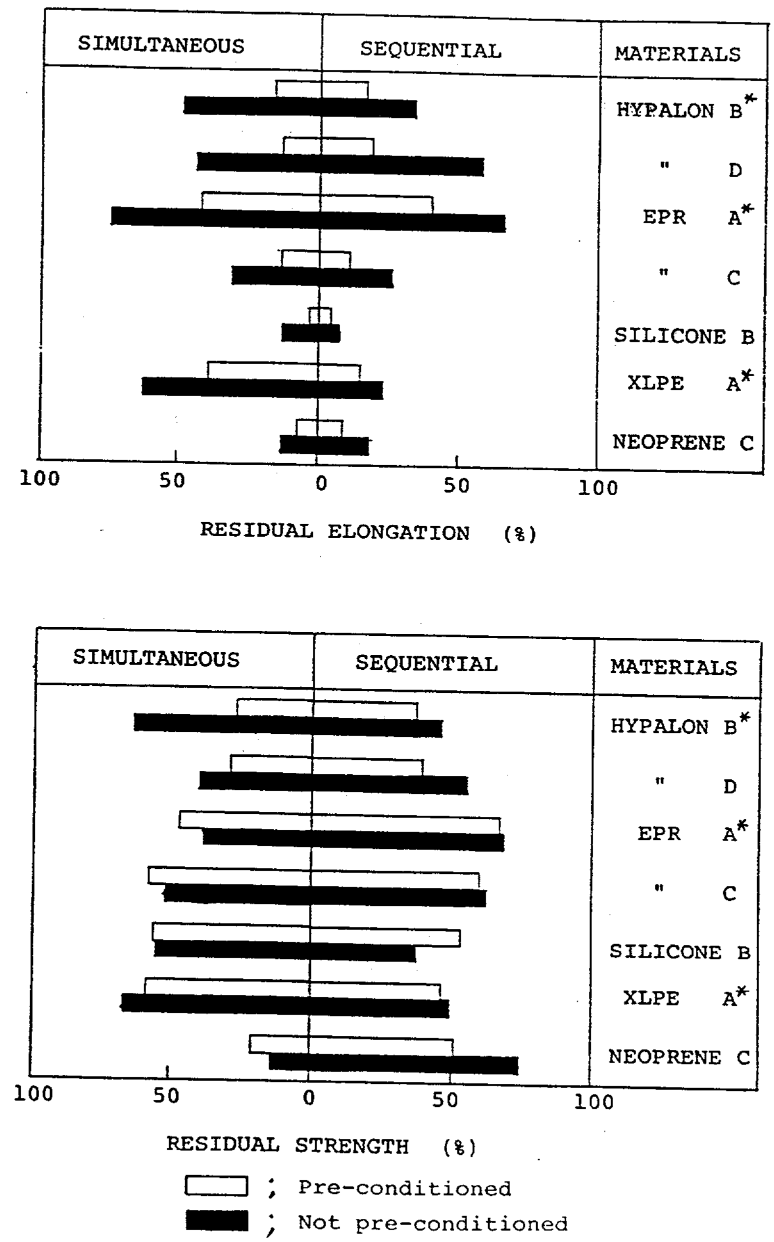


Figure 5.42 Comparison of mechanical properties after simultaneous and sequential LOCA testing (BWR conditions containing air) (Ref. 5.13)

Figure 5.43 shows data on volume resistivity for several insulating materials after LOCA simulations. For EPR, Hypalon, and Neoprene, volume resistivity was degraded by two or three orders of magnitude in simulations in air, but only degraded by zero to two orders of magnitude when air was absent. In the former, the simultaneous method degraded for the resistivity of the unaged samples the most, while the reverse sequential was least degrading. For the pre-conditioned samples, however, the degradation from both was equal. Hence, perceptions about which accident simulations are the most severe are influenced by pre-aging.

Kawakami and his colleagues studied the effect of pre-conditioning on several cable materials (Ref. 5.30). The Japanese materials studied include CSM (Hypalon), EPR, XLPE, CR (chloroprene), and SR. The testing included a sequential procedure. The pre-conditioning was done by either thermal aging (168 hrs @ 121°C) followed by irradiation of 0.5 MGy at a dose rate of 10 kGy/hr in room temperature, or irradiation of 0.5 MGy at a dose rate of 5 kGy/hr in an oxygen environment followed by thermal aging (168 hrs @ 121°C). The LOCA simulation included irradiation of 1.5 MGy for PWR or 0.26 MGy for BWR followed by a 120°C steam/spray exposure. Testing also included other pre-conditioning methods, including thermal exposure followed by irradiation in oxygen environment, and irradiation without thermal aging (see Figure 5.44).

Oxygen consumption was strongly dependent on the pre-conditioning state of the material; irradiation followed by thermal treatment caused larger oxygen consumption comparable to the simultaneous method with a similar radiation dose and thermal conditions. The effect of pre-conditioning on material degradation is not significant, except for Hypalon in a BWR environment. However, the study concluded that pre-conditioning of cable materials prior to accident simulations is an important factor in the EQ process.

5.9 Life Extension, Submergence, and High Temperature Test Results

Jacobus (Refs. 5.31-5.33) studied aging, condition monitoring, and accident testing of several safety-related cables. Table 5.13 lists the cable products included in this program. One objective was to determine the long-term aging degradation behavior of popular cable products. The experimental program consisted of two phases. Phase I was simultaneous thermal (~100°C) and radiation (~0.10 kGy/hr) aging exposures for 3 months, 6 months, and 9 months in three different chambers. (A fourth chamber, containing unaged cables, was used only for the accident exposure). Phase II was an accident exposure of the aged and unaged cables, consisting of high dose rate irradiation (~6 kGy/hr) to a total dose of 1100 kGy (110 Mrad), followed by a LOCA steam exposure. The tests followed the guidance of IEEE Std 323-1974 (Ref. 5.1) and IEEE Std 383-1974 (Ref. 5.2). No chemical spray was used during the steam exposure, but a 1000-hr post-LOCA submergence test (in a chemical solution similar to the chemical spray at 95±5°C with a slightly positive pressure) was carried out on the cables that had been aged for 6 months and accident-tested. The accelerated aging temperature was determined by equating the 6-month exposure to a 40-year life, and assuming an activation energy of 1.15 eV and a plant ambient temperature of 55°C. The accelerated radiation-aging dose-rate was determined by assuming a 40-year radiation dose of 400 kGy. Therefore, the 3-month chamber was nominally equivalent to 20 years of aging, and the 9-month chamber to 60 years of aging. Similar to the submergence test using the cable group subjected to 6-month aging and accident-tested, cables that were aged for 3 months and then LOCA-tested, were subsequently exposed to a high-temperature steam-fragility test that included a peak temperature of 400°C (750°F) to study the ultimate fragility level of typical types of cables. Insulation resistance was monitored throughout the high-temperature steam test and at discrete times during the submergence test. Dielectric withstand testing was performed before both test programs. Cables that passed the post-submergence dielectric test subsequently were wrapped around a 40 times cable diameter mandrel and subjected to a final dielectric withstand test. The results of the submergence and high-temperature steam tests are given in Reference 5.34. The following is a summary of findings for each material group.

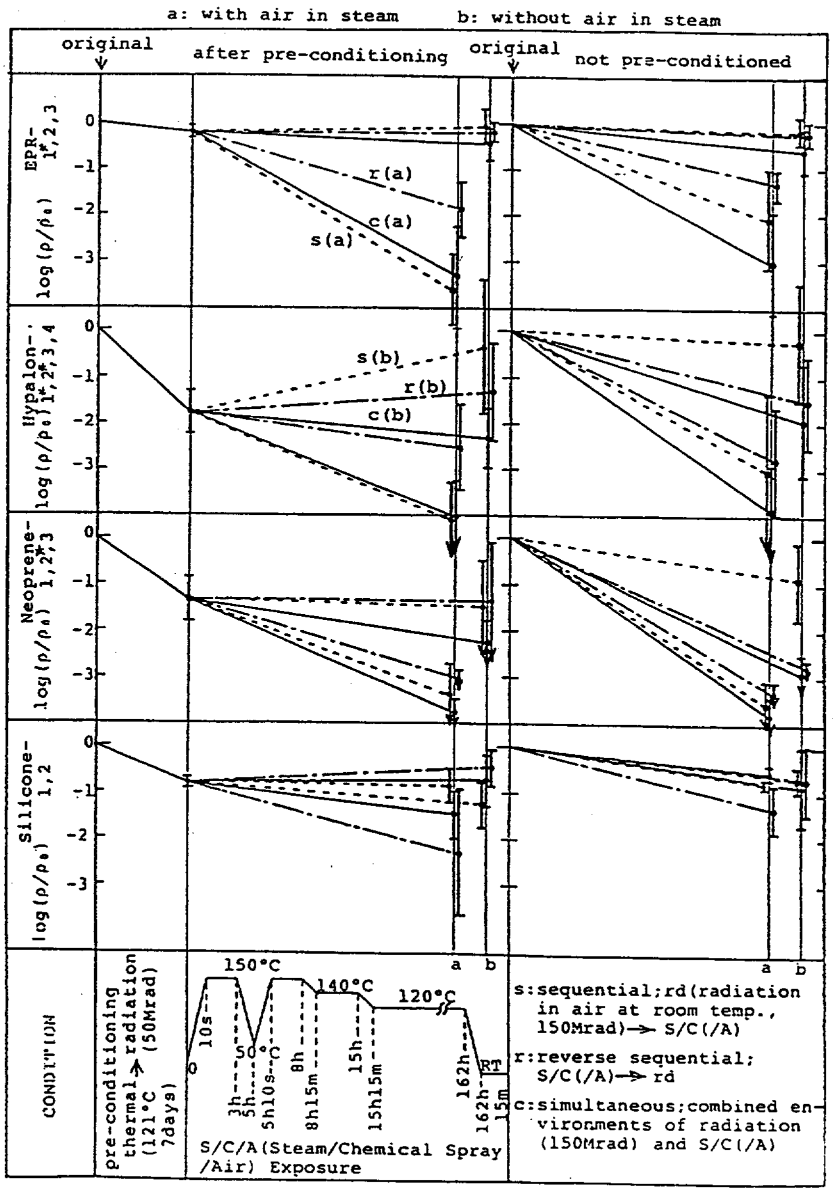


Figure 5.43 Log mean values of volume resistivity after simultaneous, sequential and reverse sequential LOCA tests (Ref. 5.13)

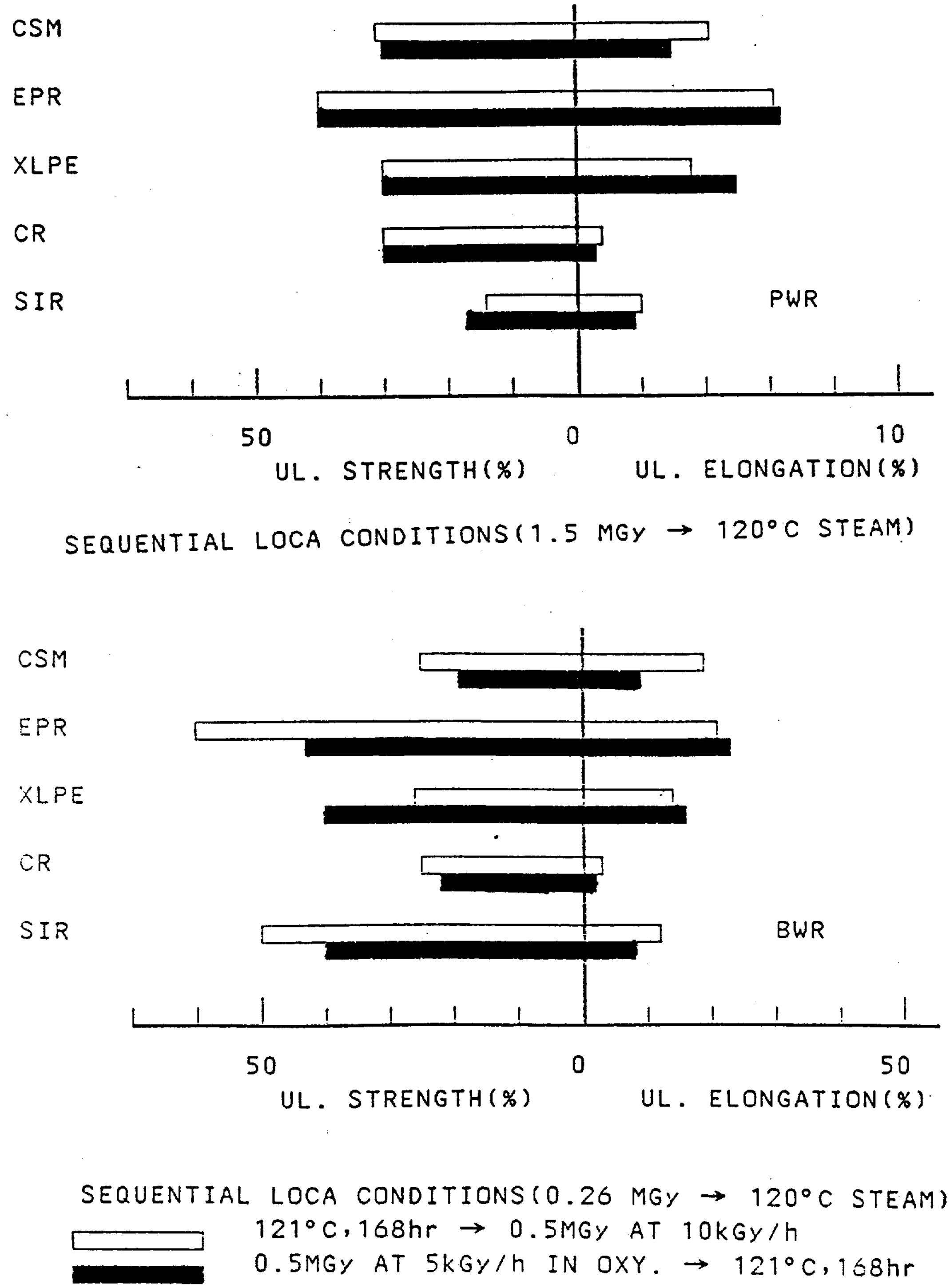


Figure 5.44 Effect of LOCA on pre-aged Japanese materials (Ref. 5.30)

Table 5.13 Cable Products Included in the Test Program (Ref. 5.31)

Supplier	Group	Description
1. Brand Rex	XLPO	XLPE Insulation, CSPE Jacket, 12 AWG, 3/C, 600 V
2. Rockbestos	XLPO	Firewall III, Irradiation XLPE, Neoprene Jacket, 12 AWG, 3/C, 600 V
3. Raychem	XLPO	Flamtrol, XLPE Insulation, 12 AWG, 1/C, 600 V
4. Samuel Moore	XLPO	Dekoron Polyset, XLPO Insulation, CSPE Jacket, 12 AWG, 3/C and Drain
5. Anaconda	EPR	Anaconda Y Flame-Guard FR-EP, EPR Insulation, CPE Jacket, 12 AWG, 3/C, 600 V
5a. Anaconda *	EPR	Anaconda Flame-Guard EP, EPR Insulation, Individual CSPE Jacket, CSPE Jacket, 12 AWG, 3/C, 1000 V
6. Okonite	EPR	Okonite Okolon, EPR Insulation, CSPE Jacket, 12 AWG, 1/C, 600 V
7. Samuel Moore	EPR	Dekoron Dekorad Type 1952, EPDM Insulation, Individual CSPE Jackets, Overall CSPE Jacket, 16 AWG, 2/C TSP, 600 V
8. Kerite	Misc	Kerite 1977, FR Insulation, FR Jacket, 12 AWG, 1/C, 600 V
9. Rockbestos	Misc	RSS-6-104/LE Coaxial Cable, 22 AWG, 1/C Shielded
10. Rockbestos	Misc	Firewall Silicone Rubber Insulation, Fiberglass Braided Jacket, 16 AWG, 1/C, 600 V
11. Champlain	Misc	Polyimide (Kapton) Insulation, Unjacketed, 12 AWG, 1/C
12. BIW	EPR	Bostrad 7E, EPR Insulation, Individual CSPE Jackets, Overall CSPE Jacket, 16 AWG, 2/C TSP, 600 V

* This cable was only used for the multiconductor samples in the 3-month chamber.

Abbreviations used in table:

XLPO - Cross-linked polyolefin
XLPE - Cross-linked polyethylene, a subset of XLPO
CSPE - Chlorosulfonated polyethylene
AWG - American Wire Gauge
/C - number of conductors
FR-EP - Flame retardant ethylene propylene
CPE - Chlorinated polyethylene
EPR - Ethylene propylene rubber
EPDM - Ethylene propylene diene monomer
TSP - Twisted shielded pair
FR - Flame retardant
BIW - Boston Insulated Wire

XLPO

(1) Out of 40 conductors tested, one from one of three conductors of a Rockbestos multiconductor cable failed during the accident tests. The failed cable was exposed to the 9-month aging chamber.

(2) The three multiconductor cable products had accident IRs[7] that were within an order of magnitude of each other. The single conductor cable tested had an IR that was 2-3 orders of magnitude higher than the multiconductor.

(3) With the exception of one conductor that failed during the accident test, all conductors afterwards successfully passed high-voltage tests at an applied voltage of 80 Vac/mil (dielectric strength as high as 400-700 Vac/mil). Three conductors (Dekoron Polyset XLPO) failed a similar high-voltage test after the post-accident mandrel-bend test, and cracking extending through to the conductor was observed.

(4) For 3 of the 4 XLPO materials aged for 9 months, elongation was greater after the accident than before; this may be the result of melting and reforming of the crystalline structure, or of moisture being absorbed into the cable and acting as a plasticizer.

(5) Most properly installed XLPO cables should survive an accident after 60 years for total aging doses up to 400 kGy (40 Mrad), and for moderate ambient temperatures about 50°C-55°C.

EPR

(1) Four conductors out of 72 failed during the accident tests. Failures also were recorded for one conductor of a Dekoron Dekorad multiconductor aged for 3 months, two conductors of the same manufacturer's multiconductors aged for 9 months, and one Okonite Okolon single conductor aged for 9 months. In addition, the aged BIW conductors had minimum IRs that were potentially low enough to affect the accuracy of some sensitive instrumentation circuits.

(2) The multiconductor cable products showed accident IRs differing by more than 3 orders of magnitude, indicating significant variation in the behavior of EPR products from different manufacturers. The single conductor-cable product from the same manufacturers had an IR generally within the range of the IRs of the multiconductors.

(3) After aging and accident testing, several conductors failed a 5-minute withstand test at a nominal voltage of 80 Vac/mil; these included the four failed during the accident test, one additional Okonite Okolon, and eight more Dekoron Dekorad conductors.

(4) The cables that survived aging for 9 months, accident testing, and post-accident dielectric tests then underwent a mandrel-bend test and a second dielectric test. All of the single conductor cables with bonded CSPE jackets cracked through to the conductor during the mandrel bend; only the Anaconda single and multiconductors and the BIW multiconductors remained functional. Part of the reason why the BIW multiconductors passed while the single conductors did not is that the latter were bent around a mandrel of much smaller diameter than the multiconductors.

(5) Most properly installed EPR cables should survive an accident after 60 years for total aging doses of about 150-200 kGy and for moderate ambient temperatures of 45°C-55°C. By 200 kGy, the residual elongation of the EPR materials that had a bonded CSPE jacket approached zero. Some of the cables with essentially zero elongation remaining at the end of aging performed acceptably in the subsequent LOCA tests.

[7]IR represents insulation resistance in this section.

Miscellaneous Cable Types

(1) Three conductors out of 35 failed during the accident tests, one Kapton conductor from each of the three aging exposures. In each case, the conductors had been damaged during installation or handling. The Rockbestos coaxial cables had minimum IRs, in some cases low enough to affect the accuracy of radiation monitoring circuits.

(2) The accident IRs of the Rockbestos coaxial cable decreased slightly as aging increased. The accident IRs of the Kerite cable decreased more significantly with aging, with up to about a two orders of magnitude difference between unaged and aged cables.

(3) After aging and accident testing, several conductors failed a 5-minute post-accident dielectric withstand test. They included conductors that had failed during the accident tests, as well as an additional five Kapton conductors after the accident test on unaged cables, one Kerite conductor after each of the accident tests of cables that had been aged for 3 and 6 months, and all three Kerite conductors after the accident test of cables that had been aged for 9 months.

(4) All the conductors from the accident test that followed the 9-month aging exposure were subjected to a mandrel bend and an additional dielectric test. All passed, including the Kerite conductors that had failed the post-accident dielectric test, and the Kapton conductor that had failed during the accident test. The Kerite conductors apparently had dried sufficiently to allow them to pass the test.

(5) If properly installed, most of the various miscellaneous cable products tested should survive an accident after 60 years for total aging doses of at least 150 kGy or higher, and for moderate ambient temperatures of 45°C-55°C. By 200 kGy, the residual elongation of the silicone rubber cables approached zero. The cables with essentially zero elongation remaining at the end of aging performed acceptably in subsequent LOCA tests.

Submergence and High Temperature Steam Testing

(1) EPR cables generally survived to higher temperatures than XLPO cables. XLPO-insulated conductors had no insulation remaining at the end of the test (after a 400°C peak exposure).

(2) XLPO cables generally performed better than EPR cables in submergence tests and in post-submergence dielectric testing. By the end of the final dielectric test (after a 40 time cable diameter mandrel bend), only 1 of 11 XLPO-insulated conductors had failed, while 17 of 20 EPR-insulated conductors had failed.

(3) Several cables that performed well during the submergence test failed post-submergence dielectric withstand testing (either before or after the mandrel bend) indicating that both the IEEE Std 383 tests can cause otherwise functional cables to fail.

(4) The IEEE Std 383-1974 dielectric withstand tests are very severe, even if a mandrel bend is not performed. This is evidenced by the failure of 9 conductors and near-failure of 3 more in the post-submergence dielectric withstand test, only 2 of which were showing strong indications of degradation during submergence.

Based on the results from LOCA testing on three groups of cables for life extension possibilities, several important conclusions are cited in Reference 5.35. Most cables successfully passed the accident exposures following accelerated aging (with a factor of 80) to normal service life of 20, 40, and 60 years (see Table 5.14). However, further studies with lower acceleration factors or naturally-aged cables are necessary. There are several cable samples which opened 1 amp fuses during accident exposures, with earliest failure (other than the damaged polyimide cables) at 80 hours into the accident simulation. Other samples had IR readings early in the accident exposure that might be marginal for some applications. Several polyimide failures were attributed to handling damages during test setup. Qualification using single conductors for multiconductor cables was found to be non-conservative, specifically in estimating accident IRs. Total thermal lag time was typically 3 minutes for the multiconductor cables and 30 seconds for the single conductors tested. Finally, the IR measurements were found independent of applied voltage range, and discrete time IR testing appeared suitable for monitoring performance. However, IR values had very little correlation with the amount of aging in the cable's insulation and jacket materials. The elongation-at-break measurements were the best condition-monitoring method to assess the physical condition of the polymeric materials. Indenter modulus testing mirrors the effectiveness of the elongation data on certain polymers. None of the electrical tests detect incipient degradation in cable's insulating system. Rather, by the time any electrical parameter indicates trouble in an electrical circuit, the degradation in the cables may have reached a point where their replacement is needed to eradicate the problem.

Based on the results presented in Tables 4.11 on aging degradation and Table 5.14 on LOCA responses of several commonly used cables in U.S. nuclear power plants, the following conclusions are made from this review:

> Most cable materials, except a few insulation materials, become completely brittle at the end of 50Mrad irradiation together with standard thermal aging conditions. At the end of accident irradiation, and before DBA steam exposure all have zero elongation values. Jacket materials degrade much faster than insulation products. Therefore, issues relating to aging sequence, synergistic effect, dose rate effect, and other relevant considerations during pre-aging of the EQ process can have very little impact on the final state of the cable before testing for the accident steam conditions.
>
> Even with zero elongation properties before the DBA steam testing, most cables survived saturated steam conditions during LOCA. Some Dekorad and Okolon multiconductors, and Kapton-insulated cables failed during LOCA after being exposed to at least 174 hours of saturated steam. Failures of Dekorad and Okolon cables presumably are attributable to severe degradation of bonded Hypalon jackets on individual conductors and the mechanical failure of the severely degraded Hypalon overall jacket. Failures of Kapton-insulated cable are found to be due to mishandling of specimens during testing. The findings from these studies indicate that accident steam conditions used in the EQ process may not be that detrimental to cable performances during an accident, as long as cables are not physically disturbed from their installed positions (which might cause cracking).
>
> Minimum IR values during accident steam exposure are important for cables qualified for certain applications. Therefore, cables passing EQ requirements should demonstrate adequate IR threshold for specific applications, especially for I&C use. To assess the physical condition of these cables, parameters such as tensile properties, indenter modulus should be monitored at each juncture of the EQ process.

5.10 TMI-2 Experience

The TMI-2 accident provides a unique opportunity to evaluate cables after a real accident. Reference 5.37 reports on TMI-2 cable sections, connected to the HP-R-214 Dome Monitor, that were removed after the accident. The testing showed:

1. No detectable difference between cable in conduit or out of conduit.
2. No damage to the cable compared to a virgin cable.

Reference 5.38 discusses analyses of the dome radiation monitor at TMI-2; this was the only instrument inside containment capable of measuring the high radiation levels which might be present during a LOCA. The

Table 5.14 Summary of Results from NUREG/CR-5772 on LOCA and NUREG/CR-5655 on Fragility (Ref. 5.36)

Cable Manufacturer	Insulation/Jacket Materials	Samples Passed DBA	Peak DBA** Temperatures(°F)	Max. TID** (Mrad)	Fragility* Temperatures(°F)	Remarks
Brand Rex	XLPE w/CSPE Jacket	9 of 9	345/385	133/200	329/725	Minimum IR10^5 Ω-100 m
Rockbestos	Firewall III; XLPE w/Neoprene Jacket	11 of 12	345/346	169/200	412/608	1 of 4 energized 9 month samples whose fuse opened at about 84 hrs into LOCA
Raychem	Flamtrol; XLPO w/CSPE Jacket	7 of 7	345/340	163/200	627/726	Minimum IR10^6 Ω-100 m
Samuel Moore	Dekoron Polyset; XLPO w/CSPE Jacket	12 of 12	345/unknown	146/unknown	408/569	Minimum IR$5x10^4$ Ω-100 m
Anaconda	Y-Flame Guard FR-EP; EPR w/CPE Jacket	9 of 9	345/385	140/200	453/742	Minimum IR10^4 Ω-100 m
	Flame Guard EP; EPR w/individual CSPE Jacket and overall CSPE Jacket	12 of 12	345/385	155/200	546/717	
Okonite	Okolon; EPR w/CSPE Jacket	10 of 11	345/355	169/200	320/729	Minimum IR10^5 Ω-100 m. One failed 174 hrs into LOCA
Samuel Moore	Dekoron Dekorad Type 1952 Single Conductor; EPDM w/individual CSPE Jacket	6 of 6	345/340	161/200	474/698	Minimum IR10^5 Ω-100 m. Three failed after 178,181,and 220 hours into LOCA.Hypalon bonded jacket and insulation interaction effect.
	Dekoron Dekorad Type 1952 Multi-conductor; EPDM w/individual CSPE Jacket and overall CSPE Jacket	13 of 16	345/340	166/200	345/345 (Failed during DBA)	
Kerite	Kerite 1977; FR w/FR Jacket Thicker insulation w/thinner Jacket	4 of 4	345/340	158/200	218/702	Minimum IR350 Ω-100 m.
	Kerite 1977; FR w/FR Jacket Thinner insulation w/thicker Jacket	5 of 5	345/340	158/200	218/702	
Rockbestos	RSS-6-104/LE Coax	6 of 6	345/331	136/200	430/712	Minimum IR10^6 Ω-100 m
	Firewall; SR w/Fiberglass braided Jacket	7 of 7	345/295	133/100	742/744	Minimum IR10^6 Ω-100 m
Champlain	Polyimide; Kapton w/o Jacket	10 of 13	345/360	144/140	743/751	4 behaved irratic including 3 failed due to handling damage
BIW	Bostrad 7E; EPR w/individual CSPE Jacket and overall CSPE Jacket	18 of 18	345/340	167/200	273/723(single) 289/707	Minimum IR2100 Ω-100 m Can affect low current ckts.

NOTES: Except fragility temperature values (from NUREG/CR-5655), all other information are taken from LOCA test results presented in 3 volumes of NUREG/CR-5772 and Ref. 5.36.
Statements in the "Remarks" column are based on results from DBA testing of 0-, 3-, 6-, and 9-month simulations.
* Minimum high temperature test values for two failure criteria; Failure Criteria @ ≤100 kΩ-100 m / ≤0.1 kΩ-100 m.
** First values are taken from NUREG/CR-5772 reports for all four LOCA simulations and the second values are industry's qualification test values on similar cables given in Ref. 5.36.

detector failure modes included moisture intrusion into the electronics package, DC feedback in the preamplifier, MOS transistor degradation, and electrolytic capacitor failure. Using degradations in transistor current gain and elastomeric material properties, the total gamma-radiation dose received by the Dome Monitor (HP-R-214) electronics inside the stainless-steel vessel and the dose to the multiconductor cable outside the vessel was estimated. Table 5.15 lists the doses received by the radiation detectors, which were analyzed at Sandia.

Table 5.15 Estimated Gamma Radiation Doses Received at TMI-2 Radiation Detectors
(Ref. 5.38)

Containment Elevation (Feet)	Instrument	Dose (Mrad)
305	HP-R-211	0.25
305	HP-R-212	0.45
347	HP-R-213	0.99
372	HP-R-214(Cable)	7.90
372	HP-R-214(Detector)	0.22

Bennett (Ref. 5.39) presented information on the accident environment at TMI-2:

Peak Temperature:	185°F
Pressure:	Atmospheric
Atmosphere:	Air
Total Dose:	1-10 Mrad
Relative Humidity:	100%

These parameters were used to establish exposure conditions for the laboratory control samples. None of the techniques (FTIR, RAMAN spectroscopy, density profiling) used to analyze surface damages was sensitive at a dose level less than, or equal to, 10 Mrad as estimated in the TMI-2 accident environment.

Table 5.16 Penetration Environment and Damage Summary (Ref. 5.40)

			Cable References to Water			
Penetration Section	**Penetration Elevation (ft)**	**Irradiation (R/hr)**	**# of Cables**	**Cable Marginal[a]**	**Cables[b] Below Water**	**Inoperable (%)**
R400, R402 & R407	292	20 to 50	117	117	0	4.3
R405	292	50 to 1000	5	4	1	80.0
R406	292	20 to 50	6	4	2	16.7
R504	323	20	10	4	0	30.0
R505	319	20	10	3	0	10.0
R506	323	20	19	4	0	31.0
R534	300	20	14	6	0	35.7
R607	292	20 to 50	52	38	14	61.5

a. Cables which were partially above and below water level. b. Peak water level 292-ft elevation.

Reference 5.40 summarizes the results of diagnostic tests conducted on selected cable channels within the TMI-2 reactor building. Two hundred and thirty-three cables were tested in situ; anomalous electrical behavior was observed in 103 (44%) of them. Of these, 57 cables (24%) contained inoperable circuits; Table 5.16 is a summary of inoperable cables, by penetration, and also includes some general environmental conditions.

Dandini and Bustard (Ref. 5.41) described the results of examining a short length of Raychem Flamtrol cable, which was connected to the HP-RT-211 radiation detector from the TMI-2 containment building. The ultimate tensile strength, the percent elongation-at-break, and the insulation resistance were measured. All three techniques detected no damage in comparison with a "virgin" specimen.

Yancey (Ref. 5.42) presented the results of instrument cables used with two Foxboro pressure transmitters and a Bailey liquid level transmitter. Raychem manufactured the cable installed with the core flood transmitters, and Anaconda supplied the test cable (FR-EPR insulation w/CSPE jacket). The average total dose of radiation received by the two coils of cables was 12 Mrad. The cables showed no major signs of deterioration during irradiation. The insulation resistance decreased 10% and the dielectric constant increased 1%; this disappeared when the fuel was removed, indicating the apparent effect of the presence of a radiation source.

Meininger (Ref. 5.43) also reported the results from in-place tests on 460 circuits; 178 abnormalities were identified, of which 36 circuits failed, 38 circuits showed significant changes, and 104 circuits showed minor changes. The circuits represented a two-wire transmission line from the reactor building wall up to and including the end device. Generally, there was no evidence of moisture and degradation which might be expected as a result of corrosion.

R607 is a 137-channel instrumentation and control penetration. Of those available channels, 49 were initially chosen for testing. Most screening tests indicated there were several broken wires and corroded contacts. Measurements of insulation resistance between wires of different cables yielded evidence of "cross talk," an interference between wires in the penetration. The penetration was at the 292-ft elevation that was submerged until the water level in the reactor building's basement was lowered, and water remaining in the penetration may be the cause of the cross talk. The predominant anomaly encountered was a shift in the cable's characteristic impedance, which also could be caused by the ingress of moisture through the insulation. Subsequently, three additional channels were tested. Of the 52 channels, 47 exhibited anomalous behavior, and 33 of these were inoperable.

Five cables were tested in penetration R405 and all exhibited anomalous behavior; four were judged inoperable. Also, fourteen instrumentation cables were tested in penetration R534; anomalies were observed in seven, of which five were judged inoperable. Cross-talk voltages were observed, which suggested possible corrosion or water contamination. However, the environmentally sealed splices survived well.

Penetration R506 contains reactor control circuits, including current transformers, level (pressure) transmitters, and temperature, pressure, and limit switches. Nineteen cables were tested; 16 exhibited anomalous behavior, of which six were judged inoperable. Additionally, of 39 pressurizer heater cables, anomalous behavior was observed in 12. Five were inoperable; one with an open circuit, one with a short circuit, and three with low insulation resistance.

Since the penetrations evaluated were selected because of their high probability of impairment, the data are not statistically representative of the 1800 circuits in the reactor building, but serve to indicate the circuit damage to be expected from this type of accident. Finally, hydrogen burn did not substantially damage the instrumentation.

The effect of TMI -2 accident and post-LOCA environments on cable/connection components were studied by Westinghouse Hanford Company (Refs. 5.44 and 5.45). These components involved penetration assemblies, terminal boxes (NEMA boxes, pull boxes), splices, terminal blocks, bulk cable, and connectors. A total of 1800 in-containment electrical channels were identified. About 10-20% of them were subjected to in situ electrical tests. During the first day of the accident, the environment inside the reactor containment was one of intense radiation, steam, temperature excursions, a hydrogen burn, and a chemical suppression spray. Post-accident environmental conditions included low-level dose rates that integrate to 0.1 Mrad and moisture exposure either by submersion or high relative humidity. As the accident progressed, spurious electrical signals were observed on plant instrumentation systems. Shortly after the reactor scram, the output signals on any of the plant self-powered-neutron-detectors rose to 3 times that for normal full power flux levels. Thermocouple signals from adjacent positions varied by as much as 2000°F. Based on the preliminary in situ test data on 25% of the 1800 circuits and laboratory testing of cables subjected to both electrical and mechanical tests, elongation was essentially unchanged over the length of the cable, and the trend of decreasing tensile strength with increasing height did not follow the radiation pattern. Therefore, it was hypothesized that the reduction in tensile strength was more likely due to heat from hydrogen burn. Moreover, no significant difference in electrical properties were observed between the different cable sections.

The analysis of polar crane pendant cable had been identified with cuts and abrasions which indicated that the impact of maintenance accidents on cables might have compromised their ability to function properly (Ref. 5.46). The radioactive contamination present on the portion of this cable lying horizontally on the D-ring was approximately 10 times greater than found on a contiguous section that hung vertically. Testing indicated that the contamination caused no dramatic changes in either the material or the electrical properties of this cable.

5.11 Effect of Hydrogen Burn

The hydrogen-burn environment differs from LOCA transient profiles and depends on the specific reactor and accident sequence. The containment's size and geometry as well as the amount of hydrogen generated, are important. The typical LOCA environmental test profile has a 10-second ramp to perhaps 340°F, which is maintained for several hours. A hydrogen-burn environment is likely to have temperature increases from LOCA temperatures up to 1500K (and pressures up to 400 kPa) with a ramp time of about 10 seconds. The temperature is not maintained and drops off relatively rapidly (depending on many factors). It should be noted that hydrogen-burn conditions are not part of the EQ requirements, and typically are considered as part of a severe accident scenario. Since cables can be affected significantly from these conditions during an accident, a short discussion on the subject is included here.

The effects of hydrogen burn on a non-safety related cable at TMI-2 (Ref. 5.46) were studied by analyzing char patterns; the results indicated that shielding plays a major role, and survivability depends on its location within the containment. The hydrogen-burn survival program concluded that each piece of equipment will respond differently because of differences in thermal mass, geometry, and location, shielding effects, and the hydrogen burn itself (Ref. 5.47). Cables installed in conduits will experience significantly smaller rises in temperature than exposed cables.

An EPRI study tested 25 cable types in a series of large-scale hydrogen-burn simulations at NTS (Ref. 5.48). From one to four specimens of each cable type, totalling 56 specimens, were exposed to hydrogen burns; 52 cable specimens from 24 cable types were classified as safety-grade cables. Each cable was exposed passively in from one to eleven experiments. Some cables had no visible damage, but those exposed to the more severe burns had extensive damage in the form of charring, cracking, and bulging of the outer jackets. The cables, submerged in water, were tested in an ac withstand-test at rated voltage, an insulation resistance test at 500 volts, and a dc withstand test at three times rated voltage. About 50 out of 52 safety-grade cables passed the performance test after the burns, even though many had been exposed in several experiments. This study also acknowledged the fact that local variations in the environment were very significant.

To augment EPRI-NTS study, NRC sponsored several tests at SNL's Central Receiver Test Facility (CRTF) to simulate the heat flux incident upon test specimens for the 13 volume-percent hydrogen burn at NTS using solar reflectors (Refs. 5.49-5.51). In addition to several electrical devices, cables included in these tests were Okonite Okolon single conductor cable, Rockbestos Firewall III 3-conductor cable, and Brand Rex XLP/CU 3-conductor cable (Ref. 5.49). Blistering and cracking of the jacket materials were observed for all cables. Unlike Okonite and Brand Rex which also exhibited flaking and charring, no significant flaking was seen on Rockbestos. However, all samples maintained the applied voltage and no short circuits were detected. Multiconductor cables were more able to withstand the effects of severe heat flux pulses than smaller diameter single conductor cables. Though multiconductor cables appeared severely degraded, their electrical properties remained essentially intact, i.e., insulation resistance remained in the range of 10^{11}-10^{12} ohm-ft. The single conductor Okonite samples, which had the largest change in the insulation resistance, had a value on the order of 10^{6} ohm-ft.

Dandini (Ref. 5.50) described the results of accelerated aged and unaged samples of Brand Rex XLP/CU 12 AWG 3-conductor cable specimens subjected to simulated hydrogen burns of increasing severity. Visible damage to the cables increased with the severity of the pulse. Generally, aged samples experienced less severe visible damage than the unaged samples at each flux level. Blistering and coating with soot were common to all cable jackets above 1.5 flux levels. Crack penetration into the jacket exposed the insulation materials and the filler materials melted. After the exposure, all cables were hi pot tested. With one exception, all insulation maintained their integrities. The exception was the black conductor from the unaged sample, in which the insulation (exposed to 3.0 pulse) broke down within seconds after applying the 2400 Vac test voltage.

From several other simulations of various hydrogen-burn environments, SNL concluded that, if the expected temperatures are higher than LOCA temperatures, cables should be qualified for the more severe hydrogen-burn environment, or their installation inside the containment should be modified to protect them from the burn (e.g., install the cable in conduits).

5.12 LOCA Testing of Damaged Cables

Experiments were conducted to assess the effects of high potential testing of cables flooded with water, and to determine the amount of insulation necessary to survive aging (equivalent to 40 and 60 years of service) and a LOCA exposure (Ref. 5.52). Three types chosen for this program included (1) Okonite Okolon cable with EPDM insulation and bonded CSPE jacket, (2) Rockbestos SR cable with a fiberglass braid jacket, and (3) Brand Rex cable with XLPE insulation. Samples from each type were damaged at five locations. Each damage consisted of one-inch length with various depths of insulation removed by grinding to simulate cable conditions.

Based on the ultimate voltage-breakdown strength, the high potential testing of virgin Brand Rex cables at 35 kVdc did not fail the cables. Also, in a limited set of tests with applied dc voltages, there were no unexpected effects on length. To detect 7 mils of remaining insulation for Brand Rex cables, a test voltage of 35 kVdc suffices (1170 Vdc/mil based on the nominal insulation thickness). A test criteria for Rockbestos cables was not established since the level of damage that would allow the cable to survive an accident simulation could not be defined.

Brand Rex XLPE cables with 7 mils of insulation remaining are likely to survive in an accident after thermal and radiation aging to the conditions defined in this program. However, if higher applied voltages (>110 Vdc) or ac voltages had been used during the LOCA simulation, earlier failures may have occurred. Rockbestos SR cables with as little as 4 mils of insulation remaining have a reasonable probability of surviving in an accident after radiation (20 Mrad aging plus 110 Mrad accident dose) followed by thermal aging to the conditions defined in this test program. However, thermal aging may have been a significant factor (together with the reduced wall thickness) in causing two failures of Rockbestos SR cables. Thus, reduced thermal aging probably would lower the failure rate of these cables. Survival data for Okonite Okolon cables were not available because of failures after thermal aging. All of the intentionally damaged Okonite EPDM/CSPE cables, with less than 15 mils of insulation remaining, failed before aging was completed. The one undamaged cable failed during LOCA exposure shortly after the test chamber was filled with saturated steam. The one cable that had approximately 15 mils of insulation remaining caused a 1A fuse to open at 182 hours into the LOCA simulation, although there were earlier indications of its erratic behavior. The major causes of the Okonite cable failures are the extent of pre-conditioning by irradiation (including both aging and accident radiation doses) followed by thermal aging, and the presence of a bonded CSPE jacket that ages more rapidly than the underlying insulation.

The failures of Okonite EPDM/CSPE cables in this program, and one Okonite Okolon and three Dekorad in a previous program (Ref. 5.32) suggest that the bonded CSPE jacket is detrimental to overall integrity of the cable. Even the undamaged cable cannot meet its rating with the bonded CSPE jacket when thermal aging is performed according to the Arrhenius theory, as used in this testing. Another interesting result indicates that even though the Okonite cables sustained cracks during thermal aging (before the LOCA simulation), all of the cables then survived for some time. The first Okonite failure (opening of 1A fuse) occurred at 11 hours (just after the chamber's environment became saturated steam) and the final Okonite failure occurred at 182 hours into the LOCA profile (although there were indications of erratic behavior and, perhaps, even failure well before the fuse opened). However, no chemical spray was used during the LOCA simulation; its use would have caused failures to appear shortly after it was started because of the enhanced ground plane it creates.

Hanson (Ref. 5.53) studied EPR and XLPE cables subjected to various mechanical damages and accelerated aging conditions. EPR samples included artificial damages by scrapes, transverse cuts, and longitudinal cuts, whereas XLPE had only scrapes and transverse damages. Some samples were aged up to 1 MGy; others were thermally aged at 130°C for up to 50 days. The breakdown voltage was measured for cables under a variety of these conditions. Theoretical models were developed for electric field calculations and were used to analyze the breakdown voltage versus thickness data.

The study concluded that as long as there was more than 0.60 mm of insulation remaining in both material types, the breakdown voltage remained unchanged. For severe damage conditions (0.60 mm or less remaining insulation), the breakdown voltage decreased linearly with the decreasing thickness of the remaining insulation. The dielectric strengths for both cable materials were not affected by mechanical damage, except for XLPE with transverse cuts, in which dielectric strength appeared to decrease.

The accelerated aging used in this study did not affect the dielectric strength of undamaged or damaged cables, except for XLPE with radiation dose above 0.5 MGy (50 Mrad) when transverse cuts failed at very low voltages. The effect was most likely due to radiation-induced cross-linking causing the XLPE insulation to become brittle. The study also concluded that this might have been caused by stress fractures which was exacerbated by radiation.

The effects of cable length, bend radius, and ambient temperature on the breakdown voltage of undamaged cables also were studied. There was no observable difference in the dielectric strength of the longest cables compared to the shortest. Similarly, the strain ranging from about 5% to 15% caused by bends had no effect on the dielectric strength of the cables. Finally, statistical comparisons of the pore radii, and thus, dielectric strength for each temperature did not reveal any effect due to different ambient conditions.

A Japanese study on the effect of initial strain on the degradation of CSPE, chloroprene, SR, and EPR during irradiation is presented in Reference 5.54. Cable samples were elongated by certain ratio from their initial length and then irradiated to different dose levels at several different dose rates. This condition may simulate excessive pulling of cables during installation or conditions at sharp bends where initial stress conditions exist. The samples were irradiated at dose rates of 1, 5, 10 kGy/hr in air and 4.5 kGy/hr under oxygen pressure of 0.5 MPa at room temperature. Total doses ranged from 0.25 and 2.0 MGy. Constant strains of 50% and 100% of the original length were considered. Several mechanical tests were made such as elongation and strength at break, gel fraction, and swelling ratio.

The stress relaxations are very small in unirradiated and already irradiated samples, but large for samples undergoing irradiation indicating faster degradation of cables under stress in radiation environment. The permanent strains in the samples increased with the dose and were not affected by irradiation and heating. The degradation of tensile properties increases with the increase in total dose and initial strain.

5.13 Summary

In reality, in an accident cables may be exposed simultaneously to environments including total radiation dose and dose rate, oxygen, chemical spray, superheated and saturated steam, steam impingement, and hydrogen burn. The environmental qualification of these cables has followed both sequential and simultaneous simulations of aging and accident conditions to provide reasonable assurance of their survivability in an accident any time during their design life. Post-accident testing assesses their residual life after exposure to severe aging and LOCA conditions. The results presented in this section cover various elements that govern the environmental qualification of Class 1E cables. The effects of steam impingement are included to the extent necessary in establishing DBE environment with shielding considerations, fracture mechanics studies, and leak-before-break scenarios, and thus are not typically needed to be demonstrated in an EQ test program. In addition, the effect of high temperature and radiation, together with the saturated conditions during the qualification process, may overpredict the real-life degradation of cable materials.

Most studies on LOCA testing were performed by NRC at SNL, including a collaborative effort with the French Regulatory Agency, and JAERI in Japan. Studies in Great Britain and Germany have not been published. Also, some qualification tests performed by test laboratories for the cable industry and utilities, and material tests performed by the manufacturers were not reviewed. However, the results from these tests could be of significant value to this research program.

Examination of cables after the TMI accident give precarious results on the survivability of cables inside the containment. However, these studies did not provide the most important information relating to the wiring systems' responses during and immediately after the accident. Although many circuit failures or malfunctions were reported, the causes of these failures or their physical conditions were not completely analyzed to derive any inferences for future cable qualification. However, studies on TMI cables after the accident indicate that the total integrated dose on any cable product was about 12 Mrad or less, and the majority of electrical circuit failures were attributed to submergence or exposure of saturated steam at the cables' interfaces. Many of these circuit failures were assumed by many as non-safety related. Some studies indicated that very few circuits failed immediately after the accident and a large number of failures occurred several days later.

Studies on LOCA-testing of the EQ process have produced a large mass of data. The variety of topics and cable materials included makes it difficult to understand and derive conclusions on a particular issue. Although most results provided some insight into the responses of various cable materials and constructions in the LOCA, in some cases, they raised more questions than answers on survivability. Many earlier studies at SNL involved detailed evaluations of failures that were reported during the test, and often, these were due to experimental anomalies. On the other hand, recent studies used an approach which considers a cable to have failed when it cannot carry a fixed amount of current (e.g., 1 amp); this test has been a subject of discussion among many researchers and the industry.

There is some information showing that a cable's condition is approximately the same after LOCA radiation, regardless of how aging is accelerated and how much the cable's condition differs at the end of aging. Further evidence could be very important; because it would simplify qualification, if it was concluded that the sequence of thermal and radiation aging (or whether thermal and radiation aging are conducted simultaneously) makes little difference to the end result.

No single research appears to have been done on the adequacy of LOCA profiles. Significant research was performed on specific elements, such as the effect of superheated steam, the presence of oxygen, and a few other variables. However, recent SNL studies (Refs. 5.31-5.34) have evaluated certain elements of the LOCA profile. Gleason (Ref. 5.36) discussed the results from these studies on LOCA profile adequacy, duration of test, single/multiple peaks, and post-LOCA mandrel bends. Based on these results, he concluded that substantial margin in LOCA profiles, excessive severity of post-LOCA mandrel bends, and no effect from multiple peak testing exist.

Issues relating to LOCA sequence, dose rate effects, synergistic effects, presence of oxygen, use of Co-60 gamma source, chemical spray effects, and hydrogen burn have been largely resolved. Questions on single versus multiconductor performance, wiring system problems, determination of how much oxygen is present in an actual LOCA environment, and margins available in LOCA-test profiles need further studies.

There is not much research on hot spots or weak links in cable systems. Recent studies by Siemens of Germany, and a cooperative program by U.S. and France provide some insights. More insights may be gained once the results from the EPRI sponsored study at UConn are available. The SNL study on artificially damaged cables partially simulated installation damages. Cables and wiring systems from operating or decommissioned reactors should be considered for further testing and the program should focus on issues and on cable products that have raised concerns in earlier studies.

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6. CONDITION MONITORING METHODS FOR CABLES

Nuclear power plants contain a myriad of electric cables of all sizes, voltage ratings, and lengths delivering electric power to much vital, as well as non-vital equipment. Invariably, cables are insulated with some form of polymeric insulation. In this section, the focus is limited to low voltage (< 1000 volts) safety-related cables that are used for power supply, control, and instrumentation applications inside the containment. The polymers used in this class of cables vary from noncrystalline types, such as plasticized PVC and Tefzel, to semicrystalline polyolefins, usually crosslinked polyethylene and EPDMs.

Despite all the advances in the technology of cable insulation, insulating materials can be damaged mechanically during transportation, installation, and maintenance, or they may gradually age from exposure to heat, radiation, moisture, and chemicals. On-site testing of the condition of these cables is necessary to ensure their continued reliability in service, and to predict their remaining life. Cables must operate safely, and reliably in the harsh steam environments produced by postulated design-basis events (e.g., MSLB, LOCA). There is a world-wide search for effective testing methods which can assess the present condition of a cable's electrical property and can also predict its remaining life and LOCA survivability with some assurance. Researchers and engineers believe that one all-encompassing method or procedure for achieving this goal does not exist.

The desirable attributes of such a condition monitoring (CM) technique are (Ref. 6.1): (a) non-intrusiveness; (b) reproducible results; (c) non-destructive; (d) unaffected by, or can be adjusted for, the environment (i.e., variations in temperature, dose rate or moisture); (e) sensitive to the rate of degradation (preferably during an incipient-failure condition); (f) applicable to a wide range of materials and construction; (g) portability of test equipment; (h) assessment along the entire length of cables; and finally (i) cost-effectiveness. An additional important attribute for safety considerations is that CM techniques be able to detect cable characteristics, the level of which reliably predicts LOCA survivability. Since the primary objective of this technique should be to monitor the rate of degradation in the cable's insulation and jacket materials in an inside-containment environment of a nuclear power plant, developing a single test method (or a combination of several techniques) satisfying all these attributes has been a challenging issue.

The EPRI conducted two workshops, the first in 1988 (Ref. 6.2) and the second in 1993 (Ref. 6.3), to bring the utilities, research organizations, cable manufacturers, test equipment manufacturers and consulting firms, and universities from all over the world to share their experiences and to formulate an aggressive research program. In the first workshop, all agreed that the conventional monitoring techniques could not characterize the gradual degradation of aging cables. As a result, EPRI-sponsored research activities were started at the University of Tennessee on fingerprinting the thermal history of polymeric materials; at the University of Connecticut on using ionized gas to troubleshoot the cables; at the University of Virginia on oxidation-induction-time testing; and at Sandia National Laboratory (SNL) on pre-ionized gas high-potential testing. Efforts at Ontario Hydro Research under the cooperative sponsorship of the EPRI, the Canadian Electric Association, and Consolidated Edison, at SNL under the sponsorship of the NRC, and at the IAEA and other foreign institutions (including Britain, France, German, Sweden, and Japan) have continued to investigate various CM techniques. Candidate CM methods for detecting incipient failures in cables were summarized at the 1988 EPRI workshop (Ref. 6.4). Recently, a working group of a technical committee of the International Electrotechnical Commission(IEC), SC15B-WG2 has been developing a guide for in-service monitoring of radiation aging of insulating materials (Ref. 6.5). The results presented at the 1993 EPRI workshop are an indication of the ongoing work although the search is far from over, as was reiterated during the discussions among the U.S. nuclear industry and the NRC at the EQ workshop (Ref. 6.1) in November, 1993.

Research efforts to develop an analytical and/or an experimental method to monitor the condition, to predict the remaining life, and to determine the degradation mechanism of cables used in radiation environment have been ongoing for over one decade. Earlier studies developed an analytical approach using shift factors for radiation and thermal aging conditions (Ref. 6.6), and included experimental methods, such as percent swelling and percent extractables (Ref. 6.7), and chemiluminescent spectra for thermo-oxidative degradation (Ref. 6.8). The extracted components then were separated by either gel permeation or liquid chromatography. Measuring the amount of antioxidant depletion and infrared spectroscopy were used to study the chemical changes in the polymer structures. Reference 6.9 presents the results from several electrical and spectrographic measurements of PE exposed to different aging conditions. Correlations were developed between aging time and electrical parameter degradation, and aging time and infrared absorption spectra. Electrical parameters included dielectric strength and loss factor, while the spectrographic parameters included infrared absorption and degree of crystallinity. These kinds of relationships between the structural and electrical changes seem to produce results which can effectively predict the electrical life of cables based on the physical or chemical changes in the insulating media.

Recent studies assessed the usefulness of various analytical and experimental methods in monitoring the condition and predicting the life of cables in nuclear power plants (Refs. 6.10-6.13). These activities included validating predictive models by tests (Ref. 6.10), assessing conditions of naturally aged cables from generating stations (Ref. 6.11), and evaluating CM methods during the EQ process (Refs. 6.12-6.13). Most findings were discussed at the two workshops held by the EPRI in 1988 and 1993. It was recognized that the weak links in a cable system lie at the cable's interfaces with other equipment or devices (e.g., connections, splices, electrical penetrations), and the intrusion of, or exposure to, a moisture/high humidity environment has the greatest impact on the overall reliability of electrical circuits (Ref. 6.14).

In this section, the results from all advancements on the CM issue are summarized. The purpose is to identify those efforts which have the potential of satisfying some of the CM attributes discussed above, together with evaluating their limitations and difficulties. All the CM methods now available in various stages are discussed, ranging from in-laboratory to in-plant installed cable applications.

6.1 Parameters for Monitoring Cable Degradation

Among all attributes of an effective CM method discussed earlier, those which involve the degradation processes in the insulation material, the sensitivity to stressors causing this degradation, and the effectiveness of the monitoring parameter to trend this degradation are important to the researchers.

One very important issue which can affect the outcome of any CM research involves a clear definition of ***what constitutes a cable failure and how CM data interpret this failure***[1]. Is this definition valid for both the normal life-aging phase and the postulated accident-phase of the cable qualification process? From the results presented in the previous two sections on pre-aging and LOCA testing, elongation-at-break for aging degradation, and insulation resistance during LOCA simulation (also weight gain before and after LOCA testing) typically are the monitoring parameters chosen by most researchers. But can the LOCA response of a cable's insulating system be predicted from the threshold value of the parameter monitoring the aging degradation? On the other hand, qualification tests are considered successful provided that after experiencing both pre-aging and LOCA simulations, the cable demonstrates its survivability in post-LOCA dielectric-

[1] Note that the role of CM is not to detect failures, but to detect the approach to a condition at which the cable is still able to function during an accident.

withstand tests and sometimes post-LOCA mandrel-bend tests (Ref. 6.15). Some researchers have expressed their reservations on the severity of these test methods on the already significantly degraded insulation materials after the LOCA exposure. It was demonstrated that insulating systems exhibiting zero tensile elongation before the accident successfully passed subsequent accident simulations (Refs.6.16-6.18).

In addition to mechanical damage during handling, installation, and maintenance, the polymers in the cable's insulating system undergo changes in chemical structure due to thermal oxidation, radiation, and other chemical reactions (Ref. 6.19). This change involves both physical changes, such as orientation, crystallization, and flow, and also chemical changes, such as scission and crosslinking. Simultaneously, changes in mechanical properties can occur within the polymeric materials under mechanical and environmental influences. Some cases are more involved and the changes in mechanical properties and structure can influence each other. To understand the degradation phenomena in a particular cable insulating material (with the proprietary nature of a specific composition of a base resin and additives, and the curing process by the manufacturer), several different types of laboratory tests may have to be undertaken.

Once the chemical and the physical (or mechanical) changes in polymeric properties are characterized, their impact on the electrical properties of the insulating material must be established. The final appraisal of the cable's performance can only be or should be, based on these electrical properties which assure the cable's ability to deliver the required electric power or transmit a signal to the safety-related equipment. Thus, the chemical and physical degradation processes must be monitored first to identify incipient cable failures (i.e., those degradation processes that can lead to subsequent deterioration in electrical properties); significant research on this aspect was performed during the last decade. The second part, which involves correlating these degradation processes with the electrical properties has been given less attention by the researchers. Hence, conflicting conclusions are being considered for defining the threshold value of these polymeric materials which can assure their survival in a LOCA environment. For example, a 50% elongation-at-break (absolute) was used as the threshold value for many cable materials, but how this relates to the electrical properties has not been discussed in the literature. On the contrary, embrittled cables have successfully passed the LOCA tests, justifying a qualified cable for application in a nuclear power plant.

Oxidation, crosslinking, chain scission, hydroperoxide breakdown, and other chemical and molecular changes in polymers first occur under the influence of an inside-containment environment (Ref. 6.20). The presence of oxygen plays an important role in these processes. The physical parameters which are affected by these chemical structural changes (or are important for monitoring their influences) typically are recognized as:

Molecular Weight or Density
Glass Transition or Melting Point Temperature
Oxygen Consumption (amount and rate).

It is desirable to characterize polymers by molecular weight, but the presence of filler materials in cables make it difficult. For basic polymers, typical methods used to determine this include measuring the osmotic pressures, the light scattering, and the viscosity of dilute solutions. These methods may not be suitable for cross-linked or other cable insulation and jacket materials.

The dimensions of the crystals in polymeric materials are small compared to the average length of the polymer molecules. The crystallites are regular arrays of segments of polymer chains. Individual polymer molecules thread their way through many crystallite and amorphous regions. Crystallinity has an important effect on mechanical properties. Several methods devised for measuring the amount of crystallinity include light scattering, density or specific-volume measurements, X-ray diffraction, refractive index, and infrared absorption peaks.

The chemical structure of polymers controls their stability both to chemical attack and to atmospheric aging. It is understood that radiation resistance does not correlate with resistance to chemical and thermal degradation. Furthermore, additives to improve physical properties may play a part in changes produced by radiation. Antioxidants are employed to reduce the attack by oxygen or ozone on the polymer molecules. These antioxidants are usually complex aromatic amines or phenols, and may react with radiation-produced molecular fragments to modify radiation effects. The effect of increasing plasticizer (a low-molecular-weight material) content in certain polymers (e.g., PVC) is to change a hard, rigid polymer first to a viscoelastic material, and then to a rubbery, flexible product. It has been hypothesized that during LOCA testing, embrittled insulating polymers can absorb water that act as a plasticizer (Refs. 6.16-6.18). The extent of this effect is roughly proportional to the amount of water absorbed.

Molecular-weight determinations can establish the extent of cross linking and chain scission in polymers under thermal and radiation environments. For thermoplastic materials such as PVC and PE, the gel point can be used to determine the inception of crosslinking (must differentiate between crosslinked and uncrosslinked materials). This gel point is a function of the molecular weight of the polymer. For degrees of cross linking higher than the gel point, the ratio of soluble to insoluble (known as gel-content) material can be measured. At high radiation doses, if scission and cross linking both occur, the soluble fraction decreases to an asymptotic value characteristic of the ratio of cross linking to scission. When cross linking has progressed to the point of complete insolubility, its extent can be determined by the equilibrium swelling of the polymer in a solvent.

Thus, cross linking increases the molecular weight of the polymer, decreases its solubility, decreases oxygen absorption, and increases the softening temperature. Cross linking draws the molecules closer together and, therefore, decreases the specific volume (low-molecular-weight materials are vaporized) and increases the density. The influence of scission is just the opposite. Crystallinity can be increased in polymers that undergo scission because there is less restraint on the shortened molecules. An increase in crystallinity will cause an increase in density (cross linking also increases the density, but for a different reason discussed above).

Table 6.1 lists several methods that have been used to monitor various parameters of polymer degradation in thermal and/or radiation environments. Except the first three methods, other methods may use only a few milligrams of specimen shaved from the cable's insulation and the tests are conducted in the laboratory. The first three methods are performed on actual cable samples. These methods can diagnose the early stage of polymer degradation and are useful for correlation studies with other methods which monitor the physical and electrical properties of cables.

Table 6.2 lists test methods which measure or monitor the physical properties (or the physical condition) of the cable materials. Some of these methods are currently used in the laboratory to investigate the degree of various degradation processes discussed in section 4.0. Except the Indenter Modulus test method, all other methods are destructive and need cable samples of various sizes. The first two methods require the removal of copper conductors from the specimens which should be shaped and sized as dumbbell/tubes tensile specimens. The use of the Indenter Modulus method has been demonstrated as an in situ test and the results can be trended to indicate aging in the cable's insulation and jacket materials. All of these methods still measure local conditions along a cable's length, and therefore, require tests at several local points to assess the overall condition of the cable.

Table 6.1 Methods to Assess Material Degradation Caused by Chemical Processes

Testing Method	Degradation Caused by the Environment(s)	Degradation Process Being Monitored	Materials Applicable
Near Infrared Reflectance(NIR)	Thermal and Radiation	Oxidation	PVC, EPR, PE
Computed Tomography (CT)*	Thermal and Radiation	Cross-link Density Gradient	EPR, PE
Sonic Velocity	Thermal and Radiation	Density Changes	PVC, EPR, PE
Fourier Transform Infra-red Spectroscopy (FTIR)	Thermal and Radiation	Oxidation(Carbonyl Peaks)	EPR, PE
Solubility - Gel Fraction	Thermal and Radiation	Cross-linking and Scission	All
- Swelling Ratio	Thermal and Radiation	Cross-linking and Scission	All
Oxidation Induction Time (OIT)	Thermal and Radiation	Depletion of Antioxidants	EPR, PE
Oxidation Induction Temperature**	Thermal and Radiation	Depletion of Antioxidants	Rubber, CSPE
Plasticizer Content	Thermal	Depletion of Plasticizer	PVC
Differential Scanning Calorimetry	Thermal	Glass Transition Temperature Crystal Melting Behavior Degree of Crystallinity	Semicrystalline Products
Thermomechanical Analysis(TMA)	Thermal and Radiation	Hardness	Elastomers, PVC
Thermogravimetric Analysis(TGA)	Thermal	Weight Losses	Elastomers, PVC

* Not considered a chemical method. ** Performed under pressure.

Figure 6.2 Methods to Monitor Physical Properties of Polymeric Materials

Testing Method	Physical Properties Being Monitored	Comments on Material Types Affected
Elongation-at-Break(EAB)	Tensile (Absolute/Relative)	All
Tensile Strength (TS)	Tensile (Absolute/Relative)	All
Indenter Modulus	Compression Elasticity	All (Tefzel possible)
Torque Tester	Torque Modulus	Not Known
Flexure Test	Bending Strength	All
Profiling - Modulus	Heterogeneous Degradation	All
- Density	Heterogeneous Degradation	All
- Hardness	Heterogeneous Degradation	All
Cross-Sectional Polishing	Chemical Degradation Profiles	All
Hardness Test	Hardness	All
Density Measurement	Density	All (Silicone possible)
Dynamic Mechanical Analysis (DMA)	Flexure, Hysterisis of Stress-Strain Relationship	Rubbers, PVC

Elongation-at-break has been the conventional method used for measuring embrittlement in polymers. Traditionally, a value of 50% absolute elongation was considered as the threshold value for aged specimens. It is assumed that this value will provide sufficient margin for the insulation to function without cracking.

Unlike the methods in Tables 6.1 and 6.2, electrical tests monitor the condition of the entire length of the cable included in an electrical circuit. One problem with these tests is that by the time any degradation is indicated by abnormal results, the cable is embrittled and may contain cracks. Again, many of these electrical methods require a well-defined, continuous ground plane to measure the electrical properties of the insulating system and this often raises more questions than answers on the effectiveness of the procedure. Theoretically, any electrical test will be insensitive to anything but gross changes in the dielectric. Table 6.3 lists several electrical tests which are being used in the field today to monitor the conditions of cables in nuclear power plants.

Table 6.3 Electrical Test Methods Monitoring the Cable Performance

Test Method	Measuring Parameter	Comments on Applications
DC Tests	Insulation Resistance	Go/No Go, Humidity
	Polarization Index(PI)	Go/No Go, Humidity
AC Impedance Tests	Capacitance	Dielectric Capacity
	Dissipation Factor (DF)	Dielectric Loss
Stepped Voltage Test	Leakage Current	Gross Insulation Failures
High Potential Test	Leakage Current	Gross Insulation Failures
Partial Discharge Test	Inception Voltage	Corona, Ionization
Voltage Withstand Test	Voltage Capacity	Withstand Voltage
Time Domain Reflectometry(TDR)	TDR Signature	Fault Detection
Dielectric Loss Measurements	Loss Factor (tan δ)	Dielectric Loss

There is no evidence that electrical tests are sensitive to morphological changes in the aged insulation, i.e., to the chemical and physical deterioration that takes place during thermal and radiation exposures. Embrittlement ultimately causes cables to crack and fail. But how to relate this to these electrical-test parameters has been a challenge to many researchers. Moreover, in situ measurements also critically depend on the level and type of electrical noise interfering with the measurement system. Connecting test equipment to electrical terminals may require disconnecting installed interfaces. The testing also may require disconnecting all equipment (or electrical loads) connected to the circuit under study. These intrusive requirements are disruptive, and the utilities have serious reservations about including them in their maintenance program.

6.2 Methods for Monitoring Chemical Degradation

When earlier plants were constructed, the cable insulating materials used were butyl rubber for high-voltage, and styrene butadiene rubber and PVC for low-voltage applications. The jacket materials were predominantly Neoprene and PVC. In the early 1970s, the insulation was mostly XLPE, PE or PVC with Hypalon or PVC jackets. Cables in newer plants typically are insulated with fire-retardant EPDM or XLPE and jacketed with improved fire-retardant Neoprene or Hypalon. Table 6.4 shows the qualitative, general physical characteristics of these cable materials which might help in understanding the limitations in using the various CM methods in Table 6.1 for studying chemical degradation under different stresses. This qualitative assessment may vary for similar materials from different manufacturers.

The NIR, CT, and sonic velocity methods are being developed. FTIR has been proven to be a useful method for identifying various functional groups that are formed due to oxidation, but this requires a skilled effort to understand the interferences caused by the presence of antioxidants, and other filler materials. Solubility measurements are easier to perform and the results provide information about whether the degradation is due to thermal or radiation stress. Based on the sample's gel content and plasticizer content, the type of degradation can be identified from the amount of cross linking (thermal or radiation) and scission (radiation). The OIT is not suitable for silicone rubber materials; however, oxygen induction temperature under pressure is useful for these materials (including Hypalon). Plasticizer content is used only for PVC material. The TMA has been good for elastomers and PVC. However, both TMA and TGA methods are not widely used for monitoring the conditions of cable materials.

Table 6.4 Cable Material Characteristics Sensitive to Aging

Basic Cable Material	Material Type	Melting Point Transition Temp. (°C)**	Crystallinity	Degradation Under Thermal	Radiation	Steam/Humidity
PE	Xlinked	90-130	Semicrystalline	N	N	N
	Low Density	90-130	Semicrystalline	S	N	S
	Chlorinated	90-130	Semicrystalline	S	S	S
EPR	Xlinked	60-90	Semicrystalline	N	N	N
	EPDM (Xlinked)	60-90	Semicrystalline	N	N	N
SR	Elastomer(Xlinked)	N/A	N/A	N	S(DR)	N
Tefzel	Thermoplastic	>200	Noncrystalline	N	S(DR)	N
SBR or BR	Elastomer(Xlinked)	N/A	N/A	S	S	S
PVC	-	~120	Noncrystalline	N	S(DR)	N
Hypalon(CSPE)*	Elastomer (Xlinked)	N/A	N/A	S	S(DR)	S
Neoprene/ Chloroprene	Elastomer (Xlinked)	95-100	Semicrystalline	S	S	S

Notes: N/A= Not Available; N=Normal (Average); S=Sensitive(more than Average); DR=Dose Rate Effect.

* Better than Neoprene.

** All values are approximate and vary with the polymer's formulations.

6.2.1 Near Infra-red Reflectance (NIR)

NIR spectroscopy (Ref. 6.21) has been applied to the characterization of polymers as a result of light absorption of organic molecules. NIR spectra arise from overtones or combinations of overtones of the fundamental vibrations that occur in the near infra-red regions of the spectrum, and hence, the technique is complementary to infra-red (IR) and Raman spectroscopy and has found some limited applications for polymer analysis. NIR has the advantage of relatively simple sample preparation. Glass has a low absorption in the near infra-red region, so glass sample holders may be used (e.g., optical fibre probes can be used for in situ samples). Much thicker samples, up to about 10 mm, also may be used. In addition, since most of the spectral lines detectable in the NIR arise from vibrations of hydrogen-containing bonds, hydrogen-free solvents such as CCl_4 may be employed without difficulty. NIR is sensitive to subtle changes and easily reproduced spectra contribute to the analysis of large numbers of components simultaneously. This feature makes NIR attractive for cable insulation systems which contain several additives in the polymer's formulation. The IR peaks are narrower than those in NIR, so that the FTIR's are designed with narrow band passes to give high-resolution discrimination of wavelengths. The tradeoff in the case of NIR is lowered resolution in the absorbance spectra.

The interrelationship of various side-groups with the main structural backbone of the substance can provide a better correlation with changes in physical properties than can the vibration of the mid-IR range. As with FTIR, strong NIR absorbers include species such as C-H, O-H, N-H, C=O, =C-H, COOH, and aromatic C-H groups. Some of these functional groups, namely, C=O, O=H, and COOH are formed as components of cable insulation and jackets age. For the NIR technique to be effective, an equation to predict chemical degradation involving single and multiple variable analysis must be run on a set of well-characterized calibration samples having accurately known aging periods. The NIR reflectance equipment can be made portable using a fibre-optic probe, and lends itself to in situ cable monitoring.

This CM technique (with the potential of future use in situ) is in its development stage at Ontario Hydro (Ref. 6.22). A Quantum 1200 NIR analyzer configured for the NIR region (1200-2400 nm) equipped with a fiber optic reflectance probe and Spectra Metrix software routines was used to study nine PVC jacketed cables aged at 110°C from 28 to 138 days. Each sample was scanned at three locations by pressing the fiber-optic probe against the jacket surface. The transmittance spectra were obtained using the Quantum 1200 NIR analyzer, and the values converted to absorbance spectra by taking the negative logarithm shown in Figure 6.1. To

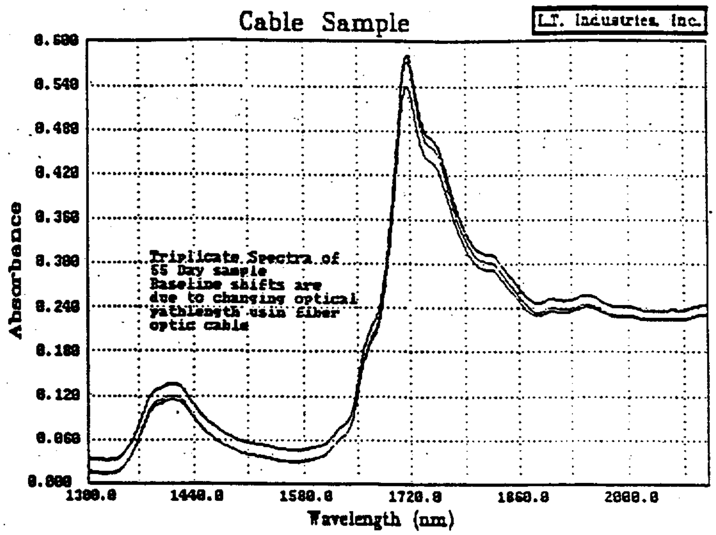

Figure 6.1 Typical variation in infrared absorbance with wavelength for cable jacket (Ref. 6.22)
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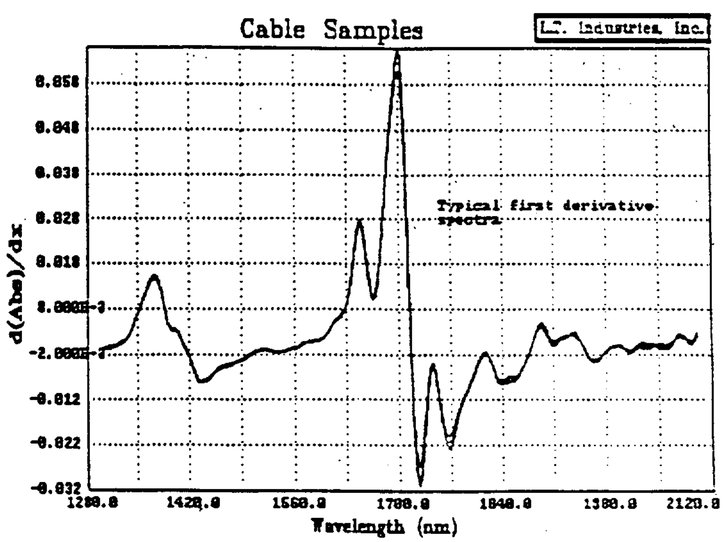

Figure 6.2 First derivative of absorbance plotted as a function of wavelength (Ref. 6.22)
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remove the effects of a constant baseline shift, the first derivative (slope) of the absorbance spectra is plotted as a function of wavelength, as illustrated in Figure 6.2.

Various regions of the spectrum correlated well with aging time. Specifically, the region between 1640 and 1650 nm experienced a distinct change in absorbance values with aging rates. Figure 6.3 illustrates the relationship between wavelength and the first derivative of absorbance with aging. Figure 6.4 compares the resulting correlation between this first derivative of absorbance in the above wavelength region with percent elongation for various aging times. The accuracy of the calibration curve was evaluated using two aged cable samples. For these two unknown samples, NIR analysis predicted 28-38 days and 120-141 days of aging, compared with actual durations of 40 and 124 days, respectively. These results indicate that the NIR technique can indicate the extent of PVC jacket aging.

The IR reflectance spectrum obtained is only from a thin surface layer of the cable material, which may not be representative of the state of degradation of the bulk of the material. Also, data are limited to the immediate area of the probe. The technique is not likely to be sensitive to the cable's geometry. Construction calibration curves would be required for each material in the cable.

6.2.2 Computed Tomography (CT)

Computed tomography (also known as computed X-ray tomography or computer-assisted tomography(CAT)) has been used almost exclusively for medical purposes. It is a non-destructive examination (NDE) which can detect and locate defects, the presence of which might have a deleterious effect on the service life of the cable. The technique also can monitor density changes (or cross-link density gradients) in both insulation and jacket materials. The measurements can be quantified in terms of the Houndsfeld CT number which is proportional to the X-ray attenuation through an object. The CT number is represented by the gray scale of an X-ray image. For organic and polymeric materials, there is an approximate linear relationship between the CT number and the material's density.

Thermo-oxidative degradation of thick-walled rubber materials has been studied by researchers at the Royal Institute of Technology in Sweden (Ref. 6.23) who compared results obtained from the CT, IR, and Swelling measurement techniques to understand diffusion-controlled oxidation, embrittlement of the exposed surface, and anaerobic aging of the interior of the rubber. Both CT and IR spectroscopy successfully revealed oxidative aging in the surface; however, they did not show thermal degradation in the bulk. Also, it was difficult to measure the degree of oxidation from swelling, due to the appearance of both oxidative crosslinking and oxidative scission. However, swelling successfully indicated thermal degradation.

The CT method also was used by the same group to detect imperfections and to measure cross-link density gradients in polymeric products, such as airplane tires, and rubber shock-absorbers (Ref. 6.24). Figure 6.5 shows the relationship between bulk density and cross-link density. These results are in good agreement with the results obtained using wet chemical methods (based on the well-known fact that cross-linked rubber material does not dissolve but swells to different degrees in different solvents, such as hexane, heptane, toluene, and methylene chloride). When the CT numbers of the different test pieces were measured with a Siemens Somatom DR CT scanner, the results plotted in Figure 6.6 show a direct correlation between the CT number and the bulk density.

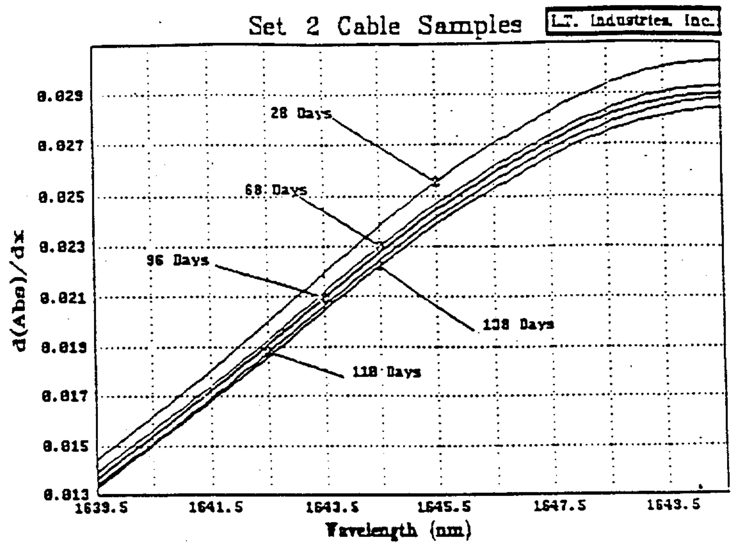

Figure 6.3 Variation in first derivative of absorbance with different aging (Ref. 6.22)
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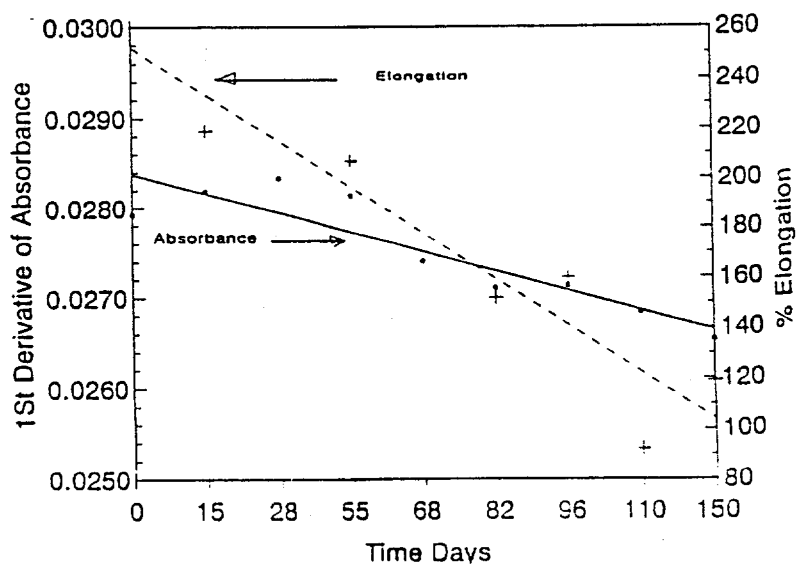

Figure 6.4 Correlation of first derivative of absorbance with elongation (Ref. 6.22)
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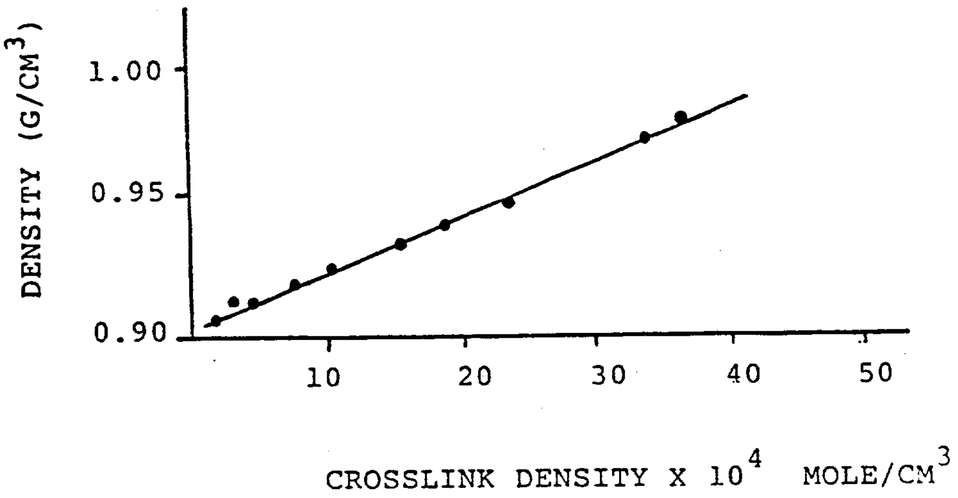

Figure 6.5 Bulk density vs cross-link density for peroxide-cured synthetic natural rubber (Ref. 6.24 Redrawn for clarity)
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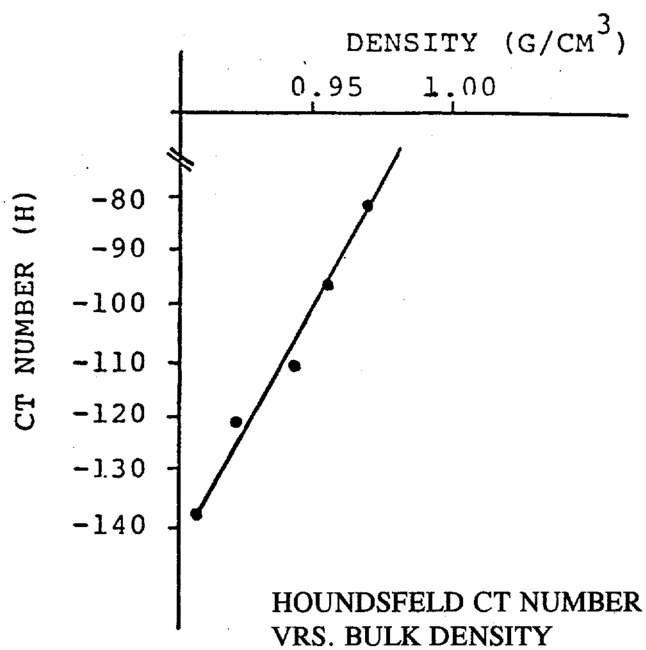

Figure 6.6 Bulk density measured by CT scanning (Ref. 6.24: Redrawn for clarity)
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Work on density and modulus-profiling for EPR-2 material using this method showed excellent similarity with SNL's profiling techniques (Ref. 6.25). Figure 6.7 illustrates the density profiles of this material, and Figure 6.8 shows the good correlation of the density measurements with CT numbers. Comparing this sensitivity to the approximate correlations found between density changes and elongation changes indicates that CT techniques may be a viable non destructive approach for monitoring power-plant cables. At this time, this methodology has not received attention among U.S. researchers, and further studies are necessary before it can be used on cables in plants. Since this method requires an X-ray source and a detector, currently it is used as a laboratory tool.

6.2.3 Sonic Velocity

This technique is based on the principle that the speed of sound through a solid medium (metals, polymers, composites) is related to both density and elastic modulus:

$$C^2 = E/\rho$$

where, C = Sonic velocity
E = Elastic modulus
ρ = Polymer density.

Since both modulus and density can change as cable material age, changes in sonic velocity also would be expected to occur. At Ontario Hydro, sonic velocities are measured using an H.M. Morgan PPR-5M Dynamic Modulus Tester (Ref. 6.22). The instrument uses "transmit" and "receive" piezoelectric transducers which are placed in contact with the surface of the cable's jacket at various distances apart. A microsecond timing circuit, gated in parallel with the transducers, measures the time required for a continuous series of recurring 20 KHz pulses to travel along the jacket's length between the probes. Signal transit times are displayed on a TEKTRONIX 221A digital oscilloscope as a displacement on the time axis between peaks associated with the "emitted" and "receive" signals. The transit time subsequently is plotted as a function of transducer separation distance (incremented successively by 1 cm) to obtain the slope which represents velocity.

This technique is at its early stage of development at Ontario Hydro. Measurements have been made on a series of PVC-jacketed cables and on strips of jacket material cut from the cables. Figure 6.9 shows the longitudinal sonic velocity obtained on them as a function of aging time. Comparison between the data showed that the technique depends on the cable's geometry and adjacent shielding and insulation components (see Figure 6.10a). The magnitude of the sonic velocity also varies considerably with different formulations of PVC. Therefore, base-line data would be required for each type of cable. Similar results are obtained when the sonic velocity data are plotted against the density (Figure 6.10b). When plotted against the jacket modulus in Figure 6.10c, the results are independent of jacket's formulations.

The sonic-velocity test measures the properties of the cable jacket over a small volume between the transducer probes. At present, the technique is more suited to laboratory evaluation than field use, but its high sensitivity to aging degradation indicates that it has potential for in situ application. However, the rate of change with age in the material may not be sufficient to monitor degradation.

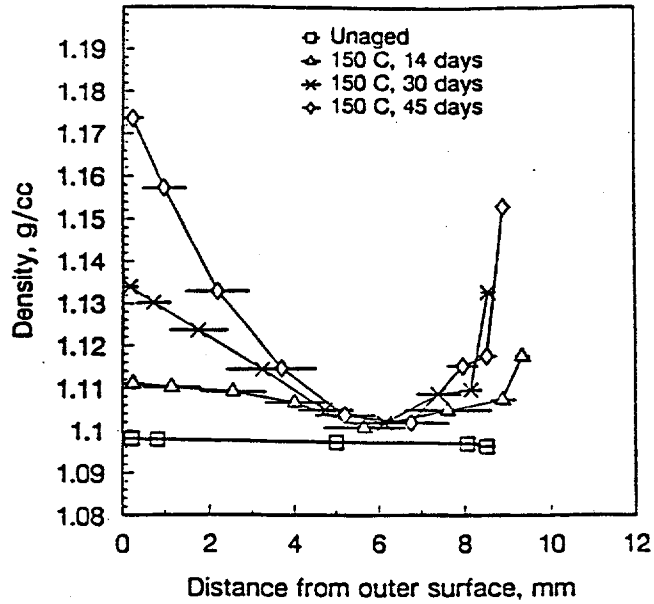

Figure 6.7 Density profiles of EPR-2 (Ref. 6.25)

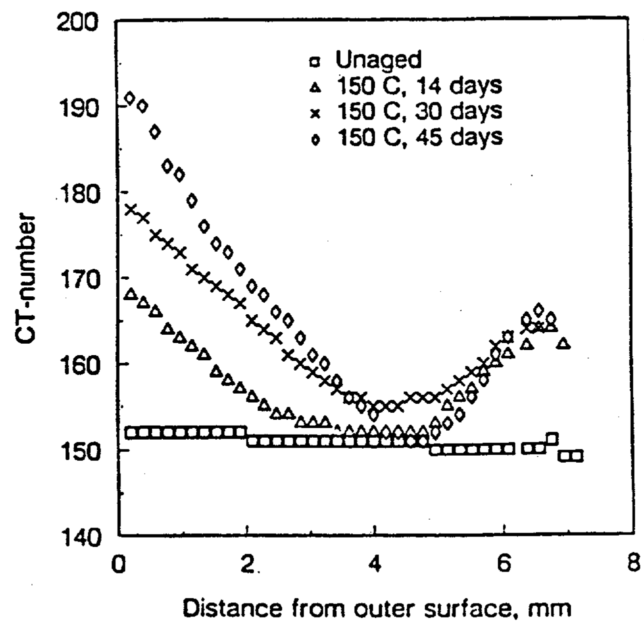

Figure 6.8 CT profiles of EPR-2 (Ref. 6.25)

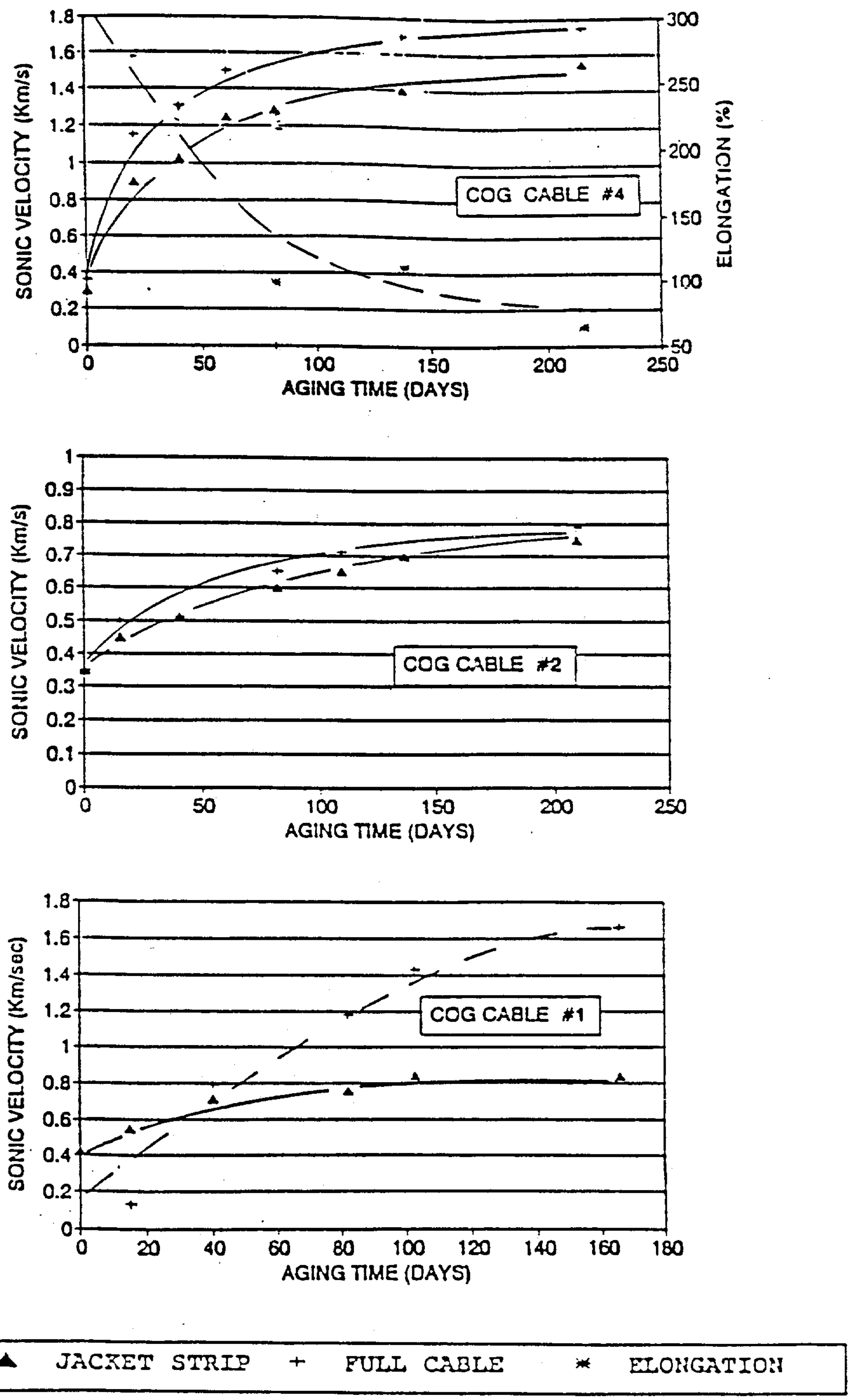

Figure 6.9 Sonic velocity as a function of aging (Ref. 6.22)
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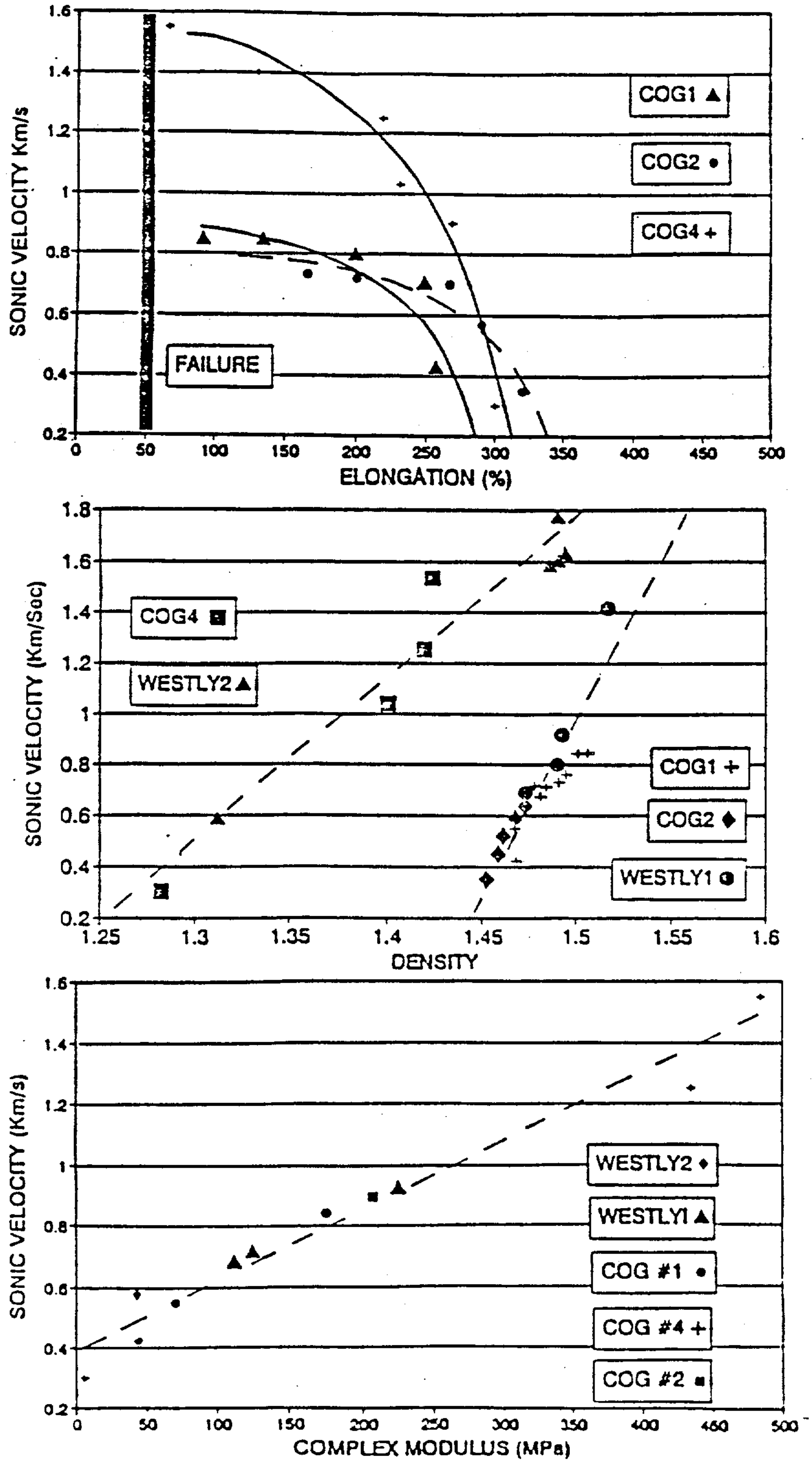

Figure 6.10 Correlation of sonic velocity with elongation, density and modulus (Ref. 6.22)
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6.2.4 Fourier Transform Infra-red (FTIR) Spectroscopy

As discussed under NIR spectroscopy, changes in the infra-red spectrum of polymers are known to occur with aging, primarily in functional groups such as carbonyl (C=O), hydroxyl (O=H), and carboxyl (COOH). An alternative to reflectance measurements in-plant is to take samples from the cable's material and measure the IR spectrum in the laboratory. Such samples usually would be scrapings or slivers of material cut from the surface, but sufficiently small to not affect the operation of the cable. When polymers like XLPE and EPR are oxidized (thermally or irradiation), a strong carbonyl peak becomes evident at about 1720 cm^{-1} in the IR spectrum; therefore, its appearance can indicate deterioration of the insulation. However, detecting the carbonyl groups generated due to oxidation aging is not a simple procedure as unaged materials also can display absorption peaks in the 1700-1750 cm^{-1} region. These peaks have been attributed to the presence of antioxidant additives, such as Irganox and Thio esters, which exhibit a strong ester band at 1742 cm^{-1}. The by-products from high-temperature crosslinking reactions with dicummyl peroxide exhibit peaks at 1724 and 1710 cm^{-1} which also can interfere.

Figure 6.11 shows the FTIR spectra for FRXLPE specimens irradiated to different doses (Ref.6.26). Peaks centered at 1740 cm^{-1} and 1720 cm^{-1} were typical of the irradiated specimens. Variation of the intensity ratio is plotted in Figure 6.12 as a function of dose rate, for specimens irradiated in air. Figure 6.13 gives similar results (Ref. 6.27) on thermal aging of this material. A long induction time for the formation carbonyl groups was observed. It is evident that an increase of 10 °C in the aging temperature reduces the induction time by 50%. This method has successfully indicated similar spectra (with long induction period) for SBR and polypropylene materials. For EPR, the results show changes in the carbonyl region only for specimens irradiated above 100 Mrad, regardless of the irradiation environment or dose rate. Therefore, it does not appear to be sensitive in detecting oxidation of stabilized FREPR insulation materials irradiated to less than 100 Mrad. Similarly, the PVC samples irradiated to 100 Mrad did not have any distinguishable differences in the FTIR spectrum compared with the unaged specimen.

IR spectra taken from samples are limited to the surface layers of the cable jacket unless exposed insulation is accessible. The depth of material sampled is greater than that for in-plant IR reflectance measurements, but may still not be representative of the bulk material. The technique is limited to those parts of the cables that are accessible for sampling and is not very sensitive to the later stages of degradation. Furthermore, a skilled engineer must interpret and evaluate the FTIR spectra.

6.2.5 Solubility Measurements (Gel Content and Swelling Ratio)

Solubility (gel content) and swelling measurements can indicate whether a polymer has undergone chemical reactions (chain scission or cross linking). In a cross-linked system, when a polymer undergoes additional crosslinking, the gel content increases and swelling ratio decreases. Chain scission has the opposite effects. In an uncrosslinked system, the initial soluble polymer will become less soluble in the presence of an oxidative cross-linking reaction.

These methods typically are used in various laboratory studies on polymer degradation (ASTM D2765). About 100 mg of material is exposed to boiling solvent for ~12 hours in these tests; the solvents used are Xylene for XLPE, Toluene for EPR, SBR, and BR, and Tetrahydrofuran (THF) for PVC. After extracting the insoluble fraction in the solvents, excess solvent is removed from the surface, and the insoluble part is weighed at room temperature. Then, the sample is dried and weighed again. Gel content and swelling ratio are calculated.

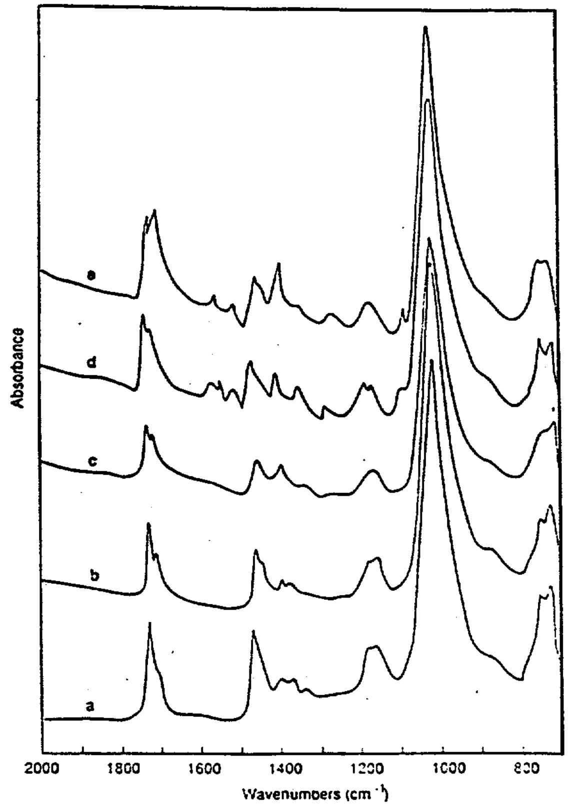

Figure 6.11 FTIR spectra for XLPE (a) unaged; irradiated at 60 °C at dose rate 0.6 Mrad/hr to (b)15, (c) 30, (d) 60, and (e) 120 Mrad (Ref. 6.26)
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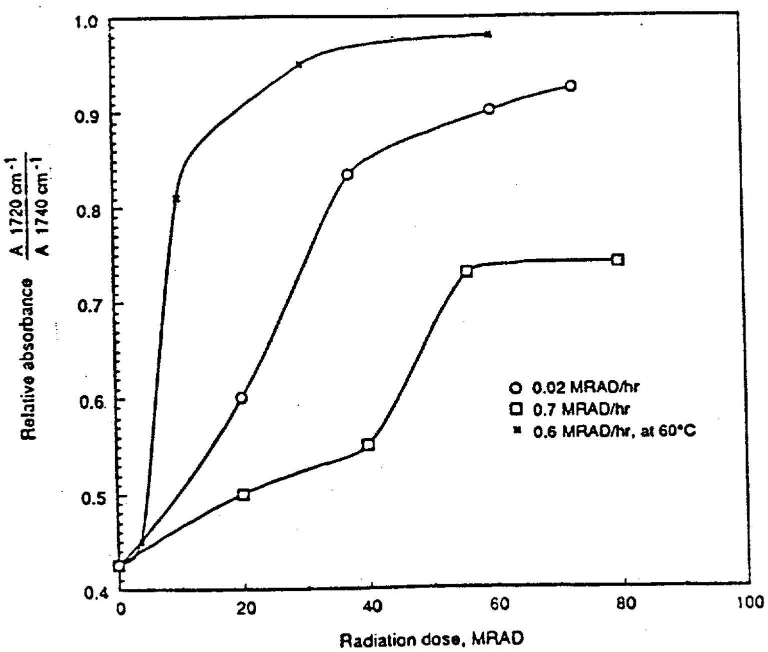

Figure 6.12 Carbonyl absorbance vs radiation dose for XLPE (Ref. 6.26)
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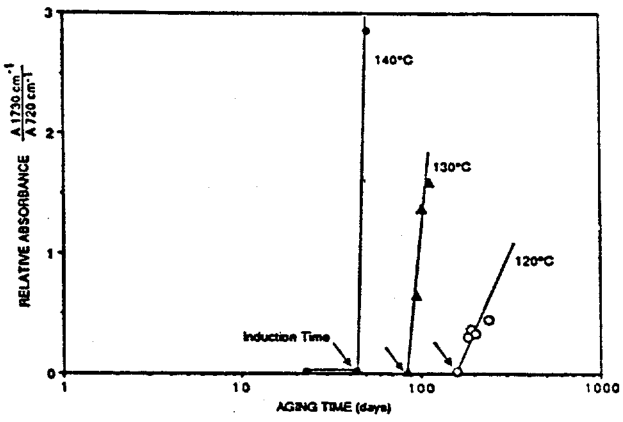

Figure 6.13 Relative absorbance with thermal aging for XLPE (Ref. 6.27)
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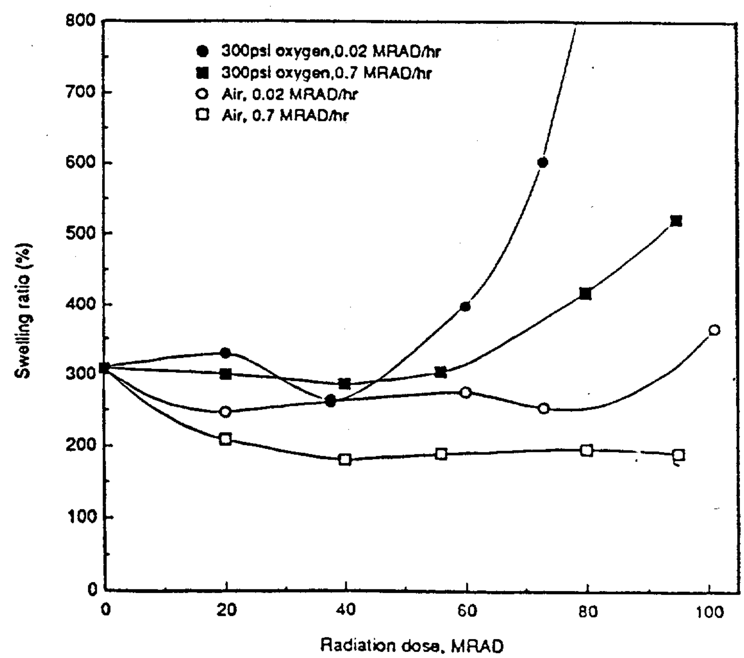

Figure 6.14 Swelling ratio for FREPR (Ref. 6.26)
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The swelling ratio of FRXLPE and FREPR can be used to determine whether chain scission or crosslinking has occurred (Ref. 6.26); chain scission increases the swelling ratio, and crosslinking reduces it. Figure 6.14 shows the swelling ratio versus radiation dose for the FREPR specimens. On irradiation, under 300 psi (in oxygen atmosphere) the swelling ratios increased from 300%, indicating that chain scission had occurred. Irradiation in air at 0.7 Mrad/hr lowered the swelling ratio for both these materials, indicating that the predominant degradation mechanism was crosslinking.

The gel content of XLPE specimens as a function of aging and temperature is shown in Figure 6.15 (Ref. 6.27). The results follow the same pattern as the carbonyl absorbance values in Figure 6.13. There was an induction period followed by a sharp increase in values. The increase in the gel content during the auto-oxidation period reveals that crosslinking was occurring. For EPR specimens, the gel content remained unchanged at 83% during aging suggesting that it is not a sensitive indicator of thermal aging. This also is true for XLPE and SBR, which originally have gel contents in excess of 80%. In these systems, only measurements of the swelling ratio show changes with aging.

PVC specimens irradiated in an oxygen atmosphere were completely soluble in THF indicating there was no crosslinking (Ref. 6.26). However, specimens irradiated in air became more insoluble with increased dose rate and total dose (see Figure 6.16). The gel fraction or crosslinking of specimen irradiated at 0.02 Mrad/hr increased at a very low rate, reaching 5% at the total dose at 80 Mrad. At the higher dose rates of 0.1 and 0.7 Mrad/hr in air, crosslinking was the predominant reaction, and its extent increased with increasing dose rate.

6.2.6 Oxidation Induction Time (OIT)/ Temperature Under Pressure

Using a differential scanning calorimeter (DSC), the time taken to the onset of exothermic oxidation at constant temperature can be monitored. In an OIT test, a small sample (~2-10 mg) of material is placed in a DSC and exposed to a constant temperature in the region 180-215°C in an oxygen atmosphere until an exothermic reaction occurs. This oxidation-induction time indicates the oxidative stability of the polymer and decreases as the antioxidants in the polymer are depleted. OIT values decrease rapidly with increasing radiation dose as well as increasing thermal aging, showing that OIT measurements are sensitive to both thermal-and radiation-induced oxidative degradation.

At Ontario Hydro, this technique was used for thermally aged specimens of XLPE and EPR samples (Ref. 6.27). Figures 6.17 and 6.18 compare the OIT values at 200°C, after aging at the temperatures shown. For unaged XLPE and EPR, the OITs were 65 min and 45 min, respectively. The figures show that the induction period decreased rapidly during the initial aging period before falling more regularly. It was concluded that the OIT measurement is the most sensitive indicator of oxidative degradation during the induction period. The technique also was used for radiation aging samples and similar trends were exhibited in the OIT values. The study also claims that a good correlation was found between elongation values and OIT values for several XLPE and EPR insulations obtained from different manufacturers.

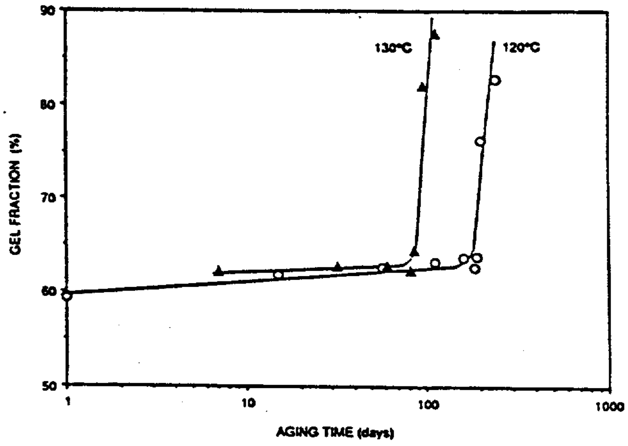

Figure 6.15 Gel fraction vs. aging for XLPE (Ref. 6.27)
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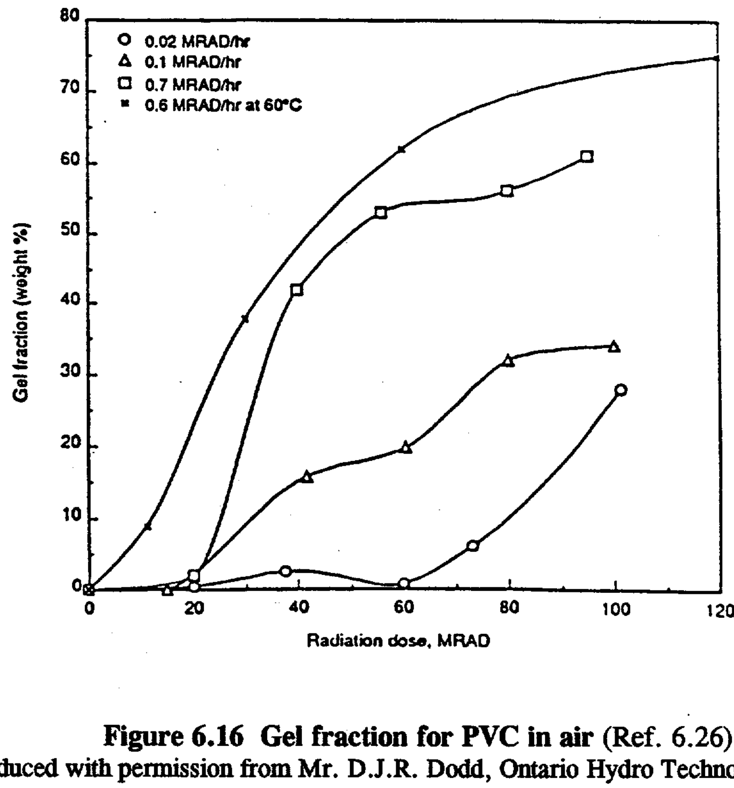

Figure 6.16 Gel fraction for PVC in air (Ref. 6.26)
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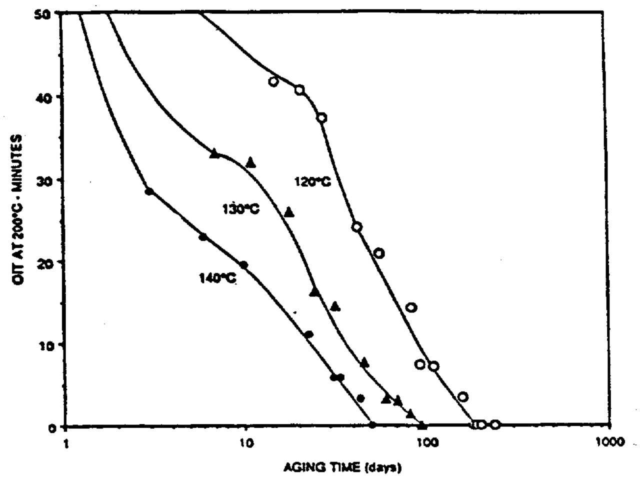

Figure 6.17 OIT at 200°C for XLPE (Ref. 6.27)
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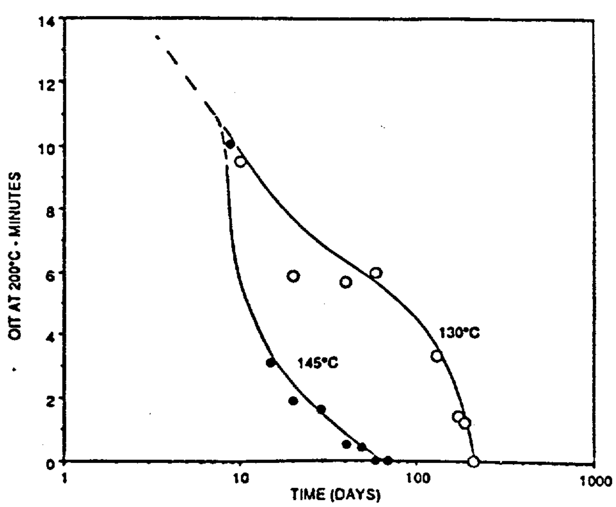

Figure 6.18 OIT at 200°C for EPR (Ref. 6.27)
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At the University of Virginia, this technique was used for the same two materials under radiation aging conditions (Refs. 6.28 and 6.29). Figures 6.19 and 6.20 show the observed variations of normalized OIT (i.e., ratio of aged and unaged OIT values) with radiation dose. The study also correlated OIT with antioxidant concentration. The variation of antioxidant concentration with a constant dose rate was linear, consistent with oxidation reaction kinetics. At present, the work is being continued to standardize the methodology for field application, to correlate the OIT values with other measurable parameters, and to investigate the effects of thermal degradation.

A variant on the OIT technique is to use oxidation-induction temperature (instead of time) (Refs. 6.30 and 6.31). This temperature is that at which exothermic reactions start as the temperature of a sample is raised in a constant atmosphere of oxygen. This method is more useful than OIT for elastomeric insulations, such as SBR and butyl rubber. Figure 6.21 compares the temperature values with the tensile properties of a SBR sample, showing that there is an excellent correlation between them.

As with any microsampling technique, only the properties of the surface layer samples are measured which may not be representative of the bulk material. Further studies on other jacket materials are needed to assess its effectiveness on all cable materials.

6.2.7 Plasticizer Content

This is a useful technique for assessing the degradation of PVC material exposed to thermal aging. The plasticizer content is an important factor in determining the usability of PVC insulations, and the volatility rate of the plasticizer governs its longevity. The plasticizer content of PVC insulations is generally between 20-30%, by mass; a content below 15% indicates that the cable has undergone thermal degradation. Figure 6.22 gives the plasticizer content (Ref. 6.30), obtained 100-200mg specimens in boiling ethyl ether, for a typical PVC insulation as a function of aging at 120°C, and compares the results with the tensile properties of the same material. During the early stages of the aging, both are directly correlated. In the final stage, the plasticizer content basically remained unchanged, whereas elongation decreases further. This behavior indicates that during the later stages, the degradation mechanism is probably controlled by oxidation and dehydrochlorination rather than loss of plasticizer.

Ontario Hydro has used this technique extensively with good results to assess field service cables. By contrast, for radiation exposure, there was no direct relationship between plasticizer content and physical degradation.

6.2.8 Differential Scanning Calorimetry

Experience has shown that one common mode of failure of cable insulation in nuclear power plants is thermally induced oxidation degradation which embrittles the insulation, leading to cracking and loss of dielectric strength. Use of a differential scanning calorimeter (DSC) to measure OIT and other indicators (such as melting point, crystallinity, and glass transition temperature) has yielded useful results for monitoring as well as understanding the polymer behavior under thermal conditions. Ontario Hydro and University of Tennessee have studied some interesting characteristics of polymer behavior and have detected changes in certain physical parameters.

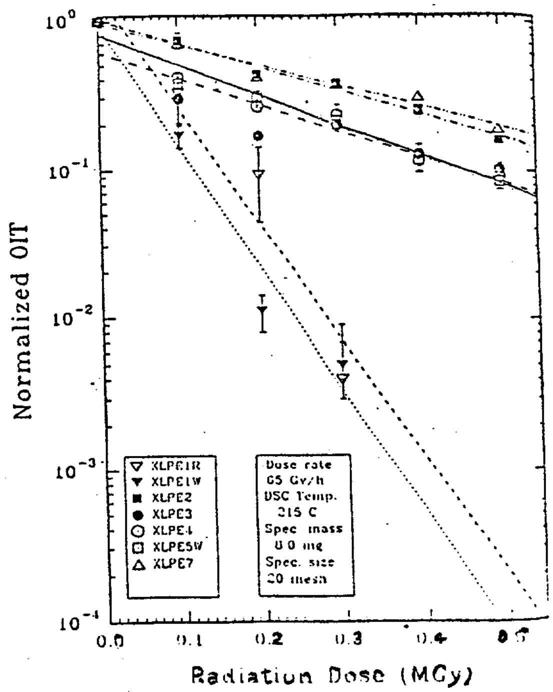

Figure 6.19 OIT as a function of radiation dose for EPR (Ref. 6.28)

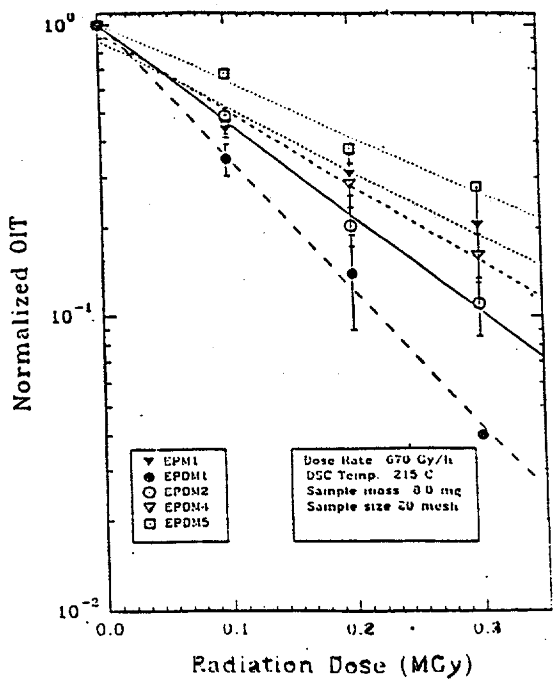

Figure 6.20 OIT as a function of radiation dose for XLPE (Ref. 6.28)

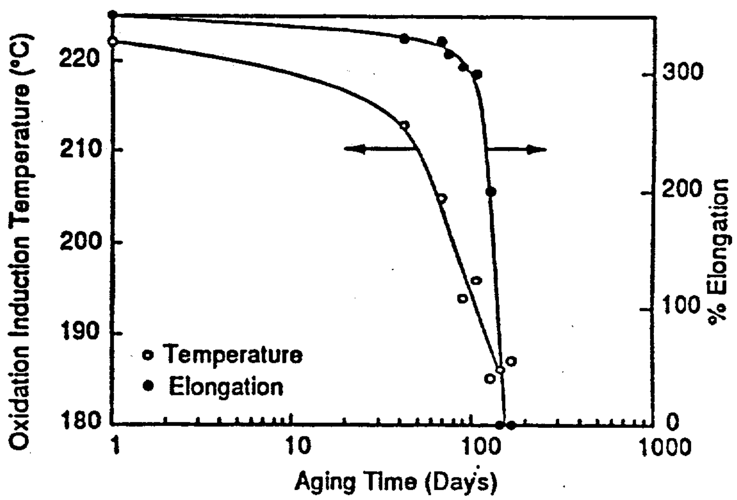

Figure 6.21 Correlation between OIT and elongation-at-break for SBR at 120°C (Ref. 6.31)
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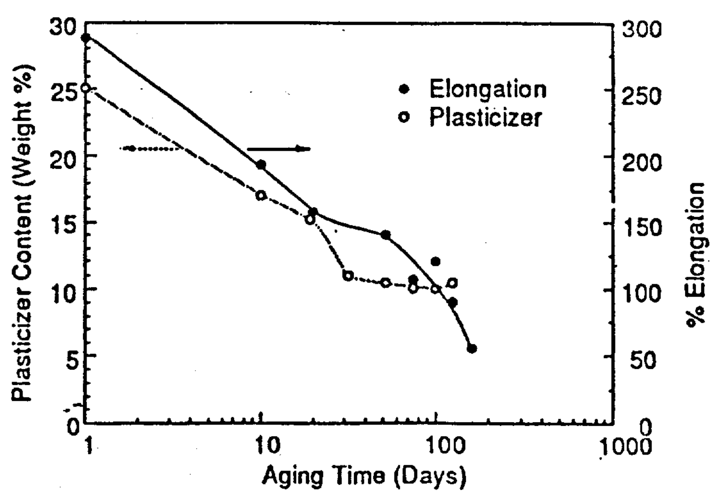

Figure 6.22 Correlation between plasticizer content and elongation-at-break for PVC (Ref. 6.31)
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Degree of Crystallinity

Figure 6.23 shows the crystallinity index of XLPE samples obtained from heat-of-fusion measurements (Ref. 6.27). The original index of 33% increased slightly during the induction period for samples aged at 120°C and 130°C, and then decreased steeply. The initial increase can be attributed to the alignment of the lamellae crystallites by an annealing (i.e., aging) process. During auto-oxidation, the lamellae crystallite regions are disrupted and the crystallinity index decreases. These results show that the degree of XLPE thermal aging can be estimated on the basis of changes in the degree of crystallinity. For EPR, the degree of crystallinity was very low (5-10%) and did not change with aging, and consequently, cannot be used as an indicator of degradation.

Melting Behavior

Melting endotherm curves of aged and unaged XLPE specimens are shown in Figure 6.24 (Ref. 6.27). For unaged XLPE, (Figure 6.24a) there is a major broad endotherm at 120°C. For the sample aged at 130°C for 71 days (Figure 6.24b), a new high-temperature, minor endotherm at 133°C is apparent. For the sample aged at 130°C for 102 days (Figure 6.24c), the major endotherm originally at 120°C has shifted to a lower temperature.

The peak melting temperatures are plotted against time in Figure 6.25. The position of the high-temperature minor endotherm peak gradually increases during the induction period, and during auto-oxidation it increases by another 5°C-10°C for samples aged at 120°C and 130°C. At aging temperatures (i.e., 130°C) above the melting point of 120°C, the minor endotherm was not evident initially but appeared after 35 days. Aging at 140°C did not produce a minor endotherm.

Throughout the aging period at 120°C and after 5 weeks at 130°C (Figure 6.25a), the appearance of the high-temperature minor endotherm peak suggests that a soluble, low-molecular-weight fraction crystallized and formed thicker crystals that melted at elevated temperatures. During auto-oxidation, the low-molecular-weight fraction phase appears to separate from the crosslinked network and form further perfect crystals that melted at a slightly higher (5-10°C) temperature.

An important feature of the melting behavior is reflected in the variation of the melting temperature of the major endotherm at 120°C (Figure 6.25b). This peak remains essentially unchanged during the induction period at all three aging temperatures. Since the melting temperature of a crystalline polymer is an index of the lattice perfection, the decrease in the melting temperature and crystalline index during the auto-oxidation period is due to the destruction of crystalline lamellae as a result of increased crosslinking of the polymer. The study concluded that the systematic appearance of the high-temperature minor endotherm peak and its dependence on the aging temperature (below 140°C) indicate that the maximum temperature to which an XLPE insulated cable has been exposed during service can be determined.

The formation of a minor endothermic peak depended on the aging temperature. Exposing the XLPE to at least 20°C above its melting temperature of 120°C destroys the thermal history, thereby eliminating the minor endotherm peak. Quenching the sample in cold water brings the polymer to its original crystalline structure, i.e., the structure of an unaged sample. The same applied to EPR, which has a melting point between 60-90°C. A detailed study on several aged cable materials (which had not reached the auto-oxidation stages) was made at the University of Tennessee and is discussed next.

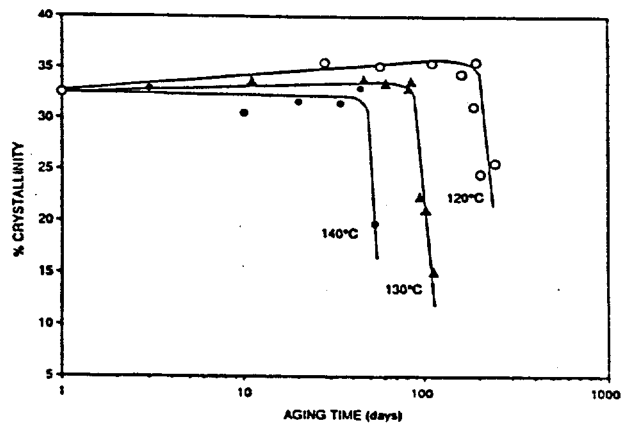

Figure 6.23 Crystallinity of XLPE as a function of age (Ref. 6.27)
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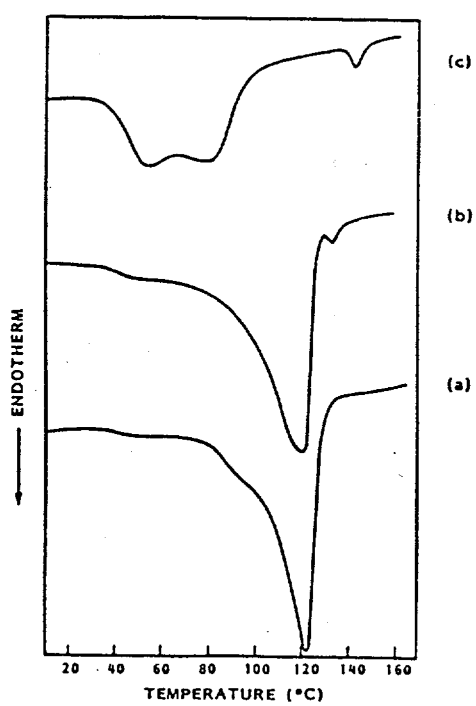

Figure 6.24 DSC curves for XLPE (a) unaged, (b) aged at 130°C for 71 days, (c) aged at 130°C for 102 days (Ref. 6.27)
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Fingerprinting the Thermal History

The presence of a crystalline phase in the insulation renders the material sensitive to changes in temperature, and the effects of such changes are recorded in the crystal (Ref. 6.32). Hence, a simple study of the crystalline phase (e.g., melting) permits the annealing information to be retrieved. Unlike metals and pure organic compounds of low molecular weight, polymers tend to exhibit melting ranges rather than single melting points. Consequently, the temperature reached during the manufacture of cable, or the temperatures during storage and service leave a fingerprint on the melting range. This thermal fingerprint can be exploited to estimate the temperature history of a cable in a power plant, and to a certain extent, the amount of time at particular temperatures. The only necessity is that one of the components of the polymeric insulation or jacket material is semicrystalline; hence, the technique can be applied to most cables. The major limitation of the method is that polymer retains the thermal history of its last maximum temperature excursion, together with all subsequent events in descending order of environmental temperature, but not any earlier events involving temperatures lower than the maximum excursion.

The melting curves for several cable materials received from SNL and the University of Connecticut (UConn) were studied by University of Tennessee using a Perkin Elmer DSC7 calorimeter. Figure 6.26 is a typical melting curve of an XLPE material exposed for 142 hours at 50°C. Compared to its unaged curve, a new peak has appeared at about 65°C, which contains information on the temperature reached and the dwell time there. The size and location of the new peak depend on this dwell time. Figure 6.27a shows the curve which resulted from subtracting the unaged material from that of the curve of the annealed (or aged) material. Figure 6.27b is the derivative of the subtraction plot (these operations typically are carried out by the DSC unit's internal computer program). Figure 6.28 illustrates various characteristics of these curves.

It is apparent that this information can be obtained through a simple program of heating and cooling in a DSC. The procedure is: (a) the weighed (5-10mg) specimen is heated at 10°C/min up to 150°C to obtain its melting curve; (b) the melted specimen is cooled at 40°C/min to -20°C to quench-crystallize; © the specimen is reheated at 10°C/min to determine the melting curve of the quenched specimen; (d) curve © from curve (a) is subtracted; and (e) the derivative of the subtracted curve is obtained. The data from these curves are further used to develop empirical mathematical analyses of the kinetics of the annealing processes in all of the materials studied. The technique was applied to a number of XLPE and EPR samples from the University of Connecticut and the results were compared with the UConn findings; there was a good correlation between the two different assessments of thermal properties.

Most cables are made from three basic classes of polyolefins, namely polyethylene (PE), ethylene-propylene copolymers (EPR), and ethylene-propylene terpolymers (EPDM). The common polyethylene (high density or linear, and low density) have been studied fairly thoroughly in both their original and crosslinked forms. The melting behavior of XLPE is well known, and ranges from 0°C to 106°C. The EPR comes as either amorphous or 20% crystalline with melting points between 50°C-60°C. Because of this lower melting range, it is more likely to suffer thermal aging at the temperatures normally encountered in power plants. In EPDM formulations, some are totally noncrystalline and others have different levels of crystallinity. Their melting characteristics are similar to that of EPR. This study also included the crystallization behavior of EPR and EPDM. Although many polymers are blended with others and additional ingredients, such as fillers, and then crosslinked, it was found that the basic annealing behavior was not substantially altered by blending, and essentially, a rule of mixtures approach could be used.

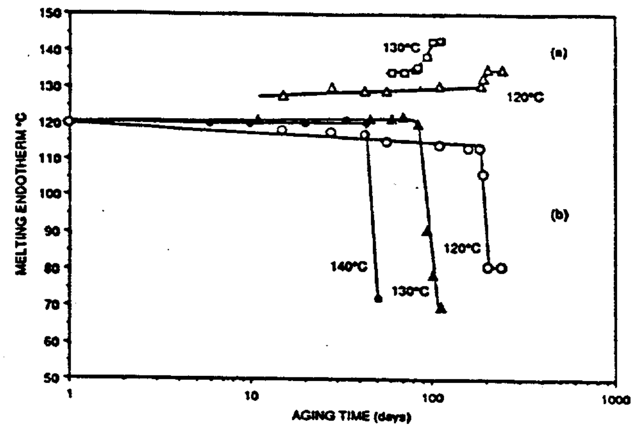

Figure 6.25 Peak melting temperatures as a function of aging for XLPE (Ref. 6.27)
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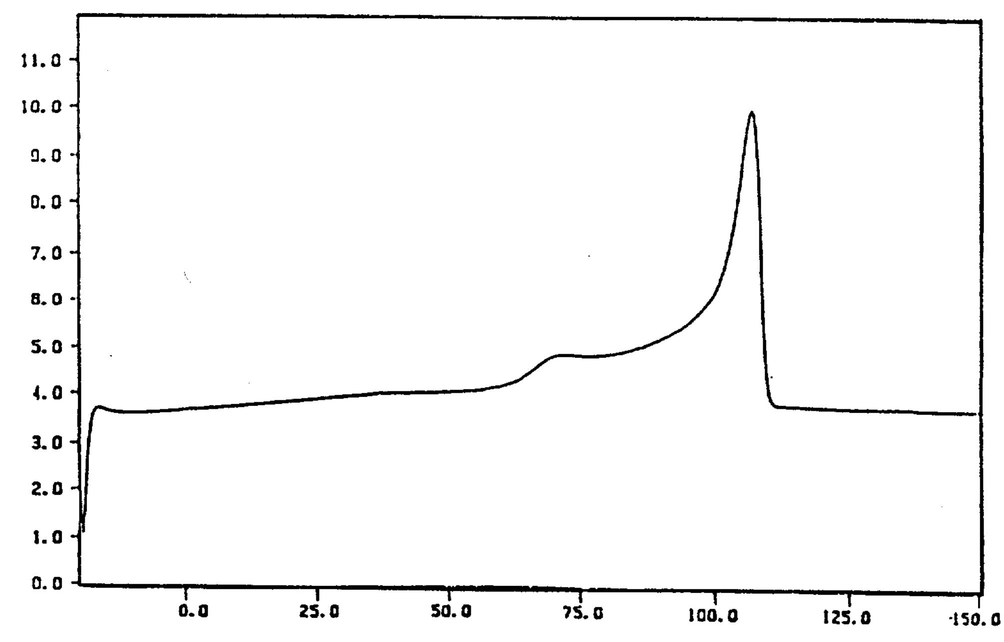


Figure 6.26 Melting curve of XLPE following 142hr at 50°C (Ref. 6.32)

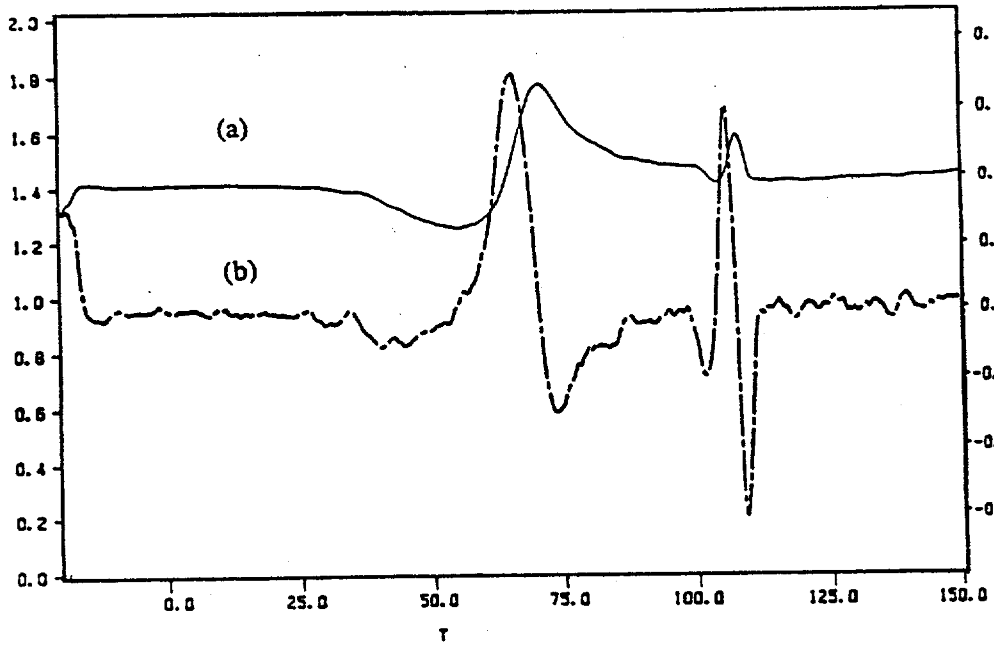
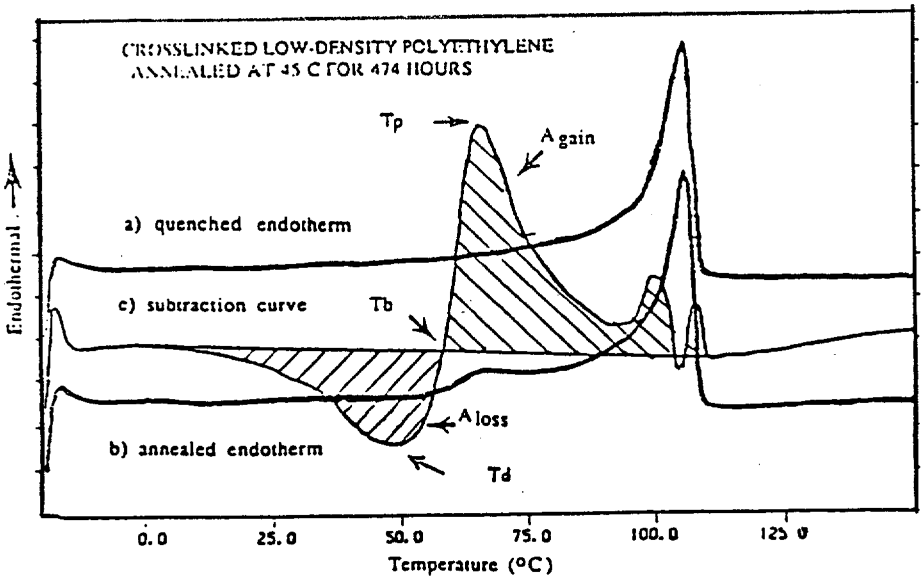


Figure 6.27 (a) Substraction curve (b) Derivative of the substraction curve (Ref. 6.32)



GENERAL FEATURES OF THE SUBTRACTION CURVE

- 45° C Annealing generates shoulder on DSC endotherm
- A_{loss} represents material "lost from the first ramp
- A_{gain} represents melting of new crystals generated by annealing
- Td remains fairly constant with annealing time
- Tp and Tb show logarithmic time dependence

Figure 6.28 Nomenclature used in describing the substraction curve (Ref. 6.32)

Table 6.5 summarizes the results which show the usefulness of the technique when there is no prior knowledge of the thermal history of cable materials. When the technique was applied to the jacket materials of all samples, the only ones that indicated some crystallinity were the three Eaton and one Okonite cables. These jacket materials had melting peaks between 45°C-60°C.

Table 6.5 Thermal Behavior of Some Cable Insulation Materials (Ref. 6.32)

		Major Endotherm Peaks		Minor Endotherm Peaks		
		Aged	Unaged	Aged	Unaged	
Manufacturer	Descriptions	°C	°C	°C	°C	Comments
Eaton	Dekoron Polyset					Blend of 2 or more
(Samuel Moore)	Triple Strand w/Jacket	70, 90,48(J)	80, 68(J)	40, 60	None	Polyolefins
Eaton	Dekoron 2/C 600V					Xinked LDPE plus
(Samuel Moore)	Double Strand w/Jacket	110, 44(J)	110, 68(J)	40, 70	None	Minor EPR/EPDM
Eaton	Dekoron 2/CD 600V					
(Samuel Moore)	Triple Strand w/Jacket	110, 54(J)	110	None	None	
Rockbestos	3/C 600V Firewall III					Xlinked LDPE and
	Triple Strand w/Jacket	122	106,120	75, 105, 115	None	HDPE
BIW	600V 2/C EPR/HYP					EPR + LDPE(hyp)
	Double Strand w/Jacket	84	86	40,60	None	
BIW	Tefzel					
	Single Strand w/Jacket	N/A	N/A	N/A	N/A	Noncrystalline
Anaconda	Flame Guard 1kV					
	Triple Strand w/Jacket	90	91	30, 70	25	
Anaconda	M Durasheath EP 600V					
	Single Strand w/Jacket	90	91	30, 70	25	
Okonite	PLT Okolon C/T 600V					
	Single Strand w/Jacket	N/A, 61&50(J)	N/A	N/A	N/A	Noncrystalline
Okonite	EPR Okoprene 2000V					
	Single Strand No Jacket	N/A	N/A	N/A	N/A	Noncrystalline
Okonite	FMR					
	Single Strand No Jacket	57, 90	None	40	None	

NOTES: N/A=Not Applicable, J = Jacket Material Behavior

6.2.9 Thermomechanical Analysis (TMA)/ Thermogravimetric Analysis (TGA)

The TMA method measures the thermal expansion coefficient, and is sometimes used to determine the location of the glass-transition temperature. Ontario Hydro used this technique to measure relative hardness in terms of TMA penetration distance into the cable's insulation and jacket materials (Ref. 6.27).

In Figure 6.29, the relative hardness values, measured in terms of TMA penetration distance, are plotted as a function of aging time for EPR samples aged at 145°C, 130°C, and 115°C. The penetration distance initially decreased slowly, falling approximately 25% after aging for 50 days at 145°C, 173 days at 130°C, and about 500 days at 115°C. Further aging caused a dramatic drop over a shorter period. This steep change can be related to the effects of thermal degradation on other properties, such as carbonyl index and OIT. The technique also was valuable for thermally aged PVC; however, it did not show significant differences for the XLPE specimens. The study developed a criterion of a 40% reduction in the initial penetration distance (i.e., 60 μm) as the end of life for the cable materials tested; this correlates well with 50% absolute elongation.

With the TGA, the mass of the sample is recorded continuously while the temperature is raised at a constant rate. Weight losses occur when volatiles absorbed by the polymer are driven off, and at the higher temperatures when degradation of the polymer occurs with the formation of volatile products. The design of the equipment is most exacting, not only because the weight losses to be measured are very small, demanding a precision weighing mechanism, but also because of the need to avoid convective forces within the heating chamber and because of the changes in the density of the gaseous environment. It is important to ensure that volatiles do not condense on the weighing apparatus, and also to control the atmosphere when this affects the process of degradation.

At JAERI, small amounts of samples (usually 4-5 mg) were used in their TGA experiments (Ref. 6.33). The thermal decomposition temperatures of unirradiated and irradiated PVC samples were measured in an gas atmosphere at a temperature rise of 10°C-20°C/min. Figure 6.30 shows the thermal decomposition behavior of the unirradiated (original) and irradiated (aged) samples. A significant change in TG curve was observed between 200°C-300°C, and irradiation causes the starting point of thermal decomposition to shift to a lower temperature. Temperature at which weight decreases by 5% (expressed as T5%) significantly changes with irradiation. Figure 6.31 shows the linear relationship of this data to the elongation properties, which suggests that radiation degradation in PVC is primarily due to a change in chemical structure.

6.3 Methods for Monitoring Physical Properties

The physical (and mechanical) properties of the insulation and jacket materials used in constructing cables change with age in nuclear power plants. These changes are manifested by the chemical degradation discussed in the previous section and are directly due to the environmental influences. Also, physical abuse during transportation, installation, and maintenance can often reduce the condition of cables. However, monitoring these abuses requires an effective quality assurance program rather than a test program, although often, the physical deterioration of cable materials is accelerated by environmental influences when there are pre-existing conditions (e.g., cuts, sharp bends, contamination).

Traditionally, tensile properties such as elongation and tensile strength, have been used to assess the embrittlement of polymers under thermal and radiation conditions. Several other methods, including compression, bending, twisting, hardness, and elasticity, yield parameters which can be trended with age of the polymers. Since one of the modes of polymer degradation includes a physical process (i.e., diffusion-limited oxidation), several profiling and polishing techniques are discussed to determine the heterogeneity in tensile or density properties across a specimen's cross-section. Table 6.2 lists all the test methods that are used in various researches related to measuring the physical condition of cables. The following section discusses the merits and demerits of several procedures used in the power industry.

6.3.1 Tensile Property (Elongation-at-Break and Tensile Strength) Measurements

Tensile strength and elongation tests are performed in accordance with ASTM D2633-82, using a tensile testing machine (e.g., Instron Model 1130) equipped with pneumatic grips and having an extensometer clamped to the sample. Special tensile specimens (dumbbells for larger cables or cylinders for smaller cables) of the insulation or jacket materials without the copper conductor are needed for these tests. Because of the difficulties in removing these conductors from an aged cable, samples of the polymeric material alone typically are obtained directly from the manufacturers or they are prepared before exposing them to thermal or radiation conditions. Sometimes these samples are installed in plant's known hot spots to monitor the aging of neighboring cables. These tests are destructive, and therefore, many samples are required if tests are conducted regularly. Furthermore, for statistical purposes 3-5 samples often are tested at each time to obtain an average value.

Figure 6.32 illustrates the results of ultimate tensile elongation for thermal and irradiation conditions (Ref. 6.30). Under thermal aging, the insulation exhibited a long induction period (Figure 6.32a), during which the elongation remained almost unchanged, followed by a sharp decrease. The results for PE, SBR, and EPR were very similar. By contrast, Figure 6.32b showed a gradual decrease in values with irradiation dose for XLPE. The aging performance of butyl rubber differed substantially (Figure 6.33a) from that of other polymers. Within 40 days of aging at 105°C, butyl rubber lost 40% of its original elongation. During the next 400 days, the elongation value remained nearly constant, but then was followed by a rapid decline, presumably when rubber started to depolymerize. Thus, elongation is not a good aging indicator for this elastomer. However, the tensile strength showed a gradual decrease to zero after 390 days (Figure 6.33b). Similarly, the elongation of PVC had no induction period but steadily decreased with time.

Diffusion-limited oxidation in certain elastomers has caused difficulties in interpreting the tensile properties in terms of Arrhenius plots (Ref. 6.34). The elongation data confirm this finding, while the tensile strength data show clearly a non-Arrhenius behavior. Further investigations indicated that the heterogeneity in modulus profiling caused this discrepancy even both elongation and tensile strength data were taken from the same experiment.

6.3.2 Indenter Modulus

The Indenter is a non-destructive device that measures the compressive modulus of jacket and insulation materials of electric cables (Refs. 6.35-6.37). The modulus is determined by pressing a probe of known shape against the wall of the cable at a fixed velocity (0.5 in/min) while measuring the force. The test is terminated when a preset force limit (generally 2 lbs) is reached. The modulus is calculated by dividing the change in force by the change in position during the inward motion of the probe. The indenter is limited to measurements on jackets except where the insulation is exposed (e.g., panels).

Measurements of the compressive modulus can be used for tracking the aging of materials in which this property changes in proportion to the cumulative effects of thermal and radiation stress. This method was effective for EPR, CSPE, PVC, Neoprene, butyl rubber, and silicone rubber. For XLPE, this method is less useful. However, a recent Swedish study (Ref. 6.38) developing a methodology of manipulating experimental data (including indenter modulus data) to derive the activation energy for degradation gave some good indenter data for Rockbestos XLPE and EPR insulation material. If a jacket is used, the Indenter value must be related to degradation of the insulation.

Figure 6.34 shows typical results of measuring the thermal aging Indenter modulus for the jacket of the Okonite Okolon. The modulus values measured with the portable indenter must be corrected for temperature to obtain comparable data to plant environment. The amount of correction required varies with the aging of the cable material (Figure 6.35). In situ tests of the unit in a nuclear power plant demonstrated that it can be used in plants to test cables in trays, panels, and junction boxes, provided that about 3 inches of exposed cable are accessible. The method has yielded good results on cables degraded under radiation (Ref. 6.39).

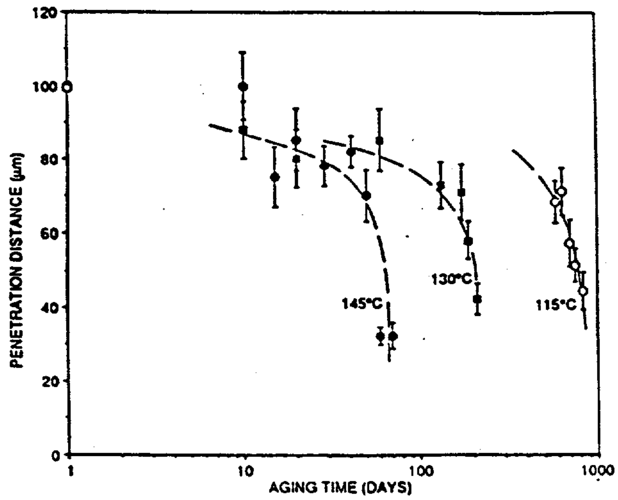


Figure 6.29 Relative hardness in terms of TMA penetration for EPR (Ref. 6.27)
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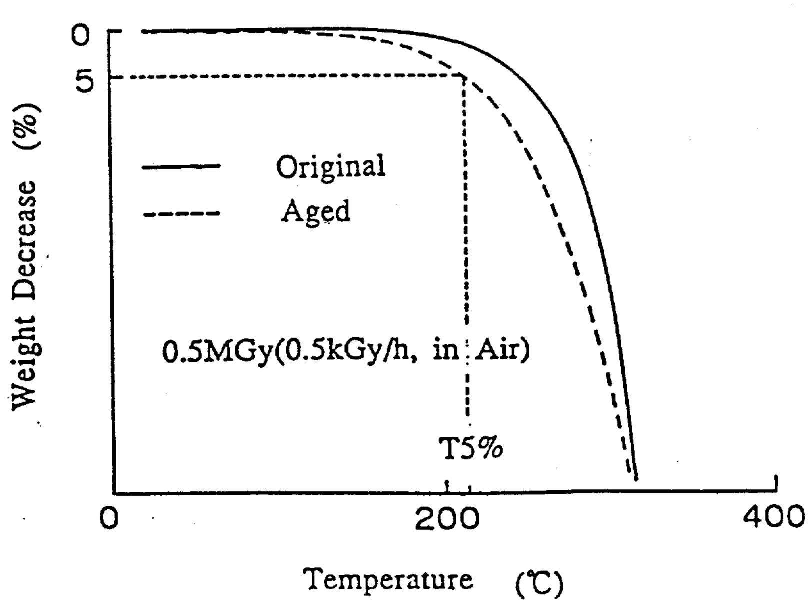

Figure 6.30 Thermal decomposition behaviors of PVC (Ref. 6.33)

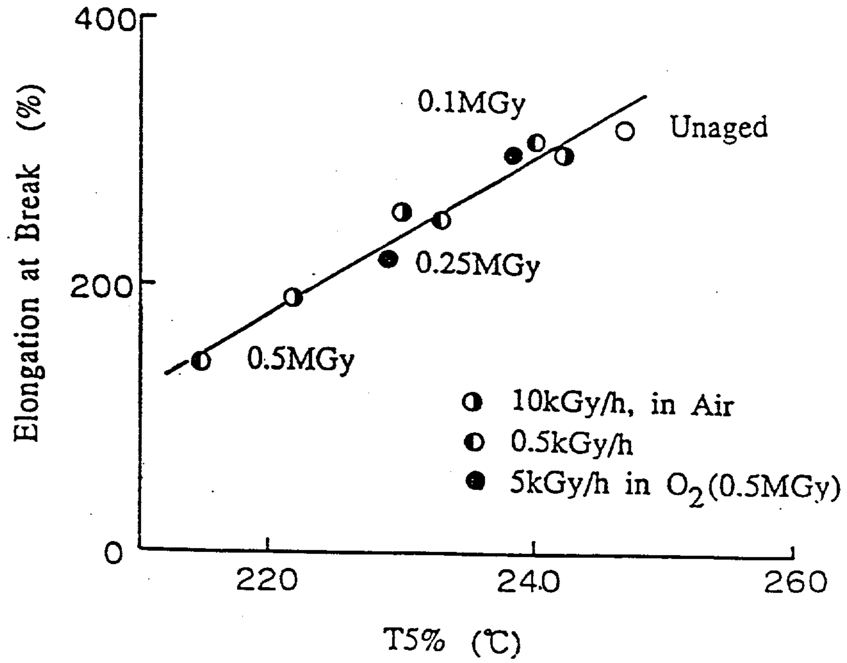

Figure 6.31 Elongation vs. thermal decomposition temperature by 5% weight loss for PVC (Ref. 6.33)

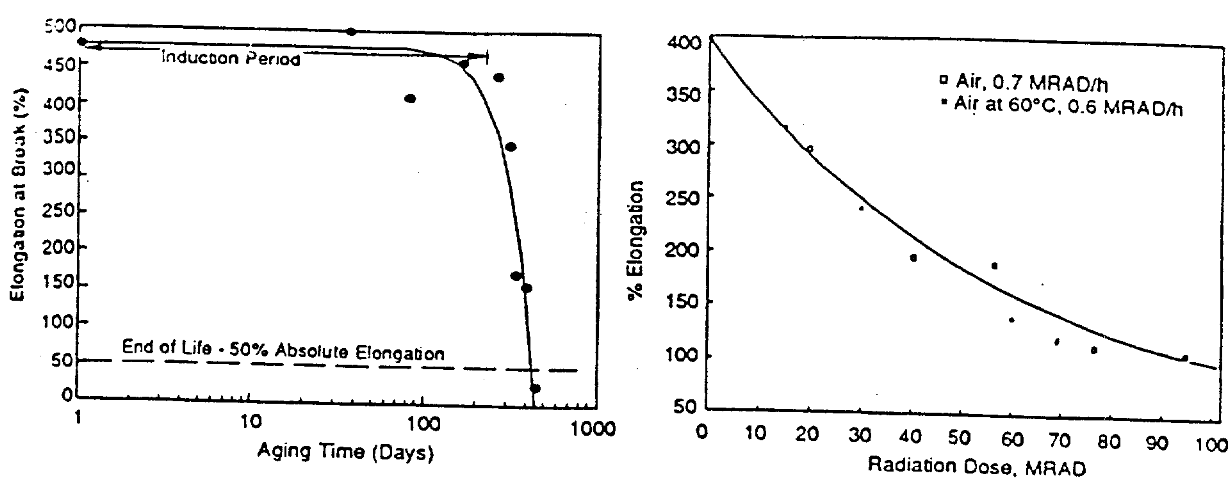

Figure 6.32 Elongation-at-break for XLPE (Ref. 6.30)
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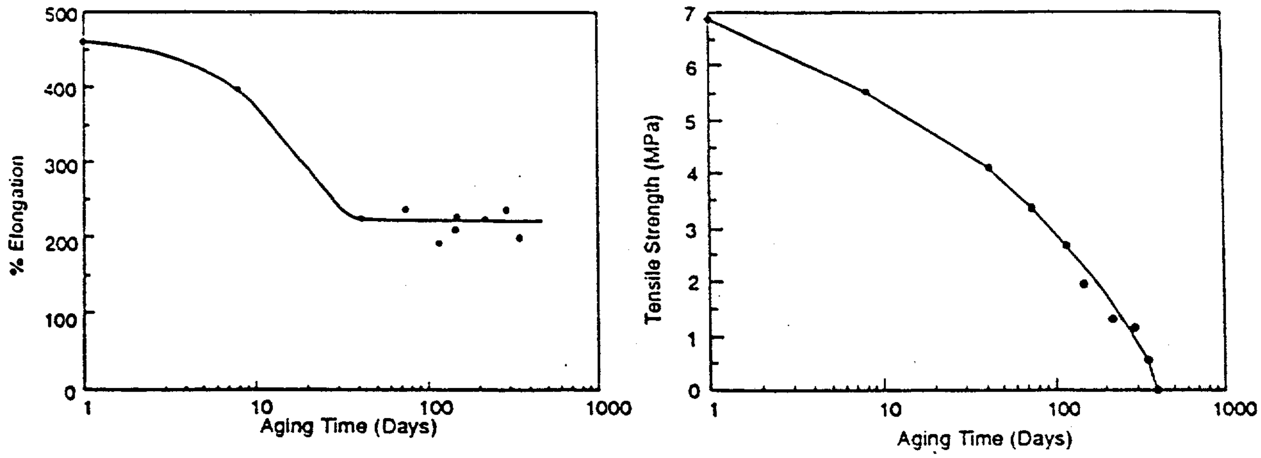

Figure 6.33 Tensile elongation and strength change for butyl insulation (Ref. 6.30)
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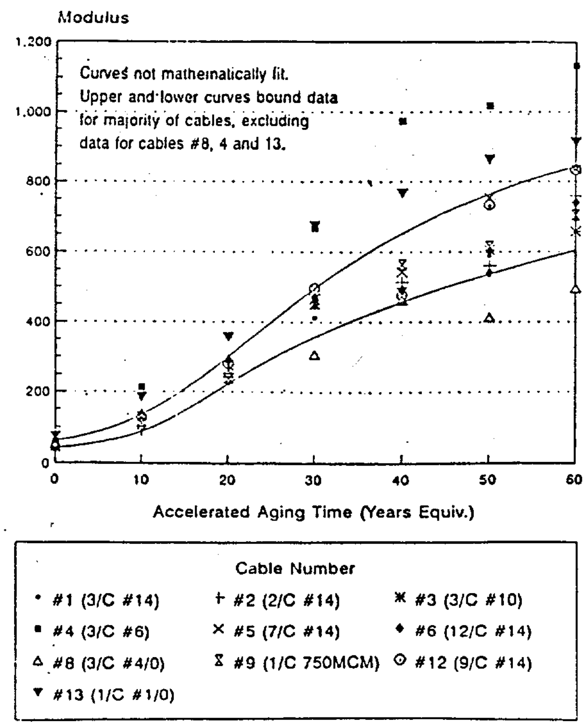


Figure 6.34 Okonite Okolon jacket moduli (Ref. 6.36)

The Indenter can only measure the properties of the cable over a limited area in the vicinity of the probe. The indenter modulus shows marked variation if the thickness of the jacket is variable, increasing as the thickness decreases. Extensive baseline data would be required to cover the range of cable materials and constructions used in nuclear power plants. Since the jacket materials tend to degrade more rapidly than the insulation, indenter measurements can give an early warning of a cable's deterioration.

6.3.3 Torque Tester

The degradation of jacket materials also can be determined using a torque-strain response method (Ref. 6.33). A pair of chucks are used to grip the outside of the cable, and a small-angle torque, in the range ± 5 to $\pm 10°$, is applied to one of the chucks at up to 2 Hz. A prototype apparatus for such measurements was developed in Japan. Preliminary data on the behavior of XLPE insulation with PVC jacketed (known as CV) cables was used to study the test parameters from this equipment. In both as-received and aged cables, the torque values increased linearly with the applied torque angle up to 10° (Figure 6.36). At higher torque angles, components other than the jacket material will significantly contribute to the values. For non-destructive purposes, a maximum of 10° torque angle was recommended. The effect of the length of the cable between the chucks also was investigated. The optimum length between chucks is 50 mm for PVC cables. At shorter lengths, the measured response strongly depends on the insulation, conductors and any shielding components, whereas with increases in cable length, the sensitivity of the torque-strain response decreases.

There is a strong correlation between the torque values measured using the prototype tester and elongation at break, both for thermally aged materials and for cables subject to sequential radiation and thermal aging (Figure 6.37). A linear relationship between elongation and torque was found over a wide range of elongation values. Deviations from this linear relationship were observed when heterogeneous oxidation occurred in the accelerated tests. The torsion test is a measure of the bulk properties of the jacket material, whereas elongation-at-break is determined by initiation of cracks in the more highly oxidized surface layer in the jacket material. In most cable applications in nuclear power plant, homogeneous oxidation is likely to occur.

JAERI in Japan is developing a portable version of the torque tester which could be clamped onto sections of a cable and would enable data to be taken non-destructively on accessible lengths of cable in situ. Since torque values will be significantly affected by differences in a cable's construction and geometry, baseline data for a wide range of cable types are needed. If the environmental conditions in a plant cause heterogeneous oxidation, the technique would underestimate the degradation of the jacket material.

6.3.4 Flexure Tests

In flexure test, the cable is physically bent by hand to examine its flexibility visually. A cable that flexes easily probably is fine. Cracking of the jacket does not necessarily imply that all such cables would fail. This method probably reflects a qualitative assessment of the cable's insulating system. No studies correlating flexure data with other parameters were found.

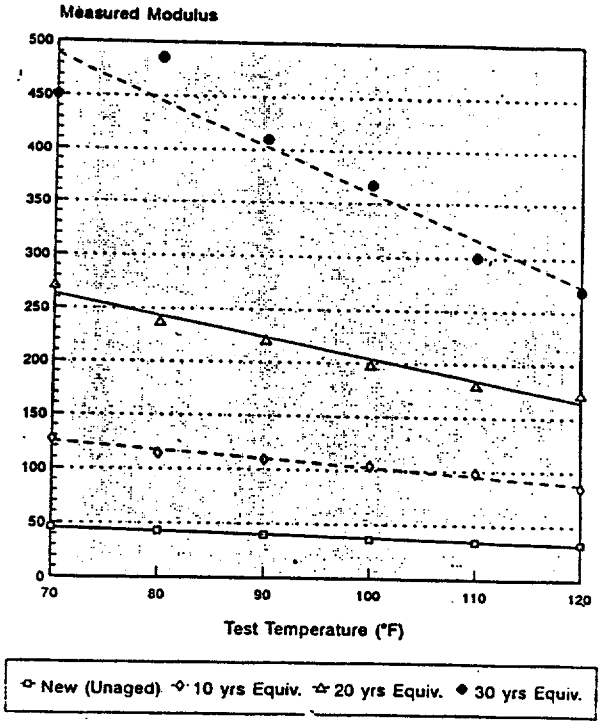


Figure 6.35 Effect of jacket temperature on Okonite jacket modulus (Ref. 6.36)

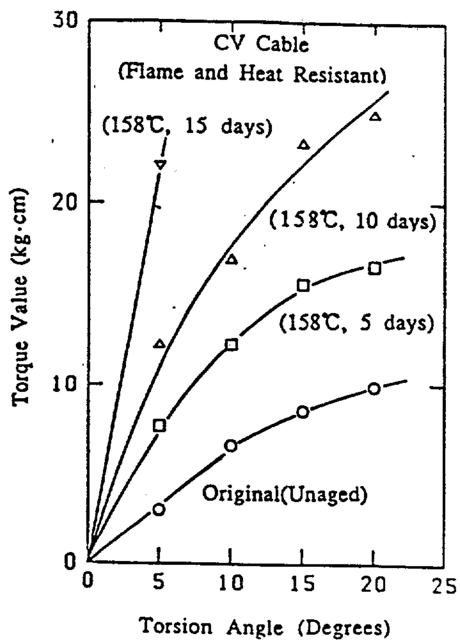


Figure 6.36 Effect of torsion angle on torque value (Ref. 6.33)

6.3.5 Profiling and Polishing Methods

SNL used the elastic modulus, density, and hardness-profiling methods, as well as polishing the cross-section of a specimen to study the uniformity of the aging process within cable materials. The results from any of the profiling methodologies show the distribution of the parameter (elastic modulus, density, or hardness) across the cross-section of the specimen. This distribution indicates that the values of these physical parameters can be heterogeneous under diffusion-limited oxygen degradation. By polishing a cross section, the variations in oxidation can be examined visually, from the end exposed to oxygen environment to the other. These techniques are not easy to carry out and require sophisticated instruments to slice the cable samples and then test each slice under mechanical testing equipment. Nevertheless, the results can provide a wealth of information for research, and their usefulness is discussed in greater detail in section 4. Alternatively, the computed tomography (CT) technique recently proved to yield similar profiling results.

Figure 6.38 (Ref. 6.40) shows photographs of a series of samples from the same material cut from a square sheet, which were irradiated, and then cross-sectioned and polished. The appearance of distinct optical bands (or rings) suggests strongly heterogeneous degradation for samples irradiated in air at the highest dose rate. Thus, rings are observable for samples B and C, which were irradiated at 0.67 Mrad/hr to 165 and 297 Mrads, respectively. In contrast, samples A, D, and E do not exhibit oxidative rings. A was an unaged sample, D was irradiated at a lower dose rate (i.e., 0.11 Mrad/hr to 175 Mrad), and E was irradiated in an inert atmosphere.

Figure 6.39A shows probe penetration profiles showing the changes in relative hardness on cross-sectioned samples of the EPR material. For unirradiated material, the profile is essentially flat (solid squares). For the samples irradiated at 0.67 Mrad/hr to a dose of 297 Mrad, a distinct flat-bottomed, U-shaped profile is seen (open circles). The boundary position between optical bands (Figure 6.38, exhibit C) corresponds to the steep part of the profile. The irradiated material has become significantly harder (i.e., increased modulus), with the largest increase occurring at the interior portion where oxygen is absent. Figure 6.39B shows data for an EPR sample irradiated at same dose rate to a total dose of 165 Mrad. A somewhat shallower profile was obtained, but with no significant change in the oxygen penetration distance (squares). For a sample irradiated at a lower dose rate (0.11 Mrad/hr to 175 Mrad), the profile becomes homogeneous showing only a slight, shallow curvature (triangles). Similar profiles were obtained by this study when the density gradient data were plotted for the same materials under similar conditions.

6.3.6 Hardness Test and Density Measurements

Hardness is a material's resistance to local penetration. One device used for such measurements is the Shore Durometer Type A2 . SNL used this method for hardness profiling, and considers that field measurements of this parameter have some correlation to polymer degradation. Figure 6.40 demonstrates the increasing trend in hardness of CSPE jacket that was irradiated (Ref. 6.16).

Density measurements (ASTM D1505: using density gradient column with water and isopropyl alcohol; ASTM D792: using displacement method) showed that the density of insulation tends to increase with age due to oxidation. Thus, as for modulus, the material may be subject to gradients resulting from oxygen diffusion effects. SNL measured bulk density, along with modulus profiling, to examine the effects of oxygen diffusion in the samples (Ref. 6.41). Figure 6.41 illustrates the density changes of the same CSPE sample as that shown in Figure 6.40 with radiation dose. Ontario Hydro used the former method for XLPE, and latter method on butyl rubber, EPR, and PVC (Ref. 6.31). For most insulations, there was a nearly linear increase in density as a function of radiation dose. An initial increase, followed by a decrease in density has been observed for irradiated XLPE. The increase was attributed to a combination of weight increase by covalently bound oxygen, and a decrease in volume due to the release of gases. Even small changes in density were readily detectable, and a change of only 1-2% was significant in terms of degradation. The density results for XLPE appear to be somewhat more sensitive than elongation (Figure 6.42).

The density values for PVC are plotted in Figure 6.43. It is evident that the change in density differs for PVC compared to XLPE; no induction period was observed. Similar trends were observed for EPR and butyl rubber. The density increase in butyl rubber appears to be caused by simple oxidation. For PVC, the initial increase in density resulted from plasticizer loss. The increase of density in EPR seems to be induced by a combination of oxidation and depletion of low-molecular-weight additives. The TGA results confirmed the presence of low-molecular-weight additives that evolved at accelerated aging temperatures. The results indicate a density change in the region of 0.10 g/cc in PVC, and 0.05 g/cc in EPR is a suitable criterion for detecting degradation, which corresponds to a reduction of 50% in elongation-at-break data.

6.3.7 Dynamic Mechanical Analysis (DMA)[2]

In dynamic mechanical analysis, the sample is deformed cyclically, usually under forced vibrations. By monitoring the stress-strain relationship while changing the temperature, information can be obtained about the relaxation behavior of the material. Many modes of vibration are possible, but the most popular are reverse bending (i.e., the double cantilever), axial tension, torsion, and shear. The vibration chosen usually is sinusoidal, simulating the conditions of terminal cables connected to heavy rotary machines in a plant causing this part of the cable to harden with age.

Exploratory experiments were carried out using viscoelastic analysis to diagnose the state of degradation of XLPE, EPR, and PVC insulation material. The dynamic properties of primary interest were storage modulus (E'), loss modulus (E"), and loss tangent (tan δ). E' is a measure of the elastic deformation of a polymer network, while E" reflects its viscosity. The elastic modulus E' is expected to be sensitive to crosslinking, and the loss of modulus E" is more sensitive to scission. Tan δ (=E"/E') maxima indicate regions of high energy loss and thereby reflect the motions of various molecular species. By analyzing the temperature dependence of the viscoelastic loss factor (tan δ), the elastic moduli (E') and the shift in the glass transition temperature (T_g), radiation induced damage can be assessed.

[2] Private Communication with Mr. D.J. Stonkus, DJS Associates. Reference report may be available directly from Ontario Hydro, Canada. Anandakumaran, K. and Stonkus, D.J., *Assessing Radiation Induced Degradation at High and Low Dose Rates,* Ontario Hydro Technologies Report 91-50-K, 1991. Figures 6.44, 6.45, and 6.46 are reproduced with permission.

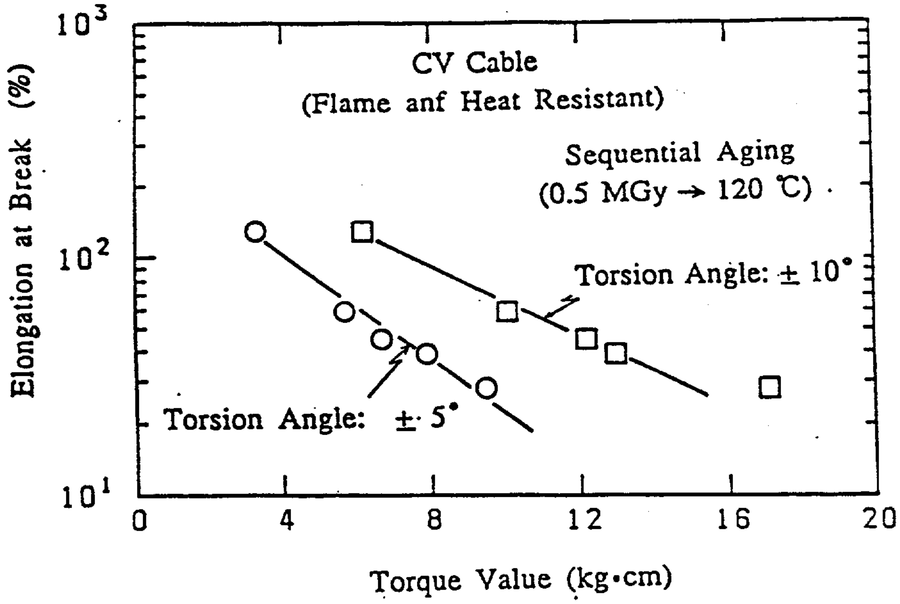
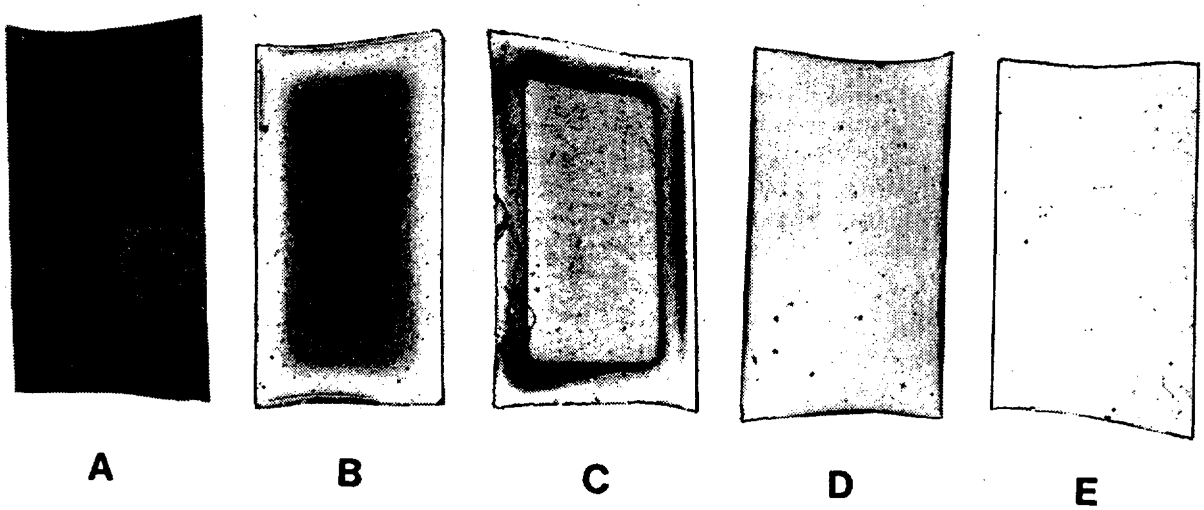


Figure 6.37 Correlation of torque value with elongation (Ref. 6.33)



A: Unirradiated material.
B: 6.7 x 10^5 rad/h (in air) to 165 Mrad.
C: 6.7 x 10^5 rad/h (in air) to 297 Mrad.
D: 1.1 x 10^5 rad/h (in air) to 175 Mrad.
E: 1.1 x 10^6 rad/h (in vacuum) to 253 Mrad.
All irradiations carried out at 70°C. Actual sample thickness = 3.15 mm.

Figure 6.38 Polished samples of irradiated EPR (Ref. 6.40)

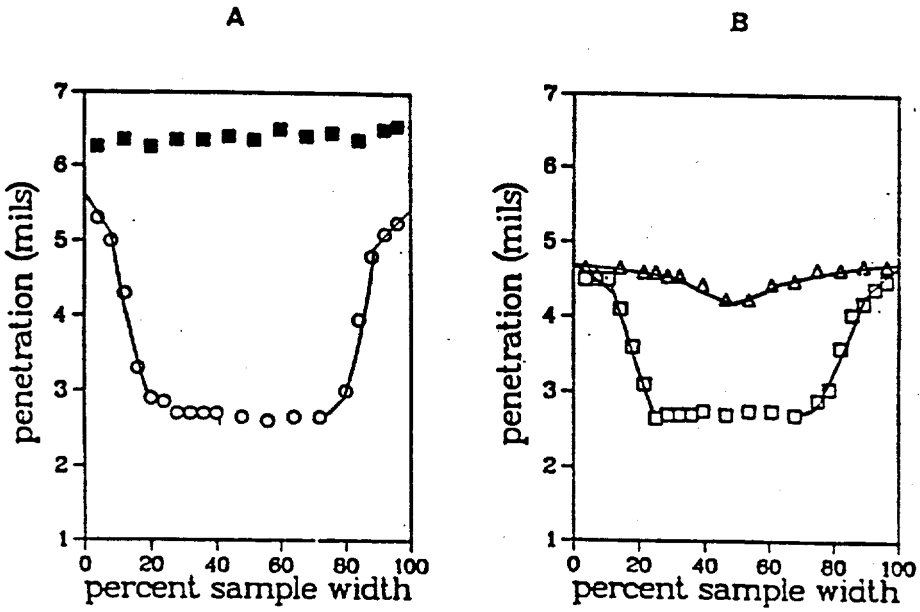


Figure 6.39 Relative hardness profiles for irradiated EPR (Ref. 6.40)

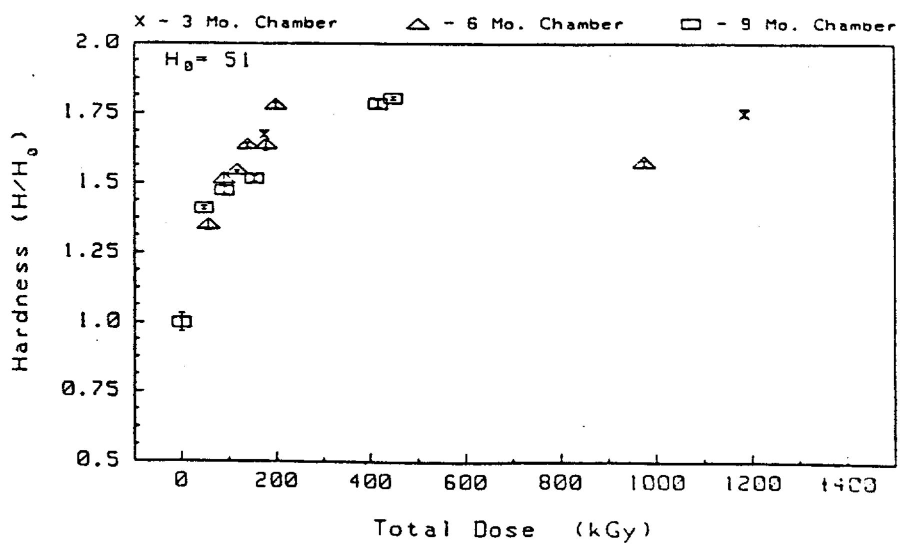


Figure 6.40 Hardness of Brand Rex jacket (Ref. 6.16)

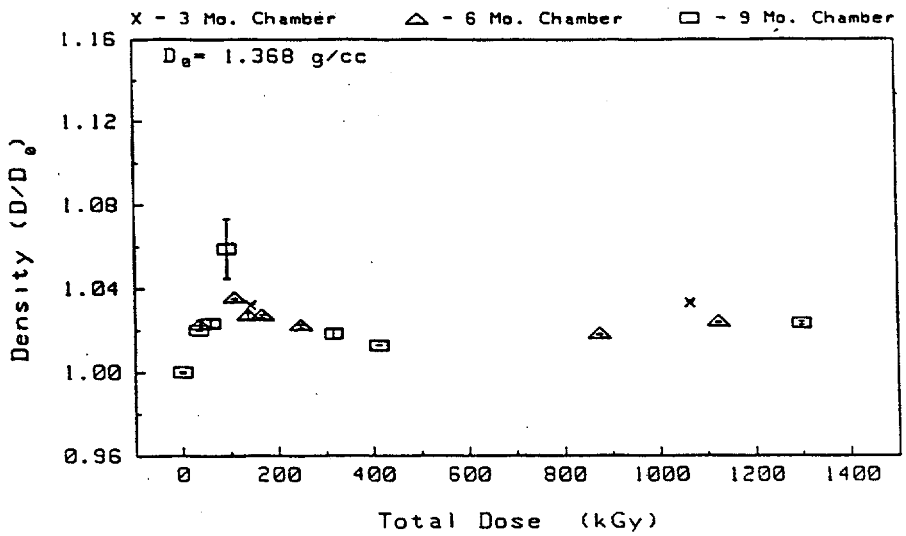


Figure 6.41 Density of Brand Rex jacket (Ref. 6.16)

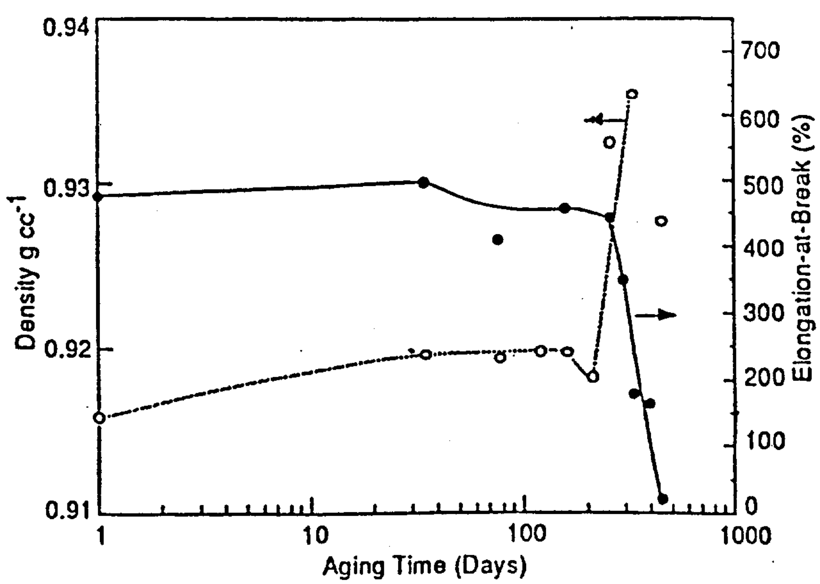


Figure 6.42 Relationship between density and elongation for XLPE (Ref. 6.30)
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Figures 6.44 and 6.45 illustrate the temperature-dependence of tan δ for unaged FREPR and for specimens irradiated to 20, 60, and 100 Mrad at 0.02 Mrad/hr both in air and oxygen. The changes in the dynamic storage moduli as a function of temperature are shown in Figure 4.46 for specimens irradiated to 100 Mrad. The tan δ spectra exhibits a well-resolved peak in the region of -50°C to 0°C, attributable to glass-transition relaxation, and the position of the T_g peak shifts to higher temperatures on exposure to radiation. Corresponding shifts in this region also were evident from the modulus plots which, in addition to glass transition, exhibit the crystalline melting region (20°C to 90°C). By analyzing these plots, the chemical changes (crosslinking or scission) which contributed to the ultimate degradation of the insulation material can be postulated. For example, samples irradiated in oxygen at 0.02 Mrad/hr (Figure 6.46) showed no measurable modulus above 80°C as the samples melted (above the crystalline melting point), thereby indicating that chain scission had occurred.

The study had found no noticeable changes in properties for XLPE and PVC using DMA. The glass-transition temperature of PVC and the melting temperature of XLPE remained unchanged. However, above these temperatures, these two materials showed a difference in storage modulus, indicative of their degradation mechanisms.

6.4 Methods for Monitoring Electrical Properties

On-site testing of the condition of safety-related cables in nuclear power plants is required to ensure their continued reliability. Several proven conventional or newly developed methods are available to assess the condition of shielded cables. Such methods are based on applying ac or dc voltages which can cause breakdown at a relatively low level only in defective cables, leaving non-defective cables unharmed. Other methods are based on detecting and locating partial discharge sites upon applying of ac voltages at levels which are below the cable's rating. Other methods, intended to evaluate the dielectric characteristics of the cable insulation, such as resistivity, dielectric loss angle (tan δ) or permittivity, also are readily available and use relatively low voltages, generally much below the cable's rating.

For non-shielded cables, the electric field is not uniform because of the lack of grounded outer electrode (shield). In a metal conduit configuration, for instance, the insulating layer surrounding each conductor is much thinner than the surrounding air and has a relative permittivity (dielectric constant) of 2.3 or more. Thus, when a voltage is applied between the conductor and the conduit, most of the voltage is impressed across the air rather than the cable insulation. Moreover, the portion of the total voltage shared by the cable insulation can vary according to the angular position of the surface of the insulation, and the radial position of the cable within the conduit. Efforts are being made to create a uniform conducting surface around non-shielded cables.

Table 6.3 lists several conventional dielectric tests which include dc tests, high-voltage-power frequency tests, low-voltage swept-frequency tests, and low-voltage impulse or step voltage tests. All these techniques are well understood by insulation researchers, and, at least, laboratory-grade instrumentation is available for these tests. Studies to improve the test configurations to obtain a well-defined ground plane, to correlate the electrical properties with the morphological changes in the insulation properties, and to detect faults in the electrical circuits are among some of the electrical tests discussed below.

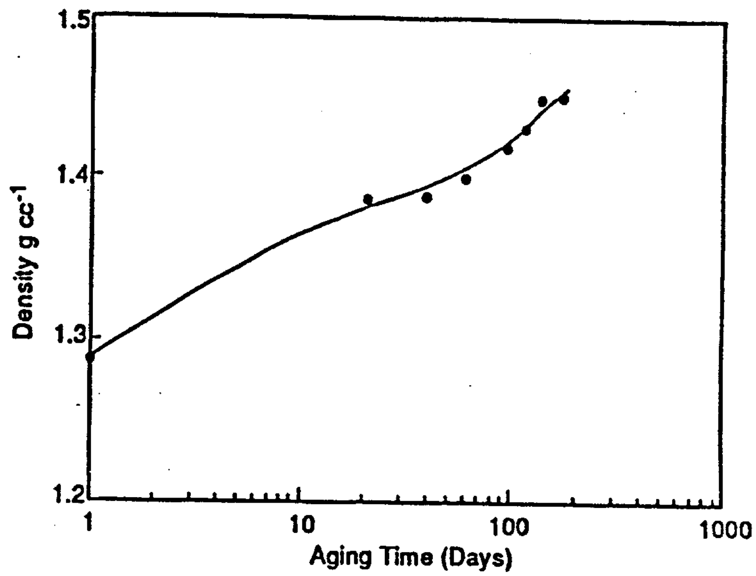

Figure 6.43 Density of PVC jacket for thermal aging at 120°C (Ref. 6.30)
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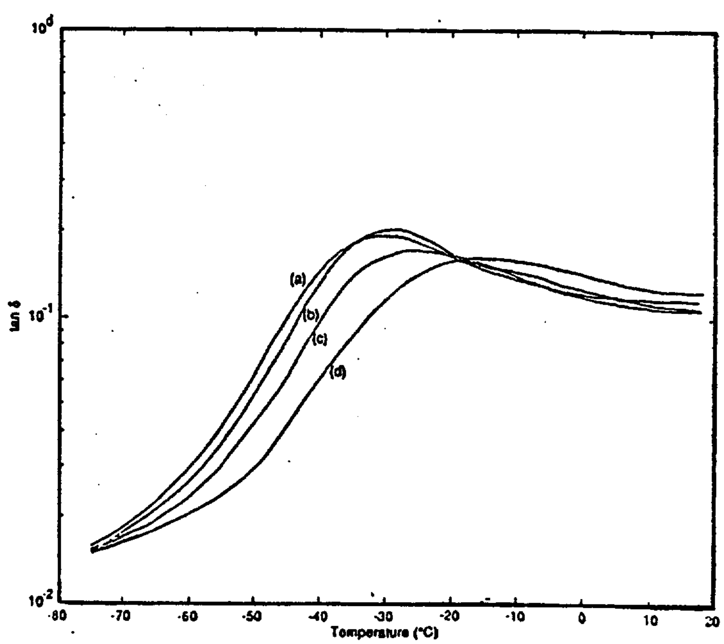

Figure 6.44 Effect of radiation on loss tangent for FREPR (a) unaged; irradiated in air at 0.02 Mrad/hr to a total dose of (b) 20, (c) 60, and (d) 100 Mrad (See footnote on page 6.39)
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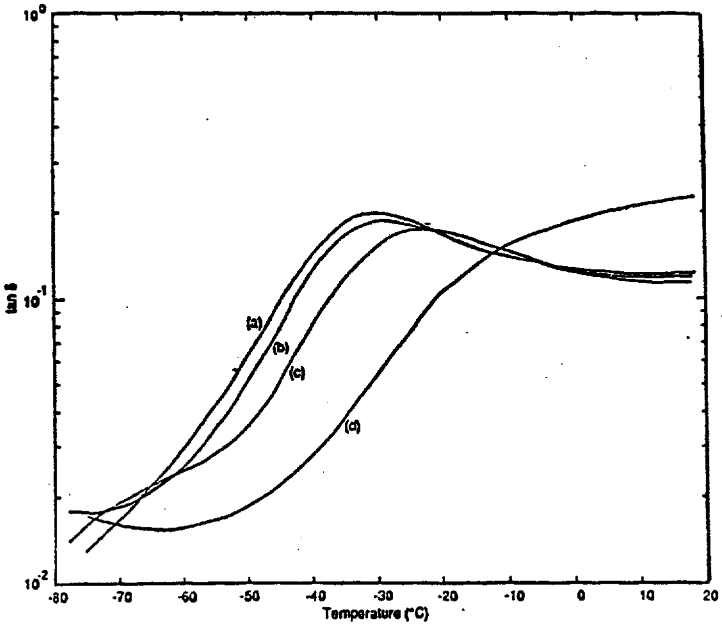

Figure 6.45 Effect of radiation on loss tangent for FREPR *(for legend see Figure 6.44: Except samples irradiated under 300 psi oxygen)* (See footnote on page 6.39)
Reproduced with permission from Mr. D.J.R. Dodd, Ontario Hydro Technologies, Canada.

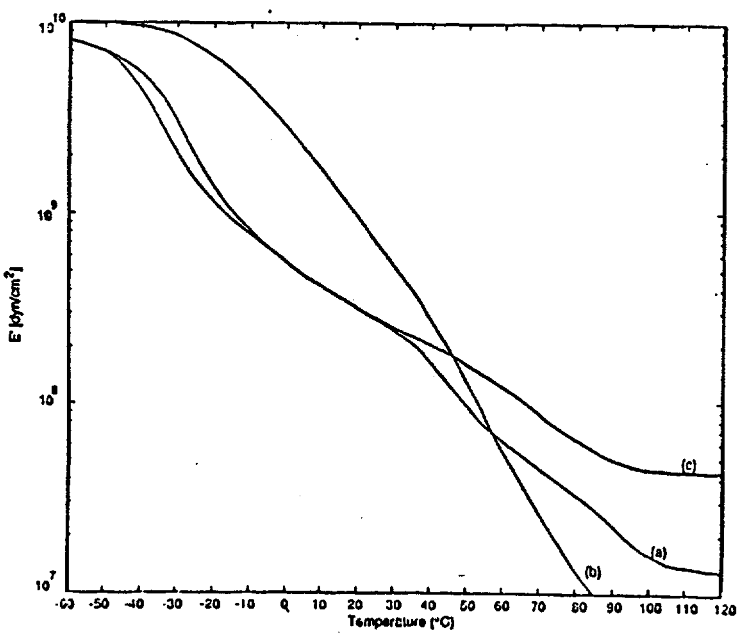

Figure 6.46 Storage modulus of irradiated FREPR (a) unaged; (b) 100 Mrad at 0.02 Mrad/hr in 300 psi Oxygen; (c) at 0.7 Mrad/hr in Air (See footnote on page 6.39)
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6.4.1 DC Tests (Insulation Resistance and Polarization Index Tests)

Measurement of DC insulation resistance is one of the commonest electrical tests performed on cables at the time of installation and periodically thereafter. The largest contributors to the initial total current are capacitance-charging current and dielectric-absorption current; these result from the flow of charged atoms (ions), and the rotation of molecular dipoles in the material. The ions are trapped on the surface of the material and contribute to its capacitance but cannot flow out as electrons. Insulations with ionic impurities or with a molecular structure having polar structural groups will have large absorption or capacitance currents. The leakage current, which includes the conduction current and the surface leakage current, predominates after the other two components have become insignificant. This leakage current, which is the electrical current that passes through the insulation, is of particular interest when evaluating the condition of the insulation.

With age and subsequent oxidation, the chemical structure of the polymer insulation can be altered so that its dielectric properties may change. For example, PE essentially is a non-polar material. However, oxidation produces relatively large polar side groups in the polymer chains, which can contribute to the loss of dielectric absorption.

The polarization index (PI) test measures the insulation resistances at one minute and ten minutes after dc voltage is applied. If the ratio of the readings at ten minutes to one minute (i.e., PI) is less than one, it means that the volumetric leakage current through the insulation is high. The insulation commonly is cleaned or dried after low readings. To overcome the strong temperature dependence of the resistance values, PI is generally used, along with the measurements of insulation resistance.

Ontario Hydro used these methods for aged samples of SBR, PVC, butyl rubber, PE and EPR (Ref. 6.30). All these materials were so brittle that they could crack if not handled extremely carefully. The researchers concluded that both insulation resistance and PI values were totally insensitive to the very advanced deterioration of the thermally aged insulation.

SNL used these measurements in their recent LOCA testing of a large number of cable materials for life-extension studies (Refs. 6.42 and 6.43). They performed these tests between the conductor and ground, with all other conductors connected to ground. Measurements were taken at 3 voltages, 50, 100, and 250 V. They found the results were independent of the test voltage, similar to many other researchers using these methods. The study used the variations in insulation resistance measurements (in terms of order of magnitude changes) in their aging assessment of various insulation materials. Figures 6.47 and 6.48 illustrate the insulation resistance and PI values for the Brand Rex cable during various aging conditions, respectively. However, they did not evaluate these measurements as effective condition-monitoring methods during pre-aging.

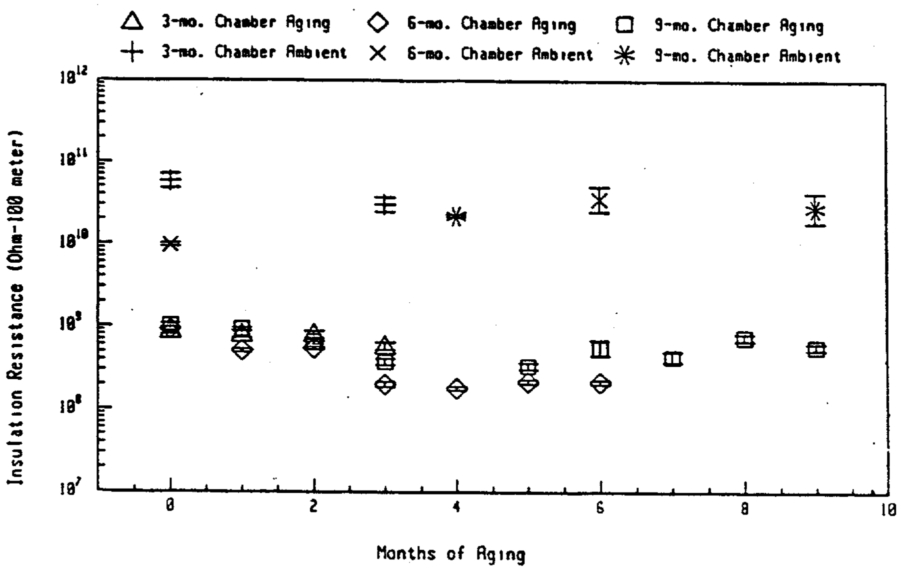

Figure 6.47 250 V insulation resistance of Brand Rex cable (Ref. 6.16)

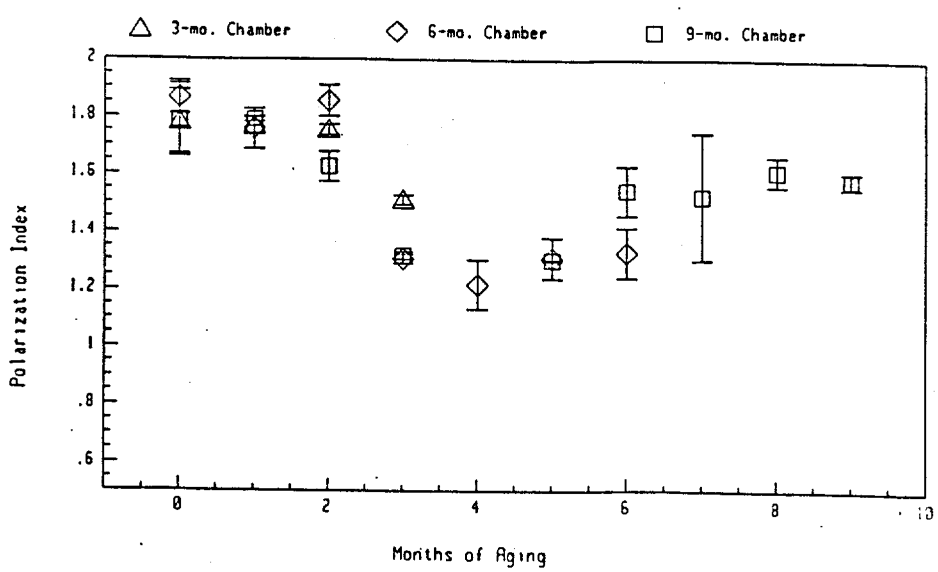

Figure 6.48 250 V PI (5min/30s) of Brand Rex cable (Ref. 6.16)

6.4.2 AC Impedance Tests (Capacitance and Dissipation Factors)

AC impedance tests are performed with standard electrical equipment available for ac tests on electrical devices such as motors, and transformers. The transfer function obtained indicates the variation of dielectric impedance (principally due to the bulk cable capacitance and conductance) as a function of frequency. The imaginary component indicates the dielectric charge/voltage characteristics at a given frequency, and the phase angle between the real and imaginary components indicates of the dielectric losses as a function of frequency. The tangent of the phase angle δ commonly is referred to as the dissipation factor (DF) and is often measured only at a single discrete frequency. The dissipation factor also gives the power factor (PF) since the two are related as $PF=DF/(1+DF^2)$. Since δ is a small angle in most instances, the PF is approximately equal to the DF.

Table 6.6 Diagnostic Test Results for the Lakeview TGS Cables (Ref. 6.44)
Reproduced with permission from Dr. J.M. Braun, Ontario Hydro, Canada.

Cable	Phase	IR 1 min 10^{12} Ω	DF @ 2.3 kV (%)	Capacitance @2.3kV (nF)	PD Inception (kV)	Unshielded BD (kV) AC	Unshielded BD (kV) DC	Shielded BD (kV) AC	Shielded BD (kV) DC
BF-PM	R	1.5	2.9	1.9	no PD	80		FO86	
	W	0.2	2.9	1.9	no PD	85		FO70	
	B	0.2	2.8	1.9	no PD	75		76	
C-PM	R	0.001	13.3	3.1	5.4		WS	85	
	W	0.001	13.3	3.1	5.8		WS	80	WS
	B	0.001	12.8	3.0	5.2		WS	80	
CCW-PM	R	0.002	7.0	4.1	6.0	40		BD	BD
	W	0.002	6.9	4.1	5.6	BD			32
	B	0.002	6.6	4.1	5.4	BD		40	
	R	0.070	1.9	4.6	no PD			65	
	W	0.002	-	-	4.7			65	WS
	B	0.040	2.4	4.5	no PD			75	
ID-FM	R	0.001	1.6	4.4	5.4	45		BD	BD
	W	0.001	1.7	4.5	4.8	BD			43
	B	0.001	1.5	4.4	5.2	BD		40	

WS=withstood(to 150 kVdc); FO=flashover; BD=damaged by adjacent breakdown; PD=partial discharge; IR=insulation resistance (dc); DF=dissipation factor. Note that CCW-PM cable was tested in two sections.

A study by Ontario Hydro included dielectric testing of a number of 5 kV (triplexed butyl rubber insulated) cables in service for 25 years in an old thermal plant (Ref. 6.44). The cables were routed in both tray and/or underground in conduit to each motor. Non-destructive tests included measurements of partial discharge (PD) insulation resistance and capacitance (C) and dissipation factor (DF). The destructive tests consisted of breaking the cables down with high ac and dc voltage. In laboratory tests, the same measurements were repeated. However, the jacket of the unshielded cables was wrapped in aluminum foil, and then tested in a grounded cable-tray.

Table 6.6 presents the results. The study concluded that there was good agreement between both sets of breakdown voltage data for shielded and unshielded configurations. The results for in situ and laboratory testing were quite consistent. These results further confirm the validity, for suitable cable configurations, of performing conductor-to-conductor tests. While the in situ tests were made on an unshielded configuration, the breakdown data are remarkably similar in both cases.

From the corresponding results of non-destructive diagnostic tests, the study concluded that there is no correlation between any of the diagnostic quantities and the condition of the cable. However, critics of the paper find the basis of this conclusion from limited data is unfounded[3]. Thus, comparing the results for two sections of the CCW-PM cables, the first section with higher DF and lower capacitance values indicate partial discharge, while the second section with opposite test data had no partial discharge. Therefore, there seems to be a strong correlation between capacitance/DF and partial discharge.

Figures 6.49 and 6.50 illustrate the capacitance and DF values versus frequency for Rockbestos conductor tested at SNL (Ref. 6.16). Here, the capacitance values increase with the age at all frequency ranges considered. On the other hand, the dissipation factor values show no significant difference with age at frequencies above 10 Hz, and decrease (except the unaged) with age at lower frequency ranges. The study concluded that none of the electrical tests were effective for monitoring the residual life of cables.

6.4.3 Stepped Voltage and High Potential Tests

The stepped voltage tests and high potential tests are high voltage ac/dc tests and are quite similar to those discussed in the previous two category of tests (sections 6.4.1 and 6.4.2). For stepped voltage tests, the voltage is applied in steps up to a maximum voltage, while, in high potential tests, the maximum voltage is applied directly. Typically, in ac tests, the maximum test voltage is twice the rated voltage plus 1000 volts, and for aged components lower values may be used. Both ac and dc tests generally are conducted on a withstand basis, with voltage applied for one minute. If no failure or sign of undue stress (e.g., rapid lowering of insulation resistance) is observed, the insulation is considered as having passed the test. Insulation characteristics (i.e., resistance, capacitance, dissipation factor, leakage currents) can be measured in conjunction with these tests. These values are helpful in interpreting the results of periodic tests. Voltages for routine maintenance tests generally range from 125 to 150% rated voltage for ac tests, and 1.7 times this value for dc tests. The 1.7 factor is an attempt to provide a direct potential corresponding to the peak alternating value.

6.4.4 Partial Discharge Test

Measurements of partial discharge (PD) are used to detect defects such as voids, cracks, or sharp conducting protrusions in a cable's insulating system. Such defects can produce discharges in the presence of an applied electrical stress, and are primarily of interest for high voltage cables. The technique applies a variable voltage ac source across the insulation. This excitation voltage is increased until partial discharge arises, producing a signal in the form of a short duration pulse. The pulse is detected both as a direct signal and after reflection from the end of the cable. The principle of the technique as it applies to cables, and the sequence of pulses obtained from a single defect site were studied extensively at the University of Connecticut (Ref. 6.45).

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[3]Letter from R.D. Meininger to J.A. Tanaka, editor of the IEEE Electrical Insulation Magazine.

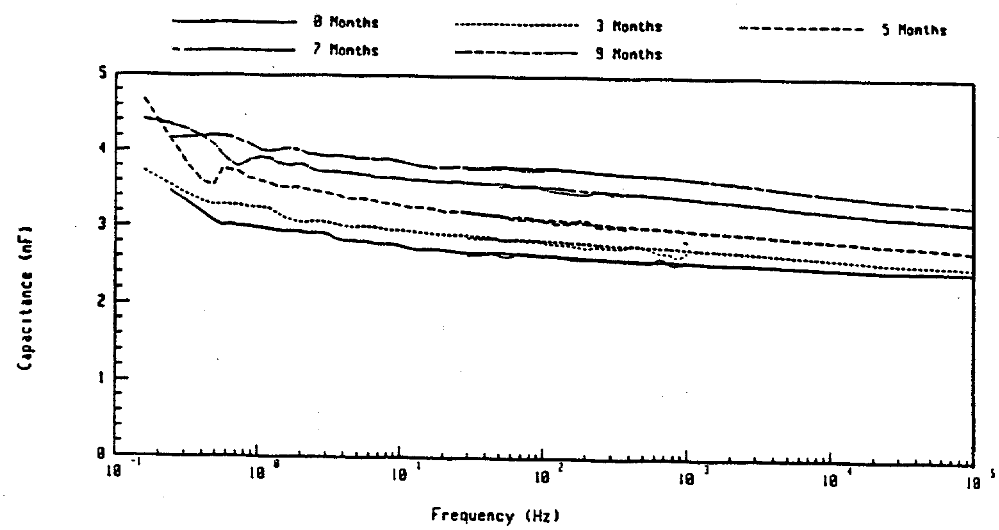


Figure 6.49 Capacitance versus frequency for Rockbestos conductor #14 (Ref. 6.16)

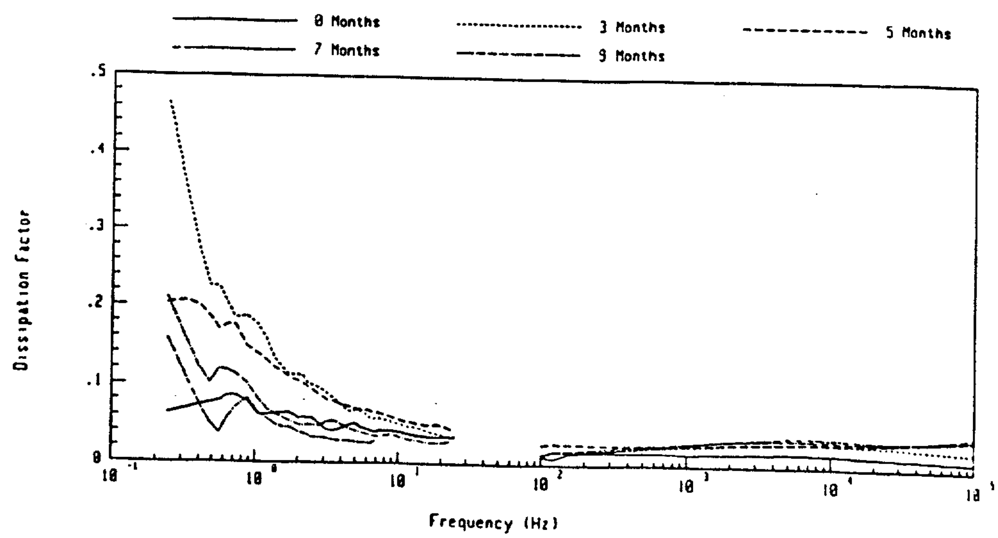


Figure 6.50 Dissipation factor versus frequency for Rockbestos conductor #14 (Ref. 6.16)

Although the technique is simple in principle, there are several practical problems associated with simulating an effective ground plane for unshielded cables, filtering other electromagnetic disturbances in a plant, and application to low voltage cables. The instrument developed at UConn uses state-of-the-art electronic hardware and advanced digital processing techniques. The partial discharge signals are reconstructed using cable traveling-wave characteristics (transfer function), and noise is reduced through a judicious choice of hardware and by modern signal enhancements.

The instrument can locate not only PD sites but also faults in the cable. If the faults are of the high impedance type, PD signals may be generated upon applying a moderately high excitation voltage. However, with low impedance faults (extensively charred insulation), a pulse voltage capable of creating an electric arc across the fault can be applied. Most studies have applied the technique in the laboratory. However, for application to field cables, the technique needs improvement; efforts are continuing at UConn. So far, the technique is applicable to shielded cables where a continuous ground plane exists.

Ground Plane Simulations Using Ionized Gas

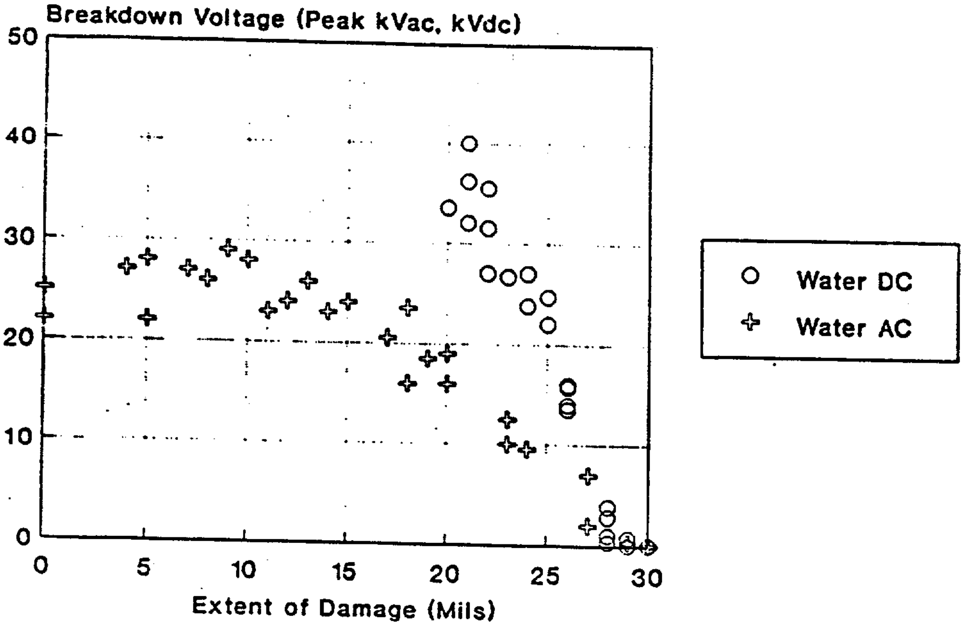
If a uniform conducting surface could be created around non-shielded cables, even temporarily, this would effectively change them into shielded cables. EPRI conjectured that one such means was to blanket the non-shielded cables with a gas that could be ionized at a relatively low voltage stress. The use of high frequency ac voltage was examined first, and it was found that a high-frequency, high-voltage source could act both as an ionizing and a breakdown source that could distinguish between cables with physically undamaged and damaged insulation. This finding led to the initiation of two programs, one at SNL and the other at UConn, to study the feasibility of a preionized gas method for such cables.

SNL conducted breakdown voltage tests on several undamaged, non-shielded, brands and sizes of cable, housed within metal conduits of various sizes (Ref. 6.46). The position and numbers of cables used were varied, as was the type of gas surrounding them. Specifically, the cases of a cable resting against the conduit wall, and that of a cable centered in the conduit were investigated. The cable was immersed in air, argon, helium, or water. Breakdown voltages were recorded upon applying a 60 Hz ac voltage increasing at a uniform rate. Plots of the ac (rms) current versus voltage characterized the onset of departure from linearity, shown as corona inception. This test was repeated with dc excitation to compare the ionization propensity of the gases as a function of the type of excitation voltage.

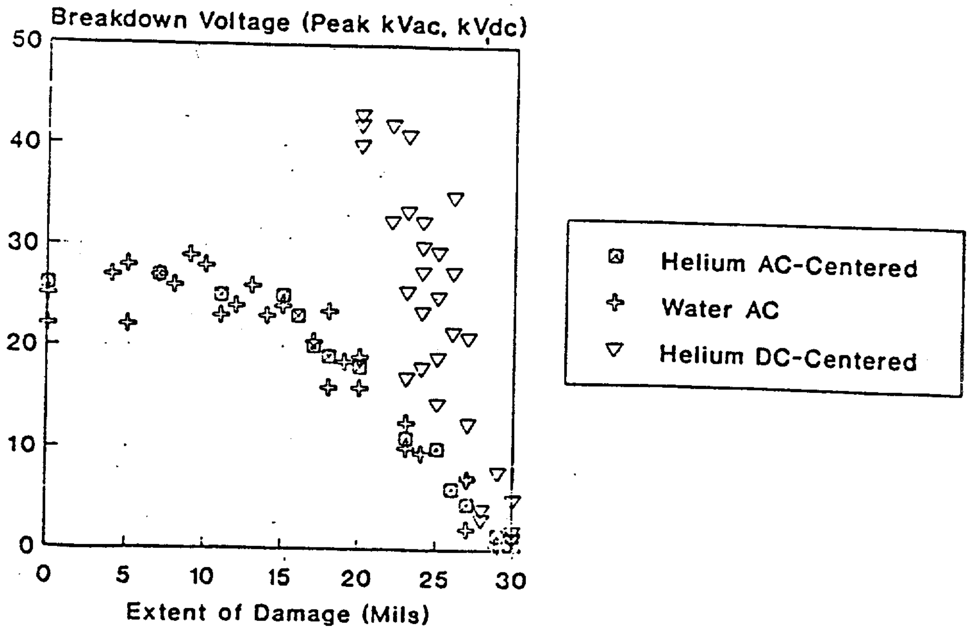
Figure 6.51 illustrates results for Brand Rex cable. Most breakdowns in this study resulted from an electrical puncture of the cable's insulation. From these results, ac testing appeared preferable to dc testing because of the variability noted in the dc results. Other conclusions reached by SNL include:

(a) The ac breakdown voltage for undamaged cable in a conduit containing argon is independent of the cable's location, even when the cable rests on the conduit. Moreover, these breakdown voltages are comparable to those necessary to cause breakdown of the cable immersed in tap water.

(b) The ac breakdown voltage for undamaged cable in air increased with distance of the cable from the conduit wall, suggesting that ionized air surrounding the cable is much thinner than the surrounding ionized argon.



Brand Rex
Partial-wall Damaged Cables



Brand Rex
Partial-wall Damaged Cables

Figure 6.51 Peak AC/DC breakdown voltages (Ref. 6.46)

(c) Detection of a through-wall cable defect occurs at voltages comparable to the inception of ionization voltages.

(d) Argon reduces by a factor of 2-3 the voltage necessary for gas ionization or detection of a through-wall damage compared to air. Helium reduces it even more. The peak of the ac voltage is in the range of the dc test voltage necessary to start ionization.

(e) The rapid rise in ac voltage breakdown of non-shielded cables varies widely, depending on type of insulation and cable's geometry. Breakdown occurs at about the same voltage as for immersion in water.

(f) Breakdown tests of a bundle of non-shielded cables in a conduit can discriminate between damaged and undamaged cables both in air and in argon.

(g) For the same cable, the breakdown voltage decreases significantly as the thickness of the insulation is reduced, but remains substantially higher than the breakdown corresponding to through-wall damage to the insulation.

At UConn , the effectiveness of the ionizable gas blanket in creating a conducting surface at ground potential (shield) around the non-shielded cables was investigated using a potentiometric probe method (Ref. 6.47). Gas ionization created a conducting space around the cables, but it failed to move the ground plane all the way to the immediate surface of the cable insulation. However, compared to air, argon provided a considerably larger voltage window above its ionization inception potential before total breakdown occurred. Unlike the SNL results, blanketing the non-shielded cable with inert gas caused sparkover without puncturing the cable's insulation. The study concluded that owing to the considerable breakdown voltage difference between that in air and in inert gases, the method offered an unambiguous means to discriminate between undamaged and defective cables in cases where the defect allows gas to escape. Further studies are necessary before a practical field method can be developed.

Ontario Hydro carried out experiments using their system on a 265 m length of XLPE, 600V triplex control cable (Ref. 6.48). The technique detected partial discharge and located it with good probability on unshielded 5 kV class cables in which adjacent conductors were grounded. However, for low voltage cables, although there was no problem in detecting PD, it was not possible to define the source of the discharge; that is, there appeared to be a multiplicity of sites along the length of the cable, unrelated to the position of an artificial defect. To simplify the problem a 10 m section was tested; Figure 6.52 illustrates the low probability of reliably locating the defect. It was concluded that the reason that the technique was successful with 5 kV cable, but not with 600V cable was related to the cable's geometry. Work has been continuing to solve this problem.

This technique is limited in practice to shielded high-voltage power cables and can only detect defects such as cracks or pin-holes. The technique is not suitable for detecting the gradual changes in a cable's properties which occur with aging.

6.4.5 Voltage Withstand Test

Voltage Withstand testing is similar to high potential testing, discussed earlier. This is a withstand testing of cables, and typically used for post-LOCA mandrel testing. Cables are wrapped on a mandrel, and immersed in tap water at room temperature. While still immersed, these specimens are required to withstand a voltage test for five minutes at a potential of 80 V/mil ac or 240 V/mil dc. Like high potential tests, these methods use high voltages so there are concerns that an undamaged cable may be damaged.

SNL used this method to assess the survivability of aged and artificially damaged cables under LOCA accidents (Refs. 6.49-6.51). Three cables were chosen: Okonite Okolon - EPDM/CSPE. Rockbestos SR with fiberglass jacket, and BrandRex XLPE insulation. In first phase, the method was used as aging method by subjecting the cables to 24 cycles of 240 Vdc/mil (80 Vac/mil for Brand Rex), each cycle consisting of five minutes on and five minutes off, giving a total of 120 minutes energized and 120 minutes de-energized. The objective was to assess whether 240 Vdc/mil high-potential testing of cables immersed in water could damage them; high potential testing did not damage the three types used. Also, based on the limited set of specimens, no effects on length were noted.

In later phases, this method was used to define the minimum thickness required to survive a LOCA after pre-aging the samples with artificial defects. Based on the results, Brand Rex XLPE single conductors with 8 mils of insulation or more remaining are likely to survive in an accident after thermal and radiation aging under the conditions defined in the program. Rockbestos SR single conductors with as little as 4 mils of insulation remaining have a reasonable probability of surviving a similar condition. Thermal aging may have been a significant factor in causing two failures in the Rockbestos SR cables. All of the intentionally damaged Okonite EPDM/CSPE single conductors with less than 15 mils of insulation remaining failed before aging was complete. The one undamaged conductor and the one that had 15 mils of insulation remaining both failed during LOCA simulation shortly after the test chamber became saturated steam. The major causes of the Okonite failures are the extent of the thermal aging and the presence of a bonded CSPE jacket that ages more rapidly than the underlying insulation.

This method was also used in the post-LOCA testing (mandrel bend and hipot) of all cable types in SNL's life-extension study (Ref. 6.51). For XLPO and miscellaneous cables this high potential test itself did not induce any failures (assuming that the cable did not crack during the mandrel bend). However, the post-LOCA testing was very severe for many of the EPR cables, and otherwise functional cables failed.

6.4.6 Time Domain Reflectometry (TDR)

The TDR technique is based on sending a low voltage waveform with a fast transition time down a cable and looking for reflection of the waveform at discontinuities in the cable impedance. The time difference between the initial and reflected pulses indicates the distance from the end of the cable to the discontinuities. The technique does not differentiate between discontinuities arising from different artifacts (e.g., cable splices and connections, and damage areas). Therefore, it is necessary to generate TDR signatures for each cable of interest in a plant to compare with later measurements. The technique is of most use in troubleshooting where its ability to locate the position of the discontinuity is very valuable. TDR is sensitive to damaged cable, i.e., abraded or cracked insulation, but is not good at detecting the more subtle changes arising from degradation. The method was used in assessing cables inside the reactor after the TMI accident (Ref. 6.52).

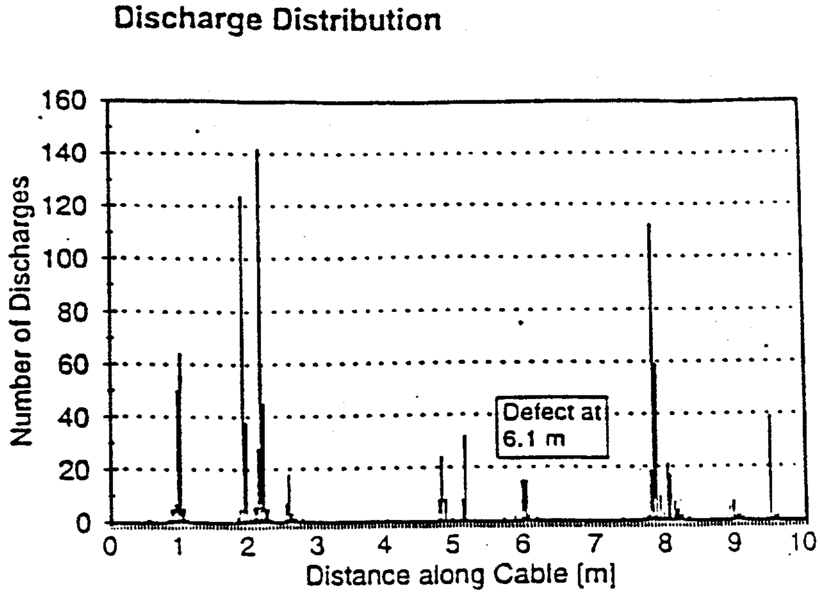


Figure 6.52 Spatial distribution of discharge pulse along cable length (Ref. 6.48)

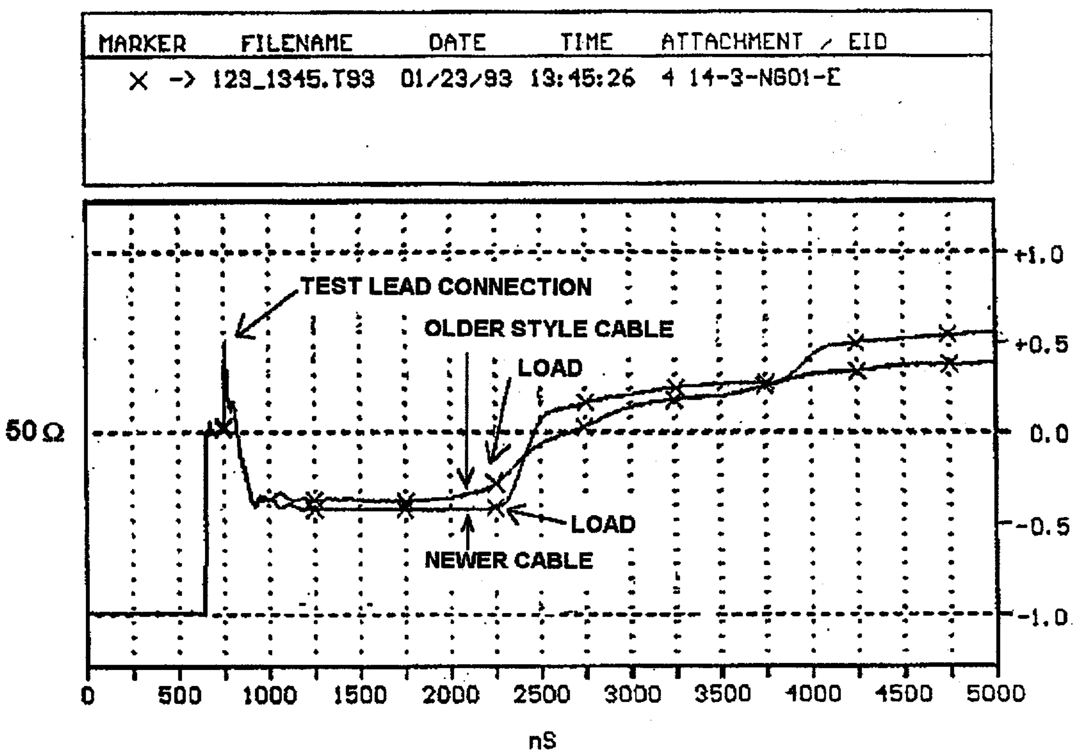


Figure 6.53 Surge impedance of 4 kV cables
Reproduced with permission from Mr. Richard Meininger, President of CHAR Services Inc., P.O. Box 119, Lebanon, PA 17042.

As a troubleshooting tool, the TDR technique has been developed into a commercial system (Ref. 6.53), which combines it with traditional measurements of capacitance, dissipation factor, and insulation resistance. An example of a problem was given that identified a wet conductor where the TDR signature before and after the conductor was exposed to wet condition indicated that the wet conductor was located at an RTD. The system can be used on a wide range of cable types and attached apparatus, and is used in power plants. CHAR Services Inc. currently provides services on their test equipment which use this technique. Figure 6.53 illustrates the output of a CHAR system and represents the measurements of the surge impedance of two different cables.

TDR cannot readily detect changes in the cable arising from aging degradation and its resolution for damage is limited, particularly in long cables length (>20 meters). The technique relies on having signature files for every cable in a power plant. On unshielded cables, this is complicated by the need to repeat the signatures every time a cable is moved. The sensitivity of the TDR technique is limited by the degradation of the waveform over long cables and cannot detect very localized damage.

At UConn, the TDR technique was used to locate partial discharge (PD) in an installed underground shielded cable (Ref. 6.54). The paper described a commercially exploitable instrument capable of locating PD of the order of 1 pC in a high noise environment. Several techniques for signal analysis also were developed by these researchers. The method is adaptive, as it allows the characteristics of the selected cable to be adapted to the real environment.

6.4.7 Dielectric Loss Measurements

Under the influence of the electric field, a reorientation of the electric charges inherent to the material occurs at the electronic, atomic, molecular, and crystalline levels, and migration of free charges (ions and electrons) takes place (Ref. 6.56). The dielectric constant (permittivity) of the material is a function of the various polarization processes (Figure 6.54). These processes are manifested within a typical frequency ranges. If the excitation voltage produces a sinusoidal electric field, the dipoles and free charges tend to move in sympathy with the field, i.e., the dipoles tend to orient themselves parallel to E (Figure 6.54), the positive free charges move in the direction of E and because of the viscosity of the dielectric material, a lag develops between the forcing function, E, and the response of the dipoles and the free charges. As a result, the permittivity assumes a complex form with a real part, E', and an imaginary part, E", and the energy required to move or reorient the charges becomes a function of frequency. The energy thus expended is known as the dielectric loss, a direct function of the ratio E"/E', also referred to as tan δ.

If the loss factor, tan δ, of the cable insulation is plotted versus frequency, it shows typical relaxation peaks which occur within certain frequency ranges. The relaxation peaks corresponding to electronic and atomic polarizations occur at extremely high frequencies ($>10^{12}$) and, therefore, are of no interest for the Time Domain Spectrometry (TDS) method. However, dipolar and interfacial relaxations as well as increased tan δ due to conduction, occur at the lower end of the frequency spectrum (Figure 6.55), and fall within the measuring capability of the instrumentation used for TDS. As a result of chemical changes in polymers, free radicals (ionic species) are released and polar molecules formed. The tan δ spectrum of the aged materials is expected to gradually increase as the frequency decreases below 1 Hz.

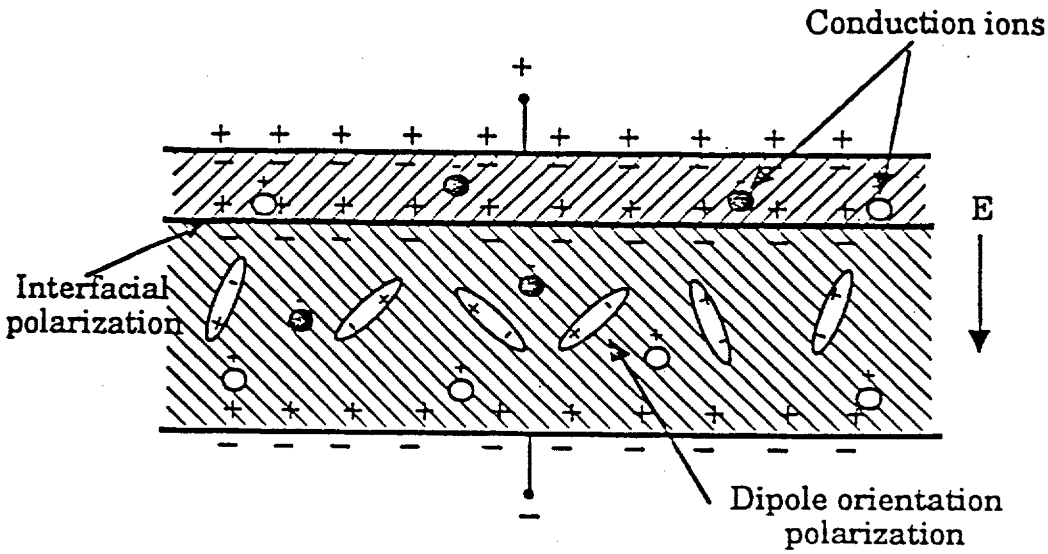


Figure 6.54 Polarization processes in a typical cable insulation (Ref. 6.56)

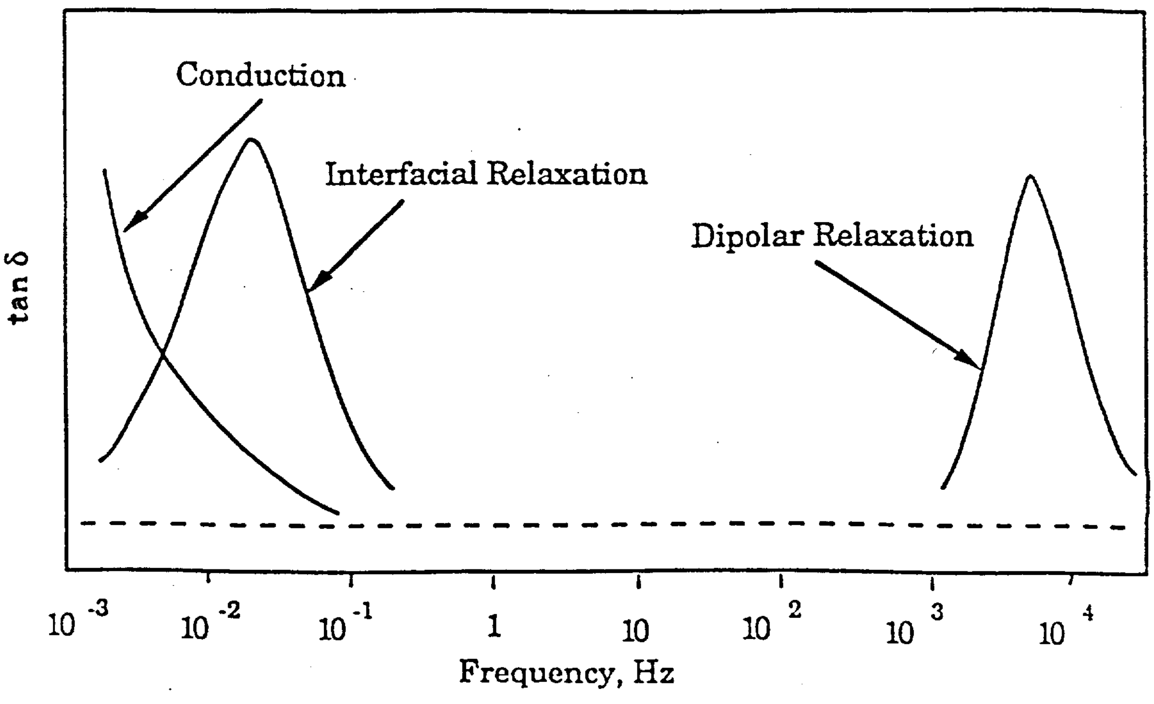


Figure 6.55 Typical loss factor vs frequency behavior of a cable insulation (Ref. 6.56)

TDS is a technique for determining the frequency spectrum of the dielectric loss of a cable material from its response to a step voltage excitation. The instrument used for TDS measurements is manufactured and sold by IMASS, and based on the system developed by the NIST (Ref. 6.55). A semiconducting splicing tape is tightly wrapped around the portion of the cable to be tested and surrounded with a metal braid electrode; a grounded guard circuit is added at each of its ends. Several other electrode configurations were tried at UConn (Ref. 6.56), including conducting tape and metallized tape. This particular configuration was selected because of its consistent performance.

A ± 100 V step voltage is applied across the combined test sample and a reference capacitor. The resulting current, integrated with time, is filtered, amplified, digitized, and subjected to a Fast Fourier analysis to yield the real and imaginary components of the sample's capacitance as a function of frequency. These values, in turn, are used to compute the real and imaginary components, E' and E", and the tan δ (=E'/E"), of the cable's insulation. Although this entire information is recorded, only the loss factor, tan δ, is presented in most studies. The frequency range capability of the instrument is 10^{-4} to 10^{4} Hz, and at the lower frequencies, processing times are longer.

Ontario Hydro (Ref. 6.30), UConn (Ref. 6.56), and Quebec Hydro (Ref. 6.57) have used TDS measurements to study the insulation properties under aging conditions. Figures 6.56 and 6.57 show some examples of their results. Figure 6.56 shows the effect of aging in a mineral environment, while Figure 6.57 illustrates the results for EPR and XLPE in water. At present, TDS measurements are restricted to the laboratory but suitable instrumentation is being developed to use in a plant.

In Britain, researchers have used a video bridge to generate signals of a fixed frequency over the range 20 Hz to 20 kHz, and claim that the dielectric loss spectrum can be developed on long lengths of cable in-plant (Ref. 6.5). The signal is applied to adjacent conductors in multiconductor cables or between conductor and shield in shielded cables. Since no external electrode is used, the loss in the whole cable is determined from measurements made at one end of the cable. The technique is less sensitive than the TDS measurements. However, the equipment is portable and its ease of use on long cables make it practical for assessing cable degradation. It is necessary to disconnect any load from the cable before using this technique. So far, the technique cannot be used on single conductor unshielded cables.

6.5 Summary

Since the first EPRI workshop in 1988 on condition monitoring methods for cables, significant advances have been made nationally and internationally in the search for an effective program to assess the condition of cables in nuclear power plants. However, no simple formula has been found, which can provide all the information to characterize the aging of cables and to assure their survivability in accidents. The complexities involved in defining an effective condition monitoring program are so great that one simple method may not provide the solutions needed. This area has the greatest potential for future research that could produce useful results.

EPRI has sponsored several research programs at its member utilities, several universities, and test laboratories such as FRC, University of Virginia and Ontario Hydro to develop methods to monitor the condition of cables inside the containment of nuclear power plants. SNL has tried several methods in their LOCA testing programs and concluded that elongation-at-break is the only one which provides a reliable indication of aging. Japan developed a torque tester, similar in principle to Indenter, and had some promising

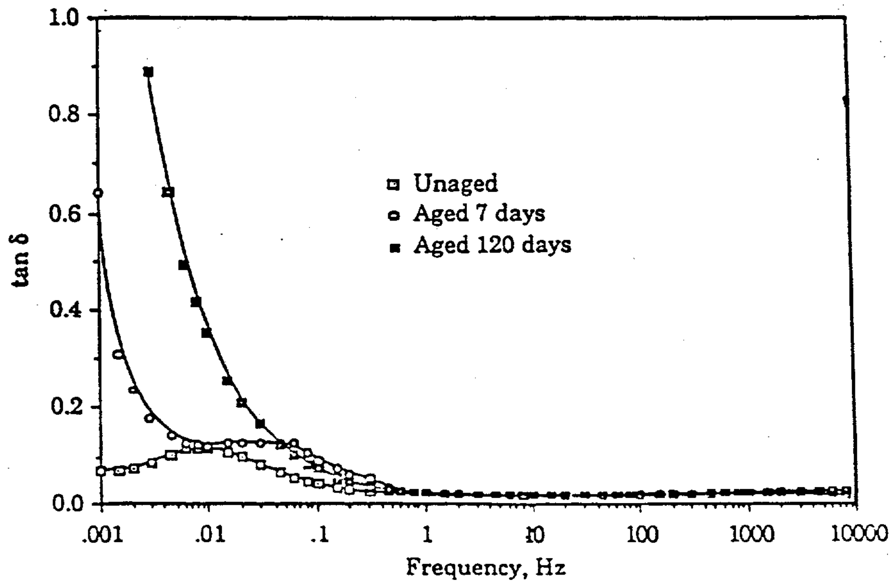


Figure 6.56 TDS results for unaged and aged samples in oil environment (Ref. 6.56)
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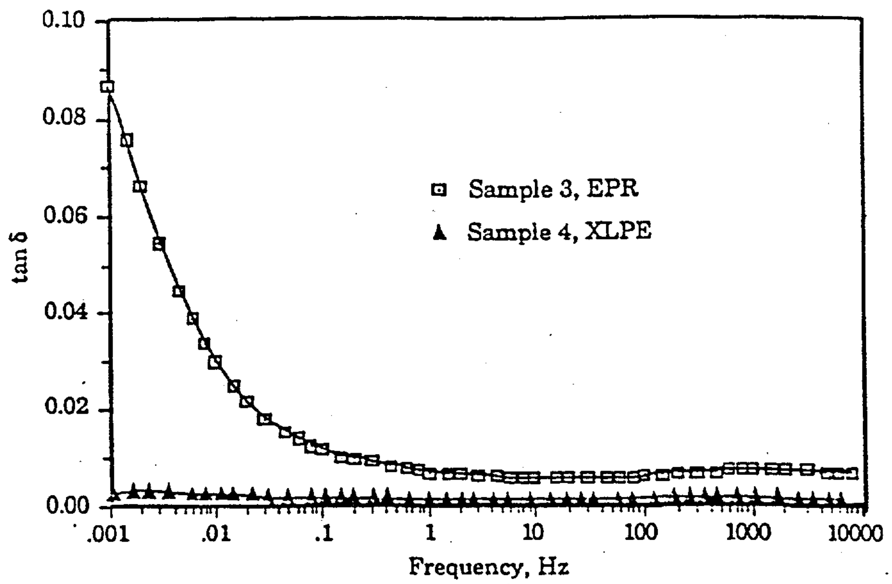

Figure 6.57 TDS results on aged wet at 90°C for 180 days (Ref. 6.56)
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results. CM research in other countries of the Western world has gained interests in recent years and the IEC standards organization and the IAEA have intensified their search for a guideline delineating several CM methods that have some promise. No study has correlated the condition of the jacket material with that of the underlying insulating material. Since the jacket is more accessible for testing than the insulation, a study relating the conditions of these cable materials is warranted.

This section has discussed all published CM methods that have been used or have the potential for monitoring a cable's condition, specifically degradation of the insulation and jacket materials. The methods are discussed in three specific categories: chemical, physical, and electrical. Some of these methods are suitable for laboratory use, and others have some potential to be used in situ. Not all attributes of an effective CM technique can be satisfied by any one method, but a combination of several methods may provide adequate information to characterize the condition of cable materials. Some methods are unlikely to be useful. Table 6.7 summarizes the preliminary findings on the results and the status of the research on these CM methods.

Table 6.7 Summary of Research on Condition Monitoring Methods

Number Section	CM Method(s)	Parameter(s) Monitored	Reference(s)	Remarks (see NOTES)
1 6.2.1	Near Infra-Red Reflectance (NIR)	Identifies functional groups that are formed due to oxidation.	6.21 & 6.22	Being studied at Ontario Hydro on PVC jackets. Has some potential for in situ application.
2 6.2.2	Computed Tomography (CT)	Develops profiles of density changes across the specimen thickness.	6.23 - 6.25	Has been used in medical applications. Being studied in Sweden for cables. Recently, Sandia has studied on EPR. Used as a laboratory tool.
3 6.2.3	Sonic Velocity	Measures sonic velocity in the cable jacket.	6.22	Being developed at Ontario Hydro on PVC-jacketed cables. Preliminary results show good correlation with elongation, density, and modulus properties. Because of its portability this has the potential for in situ application.
4 6.2.4	Fourier Transform Infra-Red (FTIR) Spectroscopy	Identifies carbonyl peaks that are formed due to oxidation.	6.26 & 6.27	Has been used as a laboratory tool and has demonstrated good results for XLPE, EPR, and SBR. Not effective for PVC samples.
5 6.2.5	Solubility Measurements (Gel Content & Swelling Ratio)	Indicates chemical degradation (chain scission, crosslinking).	6.26 & 6.27	Demonstrated promising results for EPR, XLPE, SBR, and PVC. Being studied at Ontario Hydro as a laboratory tool.
6 6.2.6	Oxidation Induction Time (OIT)/Temperature under pressure	Measures the amount of antioxidants remaining in the specimen.	6.27 - 6.31	Demonstrated as a good indicator for early stage of degradation for XLPE, EPR, and SBR. Improvements for field application are being studied at Univ. of Virginia under EPRI funding.
7 6.2.7	Plasticizer Content	Measures loss in plasticizer indicating thermal degradation of PVC.	6.30	Ontario Hydro used this technique to assess degradation in field samples of PVC and to differentiate between thermal and irradiation degradation. Has shown good results for field application.
8 6.2.8	Differential Scanning Calorimetry (DSC)	Develops melting endotherms indicating melting points, crystallinity, and glass transition temperature. (Also used for OIT measurements).	6.27 & 6.32	Ontario Hydro has used to study crystallinity and melting endotherms for XLPE. Univ. of Tennessee used this to extract thermal history recorded in the material crystals. Still used as a good laboratory tool for thermal degradation.

Number Section	CM Method(s)	Parameter(s) Monitored	Reference(s)	Remarks (see NOTES)
9 6.2.9	Thermomechanical Analysis (TMA)/ Thermogravimetric Analysis (TGA)	TMA measures the relative hardness while TGA records the mass (or weight) changes with temperature.	6.21, 6.27, 6.33	Ontario Hydro used TMA for studying EPR and PVC. Japan has used TGA experiments at JAERI on PVC samples. Still used as a good laboratory tool.
10 6.3.1	Tensile Tests	Measures tensile strength (TS) and elongation-at-break (EAB).	6.30 & 6.34	Has been proven to be the best indicator of embrittlement (or degradation) for all types of polymers used in cable construction. Widely used as the benchmark for other CM tests. Ontario Hydro suggests 50% absolute elongation as approaching end of life.
11 6.3.2	Indenter Modulus	Measures the compressive modulus.	6.35 - 6.39	Developed by Franklin Research Center under EPRI funding. Commercial units are used by utilities for in-service (or in situ) cable monitoring. Less effective for XLPE.
12 6.3.3	Torque Tester	Measures torque as a function of torsion angle.	6.33	Developed by Japan and found good correlation with other indicators for XLPE and PVC. Still at developing stage for its field application capability. No up to date information available.
13 6.3.4	Flexure Test	Physically bends cable to observe if it flexes and if cracks develop.	6.16 - 6.18	Used as a qualitative measurement of cable's insulation and jacket conditions.
14 6.3.5	Profiling and Polishing Methods	Develops profiles of elastic modulus, density, and hardness across the specimen thickness.	6.16 - 6.18, 6.40	Used as a laboratory tool for examining the variations in physical properties across thickness. Sandia used for detecting heterogeneous degradation in polymers.
15 6.3.6	Hardness and Density Measurements	Measures hardness (as resistance to penetration) and bulk density.	6.16 - 6.18, 6.31	Sandia has used as laboratory tools in their studies for all cable materials.
16 6.3.7	Dynamic Mechanical Analysis (DMA)	Monitors the stress-strain behavior and loss tangent.	Private contact with Mr. D.J. Stonkus.	Ontario Hydro has been studying this technique for XLPE, EPR, and PVC. Still in development stage as a laboratory tool.
17 6.4.1	DC Tests	Measure insulation resistance, leakage current, and polarization index (PI).	6.16 - 6.18, 6.30	All test parameters are insensitive to aging of cable polymers, specifically under dry condition. However, during LOCA testing, the resistance value can vary orders of magnitude due to high temperature and wet condition. Used as an electrical diagnostic tool in maintenance.
18 6.4.2	AC Impedance Tests	Measure transfer function (resistance, capacitance,and inductance), dissipation factor (DF), and power factor (PF) as function of frequency.	6.16 - 6.18, 6.44	Difficult to relate electrical values to cable embrittlement. However, they provide data which are important for assessing the integrities of electrical circuits and wiring systems.
19 6.4.3	Stepped Voltage and High Potential Tests (AC or DC HiPot)	Measure resistance, capacitance, leakage current, and dissipation factor (in dry condition).	6.44	Since these tests may involve higher voltage levels than the rated value for the circuit or equipment, gross degradation in the circuits and wiring systems can be assessed from the test parameters. Currently used in maintenance activities in power industry to assess insulation integrity of the cable system.

Number Section	CM Method(s)	Parameter(s) Monitored	Reference(s)	Remarks (see NOTES)
20 6.4.4	Partial Discharge (PD) Test	Measures inception voltage at which discharge due to ionization occur at cable defects (e.g. voids, cracks).	6.45 - 6.48	Univ. of Connecticut has been developing test equipment for tests in field conditions. Both Sandia and UCONN performed studies for simulating ground planes using inert gases in nonshielded cables. Ontario Hydro also has used this to assess conditions of field cables.
21 6.4.5	Voltage Withstand Test	Based on the breakdown of insulation, this test measures the insulation capacity (in V/mil) by subjecting to high voltages while immersed in water.	6.49 - 6.51	Used as pre- and post-LOCA tests as demonstration of an adequate margins of safety. Cables are wrapped on a mandrel demonstrating mechanical durability. Used more for establishing cable capacity than condition monitoring.
22 6.4.6	Time Domain Reflectometry (TDR)	Compares initial with reflected pulses indicating the distance from the discontinuities in a circuit or wiring system.	6.52 - 6.54	Portable commercial units are used in plants for troubleshooting circuits and wiring systems. Also, impedance tests for monitoring changes in electrical parameters. Used in evaluating circuit faults after TMI accident.
23 6.4.7	Dielectric Loss Measurements (Time Domain Spectrometry/ Video Bridge)	Measures dielectric loss as a function of frequency.	6.5, 6.30, 6.55 - 6.57	TDS was originally developed at NIST and commercial units are now available by IMASS. Technique being studied in laboratory by UCONN, Ontario Hydro, and Quebec Hydro. Britain has been developing this technique using a portable video bridge.

NOTES: All electrical tests require a uniform and continuous ground plane around cables, specifically for nonshielded cables.
In situ application: Testing performed in plant on installed cables. Field application: Testing performed in laboratory on field samples to assess their conditions. Laboratory tool: Testing performed in laboratory on pre-conditioned samples as a research tool.

Most physical and chemical test methods are specific to certain polymeric material, and it is difficult to generalize a method which can be used for all the insulation and jacket materials used by the cable industry. On the other hand, some electrical tests strongly depend on the availability of a reliable and continuous ground plane along the length of the cable; this is very critical for unshielded cables, which is true for most low-voltage power cables.

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7. SUMMARY AND CONCLUSIONS

This report summarizes results from a review of published literature on environmental qualification (EQ) of safety-related electric cables used in nuclear power plants. The studies performed by other researchers are discussed in three basic areas; aging characterization, LOCA testing, and condition monitoring methods. The former two areas are directly related to the EQ process of cables for nuclear application. Significant studies addressing various aspects of the EQ requirements have been undertaken at SNL under NRC sponsorship since 1975 (Refs. 7.1 and 7.2). France and Japan also have carried out research to understand the effect of EQ requirements on their cable products. Compared to LOCA testing, aging studies on polymers, typically used for the cable's insulation and jacket materials, have received most attention by the researchers not only in the United States, but also several foreign countries with nuclear programs.

During the last decade, research on the condition monitoring (CM) of cables has attracted interest among the electric utilities and affiliated industries. Significant advancements were made by EPRI who sponsored several programs at various U.S. universities, power plants of its member utilities, and the cable industry (Ref. 7.3 and 7.4). Cooperative programs with individual utilities, foreign agencies (specifically with Ontario Hydro in Canada), and NRC were formed to identify the most effective monitoring methods. Recently, Japan, Great Britain, and Sweden have been developing CM methods. Despite this recent surge, a definite CM method has not been found and work in this area remains very active.

The results from a large number of studies performed by the cable manufacturers on their own products at their own testing facilities were not available for review. Unlike the authors of published studies, these manufacturers have the advantage of knowing the actual composition and formulation of polymeric materials that were used to construct the cables. Because this information is proprietary, most publications do not identify the polymer data, and as a result, the same group of polymeric materials from different manufacturers (in some cases even from the same manufacturer) behave differently under pre-aging and LOCA simulation testing. For the same reason, studies performed in Great Britain and Germany were not readily available for this review.

7.1 Summary of Results

There are approximately 60 operating reactors in U.S. with the oldest EQ requirements, DOR Guidelines, 24 with NUREG-0588, Category II requirements, and another 24 with NUREG-0588, Category I requirements. The reactor units using cables satisfying the former two guidelines have less stringent EQ requirements in areas such as qualification by testing, application margins, and consideration of aging and synergistic effects[1]. Although almost all safety-related cables were qualified by testing in which specimens were pre-aged before they were exposed to a LOCA environment, uncertainties associated with various EQ requirements, inconsistent behavior of similar insulating materials from different cable manufacturers, and the presence of hot spots (higher than design basis temperature and radiation conditions) inside the containment, have raised concerns on their reliability. During the last two decades, research in aging and LOCA testing has produced much information, but no quantitative analyses of the adequacy of various aging methods and LOCA profiles in EQ, the influences of margins, presence of hot spots or weak links, test duration, LOCA acceleration, and PRA input. Moreover, the recent failure of certain types of cable (e.g., Okonite) during

[1] In some ways, however, early cable qualification programs, in which the duration of LOCA steam/chemical spray exposures was 30 days or longer, were more severe than recent programs. In recent programs, a questionable method (using Arrhenius equation) has been adopted to reduce the duration to 10 days or less.

LOCA tests at SNL (Ref. 7.5 to 7.8) has added further concerns on survivability of in-service cables under postulated design-basis accidents. The conclusions on Okonite Okolon cables derived from these tests are failure-based. Additional studies to identify root causes of such failures could have justified limiting their applicability under high thermal conditions.

The EQ research on cables has produced a massive amount of data on a variety of topics associated with their qualification. The following summarizes findings that are important for the objectives of this literature review.

Aging Characterization

The following summarizes the results obtained from procedures that can simulate conditions representing aged cables in a plant environment:

(1) The actual environmental conditions (i.e., radiation dose rate and temperature) inside the containment of a plant have been difficult to define in the EQ process. All hot spot locations and cables subject to adverse conditions (i.e., leaky valves) can accelerate degradation more rapidly than anticipated during qualification. During the November 1993 NRC EQ workshop, sharp differences in defining these parameters at different plants were discussed. The radiation dose rate and temperature levels can degrade the cable materials significantly. The current EPRI effort at the University of Connecticut may provide valuable information on the actual in-containment conditions exposed to cables in service; each of the monitoring locations chosen represents a worst-case scenario. Based on the limited information, typical inside-containment environment has a temperature range from 75°F-125°F (25°C-55°C) and a total integrated dose of 10 Mrad of radiation (@ a dose rate of 25-30 rad/hr) for a 40-year design life. These conditions may vary from one plant design to another and do not include hot spot locations which can have temperatures as high as 150°F (65°C) and a total radiation dose as high as 60 Mrad (@ 175 rad/hr). Design considerations during cable installation should eliminate such abnormal conditions by routing cables through a path with a less hostile environment[2].

(2) The Arrhenius method may erroneously predict the life of insulation materials (and hence the cable's life), unless appropriate measures are taken in understanding non-Arrhenius behavior at elevated temperatures, in extrapolating the elevated temperature data to actual plant conditions, and in estimating the correct activation energy values. When the range of experimental temperatures encompasses a physical transition of the polymeric material (e.g., crystalline melting point), the degradation process may change within the material, and hence, the activation energy and the Arrhenius behavior. Studies have shown that EPR and XLPO are semicrystalline under typical operating conditions, forcing extrapolations to be made across crystalline melting regions (i.e., 87°C-126°C). The situation is even more complicated for commercial materials, since diluents and plasticizers can lower the melting temperature, and crystalline additives can give peaks of their own.

Since oxidative degradation takes place in the amorphous regions of semicrystalline polymers, extrapolations through the melting temperature of aging results taken above this temperature supposedly would be conservative. Unfortunately, several Japanese studies have shown that an

[2] When this is not feasible, it may be necessary to re-evaluate the qualified life of cables in hot spot areas, where the service conditions are more severe than those assumed in the EQ process.

increase in material crystallinity enhances oxidative degradation rates in a gamma-radiation environment, further complicating the extrapolation of the accelerated aging data to the plant environment.

(3) Effects of dose rates, presence of oxygen, and other factors (e.g., additives) are recognized by majority of studies. If the dose rate can be lowered to a point suitable for the material under consideration, physical degradation caused by diffusion-limited oxidation can be eliminated. However, this effect should be investigated on commercial cable materials with thicker specimens than the materials used in SNL studies. Also, other chemical effects on these specimens need to be better understood.

(4) Figure 4.13 for XLPO, Table 4.10 for EPR, and Table 4.17 for EPR and XLPE indicate that under combined radiation and thermal environments these insulation materials mechanically degrade faster at room temperature than they do at elevated temperatures. Research on this phenomenon is ongoing at Sandia. If this behavior can impact the overall aging characteristics that have been seen in the accelerated aging procedures, the qualification of these insulating materials may require further scrutiny.

(5) Some insulating materials are sensitive to the ordering sequence of the environment when compared to the results from the simultaneous environment conditions. Some studies have shown significant synergistic effects among the individual effects from each environmental condition. Most of these studies were performed at elevated temperatures and high radiation dose rates. Comparison with the actual plant environmental conditions needs to be made so that these synergistic or ordering effects can be taken into account in simulating the actual aging conditions.

(6) The time-temperature-dose rate superposition method seems to predict the actual life estimates, provided that the underlying causes of the degradation processes at such elevated conditions are known. Additional applications of this methodology and comparisons with actual plant aging-data should be made. Methods developed by others should be considered.

(7) Several studies on aging used small laboratory samples (with all additives, different formulations, and thinner specimens). The validity of these results to actual cables needs further assessment.

(8) Based on accelerated testing, most jacket materials lost their elongation-at-break values by the time they were exposed to 40 Mrad radiation, while most insulating materials possess only 30% of their original elongation after being irradiated to 50 Mrad and 0% after 130 Mrad. Some of these materials may degrade even further under low dose rates. Before exposing to steam and chemical spray conditions, most cable qualification tests have used 200 Mrad of irradiation which includes 50 Mrad for preaging and 150 Mrad accident radiation. Evaluation of a threshold elongation value for a reasonable assurance of LOCA survivability must consider this intrinsic aging behavior of cable polymers. In view of this, the temperature/radiation sequence or simultaneity may be of secondary importance.

(9) Cable materials exposed to actual plant environments (i.e., 50°C-65°C and ~5-10Mrad) have indicated degradation in their elongation-at-break (i.e., 0-50% decrease for insulation) after 5-9 years of service. Some EPR and XLPO insulations exposed to normal plant conditions exhibited very little (0-10%) change in their elongation properties. Comparison of these characteristics with accelerated aging test results of similar materials could be beneficial.

LOCA Testing

The following summary covers the research on the LOCA simulations for cables in the environmental qualification process. These topics include polymer behavior and monitoring its physical parameters during the LOCA testing, the effect of different constructions of cables including insulation and jacket materials and conductors, the effect of the simulated environmental conditions, the effects of pre- and post-accident conditions, and the results from post-accident tests.

(1) Under long-term radiation and high thermal conditions, embrittlement is the predominant aging degradation of a cable's polymeric materials. The physical parameter, elongation-at-break, has been universally accepted to be the most consistent and reliable way to monitor this degradation. However, during LOCA testing, the high dose of radiation in relatively short duration and the hot steam can degrade the already deteriorated insulating system to a zero elongation value. Still, the cable can pass electrical tests indicating its survivability during and after a LOCA event. Many researchers have chosen other physical parameters, such as weight, and tensile strength, to monitor the insulation's condition during such tests. A completely embrittled insulation or jacket is vulnerable to mishandling or mechanical damage (including impingement of the steam). Monitoring service environments to identify hot spots and inspecting cables so that embrittlement, if it occurs, is observed, can assure LOCA survivability.

(2) The response to LOCA conditions of cable insulation and jacket materials depends on material types, manufacturing processes, and the formulation of chemicals, including additives. In some cases, interaction of the insulation material with the jacket material has exposed bare conductors to the LOCA environment. Sometimes, the cables performed well during accident transient period, but showed signs of failure during the less severe post-transient environment.

(3) Failure of Kapton cable products during LOCA testing often is related to mishandling the specimens. This problem should be investigated further to understand the reasons and appropriate measures should be identified to supplement the existing qualification procedures.

(4) Multiconductor cables seem to respond more poorly to LOCA conditions than a single conductor counterpart. Sandia researchers suggested several reasons for the longitudinal cracks in the CSPE and Neoprene jackets. Similarly, the behaviors of coaxial cables and cables with bonded jackets require further characterization during LOCA exposures.

(5) Based on this literature review, pre-aging has a significant effect on the final response of a cable during LOCA simulations. Extensive results indicate that the cable's responses vary, not only from one aging simulation technique to another, but also from material to material, and with their chemical composition.

(6) Since the duration of the transient part of an accident is limited, the amount of oxygen or ozone available during this period can significantly affect the overall degradation of cable materials. Therefore, the amount of oxygen that should be included in simulations can be a large factor in selecting the LOCA environments for testing.

(7) The cable's responses to LOCA conditions do not significantly depend on the steam conditions (superheated or saturated), the chemical spray, synergism between radiation and thermal conditions,

and the high radiation dose rates. Although studies on these issues are limited, compared to the effects of total radiation dose and the high temperature saturated steam conditions dominating the LOCA, these parameters can be considered marginal.

Condition Monitoring

Monitoring the physical and electrical properties of cables can adequately assure their performance during the design life of a nuclear power plant. Studies on CM methods are recent, and several methods currently being studied are summarized in this report. Some general observations from these studies are given below:

(1) Chemical tests are useful in revealing the causes of polymer degradation under thermal and radiation environments. Most of these methods are suitable for determining the underlying cause of cable failures, rather than monitoring the condition of cables.

(2) Physical methods are necessary to characterize the mechanical or physical strength of polymers and provide adequate information on the degradation process. Tests have indicated that cables with zero mechanical strength can survive a design basis accident and can perform their design function (i.e., delivering electric power and transmitting signals to and from connected safety equipment).

(3) Electrical tests are very important to define the failure of cables under any environmental condition. Presently, most tests have significant limitations in application inside a plant.

(4) Some efforts are being made to correlate data from chemical and physical tests, but there is little correlation of electrical data with other degradation parameters. This may be due to the fact that electrical tests may not be sensitive to morphological changes in the aged insulation. Nevertheless, morphological changes in the cable's insulation materials must be correlated to changes in electrical property to develop any criterion for its reliable function.

(5) It is obvious that the jacket material degrades first before there is any sign of deterioration in the insulation. No studies relating the jacket's degradation to that of the insulation material were found.

(6) Most research on CM methods focused on the technical aspects of the methods. Very few have attempted to establish threshold values or other relevant parameters which can assure the cables with certain aging conditions to survive an impending accident during the design life of a nuclear power plant.

7.2 Conclusions

This literature review encompassed various aspects of the environmental qualification requirements applicable to cables and cable materials. The results presented may not have included all studies in any specific area, but the major concerns and findings affecting the issue are identified. To completely understand the problem, results from ongoing studies should be augmented. Based on the current state of the findings, programs to further clarify technical issues should be developed for future research. Elements that are important in formulating a future research program on the three general areas are discussed in this Section. Finally, some general aspects of the environmental qualification process for cables also are discussed.

Aging Characterization

Using elevated temperatures and high dose-rates for accelerated aging simulation of a plant environment can yield erroneous cable conditions during qualification tests. For some insulation materials, these extreme conditions may not always simulate the worst aging condition at the end of their service life (Accelerated aging can either overshoot or undershoot the conditions reached in actual service). To properly achieve the pre-aging condition of cables before they are exposed to an accident, the following conditions should be considered:

- If the tensile property of the insulation and jacket materials is negligible after the cable is exposed to high accident radiation before exposing to LOCA steam conditions, then the sequence of aging simulation and dose rate effects can be of no significance.

  If sequential testing for the environmental conditions is chosen, the ordering and synergistic effects for the material should be assessed. For simultaneous aging conditions, the underlying causes of the effects of different combinations of thermal and radiation conditions should be evaluated.

- The chosen elevated temperatures should be such that the extrapolation does not cross the materials' crystalline melting temperature. The causes of any non-Arrhenius behavior within the temperature range should be examined. The lowest elevated temperature should be close to the actual environmental temperature in the plant so that a different mechanism of degradation (i.e., activation energy) could not dominate in this range; in this way, confidence in the prediction can be high.

- If the material shows a strong dose-rate effect, the rate chosen for the accelerated aging should be as low as possible. The underlying causes for the dose-rate effects should be understood. The equal dose - equal damage criterion can be used only if the dose-rate effects are negligible for the material. Otherwise, time-temperature-dose rate superposition method or other available prediction models can be used.

- Since the presence of oxygen is an important factor affecting the aging of polymers, an adequate supply of air is needed during aging to properly simulate natural environments containing air or oxygen.

LOCA Testing

Proper simulation of LOCA conditions during the qualification can avoid questionable responses. Parameters monitoring the cable's state during the LOCA testing can differ from those during the aging simulations. Moreover, post-LOCA tests (mandrel bend and dielectric withstand) can induce degradation of cables that are otherwise functional. The following suggestions may help formulating the future studies on the subject:

- Cables pre-aged prior to LOCA testing should be compared with naturally aged cables from a variety of in-plant configurations and locations (including bends, vertical runs, and high stress areas, such as thermal and radiation hot spots, high humidity areas, high vibration areas, water/liquid impingement, installation damage, and fire protection coatings) to gain confidence on the qualification process.

- Physical parameters that should monitor the overall state of cables during the test should be identified. Although insulation resistance and leakage currents typically are used, other physical parameters, such as weight change (or density), should be considered and their validity established.

- Defining the failure of a cable during LOCA testing (i.e., establishing acceptance criteria) is another unknown. SNL was using 1 amp fuses to monitor cable functionality. Simulating the performance of cables using actual electrical loads (e.g., power cables with small motors, control cables with SOVs, and instrument cables with transmitters or RTDs) and their ability to operate during the test can be more realistic. Cable application should be simulated and the installed conditions are represented in the LOCA simulation, with considerations for multiconductor, single conductor, and unique installations.

- Post-LOCA mandrel bend testing, in which cable is removed from one mandrel, straightened, and recoiled on another mandrel, imparts an unrealistic stress on the cable which induces failure of good cables. Since most cable materials are brittle at the end of a LOCA test, the use of the mandrel bend test (with a mandrel 40 times the cable diameter) should be evaluated further.

- No research has been undertaken on the adequacy of the LOCA profile, including double-peak versus single-peak profile, LOCA test duration, the influence of margins, and PRA considerations. Research evaluating these factors and the overall level of conservatism in LOCA test profiles would provide important contributions to the EQ process.

Condition Monitoring

Research in developing condition monitoring methods for cables is the weakest compared to aging and LOCA studies. Although the direction of all efforts is indicative of some progress, it is still nowhere near finding the solution soon. However, by looking for all plausible methods that would define the conditions of polymeric materials (with similar formulation and manufacturing process) one at a time, then the chemical and physical degradation of this material can be better understood. Once the behavior of polymers under the influence of temperature, radiation, and humidity is understood, then its impact on electrical properties should be assessed. Correlation of the electrical characteristic with the physical/chemical deterioration of the insulation and jacket materials is an important element for the condition monitoring method. Several suggestions, given below, may enhance the CM research effort and help formulate a research program which can augment the ongoing studies.

- A correlation study of the aging effects on insulation and jacket materials may help in predicting the cable's life.

- Using test methods on naturally aged cables from known environmental conditions might enhance confidence in the test's parameters.

- Based on the aging monitoring data, a threshold value should be identified which will ensure the cable's survival in an accident. For this, reliability studies should be undertaken to develop confidence on the threshold parameter.

- CM techniques should be identified that can detect hot spots in a plant's environment, so that appropriate measures can be taken to minimize their effects on the degradation of cables.

Environmental Qualification of Cables

Based on results presented in this literature review of published studies worldwide, the jacket and the insulation materials of low-voltage safety-related electric cables can lose their entire tensile properties, specifically elongation-at-break, after they are exposed, respectively, to total integrated doses (TIDs) of 50 Mrad of aging and 150 Mrad accident dose in a reactor environment. The qualification of most cables uses testing for a total dose of 200 Mrad first in a sequential method before they can be exposed to steam/chemical spray environment simulating an accident. Therefore, some cables which passed this qualification must have completely embrittled (i.e., zero elongation value) insulation/jacket materials by the end of the accident radiation exposure. Unfortunately, no qualification data on elongation of these cable polymers is available. However, all cables passed the insulation resistance (IR) tests indicating no gross failures or cracks in the insulating system. At least in the few reports available on early cable qualification tests, no voltage withstand test on a 20 times cable diameter mandrel was performed as required by IEEE Std 383-1974. Typically, cable specimens originally mounted on 20 times cable diameter mandrels during pre-aging and accident radiation exposure were directly taken into the steam chamber for steam/chemical spray test.

Furthermore, the tensile properties of embrittled cables without cracks or defects in the insulation materials can improve when exposed to steam. Although there were indications of lowering IR values during the steam test, no appreciable change in this electrical property was noted when the cables were dried after exposure. Almost all cables passed the voltage withstand test on a 40 times cable diameter mandrel after the LOCA test, since the water from the steam acted as a plasticizer, improving the tensile properties of embrittled cable insulations, and thus, providing the necessary flexibility for the mandrel bend. If this scenario is true, then cables now in service in nuclear power plant have the characteristics presented here. Therefore, concerns on various aging and accident simulation methods can be of no significance if the end point of all cables tested is governed by zero elongation-at-break before exposing cables to thermodynamic conditions. The key to maintaining the safety and reliability of the reactor for a safe operation and survival during a design-basis accident is that the embrittled cables are not subject to any mechanical abuse to cause cracks or damages which can be detrimental to their electrical performance.

The limited published data supports the fact that the total normal radiation dose of 10 Mrad (excluding hot spots) during a 40-year design life and another 15-20 Mrad of accident dose (as found in TMI) are more realistic values to which cables in a nuclear power plant can be exposed. The EQ radiation source term in the EQ risk-scoping study (Ref. 7.9) gives a total accident dose of 15 Mrad gamma accident exposure for cables installed in conduits. Cables without shielding could experience larger doses (the report does not mention any quantitative value). Also, depending on the location inside the containment these unshielded cables can be exposed to beta radiation (A typical one year beta dose could be approximately 220 Mrad. Note that the effect of beta radiation are limited to near the surface of insulation or the cable jackets. Metal is a very effective shield for beta radiation, and for cables inside conduits beta effects are not important). At this low dose level of gamma radiation, exposure of neither the jackets nor the insulations could reduce their tensile properties completely, thus assuring their physical integrity, and hence, their electrical reliability. An effective condition monitoring method can provide the necessary assurance on the physical condition of cable's jacket and insulation materials and therefore, can enhance the safety and reliability of this class of cables in nuclear power plants.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT *(200 words or less)*

This report summarizes the findings from a review of published documents dealing with research on the environmental qualification of safety-related electric cables used in nuclear power plants. Simulations of accelerated aging and accident conditions are important considerations in qualifying the cables. Significant research in these two areas has been performed in the United States and abroad. The results from studies in France, Germany, and Japan are described in this report. In recent years, the development of methods to monitor the condition of cables has received special attention. Tests involving chemical and physical examination of cable's insulation and jacket materials, and electrical measurements of the insulation properties of cables are discussed. Although there have been significant advances in many areas, there is no single method which can provide the necessary information about the condition of a cable currently in service. However, it is possible that further research may identify a combination of several methods that can adequately characterize the cable's condition.

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