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Literature Review of Environmental Qualification of Safety-Related Electric Cables

Summary of Past Work

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Prepared for
U.S. Nuclear Regulatory Commission

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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 Background

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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1.3 "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," IEEE Std 323-1974.

1.4 "Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Generating Stations," IEEE Std 383-1974.

1.5 "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants," NRC Regulatory Guide 1.89, Rev.1, 1984.

1.6 "Environmental Qualification of Electric Equipment Important to Safety for Nuclear Power Plants," Code of Federal Regulations, Title 10, Part 50.49, 1983.

1.7 "Guidelines for Evaluating Environmental Qualification of Class 1E Electrical Equipment in Operating Reactors," U.S. NRC Inspection and Enforcement Bulletin No. 79-01B, Attachment 4, 1979.

1.8 "Interim Staff Position on Environmental Qualification of Safety-Related Electrical Equipment," U.S. NRC NUREG-0588, 1981.

1.9 "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Section 3.10 and Section 3.11, U.S. NRC NUREG-0800, 1981.

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1.11 "Environmental Qualification of Electric Equipment," U.S. NRC RES Program Plan, EQPLAN-5.3, 1994.

1.12 Jacobus, M.J., "Aging, Condition Monitoring, and Loss-of-Coolant-Accident (LOCA) Tests of Class 1E Electrical Cables: Crosslinked Polyolefin Cables," NUREG/CR-5772, SAND91-1766/1, Vol.1, 1992.

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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.

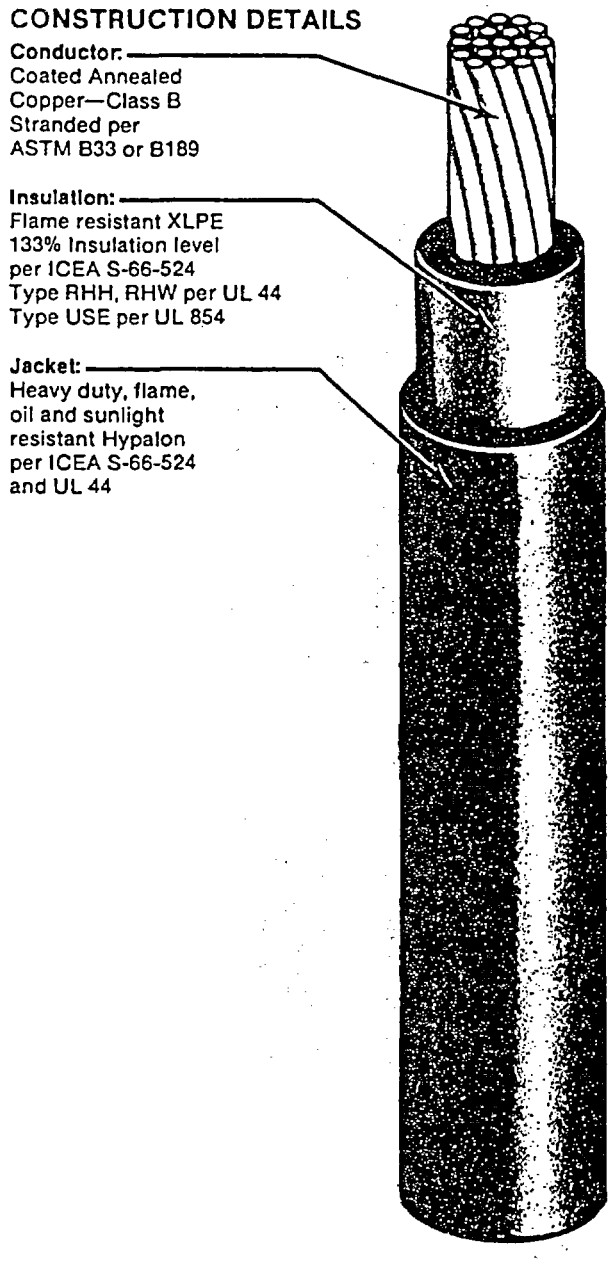
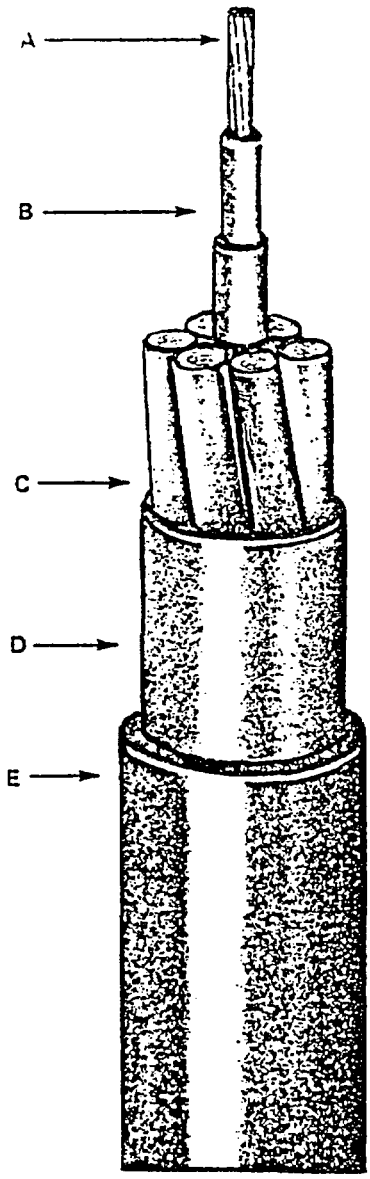
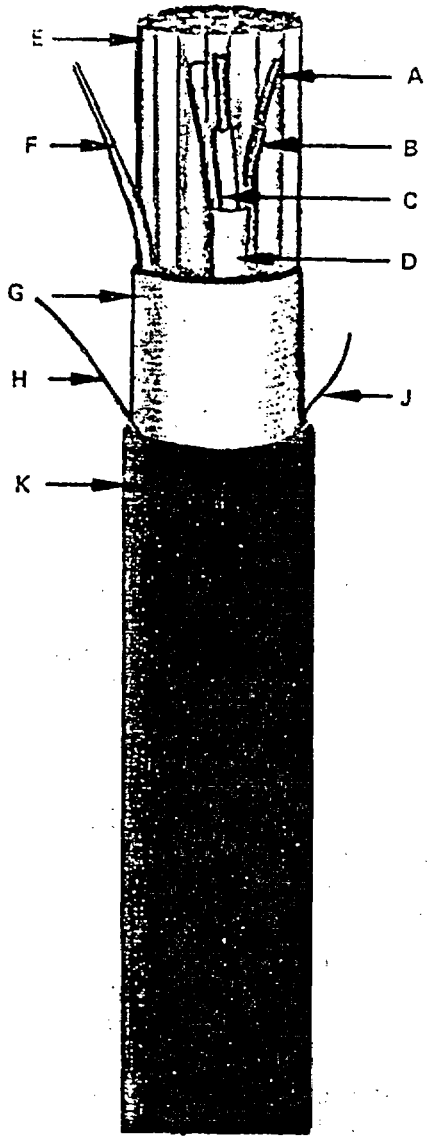


Figure 2.1 Low-voltage power cable (Ref. 2.1)



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)

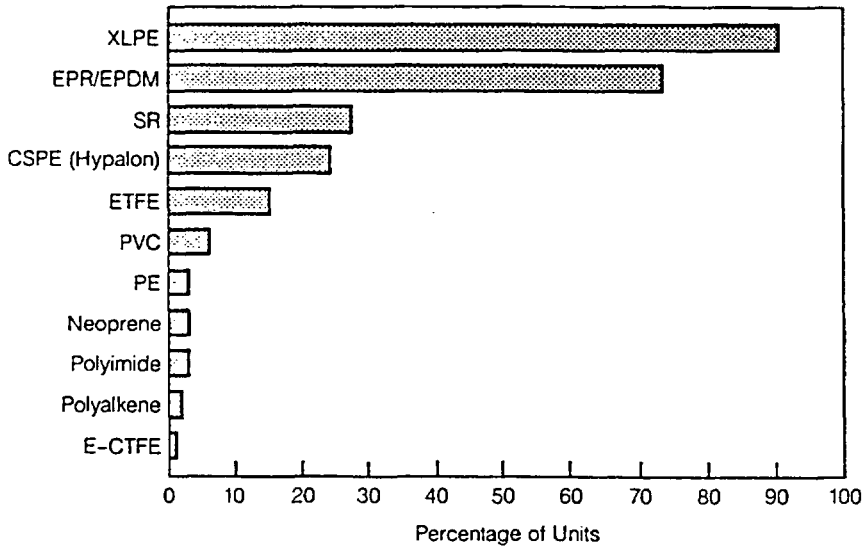


Figure 2.4 Cable-insulating and jacket materials inside containments of U.S. nuclear plants (Ref.2.5)

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.

2.5 References

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2.7 "Physical Independence of Electric Systems," NRC Regulatory Guide 1.75, Rev. 2, 1978.

2.8 "EQDB - Equipment Qualification Data Bank," NUS under EPRI Sponsorship, BNL Contract with NUS/EPRI, 1994.

2.9 "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report; Revision 1," EPRI TR-103841, 1994.

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

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

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).

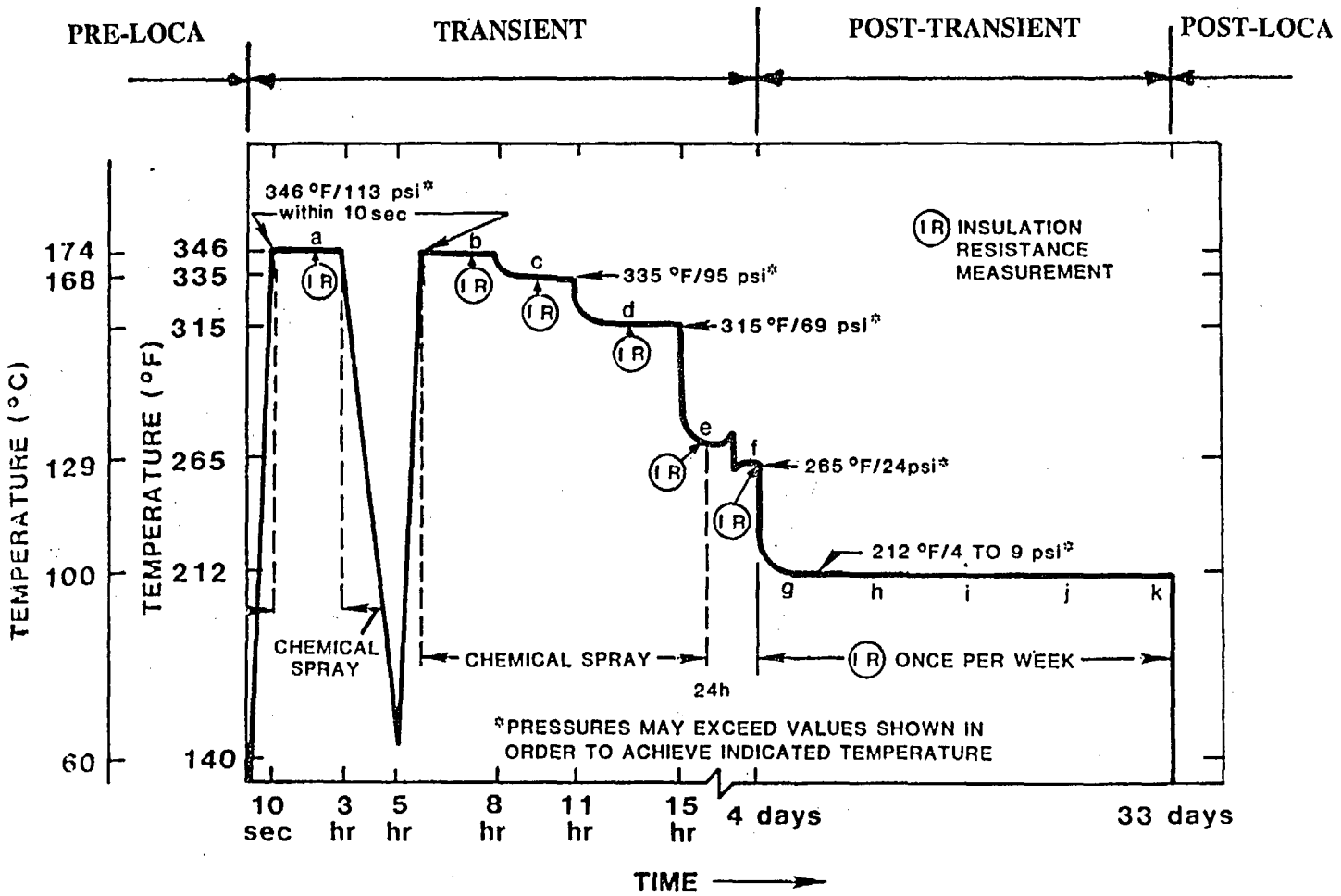

Figure 3.1 Typical temperature/pressure profile used in early steam/chemical spray exposure tests (Ref. 3.12)

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 $\pm 10\%$ (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

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.)	NORMAL/ABNORMAL ENVIRONMENT DATA	Normal/ Design / Abnormal/ Hot spots -Temperature X X -Radiation X X -Humidity X X -Fluid Leaks n/a X	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.	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.	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.
	ACCIDENT ENVIRONMENT DATA	-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)	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.	Wide variations in defining accident conditions may need a closer evaluation against the actual plant data.	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.
	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	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. VI FT IR MB HP TP SM Baseline x x x x x x x Pre-aging x x x x Dur Aging x x x x Post-aging x x x x x x x Dur LOCAx x x Dur PostL x x x x FINAL x x x x x x x	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).	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.	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

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.

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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 11 days 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.

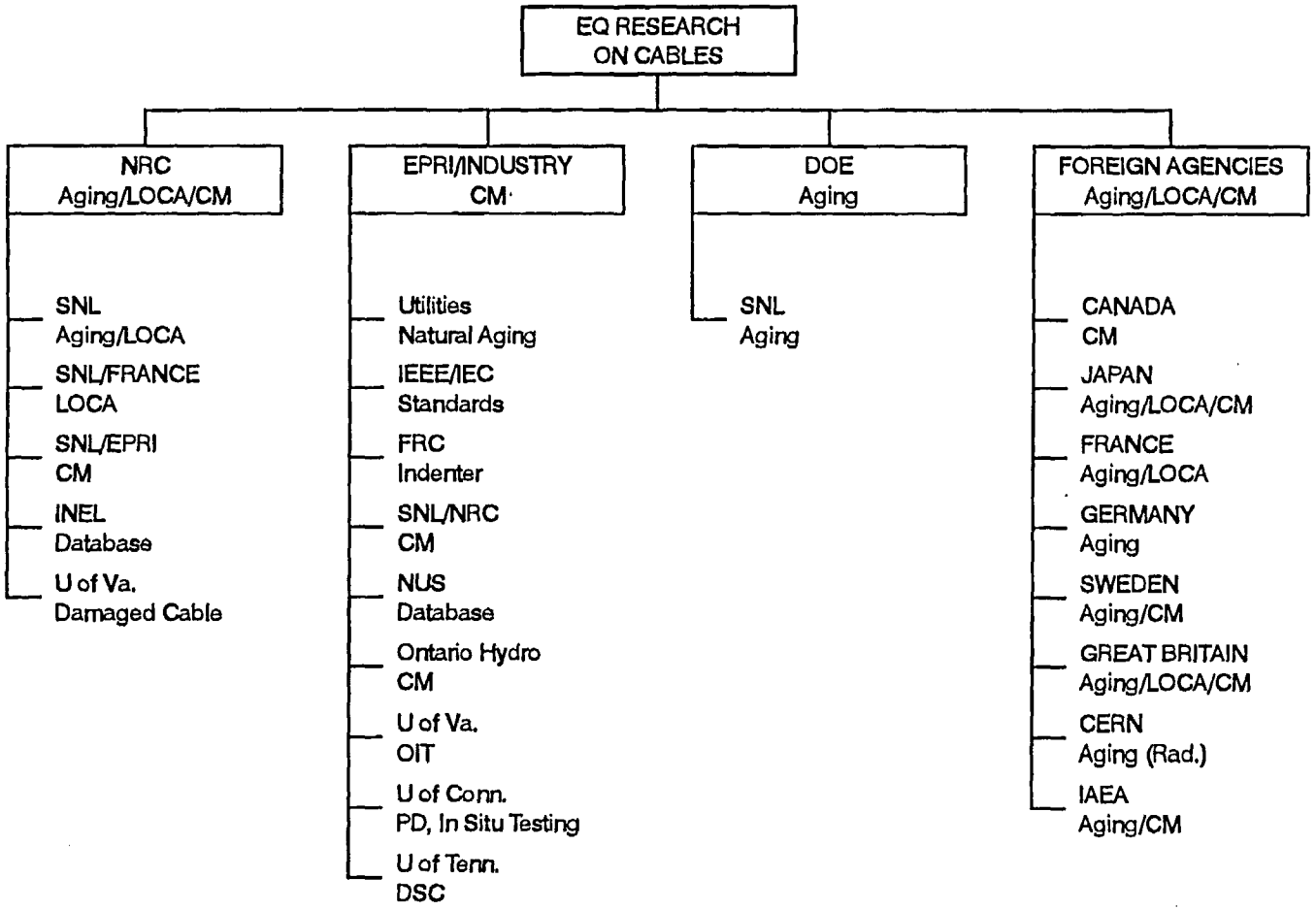

Figure 3.2 EQ research on cables

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)

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)

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 4×10^{-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 $\pm 0.3\%$ (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.

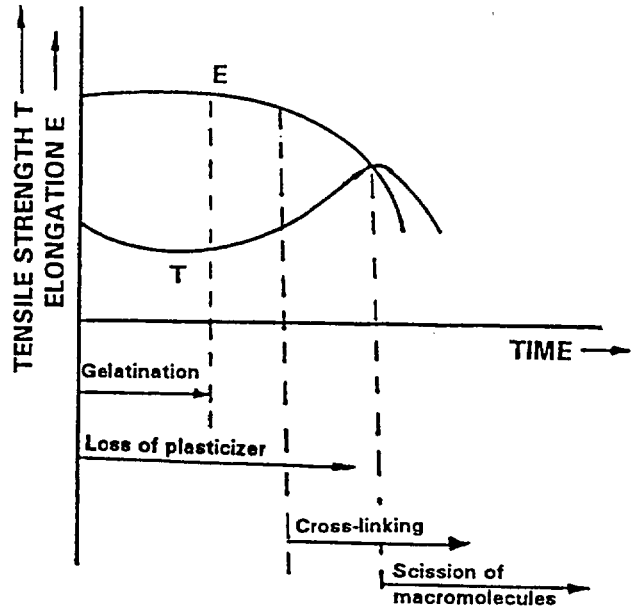

Figure 4.1 Changes of tensile strength and elongation during aging of PVC (Ref.4.29)

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 ($=8.167 \times 10^{-5}$ 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.

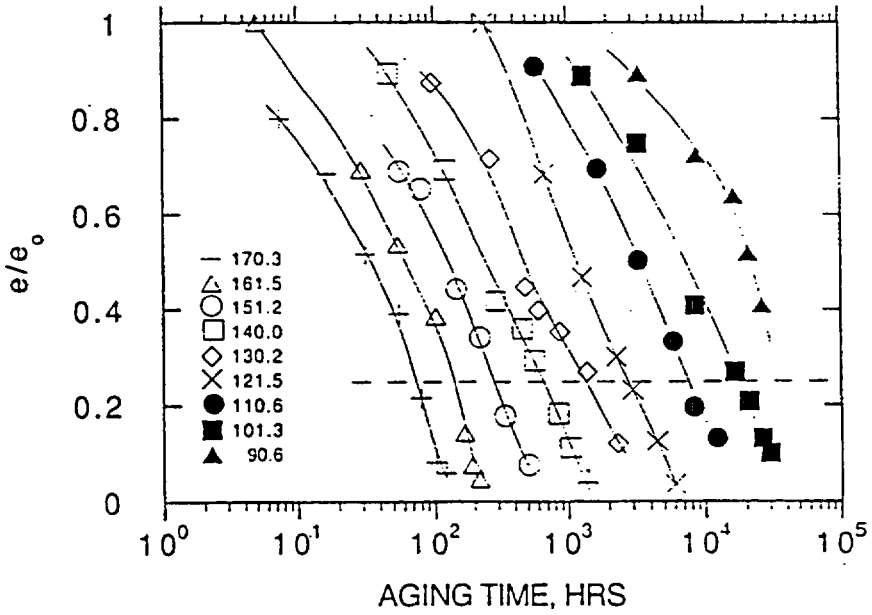

Figure 4.2 Ultimate tensile elongation versus aging time in air for CLPO-A (Ref. 4.31)

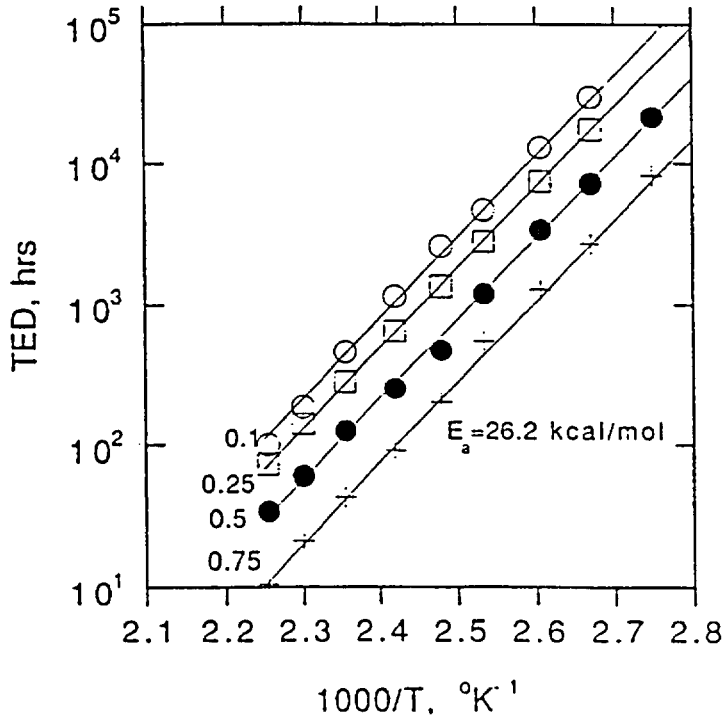

Figure 4.3 Arrhenius plot for thermal aging data for CLPO-A (Ref. 4.31)

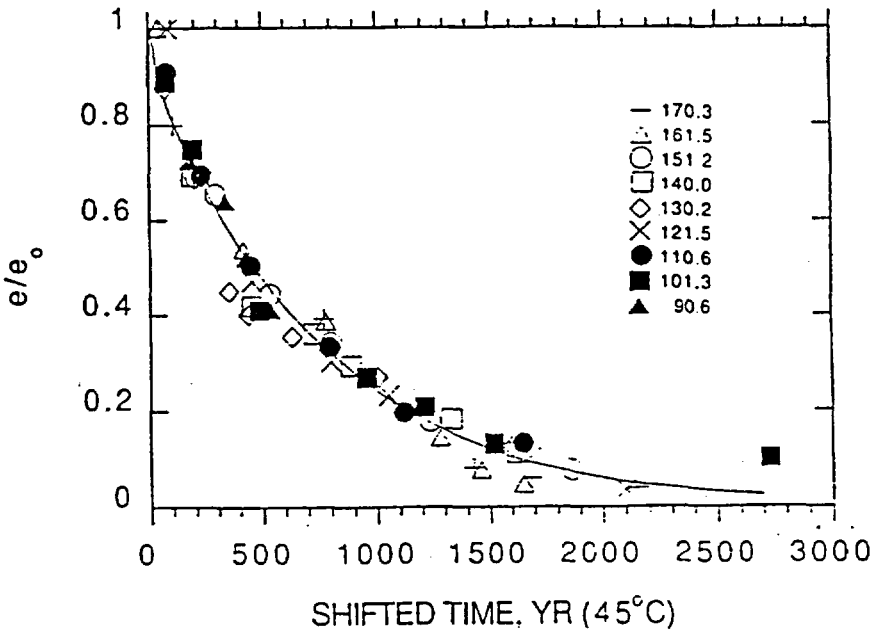

Figure 4.4 Time-temperature superposition at 45°C for CLPO-A from Fig. 4.1 (Ref.4.31)

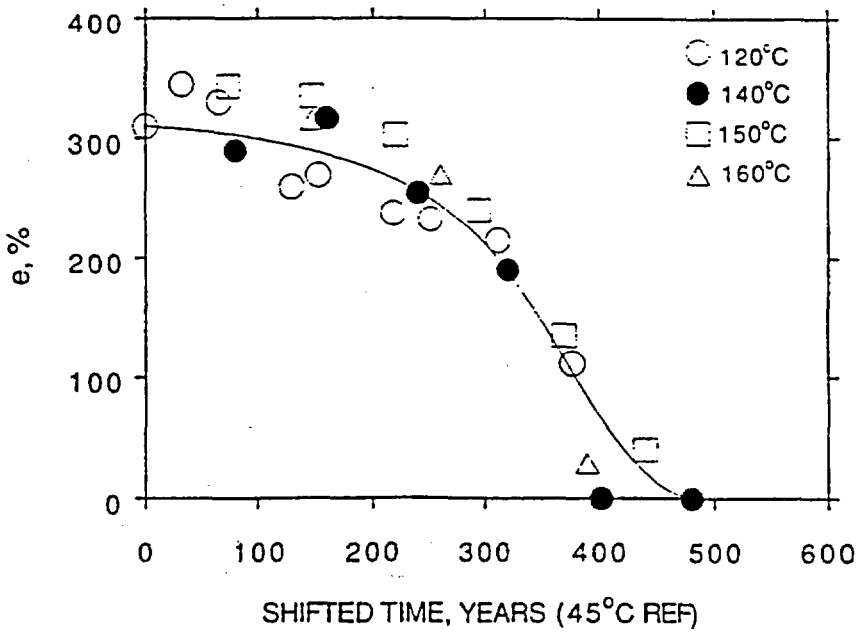

Figure 4.5 Time-temperature superposition at 45°C for CLPO-B (E_a=21 kcal/mol) (Ref. 4.31)

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).

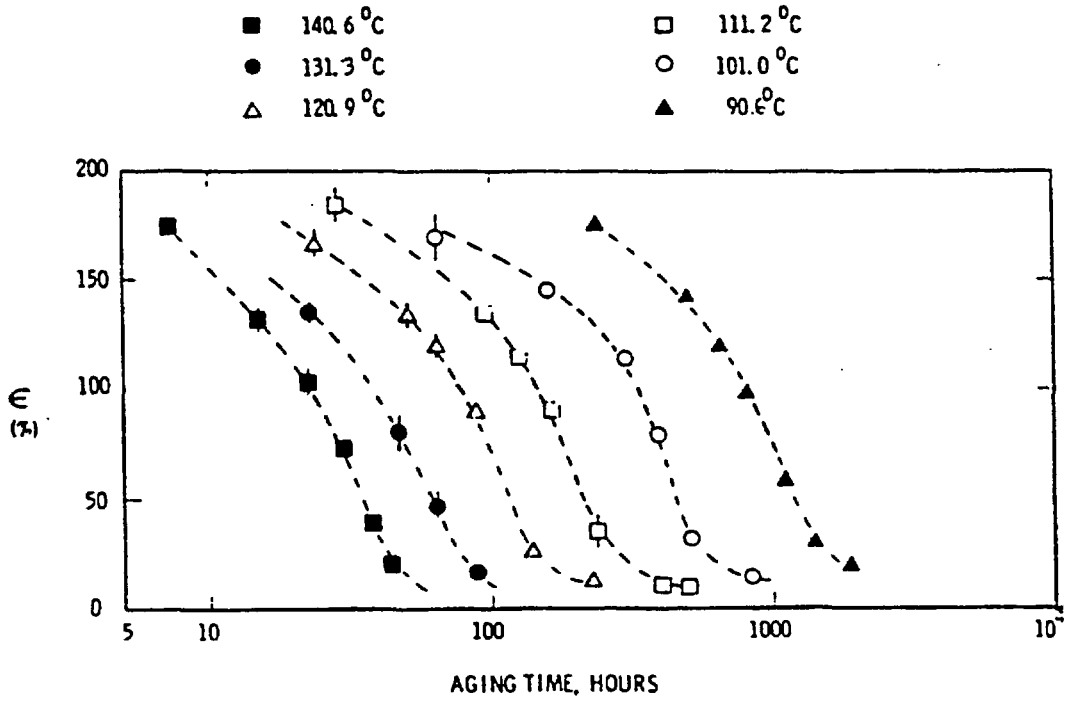

Figure 4.6 Ultimate tensile elongation versus aging time for chloroprene (Ref.4.33)

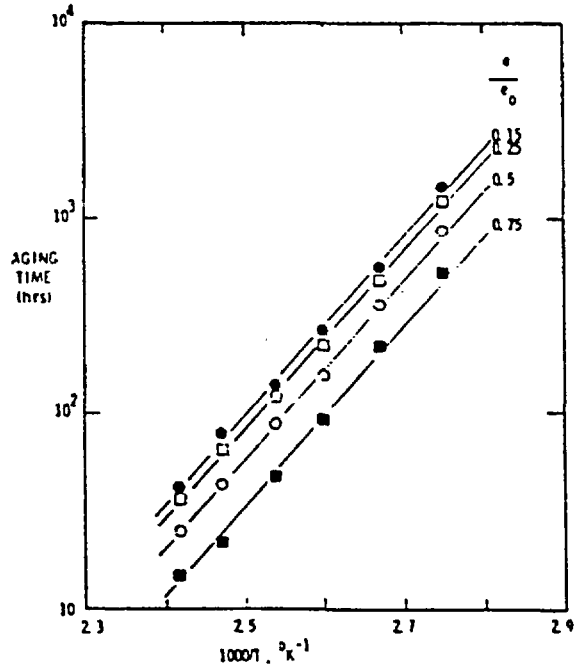

Figure 4.7 Arrhenius plot for chloroprene data (Ref. 4.33)

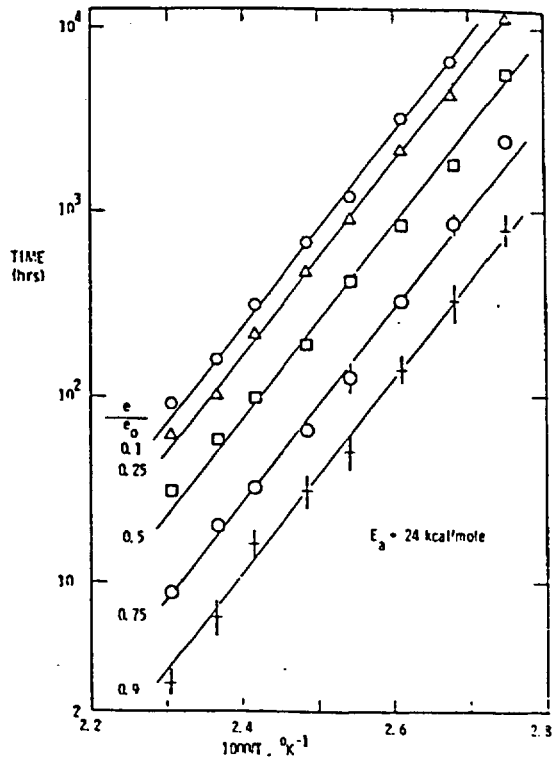

Figure 4.8 Arrhenius plots for Hypalon (Ref. 4.35)

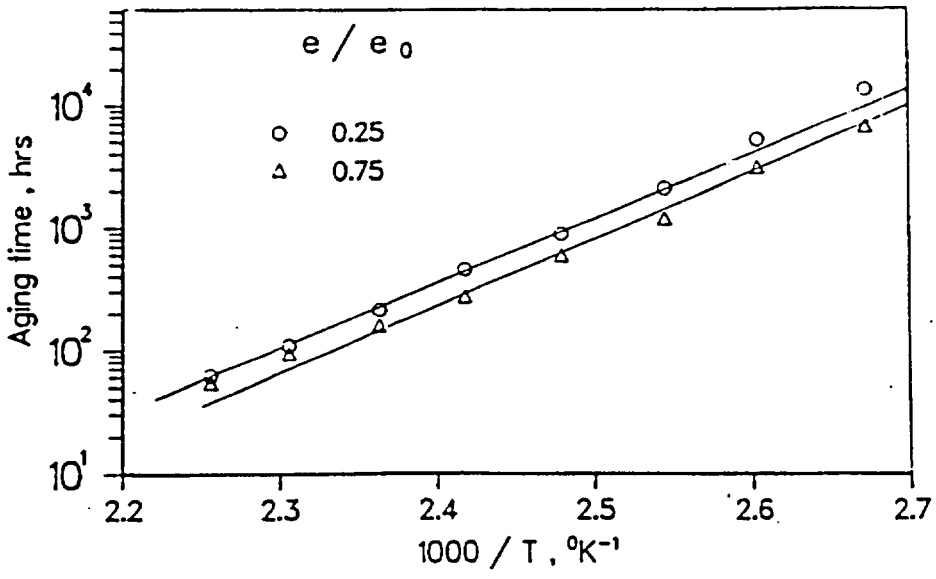

Figure 4.9 Arrhenius plots for thermal aging on EPR (Ref. 4.36)

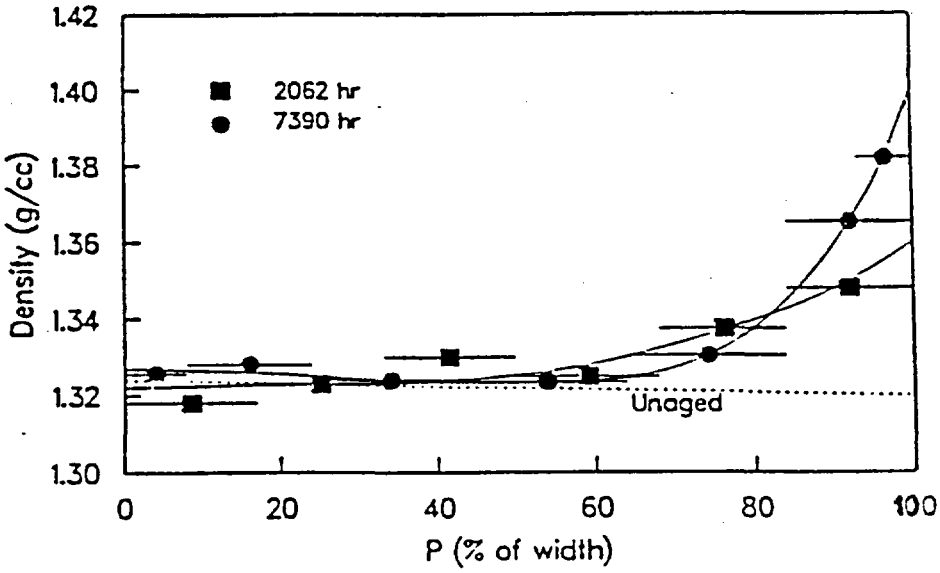

Figure 4.10 Density profiles for EPR heat-aged at 100°C (Ref.4.37)

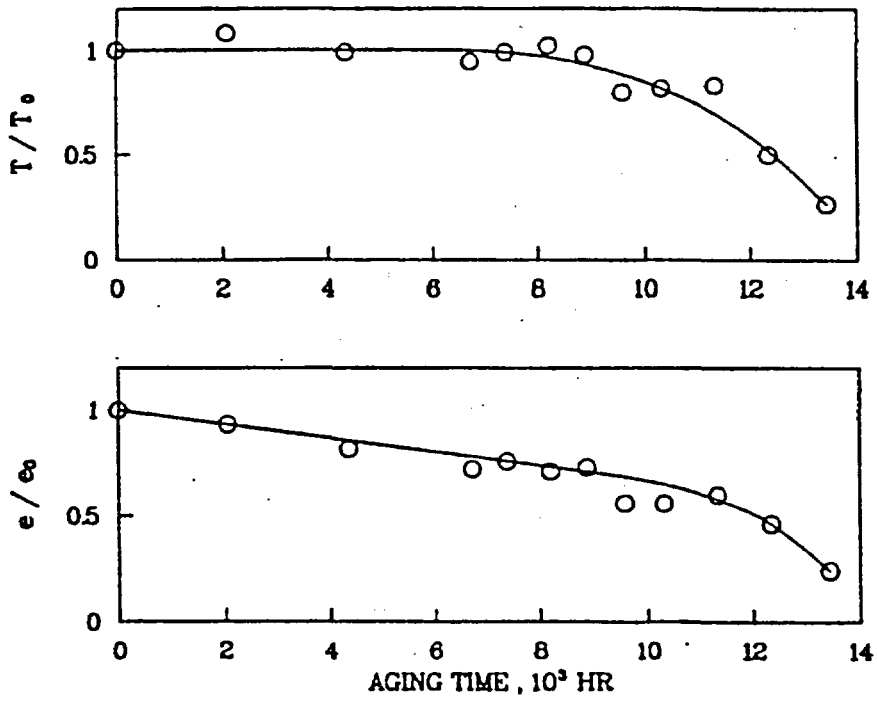

Figure 4.11 Changes in mechanical properties after heat-aging at 100°C for EPR (Ref. 4.37)

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.

[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.

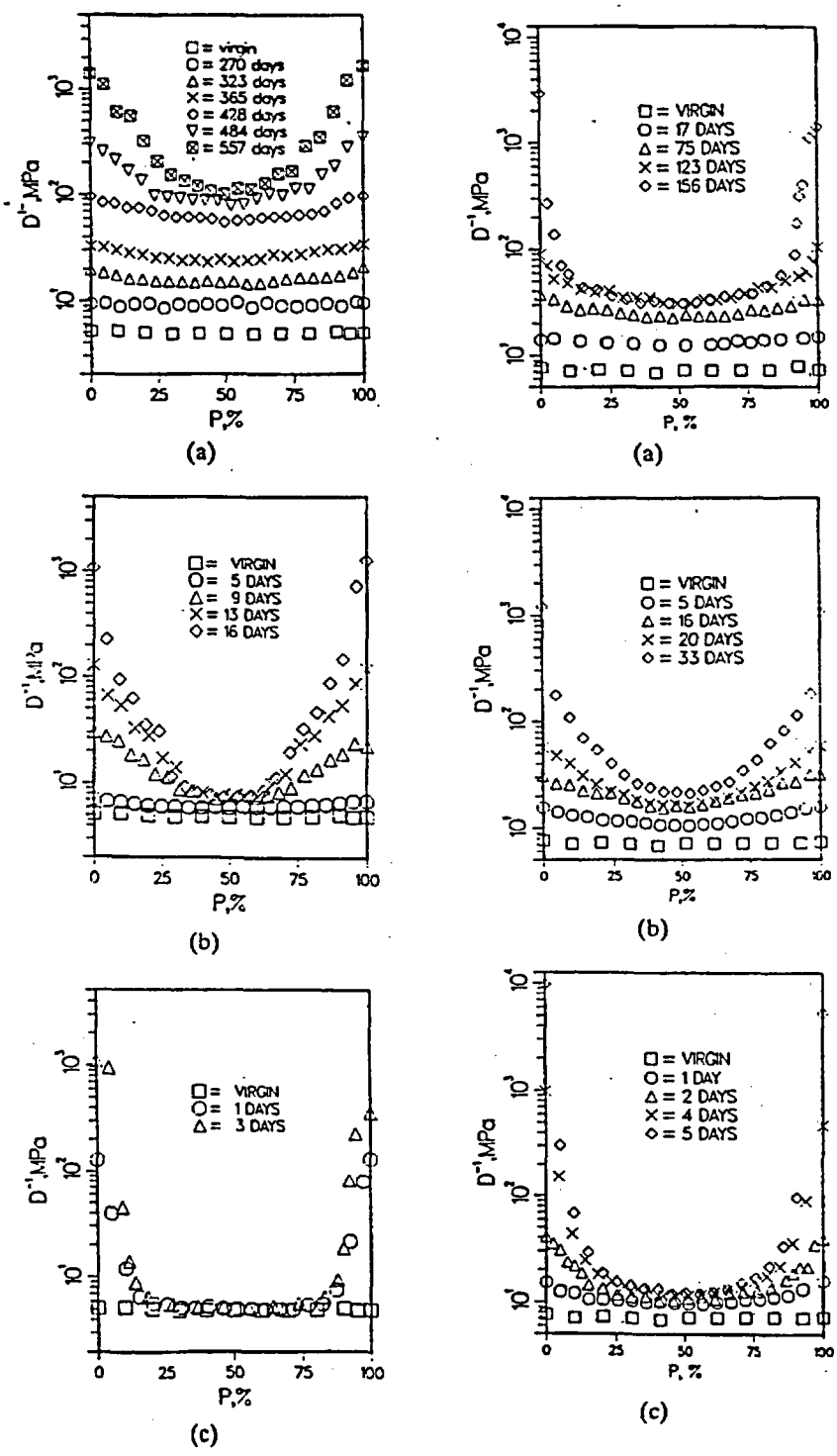

Figure 4.12 Modulus profiles for 2.2-mm thick samples of SBR (left) and NR (right) following thermal aging in air. (a)100°C; (b) 120°C; (c) 150°C. P=percentage of distance from one air-exposed surface to opposite air-exposed surface. (Ref. 4.28)

Reprinted from Polymer Degradation and Stability, Vol. 38, R.L. Clough and K.T. Gillen, *Oxygen Diffusion Effects in Thermally Aged Elastomers,* pp. 47-56, © 1992, with kind permission from Elsevier Science Ltd., The Boulevard, Langford Lane, Kidlington OX5 1GB, U.K.

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 limited 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.

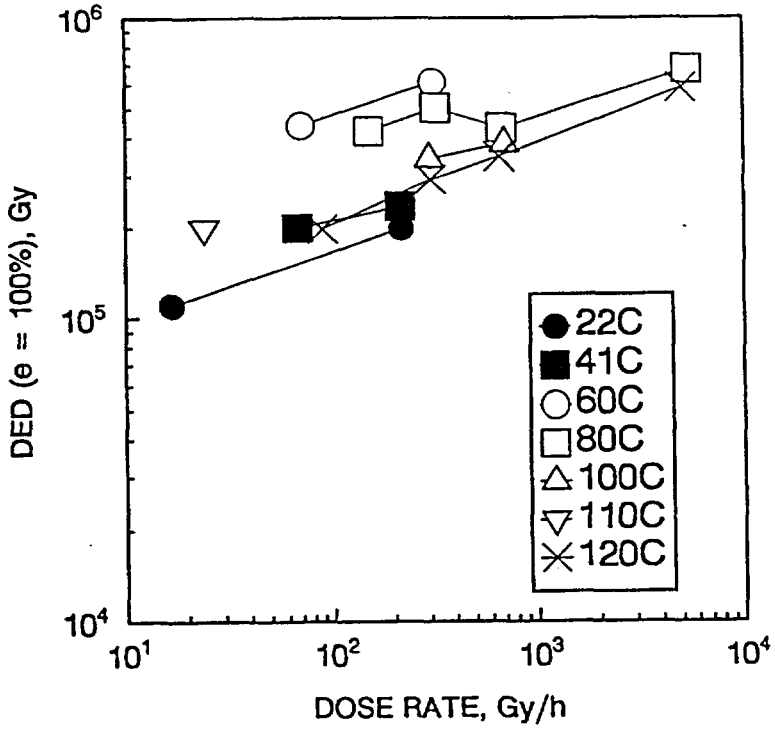

Figure 4.13 Radiation Dose required for elongation-at-break to 100% versus dose rate and temperature (Ref. 4.41)
Reprinted with permission from Dr. Kenneth T. Gillen, Sandia National Laboratory, Albuquerque, NM.

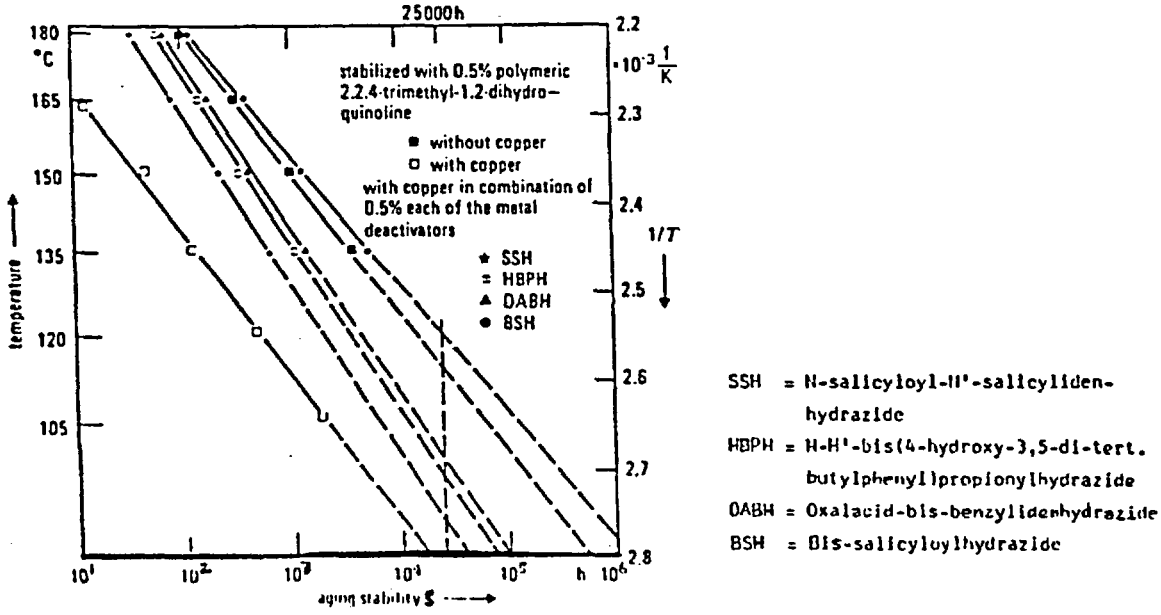

Figure 4.14 Comparison of temperature-dependence of XLPE in presence of copper (Ref. 4.42)
Reprinted with permission from Radiation Physics and Chemistry, Vol. 18, No. 5/6, pp 1217-1225, Kammel, G. and Knoch, G., *Thermal-Oxidative Aging of Radiation-Crosslinked XLPE Insulations in the Presence of Copper Conductor, A New Test Method and Results,* 1981, Elsevier Science Ltd., Oxford, England.

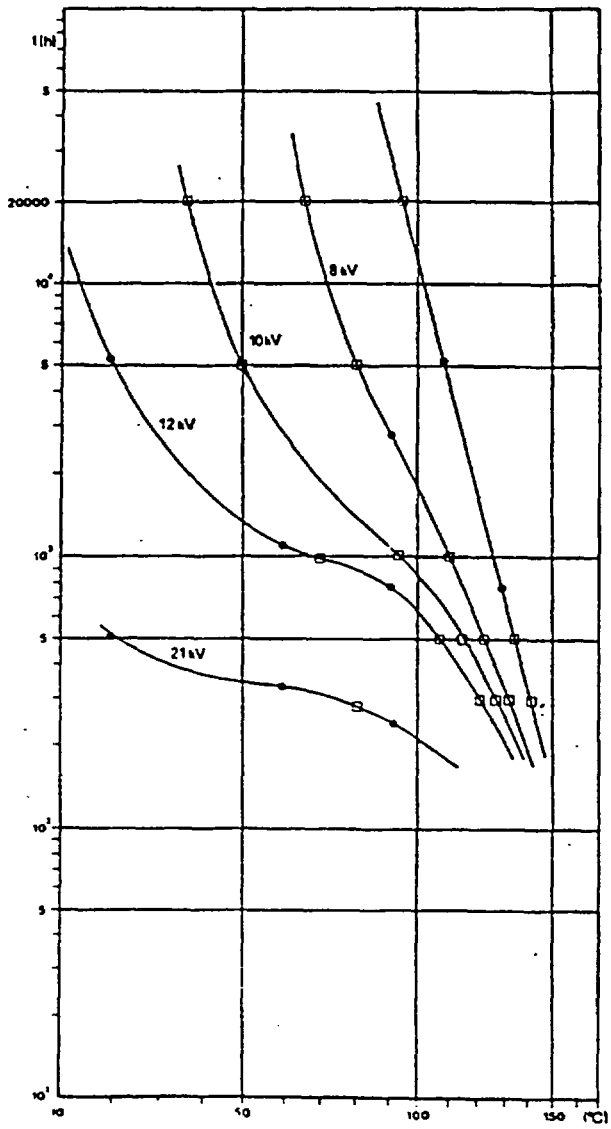

Figure 4.15 Thermal life curves at constant voltage for an XLPE (Ref. 4.43)
Reproduced with permission from Prof. G.C. Montanari, Italy.

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.

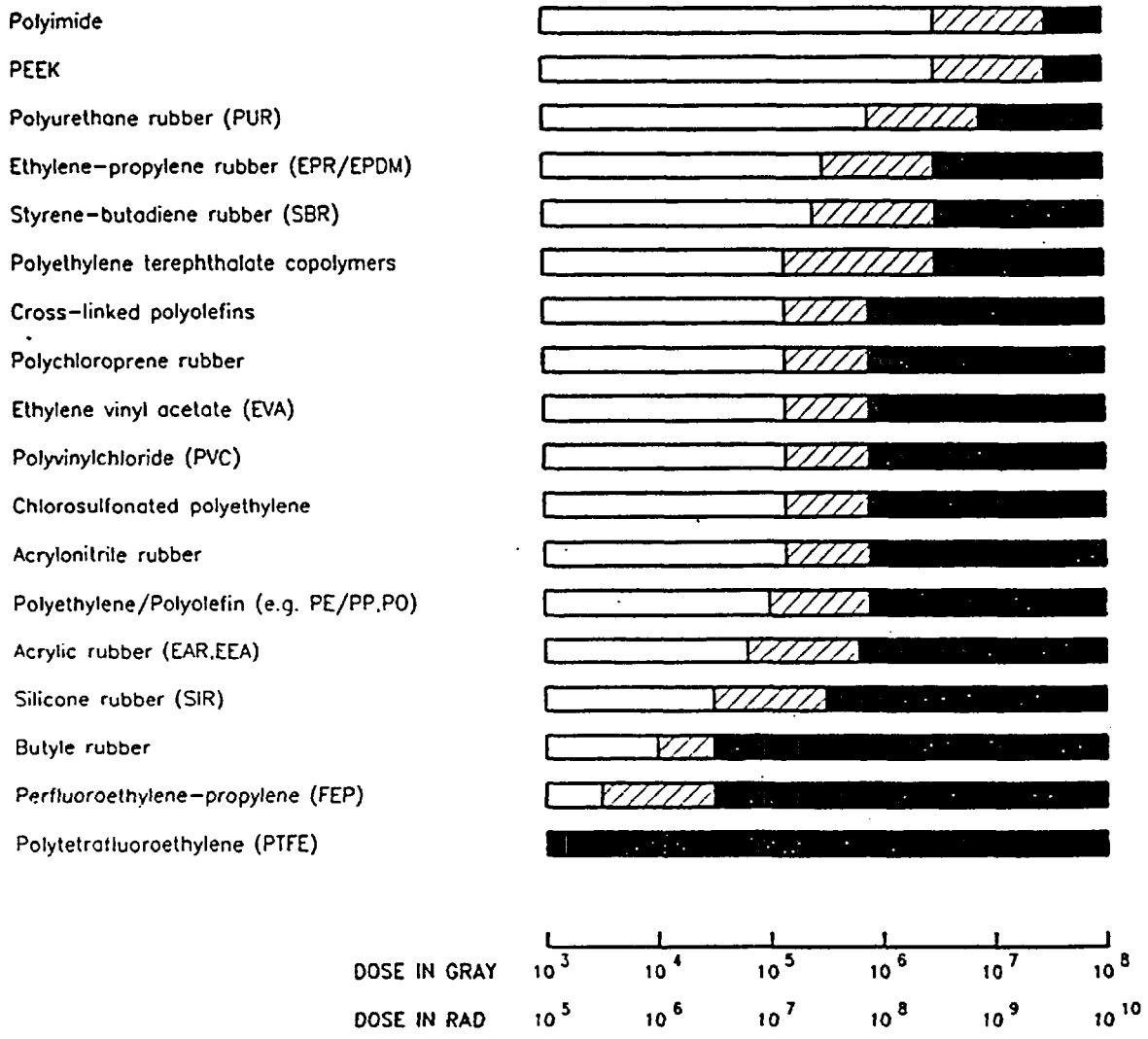

Figure 4.16 Classification of materials according to their radiation resistance (Ref. 4.4)
Reproduced with permission from Dr. Helmut Schonbacher, CERN, Switzerland.

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.

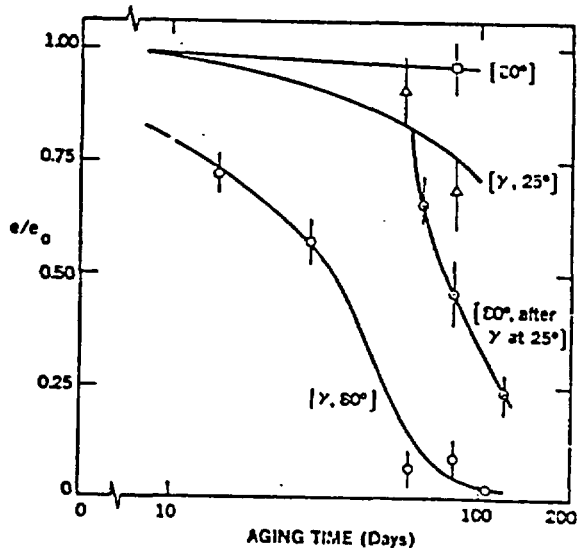

Figure 4.17 Aging of PE in various environments (Ref. 4.60)

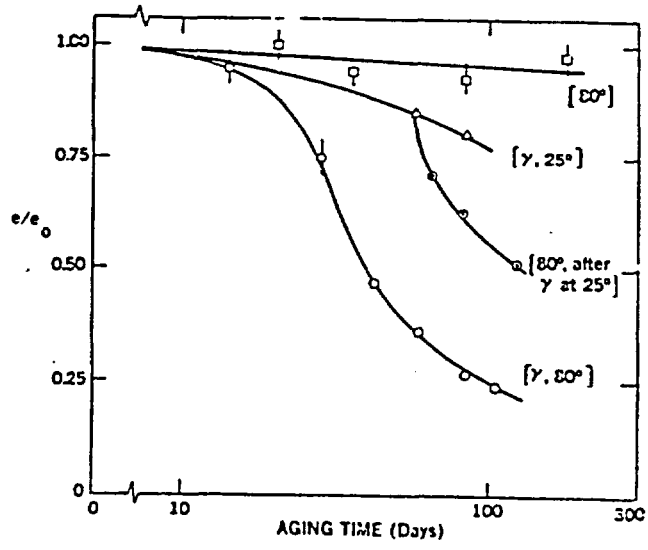

Figure 4.18 Aging of PVC in various environments (Ref. 4.60)

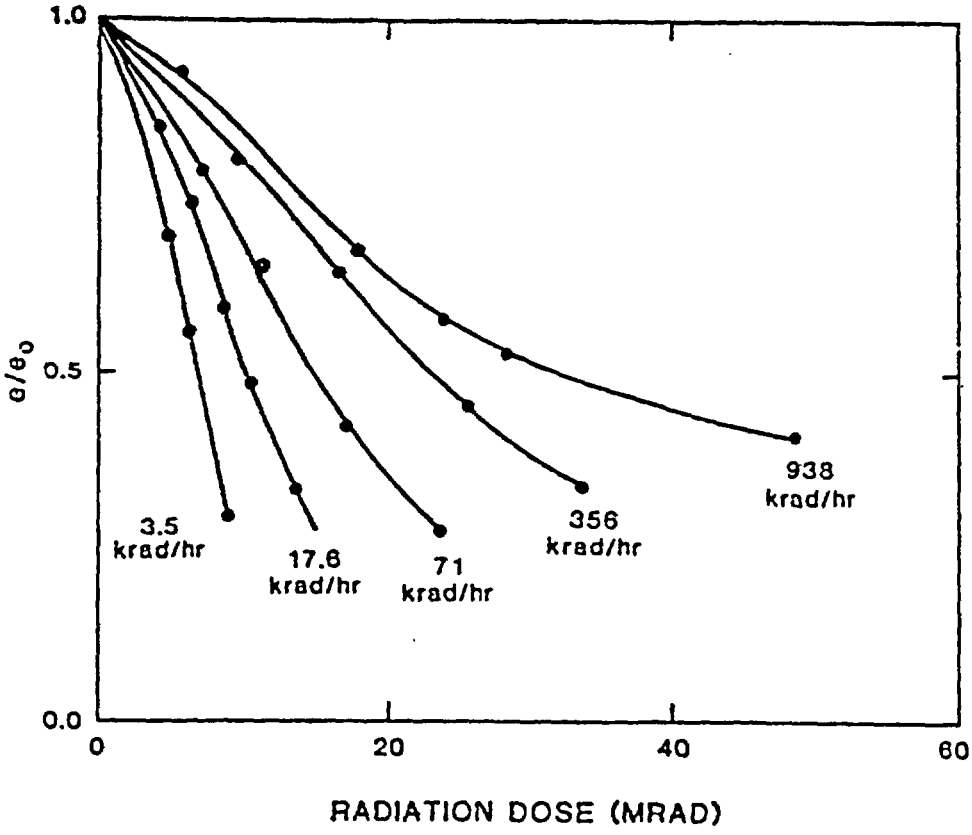

Figure 4.19 Aging of PVC at 60°C at a series of radiation dose rates (Ref. 4.60)

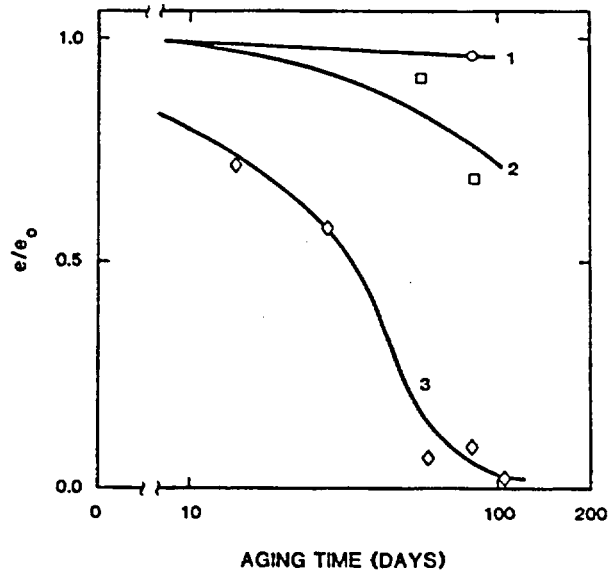

Figure 4.20 Tensile elongation for PE for (1) 80°C; (2) radiation 5 krad/hr at 25°C; (3) radiation 5 krad/hr at 80°C. (Ref. 4.61)

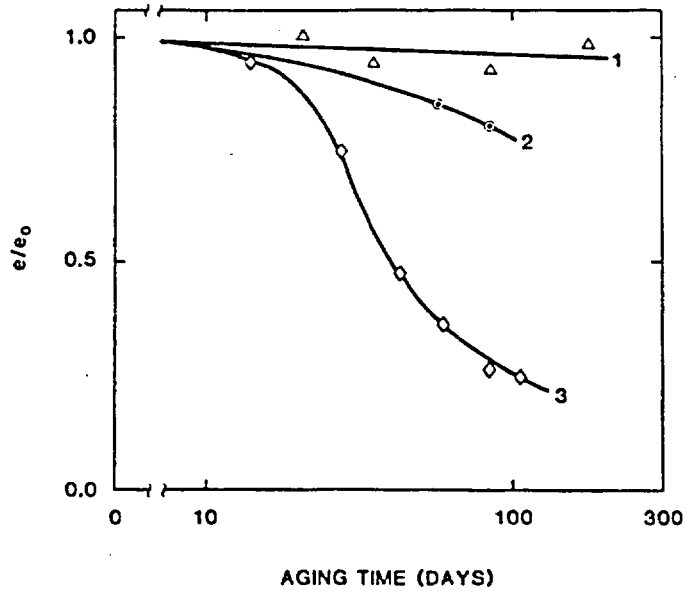

Figure 4.21 Tensile elongation for PVC for (1) 80°C; (2) radiation 4.4 krad/hr at 25°C; (3) radiation 4.4 krad/hr at 80°C. (Ref. 4.61)

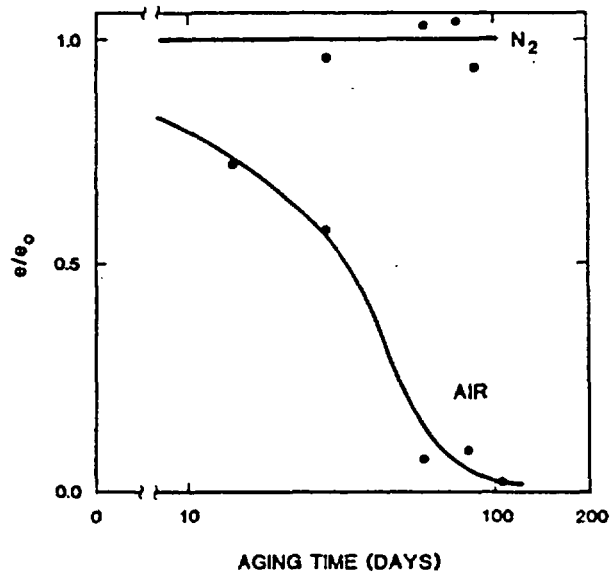

Figure 4.22 Tensile elongation for PE at 5 krad/hr, 80°C in air and nitrogen (Ref. 4.61)

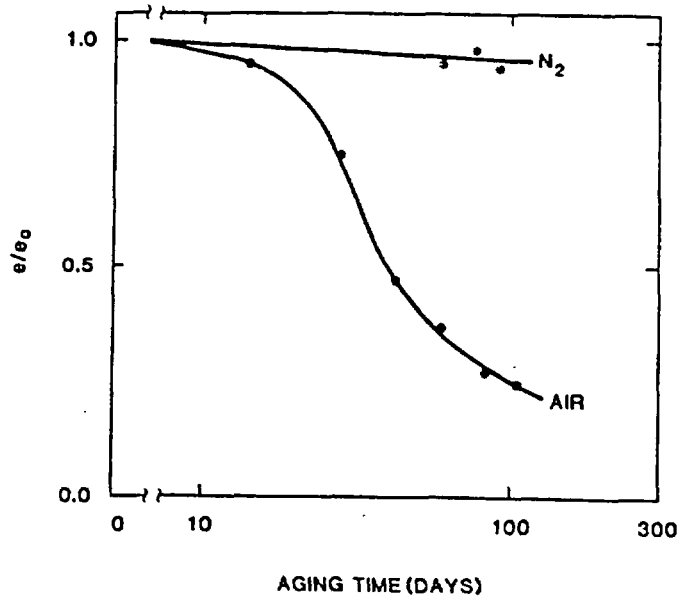

Figure 4.23 Tensile elongation for PVC at 4.4 krad/hr, 80°C in air and nitrogen (Ref.4.61)

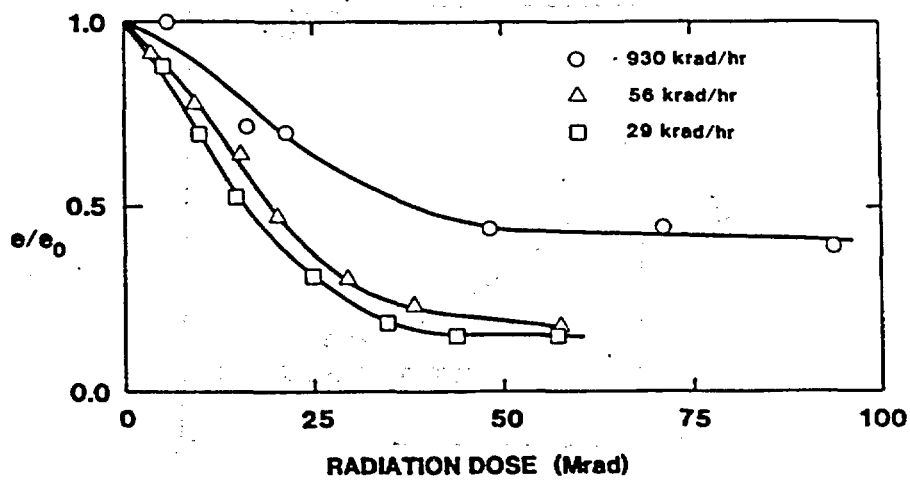

Figure 4.24 Tensile elongation for PVC at 43°C for three different dose rates (Ref. 4.61)

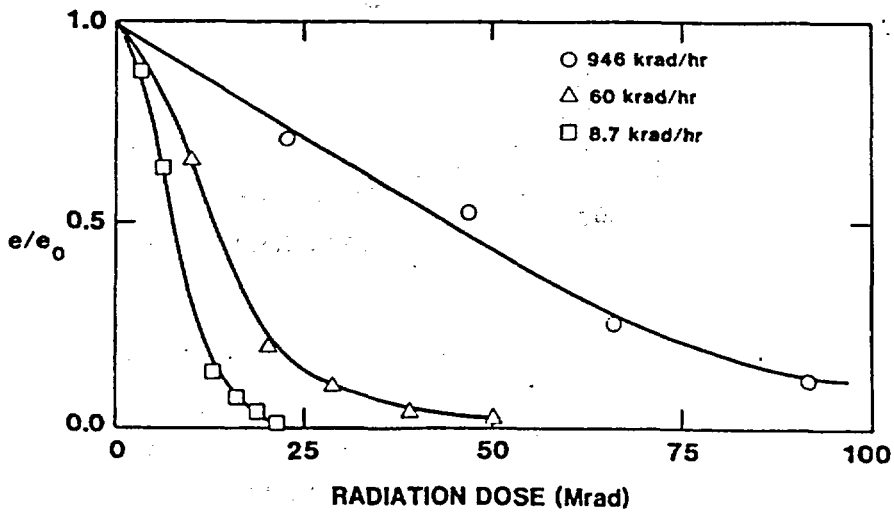

Figure 4.25 Tensile elongation for PE at 43°C for three different dose rates (Ref. 4.61)

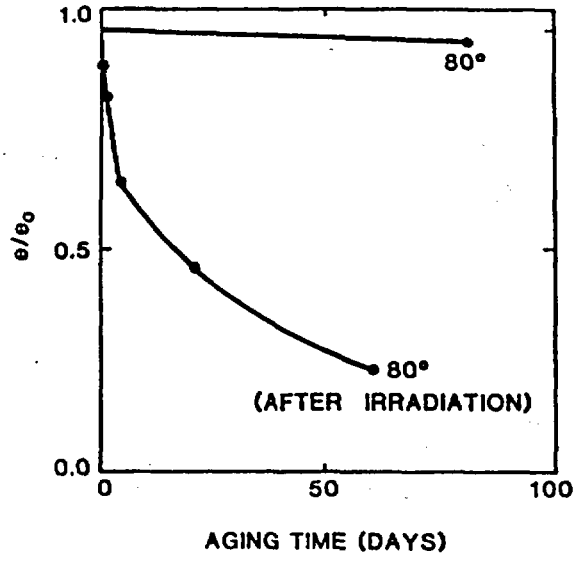

Figure 4.26 Tensile elongation for PE - effect of pre-irradiation at 5 krad/hr at 25°C in air for 83 days (Ref. 4.61)

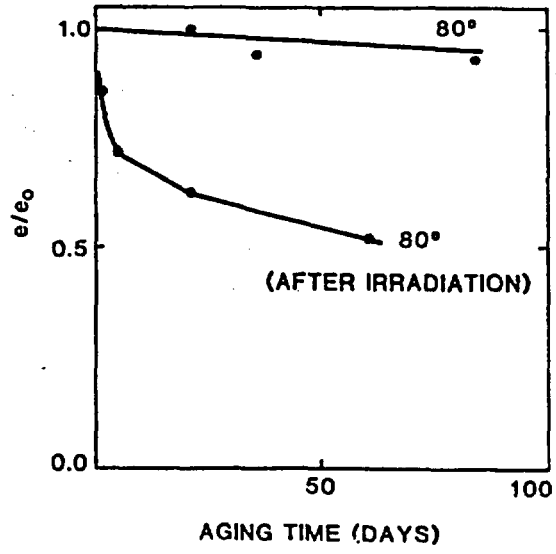

Figure 4.27 Tensile elongation for PVC - effect of pre-irradiation at 4.4 krad/hr at 25°C in air for 83 days (Ref. 4.61)

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.

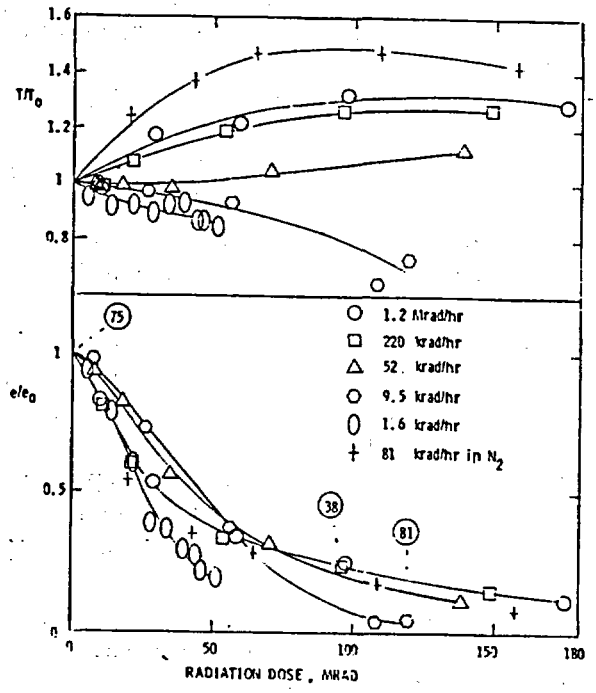

Figure 4.28 Aging of CLPO. Circled numbers indicate swelling ratios. (Ref. 4.63)

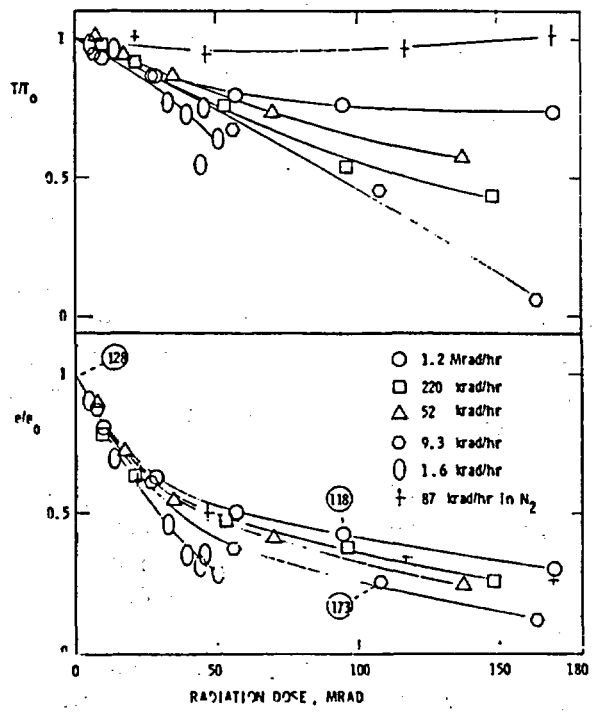

Figure 4.29 Aging of EPR. Circled numbers indicate swelling ratios. (Ref. 4.63)

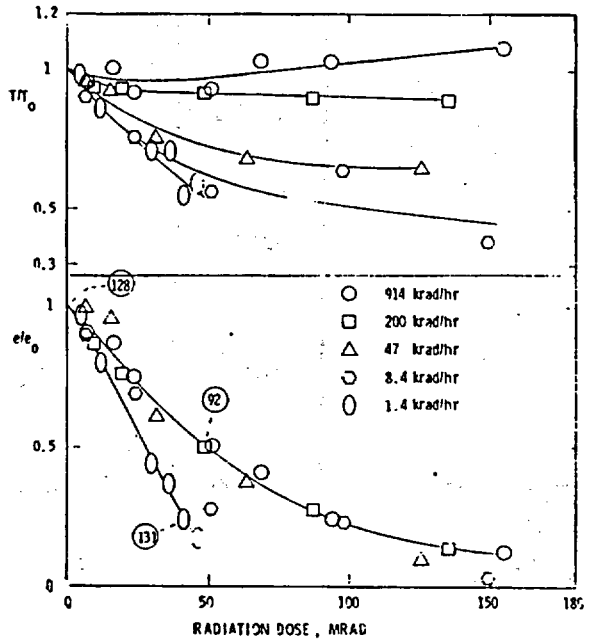

Figure 4.30 Aging of chloroprene. Circled numbers indicate swelling ratios. (Ref. 4.63)

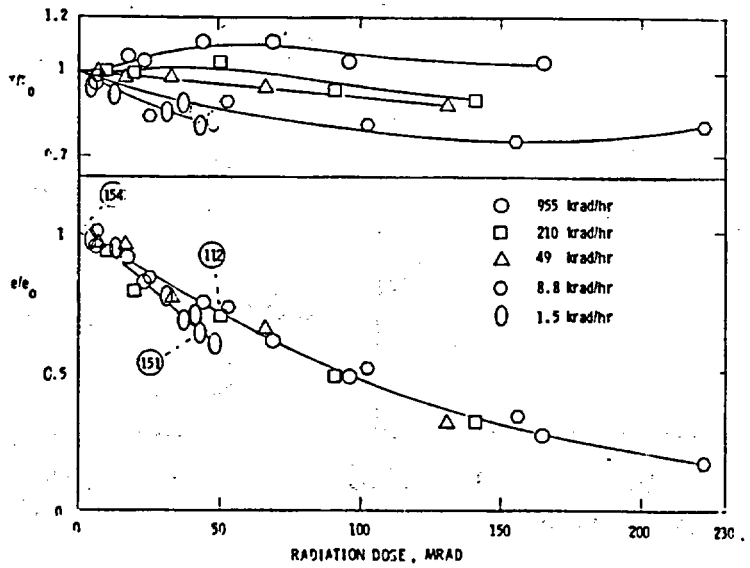

Figure 4.31 Aging of CSPE. Circled numbers indicate swelling ratios. (Ref. 4.63)

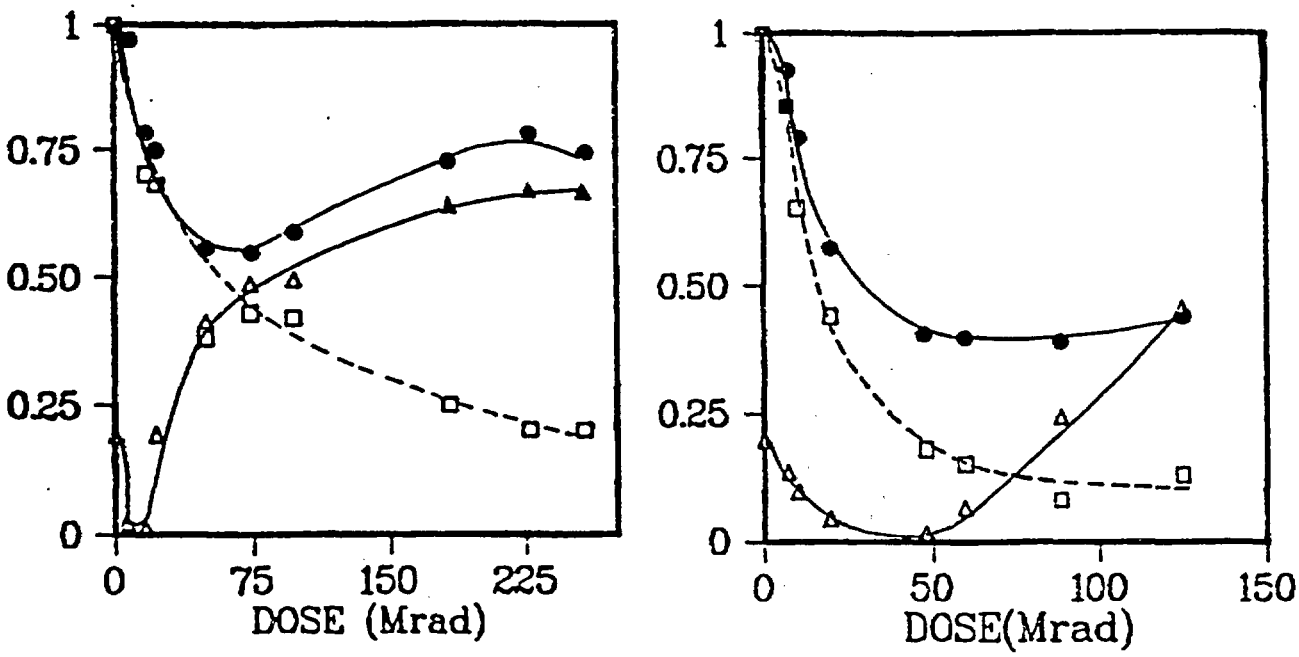

Figure 4.32 Radiation aging of PVC-I at 700 krad/hr (left) and 24 krad/hr (right), 43°C in air. Tensile strength (circles); elongation (squares); nonextractable fraction (triangles) (Ref. 4.64)

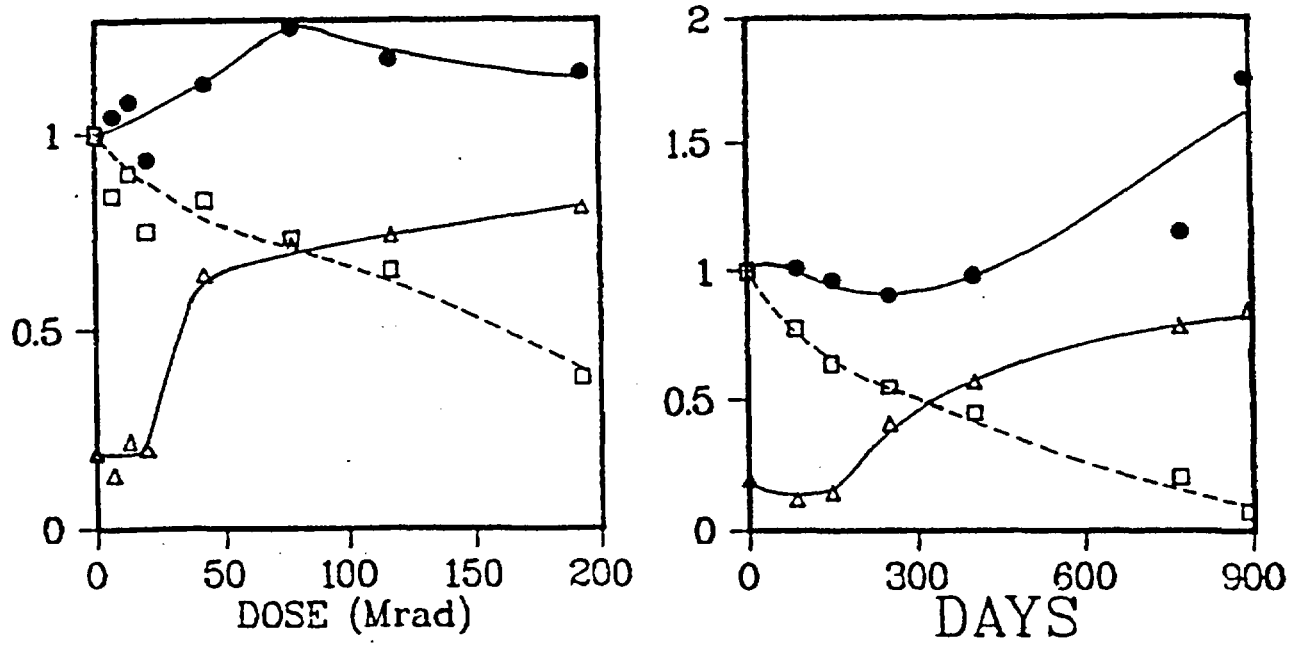

Figure 4.33 PVC-I: Radiation aging at 700 krad/hr in N_2 (left) and thermal aging at 110°C in air. Tensile strength (circles); elongation (squares); nonextractable fraction (triangles) (Ref. 4.64)

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	0.10-0.45
	0.05-0.66	0.016-0.027
XLPE	50	0.15-0.58
	0.06-3.0	0.02-0.13
XLPO	50	0.14-0.24
	0.0264-3.3	0.08-0.20
EP Copolymers	50	0.11-0.52
	0.025-3.0	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.

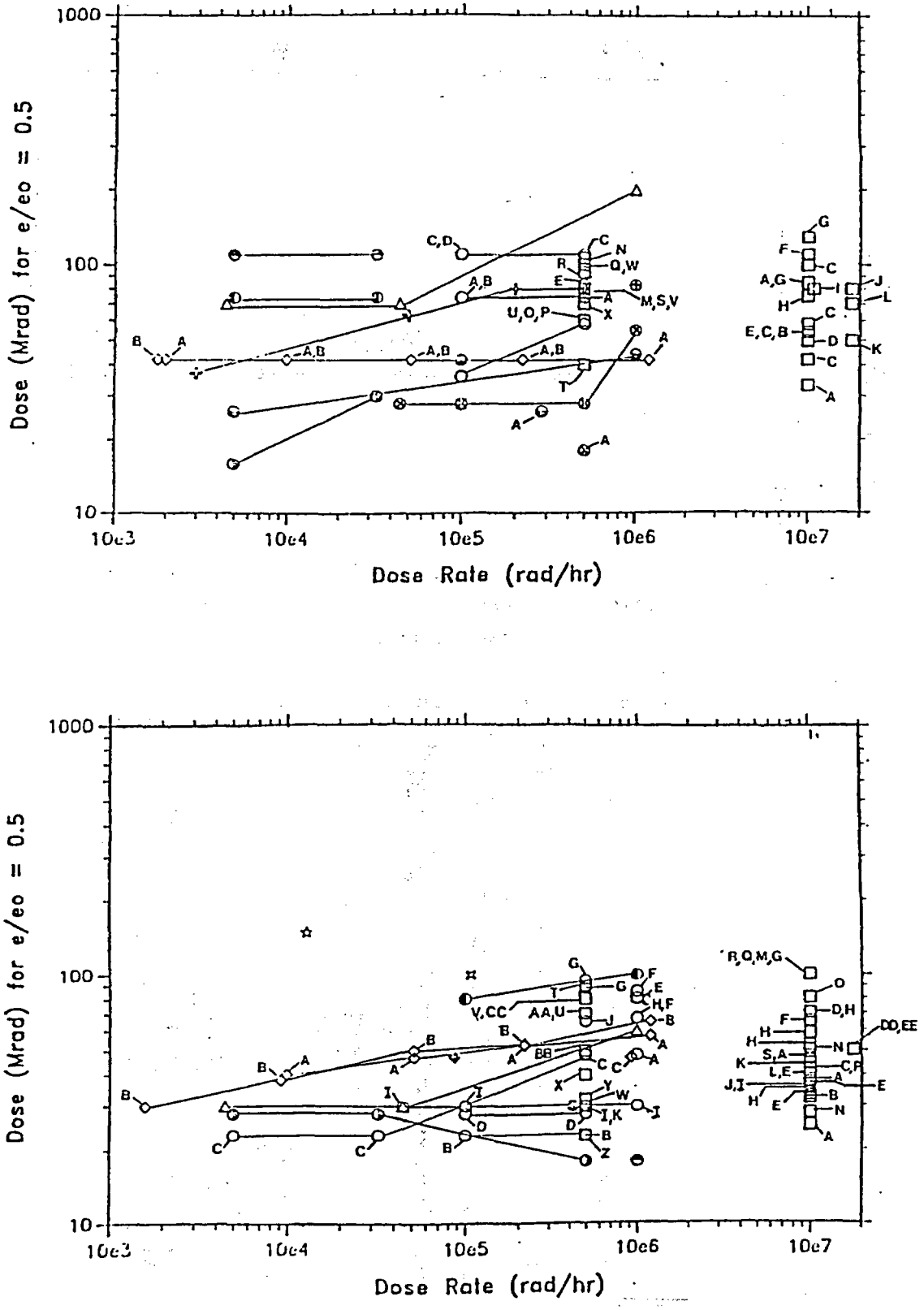

Figure 4.34a Dose rate effects in XLPE (top) and EPR (bottom) (Ref. 4.68)
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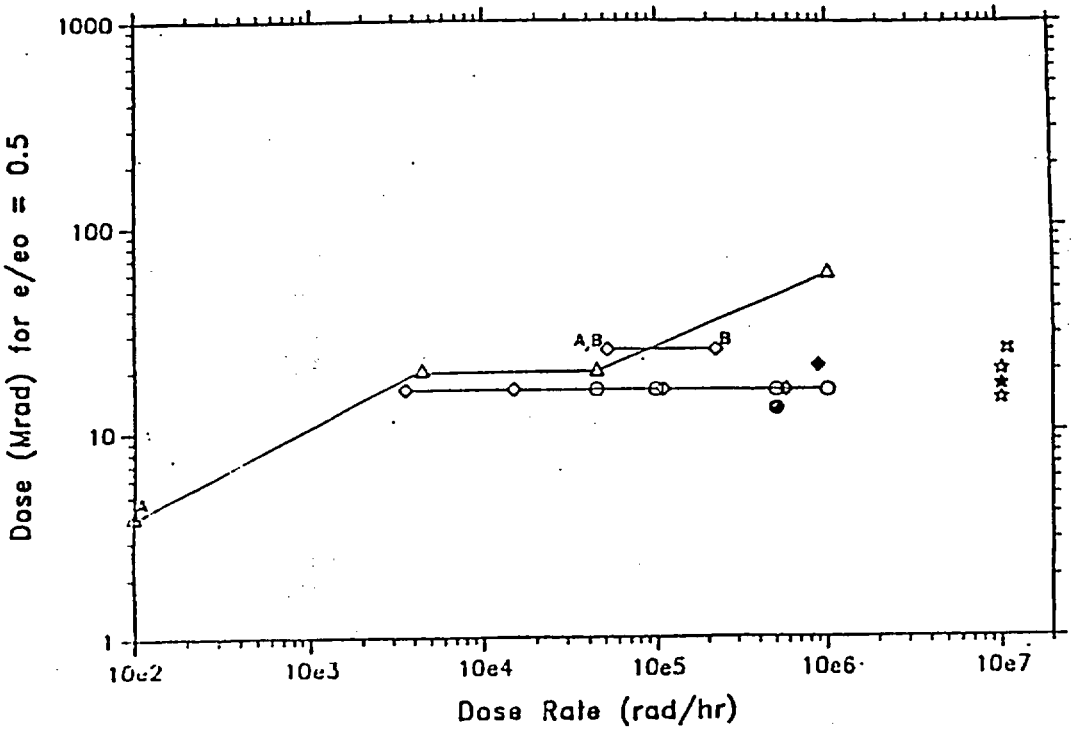

Material	Reference	Source	Year	Symbol	Atmosphere[a]	Temperature[b]	Comments
EPR	17	SNL	1978	◇A			0% and 70% relative humidity
	18	↓	1981	◇B			
				◆	N_2		
	10		1982	◇C		44.5°C	
	20	Japan	1981	○C,◑			
				○B,D	O_2(5 atm)		
				○A,◓	Vacuum		
	22		1982	□T			Without flame retardant
				□U,V			With flame retardant
	24		1983	□W	Vacuum		No antioxidant
				□X,Y,Z	Vacuum		HBC,DTTD,I-1010 antioxidant
				□AA-CC			HDC,DPPD,I-1010 antioxidant
	25		1985	○F			
				○G			
	11		1985	○H,◧	O_2		
				○J		70°C	
	12		1986	○I			
				○K		70°C	
				●	O_2		
	27	Germany	1985	△			
	28	CERN	1975	□A-S			Different suppliers
	29		1982	×I		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	□H-I			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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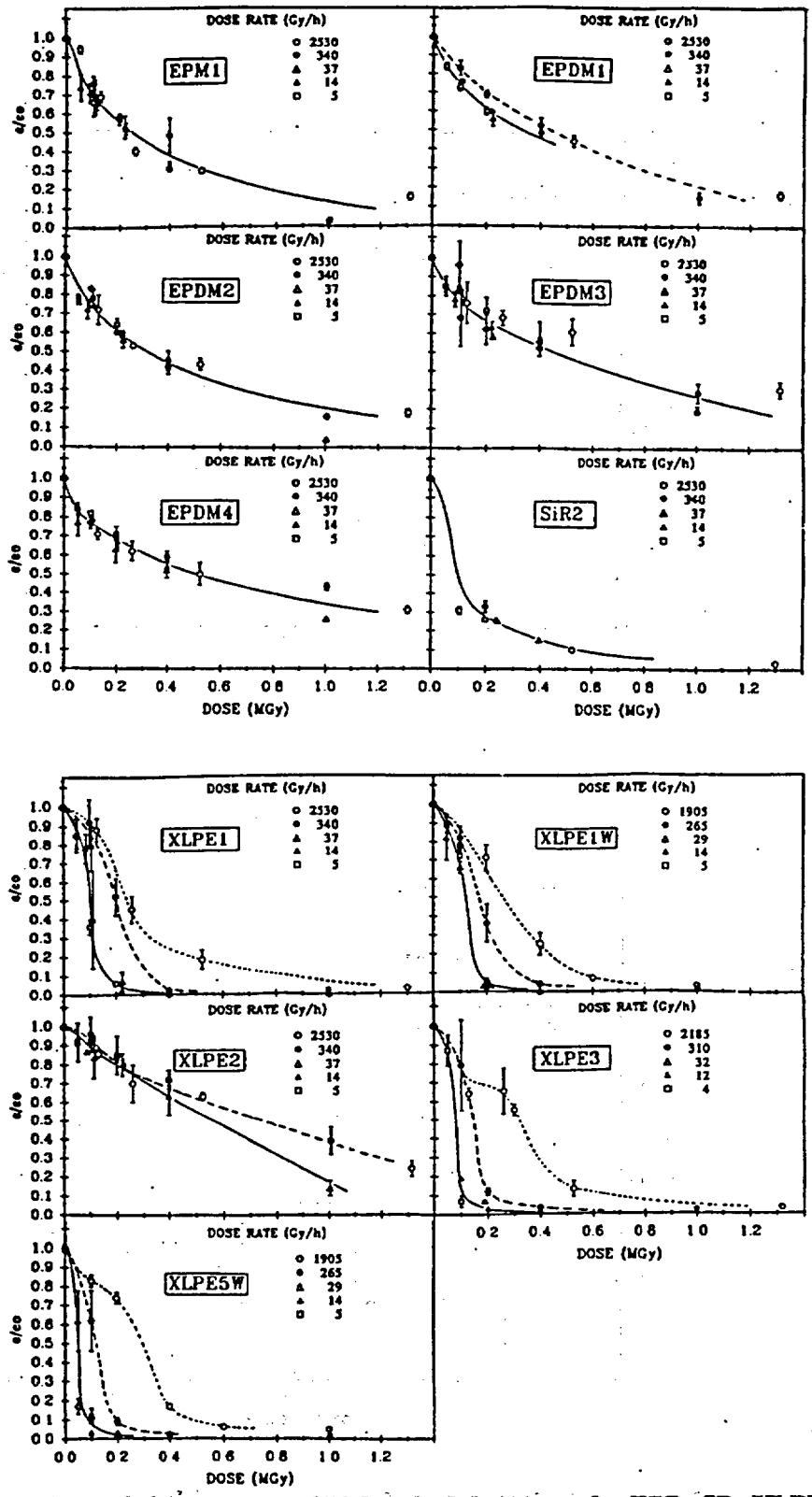
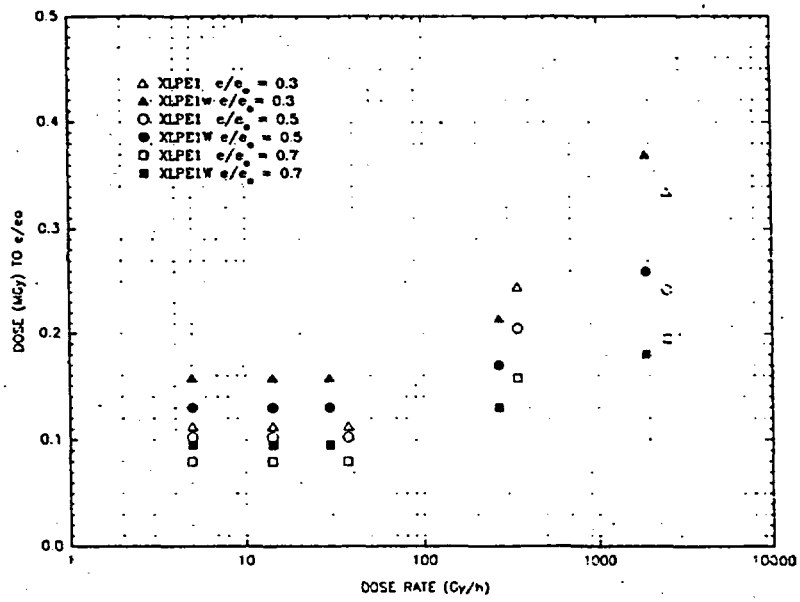


Figure 4.35 Relative elongation as functions of dose and dose rates for EPR, SR, XLPE (Ref. 4.69) Reprinted with permission from Radiation Physics and Chemistry, Vol. 45, No. 1, pp. 103-110, Reynolds, A.B., Bell, R.M., Bryson, N.M., et al., *Dose-Rate Effects on the Radiation-Induced Oxidation of Electric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



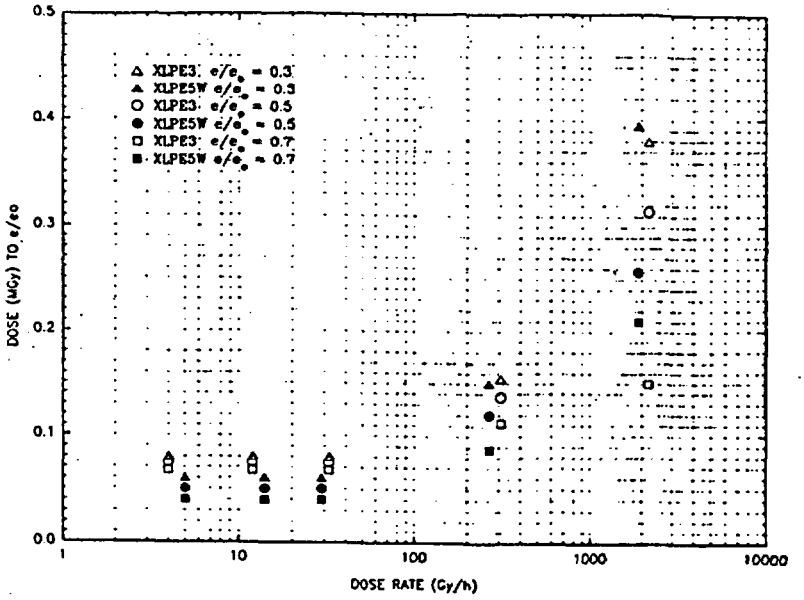


Figure 4.36 Dose to equivalent damage for two XLPE cable materials versus dose rate (Ref. 4.69) Reprinted with permission from Radiation Physics and Chemistry, Vol. 45, No. 1, pp. 103-110, Reynolds, A.B., Bell, R.M., Bryson, N.M., et al., *Dose-Rate Effects on the Radiation-Induced Oxidation of Electric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

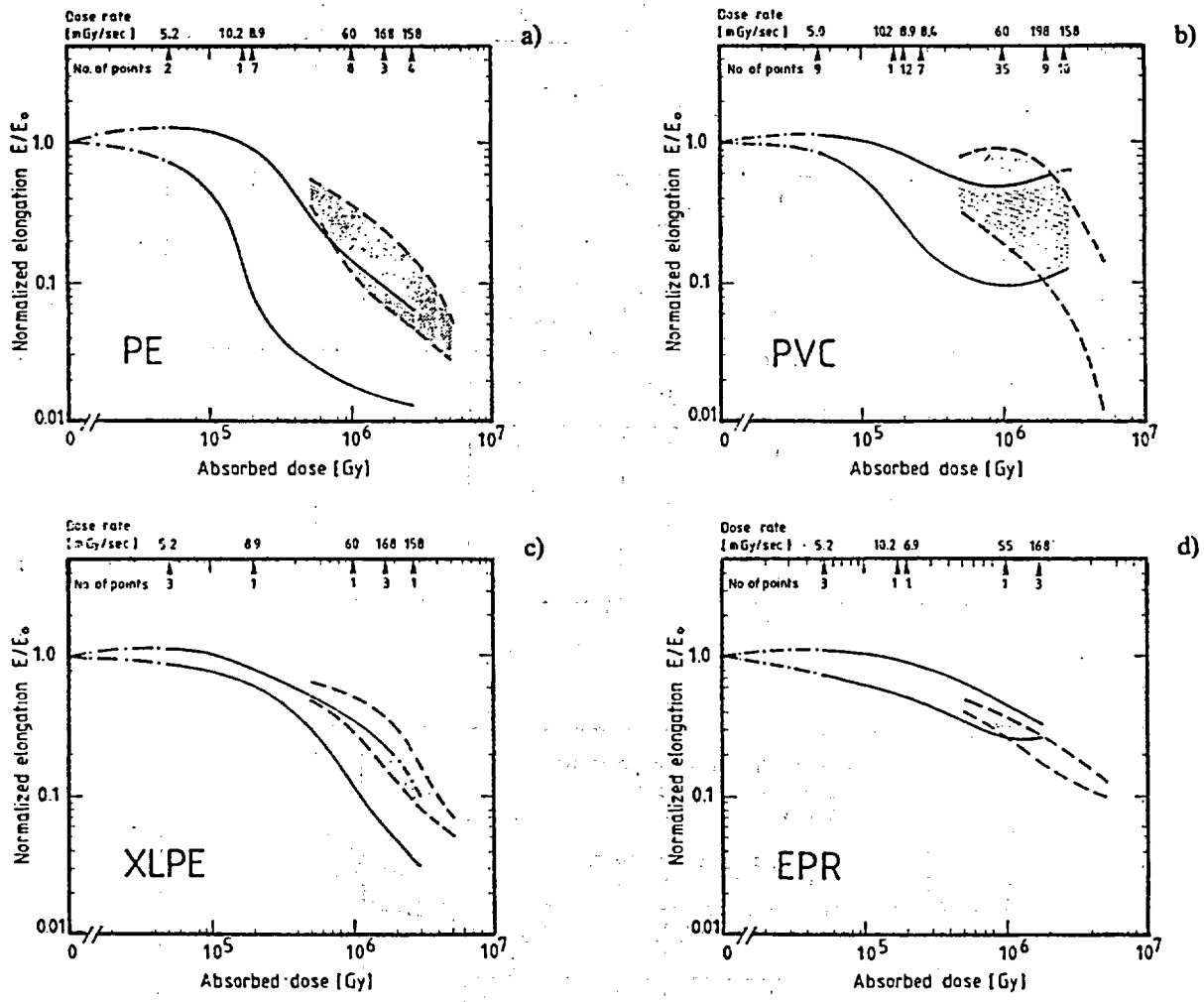


Figure 4.37 Relative elongation versus dose for PE, PVC, XLPE, and EPR. Low dose rates: Data between solid lines. High dose rates: Data between dashed lines. (Ref. 4.55)
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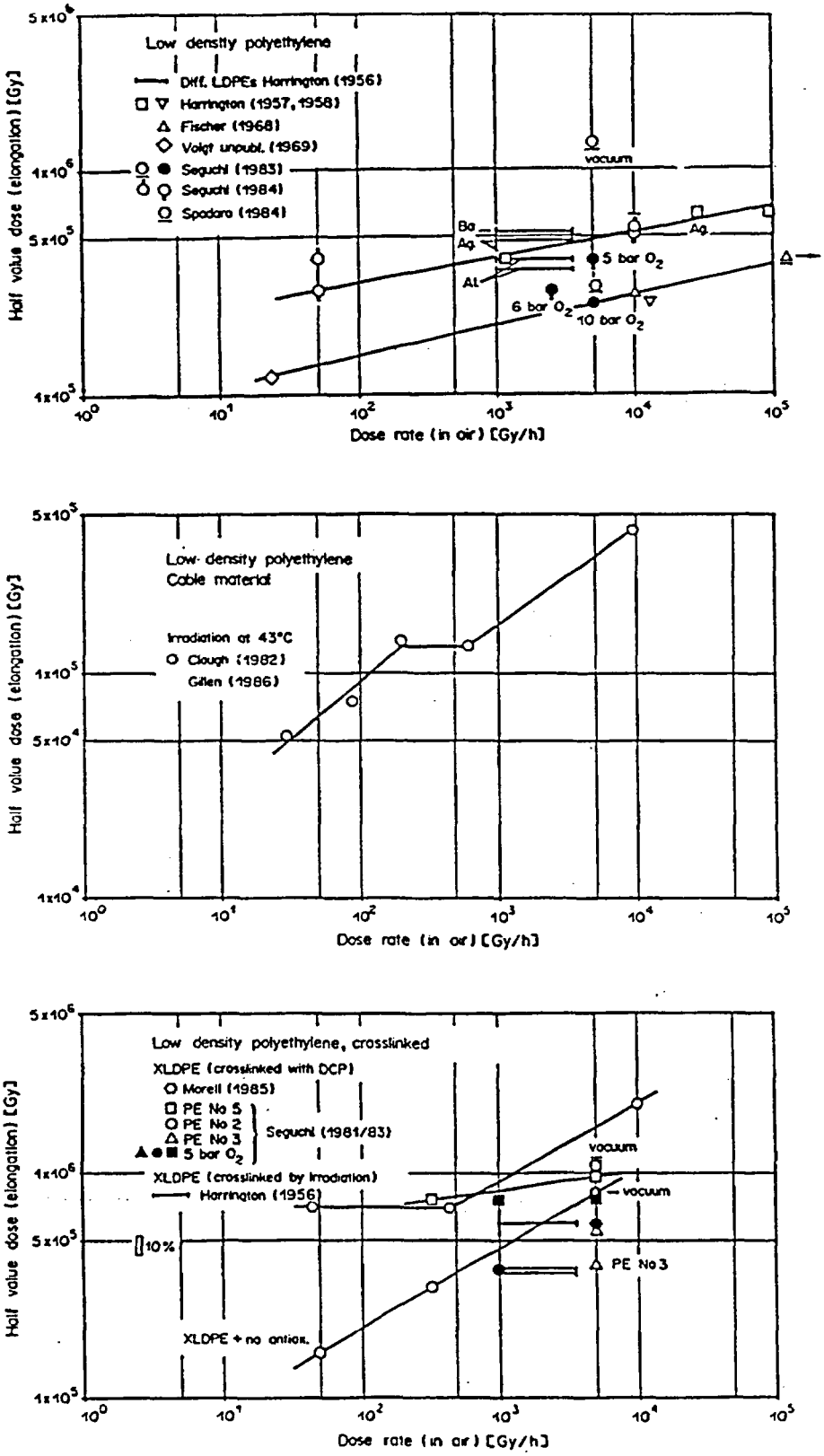

Figure 4.38 Half value dose (elongation) versus dose rate for LDPE (Ref. 4.70)
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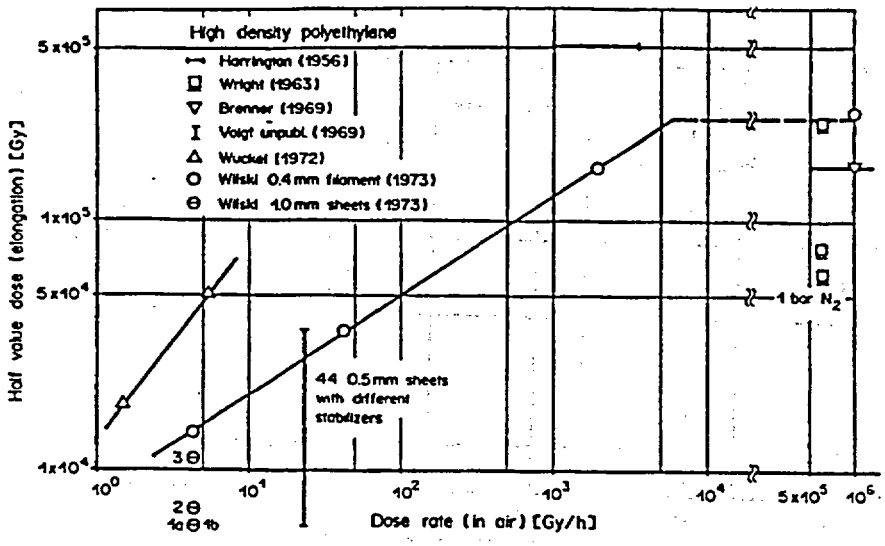

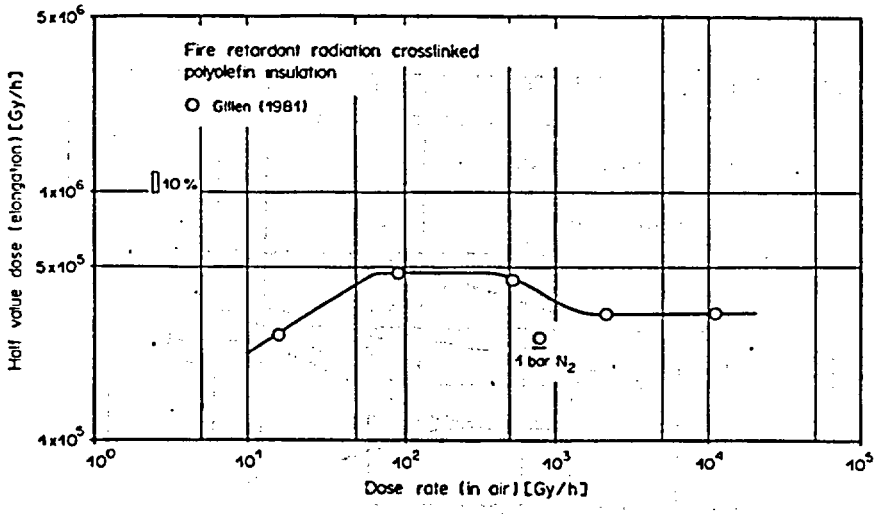

Figure 4.39 Half value dose (elongation) versus dose rate for HDPE and XLPE (Ref. 4.70)
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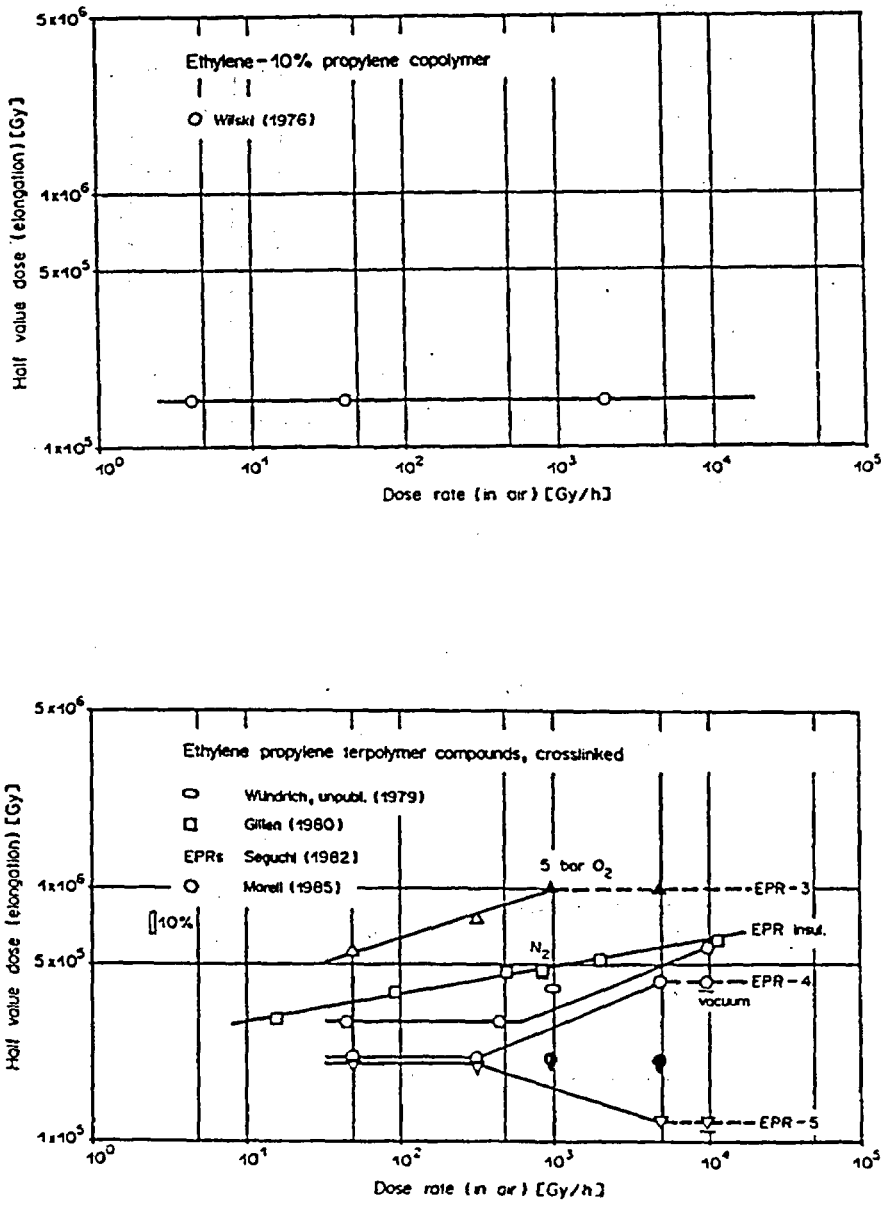

Figure 4.40 Half value dose (elongation) versus dose rate for EPR (Ref. 4.70)
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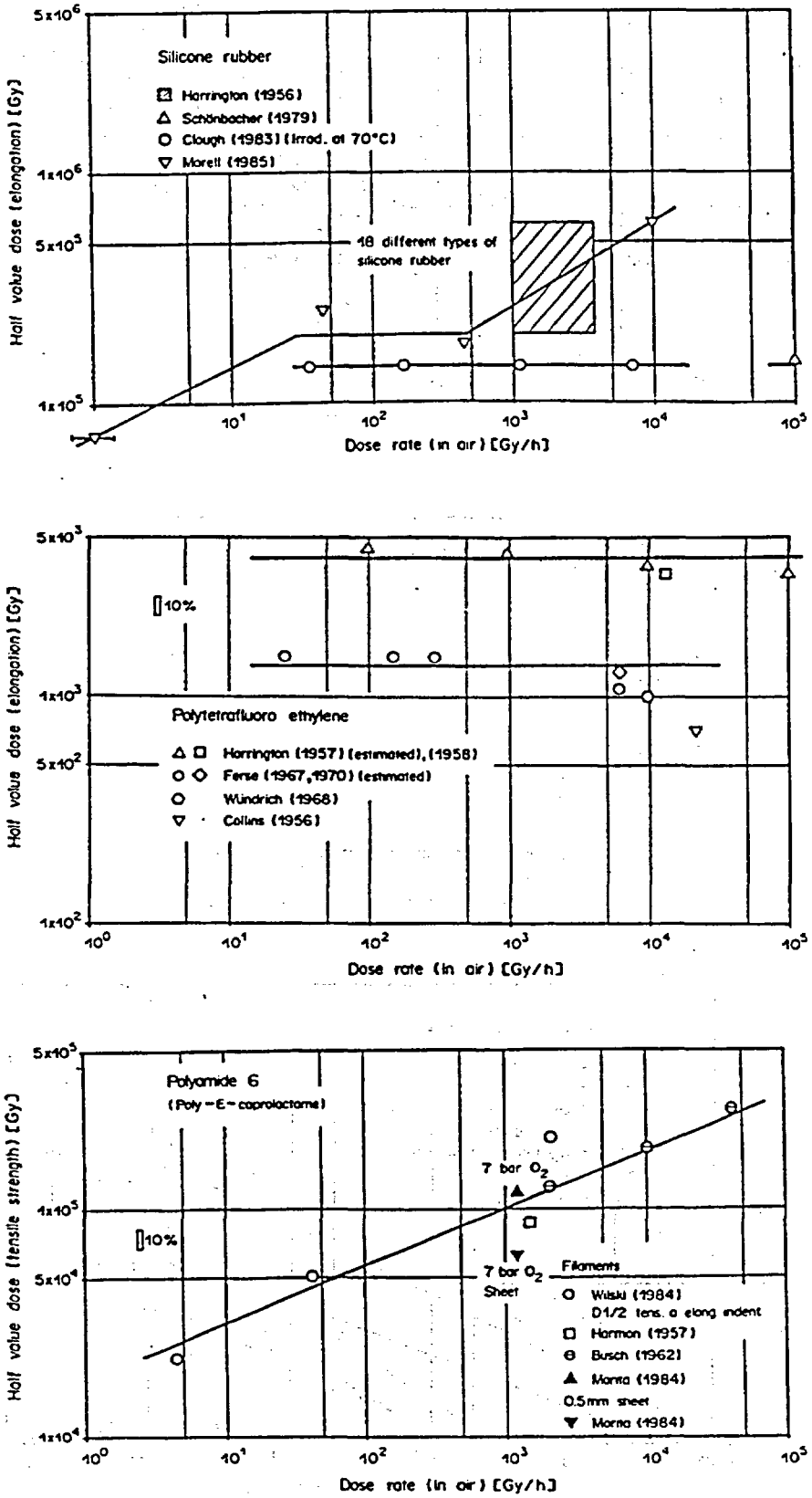

Figure 4.41 Half value dose (elongation) versus dose rate for SR, Teflon, Polyamide (Ref. 4.70)
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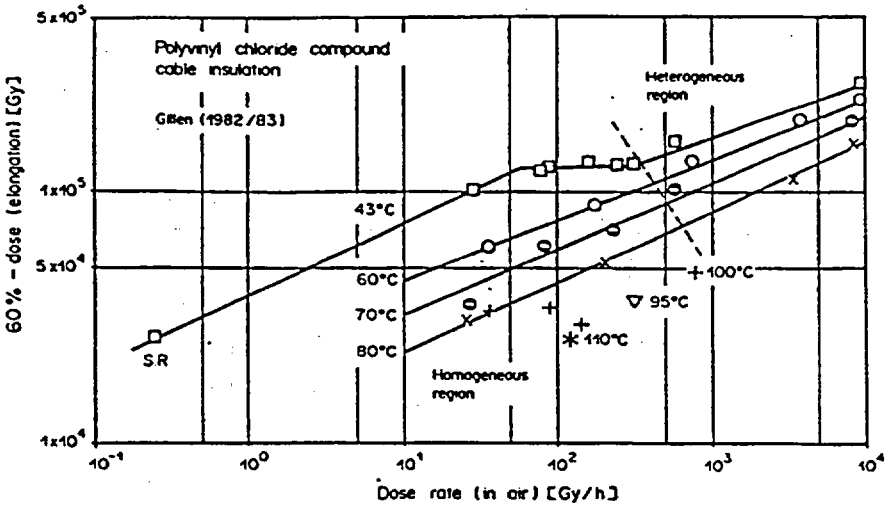

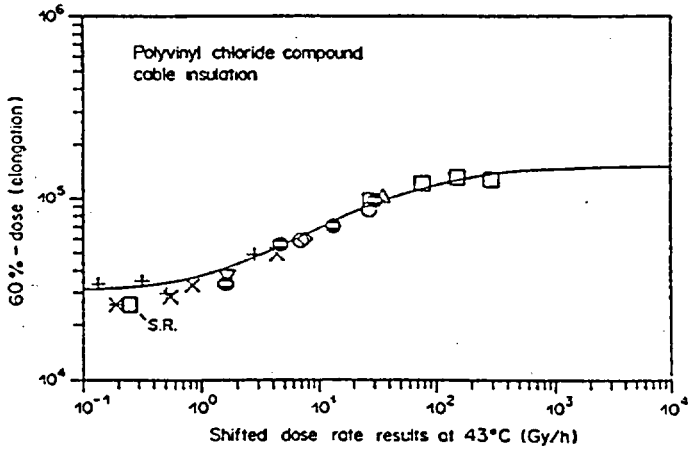

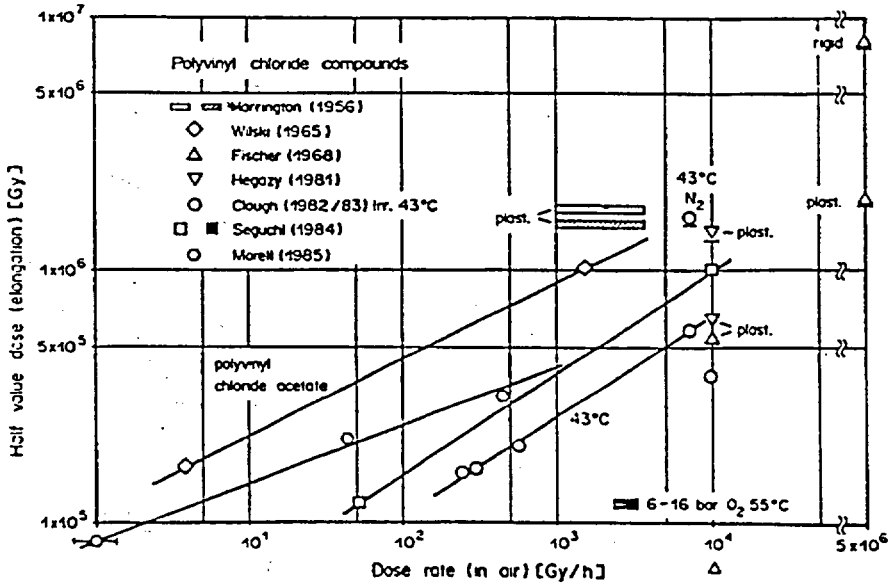

Figure 4.42 Half value dose (elongation) versus dose rate for PVC (Ref. 4.70)
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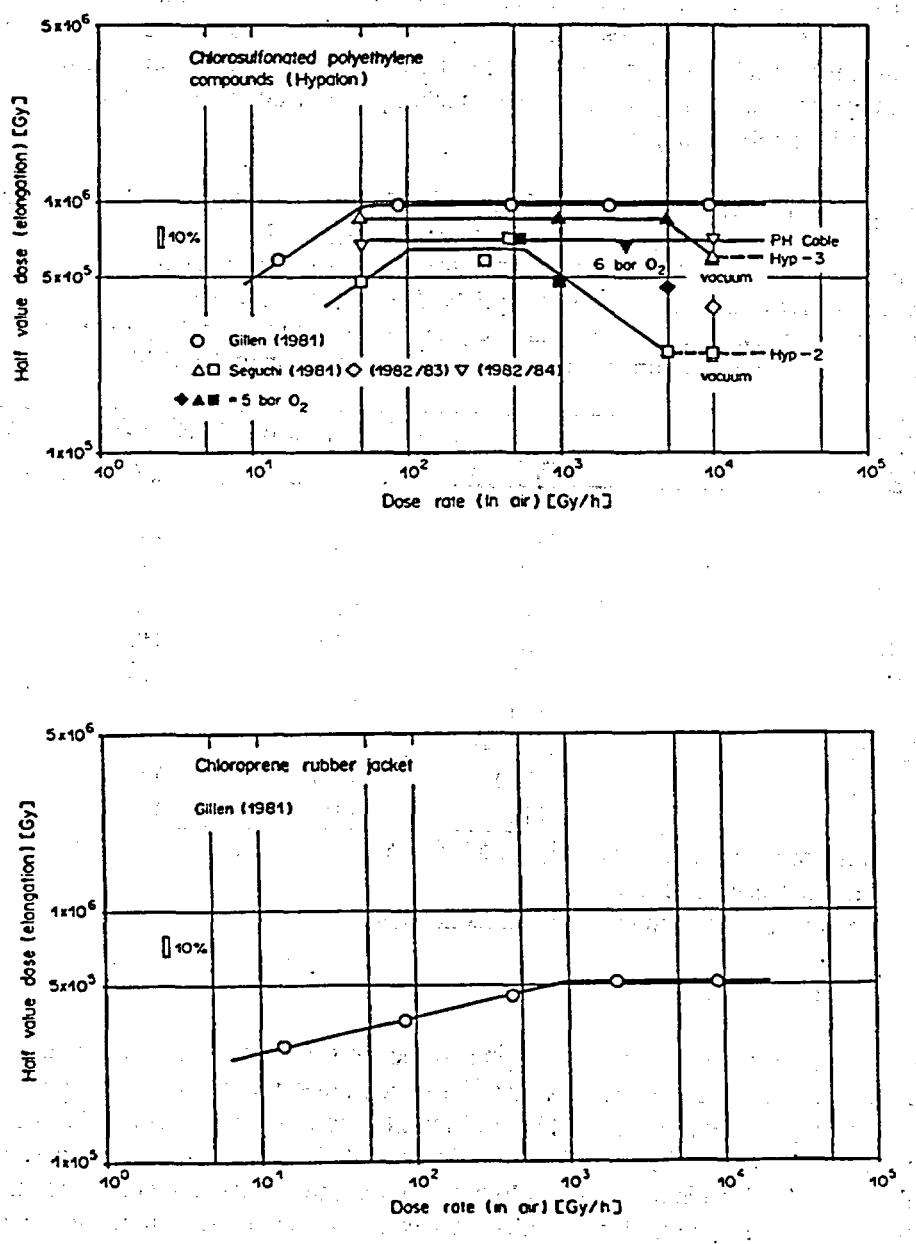

Figure 4.43 Half value dose (elongation) versus dose rate for CSPE and Chloroprene (Ref. 4.70)
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Based on the findings so far, the magnitude of dose-rate effects varies tremendously from one type of material to another, as well as from one degradation 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

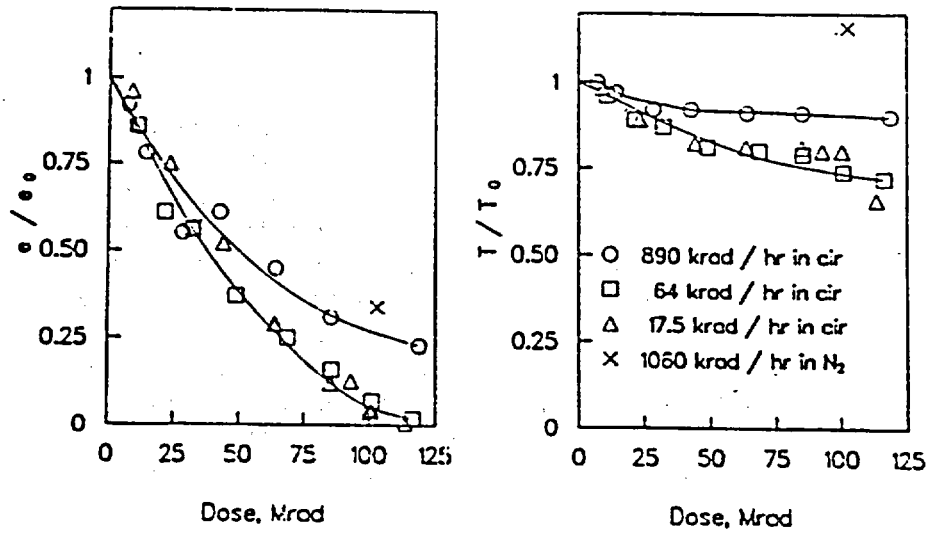


Figure 4.44 Radiation aging of chemically XLPE at 43°C (Ref. 4.37)

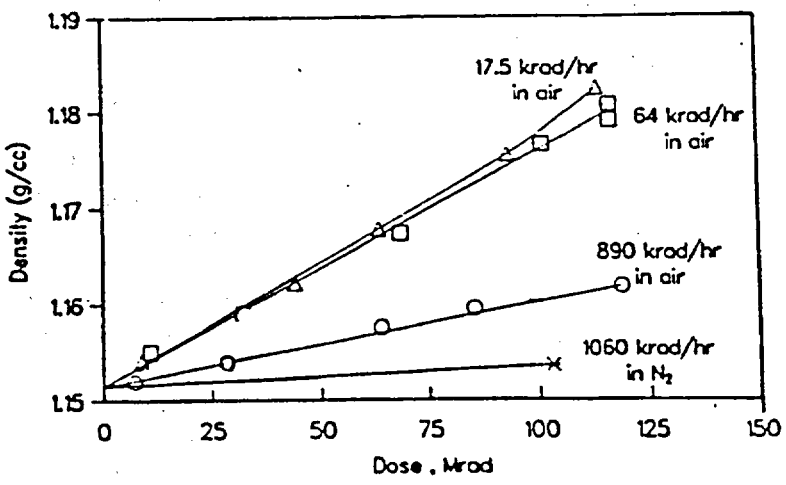


Figure 4.45 Overall density results for chemically XLPE (Ref. 4.37)

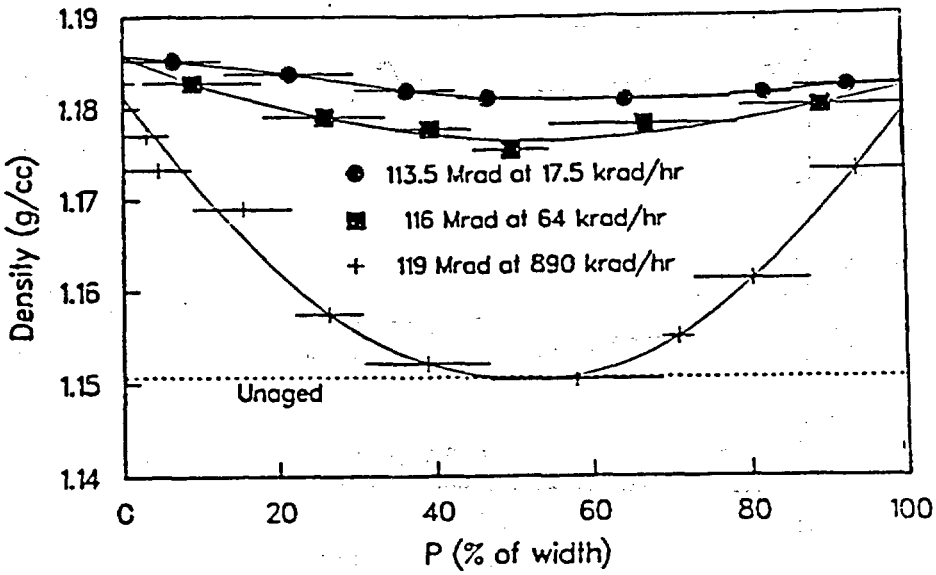


Figure 4.46 Density profiles for chemically XLPE (Ref. 4.37)

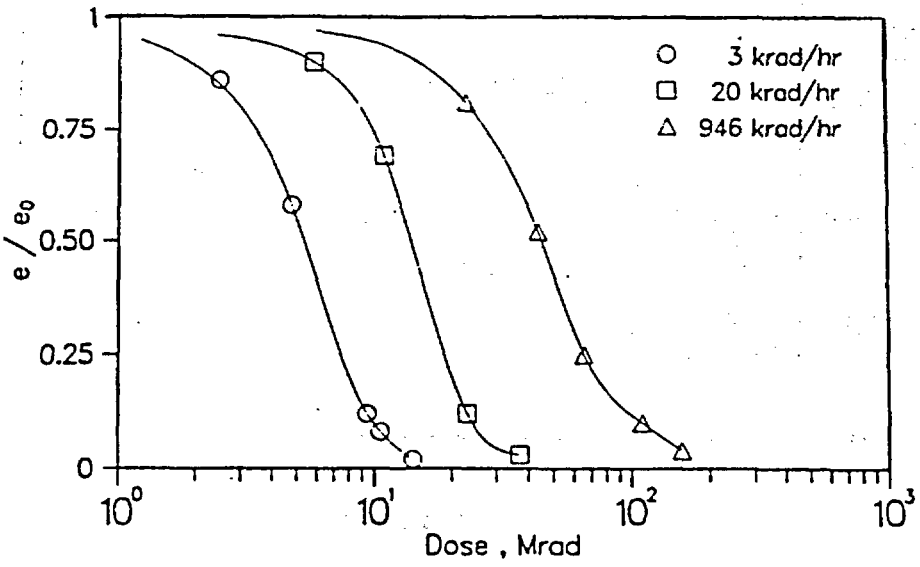


Figure 4.47 Tensile elongation for LDPE at 43°C (Ref. 4.37)

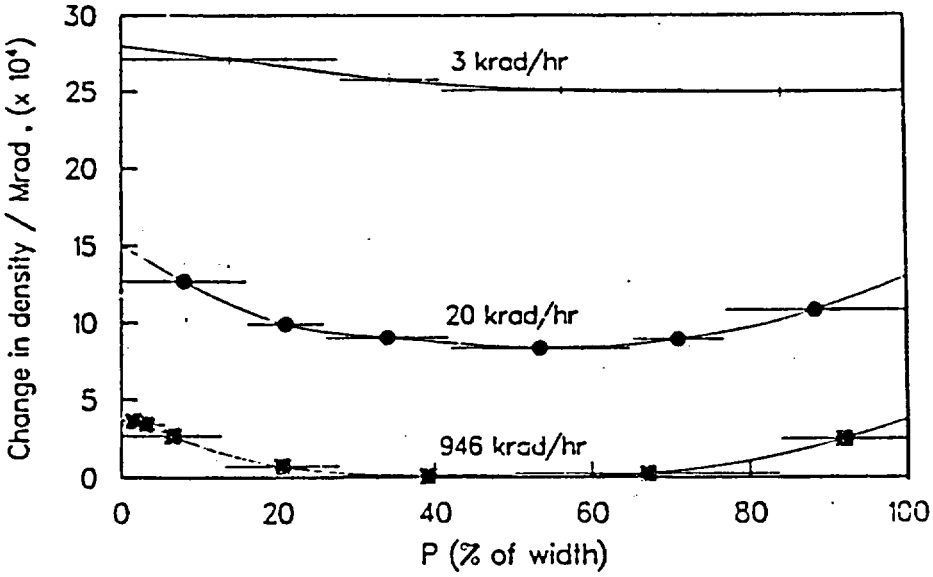


Figure 4.48 Density profiles for LDPE (Ref. 4.37)

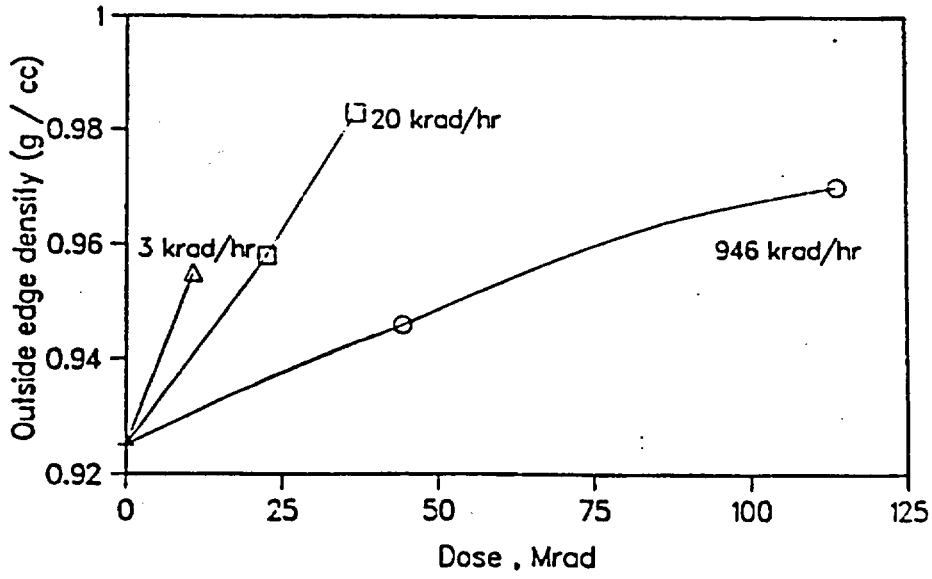


Figure 4.49 Density of outer edge of the LDPE material (Ref. 4.37)

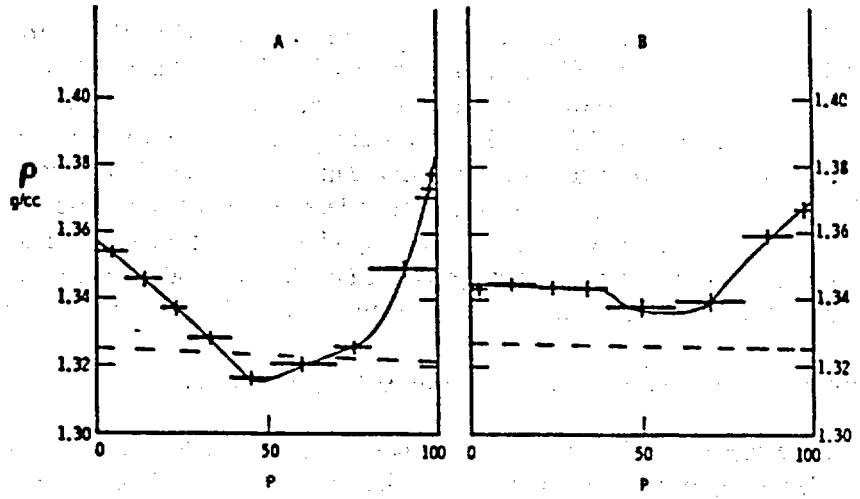


Figure 4.50 Density profiles for EPR; A: unaged (dashed), 172 Mrad at 1.2 Mrad/hr in air (solid); B: 117 Mrad at 87krad/hr in nitrogen (dashed), 150 Mrad at 220 krad/hr in air (solid) (Ref. 4.73)

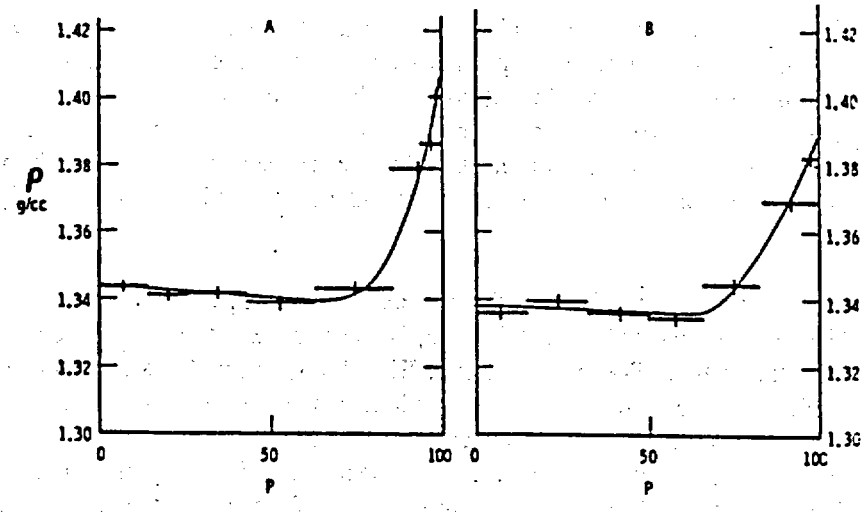


Figure 4.51 Density profiles for EPR. A: 135 Mrad at 52 krad/hr in air; B: 53 Mrad at 1.6 krad/hr in air (Ref. 4.73)

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)	Total Dose in EPR (Mrd)	Ultimate Tensile Strength T/T_0	Ultimate Tensile Elongation e/e_0
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%)	e/e_o 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$_o$					
	e$_o$=	CSPE 383%	CPE 357%	EPR-1 419%	EPR-2 223%	XLPO-1 389%	XLPO-2 336%
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.

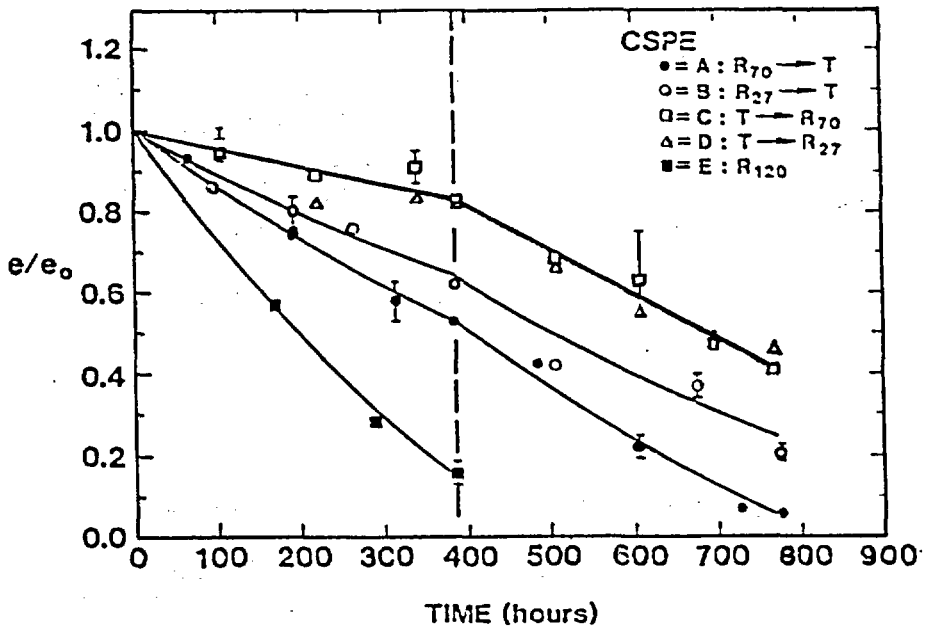


Figure 4.52 Tensile elongation of CSPE in various environments (Ref. 4.81)

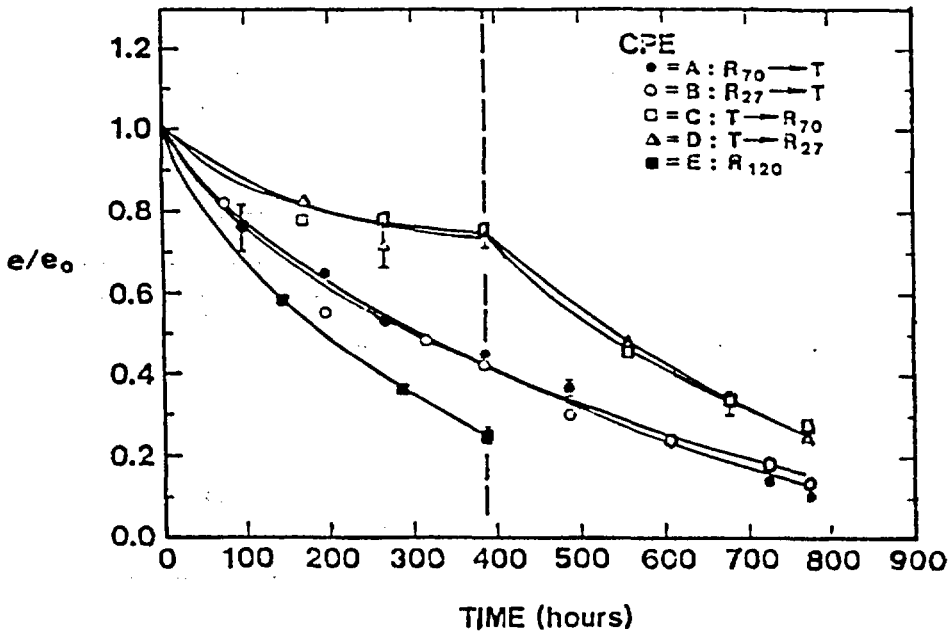


Figure 4.53 Tensile elongation of CPE in various environments (Ref. 4.81)

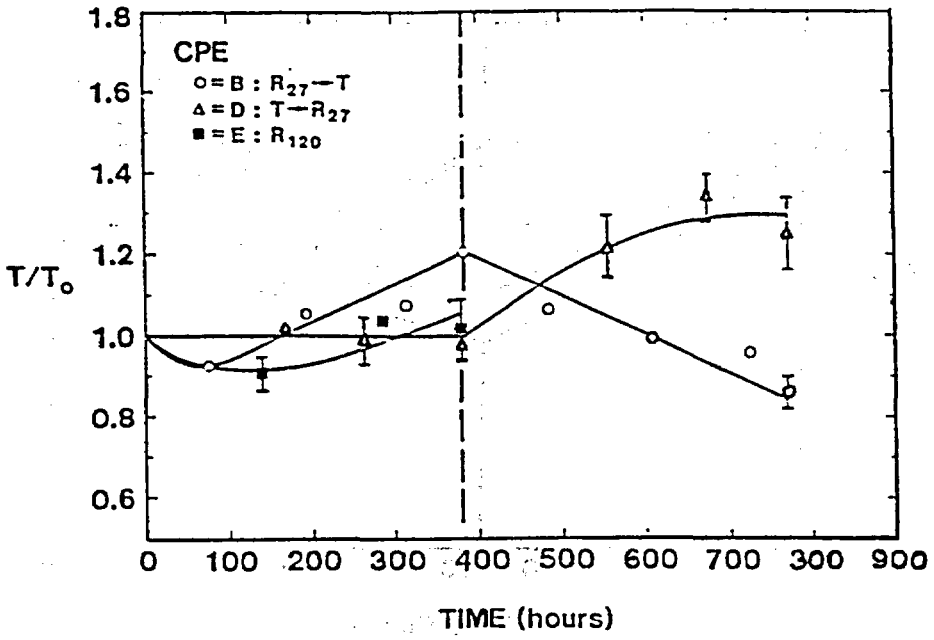


Figure 4.54 Tensile strength of CPE in various environments (Ref. 4.81)

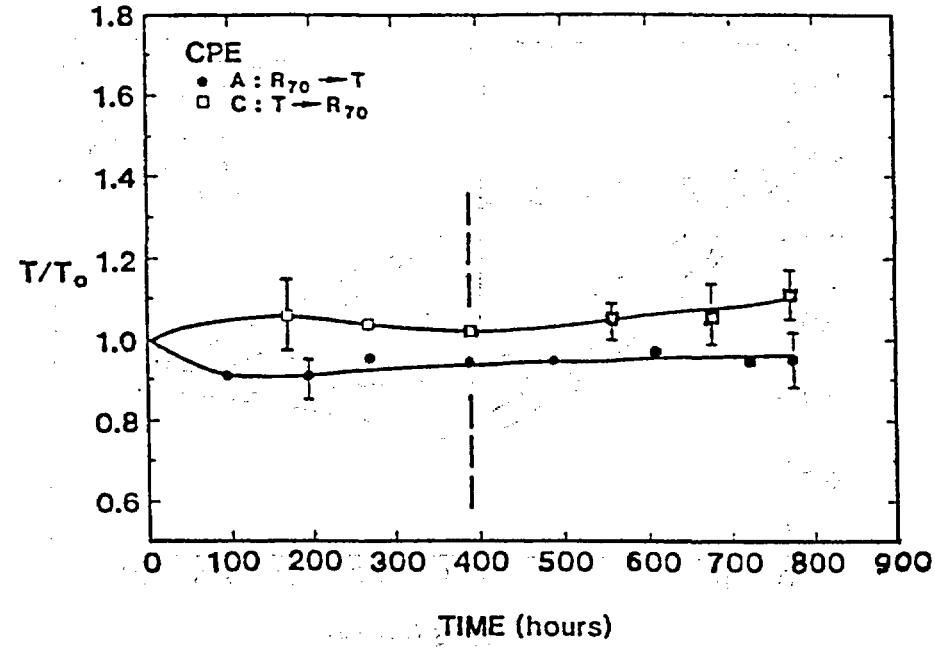


Figure 4.55 Tensile strength of CPE in various environments (Ref. 4.81)

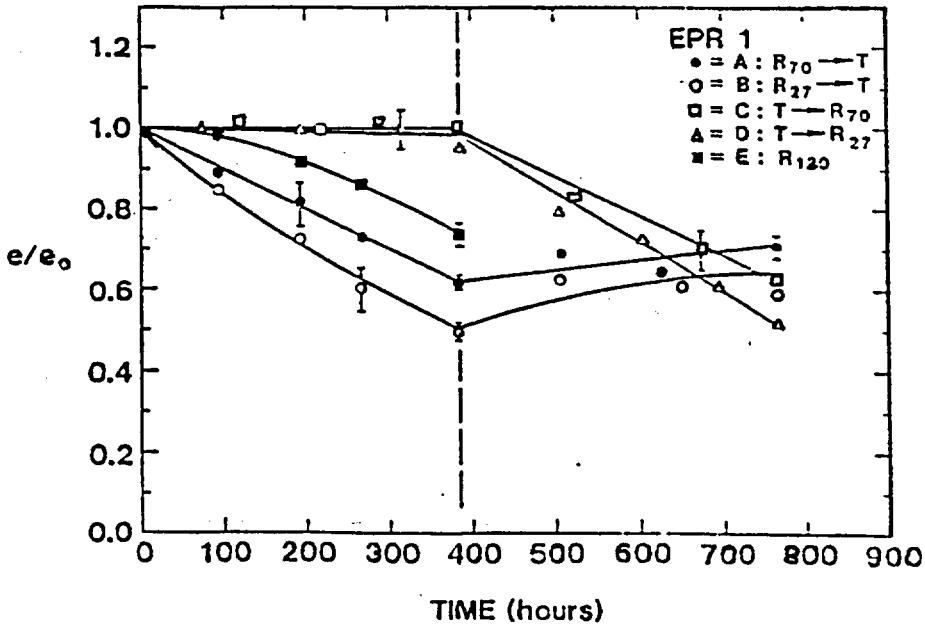


Figure 4.56 Tensile elongation of EPR-1 in various environments (Ref. 4.81)

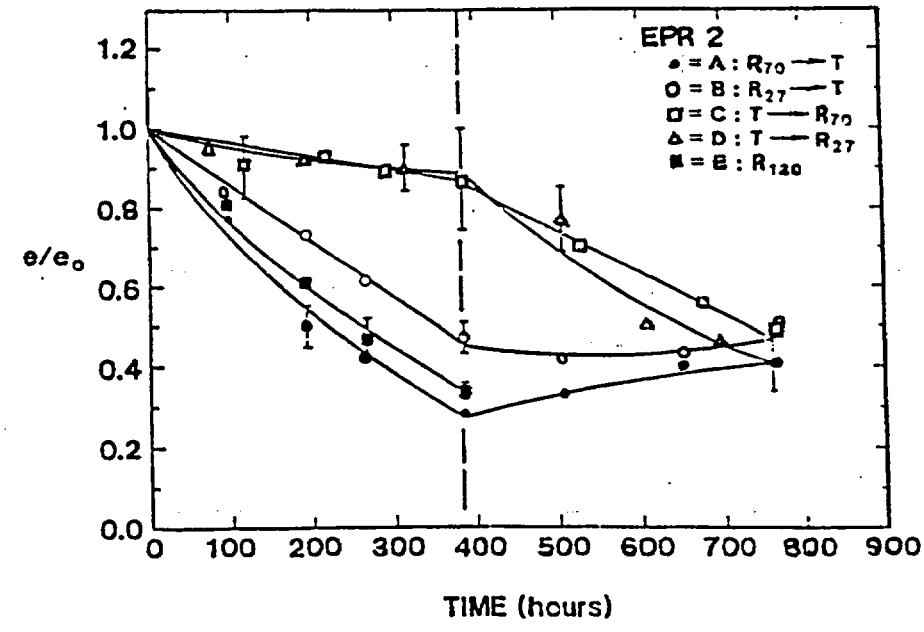


Figure 4.57 Tensile elongation of EPR-2 in various environments (Ref. 4.81)

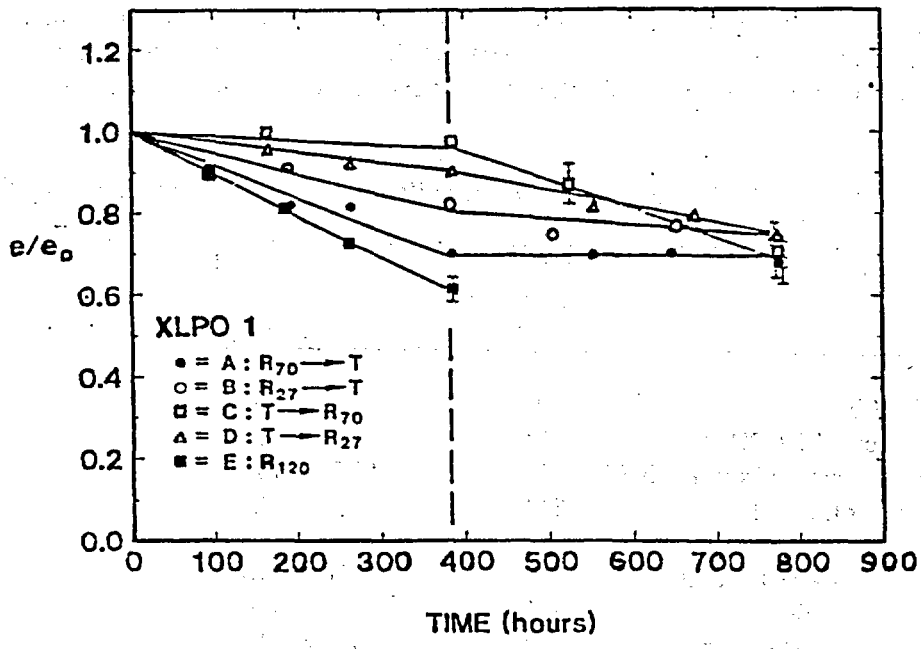


Figure 4.58 Tensile elongation of XLPO-1 in various environments (Ref. 4.81)

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.

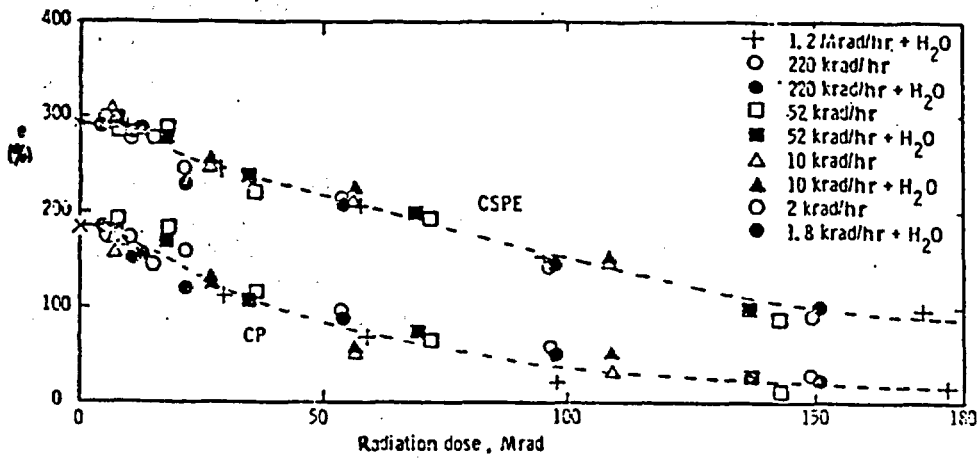
4.3.4 Effect of Other Conditions During Aging Simulations

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.

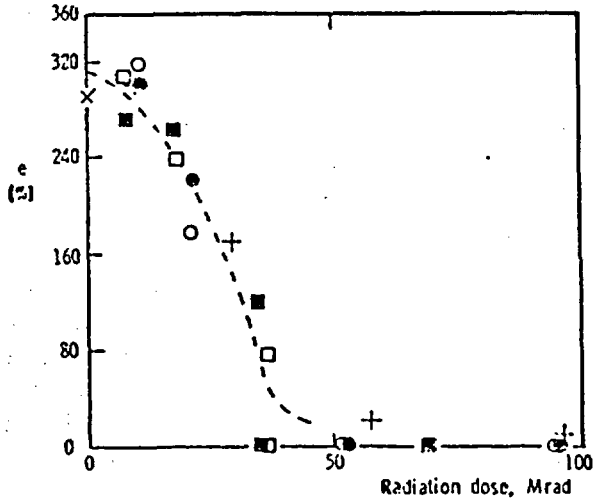
4.3.4.1 Effects of humidity

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)

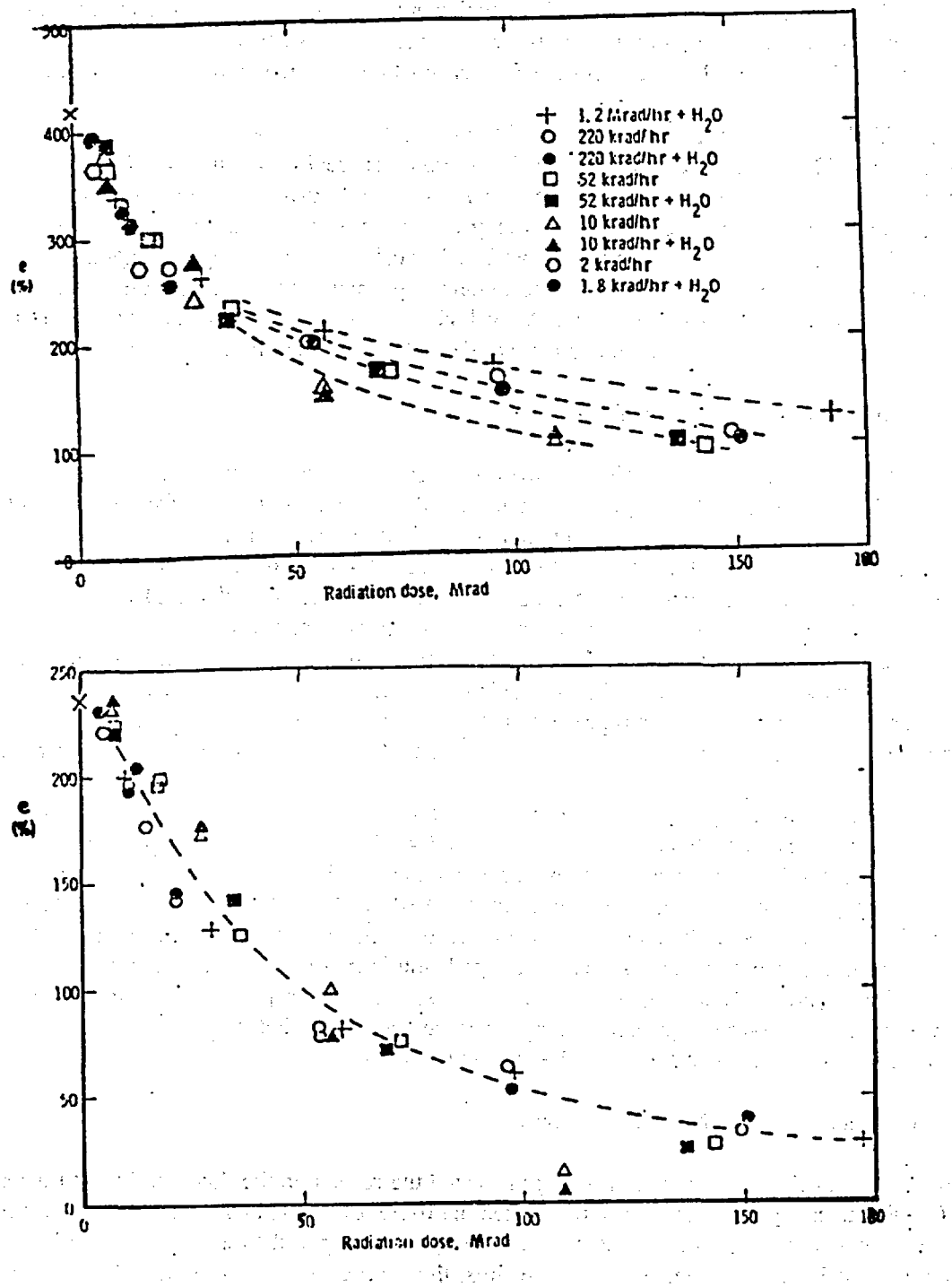


Figure 4.60 Ultimate elongation; radiation aging under dry air and 70% humidity upper: EPR; lower: XLPE (Ref. 4.87)

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).

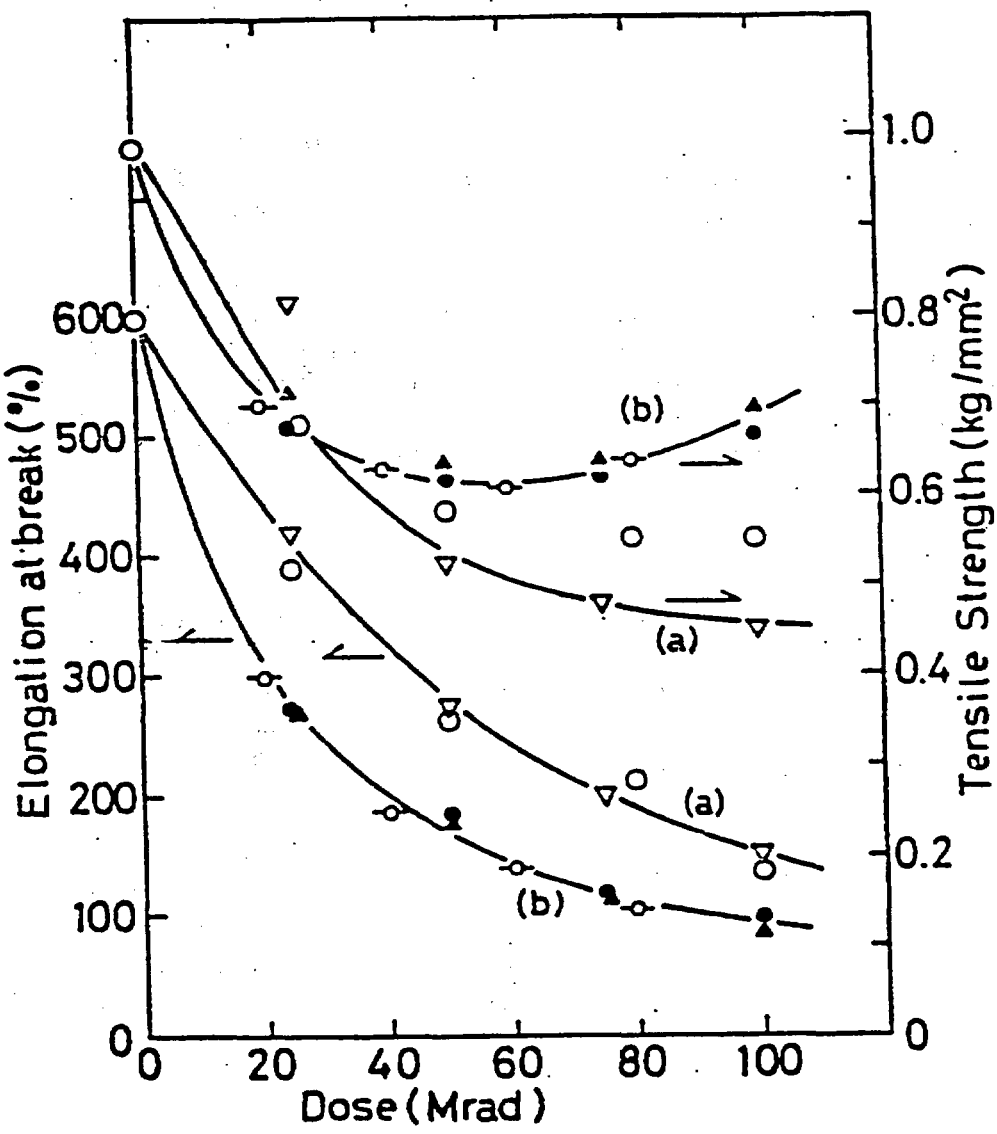


Figure 4.61 Tensile properties for EPR irradiated at various conditions at room temperature. Open triangle: In vacuum with 1 Mrad/hr; open circle: In air with 1 Mrad/hr; open circle with bar: In air with 5 krad/hr; solid circle: In oxygen 5 atm with 0.5 Mrad/hr; solid triangle: In oxygen 5 atm with 0.1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

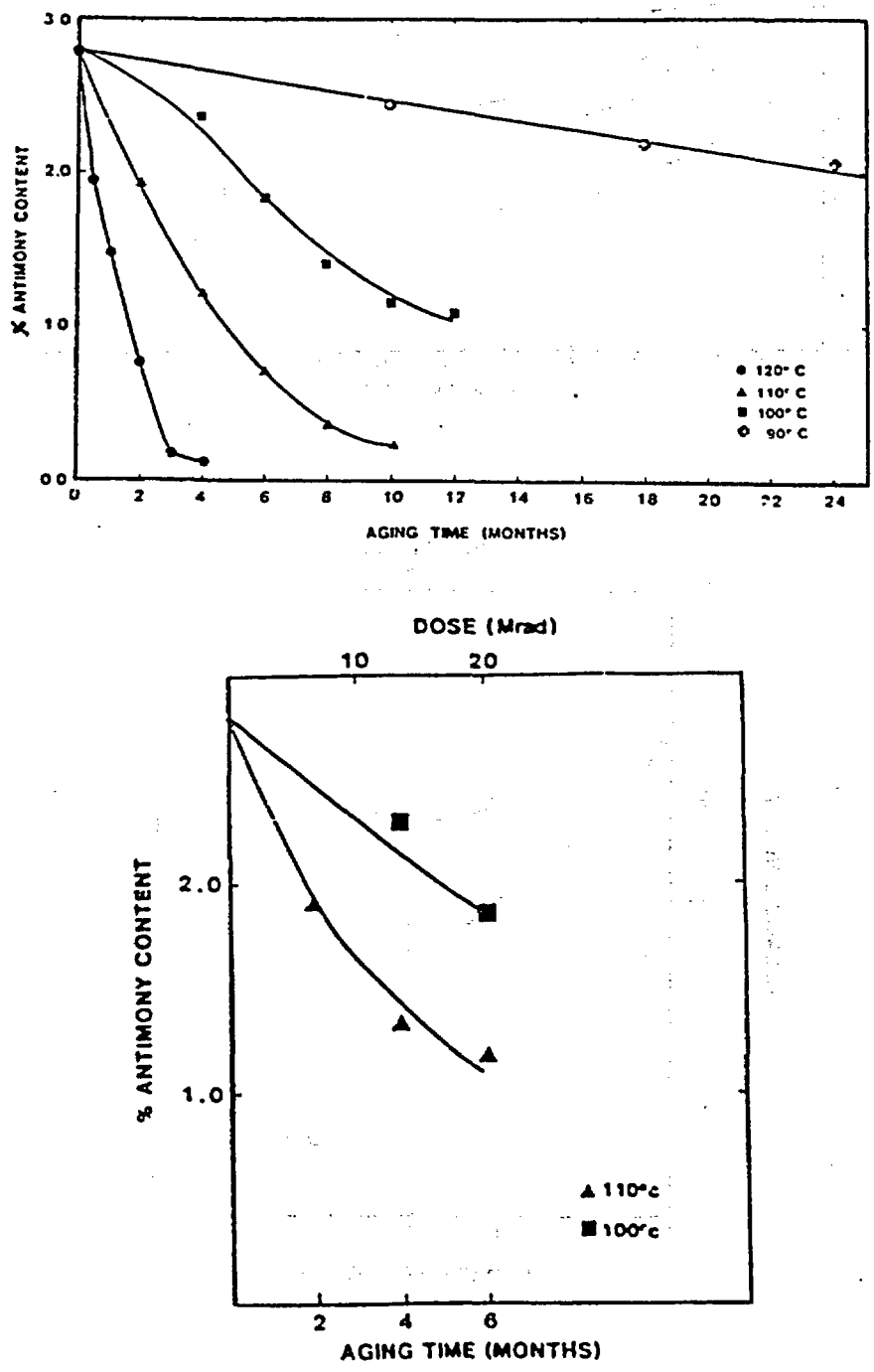
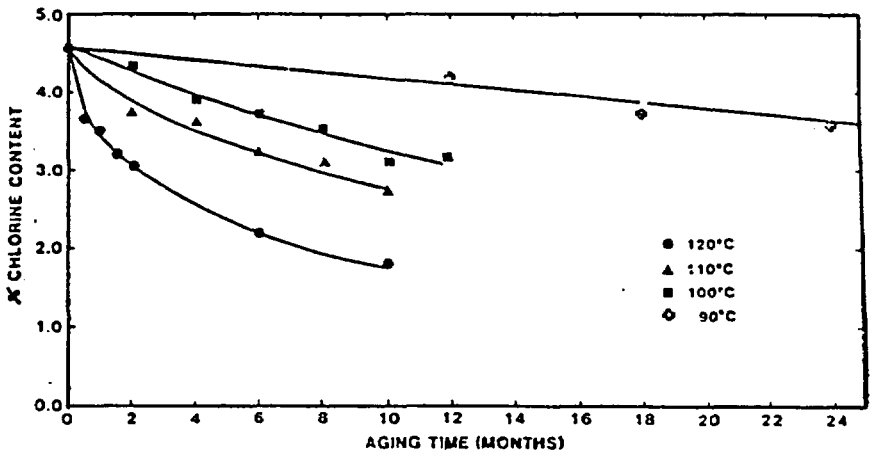


Figure 4.62 Antimony content (weight percent) on fire-retarded EPR-V; Upper: thermal aging only; lower: thermal plus radiation at 5 krad/hr (Ref. 4.92)



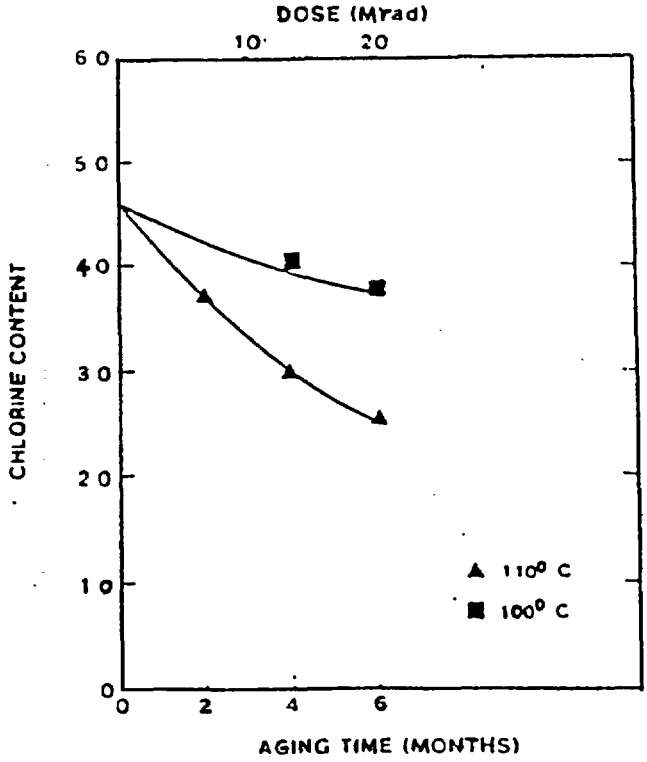


Figure 4.63 Chlorine content (weight percent) on fire-retarded EPR-V; Upper: thermal aging only; lower: thermal plus radiation at 5 krad/hr (Ref. 4.92)

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.

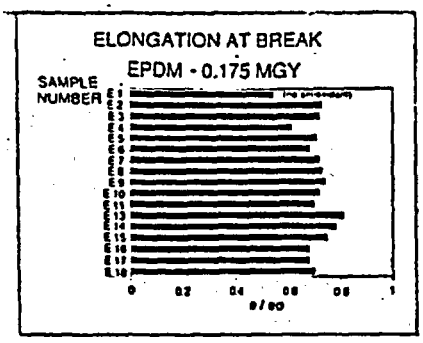
To the extent measured in this study, degradation from radiation aging and thermal aging could be superposed. Whether aging is synergistic, as determined by sequencing of aging versus simultaneous aging, was not determined.

4.3.4.7 Effects of mechanical stresses

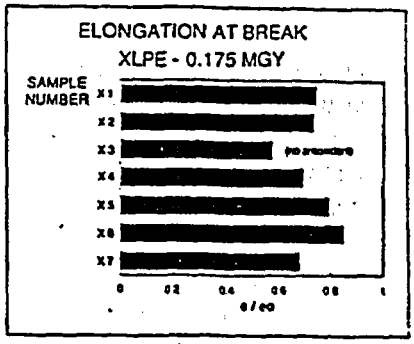
Electric cables potentially are subject to two failure mechanisms caused by mechanical stress (Ref. 4.98). First, if the cable is stretched by an applied force (or by its weight) over an edge with small curvature, the metal wires will gradually creep through the soft polymeric insulation resulting in 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.

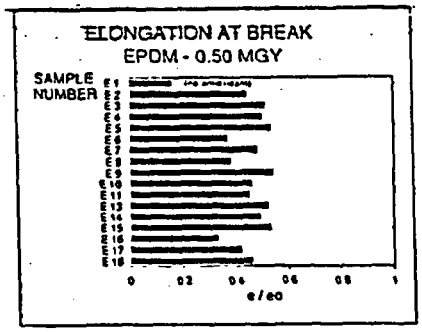
For realistic geometries, creep short-circuit is observed only at very high temperatures (>175°C) in combination with high stress (>500 psi) where failure will occur quickly within hours or days. Temperature and radiation hardening slow down creeping with increasing exposure time, and the mitigating 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.



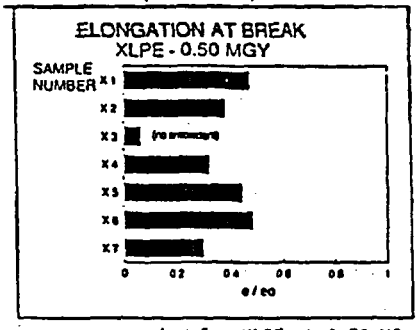
e/e_0 for EPDM at 0.175 MGy (17.5 Mrad).



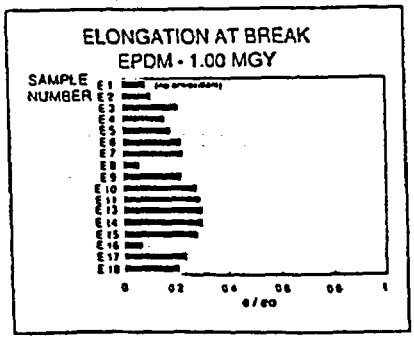
e/e_0 for XLPE at 0.175 MGy (17.5 Mrad).



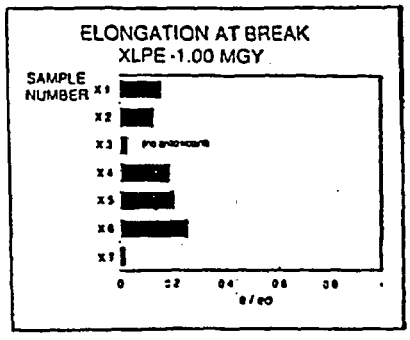
e/e_0 for EPDM at 0.50 MGy (50 Mrad).



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



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)

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.

[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 some 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.

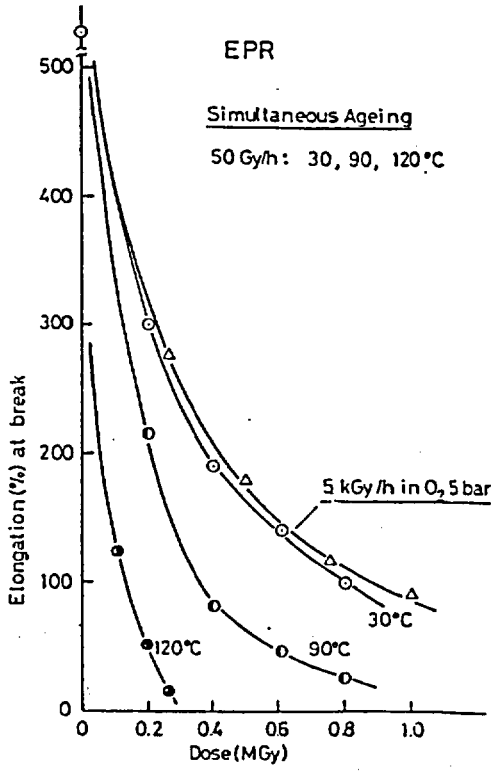


Figure 4.65 Simultaneous aging of EPR at 50 Gy/h and 30, 90, 120°C (Ref. 4.108)
Reproduced with permission from Dr. Tadao Seguchi, JAERI, Japan.

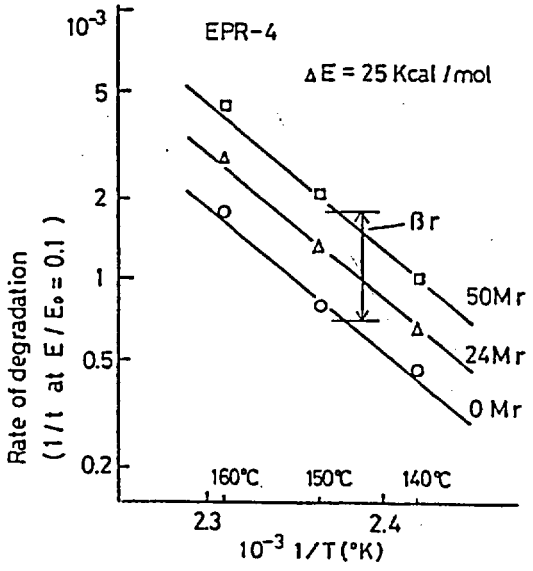


Figure 4.66 Arrhenius plots at different aging conditions for EPR-4 (Ref. 4.108)
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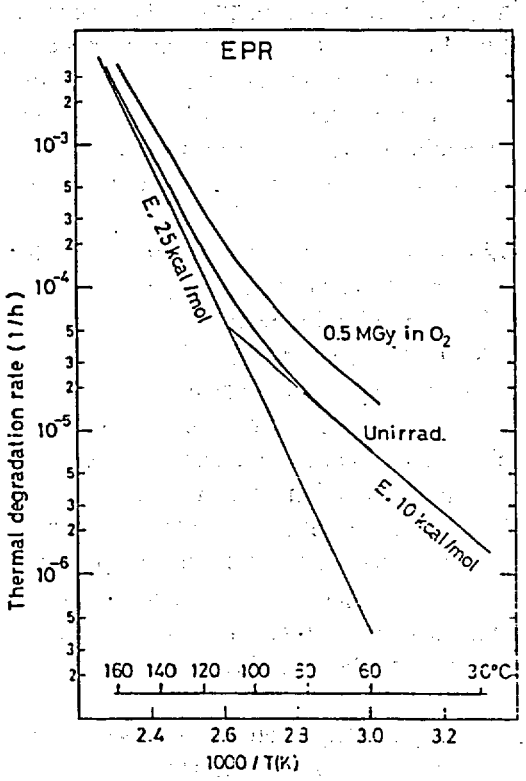

Figure 4.67 Arrhenius plots for combined aging conditions for EPR (Ref. 4.108)
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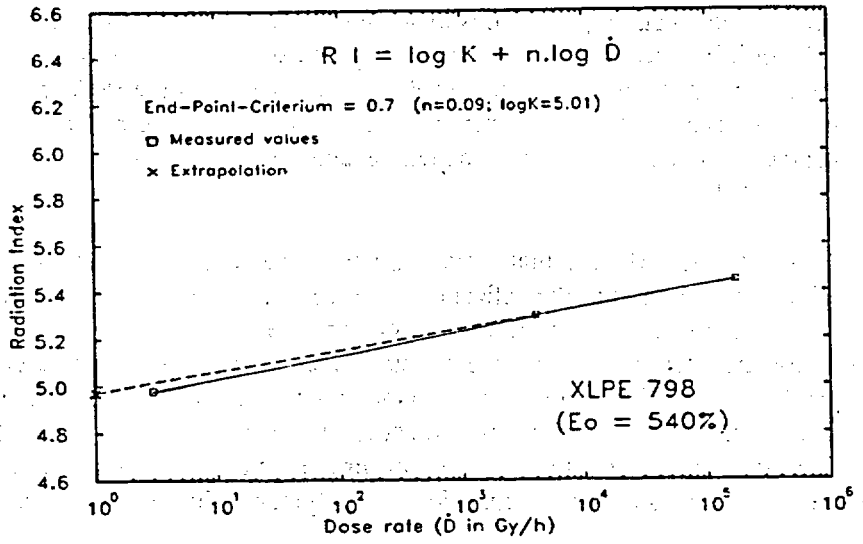

Figure 4.68 Examples of long-term aging and extrapolation for XLPE (Ref. 4.109)
Reproduced with permission from Dr. Helmut Schonbacher, CERN, Switzerland.

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

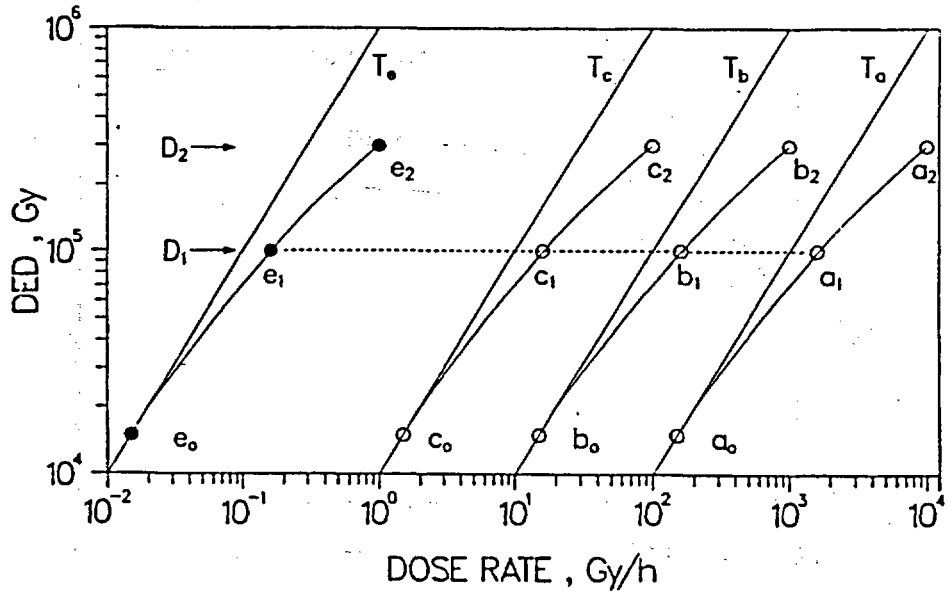

Figure 4.69 Hypothetical DED versus dose rate curves under isothermal conditions (Ref. 4.112)

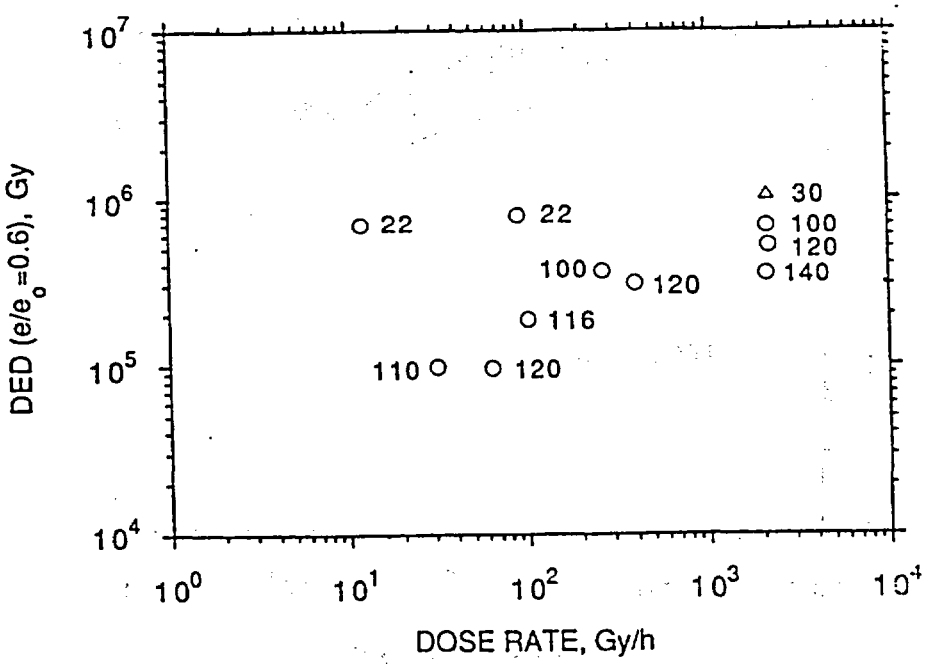

Figure 4.70 Combined thermal and radiation aging data for Hypalon-B (Ref. 4.112)

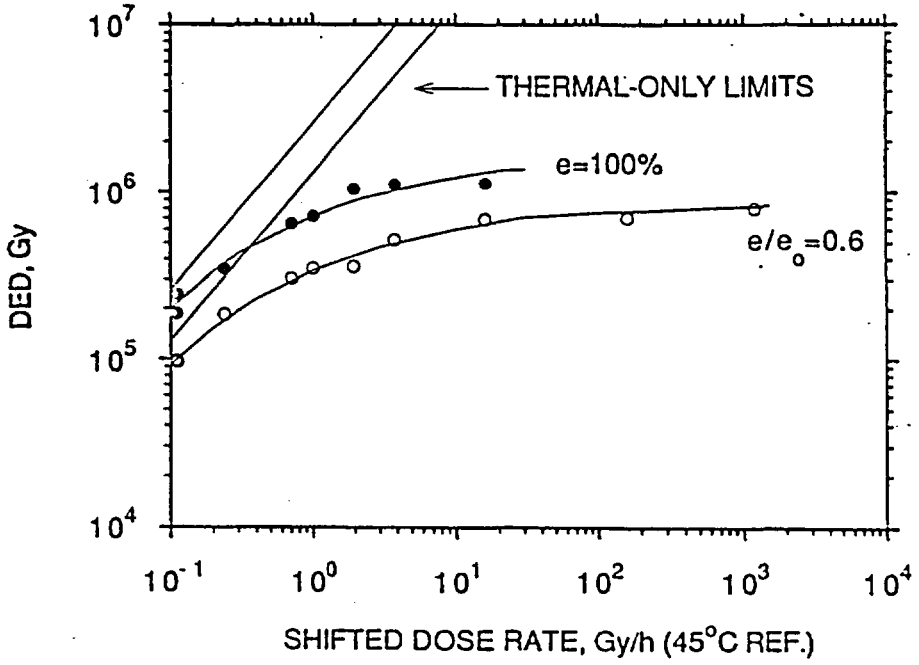

Figure 4.71 Predictions for Hypalon-B (DED vs dose rate) (Ref. 4.112)

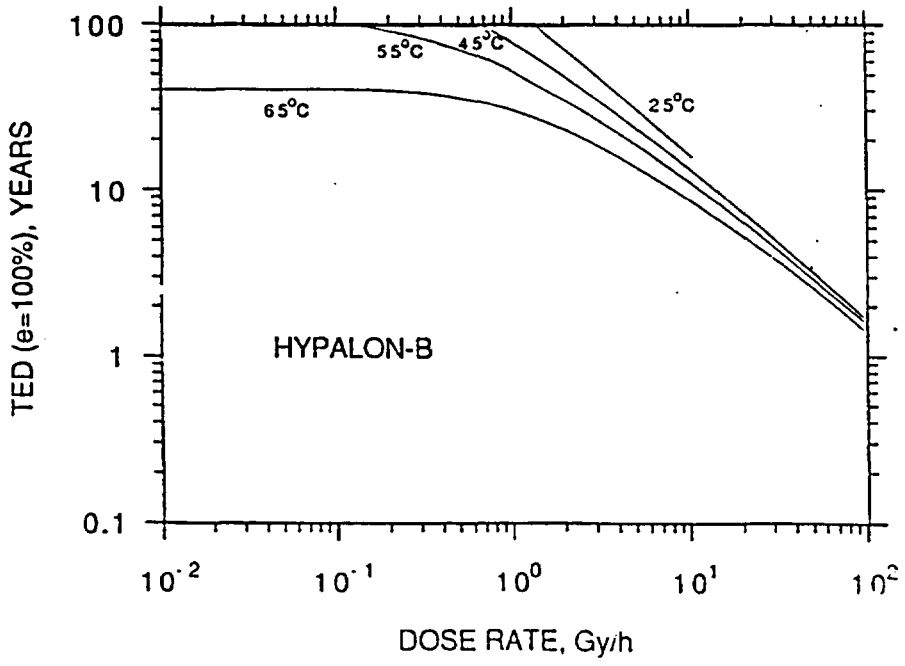

Figure 4.72 Predictions for Hypalon-B (TED vs dose rate) (Ref. 4.112)

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)

		Predicted/Expected Dose to 100% Absolute Elongation (Gyx10^6)			
Material	Activation Energy (kcal/mol)	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.

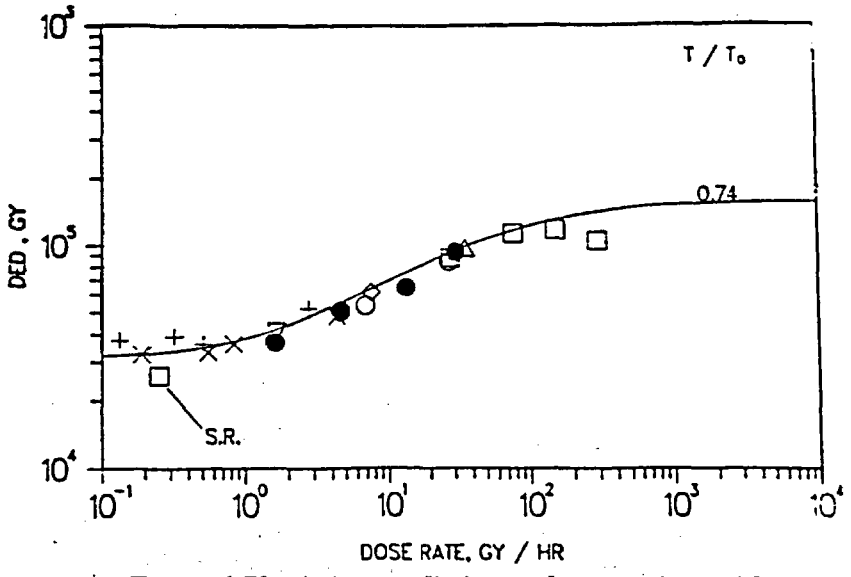

Figure 4.73 Aging prediction and comparison with Savannah River PVC sample (Ref. 4.61)

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.

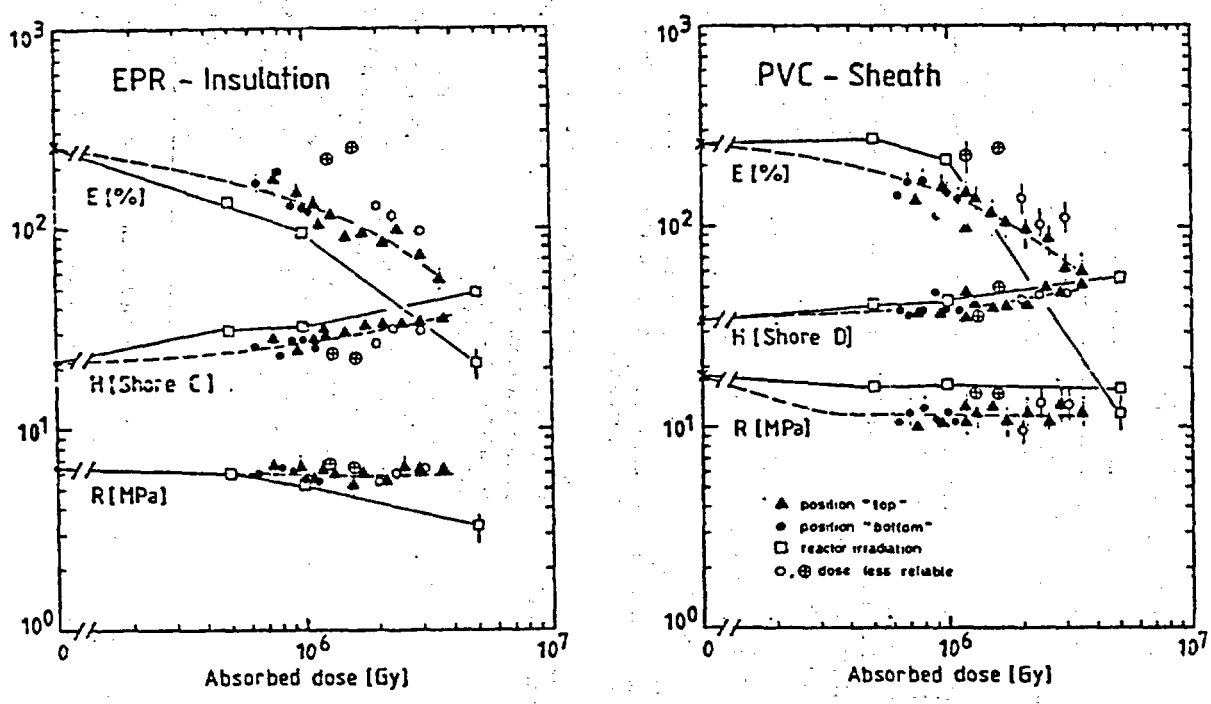

Figure 4.74 Comparison of EPR and PVC subjected to service and reactor irradiation (Ref. 4.117)
Reproduced with permission from Dr. Helmut Schonbacher, CERN, Switzerland.

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.		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.	Aging exposure affects LOCA performance (F). Note, all three Hypalon formulations were different. In fact, US(EPR)Hyp. was less dense than other two.		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.	Specimens pre-aged with lower 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_o 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_o 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 Material	e/e$_o$ at Different Dose Rates			
	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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