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Expanded Materials Degradation Assessment (EMDA)

Volume 5: Aging of Cables and Cable Systems

Office of Nuclear Regulatory Research

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Expanded Materials Degradation Assessment (EMDA)

Volume 5: Aging of Cables and Cable Systems

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ABSTRACT

In NUREG/CR-6923, “Expert Panel Report on Proactive Materials Degradation Assessment,” referred to as the PMDA report, NRC conducted a comprehensive evaluation of potential aging-related degradation modes for core internal components, as well as primary, secondary, and some tertiary piping systems, considering operation up to 40 years. This document has been a very valuable resource, supporting NRC staff evaluations of licensees’ aging management programs and allowing for prioritization of research needs.

This report describes an expanded materials degradation assessment (EMDA), which significantly broadens the scope of the PMDA report. The analytical timeframe is expanded to 80 years to encompass a potential second 20-year license-renewal operating-period, beyond the initial 40-year licensing term and a first 20-year license renewal. Further, a broader range of structures, systems, and components (SSCs) was evaluated, including core internals, piping systems, the reactor pressure vessel (RPV), electrical cables, and concrete and civil structures. The EMDA uses the approach of the phenomena identification and ranking table (PIRT), wherein an expert panel is convened to rank potential degradation scenarios according to their judgment of susceptibility and current state of knowledge. The PIRT approach used in the PMDA and EMDA has provided the following benefits:

- Captured the status of current knowledge base and updated PMDA information,
- Identified gaps in knowledge for a SSC or material that need future research,
- Identified potential new forms of degradation, and
- Identified and prioritized research needs.

As part of the EMDA activity, four separate expert panels were assembled to assess four main component groups, each of which is the subject of a volume of this report.

- Core internals and piping systems (i.e., materials examined in the PMDA report) – Volume 2
- Reactor pressure vessel steels (RPV) – Volume 3
- Concrete civil structures – Volume 4
- Electrical power and instrumentation and control (I&C) cabling and insulation – Volume 5

This volume summarizes the results of an assessment of the aging and degradation of cable and cable insulation by an expert-panel. The main objective of the work was to evaluate these cable systems in NPPs where, based on specific operating environments, degradation is likely to occur, or may have occurred; to define relevant aging and degradation modes and mechanisms; and, to perform systematic assessment of the effects of these aging related degradation mechanisms during continued operation up to 80 years. The approach utilized by each expert panel was based on the Phenomena Identification and Ranking Technique (PIRT) process to identify safety-relevant phenomena and assess their importance as well as identify and prioritize research needs. Additional objectives of this effort are to determine the degradation mechanisms known for cable systems (cables, wires, insulation, terminations, and

splices) specifically listing the current knowledge on aging degradation of cable and cable systems and the confidence level of this knowledge

The panelists used the PIRT process to prioritize the different material/environmental concerns and the PIRT scores are shown in Appendix A. There are several notable trends. First, the panelists were in agreement as to the present levels of knowledge and overall aging related susceptibility of cable insulation materials, as demonstrated by the uniformity of the knowledge and susceptibility scores. Further, there were very few material/mode combinations where susceptibility was ranked above “3” with the generic susceptibility increasing with increasing severity in environment conditions. The knowledge ranking was either 2 or 3 for all materials, environments, and conditions considered. This is likely a reflection on the 40 years of accumulated information on generic aging although this may not extend to specific plant locations/conditions, as noted above.

The panelists found that the main area of uncertainty for extending NPP life beyond 60 years relates to the pre-aging carried out during the equipment qualification (EQ) process and whether it can adequately predict aging over that time scale. However, most concerns are based on the premise that cables will be exposed to the operating and design basis environments (temperature, radiation, humidity, chemical spray, and other environmental factors) that were used in the EQ process. The current understanding, based on general opinion and utility experience, is that most cables are exposed to environments that are considerably less severe than the design environment. Actual environmental conditions should be quantified by measurement and analysis so that the temperatures and dose rates to which different types of cable are exposed are quantified over their qualified life. That information would clarify the necessity and priorities for addressing the concerns raised in Chap. 5.

FOREWORD

According to the provisions of Title 10 of the *Code of Federal Regulations* (CFR), Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," licensees may apply for twenty-year renewals of their operating license following the initial forty-year operating period. The majority of plants in the United States have received the first license renewal to operate from forty to sixty years and a number of plants have already entered the period of extended operation. Therefore, licensees are now assessing the economic and technical viability of a second license renewal to operate safely from sixty to eighty years. The requirements of 10 CFR, Part 54 include the identification of passive, long-lived structures, systems, and components which may be subject to aging-related degradation, and the development of aging management programs (AMPs) to ensure that their safety function is maintained consistent with the licensing basis during the extended operating period. NRC guidance on the scope of AMPs is found in NUREG-1800 "Standard Review Plan for Review of License Renewal Applications for Nuclear Power Plants" (SRP-LR) and NUREG-1801, "Generic Aging Lessons Learned (GALL) Report."

In anticipation to review applications for reactor operation from sixty to eighty years, the Office of Nuclear Reactor Regulation (NRR) requested the Office of Nuclear Regulatory Research (RES) to conduct research and identify aging-related degradation scenarios that could be important in this timeframe, and to identify issues for which enhanced aging management guidance may be warranted and allowing for prioritization of research needs. As part of this effort, RES agreed to a Memorandum of Understanding with the U.S. Department of Energy (DOE) to jointly develop an Expanded Materials Degradation Assessment (EMDA) at Oak Ridge National Laboratory (ORNL). The EMDA builds upon work previously done by RES in NUREG/CR-6923, "Expert Panel Report on Proactive Materials Degradation Assessment." Potential degradation scenarios for operation up to forty years were identified using an expert panel to develop a phenomena identification and ranking table (PIRT). NUREG/CR-6923 mainly addressed primary system and some secondary system components. The EMDA covers a broader range of components, including piping systems and core internals, reactor pressure vessel, electrical cables, and concrete structures. To conduct the PIRT and to prepare the EMDA report, an expert panel for each of the four component groups was assembled. The panels included from 6 to 10 members including representatives from NRC, DOE national laboratories, industry, independent consultants, and international organizations. Each panel was responsible for preparing a technical background volume and a PIRT scoring assessment. The technical background chapters in each volume summarizes the current state of knowledge concerning degradation of the component group and highlights technical issues deemed to be the most important for subsequent license renewal.

Detailed background discussions, PIRT findings, assessments, and comprehensive analysis for each of these component groups are presented in the following chapters.

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ABBREVIATED TERMS

%, percent

°C, degrees Celsius

°F, degrees Fahrenheit

γ, gamma

γ', gamma prime

Δ, delta; denotes change

$\Delta\sigma_y$, change in yield strength

σ, sigma; denotes variability

τ, UMD recovery time

ϕ, flux

ϕt, fluence

<T_{dam}>, total average damage energy per atom

0.5T, ½T compact tension specimen

1TC(T), 1T compact tension specimen

3/4-t, three-quarters of the way through the vessel

3DAP, three-dimensional atom probe

41J, 41 joules (absorbed energy level in which Charpy v-notch specimen reaches the ductile-to-brittle transition temperature)

AAR, alkali-aggregate reaction

ADP, annealing demonstration project

AERE, Atomic Energy Research Establishment (UK)

AFCEN, French Society for Design and Construction and In-Service Inspection Rules for Nuclear Islands

AMP, aging management program

AMR, aging management review

ANO-1, Arkansas Nuclear One Unit 1

APT, atom probe tomography

ASME, American Society of Mechanical Engineers

ASTM, American Society for Testing and Materials

at %, atomic percent

ATI, ATI Consulting

ATR, Advanced Test Reactor

B&W, Babcox and Wilcox

BAC, boric acid corrosion

BR3, Belgian reactor 3

BWR, boiling water reactor

C, carbon

C&LAS, carbon and low alloy steels

CASS, cast austenitic stainless steel

CFR, *Code of Federal Regulations*

Cl^-, chloride ion

cm, centimeter

Cr, chromium

CR, cold rolled

CRD, control rod drive

CRDM, control rod drive mechanism

CREEP, thermal creep

CREV, crevice corrosion

CRIEPI, Central Research Institute of Electric Power Industry (Japan)

CRP, Cu-rich precipitates

Cu, copper

CUF, cumulative fatigue usage factor

CVCS, chemical and volume control system

CVN, Charpy V-notch

CW, cold-worked

DBTT, ductile-to-brittle transition temperature

DEBOND, debonding

DH, dissolved hydrogen

DOE, U.S. Department of Energy

dpa, displacements per atom

E, neutron spectrum flux

EBSD, electron backscatter diffraction

EC, erosion–corrosion

ECCS, emergency core cooling system

ECP, electric chemical potential

$\mathbf{E_d}$, displacement threshold energy

EDF, Electricite de France

EDS, energy-dispersive X-ray spectroscopy

EK, Erickson Kirk

Emb., Embrittlement

EMDA, Extended Materials Degradation Assessment

Env., environmental

EONY, Eason, Odette, Nanstad, and Yamamoto

EPMDA, Extended Proactive Materials Degradation Assessment

EPR, electrochemical potentiokinetic reactivation

EPRI, Electric Power Research Institute

eV, electron volt

FAC, flow-accelerated corrosion

FAT, corrosion fatigue

Fe, iron

$\mathbf{f_p}$, volume fraction

FR, fracture resistance

GALL, generic aging lessons learned

GALV, galvanic corrosion

GC, general corrosion

h, hour

HAZ, heat-affected zone

HC, high cycle

HSSI, Heavy-Section Steel Irradiation

HSST, Heavy Section Steel Technology

HWC, hydrogen water chemistry

HWR, heavy water reactor

I&C, instrumentation and controls

IA, irradiation assisted

IAEA, International Atomic Energy Agency

IASCC, irradiation-assisted stress corrosion cracking

IC, irradiation creep

IG, intergranular

IGC, intergranular corrosion

IGF, intergranular fracture

IGSCC, intergranular stress corrosion cracking

IMP, Implementation

IMT, Issue Management Table

in., inch

INL, Idaho National Laboratory

IPA, integrated plant assessment

IVAR, irradiation variables

JAEA, Japan Atomic Energy Agency

JAERI, Japan Atomic Energy Research Institute

JMTR, Japan Materials Testing Reactor

JNES, Japan Nuclear Safety Organization

JPDR, Japan Power Demonstration Reactor

K, stress intensity

keV, thousand electron volt

$\mathbf{K_{Ia}}$, crack-arrest toughness

$\mathbf{K_{Ic}}$, fracture toughness

$\mathbf{K_{Jc}}$, elastic-plastic fracture toughness at onset of cleavage fracture

LAS, low alloy steel

LBP, late-blooming phase

LC, low cycle

LMC, lattice Monte Carlo

LRO, long-range ordering

LTCP, low-temperature crack propagation

LTO, long-term operation

LWR, light water reactor

LWRS, Light-Water Reactor Sustainability

LWRSP, Light Water Reactor Sustainability Program

MA, mill-anneal

MDM, materials degradation matrix

MeV, million electron volts

MIC, microbially induced corrosion

MF, matrix feature

MIG, metal inert gas (welding)

Mn, manganese

MO, Mader and Odette

Mo, molybdenum

MOU, memorandum of understanding

MOY, Mader, Odette, and Yamamoto

MPa√m, stress intensity factor; fracture toughness in units of megapascal square root meter

MPC, Materials Properties Council

n/cm², fluence

n/cm²·s, flux

NE, DOE Office of Nuclear Energy

NEI, Nuclear Energy Institute

Ni, nickel

NMCA, noble metal chemical addition

NOSY, Nanstad, Odette, Stoller, and Yamamoto

NPP, nuclear power plant

NRC, U.S. Nuclear Regulatory Commission

NWC, normal water chemistry

ORNL, Oak Ridge National Laboratory

P, phosphorous

PA, proton annihilation

PIA, postirradiation annealing

PIRT, phenomenon identification and ranking technique

PIT, pitting

PLIM, Nuclear Power Plant Integrity Management

PMDA, Proactive Materials Degradation Assessment

PMMD, proactive management of materials degradation

PNNL, Pacific Northwest National Laboratory

PRA, primary recoil atom

PRE, Prediction of Radiation Embrittlement

PREDB, Power Reactor Engineering Database

PSF, Poolside Facility

PT, penetration test

PTS, pressurized thermal shock

PWHT, post-weld heat treatment

PWR, pressurized water reactor

PWROG, Pressurized Water Reactor Owners Group

PWSCC, primary water stress corrosion cracking

R&D, research and development

RADAMO, SCK-CEN TR model and corresponding TR database

RCS, reactor coolant system

RES, NRC Office of Nuclear Research

RHRS, residual heat removal system

RIS, radiation-induced segregation

RPV, reactor pressure vessel

RSE-M, Rules for In-Service Inspection of Nuclear Power Plant Components (France)

RT, reference temperature

SA, solution anneal

SANS, small-angle neutron scattering

SCC, stress corrosion cracking

SCK-CEN, Studiecentrum voor Kernenergie—Centre d'Etude de l'Énergie Nucléaire (Belgian Nuclear Research Centre)

SE(B), single-edge, notched bend

SEM, scanning electron microscopy

SG, steam generator

SIA, self-interstitial atom

SIS, safety injection system

SM, Stationary Medium Power

SMF, stable matrix feature

SR, stress relaxation

SS, stainless steel

SSC, system, structure, and component

SSRT, slow strain rate test

SW, swelling

T_0, fracture toughness reference temperature

T_{41J}, ductile-to-brittle transition temperature measured at 41 joules of Charpy impact energy

TEM, transmission electron microscopy

TG, transgranular

Th, thermal

T_i, irradiation temperature

TIG, tungsten inert gas (welding)

TiN, titanium nitride

TLAA, time-limited aging analysis

TMS, The Minerals, Metals and Materials Society

TR, test reactor

TT, reference transition temperature; thermal treatment

TTS, transition temperature shift

UCSB, University of California, Santa Barbara

UK, United Kingdom

UMD, unstable matrix defect

UNS, Unified Numbering System

U.S., United States

USE, upper-shelf energy

UT, ultrasonic test

VS, void swelling

VVER, Voda-Vodyanoi Energetichesky Reaktor (Water-Water Energetic Reactor)

WEAR, fretting/wear

Wstg., wastage

wt %, weight percent

Zn, zinc

1. INTRODUCTION

1.1 BACKGROUND

A variety of environmental stressors in nuclear power plants (NPPs), such as temperature, radiation, moisture/humidity, vibration, chemical spray, mechanical stress, and the oxygen present in the surrounding gaseous environment (usually air), can influence the degradation of low and medium electrical power and instrumentation and control (I&C) cables and their insulation. Over time these stressors can lead to degradation that, if not appropriately managed, could lead to insulation failure of the associated components, and potentially resulting in cables being unable to perform their intended safety function.

In the context of this report, low-voltage cables have ratings below 2,000 volt (V) and generally operate at voltages of 525 V alternating current (ac) and below or 250 V direct current (dc) and below. Medium-voltage cables are rated at 46 kilovolts (kV) and below. Most in-plant and underground cables are rated at up to 15 kV and are operated at 13 kV or less. Most safety-related medium-voltage cables rated at 5 kV are operated at 4,160 V. Some plants have short lengths of cable with operating voltages between 100 and 230 kV; these are plant-specific cables and are often not insulated with a polymer. As such, unique plant-specific cables are not covered by this report. Furthermore, high-voltage cables are not covered by this report.

This report uses the Phenomena Identification and Ranking Technique (PIRT) to1) identify safety-relevant phenomena, 2) assess their importance, and 3) identify and prioritize research needs (see Appendix A). The objective of this report is to determine the degradation mechanisms for the most-commonly utilized subject cables and their insulations that may prevent their intended performance of safety functions by specifically determining: (a) the current knowledge of these degradation mechanisms; (b) areas where there is a lack of knowledge; and, (c) the confidence level of the knowledge. The scope of this report includes low- and medium-voltage I&C and power cables and their insulation.

The purpose of this report is to establish the technical gaps for the operation of cables for 60–80 years. The need to monitor the condition of aging passive long-lived systems, structures, and components (SSCs), such as cables, is one of the most important aspects of plant life extension. Operating experience with cables has given rise to uncertainties about long-term performance of cables in nuclear facilities [1].

With respect to currently known degradation of cables aging and their management, the *Generic Aging Lessons Learned (GALL) Report* [2] describes the criteria for cable-condition monitoring in the following sections of Chap. XI, “Aging Management Programs (AMPs)”:

- XI.E1, “Insulation Material for Electrical Cables and Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements,”

- XI.E2, “Insulation Material for Electrical Cables and Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements Used in Instrumentation Circuits,” and

- XI.E3, “Inaccessible Power Cables Not Subject To 10 CFR 50.49 Environmental Qualification Requirements.”

These AMPs include low and medium voltage power and instrumentation cables in the scope of license renewal as a result of industry operating experience.

Operating experience has indicated failures of buried medium-voltage ac and low-voltage dc power cables due to insulation failure. NRC's Generic Letter (GL) 2007-01 [3] indicates that low-voltage cables have failed in underground applications due to a variety of causes, including manufacturing defects, damage caused by shipping and installation, exposure to electrical transients, and abnormal environmental conditions during operation. The NRC staff concluded that the likelihood of failure from any of these causes increases over time as the cable insulation degrades [4].

Industry reports such as the Electric Power Research Institute's (EPRI) reports TR1021629, 1020804, and1020805 [5–7] focus on cable aging management and describe testing and assessment criteria and potential corrective actions.

1.2 APPROACH

The expert elicitation process conducted in this study is based on PIRT, which has been used by NRC in many applications in the last decade. The PIRT process provides a systematic means of obtaining information from experts and involves generating lists (tables) of degradation phenomena where "phenomena" can also include a particular reactor condition, a physical or engineering approximation, a reactor component or parameter, or anything else that might influence some relevant figure-of-merit. The process usually involves ranking of these phenomena using some scoring criteria in order to help determine what are more important. That ranking as well as the information obtained to explain the ranking allows users to prioritize research needs for providing technical basis to address a safety issue, or to support some other decision-making process. The PIRT methodology brings into focus the phenomena that dominate an issue, while identifying all plausible effects to demonstrate completeness.

The cable system expert panel used the PIRT process to identify safety-relevant phenomena, assess their importance, and identify and prioritize research needs. The PIRT process followed by the panel consisted of the following steps:

1. A list of relevant insulation materials was developed, along with a hierarchical identification of the various degradation modes and environments that could impact each of the insulation materials and their performance. A consensus of the issues to be assessed was obtained through discussions among the members of the panel. Crosscutting issues were identified.

2. A database was developed, containing the independent scoring for each of the above PIRT criteria by each panelist for each insulation material and their related degradation modes. The panel then discussed the individual scoring, and each panelist was provided the opportunity to keep or revise their original scores based on this discussion.

3. Based on the final set of scores, the mean, median, and standard deviation were determined for each potential degradation mode/mechanism.

2. U.S. NUCLEAR PLANT CABLE INSULATION AND JACKET MATERIALS

2.1 INTRODUCTION

NPPs may have hundreds of miles and several hundred different types and sizes of electrical wire and cable. Most cables used in NPPs can be grouped into the following categories, based on their application and design:

- power cables
- control cables
- instrument cables
- thermocouple cables
- specialty cables

Power cables may be further separated by voltage rating into low-voltage (2,000 V or less), medium-voltage (greater than 2,000 through 46,000 V), and, high-voltage (greater than 46,000 V).

2.2 APPLICABLE STANDARDS

The Institute of Electrical and Electronics Engineers (IEEE) Standard 383-1974, *IEEE Standard for Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stati*ons, Sect. 2.3, "Testing to Qualify for Normal Operation," [8] provides many of the standards that were used to make cables for existing U.S. nuclear plants.

For low-voltage cables, the following Insulated Cable Engineers Association (ICEA) and National Electrical Manufacturers Association (NEMA) standards were specified:

- NEMA WC3/ICEA S-19-81, *Rubber Insulated Wire & Cable for the Transmission & Distribution of Electrical Energy* [9].

- NEMA WC7/ICEA S-66-524, *Cross-Linked Polyethylene Insulated Wire & Cable for Transmission & Distribution of Electrical Energy* [10].

- NEMA WC8/ICEA S-68-516, *Ethylene-Propylene Insulated Wire & Cable for the Transmission & Distribution of Electrical Energy* [11].

For medium-voltage cables, the following more recent standards are utilized:

- Association of Edison Illuminating Companies (AEIC) CS5, S*pecifications for Polyethylene and Cross-Linked-Polyethylene-Insulated Shielded Power Cables rated 5000–35000 V*. [12]

- AEIC CS6, *Specifications for Ethylene-Propylene-Rubber-Insulated Shielded Power Cables Rated 5 - 46 kV* [13] (AEIC CS6 was replaced by AEIC CS8 [14].)

The insulation for medium-voltage cables used in existing U.S. NPPs includes butyl rubber, ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE), and silicone rubber. Most of the cables are insulated with EPR; black EPR (calcined clay) was used in the early 1970s, and pink EPR (calcined, silane-treated clay) was used in the late 1970s. High-temperature Kerite® (HTK) is a special, discharge-resistant formulation that is brown in color. A limited number of the cables installed in the late 1960s or early 1970s were insulated with butyl rubber. Jackets were made of neoprene, Hypalon® [chlorosulfonated polyethylene (CSPE)], and chlorinated polyethylene (CPE). Polyvinyl chloride (PVC) was used on some XLPE-insulated medium-voltage cable.

TheTR-103841, *Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report*, Rev. 1 [15] contains a review of materials used in safety-related applications. It is stated that XLPE and EPR are the two most widely used insulations; silicone rubber and CSPE are used to a significantly lesser extent. Predominant materials for jackets are CSPE (Hypalon®), neoprene, and, to a limited extent, CPE. Neoprene was the dominant jacket material in the early 1970s; CSPE became dominant in the late 1970s. Neoprene was rarely used after the early 1980s.

2.3 DATABASE

In the Sandia National Laboratories (SNL) contractor report SAND96-0344, *Aging Management Guideline for Commercial Nuclear Power Plants Electrical Cable and Terminations* [16], and in EPRI report EPRI TR-103841 [15], a database was used to look at manufacturers and insulations used in nuclear plants. The predominant manufacturers are shown in Table 2.1.

Table 2.1. Top Ten manufacturers and insulations used in nuclear plants [15]

Rank	Manufacturer	Database Entries	Percentage of total
1	Rockbestos/Cerro	363	23
2	Okonite	359	23
3	Boston Insulated Wire	150	9
4	Anaconda Wire and Cable	128	8
5	Kerite Company	109	7
6	Brand-Rex	98	6
7	Samuel Moore	77	5
8	General Electric	69	4
9	Raychem	46	3
10	Continental Wire & Cable Corporation	37	2
	Subtotal of top ten manufacturers/suppliers	1,436	90
	Total	1,590	100

Source: EPRI TR-103841 (1994) [15]

There were 34 manufacturers listed; of those, 10 manufacturers supplied 90% of the total, and the top 3 represent 55% of the total. However, Boston Insulated Wire (BIW), Anaconda Wire and Cable, General Electric (GE), Raychem, and Continental Wire & Cable Corporation no longer supply cables to the nuclear industry. Kerite discontinued its low-voltage cable line.

Presently, only Okonite, Rockbestos, and Brand-Rex supply nuclear-grade low-voltage cables. Kerite supplies medium-voltage cables through Rockbestos-Suprenant Cable Corporation.

A sorting of the 34 manufacturers' insulations (Table 2.2) shows that XLPE and EPR are the predominant insulation materials.

Table 2.2. A sort of the 34 manufacturers' insulations for U.S. NPPs [15, 16]

Rank	Manufacturer	Insulation	Plants
1	Rockbestos	Firewall III XLPE	61
2	Anaconda Wire and Cable	EPR	35
3	Brand-Rex	XLPE	30
4	Okonite	EPR	26
5	Kerite Company	HTK	25
6	Rockbestos	Coax XLPE	24
7	Raychem	XLPE	23
8	Samuel Moore	EPR	19
9	BIW	Bostrad 7E EPR	19
10	Kerite®	Flame retardant EPR	13

A sorting of the insulation materials (Table 2.3) shows that XLPE and EPR are 72% of the total entries. The top four materials (XLPE, EPR, silicone rubber and Kerite®) are over 80% of the total.

Table 2.3. A sort of the insulation materials for U.S. NPPs [15]

Rank	Insulation Material	Database Entries	Percentage of total
1	XLPE	439	36
2	EPR	434	36
3	Silicone rubber	63	5
4	Kerite®	61	5
5	Polyethylene	52	4
6	ETFE	39	3
7	Flame retardant	36	3
8	CSPE	28	2
9	Butyl rubber	20	2
10	Mineral	12	1
11	PVC	12	1
12	Polyimide	8	1
13	Polypropylene	3	0
14	XLN (cross-linked neoprene)	3	0
15	Neoprene	2	0
16	Industrite®	2	0
17	Styrene	1	0
	Total	1,215	

2.4 INSULATION MATERIALS

The 3 most common materials used conform to the ICEA/NEMA specifications: XLPE per ICEA S-66-524 [10], EPR per ICEA S-68-516 [11], and silicone rubber per ICEA S-19-81 [9]. The formulations for the materials are specified by the manufacturer. Kerite Company, as an example, uses special formulations that at one time may not have been to ICEA standards. ICEA standards have since been modified to include these unique materials. The term “flame retardant” may refer to low-voltage XLPE or EPR insulations with flame retardants. For low-voltage cables, most XLPEs were flame retardant, but EPRs may have been manufactured with or without flame retardants. When no flame-retardants were employed, a CSPE jacket was commonly used over the EPR to provide the required flame retardant characteristics. In most cases, the CSPE layer was bonded to the EPR. In this two-layer material, the more age-sensitive CSPE layer becomes the life-limiting component of the cable, both in susceptibility to exposure during a loss of coolant accident (LOCA) and handling due to enhanced embrittlement.

Most insulation materials are thermoset (i.e., they are materials that are cross-linked at the fabrication stage). Polyethylene, ethylene tetrafluoroethylene (ETFE), PVC, polyimide, and polypropylene are all thermoplastics. Styrene may be polystyrene, a thermoplastic, or styrene butadiene rubber, which is a thermoset material; neither styrene insulation is commonly used today. Industrite® is a BIW cable with EPR insulation and a thermoset jacket. Low-temperature thermoplastics are not used where high thermal excursions can occur because the materials will melt. These materials will not be used in new nuclear plants because their low melting point is incompatible with higher temperatures postulated for current potential accident scenarios.

Polyimide is used in a tape form and has limited application in nuclear plants [17]. Under extreme conditions (high temperatures, high humidity, and extend time) polyimide has the potential to deteriorate via hydrolysis. Deterioration of the film may result in cracking, leading to shorting or low insulation resistance in the presence of water or condensation. Fluorinated ethylene propylene (FEP) is commonly used as an adhesive in a polyimide tape wrap system. FEP loses about half of its original elongation when irradiated to 0.35 Mrad [3,500 gray (Gy)]. Failure of the adhesive may allow unraveling and separation of the film layers.

ETFE is available in many different formulations. It is used in limited non-safety-related applications, where thin walls are required and high radiation resistance is not needed, but cables insulated with EFTE are not widely used as nuclear cables. Comparatively, neoprene is generally not used as insulation either. Alternatively, EPR insulation has been used in conjunction with a neoprene jacket and is in service in some plants today. It was also applied to individual EPR-insulated systems to provide fire retardancy; these configurations are found in many plants that were built in the 1970s.

CSPE was used in limited applications as insulation in the late 1960s and early 1970s but is no longer used as insulation. CSPE became the dominant jacket material in the late 1970s to early 1980s. DuPont ceased making CSPE in 2009. Most manufacturers are no longer using CSPE as a jacket, with the exception of Rockbestos, which has found and qualified an alternate source. A few plants have some butyl-rubber-insulated low- and medium-voltage cables. However, even in the plants having some low-voltage cables insulated with butyl rubber, much of the cable system has cables that are insulated with either EPR or XLPE. In containment, cables insulated with butyl rubber were replaced with cables requiring environmental qualification.

2.5 JACKETING

Jacketing refers to a broad range of coverings used in cable constructions to protect various cable components from environmental effects. The external (outer) jacket is used to protect the underlying insulation, shields, and tapes from mechanical damage (e.g., abrasion or cutting), fire (one example for fire mitigation includes Neoprene or CSPE jacketing over EPR insulation), chemicals/solvents, sunlight, moisture, and the effects of direct burial. A jacket may also be used as a beta shield and to seal against moisture in a splice or termination. Electrically, jacketing may also be required to insulate a shield or to armor it from ground. For some low-voltage cables, the jacket may also be part of the insulation system, i.e. the jacket is bonded to the insulation. In unshielded medium-voltage power cables, the jacket is specially formulated for resistance to surface tracking and discharge. In either case, the jacket may be the life-limiting factor of the conductor if it is bonded to the insulation.

ICEA standards have called out jacketing specifications in the past. The most abundant jacketing materials employed in existing NPPs (unless they have been replaced) are PVC, CSPE (Hypalon®), Neoprene, and CPE. However, PVC was banned in the late 1970s and is no longer used. Comparatively, CPE has been deployed as jacketing material over medium voltage cables, but is also no longer used in manufacturing of new cables for NPPs. Due to poor thermal performance, neoprene was replaced as a jacket material with CSPE jacketing and is also no longer used in manufacturing of new cables for NPPs. In very limited cases, XLPO, ETFE, and other specialized jackets can be used. For silicone rubber, inorganic braids were generally employed (e.g., asbestos); however, glass braiding is now the accepted replacement for inorganic braids.

3. OPERATING EXPERIENCE, RESEARCH, OR LABORATORY EXPERIENCE

Cable insulation may gradually degrade for a variety of reasons. The most common causes of electrical cable failures are manufacturing defects, damage caused by shipping and installation, and exposure to electrical transients or abnormal environmental conditions during operation. Further, the likelihood of failure from any of these causes increases over time as the cable insulation ages. Other causes of degradation include overheating, water treeing, high-voltage stress, moisture ingress, and design-basis accident (DBAs). These electrical cable failures could result in safety-related and nonsafety-related equipment failures. Although NPP safety-related electrical systems are designed to be single-failure proof, undetected degradation of cables can result in multiple equipment failures. For example, as described in Generic Letter 2007-01 [2]:

- The failure of power cables that connect the offsite power to a safety bus can prevent offsite power recovery for far longer than the coping time originally considered for station blackout (SBO) conditions. An incipient failure of these cables may be hard to detect because, in some plants, these cables remain de-energized during power generation, or not loaded if energized, and are not periodically energized for testing.

- The failure of the power cables from an Emergency Diesel Generator (EDG) to the safety buses can prevent recovery of standby power from the EDG and result in the unavailability of one (or more) train(s) of accident mitigation systems during a loss-of-offsite-power event.

- The failure of the power cables to an emergency service water (ESW) or component cooling water pump can disable one (or more) train(s) of emergency core cooling systems unless redundant pump(s) are available in the same train and lined up to supply sufficient cooling for the entire train. If the EDGs are cooled by ESW or service water, the cable failure can disable the EDG and cause the loss of one (or more) train(s) of emergency standby power.

Significant literature is available on pre-aging, condition monitoring, and aging management. This section highlights relevant publications in the aforementioned areas in addition to results from Generic Letter 2007-01.

3.1 GENERIC LETTER 2007-01 RESULTS

Generic Letter (GL) 2007-01 [3] discussed a significant number of cable failures that occurred under normal service conditions within a service interval of 20 to 30 years, which is before the renewed license period and before the end of the expected life span of the cables (Figures 3.1 through 3.4).

The GL 2007-01 Summary Report [1] states that there is an increasing trend of both in-service and during testing of cable failures. Cable failures have resulted in plant transients and shutdowns, loss of safety redundancy, entries into limiting conditions for operation, and challenges to plant operators. The increasing number of cable failures occurred before the renewed license period and before the end of the expected life span of the cables, as shown in Figures 3.1 through 3.4.

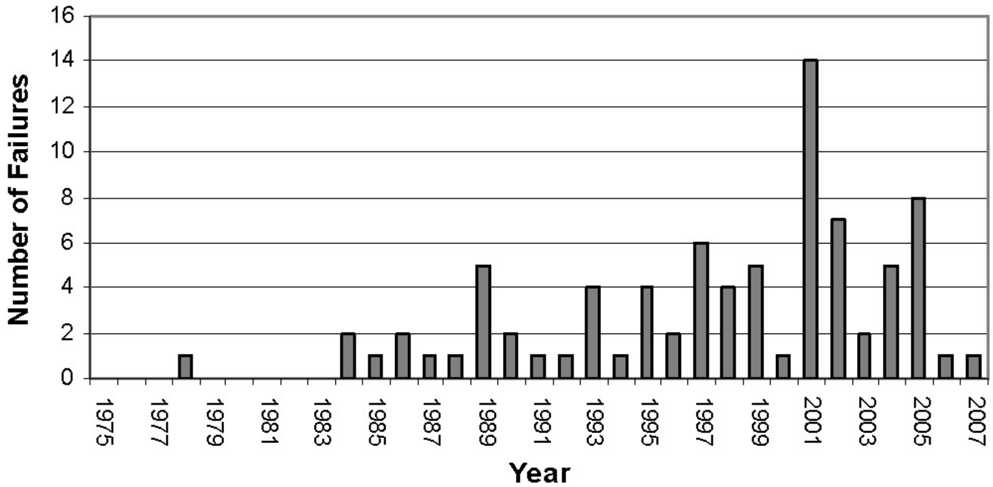

Figure 3.1. Cables that failed while in service. Source: GL 2007-01 Summary Report (Figure 2) [1].

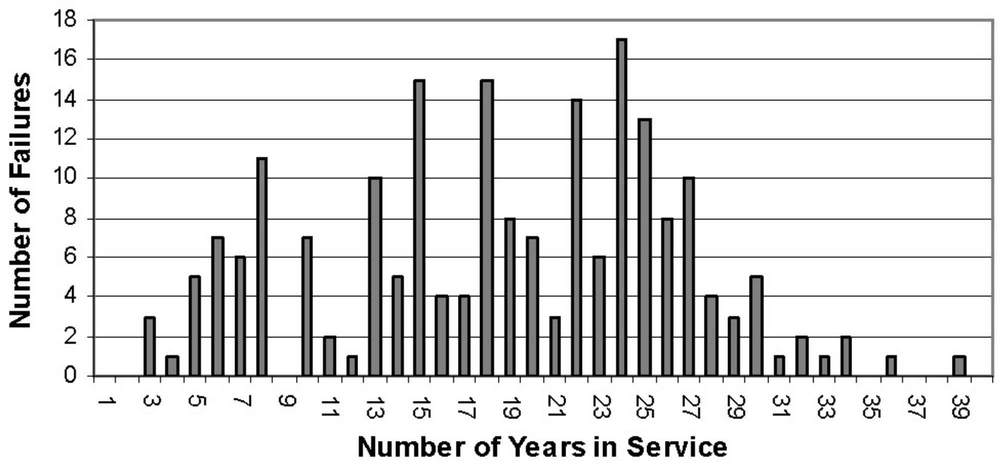

Figure 3.2. Failures per cable age (years in service). Source: GL 2007-01 Summary Report (Figure 4) [1].

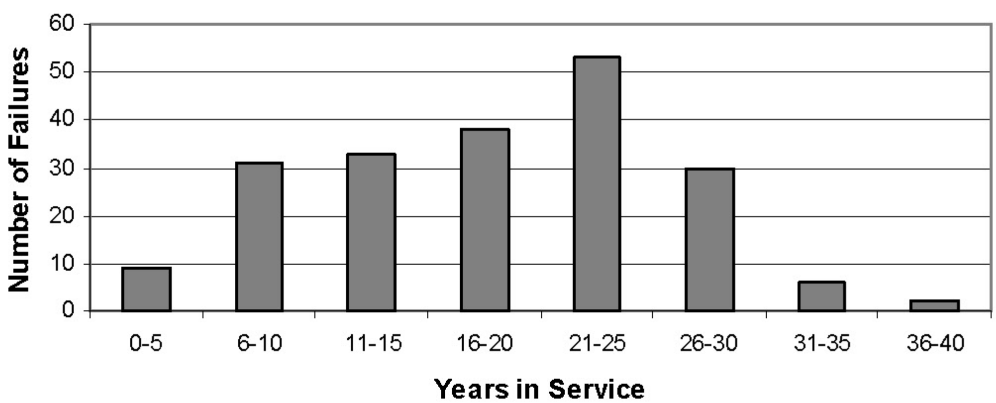

Figure 3.3. Number of failures per five year service intervals. Source: GL 2007-01 Summary Report (Figure 5) [1].

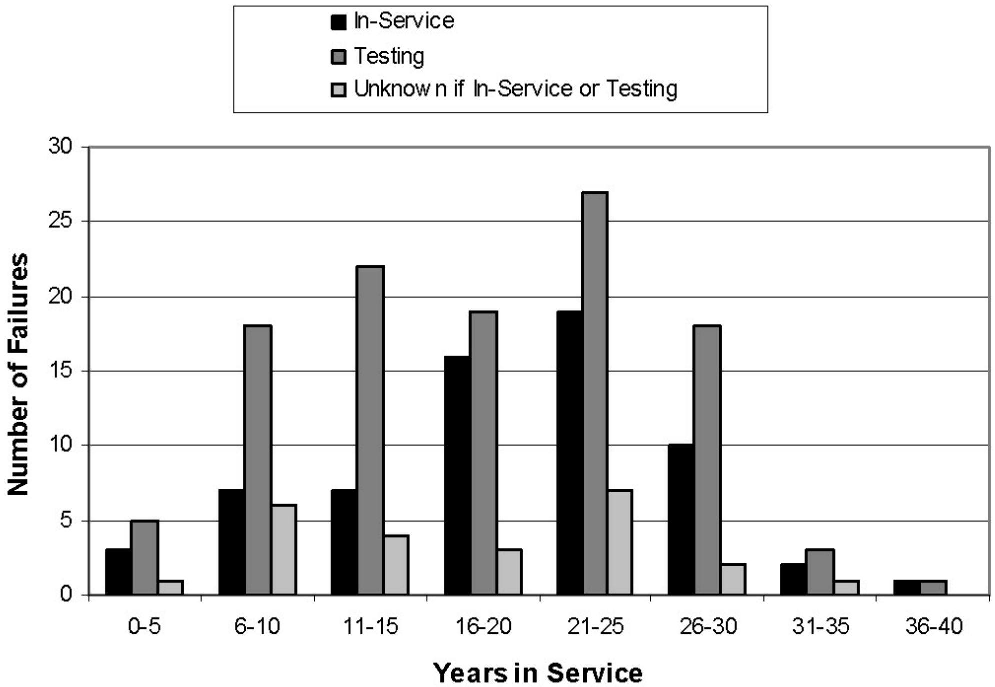

Figure 3.4. Failures per five-year service intervals (in service, testing, unknown). Source: GL 2007-01 Summary Report (Figure 6) [1].

The *GL 2007-01 Summary Report* concludes that for the failures reported, the licensees identified a variety of root causes and contributing factors for the remaining cable failures (Figure 3.5). Some of the responses indicated that the cause was unknown, but described conditions surrounding the cable failure. However, multiple causes and factors may have contributed to one failure, and possible causes can be assigned to responses that indicated an unknown cause with known conditions, such as the presence of water or moisture [17].

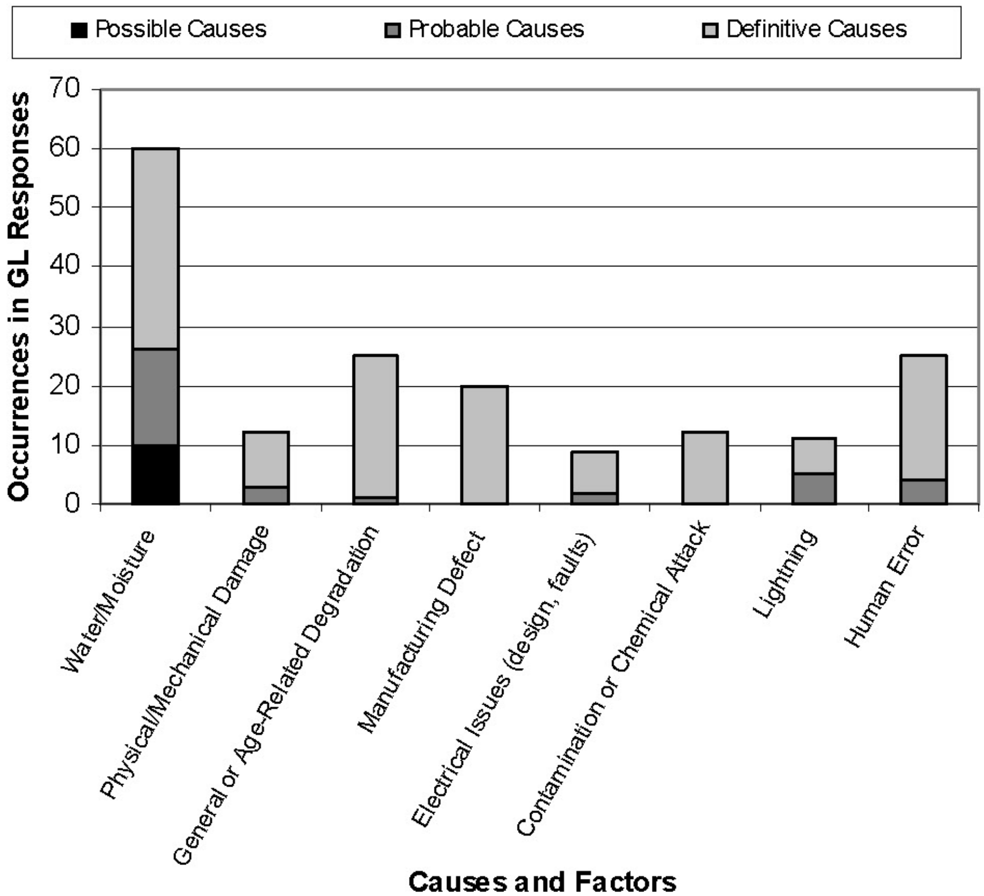

Figure 3.5. Causes and causal factors for all cable failures. Source: GL 2007-01 Summary Report (Figure 22) [1].

3.2 AGING

3.2.1 Aging—United States

Cable aging and degradation has been studied and evaluated by a number of institutions during the past 30 years. There are a number of key reports in the open literature, which summarize past histories, and key trends in insulation degradation. These include:

- NUREG/CP-0179, *Proceedings of the International Conference on Wire System Aging* [18], discusses the topics covered in a conference held in April 2002. The conference focused on reliability physics modeling of wire system aging, fire risk assessment of wire system aging, risk significance of wire system aging, and prognostics and diagnostics for installed wire systems. Technical Session 4 focused on condition monitoring, and several presentations were made on various techniques. The following highlights key conclusions from Technical Session 4. The aerospace community has investigated wiring integrity and nondestructive assessment of insulation degradation to provide tools, which detect flaws and predict remaining life. Specifically, ultrasonic inspection, infrared thermography, and chemical sensing of by-products are demonstrated as diagnostic tools to characterize cable insulation. A nuclear magnetic resonance (NMR) relaxation technique for detecting aging in XLPO insulations and CSPE cable jackets has been demonstrated. Broadband impedance is discussed and shown to be sensitive to changes in the physical and chemical state of aircraft wiring. In addition, wire impedance was measured for wires exposed to humidity, and it was shown that the resistance increases. To determine remaining life of insulation through detection of microvoid characteristics, the energy stored within the electric field between the wires is affected by microvoid growth and thus, capacitance can be correlated to microvoid content.

- NUREG/CR-6384, *Literature Review of Environmental Qualification of Safety-Related Electric Cables* [19], is a comprehensive review of literature related to aging characterization, LOCA testing, and condition-monitoring methods. Volume 1 is a summary of past work; Volume 2 provides the literature analysis and appendices. Volume 1 summarizes uncertainties in the Arrhenius methodology, effects of dose rates, inverse temperature considerations for semi-crystalline materials, and simultaneous vs. sequential aging. For LOCA simulations, although elongation-at-break has been the most consistent way to monitor degradation, weight and tensile strength have also been chosen to monitor the condition of cable insulation. This literature review states that the behaviors of coaxial cables and cables with bonded jackets require further characterization during LOCA exposures. Furthermore, acceptance criteria for condition-monitoring tests should be established to assure that cables with certain aging conditions could survive an accident during the design life of a nuclear plant.

- NUREG/CR-2763, *Loss of Coolant Accident (LOCA) Simulation Tests on Polymers: The Importance of Including Oxygen* [20], presents results from experiments to survey the effects of material degradation on both aging conditions and the oxygen concentration during a LOCA simulation. For several materials, including EPR, the concentration of oxygen during a LOCA simulation was found to be an important parameter, and more degradation occurred when oxygen was present. In addition, this study concludes that for EPR insulation, dose-rate-induced effects are amplified during the LOCA simulation.

- NUREG/CR-5772, Volume 1, *Aging, Condition Monitoring, and Loss-of-Coolant (LOCA) Tests of Class 1E Electrical Cables: Crosslinked Polyolefin Cables* [21], describes the results of aging, condition monitoring, and accident testing of XLPO cables. The cables were aged for up to 9 months under simultaneous thermal and radiation aging followed by a sequential accident exposure, which included high-dose-rate irradiation followed by a simulated LOCA steam exposure. The test results indicate that most properly installed XLPO cables should be able to survive an accident after 60 years for total aging doses on the order of 400 kGy (40 Mrad) and for moderate ambient temperatures on the order of 50 °C to 55 °C (122 °F to 131 °F) (potentially higher or lower, depending on material specific activation energies and total radiation doses), Of the measurements tested, elongation was found to be the best condition-monitoring method and compressive modulus and density could also be effective for monitoring residual life.

- NUREG/CR-5772, Volume 2, *Aging, Condition Monitoring, and Loss-of-Coolant (LOCA) Tests of Class 1E Electrical Cables: Ethylene Propylene Rubber Cables* [22], discusses the results of aging, condition monitoring, and accident testing of EPR cables. The research program consisted of simultaneous thermal and radiation aging of EPR cables followed by a sequential accident exposure, which included high-dose-rate irradiation followed by a simulated LOCA steam exposure. The research concluded the following: (1) the test results indicate that most properly installed EPR cables should be able to survive an accident after 60 years for total aging doses on the order of 150 to 200 kGy (15 to 20 Mrad) and for moderate ambient temperatures on the order of 45 °C to 55 °C (81 °F to 131 °F) potentially higher or lower, depending on material specific activation energies and total radiation doses); and, (2) of the methods tested, elongation is the best condition monitoring method. Although a quantitative generic acceptance criterion is difficult to establish based on these tests, a reasonable range (that is likely to be fairly conservative) would be about 50% to 100% remaining absolute elongation, Results of accident testing of cables aged at lower temperatures and radiation dose rates are included in this report.

- NUREG/CR-5772, Volume 3, *Aging, Condition Monitoring, and Loss-of-Coolant (LOCA) Tests of Class 1E Electrical Cables: Miscellaneous Cable Types* [23], describes the results of aging, condition monitoring, and accident testing of other cable types, including cables with SiR, Kerite® , and Kapton insulations. Table 1 in the report describes the cables included in the test program. The research program consisted of simultaneous thermal and radiation aging followed by a sequential accident exposure, which included high-dose-rate irradiation followed by a simulated LOCA steam exposure. Of the condition-monitoring parameters tested, elongation at break showed the most correlation with aging. The test results indicate that, properly installed, various miscellaneous cable types tested should be able to survive an accident after 60 years for total aging doses of at least 200 kGy (20 Mrad) and for moderate ambient temperatures on the order of 45 °C to 55 °C (81 °F to 131 °F) (potentially higher or lower, depending on material-specific activation energies and total radiation doses). However, by 200 kGy, (20 Mrad) the residual elongation of the SiR cables approached 0% but performed acceptably in subsequent LOCA tests.

- NUREG/CR-2156, *Radiation-Thermal Degradation of PE and PVC: Mechanism of Synergism and Dose Rate Effects* [24], documents a study of PVC and polyethylene (PE) degradation under combined gamma radiation and elevated temperature environments. Specifically, strong dose-rate dependent effects were found in PE and PVC over a wide range of dose rates. Experiments also showed enhanced degradation in PE when exposed to radiation at room temperature followed by elevated temperature. The importance of oxygen is shown by comparing aging in inert environments where degradation was found to be completely unchanged and sequential aging experiments of radiation followed by thermal environments, where there was rapid deterioration of the materials. The study also discusses the role of peroxides in the degradation mechanisms.

- NUREG/CR-2157, *Occurrence and Implications of Radiation Dose-Rate Effects for Material Aging Studies* [25], discusses dose rate effects for XLPO, EPR, CSPE, and CP. For these materials aged in air environments, tensile results indicate that radiation dose rate effects are important, with more mechanical damage occurring as the dose rate is lowered. The authors explain that a competition between cross-linking and oxidative scission occurs, in which scission becomes more important as the dose rate is lowered. This study concludes that "the mechanism of degradation is often quite different (and the amount usually more severe) under the low dose rate exposures characteristic of actual aging conditions compared to the mechanism occurring under the high dose rate exposures normally utilized for aging simulations."

- NUREG/CR-3629, *The Effect of Thermal and Irradiation Aging Simulation Properties on Polymer Properties* [26], specifically investigates irradiation temperature, the presence of oxygen during accident exposures, and simultaneous vs. sequential accident exposures. This study tested XLPO, EPR, CSPE, CPE, ethylene propylene diene monomer (EPDM), and several other materials. This joint French-U.S. research concluded that if sequential ordering of irradiation and thermal exposures was important to the aging degradation of tensile properties, usually the irradiation followed by thermal exposure sequence was the most severe. In addition, the study exposed samples to sequential irradiation and thermal exposures, with the irradiation temperature at ambient [~27 °C (81 °F)] and at 70 °C (158 °F). The results indicated that for most materials, the choice of irradiation temperature was secondary to the choice of aging sequence in its effect on polymer properties. However, for Tefzel® and CSPE, irradiation temperature did influence the degradation behavior.

- NUREG/CR-6794, *Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants* [27], examines medium-voltage power cables (2 to 15 kV) used in safety-related applications in NPPs, including control power cables in switchgear and motor control centers. This report discusses the effects of aging on power cable performance and reliability. The research program found that the predominant aging mechanism is moisture intrusion. However, other important aging mechanisms include embrittlement of the insulation due to elevated temperatures and chafing or cutting of the insulation due to vibration or cyclic movement of the cable. Based on operating experience review and analysis, the research concluded that while the number of failures is relatively low, power cables are susceptible to aging degradation that can lead to failure and an aging management program to monitor and mitigate the effects of cable aging may be beneficial in anticipating potential issues.

- NUREG/CR-5655, Submergence and High Temperature Steam Testing of Class 1E Electrical Cables [28], discusses the results of a research program that performed simultaneous thermal and radiation aging exposure followed by a sequential accident exposure on 12 different cable products. The cables were aged to simulate 40-year life. The accident was simulated via high dose-rate irradiation and followed by LOCA steam exposure. The research concluded that EPR cables generally survived to higher temperatures than XLPO cables in the high temperature steam exposure. However, XLPO cables generally performed better than EPR cables in the submergence tests and post-submergence dielectric testing.

SAND2010-7266, *Review of Nuclear Power Plant Safety Cable Aging Studies with Recommendations for Improved Approaches and for Future Work* [29], concentrates on the progress made during the 20–30 years or so prior to 2010, and highlights many of the most thorough and careful published studies not listed above. Some of the conclusions and recommendations for future work include the following.

Operating Environments

Knowledge of actual nuclear plant in-containment aging environments must be collected and distributed to LTO and aging personnel. This knowledge can be leveraged to aid in determining the importance of thermal aging vs. radiation effects and, therefore the relevance and applicability of the "inverse temperature" effect (e.g., faster degradation at a given dose rate as the temperature is reduced). Additionally, this key environmental data can be used to refine existing lifetime predictions for materials where data already exists.

Aging Data Analysis

Time-temperature superposition (i.e., the "normalization technique" where similar shapes for degradation curves is observed at all temperatures when data is plotted vs. log of the aging time) should always be used to ensure that the underlying chemical degradation pathway does not vary as the temperature changes. Likewise, the dose-equivalent damage (DED) approach is the superior and recommended technique for analyzing and extrapolating accelerated combined environment (i.e., radiation/thermal) data.

In the case of EPR/EPDM and XLPO/XLPE materials aged under combined radiation/thermal environments, the possible presence of the "inverse temperature" effect warrants further investigation. Data suggesting that the inverse temperature effect exists should be considered in any predictive models. For radiation studies where the inverse temperature effect is absent, the DED approach is the best methodology for the development of predictive models.

For LOCA simulations, the importance of the oxygen concentration in the atmosphere during the actual LOCA and during the simulation should be considered.

Development of Predictive Models and Condition Monitoring

In looking for non-Arrhenius behavior for thermal aging data, greater confidence in conclusions can be obtained through the use of "direct" evidence, which entails obtaining evidence directly from data on the primary degradation parameter of interest (i.e., tensile elongation). When "direct" evidence is unavailable, "indirect" evidence should be obtained from a sensitive secondary degradation parameter (i.e., oxygen consumption, gel/solvent uptake factors, density, etc.) that can be shown to (1) be closely related to the primary degradation parameter and (2) have the same activation energy (E_a) value at aging temperatures that overlap those of the primary degradation parameter. Oxygen consumption and other secondary parameter results may be useful in determining the E_a values of materials in a reasonable timeframe compared to the primary degradation parameter. Data measured for the secondary parameter must be employed as a supplement to primary parameter data, and not used as the sole source of E_a determination.

The wear-out approach is highly recommended for estimating the remaining lifetimes of materials that are readily accessible in nuclear plants (e.g., at cable terminations).

3.2.2 Aging—International Atomic Energy Agency (IAEA)

Section 3 and Annex A in IAEA TECDOC 1188, *Assessment and Management of Aging of Major Nuclear Power Plant Components Important to Safety: In-Containment Instrumentation and Control Cables* [30], discuss in detail the chemical and physical aging mechanisms and underlying principles, including evidence of non-Arrhenius behavior and of instances, where lowering the aging temperature at constant dose rate leads to a surprising increase in degradation rate (so-called inverse-temperature or reverse-temperature effect). This document is the outcome of a round-robin test to investigate condition-monitoring techniques. An in-depth discussion on a condition-monitoring program and available techniques is provided in Section 6 of this IAEA report. Of particular note, Section 6.5 discusses the correlation of a condition monitoring technique with DBE survivability. Part II presents key attributes of an effective cable aging management program.

NP-T-3.6, *Assessing and Managing Cable Aging in Nuclear Power Plants*, [31] is a follow-up/update to IAEA TECDOC 1188. It provides general guidelines for cable qualification and cable-aging management in nuclear facilities and in particular, discusses cable qualification, performance monitoring, and aging management. As plant life extension and license renewal activities (for up to 60 and potential license renewal, up to 80 years) have given rise to concerns over performance of cables, especially those that are expected to help mitigate the potential consequence of a design-basis accident (DBA), new techniques have been developed to enable condition assessment of cables and verify that important cables are still reliable, or decide that they must be replaced. Furthermore, much more is now known about the behavior of cables in both normal and abnormal conditions. These developments are reflected in this document in three distinct areas as follows:

- qualification processes, including pre-installation laboratory qualification testing and post-installation measures to verify adequate cable performance while the plant is operating and in case of design-basis accident (DBA);
- cable life extension in support of the current and future licence renewal activities, which call for existing NPPs to operate for up to 80 years; and
- cable condition monitoring involving methods that can be used to determine the performance of cable insulation material, or try to identify problems in cable conductors.

Section 5.3 of this IAEA document specifically addresses life extension and an aging management program for cables. Section 6 provides recommended practices related to qualification and cable aging management, including inspection, maintenance, and maintaining qualification. Aspects for maintaining qualification include condition monitoring, cable deposits, and the replacement of cables.

3.2.3 Aging—Japan

The nuclear industry in Japan has also examined cable insulation degradation in depth. JNES Report SS-0903 *The Final Report of the Project of "Assessment of Cable Aging for Nuclear Power Plants,"* [32] describes a multi-year project that aimed to accomplish the following:

- obtain thermal aging data and simultaneous thermal and radiation aging . . . data of safety-related cables
- conduct comprehensive evaluations of aging characteristics of the cables while taking into consideration the most recent knowledge,
- establish cable aging evaluation methods corresponding to the actual operating conditions, including the actual aging for cables of nuclear power plants, based on the study of suitable accelerated aging technique, appropriately assumed environmental conditions and integrity judgment methods,
- contribute to the development of "The Guide for Cable Environmental Qualification Test for Nuclear Power Plants (hereinafter referred to as "The Guide for Cable EQ Test" [33].

In addition to the development of “The Guide for Cable EQ Test” [33], the following results were obtained within the framework of the Assessment of Cable Aging (ACA) project:

1. It was confirmed that the trends of thermal aging characteristics and the simultaneous thermal and radiation aging characteristics of the tested cables can be classified into four or five types. As a consequence, a significant difference may be observed at times in the aging progress, depending on the insulator manufacturers, even if the insulator type is identical. The presence or absence, amount, and type of additives such as antioxidant and stabilizer are suspected as contributing factors of the difference in aging that occurs, even among the insulators using the identical type of base polymer.
2. Activation energy values calculated from the thermal aging test data are smaller than those currently used. Furthermore, as a result of the collation of sampling cables for actual operating plants with the results of the thermal aging tests, it is possible to suppose that the activation energy in the temperature region of actual operating plants would become even smaller. Based on those results, the principles of calculation and application were developed for the activation energy to be used for evaluation, and they were documented in “The Guide for Cable EQ Test for Nuclear Power Plants”.
3. Based on the results from the simultaneous thermal and radiation-aging test, superposition of time-dependent data and superposition of DED data were judged as applicable to the specification of the accelerated aging conditions. Therefore, the method of specifying the accelerated aging conditions using these techniques was developed and reflected in The Guide for Cable EQ Test. The superposition of DED data was judged more applicable to wider range of insulator materials than the range for which superposition of time dependent data is applicable. Further, the simplified method of specifying the accelerated aging conditions using the superposition of DED data was also developed.
4. Based on The Guide for Cable EQ Test, evaluation of long-term integrity was carried out for 14 types of tested cables. The evaluation made it possible to discern cables with poor environmental characteristics from those with acceptable environmental characteristics.
5. As a result of the investigation of the applicability of nondestructive degradation diagnostic technique to actual operating plants, it was evaluated that, the indenter was applicable to insulators of the cross-linked polyethylene family, the ethylene propylene rubber family, silicone rubber, and special heat-resistant PVC, except insulators made by certain manufacturers.

3.3 INVERSE TEMPERATURE EFFECTS

The observed inverse temperature effect, where polymer degradation occurs more rapidly for constant dose rates as the combined environment temperature is lowered, represents an example in which material aging and lifetime prediction cannot be represented adequately by conventional approaches, such as the Arrhenius methodology. The inverse temperature effect is applicable to certain XLPO and EPR insulation materials and is further investigated in the literature [34–36]. References [34] and [35] describe results for several XLPO and EPR materials; Reference [36] describes results for semi-crystalline cross-linked polyolefin materials that, under combined radiation plus thermal environments, mechanically degrade faster at room temperature than it does at elevated temperature.

As detailed in a recent document [29], the inverse temperature effect was not observed in JNES Report SS-0903 [32], primarily because all their combined radiation-thermal aging tests were carried out at elevated temperature [80–100 °C (176–212 °F)]. This highlights the need to carry out radiation aging at near-ambient temperatures as well as at elevated temperatures to determine whether inverse temperature effects are significant for a specific formulation.

3.4 CONDITION MONITORING

The NRC Information Notice (IN) 2010-26, *Submerged Electrical Cables* [37], discusses recent cases of cables subjected to adverse conditions, such as long-term submergence in water. It states:

> Cables not designed or qualified for, but exposed to, wet or submerged environments have the potential to degrade. The long-term corrective actions could involve establishment of a condition monitoring program for all cables which are inaccessible and underground and under the maintenance rule, including testing of cables to verify the cables are not degraded and visual inspection of manholes for water accumulation to ensure continued operability.

Several other key industry and regulatory documents address condition monitoring. These reports include:

- EPRI 1011873, *Cable Polymer Aging and Condition Monitoring Research at Sandia National Laboratories under the Nuclear Energy Plant Optimization (NEPO) Program* [38], describes cable polymer aging and condition monitoring research performed at SNL under the NEPO program from 2000 to 2005. The research results apply to low-voltage cable insulation and jacket materials that are commonly used in U.S. nuclear power plants. Specifically, this report concentrated on the development of better lifetime prediction methods and the development and testing of cable-condition-monitoring techniques. With respect to plant aging, the goal is to ensure that current plants can continue to deliver adequate and affordable energy supplies for the term of their licenses, which can be 60 years, by providing a strong technical basis for long-term operation. Section VI of the report discusses the implications of diffusion-limited oxidation (DLO) effects on the use of condition monitoring approaches. Sections VII, VIII, IX, and X discuss and present test data on various condition-monitoring techniques for several polymers. Section XI focuses on the "wear-out approach," a method for estimating residual lifetimes of cable jacketing and insulation materials. This method is especially useful for materials that show "induction-time" behavior because condition-monitoring techniques applied to such materials may give little warning of impending end of life.

- NUREG/CR-6904, *Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in Nuclear Power Plants* [39], shows that the broadband impedance spectroscopy method has potential to be an effective in-situ nondestructive condition-monitoring method for cables. Specifically, this method was able to detect the presence of localized thermal degradation and also, the presence of abrasion-related degradation and simulated cracking damage. Furthermore, models using the cables electrical properties were able to predict hot-spot location to within ±10%.

- NUREG/CR-6794, *Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants* [27], evaluates condition-monitoring methods for medium-voltage power cables. Table 6 in the report provides a summary for applicable condition monitoring methods, describing the advantages and limitations of various mechanical, chemical, and electrical methods. A recommended first step for aging management is a visual inspection of accessible cables, such that valuable information on the condition of the cable can be gathered and based on the information, decisions can be made about additional intrusive testing and/or increased frequency of condition monitoring.

- NUREG/CR-7000, *Essential Elements of an Electric Cable Condition Monitoring Program* [4], provides recommendations for a comprehensive cable condition-monitoring program, including periodic cable condition monitoring inspections and tests, in-service testing, cable operating environment monitoring and management activities, and the incorporation of cable-related operating experience. The report discusses commonly used condition monitoring techniques but did not specify which techniques would be applicable to particular materials. It develops nine recommended essential elements for an effective cable condition-monitoring program and provides a discussion and analysis of the failure modes for power and I&C cables that can be addressed by those elements.

- Regulatory Guide 1.218, *Condition Monitoring Program for Electric Cables Used in Nuclear Power Plants* [40], outlines the essential elements of a cable condition-monitoring program. It provides specific guidance for condition monitoring of cables to provide reasonable assurance that the cables are capable of performing their intended functions during their installed life. In particular, the regulatory guide will describe a programmatic approach to condition monitoring of electric cable systems and their operating environments and acceptable condition-monitoring techniques.

- EPRI 1022969, *Plant Engineering: Electrical Cable Test Applicability Matrix for Nuclear Power Plants* [41], provides a correlation between specific cable problems and appropriate tests that may be used to assess the severity of the condition and resolve the issue. Specifically, this document discusses the applicability of tests based on insulation, voltage rating, and design of the cable. Table 2-1 in the report lists the aging effects of elevated temperature, radiant heating, and radiation on the types of insulation used in nuclear plant cables. Table 3-2 provides a list of applicable condition monitoring tests for various aging concerns. Appendix A provides the uses, description, acceptance criteria, material applicability, and limitations of each test method.

3.5 AGING MANAGEMENT/LICENSE RENEWAL

For license renewal, NUREG-1801, *Generic Aging Lessons Learned (GALL) Report*, [2] recommends a condition monitoring program in Chap. XI.E3, “Inaccessible Power Cables Not Subject to 10 CFR 50.49.” Chapter XI.E2, “Insulation Material for Electrical Cables and Connections Not Subject to 10 CFR 50.49 Environmental Qualification Requirements Used in Instrumentation Circuits,” documents two methods that can be used to identify the existence of aging degradation. In the first method, calibration results or findings of surveillance testing programs are evaluated to identify the existence of cable and connection insulation material aging degradation. In the second method, direct testing of the cable system is performed. In addition to the guidance in Chap. XI.E2 and XI.E3, Chapter XI.E1, “Insulation Material for Electrical Cables and Connections Not Subject To 10 CFR 50.49 Environmental Qualification Requirements,” recommends a condition monitoring program for accessible electrical cables and connections within the scope of license renewal that are located in adverse localized environments caused by temperature, radiation, or moisture.

Other key reports and technical documents address related issues in this area. These include:

- NUREG/CR-6704, *Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low Voltage Electric Cables* [42], addresses technical challenges related to the qualification process for low-voltage I&C cables used in commercial NPPs. Three commonly used types of I&C cable were tested: XLPE insulation with a neoprene jacket, EPR insulation with an unbonded Hypalon® jacket, and EPR with a bonded Hypalon® jacket. Each cable type received accelerated aging to simulate 20, 40, and 60 years of qualified life, and each was subjected to simulated LOCA conditions, which included the sequential application of LOCA radiation followed by exposure to steam at high temperature and pressure as well as exposure to chemical spray. The report states, "the results indicate that degradation due to aging beyond the qualified life of the cables, based on extrapolation of the aging parameters used in the original qualification to a 60 year service life, may be too severe for the insulation material to withstand and still be able to perform adequately during a LOCA. For life extension purposes, the aging protocols used to establish the qualified life of the cables should be reviewed and compared to actual service environments in a plant. A determination then can be made as to whether the additional exposure to aging stressors during a period of extended operation will be acceptable for the cable materials."

- EPRI TR-103841, *Low Voltage Environmentally-Qualified Cable License Renewal Industry Report; Report 1* [15], provides a technical basis for license renewal of low-voltage environmentally qualified cables. Specifically, the evaluation discusses age-related degradation mechanisms, the effects of age-related degradation on functionality of equipment, and aging management options.

- EPRI 1020804, *Plant Support Engineering: Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants* [6], describes a common approach for developing and implementing a low-voltage power cable system aging management program that will identify and resolve cable circuit aging concerns. Similarly, EPRI 1020805, *Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants* [7], provides testing and assessment criteria for medium voltage cables.

- EPRI 1008211, *Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets* [43], develops a basis for acceptance criteria and evaluates the aging profiles for many commonly used cable jackets and polymers. The report presents and discusses using 50% elongation-at-break as a conservative practical end of life for cables that may be disturbed during maintenance or subjected to LOCA exposure and discusses the basis for continued use beyond that point.

4. HISTORIC AND CURRENT INDUSTRY PRACTICES FOR ELECTRICAL CABLE QUALIFICATION

4.1 INTRODUCTION

Initial environmental qualification of electrical cables was performed using state of the art techniques, standards, and regulations at the time qualification. Of significance, differences exist in the way that aging was performed during the initial cable qualifications. The regulations and the history of the development of standards will be reviewed in this Chapter along with changes in state of the art.

4.2 BACKGROUND

Polymers are relatively new in the materials world relative to metals, glasses, and ceramics. Early polymers, pursued in the late 1800s were derived from natural materials. Vulcanized natural rubber was discovered by Charles Goodyear in the 1850s. The first semisynthetic polymers were developed in the early 1900s (e.g., Bakelite in 1909 and rayon in 1911). In the 1930s, neoprene was developed in the laboratories of DuPont. It wasn't until World War II that interest significantly focused on synthetic polymers because of the scarcity of natural polymers caused by the war. During that time, the development of nylon, acrylic, neoprene, styrene butadiene rubber, polyethylene, PTFE, and many other polymers took the place of the natural materials that were no longer available. Polyethylene became a critical material for insulating electronics for radar applications. Several other polymers became important for use during the Manhattan Project because of their corrosion resistance of acids and bases and swelling/degradation resistance to chemicals. Additionally, the invention of injection molding and extrusion equipment significantly enhanced the high-volume manufacturing of polymeric materials into products.

In the late 1950s and early 1960s, R. Harrington and R. Giberson published a series of articles in *Rubber Age* related to radiation effects on polymers and elastomers of various types. The articles relied on American Society for Testing and Materials (ASTM) testing standards for materials for radiation, established by the ASTM Committee in 1959. Test standard ASTM D 1672-61T [44] was being used as the standard for exposure. Other ASTM standards followed for testing the physical and mechanical properties of polymers and for certain special testing procedures that had been developed specifically for polymers. Two other key IEEE standards in this area are also relevant.

- IEEE Std 383 [8, 45] is the standard for type testing of safety-related cables. The initial issue of IEEE Std 383 was in 1974. It is also used for qualifying splices and was originally used for qualifying connections. IEEE 572 [46, 47], first issued in 1985, is now used for qualifying connection assemblies. RG 1.131 [48], issued as a draft in August 1977, endorses IEEE 383, with exceptions.

- IEEE Std 323 [49, 50] is the parent document of IEEE Std 383. IEEE Std 323 discussed the qualification of safety-related equipment for NPPs. The first issue was as a trial use standard in 1971 [51]. IEEE Std 323 was revised in 1974 and in 2003. Regulatory Guide 1.89 [52], issued in November 1974, endorsed with some exceptions IEEE Std 323-1974 as one method acceptable to the NRC staff for complying with the Commission's regulations regarding design verification of safety-related equipment. RG 1.89 applied to construction permit applications for which a staff's safety evaluation report was issued after July 1, 1974. It was the practice to require that all other applicants with construction permits prior to July 1, 1974, comply with IEEE Std 323-1971. This was later modified with some exceptions.

In March 1975 a fire occurred at the Browns Ferry Nuclear Plant. One of the many significant outcomes of that event was to include more emphasis on the flame tray flame testing, such as that described in IEEE Std 383. It also contributed to the discontinuation of the use of PVC as a cable jacket or insulation in U.S. NPPs. Key resulting regulatory bulletins and guidance included:

- NRC Inspection and Enforcement (IE) Circular 78-08 [53] was issued in May 1978. It documents a series of actions initiated by the NRC to confirm the environmental qualification of electrical equipment required to perform a safety function under postulated accident conditions. The actions were in response to a petition from the Union of Concerned Scientists. Information from licensee equipment tests and evaluations indicated potential problems in qualification of installed equipment. An environmental review of safety-related electrical equipment at selected older plants was performed. The review did not identify generic qualification deficiencies. However, as a result of IE bulletins and the testing to confirm qualification, specific deficiencies were identified. Poor installation practices, inadequate consideration of subcomponents, and omission of certain environmental parameters in the design were noted. In addition, qualification documentation was found to be inadequate in many cases, and the initial response to some licensees indicated a lack of detailed knowledge of the quality of installed equipment. Additional issues regarding cables included the use of unqualified cables and splices with penetrations and testing of environmental parameters such as radiation and temperature by separate effects vs. sequential testing.

- NRC IE Bulletin 79-01 [54] was issued in February 1979. It raised the threshold of IE Circular 78-08 to the level of a bulletin, requiring a response from all licensees (11 plants were exempted). Bulletin 79-01 required the licensee to perform a detailed review of the environmental qualification of Class 1E electrical equipment to ensure that the equipment will function during and following postulated accident conditions.

The Three Mile Island accident occurred on March 28, 1979. It had many ramifications for nuclear plants, including more focus on equipment qualification. These ramifications were spelled out in the following bulletins, guidelines, and rules:

- NRC IE Bulletin 79-01B [55] and supplements were issued in 1980. In addition to requesting more detailed information, the scope of the bulletin was expanded to resolve safety concerns relating to design-basis environments and current qualification criteria not addressed in the facilities final safety analysis report. Omissions include high-energy line breaks inside and outside primary containment, aging, and submergence. This bulletin also required a master list of all engineered safety feature systems (including cables) required to function under postulated accident conditions. Equipment qualification binders to document qualification were also outlined. Staff guidance was provided in Enclosure 4, which stated that a plant did not have to demonstrate a qualified life if the plant was already constructed and operating unless the plant used materials that had been identified already as being susceptible to significant degradation due to thermal and radiation aging. Maintenance or replacement schedules were to include consideration of the specific aging characteristics of the materials, and ongoing programs were to be established to review surveillance and maintenance records to verify that equipment that was exhibiting age-related degradation was identified and replaced as necessary.

- NUREG-0588 [56] applies to all then existing plants except for those covered by the staff's IE Bulletin 79-01B guidelines. NUREG-0588 was initially published for industry comment in December 1979; it was subsequently revised and issued in July 1981. NUREG-0588 divided the population of safety-related electrical equipment into two categories, namely, Category I for equipment qualified in compliance with IEEE Std 323-1974 [49] and Category II for equipment qualified in compliance with IEEE Std 323-1971 [51]. Section 4 of the Interim Staff Position in NUREG-0588 required that aging effects on all equipment, regardless of its location in the plant, should be considered and included in the qualification program for Category I equipment. Category II equipment had to comply in the same manner for qualification of valve operators and motors. For all other equipment, aging had to be addressed to the extent that the equipment is composed of material susceptible to aging effects. NUREG-0588 also specified that a schedule for periodically replacing the equipment and/or materials should be established.

- Section 49 to Part of Title 10 to the *Code of Federal Regulations* (10 CFR 50.49), "Environmental Qualification of Electric Equipment Important to Safety for Nuclear Power Plants" [57], issued in February 1983, applies to electric equipment located in harsh environment areas that are important to safety. The holder of an operating license at that time had to identify electric equipment important to safety that was already environmentally qualified and to submit a schedule for either achieving environmental qualification, or for the replacement of existing nonqualified equipment that is important to safety with environmentally qualified electrical equipment. If the equipment had been previously qualified to the requirements of the IE Bulletin 79-01B staff guidelines or those found in NUREG-0588, then it did not have to be re-qualified to the requirements of 10 CFR 50.49. Replacement equipment is to be qualified in accordance with 10 CFR 50.49, unless there are staff-approved, technically justified reasons to the contrary.

In EPRI TR-103841 [15], a database was developed to characterize in-containment cable types installed in NPPs. Sixty percent of the entries in the databases were for cable types manufactured prior to 1971, and 81% are prior to 1974, which correlates with the dates that plants were given construction permits. About 58% of the entries showed a qualification type. Of those, 41% were shown as Category II. This would indicate that much of the initial qualification did not have to address qualified life. SAND96-0344 [16] also had a database that was used to examine manufacturers in nuclear plants. The predominant manufacturers were shown above in Table 2.1.

There were about 34 manufacturers listed, and the top ten represent 90% of the total. The top three represent 55% of the total. Some of the top manufacturers compared the aging of their materials to other materials with a history [58].

4.3 STANDARDS

IEEE Std 279-1968, *Proposed IEEE Criteria for Nuclear Power Plant Protection Systems* [59], was the first IEEE document to address equipment qualification testing for nuclear plants. Equipment qualification was given its own standard in 1971 as IEEE Std 323 [49–51]. IEEE Std 323-1971, "IEEE Trial-Use Standard: General Guide for Qualifying Class I Electric Equipment for Nuclear Power Generating Stations," was a trial use document that described the basic requirements for the qualification of equipment that is essential to the safe shutdown and isolation of the reactor or whose failure or damage could result in significant release of radioactive material. Qualified life and aging were not addressed in IEEE Std 323-1971. Consequently, cables qualified to the requirements of IEEE Std 279-1968 are not required to address aging.

IEEE Std 323 was updated in 1974, 1983, and 2003. IEEE 323-2003, “IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations,” included specific requirements for aging, margins, and maintaining documentation records. In addition, this revision provided a definition of qualified life as “the period of time for which satisfactory performance can be demonstrated for a specific set of conditions.” The definition was changed in the 1983 revision of IEEE Std 323 to be “the period of time, prior to the start of a DBE, for which equipment was demonstrated to meet the design requirement for the specified service conditions.” The 1983 revision has not been endorsed by the NRC, but the same definition is in the 2003 version of IEEE Std 323. The 2003 version of IEEE Std 323 also expanded on its use in mild environments, updated margins (only recommending one transient), addressed electromagnetic interference (EMI) and radio-frequency interference (RFI) for new digital and advanced analog systems and added information on qualified condition.

The standard for qualifying cables is IEEE Std 383 [8, 45], initially published in 1974. It provides guidance for developing a program to type-test cables and field splices. It supplements IEEE Std 323-1974, which describes basic requirements for equipment qualification. Qualification of the cable for mild environments may be demonstrated by providing certified evidence that the cable has been manufactured and tested per the American National Standards Institute (ANSI), the Insulated Power Cable Engineers Association (IPCEA, now ICEA), or AEIC standards.

Type tests are used primarily to indicate that the representative cable can perform before, during, and after a DBE. Although there were some interpretations of what the representative samples were, Table 1 of IEEE Std 383 has categories for multiconductor control/signal cables, single conductor power cables, shielded pair/triad/quad, coaxial/triaxial or special instrumentation, thermocouple, and medium-voltage cables.

Both aged and unaged cable samples are tested. Aging includes both thermal and radiation aging. Thermal aging is accelerated by Arrhenius-aging, using IEEE standards (IEEE standards 1, 98, 99, and 101) [60–63] or another method of proven validity and applicability for the materials in question. The Arrhenius method has been used for more than 40 years, and no other IEEE document provides an alternative, proven method for acceleration of aging. A minimum of three data points, including 136 °C (277 °F) and two others at least 10 °C (18 °F) apart in temperature, are required by IEEE 383-1974. IEEE Std 98 and 99 have additional criteria (e.g., on samples shape, thickness, over 5,000 h for the lowest aging temperature). Laboratory experience over the last three decades indicate that lifetime predictions are usually not conservative, e.g. the Arrhenius approach often over-predicts lower temperature lifetimes since the Arrhenius activation energy measured at high accelerated aging temperatures often decreases in the lower temperature extrapolation region. Section 5 of this document goes into more detail on this issue.

Radiation and thermal aging may be applied in sequence or simultaneously in an accelerated manner. For practical reasons, generally a sequential application was done. Thermal aging is specified before radiation as the sequence to use. Radiation aging for normal dose was specified as 500 kGy (50 Mrad) at less than 10 kGy/hr (1 Mrad/hr) per hour from a gamma source. A 20× bend test and a voltage test were done to check functionality for normal conditions after aging to normal service with the normal dose radiation. Per IEEE Std 323-1974, 1,500 kGy (150 Mrad) at less than 10 kGy/hr (1 Mrad/hr) from a gamma source was generally used for the accident dose. Chapter 5 in this report shows the potential issues involved in using such high dose rates.

The DBE was generally chosen to simulate the most severe postulated conditions and specified conditions of installation. The general test profile used was from IEEE Std 323. The combined profile with chemical spray and two peaks was generally used. A margin was generally added. The cable was usually hooked up to rated voltage and current or hooked up to perform its function. A 40× bend test was done at the end with voltage withstand test and insulation resistance measurement.

Fire testing was also outlined in IEEE Std 383-1974. The tray flame test was shown in the standard, and flame testing of singles was usually from Sect. 6.19.6. of ICEA S-19-81 [9].

4.4 IEEE STD 383-2003

IEEE Std 383-2003, " IEEE Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations," [45] is not being used with the current operating reactors, but a review of the changes made in the 2003 revision can provide some insight into the lessons learned from past qualification. The changes noted in the introduction include the following:

1. The 1974 version of IEEE Std 383 primarily dealt with type testing. The 2003 version adds alternative methods of qualification by past operating experience, ongoing qualification, and qualification by analysis that were in IEEE Std 323.
2. Although no exclusion of a specific DBE was mentioned in the 1974 version of IEEE Std 383, the 2003 version does have a specific inclusion of high-energy line break testing to highlight this.
3. The tray flame test in IEEE Std 383 has been removed, and instead the flame test in IEEE Std 1202 [64] is now referenced. The IEEE Std 1202 flame test is generally considered a more stringent flame test.
4. Connections have been removed from the title and scope of IEEE Std 383 because IEEE Std 572 now covers connectors.
5. The table for sample selection has been deleted. This was meant to allow more flexibility in determining the representative samples as well as not limiting samples that may need to be tested.

There are other changes. Some definitions were deleted that are in other IEEE standards. The two new definitions of consequence are representative cable and representative splice. One part of the definition is that the representative splice or cable is from a specific manufacturer using the same processes and controls. This was in recognition that for some low-voltage materials such as ETFE and for some medium-voltage cables that a generic material qualification cannot be done because processing can affect the resultant cable. ETFE and other high-temperature polymers can be affected by extrusion equipment, tooling, and processing. With some medium-voltage cables, the cleanliness, smoothness of extrusion, and type of cure system are thought to affect long-term performance.

It has been made clear that single strands from a multiconductor cable must be tested separately. The separate testing is intended to establish the ability of the insulation to perform its intended function independent of the jacket. Medium-voltage cable is tested as a completed cable, including jackets, shields, and stress control layers where applicable, but the activation energy and qualified life of the stress control layers must also be considered. Jacketed single conductors are also tested to address compatibility as well as aging of the jacket and possible crack propagation (as was seen with certain EPR/CSPE bonded jackets). Jacket-qualified life must also be considered for other applications, where the jacket must maintain integrity. Additional requirements for coaxial cables have been added to address construction properties that can effect qualification.

IEEE Std 383-2003 notes that:

> "Where substantial service-related synergistic, dose rate, and diffusion-limited oxidation or acceleration related dose rate effects of pertinent insulating and jacketing material types have been identified, and where methods to reproduce them in accelerated testing are known, such methods shall be used with due consideration to cost, time, and complexity. Thermal and radiation aging synergistic effects may be addressed by simultaneous exposure to radiation and thermal environments or an appropriate choice of sequential exposure order, level, or duration. Dose rate and diffusion-limited oxidation effects are often minimized by reducing the acceleration level thereby extending the exposure duration. As a minimum, if no evidence of a synergistic effect exists, a clear statement, noting that this is the case, shall be included with the qualification report. "

The quoted passage is an attempt to address questions such as those involving sequence and synergistic effects, which have been studied but for which no clear consensus was available for developing specific requirements.

Reference is made to IEEE standards on Arrhenius behavior that have also been updated over the years [45, 60, 61, 63]. Those standards provide guidance on variables such as sample shape, thickness, maximum extrapolation, minimum time for one point to be 5,000 h, and the number of air exchanges in the oven. Mastics for splices, when credited for qualification, must also be addressed for qualified life. Because there may be multiple activation energies in a construction, some guidance is given on how to handle this.

Additional information is provided on general operability of cables, including specialty cables where performance is assessed for the specific application and for which special performance criteria should be defined. RG 1.211 [65] provides additional guidance on this. Additional information is also provided on documentation, traceability, and modifications.

4.5 IEEE STD 775-1993

IEEE Std 775-1993, *Guide for Designing Multistress Aging Tests of Electrical Insulation in a Radiation Environment* [66], provides guidelines for evaluating insulation materials that are subjected to more than one significant aging stress. This standard has been withdrawn but still may provide insight. The focus is on materials or equipment intended for use in nuclear facilities such as power stations where thermal, moisture, and radiation stresses are of importance. In particular, the importance of considering diffusion-limited oxidation effects and a discussion of the DED combined environment-aging method are highlighted.

4.6 CONCLUSIONS

There have been advances in the fundamental understanding of some areas of cable qualification; however, other aspects have remained unchanged for 40 years. The variation in the treatment of thermal aging has been one of the key differences noted in qualification tests. A few manufacturers produce most of cables used. Much testing has been done over the last 30 years to understand and quantify the aging mechanisms of the cables used in NPPs. As issues with cable aging have been identified, the affected cables have been inspected and tested, or other actions, including cable replacement, have been taken. In addition, manufacturers have updated cable qualification testing using updated industry guidance, standards, and NRC requirements and guidance. Since many of the safety-related cables are I&C cables, and, based on actual ambient temperatures, there have not been many issues with aging of the cables, including degradation due to localized environments (hot spots). IEEE standards have been updated with the lessons learned from past testing, and they continue to be updated periodically with the latest information.

5. POTENTIAL CONCERNS IN QUALIFICATION METHODOLOGY/GAPS IN KNOWLEDGE FOR LONG-TERM OPERATION

The qualification approach used for cables in U.S. plants was specified in two IEEE documents from 1974 [8, 49]. Since these standards were published additional knowledge has been acquired to improve qualification methodology. For example, per the IEEE documents, lifetime predictions could be developed by measuring physical properties (elongation at break) at elevated temperatures, and subsequently extrapolating physical property behavior to lower temperatures relevant to power plant conditions, assuming Arrhenius behavior (and no change in activation energy). The following selected literature studies and reviews show evidence for non-Arrhenius behavior in important nuclear power plant cable materials:

- K. T. Gillen, R. Bernstein, and D. K. Derzon, "Evidence of non-Arrhenius Behavior from Laboratory Aging and 24-year Field Aging of Chloroprene Rubber Materials," *Polymer Degradation and Stability* 87, 57 (2005) [67].

- K. T. Gillen, R. Bernstein, and M. Celina, "Non-Arrhenius Behavior for Oxidative Degradation of Chlorosulfonated Polyethylene Materials," *Polymer Degradation and Stability* 87, 335 (2005) [68].

- JNES, *The Final Report of the Project of "Assessment of Cable Aging for Nuclear Power Plants,"* Report SS-0903, The Japan Nuclear Energy Safety Organization, July, 2009 [32] (finds non-Arrhenius for EPR insulations).

- EPRI, *Cable Polymer Aging and Condition Monitoring Research at Sandia National Laboratories under the Nuclear Energy Plant Optimization (NEPO) Program*, EPRI 1011873, Electric Power Research Institute [38] (summarizes non-Arrhenius results for several neoprene, CSPE and XLPO cable materials).

- IAEA, *IAEA Nuclear Energy Series Report, Assessing and Managing Cable Ageing in NPPs,* No. NP-T-3.6, 2012 [31] (very recently released, the report reviews the significance of non-Arrhenius effects for cable materials).

Comparatively, an equal damage-equal dose assumption was employed such that the total dose of interest was typically simulated at high dose rates, such as 10 kGy/h (1 Mrad/h). Additionally, aging simulation was usually done sequentially, with the thermal environment preceding the radiation environment. SAND 2013-2388 [69] discusses in detail the above issues for the current and renewed license periods. Over the past 35 years, substantial efforts have been devoted to determining whether the aging assumptions employed by the original IEEE standards could be improved. The studies have led to a better understanding of accelerated aging methods and more confident lifetime predictions. There are several areas of potential concern in the qualification methodology adopted, and hence gaps exist in the knowledge required to support lifetime predictions for long-term operation (i.e., beyond 60 years). The gaps areas are briefly addressed in the following sections.

5.1 ACTIVATION ENERGY VALUES USED FOR THERMAL AGING

The Arrhenius equation is widely used as the basis for accelerated thermal aging, but some of its limitations need to be appreciated. It is only applicable if the same balance of reactions occurs at both the elevated accelerated aging temperatures and service temperatures. If the degradation mechanisms change, the equation is not directly applicable.

Long-term studies indicate that many materials exhibit non-Arrhenius behavior, such that the Arrhenius E_a determined under short-term, high temperature aging conditions drops to a lower value as the temperature is reduced to conditions closer to the ambient plant conditions [70–74]. The reduction in E_a implies that low-temperature predictions made from extrapolating high-temperature E_a values can significantly over-estimate the lifetime of materials (i.e., non-conservatively) at lower temperatures.

An example of this type of decrease in activation energy (E_a) at lower aging temperatures is shown in Figure 5.1 for an Okonite neoprene jacket material, where the value decreases from 89 kJ/mol to 71 kJ/mol at temperatures below 70 °C (158 °F). Similar changes were observed for Rockbestos Firewall III neoprene (Figure 5.2) and in several different CSPE jacket materials (Figures 5.3 and 5.4) [67]. Ethylene propylene–based materials can exhibit complex behavior during thermal aging, dependent on the degree of crystallinity. At present, there is insufficient data in the low-temperature region to confirm whether the value of E_a changes at temperatures closer to service conditions. This is an area that would benefit from future studies in which oxygen consumption measurements are employed to determine E_a in the temperature region below 100 °C (212°F).

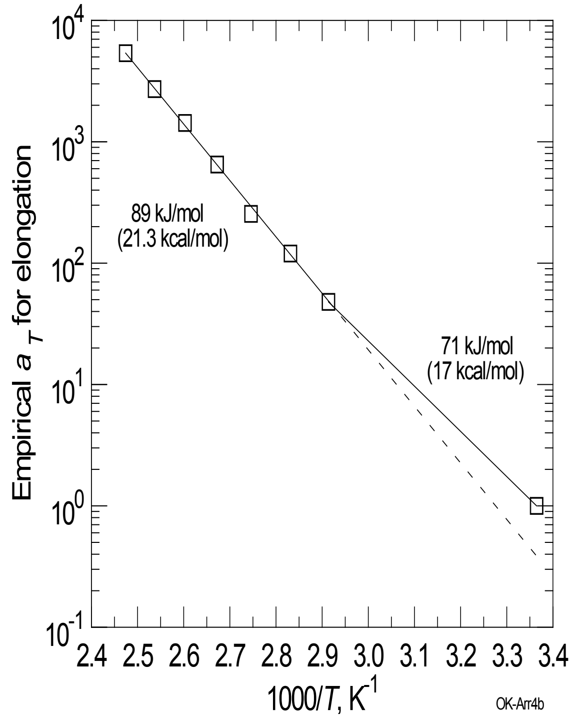

Figure 5.1. Arrhenius plot for the shift factors for elongation at break aging data for the Okonite neoprene jacket material [75].

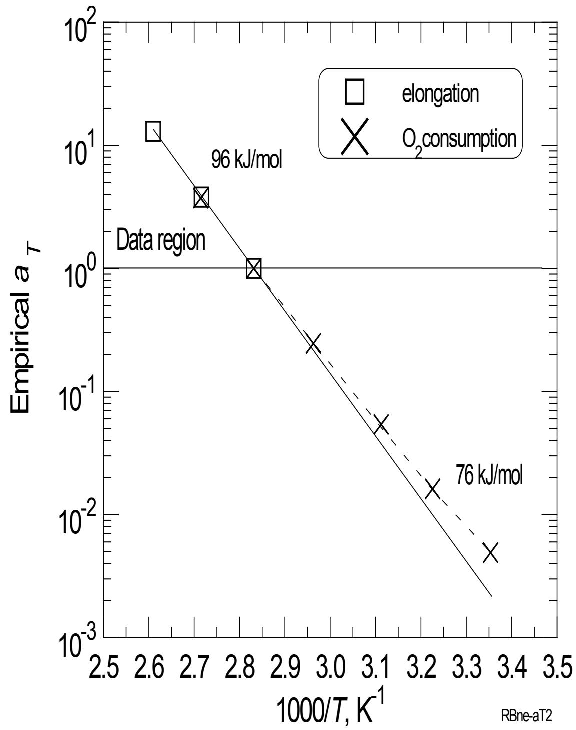

Figure 5.2. Arrhenius plot for the shift factors for elongation at break and oxygen consumption data for the Rockbestos Firewall III neoprene jacket material [75].

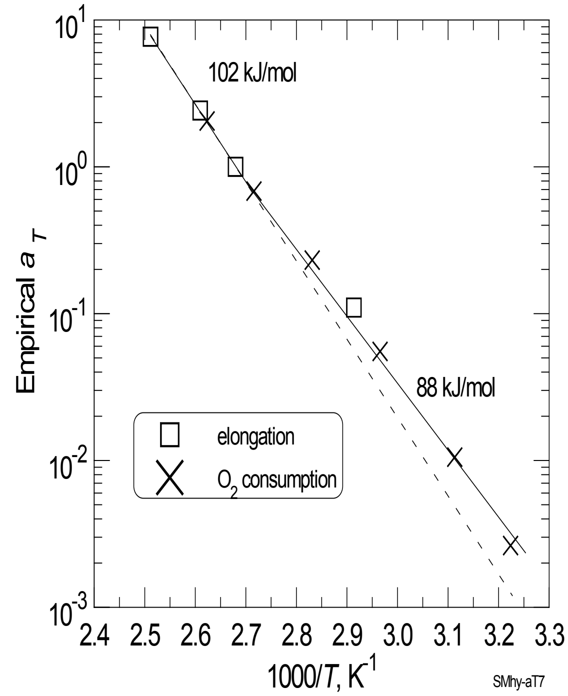

Figure 5.3. Arrhenius plot for the shift factors for elongation at break and oxygen consumption data for the Samuel Moore Dekoron CSPE jacket material [75].

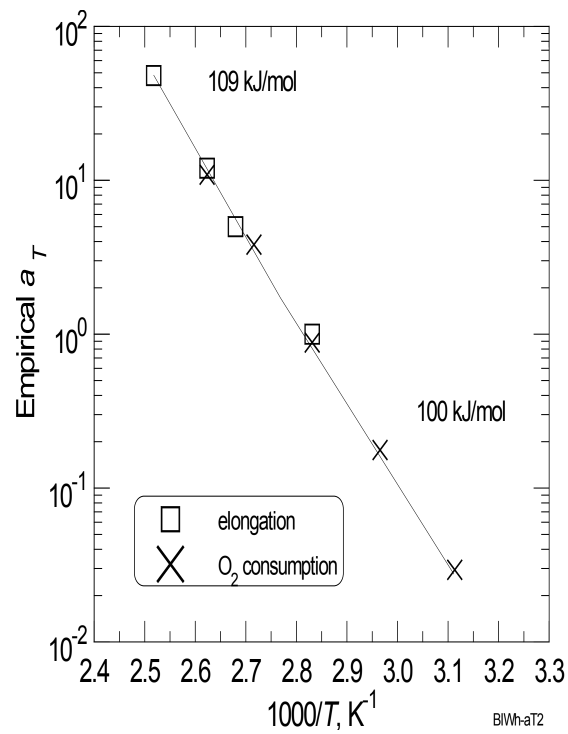

Figure 5.4. Arrhenius plot for the shift factors for elongation at break and oxygen consumption data for the BIW Bostrad 7E CSPE jacket material [75].

In order to determine whether the Arrhenius activation energy changes as the temperature is reduced to near ambient conditions, it is ideal to utilize a sensitive secondary degradation technique that is correlated with the primary degradation parameter (typically tensile elongation) used to monitor changes in mechanical properties. At higher temperatures in air/oxygen-containing environments, mechanical property degradation, reflected by changes in tensile elongation values, is normally dominated by oxidation reactions. Because of this connection, oxygen consumption measurements would be generally expected to correlate with the mechanical property results. This correlation must be confirmed by showing that elongation results and oxygen consumption results have similar Arrhenius activation energies in the temperature range accessible to mechanical property measurements. If such a correlation can be confirmed at high temperatures, the sensitive nature of oxygen consumption measurements will enable these measurements to be extended to lower temperatures. This capability leads to estimates of how the Arrhenius activation energy behaves in the normal extrapolation region. Other extremely sensitive techniques may also be available for extending Arrhenius curves to lower temperatures. However, it is critical that any technique used must first be shown to correlate at the high temperatures by confirming that the activation energies for this secondary technique are identical to those found for elongation [70, 74, 75].

5.2 DIFFUSION-LIMITED OXIDATION

Diffusion-limited oxidation (DLO) occurs when aging simulations employ highly accelerated aging conditions (e.g., very high radiation dose rates and/or very high aging temperatures). Under such conditions, the oxidation rate in the polymer with dissolved oxygen is much faster than the dissolved oxygen can be replenished by diffusion effects from the surrounding air atmosphere. This leads to significant drops in dissolved oxygen concentration (often to zero), thereby significantly reducing or completely eliminating oxidation reactions in the interior parts of materials. Since oxidation typically dominates the degradation of most cable insulation materials—in both thermal and radiation environments—and DLO effects are completely absent for the low-level environments experienced over a multi-decade NPP lifetime, highly accelerated simulations containing significant DLO effects may overestimate cable insulation lifetimes. More explicitly, under normal NPP operating conditions, degradation (oxidation) will proceed at a rate that is sufficiently slow for oxygen to diffuse into the polymeric material from the surrounding atmosphere. The oxidation processes will not be limited by the rate of diffusion under these conditions, and oxidation will be homogenous through the thickness of the polymer.

However, under accelerated aging conditions, the rate of oxygen consumption will be much higher and may be faster than the rate at which dissolved oxygen can be replenished by diffusion from the surrounding air atmosphere. Under those conditions, there will be a smooth decrease in the steady state oxygen concentration from its equilibrium sorption value at the sample surface to a reduced or even nonexistent value further inside the material. The rate of oxidation at any position in the polymer will decrease as the dissolved oxygen concentration decreases, leading to oxidation rates that decrease with depth from the surface. This can give rise to DLO, the heterogeneous oxidation through the thickness of the polymer.

5.2.1 Calculating and Measuring DLO Effects

It is valuable to examine the theory and background on DLO effects when assessing their potential impact on material performance. The importance of DLO will depend on the geometry of the material combined with the oxygen consumption rate, the permeability of the polymer to oxygen, and the partial pressure of oxygen in the surrounding atmosphere. The consumption rate and the permeability will also be functions of temperature and/or radiation dose rate. The DLO effects are of significant concern when carrying out accelerated testing of thick samples (e.g., whole cables) for both thermal and radiation aging.

An estimate of the sample thickness (L) at which DLO is insignificant can be made using the following equation, appropriate for a planar sample with oxygen (e.g., air) on both sides of the sample.

$$L \sim 2\,[p\,P_{ox} / \varphi\,]^{0.5} \qquad (1)$$

where p is the partial pressure of oxygen surrounding the sample, P_{ox} is the oxygen permeation rate, and φ is the oxygen consumption rate in the material [75]. If this condition is satisfied, then the integrated oxidation through the thickness will be at least 95% of the homogeneous value.

When air (oxygen) is available on only one side of the sample thickness (e.g., for a cable jacketing material), the thickness for ~95% oxidation (l) is reduced by 50%; that is,

$$l \sim [p\,Pox / \varphi\,]^{0.5} \qquad (2)$$

An example of heterogeneous oxidation is shown in Figure 5.5 [76]. Modulus profiling was used to show the changes that occur through the thickness of a sample at progressive aging intervals during thermal aging in an air-circulated oven. The hardness at the edge of the sample after 63 and 70 days at 125 °C (257 °F) is approximately three times higher than the hardness in the center of the sample, indicating a significant difference between the degradation at the surface and that in the middle of the sample.

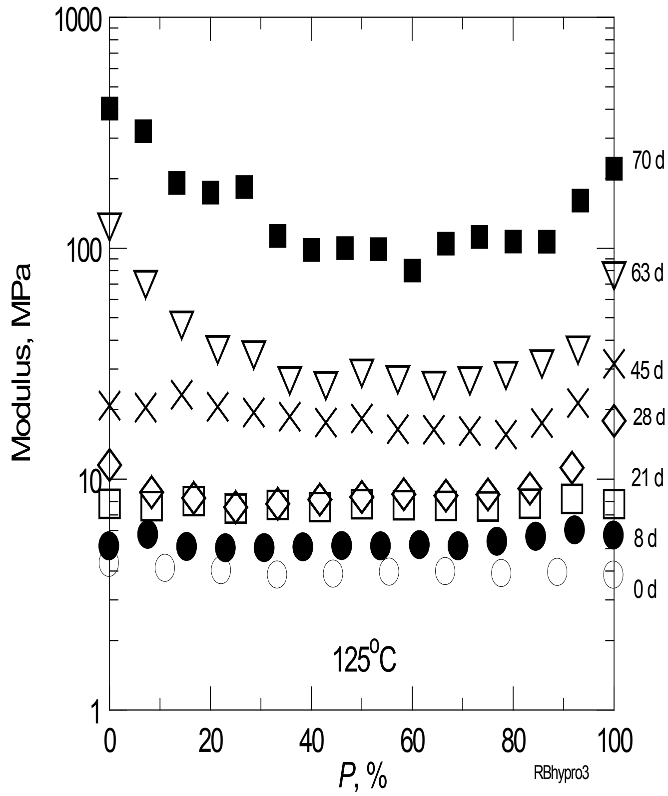

Figure 5.5. Modulus profiling of a 1.3 mm thick CSPE material aged at 125 °C (257 °F) for the indicated times in days (d), where P is the percentage of the distance from one air-exposed surface to the opposite air-exposed surface [76]. Reprinted from K. T. Gillen, R. A. Assink, R. Bernstein, and M. Celina, "Condition-Monitoring Approaches Applied to the Degradation of Chlorosulfonated Polyethylene Cable Jacketing Materials," ***Polymer Degradation and Stability*** **91, 1273–1288 (2006), with permission from Elsevier.**

This example is representative of numerous materials [70–72, 74, 75] where a decrease in oxidation away from the surface of a material due to the presence of DLO effects leads to a reduction in the rate at which the material hardness increases with time in these areas. Fortunately, in many such instances, tensile elongation measurements are unaffected by such DLO effects. This is due to the fact that cracks that originate at the hardened sample surface during elongation testing quickly propagate through the sample, implying that the surface chemistry reflected in the surface modulus values determines the elongation. This turns out to be the case for many important nuclear power plant CSPE and neoprene cable jacketing materials [75–77]. For other materials and environments this may not be the case. For instance, in radiation dominated environments, hardening due to cross-linking may become more significant as the dissolved oxygen concentration drops leading to elongation results that are significantly dependent on the importance of DLO effects [78].

The effect of DLO on the mechanical properties of cable jacket and insulation materials is therefore dependent on both the material and the environment. It also depends upon the particular mechanical property of interest. For example, the elongation of a material may be insensitive to DLO effects if edge hardening leads to crack propagation. However, because tensile strength results for the same material will depend on the integrated force generated across the entire sample cross section, this measurement will be sensitive to DLO effects [70].

5.2.2 Implications of DLO Effects

From a historical perspective of cable qualification, there are notable implications of DLO effects. Typical cable qualification employed high-temperature aging [150 °C (302 °F)], followed by radiation aging at high dose rates [~5 kGy/h (0.5 Mrad/h]. A recent report has presented evidence that at such aging conditions, the DLO effects can be very significant such that the insulation materials in a typical cable experience little or no oxidation during the aging exposures [69]. Since oxidation degradation chemistry is typically more aggressive than any anaerobic degradation chemistry, such simulations may totally miss the dominant degradation chemistry that will occur during natural, long-term aging, where DLO effects are unimportant. The cable manufacturer typically provides activation energies, utilized in Arrhenius methodology to determine aging conditions. They can be calculated from other values, but many assumptions must be made and this increases potential uncertainties in accelerated aging or pre-aging.

To understand the implications of the above, simplistic DLO modeling of the cross section of a typical three-conductor (3/C) cable with 30 mil (0.076 cm) XLPO insulations and a 60 mil (0.152 cm) CSPE jacket will illustrate the problem. At the start of aging, oxygen will be dissolved at its equilibrium value both in the jacket and the insulation materials. When aging begins, this dissolved oxygen will be used up quickly by reaction, after which it will need to be replenished by diffusion effects from the air surrounding the outside of the cable. Since the mid-point circumferential length of the jacket is similar to the sum of the mid-point circumferential lengths of the three insulations, we can approximate the cable geometry as two parallel adjacent sheets. The inside surface of the inside sheet (the XLPO insulation) is adjacent to the copper conductor and has no source of oxygen. The outside surface of the outside sheet (the CSPE jacket) is next to an air source that supplies any replacement oxygen through diffusion effects. Using a typical one-dimensional finite element approach of combining the oxidation chemistry with diffusion equations leads to predictions of the importance of DLO effects in such situations [69, 79, 80]. The most important parameters needed to apply this approach are estimates of the oxygen consumption rates (φ) and the oxygen permeability coefficients P_{ox} at the aging conditions being modeled. Other required parameters include the thicknesses of the two materials (known), plus their densities (known or easily measured) and solubility coefficients (no effect on the oxidation results). Also required are the oxygen partial pressure p in the surrounding air atmosphere (16 cm Hg for sea-level air) and an oxidation parameter β. For thermal aging, β is typically close to unity [79]; for radiation-dominated aging, β has been found to be around 10–30 [69], but few such measurements have been made in radiation-dominated environments.

For the simulation of the typical 150 °C (302 °F) thermal aging part of the historical qualification approach, we would like to estimate the oxygen consumption rates and the oxygen permeability coefficients for the CSPE jacket and the XLPO insulation. Many CSPE jacketing materials have similar degradation behaviors and similar activation energies [74]. A typical result for oxygen consumption is ~8 × 10^{-11} mol/g/s at 108 °C (226 °F). Since 107 kJ/mol represents the high-temperature E_a for CSPE jacketing materials [74], this leads to an estimate of 2.3 × 10^{-9} mol/g/s at [150 °C (302 °F)] for the oxygen consumption rate. A rough estimate for the 150 °C (302 °F) permeability coefficient is 5.9 × 10^{-9} ccSTP/cm/s/cmHg [75].

For XLPO materials, the estimate for oxygen consumption depend on the material since thermal E_a values are found to vary quite significantly. For instance, the Brandrex data (E_a ~ 72 kJ/mol) leads to an extrapolated φ of ~4.4×10^{-11} mol/g/s at 150 °C (302 °F) [75]. On the other hand, the results for a Rockbestos XLPO, with a much larger high-temperature E_a (135 kJ/mol), provide an extrapolated φ of ~2.7×10^{-10} mol/g/s at 150 °C (302 °F) [75]. We will utilize the lower value (4.4×10^{-11} mol/g/s), which will lead to less important DLO effects. For the at 150 °C (302 °F) permeability coefficient we choose 1.7×10^{-8} ccSTP/cm/s/cm Hg [75]. With these estimates and typical densities (1.5 g/cc for CSPE, 1.3 g/cc for XLPO), plus choosing a value of unity for the oxygen parameter β, we are now able to model the importance of DLO effects for this "generic" CSPE/XLPO cable at 150 °C (302 °F). The results are shown in Figure 5.6

The results indicate that DLO effects are important with the relative oxidation decreasing rapidly across the CSPE jacket and reaching ~1% oxidation across the XLPO insulation. Therefore, little oxidation would be expected in XLPO within our model cable during a typical historical thermal aging simulation. If the larger value for the consumption rate of XLPO (2.7×10^{-10} mol/g/s) were used, DLO effects would be even more important.

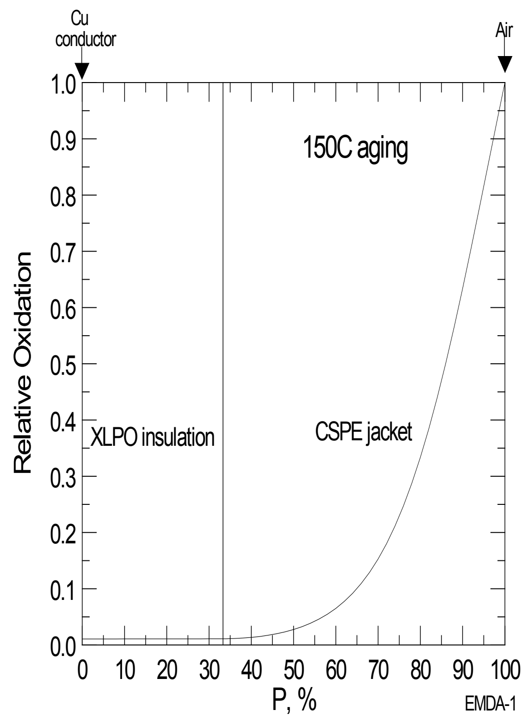

Figure 5.6. Estimated oxidation profile [78] across a "generic" 3/C cable with a 60-mil-thick CSPE jacket and 30-mil-thick XLPO insulations aged at typical 150 °C (302 °F).

The second part of historical aging simulations of cables involves room-temperature radiation aging at doses around 5 kGy/h (0.5 Mrad/h). Arakawa and colleagues [81] measured the oxygen consumption rate for two formulated CSPE materials at 2 kGy/h (0.200 Mrad/h) and determined φ to be equal to 5×10^{-10} mol/g/Gy for one compound and 3.2×10^{-10} mol/g/Gy for the second. We will use the 3.2×10^{-10} mol/g/Gy result, lowering the importance of DLO effects relative to the use of 5×10^{-10} mol/g/Gy. At 5 kGy/h (0.5 Mrad/h), 3.2×10^{-10} mol/g/Gy leads to $\varphi \sim 4.4 \times 10^{-10}$ mol/g/s. For the XLPO materials, we utilize a measured value of 1.2×10^{-9} mol/g/Gy [82]. At 5 kGy/h (0.5 Mrad/h) this gives $\varphi \sim 1.67 \times 10^{-9}$ mol/g/s. At room temperature, the oxygen permeability coefficient of a typical XLPO insulation is ~ 3×10^{-10} ccSTP/cm/s/cmHg [83]. For CSPE at room temperature, the oxygen permeability coefficient of a typical commercially formulated CSPE compound is ~1×10^{-10} ccSTP/cm/s/cmHg [84]. With these estimates and the same densities used above (1.5 g/cc for CSPE, 1.3 g/cc for XLPO) plus a β chosen to be 1, we are now able to model the importance of DLO effects for this "generic" CSPE/XLPO cable at 5 kGy/h (0.5 Mrad/h) and room temperature. Figure 5.7 indicates DLO effects with essentially zero oxidation in the XLPO insulation. If we had used a higher value of β that might be appropriate for radiation dominated situations, the DLO effects would have been similar except having a slightly different drop-off shape. It is noted that the DLO effects are so severe in this instance that one could have eliminated the XLPO material from the analyses and obtained the same result by simply modeling the CSPE as a single sheet of 0.152 cm thickness with an oxygen source on the outside [69, 79, 80].

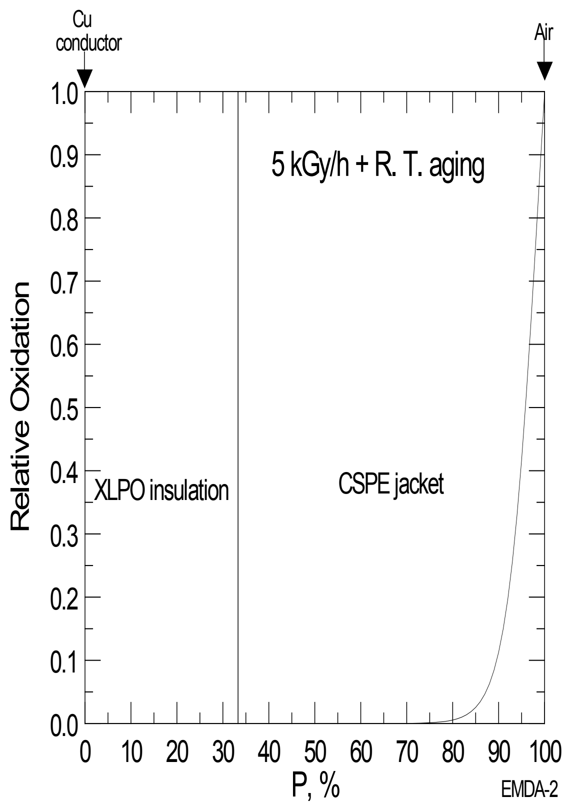

Figure 5.7. Estimated oxidation profile [69] across a "generic" 3/C cable with a 60-mil-thick CSPE jacket and 30-mil-thick XLPO insulations aged at room temperature and 5 kGy/h.

It is also interesting to apply Eq. (2) to estimate how thin the CSPE would have to be in order to have the oxidation achieve ~95% of its equilibrium (non-DLO affected) oxidation.

$$l \sim \left[\frac{pP_{Ox}}{\varphi}\right]^{0.5} = \left[\frac{(16\ \text{cmHg})(1e-10\ \text{ccSTP/cm/s/cmHg})}{(4.4e-10\ \text{mol/g/s})(2.24e4\ \text{ccSTP/mol})(1.5\ \text{g/cc})}\right]^{0.5} = 0.0104\ \text{cm}$$

Since the sample thickness (0.152 cm) is ~14 times thicker than the calculated value of *l*, it can be seen that the DLO effects are very important. We can contrast this result with the situation expected under typical 60-year ambient aging conditions [dose rates up to ~0.5 Gy/h (50 rad/h)]. If the oxygen consumption rate per gray remains constant, down to 0.5 Gy/h (50 rad/h) [a factor of 10^4 lower than the accelerated dose rate of 5 kGy/h (0.5 Mrad/h)], *l* will be 100 times larger (~1 cm). Clearly under ambient conditions, the DLO effects will be expected to be unimportant. Future work should involve detailed forensic analysis (e.g., chemical, electrical, and mechanical testing) of service cables, which were in radiation/thermal environments as a means to validate the severity of DLO effects in actual plant environments.

Although the above example is for a “generic” 3/C XLPO/CSPE cable, similar modeling on other typical cable configurations is expected to also show important DLO effects. For thermal aging part of the sequence, certain single-conductor cables with thin individual jackets aged at lower aging temperatures [e.g., 121 °C (250 °F)] may not have exhibited substantial DLO effects. However, even these cables will be expected to have significant DLO issues for the sequential radiation aging exposures at high dose rates. A major issue with past qualifications is the likely presence of severe DLO effects for one or both parts of the sequential aging sequence. These effects are due to the highly accelerated aging conditions used (very high thermal aging temperatures and very high radiation dose rates). These effects imply that the cable insulation materials were often aged essentially under inert aging conditions. Since the slow ambient aging conditions operate over decades-long natural aging conditions, these ageing effects are unaffected by important DLO effects; the chemistry underlying natural aging is usually dominated by oxidative processes. For insulation materials aged under historic sequential qualification conditions, this oxidation chemistry is either significantly reduced or totally absent. An apparent viable method of reducing or eliminating DLO effects during aging simulations of whole cables is to significantly slow down the accelerated conditions by reducing the aging temperatures and dose rates while aging for much longer aging times.

5.3 DOSE RATE EFFECTS

One of the shortcomings of the IEEE approach is the use of the “equal dose, equal damage” assumption for simulating radiation-aging effects. This is equivalent to the assumption that dose rate effects (DREs) are absent. Numerous studies now show that DREs are very common [32, 82–85]. In most polymers, observed degradation is dependent on the total absorbed radiation dose and the dose rate. Degradation at low dose rates, such as those present under normal reactor operational conditions, is significantly higher than the degradation that occurs for the same total dose at a higher dose rate, such as in accelerated testing.

DREs are caused by many different phenomena. First, radiation aging is always undertaken at some temperature *T*, and the thermally-induced chemical degradation pathways can interact with the radiation-induced pathways to enhance the overall degradation rate. Thus, if the dose rate is changed at a given temperature, the relative ratio of thermally-induced chemistry and radiation-induced chemistry will change, leading to DREs. In other instances, true chemical DREs result directly from the radiation-induced chemical pathways, as found for PVC and low-density polyethylene materials [86].

In many cases, an observed DRE arises from the effects of DLO, which results in heterogeneous oxidation (as discussed in Section 5.2), particularly in thick samples and/or at highly accelerated aging conditions [82–85, 87, 88]. Since DLO effects become much more significant when degradation occurs quickly (e.g., at high temperatures or high dose rates), the high temperatures and high dose rates, allowed by the IEEE standards, usually guaranteed significant DLO effects as illustrated above [89].

Under combined thermal- and radiation-aging at slightly elevated temperatures typical of "worst-case" service conditions [~50 °C (122 °F) plus 0.1 to 0.5 Gy/h (10 to 50 rad/h)], apparent or real DREs are often material-dependent. Three different cases are illustrated: for a neoprene jacketing material (Figure 5.8), several CSPE jacketing materials (Figure 5.9) [90], and an XLPE cable insulation material (Figure 5.10). The first two figures show modeling results at 50 °C (122 °F) that predict the dose required for the elongation of the material to reach 100% vs. the dose rate of the exposure, whereas the third figure shows actual experimental results vs. dose rate at 20 °C (68 °F). For the neoprene material, which generally exhibits lower temperature resistance, (Figure 5.8), the ambient conditions (0.1 to 0.5 Gy/h) lie in the region where thermal aging totally dominates the degradation. Thus, even though the predicted results at 50 °C (122 °F) appear to have DRE, the DRE, in fact, do not exist under ambient aging conditions. For the CSPE materials (Figure 5.9), the ambient conditions [0.1 to 0.5 Gy/h (10 to 50 rad/h)] lie in the region where a transition occurs between radiation dominant and thermal dominant regimes. As such, the DREs in this instance are due to the relative changes in importance of radiation and thermal effects as the dose rate is lowered. For the XLPE material (Figure 5.10), which is a much more robust material from a thermal-aging point of view, the observed dose-rate effects reflect the radiation-dominated regime and therefore represent true chemical DRE.

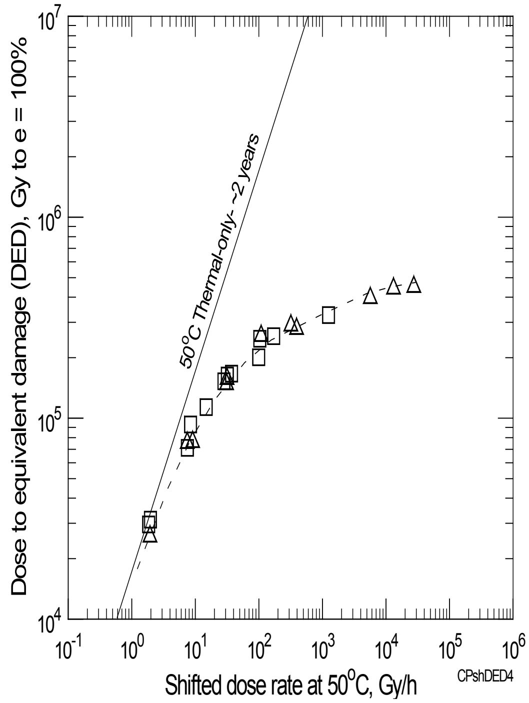

Figure 5.8. Time-temperature-dose rate superposition at 50 °C 122 °F) for the Okonite neoprene for the dose required to reach 100% elongation under combined radiation/thermal environments [90]. The homogeneously aged results are plotted as squares whereas the non-homogeneous (DLO-affected) are plotted as triangles.

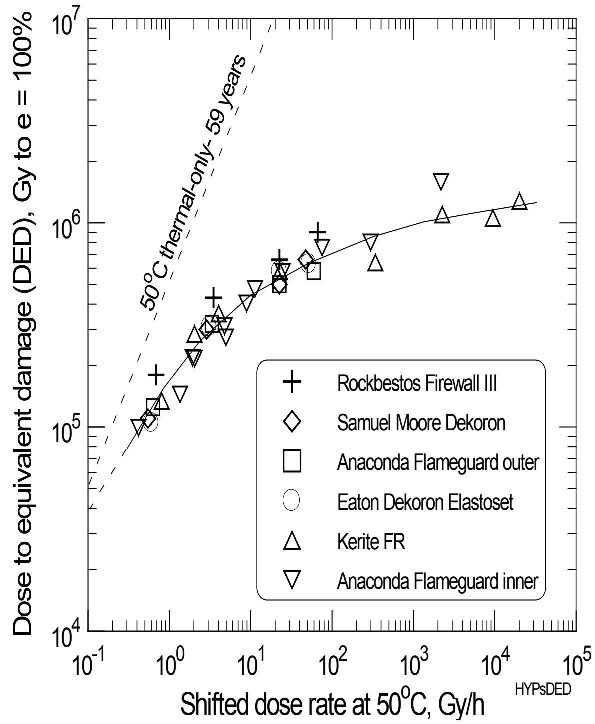

Figure 5.9. Time-temperature-dose rate superposition at 50 °C (122 °F) for several CSPE materials for the dose required to reach 100% elongation under combined radiation/thermal environments [90].

An example of DRE in the radiation-dominated region (i.e., near ambient temperature combined environments) is shown in Figure 5.10 for an XLPE cable insulation material.

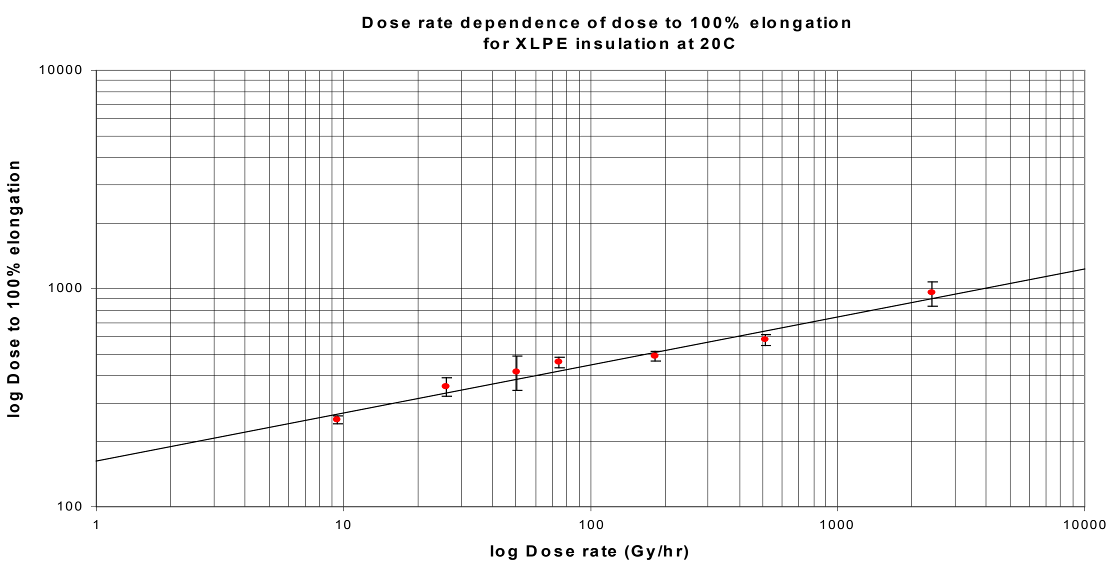

Figure 5.10. Dose in kGy required to reach 100% elongation for a XLPE cable insulation material at 20 °C (68 °F) [90].

5.4 SYNERGISM BETWEEN THERMAL AND RADIATION AGING

Qualification testing is conducted under the assumption that thermal-degradation and radiation-degradation are independent and additive and that there are no synergistic effects. However, for many polymers, synergistic effects can be significant so that the degradation becomes a complex function of temperature, dose, and dose rate. There are predictive models available that can take into account such effects [75, 91]. Figure 5.11 shows an example of the typical generic shape of curves of DED as a function of temperature and dose rate. (DED is the radiation dose required to reach a specific level of degradation; e.g. an elongation at break of 100% absolute.)

At high dose rates, an increase in temperature has little effect on the DED value, whereas at low dose rates, temperature has a large effect. At high dose rates, radiation-degradation mechanisms will dominate the overall degradation process. At low dose rates, thermal-degradation processes will dominate, and the slope of the plot of DED vs. dose rate will approach a value of 1 (i.e., a constant time). In polymers that show no significant synergy, the curves at high dose rate will approach a single line of constant DED independent of temperature. For the example shown in Figure 5.11, there might be some small synergism since the lowest temperature curve seems to still have the DED increasing slightly at the highest dose rate. Since the curves at the various temperatures will superpose when shifted horizontally by the thermal shift factors, the fact that they are displaced horizontally at the highest dose rate (0.2 Gy/s) does not necessarily imply synergism. At the temperatures and dose rates that are applicable in normal operational aging in NPPs [up to ~50 °C (122 °F) and 0.5 Gy/h (50 rad/h)], the degradation of some important cable materials will be dominated or partially influenced by thermal aging (e.g., neoprene and CSPE, respectively as seen in Figure 5.8 and Figure 5.9). The degradation of other, more thermally robust materials (e.g., silicone, XLPO, and EPR) will be dominated by radiation effects.

The existence of synergistic effects can be determined by carrying out concurrent radiation- and thermal-aging on polymer material samples. Tests carried out at dose rates < 500 Gy/h (50,000 rad/h) and at moderate temperatures [e.g., 25 °C (77 °F) and 60 °C (140 °F)], will usually indicate whether synergistic effects need to be taken into account during accelerated testing.

Another type of synergistic effect that may need to be considered arises from interactions between the different materials used in the cable construction. Degradation products from one part of the cable may affect other parts of the cable. This can be confirmed by comparing the aging observed in samples aged as whole cable with samples aged as separate components.

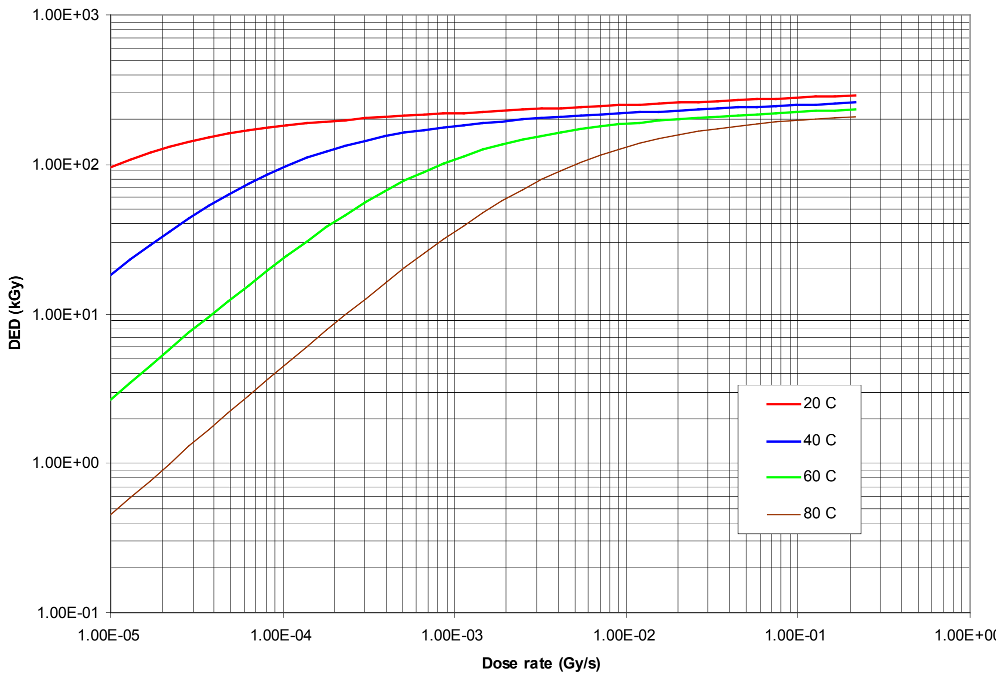

Figure 5.11. Generic shapes of the dose required to reach a specific level of degradation (dose-equivalent damage) as a function of dose rate at different temperatures for a typical polymeric cable material [75, 91].

5.5 SEQUENTIAL VS CONCURRENT AGING

The interaction between the chemical pathways arising from thermal aging and those arising from radiation aging give rise to the synergistic effects seen in many polymers. These synergistic effects will also affect the result of sequential aging compared with concurrent aging. In many of the polymeric materials of interest in cable insulation and jackets, degradation is most severe in concurrent aging and least severe in sequential aging where the thermal aging is carried out before radiation aging.

5.5.1 Inverse Temperature Effects

In combined radiation and temperature environments, many EPR/EPDM and XLPE/XLPO materials exhibit "inverse temperature" effects, where the degradation rate at a constant radiation dose rate is found to be faster at low temperatures, typically initiating when temperatures drop below around 50 °C (122 °F) to 60 °C (140 °F), depending on the material, than at more elevated aging temperatures [30, 92, 93, 94]. Figure 5.12 illustrates this phenomenon, showing that the data for 100% elongation in a Brandrex CLPO behaves as expected for combined environments at 60 °C (140 °F), and above [the open squares represent data obtained at 60 °C to 120 °C (248 °F)], but at lower temperatures (filled squares), this material degrades considerably faster. Because this anomalous behavior occurs in the temperature range that exists for NPP aging and that such behavior is in contradiction with common aging models (i.e., an increased aging rate corresponds to a decrease in temperature), this phenomenon is of concern. These counterintuitive effects must be understood in making lifetime predictions for such materials with reasonable confidence [9]. Better characterization of the temperature and radiation service environments would enable a sound assessment of the impact of inverse-temperature phenomenon.

The inverse temperature effect is a phenomenon that has only been recognized relatively recently (first manuscript discussing to nuclear power plant cable insulations published in 1994). It has been observed in semi-crystalline polymers that have been radiation-aged in air at temperatures below their crystalline melting point [92, 94, 95]. Under these conditions, the degradation is more rapid at the lower temperatures than at higher temperatures, which is opposite to what would be expected from normal kinetics of chemical reactions. However it is now realized that the inverse temperature effect is a function of the semi-crystalline nature of these polymers. This effect is not expected to be significant in polymers with limited crystallinity. For example, although an EPR that is very crystalline [75] shows an inverse temperature effect (Figure 5.13), an EPR specimen with low crystallinity [75] does not show this same effect (Figure 5.14).

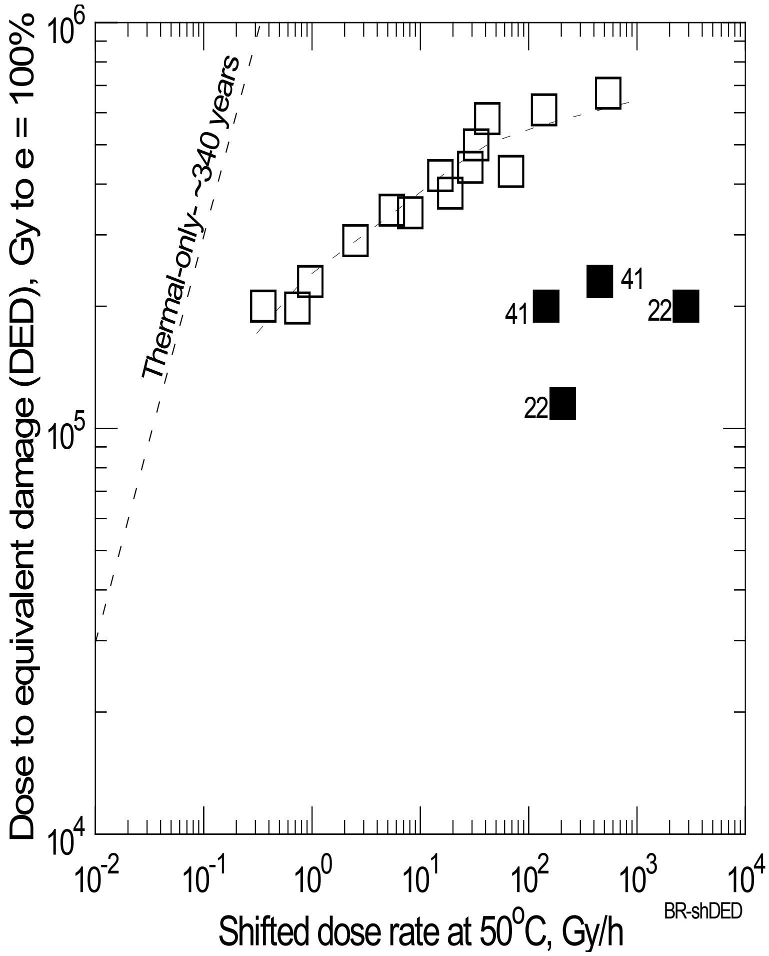

Figure 5.12. Time-temperature-dose rate superposition at 50 °C (122 °F) for Brandrex CLPO insulation for the dose required to reach 100% elongation under combined radiation/thermal environments. The numbers by the filled squares denote the aging temperatures in °C [90].

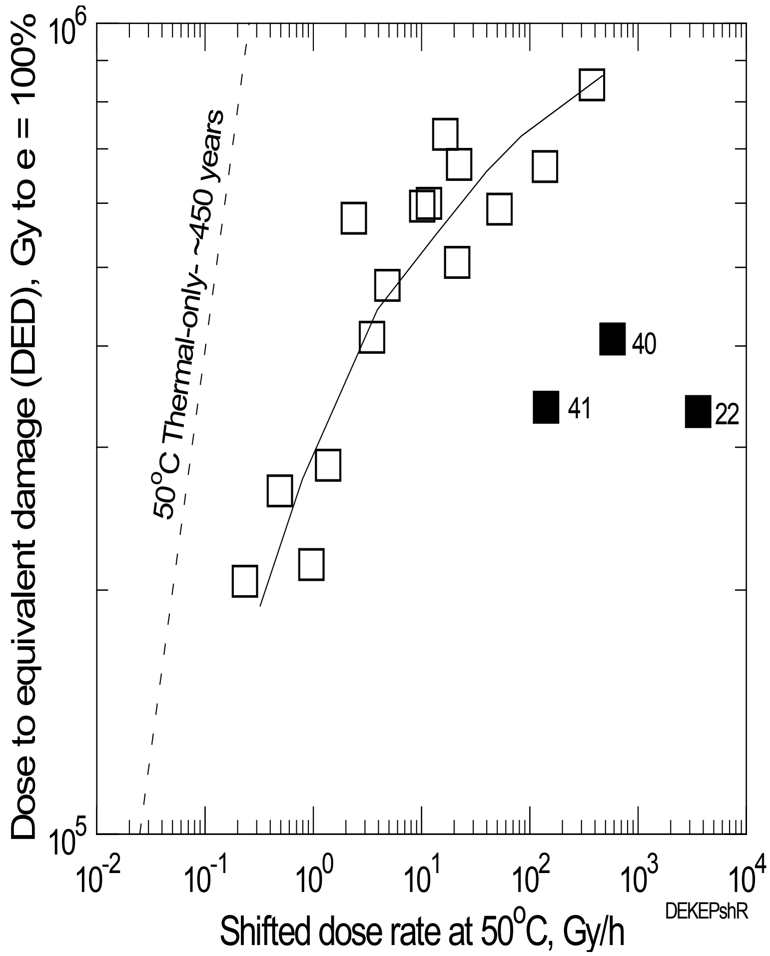

Figure 5.13. Time-temperature-dose rate superposition at 50 °C (122 °F) for Eaton Dekoron Elastoset EPR insulation (significant crystallinity) for the dose required to reach 100% elongation under combined radiation/thermal environments. The numbers by the filled squares denote the aging temperatures in °C [90].

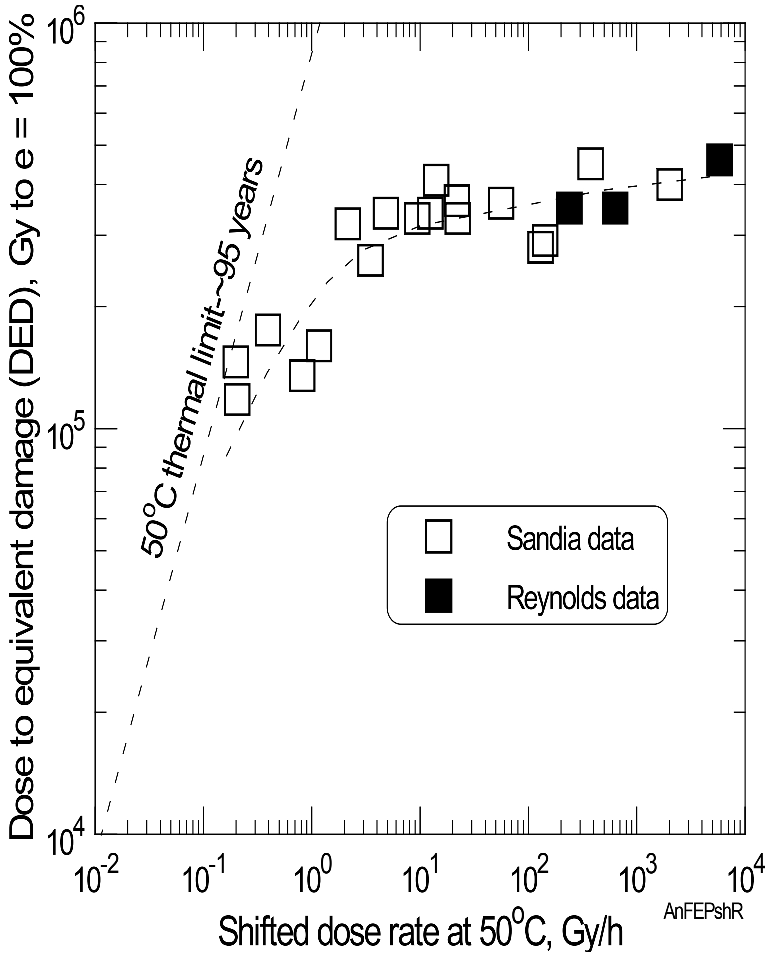

Figure 5.14. Time-temperature-dose rate superposition at 50 °C (122 °F) for Anaconda Flameguard EPR insulation (limited crystallinity) for the dose required to reach 100% elongation under combined radiation/thermal environments [90].

The mechanical properties of semi-crystalline polymers are determined by their microstructure at the supermolecular level. The material contains randomly oriented crystalline regions linked by amorphous tie molecules. During radiation aging, reactive species, such as radicals, are generated uniformly throughout both crystalline and amorphous regions. At temperatures well below the crystalline melting point, the reactive species are trapped in the crystalline regions and are unable to react to form oxidative products because of the low chain mobility and the low oxygen diffusion rate. Degradation then proceeds primarily through oxidative scission reactions in the amorphous regions, where both chain mobility and oxygen diffusion rates are higher. Since the amorphous regions form the tie molecules between the crystalline blocks, chain scission in those regions has a marked effect on the mechanical properties.

If the radiation aging occurs at slightly higher temperatures, nearer the melting region for the crystalline portion, then chain mobility is high enough for the trapped species to react to form chemical cross links. In addition, the enhanced mobility enables some re-crystallization to occur that can reform tie molecules that were broken by oxidative scission in the amorphous regions. The combination of these effects is to effectively "heal" some of the damage created by the radiation aging. The overall macroscopic effect is a reduced rate of degradation at the higher temperature during radiation aging.

5.6 PRE-AGING OF SEMI-CRYSTALLINE MATERIALS

During qualification of cable materials, there is a requirement to pre-age samples to degradation levels equivalent to the expected lifetime of the NPP, prior to carrying out a DBE test. In semi-crystalline polymers, such as XLPE and some EPR materials, where the crystalline melting points lie between the temperatures used for accelerated aging and those in service, there are concerns for both thermal aging and radiation aging that need to be addressed.

Firstly, when using the Arrhenius equation to extrapolate accelerated thermal aging behavior to the service temperatures applicable under NPP operating conditions, it is generally recommended that such extrapolations should not be performed through a physical transition, such as a melting point. Extensive studies using ultrasensitive methods to measure activation energies at low temperatures [93] indicate that it may still be practical to use the Arrhenius equation for some of the materials, provided that a suitable value for E_a (typically 70–75 kJ/mol) is used. The value of E_a needs to be confirmed by measurements made over a temperature range that overlaps mechanical property measurements (e.g., using oxygen consumption methods) (Figure 5.15).

Secondly, many semi-crystalline polymers show an inverse temperature effect when exposed to concurrent thermal and radiation aging. For those materials, the degradation is faster at lower temperatures than at high temperatures, typically in the temperature range from 20 °C (68 °F) up to 40 °C (104 °F) or even 60 °C (140 °F), depending on the material, which is the temperature range of most interest in an NPP. Thus the question arises as to how to carry out realistic pre-aging of semi-crystalline polymers in qualification.

Finally, as was demonstrated above in Section 5.3, the potential importance of DLO effects for past qualifications, where these materials were room-temperature-aged at the high dose rates need to be considered. For radiation-aging of cables at dose rates on the order of 5 kGy/h, (0.5 Mrad/hr) little or no oxidation would be expected in the insulation material, so crystalline insulations would be aged in the absence of oxygen. The absence of oxygen would result in inert aging that effectively eliminates the inverse-temperature phenomena and drastically slows down the degradation rate [92]. This experimental procedure results in pre-aged samples that are not representative of the condition expected to occur for samples aged under ambient conditions over their lifetime.

One possible approach to pre-aging such materials could make use of the typical radiation-aging behavior of the materials, where the power law model is known to apply well at near-ambient temperature. This potentially gives a starting point for modeling when data are available from radiation aging. In the power law model, the dose required to reach a specific end-point criterion (for example, a decrease in elongation to 50% of initial value) is found to follow a simple power law, where

$$\text{Dose to end-point} = K.D^n$$

Where D is the dose rate and K and n are material-specific parameters; typically, n is in the range 0 to 0.3.

The general constant temperature shape of the transition from constant time to failure (dominated by thermal degradation) to a dose-rate-dependent time to failure (dominated by radiation degradation) is also known from the superposition model [91]. As a first approximation, (using a value of $x = 1 - n$ in the superposition model), this curve shape could be used to predict how the transition may occur in semi-crystalline polymers. The dose rate at which the curves will diverge is unknown. The first indication of this would be a nonlinearity of the power law line at low dose rates.

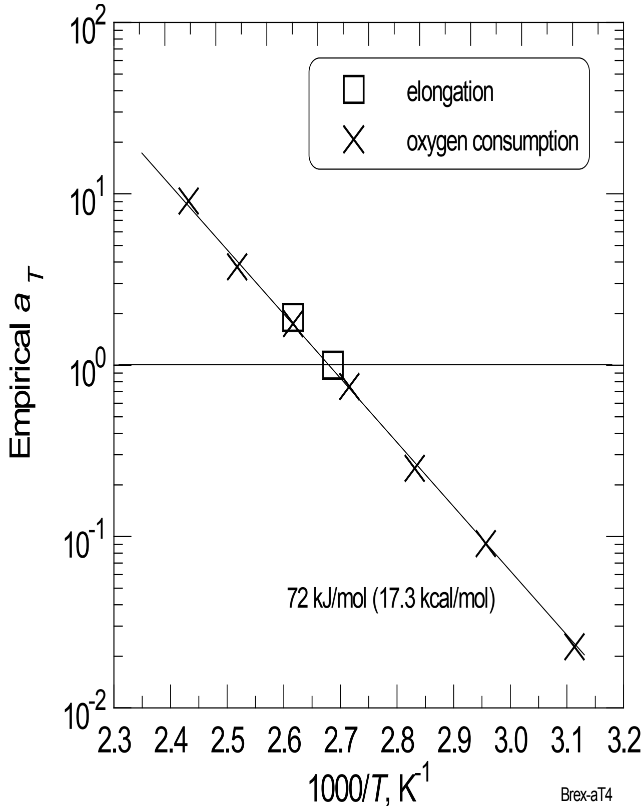

Figure 5.15. Arrhenius plot of the shift factors for elongation and oxygen consumption for Brandrex CLPO insulation [75, 90].

This approach would give an estimate of the material behavior under NPP conditions. However, the pre-aging required for environmental qualification (EQ) testing is usually assumed to be dominated by the thermal aging component in cables. These materials may show non-Arrhenius behavior and often an inverse temperature effect, so using accelerated aging at higher temperatures to simulate thermal aging may not be valid.

A possible way forward is to use the estimated service dose and dose rate to estimate the likely degradation at the intended service life, then calculate the dose rate and time required to reach the same degree of degradation in a practical time-scale-based on the power law. This approach would require preliminary work on radiation aging at different dose rates to generate the power law parameters and the shape of the degradation curve. Because the lowest service temperature would be the worst-case scenario, the radiation testing should be conducted at or near ambient temperature. In such a procedure, however, one must choose an accelerated dose rate that does not significantly reduce oxidation chemistry by allowing DLO effects to become dominant. Unfortunately, this effectively eliminates high-dose-rate-accelerated exposures and will typically result in a fairly long time scale for the simulation of the radiation-aging.

When using this approach, it would also be necessary to carry out some confirmatory experiments at low dose rate and at elevated temperature (at the maximum service temperature). Also, purely thermal aging experiments are recommended to verify the absence of inverse temperature effect. This would confirm that radiation aging at ambient temperature is the worst case.

An example of operating experience data for a XLPE insulation material is shown in Figure 5.16. The material exhibits endothermic behavior with a broad melting temperature range, peaking at about 120 °C (248 °F), with a wide shoulder to the endotherm starting at about 60 °C (140 °F) (Figure 5.16). There is extensive radiation-aging data for this material for at 20 °C (68 °F), over a wide range of dose rates, showing that it obeys the power law. This material has also been the subject of combined thermal/radiation aging measurements at elevated temperature and is known to obey the time-dependent superposition model for temperatures > 90 °C (194 °F) (i.e., above the crystalline melting point).

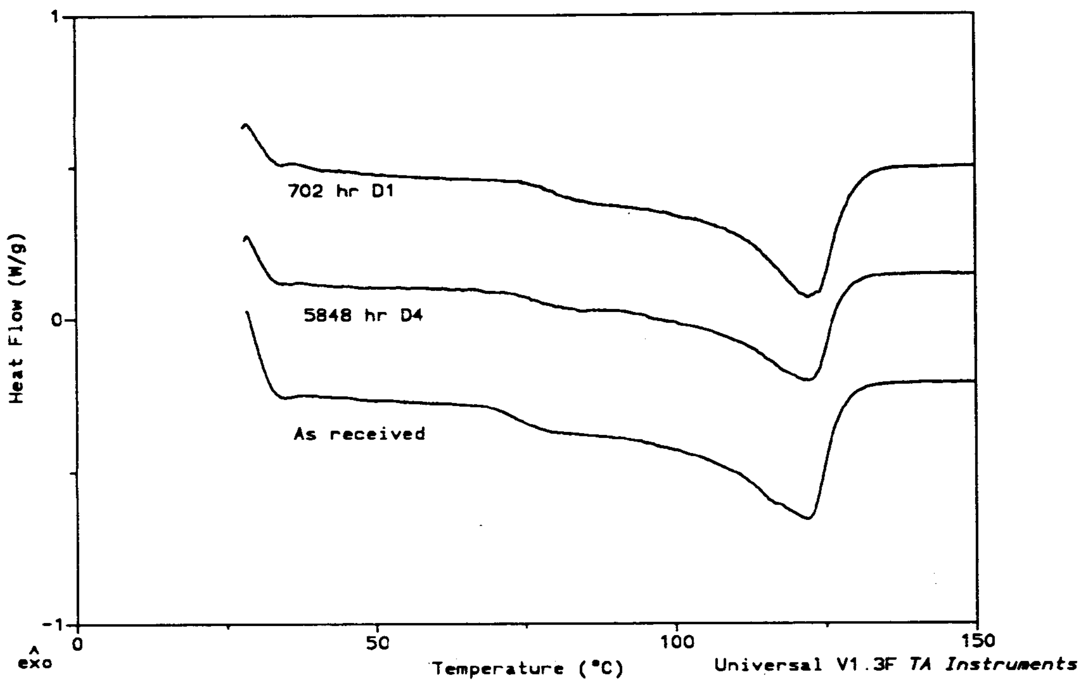

Figure 5.16. DSC traces for a XLPE insulation material, showing the crystalline melting endotherm in both unaged and aged material [31].

Figure 5.17 shows the total dose required to reach 100% elongation (DED) as a function of dose rate for this XLPE material. The red data points are for radiation aging at 20 °C (68 °F); the red line shows the best fit of the power law model to the data. The blue line and the green line show the predicted behavior at 60 °C (140 °F) and 90 °C (194 °F), respectively, from the superposition model for the material. Although the 90 °C (194 °F) data point (green) lies on the predicted curve, the 60 °C (140 °F) data point (blue) shows much higher degradation than predicted by the superposition model. This demonstrates that this material has a marked inverse temperature effect in the region 20 °C (68 °F) to 90 °C (194 °F).

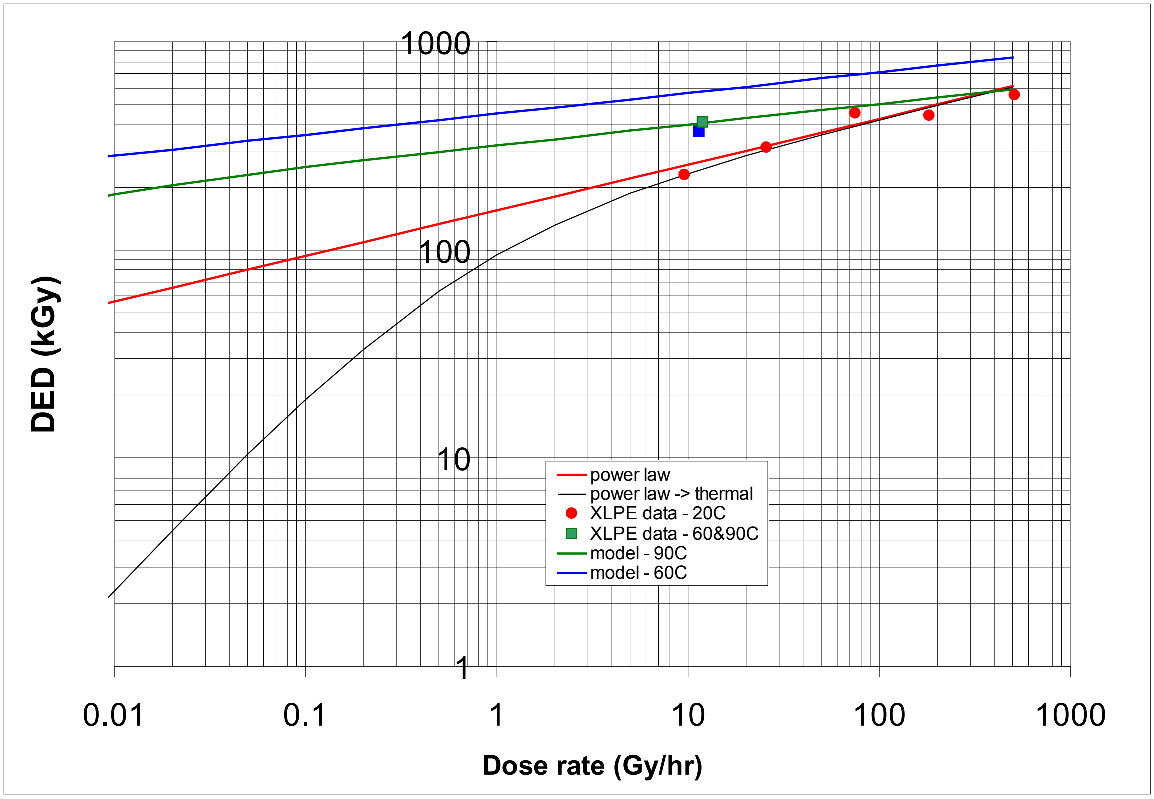

Figure 5.17. Radiation aging data for a XLPE insulation material as a function of dose rate [31].

The data for this XLPE material indicate that the power law approach appears valid, but there is still the uncertainty as to the dose rate at which thermal-aging effects become becomes dominant as the cause for material degradation. This would appear as a divergence from the power law line behavior as the dose rate decreases. In the example shown in Figure 5.17, if we assume that the lowest data point is showing some divergence, the predicted curve at lower dose rates might be approximated, as shown by the black line. This would be an extreme case, in that the predicted time to reach 100% elongation in the absence of radiation would be about 22 years, which is much less than the expected operational life for an XLPE insulation at 20 °C (68 °F). However, if this data point is regarded as being still within the power law (bearing in mind the standard deviation of the data), the divergent curve would be more like the example shown in Figure 5.18. The behavior under plant operation can most likely be expected in between these extremes.

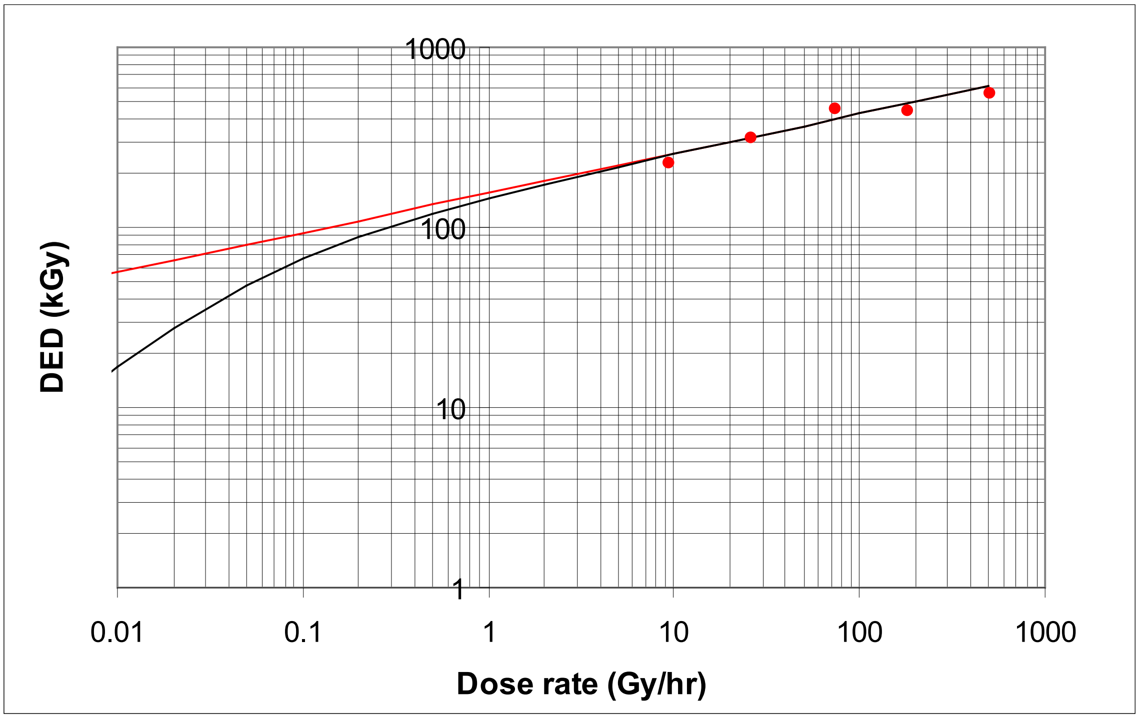

Figure 5.18. An illustration of how the degradation curve for this XLPE might behave at lower dose rates (black line), compared to the power law model (red line) [31].

5.7 MOISTURE EFFECTS

The industry responses to generic letter summary report (GL) 2007-01 indicated that water intrusion and/or water treeing is the most significant failure mechanism in the medium-voltage category (rated ≥5,000 V) [1]. The GL responses show that for low-voltage cables (rated <2,000 V), general or age-related degradation is the significant failure mechanism followed by physical/mechanical damage and water/moisture intrusion. It was noted in the GL that, overall, the presence of water or moisture appears to be the predominant factor contributing to cable failures.

Another area of concern not reviewed in the current document involves safety-related cables that are often submerged in water for long periods of time [96]. Although submerged cables are a concern for operating plants rather than for long-term operations, the aging of cables under submergence conditions is not well-understood. Medium-voltage cables in wet environments are known to degrade and eventually fail in various ways, including by the development of water trees. For that reason, at a recent NRC/U.S. Department of Energy (DOE) Workshop [97] it was recommended that future research be considered looking into the aging effects of very long-term wetting for both low- and medium-voltage safety-related cables with the goal of developing an accurate aging model.

In 2010, the NRC published Information Notice (IN) 2010-26, *Submerged Electrical Cables* [37], as a follow-up to IN 2002-12, *Submerged Safety-Related Electrical Cables* [96], to inform licensees of updated operating experience information on submerged cables. IN 2010-26 stated that the NRC expects licensees to identify conditions, which could potentially affect the quality of cables, which are exposed to long-term submergence in water. Upon discovery of a submerged condition, the licensee should take prompt corrective actions to restore the environment to within a cable’s design specifications, immediately determine the operability of the cable to perform its intended function, and determine the impact of the adverse environment on the design life of the cable. These corrective actions typically involve removal of water, installation of a sump pump, or the repair of dewatering/drainage systems, and evaluation of operability of the cable, including testing.

5.8 OHMIC HEATING

Cables used in NPP rarely suffer from significant ohmic heating due to the conservative ampacity limits. Safety-related applications are limited to 80% of allowed ampacity when sizing conductors. Frequently voltage drop and fault current calculations require even large conductors to be used that further limits the effects of ohmic heating. The only place where significant ohmic heating has been identified is in high-energy power circuits having multiple conductors per phase. In some cases, imbalances in impedance and magnetic fields have caused some conductors to be lightly loaded and others to be loaded beyond ampacity limits that resulted in aging and hardening of the insulation. The low and medium-voltage power cable aging management program implementation guides, EPRI 1020804 [6] and EPRI 1020805 [7], direct users to review such circuits and verify that significant ohmic heating has not occurred.

5.9 SUMMARY OF GAPS IN KNOWLEDGE

The Sections 5.1 through 5.8 have identified a number of areas of potential concern for the use of electrical cables in NPPs for operation beyond 60 years. There are several areas where specific experimental and analytical research could provide better methods for accelerated simulations for beyond 60 years using accelerated ambient nuclear-power aging environmental conditions. Although the purpose of this EMDA is to identify areas of technical issues for cables aged beyond 60 years, the issues raised in Sections 5.1 to 5.8 are also of potential concern for NPP cable aging in the 40 to 60 year time periods.

5.9.1 Activation Energies

Experiments to derive Arrhenius activation energies with reduced uncertainty at low temperatures for the specific cable materials of interest in U.S. NPPs would provide needed data for computer (analytical) simulations of thermal aging. An approach involving oxygen consumption measurements under conditions where DLO effects are totally absent as a function of aging temperature made on thin enough samples is favored.

5.9.2 DLO and Dose Rate Effects

With respect to choosing combined radiation plus temperature-accelerated aging conditions, and also for refining DLO calculations on cables under those conditions, the following experimental methods are suggested for consideration in the future.

- The dependency of aging on oxygen partial pressure can be studied under radiation conditions to provide information on oxygen consumption and to provide data for estimating values of β for DLO modeling.

- Oxygen permeability measurements on actual cable jackets and insulations up to at least 100 °C (212 °F).
- Development of two-dimensional finite element models for typical cable cross-sections to improve the accuracy of DLO modeling.

5.9.3 Inverse Temperature Effects

Research to better understand inverse-temperature effects, identify which cable materials are most susceptible to these effects, and develop suitable methods to accelerate the aging of these materials are of significance for understanding the expected behavior for operation beyond 60 years.

5.9.4 Moisture Effects

The effect of long-term wetting of both low- and medium-voltage cables is still not well understood. Research in this area would provide information on the extent of the significance of potential degradation in cable performance during long-term submergence.

Wet-energized aging is yet to be better-understood technical issue for medium-voltage cable. Results are available from a large volume of wet-aging research on medium-voltage XLPE cable, which is the most common distribution industry cable insulation. Less information on wet aging is available for medium-voltage EPR cables used in NPPs. The EPRI has been performing failure mechanism research on EPR cables removed from NPPs after failure or recognition of aging through testing. The EPRI 1018777 [98], EPRI 1021069 [99], and EPRI 1022965 [100] technical documents provide the results of this work.

5.9.5 Understanding of Actual NPP Environments

The NPP environments and their importance with respect to the aging of the cable system need to be understood more fully. Many phenomena of seeming concern are related to in-containment cables that could experience a pressurized steam condition and elevated normal radiation conditions. However, no safety or maintenance rule requires that medium-voltage cables be located in containment. A relatively small portion of the population of low-voltage cables is located inside containment. An understanding of the environments with respect to the populations of cable that they affect would help focus both concerns and research with respect to those concerns.

5.10 SUMMARY

The previous sections have identified a number of gaps in the generic knowledge of cable system and insulation material performance. Key modes of degradation and environmental uncertainties have been discussed. The impact of these knowledge gaps on predicting future performance will be discussed in more detail in a later section. This is also reflected in Appendix A with the PIRT.

6. CONDITION MONITORING

The environmental qualification (EQ) of cables has evolved during the past two decades, and provides methods and improved confidence in cable performance prediction. To make best use of condition–based qualification (CBQ) it is essential that suitable condition monitoring tools are available. This section briefly outlines the basic concept of CBQ and discusses the currently available condition monitoring (CM) methods.

6.1 CONDITION-BASED QUALIFICATION

The CBQ process differs from earlier practices in that it requires CM techniques to be utilized at intervals through the pre-aging phase of the qualification process. The CM activities measure and record the level of cable degradation to determine the shape of the degradation property vs. aging time of the cable being tested. Provided the cable is demonstrated to withstand a DBE environment after pre-aging, the CM values can then be used to determine the qualified level of degradation (QLD) that can be applied to installed cable. This approach is described in detail in Reference [31].

Figure 6.1 illustrates the concept of CBQ. The blue line is the degradation curve as a function of pre-aging, determined using one or more CM techniques. The shape of this curve will vary depending on the specific condition indicators being measured. Provided the cable is able to withstand a DBE test, including a post-accident environment (where appropriate), the QLD is determined from the maximum degradation at the end of pre-aging with a margin that will be dependent on the accuracy of the CM method. If the equipment has passed the required tests, and the QLD has been established, the QLD will be the value with which future CM measurements on installed cable are compared.

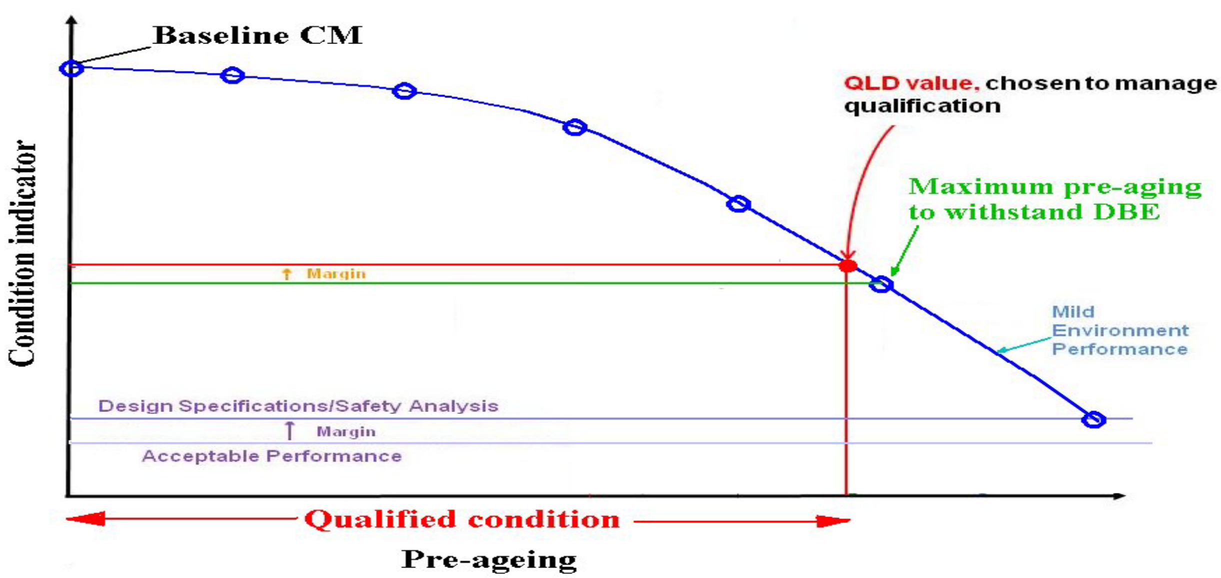

Figure 6.1. Schematic representation of the concept of condition-based qualification [31].

With CBQ, uncertainties in pre-aging, as discussed in Section 5, must be addressed to predict degradation with reasonable confidence. Also, certain materials (e.g., many of the EPRs) exhibit “induction-time” behavior, where the CM technique might show little indication in aging until a dramatic change occurs just before failure [101, 102]. Such behavior can complicate the approach depicted in Figure 6.1. In such instances, an alternative approach, referred to as the “wear-out” approach, may offer a solution if very small sacrificial samples can be obtained [102].

Nondestructive CM measurements could be made on deposited samples or on cables in service to confirm that the QLD is not exceeded. Furthermore, an incremental qualification approach, which involves aging the cable for another 10 years (or other suitable increments) and performing design-basis accident (DBA) testing, could be used for the life extension of cables.

In addition, this approach can be used for evaluating degradation of equipment in mild environments by determining an acceptable level of degradation (i.e., not less than the design specification) with sufficient margin and utilizing condition-monitoring activities to measure the rate of degradation.

6.2 CONDITION-MONITORING TECHNIQUES

For CBQ to be applied to cables in NPPs, suitable CM methods are needed. The ideal CM technique would need to satisfy a range of requirements. Important considerations are as follows:

- no disturbance of cables or sample removal during testing
- indicator of structural integrity and electric functionality
- no disconnection of equipment
- usable during normal operation where appropriate
- applicable to all materials
- well-correlated with actual cable degradation
- useable in areas of limited access
- reproducible in different environments (e.g., temperature, humidity, and vibration); cost-effective
- able to detect defects at any location;
- provides adequate time for corrective action to be taken before cable failure.

Current techniques do not satisfy all the listed considerations, but a wide range of methods have been evaluated for use in NPPs as part of a monitoring program. For the most-developed CM techniques, standards for the test method have now been published for use in CBQ [103–106].

Most methods are appropriate for evaluation of aging degradation in laboratory studies and potentially for use in NPPs. Not all have been fully evaluated yet, but the methods briefly discussed in the following sections have been selected because encouraging results have been achieved by several organizations around the world. A more detailed discussion of each of the methods is given in IAEA Nuclear Energy Series Report NP-T-3.6 [31].

One should note the potential significance of diffusion-limited oxidation (DLO) effects on condition monitoring approaches. The DLO was discussed in the previous sections. The most common methodology utilized for condition monitoring is to first carry out accelerated aging studies where the CM parameter of interest is typically correlated to tensile elongation results. This correlation is then assumed to hold for ambient aged materials so that CM measurements on such materials can be used to estimate the state of the elongation of the ambient material. Unfortunately the DLO effects can have a large impact on the correlation, and this effect and its consequences do not appear to have been addressed in any of the recent documents including this one. Not only are potential DLO effects important for the aging of samples, they can also enter during the application of the CM measurement technique. For example, CM techniques that utilize high temperatures (e.g., OIT, OITP) for the CM measurement can have DLO effects on the measurement technique because of the high temperature exposures. In such cases, the CM parameter measured can depend on the geometry (thickness) of the sample under measurement. When a material that has been aged under important DLO effects is subsequently tested with a CM technique that is affected by DLO, a complicated situation becomes even more complex (e.g., doublets observed in infrared analysis, washed out and hard to interpret signal responses, etc.). This limitation should be noted when choosing, performing condition monitoring tests and interpreting their results.

6.3 QUALITATIVE METHODS

It is not appropriate to apply the more sophisticated CM techniques to all of the cables in an NPP. Qualitative methods are useful in identifying cables, which should be considered for more detailed testing.

Visual and tactile inspection is a very valuable tool for the evaluation of cable condition when carried out by a trained technician [107]. It can be used to detect structural inhomogeneity from manufacture or due to operational conditions as well as to detect possible loss of additives or absorption of moisture. When aging is detected by visual inspection, more sophisticated CM techniques could be chosen, such as those described in the following sections, to quantify the degree of aging.

The use of an illuminated borescope to inspect inaccessible cables has been useful for identifying stressors that can lead to cable degradation. It can also detect visible cable damage. The borescope can be inserted into conduits or other locations containing cables that would ordinarily be inaccessible for inspection of mechanical damage that may have been caused during installation or service, or for indications that water has been present, signifying submergence of the cables during service. The borescope can also detect the presence of other contaminants, such as dirt, sharp metal debris, or chemicals that can cause accelerated degradation of the cables. Based upon the results of a borescope inspection, a decision can be made as to whether additional, more intrusive testing is needed.

6.4 TECHNIQUES REQUIRING SAMPLE REMOVAL

The CM techniques described in this section require some form of sample removal or intrusion. The methods described in this section are best applied to sacrificial samples in a cable deposit or from cables taken out of service. Microsampling of operational cables may be possible if approved sampling techniques are available. These methods will only provide information on the cable condition at the specific locations from which samples are removed.

Cable samples exposed to actual NPP service environments should be used for ongoing qualification, destructive examination, and other requalification practices based on evolving needs. Cable samples could be placed at critical locations (i.e., subject to extreme environmental conditions), at potential age-sensitive locations, and at hot-spot locations for radiation and temperature. The most developed of the methods for which standards have been developed (elongation at break and oxidation induction) may be appropriate to use in a CM program for CBQ.

Each of the following methods is briefly discussed:

- elongation at break
- oxidation induction methods
- thermogravimetric analysis (TGA)
- gel content and solvent uptake factor
- density
- modulus profiling
- nuclear magnetic resonance (NMR)
- infrared (IR) analysis
- electron microprobe analysis.

6.4.1 Elongation at Break

The elongation at break of a polymer based cable insulation during a tensile test is the benchmark physical property by which the structural integrity of the cable, and therefore its performance, is usually assessed. Historically, a value of 50% absolute elongation at break is used to indicate the end of useful service life. However, the value of elongation at which a cable would fail a DBE test is strongly dependent on the specific material formulation. For example, in a recent study, silicone rubber (SiR) cables were found to survive a DBE at 30% to 40% absolute elongation, whereas EPR cables required between 70% to 230% and XLPE between 70% and 310%, depending on formulation [33]. It is important to define the test methodology and keep parameters such as sample size and tensile test speed consistent because variations in test parameters can lead to varying test data, potentially contributing to misinterpretation of test results. In many cases, appropriate "dumbbell" samples can be cut out of cable jackets and bedding layers, but the smaller cable insulation samples usually comprise hollow tubes, in which case it is important to ensure that sample preparation methods are consistent. Standards for the use of elongation at break as a CM technique are now available [103–106].

Although the elongation at break test method generates the optimum data for cable condition assessment, it is impractical to use as a routine CM method. However, it is particularly useful where cable samples have been placed in a sample deposit, specifically for CM.

6.4.2 Oxidation Induction Method

In most polymers, many of the dominant processes associated with radiation and thermal degradation are controlled by oxidation. During exposure to radiation and thermal aging conditions, antioxidants in the polymer formulation act as radical scavengers and are consumed at a rate defined by the severity of the aging conditions. When they have been consumed, the polymer usually begins to degrade rapidly. Polymer properties known as oxidation induction time (OIT) and oxidation induction temperature (OITP) can be determined on standard differential scanning calorimetry (DSC) instruments. Microsamples (about 10 mg) can be used, and their properties are dependent on the remaining levels of antioxidants and the extent of oxidation (or degradation). The methods have been standardized for use in CM [103–106, 108].

The OIT and OITP measurements have been shown to correlate well with degradation of some cable insulation materials [109].

6.4.3 Thermogravimetric Analysis

TGA is carried out using commercially available thermal analysis instruments and requires sample sizes similar to those used for OIT/OITP. TGA testing is usually carried out as an alternative to OIT/OITP on samples that evolve corrosive degradation products [e.g., CSPE, chloroprene (CP), PTFE] because the sample chambers in TGA equipment are chemically far more robust than those used in DSC.

6.4.4 Gel Fraction and Solvent Uptake

The competition of cross-linking and chain scission usually defines the level of aging in a polymer, and a common method for evaluating the level of competition is the determination of the gel fraction (which increases when the crosslinking dominates) and solvent uptake factor (increases when scission dominates). A measure of cross-link density or level of chain scission should correlate with structural integrity and therefore with elongation at break. Data in the literature suggest some success in correlations of these parameters for polyethylene, XLPO, CSPE, and CP on samples weighing as little as 1 mg.

6.4.5 Density

Density measurement is a well-established means to evaluate polymer aging. As oxidation dominates the degradation processes when polymers are exposed to air, the resulting oxidation products that become incorporated in the polymer usually lead to an increase in density. The greater the degree of aging, the larger the concentration of oxidation products and the higher the density. The density of small samples of polymer can be measured using the Archimedes approach or by using a density gradient column [101].

Density measurement in general has been correlated to degradation for many polymeric materials, including CSPE, neoprene, polyethylene, and SiR [101]. Since it is a nondestructive measurement technique, density is particularly useful in applying the “wear-out” approach to lifetime prediction [102].

6.4.6 Modulus Profiling

Modulus profiling can measure how the modulus varies across the cross section of a material [101]. Since the modulus tends to increase with aging under thermal and radiation aging environments, the modulus profiling technique allows correlation to be made between modulus measurements and elongation results. It has been found to be useful for following the aging of CP and CSPE jackets plus EPR and silicone insulations. For numerous CP and CSPE jackets, modulus values reaching ~35 MPa correspond to elongation values reaching ~50% absolute. An additional use for modulus profiling involves its ability to screen for DLO effects or other heterogeneously based effects that might occur during accelerated aging exposures or under ambient aging conditions.

6.4.7 Nuclear Magnetic Resonance

Another CM technique, based on swelling a sample in an appropriate solvent, is NMR relaxation time (often abbreviated to T_2), which is related to the mobility of the polymer chains. As the polymer degrades, the chain mobility will alter, producing a measurable change in T_2. The method is based on the fact that the sensitivity of NMR relaxation increases when the sample is swollen with a solvent. The NMR relaxation times are sensitive to the cross-link density in the amorphous phase of a polymer and are therefore applicable to most polymer types [101].

6.4.8 Infrared Analysis

The IR analysis utilizes the fact that, as polymers degrade, the changes in structure that occur result in the formation of new chemical bonds, which have light-absorption characteristics that are different from the bonds in the original unaged material. The dominant oxidation mechanisms for polymers aged in air produce carbonyl species, which absorb IR light at characteristic wavelength (around 1,720 cm^{-1}). Therefore, a measurement of the amount of degradation in a polymer can be inferred from the ratio of absorbance at ~1,720 cm^{-1} and another characteristic absorbance in the spectrum for that particular polymer, which will give a measurement of the oxidation levels. The IR analysis is limited to thin samples as thicker samples absorb all incident light.

With the development of more advanced technologies, handheld Fourier transform infrared (FTIR) reflectance laser instruments have become available. These have the potential to become useful noninvasive test instruments for CM.

6.5 TECHNIQUES NOT REQUIRING SAMPLE REMOVAL

All of the above CM methods provide information on the cable condition only at the location tested. In principle, all the methods could be used on operational cables. The most developed of the methods, indenter modulus (IM), would be appropriate to use in a CM program for CBQ.

The following methods are discussed in this section:

- indenter modulus
- recovery time
- near-IR reflectance
- sonic velocity

6.5.1 Indenter Modulus

Indentation is one of the few nondestructive, and mainly nonintrusive cable CM method currently available that is also widely used (some cable movement is usually required, so care is required when handling heavily aged cables). To carry out a measurement, the instrument must clamp around the cable jacket or insulation to be measured. In taking an IM measurement, the probe only penetrates the surface of the test material a few hundred microns. Standards for use of the indenter as a cable CM tool are now available [103–106].

Good correlation data between IM and degradation have been demonstrated for elastomeric materials (e.g., some EPR, CSPE, SiR) but little or no correlation has been observed for the semi-crystalline polymeric cable materials (e.g., XLPE, XLPO), some EPRs).

6.5.2 Recovery Time

Indenters can also be used to generate relevant post-indentation parameters. A parameter that has recently been shown to be very useful in assessing the degradation of cables is the time to recover a set deformation resulting from prior indentation. The recovery time is measured during the post-indentation phase, following a force relaxation phase, and upon retraction of the indenter probe. This parameter has been shown to be very sensitive to degradation resulting from thermal aging and/or irradiation for a variety of materials tested to date (PVC, XLPE, EPR, CSPE) [110]. For all cases tested to date, the sensitivity to degradation was higher than when using the IM value, and in many cases, the correlation of recovery time with elongation was very strong.

6.5.3 Near-IR Reflectance

Polymer aging causes the development of IR absorptions due to the formation of oxidized species during aging. The ability to carry out IR analyses in reflectance mode has allowed the development of a portable near IR spectrometer. Although it has only been used so far in a cable identification capacity [111], near-IR reflectance has the potential to be more widely useful in assessing degradation.

6.5.4 Sonic Velocity

Sonic velocity test is based on the principle that the velocity of sound in a solid medium is dependent on both the density and the modulus. Since both the elastic modulus and density can change during aging of cable materials, changes in sonic velocity would also be expected to occur as the cable material ages. A sonic velocity test instrument uses piezoelectric transducers to transmit and receive a series of pulses. The sonic velocity tester measures properties of the cable jacket over a small volume between the transducer probes. The measurements obtained can be strongly dependent on the cable construction and the specific formulation of the jacket material. Therefore, extensive baseline data may be required.

The technique is still under development and has so far only been tested on PVC-jacketed cables. At present a prototype portable tester has been developed, but it has not been used in the field. Its high sensitivity to detect aging degradation indicates it could be beneficial if applied in the field and further developed.

6.6 TECHNIQUES BASED ON ELECTRICAL MEASUREMENTS

The ideal CM methodology for the assessment of cables in an NPP would be based on structural integrity and electrical functionality information. Some examples of electrical functionality tests are insulation resistance, polarization index, voltage withstand, and dielectric breakdown. Most of the tests are effectively pass/fail indicators of functionality, but studies over many years in the nuclear industry suggest that there are yet no reliable data to correlate these measurements and cable aging. Some of these tests require high voltages (dielectric breakdown is a destructive test), and so are not amenable for I&C cables in situ for fear of insulation damage.

Electrical measurements are mostly applicable to cabling systems, including conductors, connectors, splices, and penetrations, although they can also reveal degradation in cable insulations. The advantage of electrical techniques is their use in-situ and remote-testing capability. Many of the discussed electrical measurements can be performed on installed cables in an operating plant, and they can often reveal problems along the whole length of a cable. This is in contrast with methods that are limited to providing data at the localized point where the test is performed.

At present, CM methods based on electrical measurements applicable to CBQ programs are limited. They are most useful in identifying and locating problems in cable systems in plant and confirming cable performance. Some have shown potential for measuring aging degradation, but more research is needed to validate their use.

The following methods are briefly described in this section:

- partial discharge (PD)
- frequency domain reflectometry (FDR)
- time domain reflectometry (TDR)
- reverse time domain reflectometry (RTDR)
- dissipation factor
- inductance, capacitance, and resistance (LCR) measurements
- insulation resistance

6.6.1 Partial Discharge

PDs are electrical discharges that occur in gaseous inclusions, which may accidentally occur in solid insulation. During testing in which the voltage is slowly raised, the voltage at which PDs are observed in each cycle is known as the PD inception voltage. Decreases in the PD inception voltage are an indication of significant degradation of the insulation material.

The PD test is potentially damaging since the discharges induced can induce insulation degradation over a period of time due to localized overheating. The PD test has limitations for use in the field since it requires relatively high voltages to be applied to the cable, which would be a concern due to the potential to damage the cable or surrounding equipment. As a result, PD test is typically performed on medium-voltage cables and not on low voltage cables [112].

6.6.2 Frequency Domain Reflectometry

FDR is a nondestructive cable-testing technique based on transmission line theory. The FDR technique uses a sweeping frequency signal to transmit through an electrical cable circuit and analyzes the circuit impedance changes that are reflected. The reflected signals are measured in the frequency domain and then converted into the time domain using an inverse Fourier transform. The FDR method generally requires comparison with a baseline measurement to identify anomalies along the conductor or insulation material.

FDR methods include line resonance analysis (LIRA) [113, 114] and combined frequency and time domain reflectometry (FTDR). Preliminary data indicate the potential for determining both global and local degradation severity using such techniques, for both thermal and mechanical degradation/damage. This is an area of on-going research and evaluation.

6.6.3 Time Domain Reflectometry

The TDR technique is also based on transmission line theory, just as FDR. However, the TDR test involves sending a direct current pulsed signal through a cable circuit and measuring its reflection to identify the location of any impedance change in the cable and the end device (load). Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity (fault) in the cable, connector, or end device. The TDR method provides diagnostic information about the cable conductor and any connector or connection in the circuit, and to a lesser extent, the cable insulation material. It can also provide diagnostics about a device at the end of the cable, such as a resistance temperature detector (RTD) or a thermocouple. The test depends largely on comparison of the data with a baseline TDR.

6.6.4 Reverse Time Domain Reflectometry

The RTDR is a method that simulates the coupling of electrical noise signals into a signal transmitted on an instrument cable. The electrical noise interference typically couples at poor connections or terminations in the cable circuit that tend to degrade through the aging process, but may also result from damage to the cables or inherent properties of any inline devices. The location of degraded connectors or cable shields is detected by using time delays to determine where the electromagnetic interference couples into the cable system. The RTDR test is particularly important in I&C systems, such as source range nuclear instrumentation systems that have low signal levels (< 100 mV) that are easily affected by electrical noise intrusion. Standard TDR signatures are typically used in conjunction with RTDR to determine the location of cable connections.

6.6.5 Dissipation Factor

One technique for cable CM that has been studied with some success has been the measurement of the dielectric loss tangent (or dissipation factor tan δ) for shielded medium-voltage cable insulation. Tan δ is a dimensionless property of a dielectric, which is determined by the insulator's structure. Therefore, changes in structure brought about by aging should affect tan δ. The measurement can be carried out over a range of frequencies at low voltages (500 mV) on lengths of cable using standard impedance bridge instruments. Testing with very low frequency (0.1 Hz) and elevated voltage has proven effective in assessing wet aging and in some rare instances on dry cables [115]. Dielectric spectroscopy also is effective and assesses the dissipation factor over a range of frequencies and voltages [116, 117].

Dissipation factor measurements give an overall indication of the degradation of a cable insulation material, but some differentiation can be made between severe localized degradation and less-severe distributed degradation. The technique has also been shown to be very sensitive to the detection of water ingress in cables. Withstand testing has been used in conjunction with dissipation factor testing to determine the presence of severe local defects.

6.6.6 Inductance, Capacitance, and Resistance Measurements

LCR measurements are made using an LCR instrument at specific frequencies to verify the characteristics of a cable conductor, insulating material, and the end device. Results are evaluated to determine whether they are as expected for the type of circuit being tested. Imbalances, mismatches, or unexpectedly high or low impedances between the cable leads would indicate problems due to cable degradation and aging, faulty connections and splices, or physical damage.

6.6.7 Insulation Resistance

Insulation resistance measurements are made at specific voltages to validate the characteristics of cable insulating material. Insulation resistance measurements have been used for many years to evaluate the isolative quality of the cable insulation. Typically, a voltage lower than the maximum rated voltage of the cable is applied to an inner conductor or the cable shield (if the cable has one) and a ground plane in contact with the cable. The current in the cable is limited to avoid cable damage. Although insulation resistance is expected to change as a cable ages, it does not appear to be particularly sensitive to aging degradation and is usually used as pass/fail test [116, 118].

7. DISCUSSION OF LOW-VOLTAGE POWER AND I&C CABLES

While there are areas in the containments of some plants where radiation doses may reach 500 kGy (50 Mrad) in 40 years, most in-containment cables are not located in such high-radiation areas. Areas outside containment have much lower radiation doses than inside. Table7.1 shows data from a GE BWR IV Mark 1 containment; Table 7.2 shows data for areas outside the biological shield wall. The data are reasonably consistent with Figure 7.1. Figure 7.2 provides a physical map of the Table 7.1 zones. Nearly all safety cables are located in Zones 4 and 5. On Figure 7.1, they would be the areas in the bottom right quadrant below the core line.

Table 7.1. GE BWR IV Mark 1 containment

Area type	Temperature range	Dose rate	80 year dose
General, no radiation	up to 35 °C (95 °F)	0	0
Intermediate temperature, low radiation	35 to 50 °C (95 to 122 °F)	Up to 0.01Gy/hr (1 rad/h)	7 kGy/80 years (700 krad/80 years)
Elevated temperature, elevated radiation	45 to 55 °C (113 to 131 °F)	0.01Gy/hr to 0.1Gy/h (1 rad/hr to 10 rad/h)	7 kGy/80 years to 70 kGy/80 years (700 krad/80 years to 7 Mrad/80 years)
Elevated temperature, high radiation	45 to 55 °C (113 to 131 °F)	0.1Gy/h to 1Gy/h (10 rad/h to 100 rad/h)	70 kGy/80 years to 700 kGy/80 years (7 Mrad/80 years to 70 Mrad/80 years)
High temperature, little radiation	>60 °C (>140 °F)	<0.01Gy/h (<1 rad/h)	<7 kGy/80 years (<700 krad/80 years)

Table 7.2. Sixty year doses in containment, outside biological shield wall

Zone	Region	Gamma integrated dose (Mrad)*	Neutron integrated dose (Mrad)*	Total dose (Mrad)*
1	Above the core	16	8.16	24
2	Core region	32	22	54
3	Under the vessel	4.5	~0	4.5
4	Near recirc system	16	0.33	16.33
5	>15 feet from recirc system	2.5	0.33	2.83

*1 Gy = 100 rad

Figure 7.1 is a dose map for a GE BWR IV Mark 1 containment. In this design, all electronic transmitters and their cables are outside containment in low dose zones. Control, RTD, and motor-operated valve (MOV) cables are in containment. Containment cooler motor cables (safety cables in some plants but not others) are located in containment. Main steam isolation valve control and position cables for the in-board cables are in containment. Cables that are connected to devices near the sacrificial shield are run radially to the containment wall such that only short sections are located at the shield wall in the higher dose areas. The higher radiation zones are located at the core centerline. The safety cables are located outside the (biological) shield.

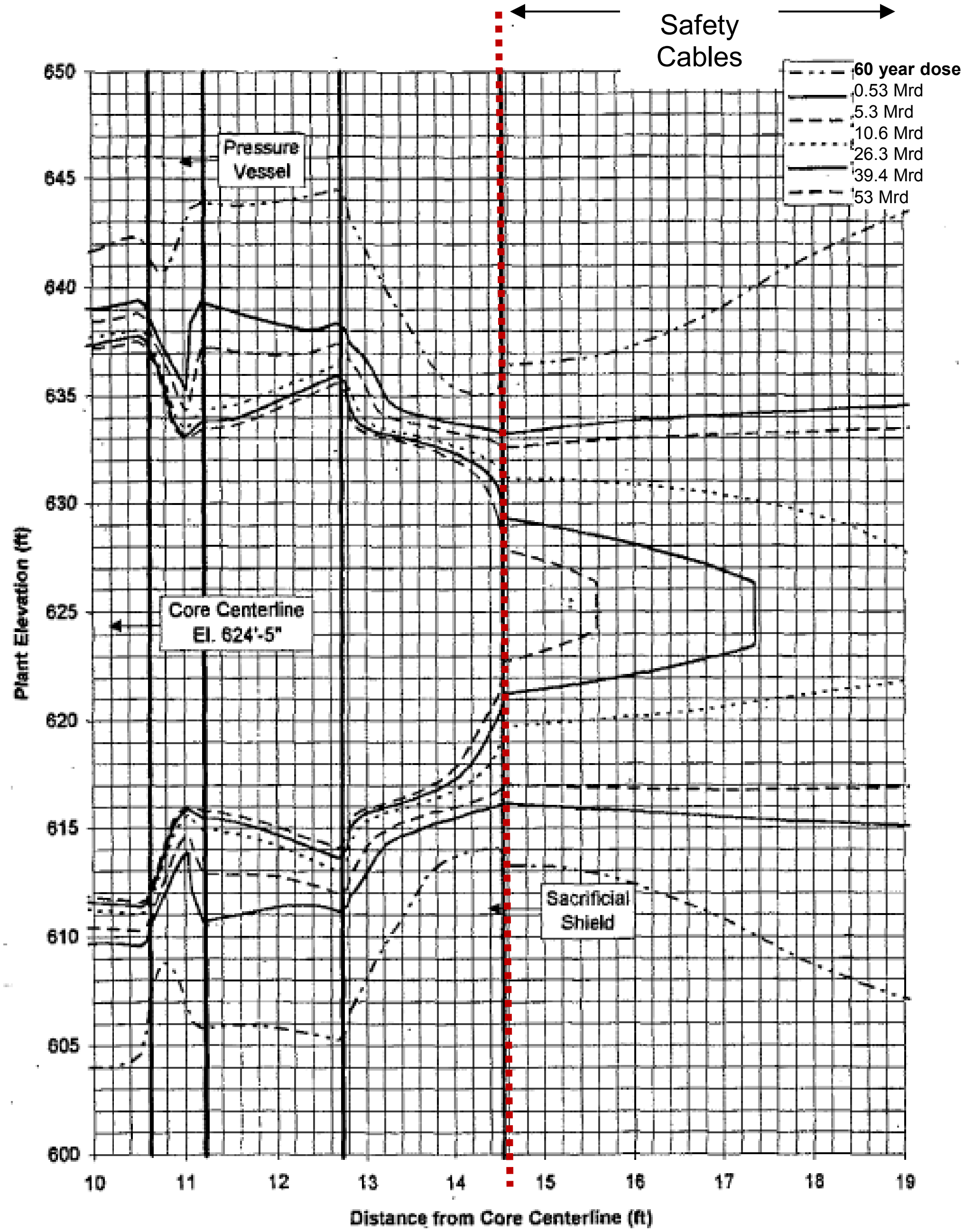

Figure 7.1. BWR IV Mark 1 containment gamma dose (rad carbon) unpenetrated sacrificial shield.

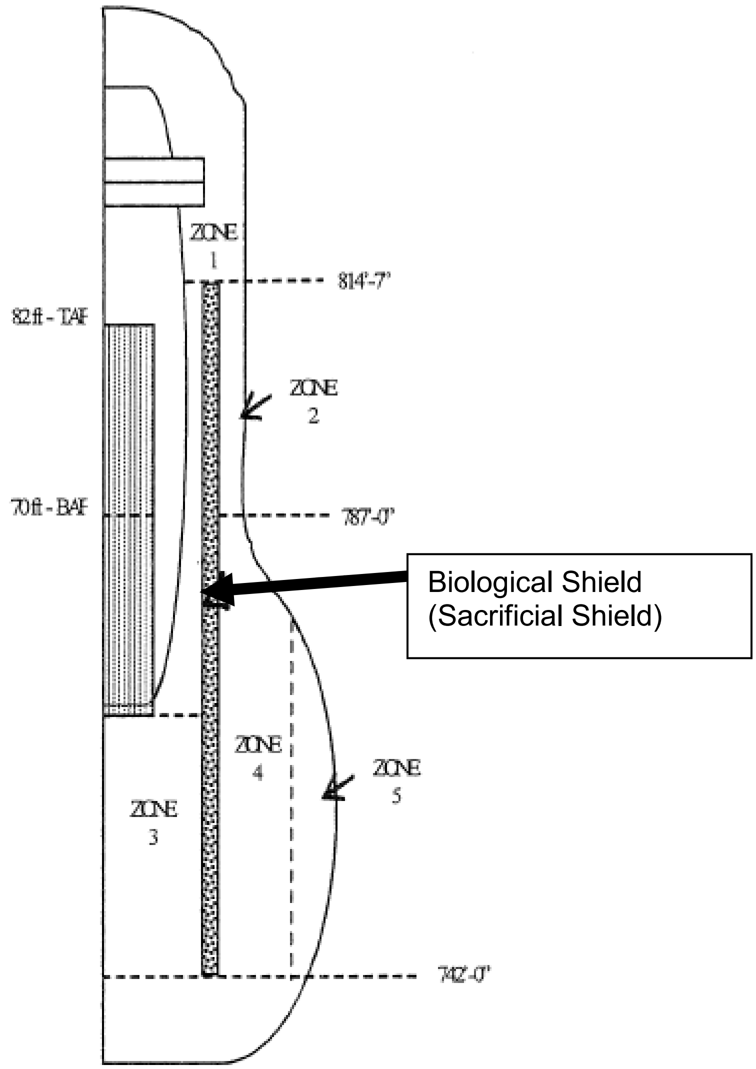

Figure 7.2. Zone associated with Table 7.1.

Table 7.3 provides dose data for a Combustion Engineering plant. Nearly all safety cables are located in the containment general area, away from the containment filters.

Table 7.3. Eastern U.S. Combustion Engineering PWR 60 year normal doses

Area	Dose (Mrad)*
Containment maximum	30.4
Containment general area at least 10 ft from filter	1.52
RCP bay	30.4
Above reactor vessel head	15.2

*1 Gy = 100 rad

Table 7.4 shows data for another Combustion Engineering plant. Table 7.5 shows data for a Westinghouse ice condenser plant.

These radiation dose distribution information, shown in figures and tables, indicate that the worst-case radiation doses are located in limited portions of containment, often inside the biological shields or adjacent to the area across from the reactor core midline. Most electrical and electronic components are not located in these high normal radiation areas. Safety-related cables are generally below and away from these zones. A formal assessment of plant radiation zones may be performed to determine the number of circuits that are in the high radiation zones. Most cables are likely to be in areas where doses and dose rates are below the levels where concern for laboratory synergisms exist.

Outside containment, the normal doses are generally low. The accident doses are also low. The high-energy line break conditions have low, transient pressures of generally less than 2 psig, (0.013 MPa) and the thermal content is very low by comparison to a LOCA. Accordingly, the effects of normal aging and accident conditions are much less severe than containment except where adverse localized environments exist that could cause severe aging under normal conditions.

Table 7.4. Containment radiation data for a Combustion Engineering plant

Zone	40 year dose (Mrad)*	60 Year dose (Mrad)*
Lower Containment, 1	10	15
Lower Containment, 2	0.3	0.45
Lower Containment, 3	0.03	0.045
+20 ft, 1	30	45
+20 ft, 2	0.03	0.045
+48 ft, 1	30	45
+48 ft, 2	0.03	0.045
+67 ft, 1	30	45
+67 ft, 2	0.03	0.045

*1 Gy = 100 rad

Table 7.5. Reactor building dose for a Westinghouse ice condenser PWR

Zone	40 year dose (Mrad)*	60 year dose (Mrad)*
Lower Containment	10	15
+29 ft, 2	20	30
+29 ft, 3	1	1.5
+29 ft. 4	0.04	0.06
+42 ft, 5	5	7.5
+42 ft, 6	20	30
+42 ft, 7	0.1	0.15
+42 ft, 8	0.02	0.03
+42 ft, 9	0.2	0.3
+42 ft, 10	0.01	0.015
+72 ft, 11	5	7.5
+72 ft, 12	2	3
+72 ft, 13	20	30
+72 ft, 14	0.1	0.15
+72 ft, 15	20	30
+72 ft, 16	0.02	0.03
+72 ft, 17	0.01	0.015
+82 ft, 18	3.5	5.25
+82 ft, 19	0.1	0.15
+82 ft, 20	5	7.5
+82 ft, 21	2	3
+82 ft, 22	0.02	0.03
+82 ft, 23	0.05	0.075
+82 ft, 24	0.01	0.015
+104 ft, 25	5	7.5
+104 ft, 26	5	7.5
+104 ft, 27	2	3
+104 ft, 28	1	1.5
+106 ft, 29–30	0.01–0.05	0.015–0.075

*1 Gy = 100 rad

8. DISCUSSION OF MEDIUM-VOLTAGE CABLES

Medium-voltage cables are rated at 5 to 46 kV; however, the most commonly used cables are rated at 5 to 15 kV and operate at discrete voltages between 4.16 to 13.8 kV. Most U.S. NPPs use rubber-insulated medium-voltage cables, although a few cables are insulated with XLPE. Older plants tended to have 4.16 kV cable systems, while newer plants have 4.16 kV and 12 kV or 13.8 kV systems. The medium-voltage safety systems at nearly all plants are 4.16 kV. At that voltage, utilities had the option of using shielded or non-shielded cable. Many plants used non-shielded cable for safety systems, based on the premise that if the cable had a single fault under accident conditions, the circuit could continue to operate for a period. Non-shielded cables have a wall thickness that is either 33% or 77% thicker than shielded cable.

Shielded cables have an insulation shield that is generally composed of a semiconducting layer covered with a helically wrapped tape shield. With respect to cable longevity, the insulation shield provides a uniform ground plane that allows electrical testing to be performed to determine the condition of a cable that has been in service for an extended period. Electrical testing is not possible for non-shielded cables, because there is no uniform ground plane and that test voltages would tend to be distributed in the air around the cable rather than in the insulation over much of the cable's length.

Wet or submerged conditions are an aging concern for energized medium-voltage cable, especially for early cable designs. The XLPE insulation from the early 1970s was found to be prone to water treeing such that the XLPE insulation degrades at flaws or inclusions in the normally hydrophobic material. Water treeing causes the stress to increase (in the surrounding XLPE) to the point where PD occurs under normal operating conditions and results in insulation breakdown. The onset of advanced water trees was seen about 25 years into operation for the population of XLPE cables in NPPs. However, deterioration is not uniform, and many older XLPE cables remain in underground service with periodic testing to assess their condition. While XLPE cable quality has improved over time and tree-retardant XLPE is available, plants with XLPE cables generally employ cables insulated with pink EPR as replacements.

The earliest plants using rubber insulations used butyl rubber. These plants went into operation in the very early 1970s. Very soon thereafter, cables insulated with black EPR became available with compounds that were similar in nature to that of the butyl rubber, especially with respect to the clay used to make the rubber insulations extrudable and sturdy. The early clays were cleaned and heat-treated to drive off water before being added to the compound. In approximately 1976, manufacturers transitioned to silane-treated clay. The silane strengthens the clay/EPR interface and tends to keep the clay dry. At about the same time, the EPR manufacturers converted the semiconducting layers from tape designs to extruded designs. To date, no water-related degradation has been reported for the "modern" (post ~1976) cables with silane-treated clay. Occasional failures under wet conditions have occurred from random manufacturing defects or post-manufacturing damage.

The first failures for black EPR and butyl rubber cables under wet conditions occurred at approximately 30 to 35 years. The failure distribution of the cables is expected to be quite wide, possibly 40 to 50 years, such that periodic testing is appropriate to identify when cables should be replaced. The industry committed to such testing in 2010, by a letter from the Nuclear Energy Institute to the NRC [119]. The letter committed the industry to implementing two EPRI reports [6, 7] for aging management of low- and medium-voltage power cables. Implementation progress has been rapid with approximately 60 units having begun testing of medium-voltage cables by the third quarter of 2011.

Most medium-voltage cable insulations are discharge free. They are designed to have no partial discharge and high inception voltages at which partial discharging could occur. One company, Kerite, uses an alternate design, which is discharge resistant. The Kerite® insulation system is tolerant of partial discharge. That design has been available since the early 1970s.

Medium-voltage cables are not located inside containment and are rarely used in radiation zones of significance with respect to cable longevity. These cables are tolerant of relatively high temperatures but can degrade under severe thermal aging. Most rubber cables will harden with exposure to elevated temperature; however, sulfur-cured butyl rubber can revert to the pre-cured state when subjected to elevated temperature for an extended period of time. Insulation softening allows the insulation shielding material to drift toward the conductor and cause a short.

With the exception of elevated temperature conditions or exposure to oils, hydraulic fluid, or chemicals, medium-voltage cables are expected to have a very long life under dry conditions.

9. TERMINATIONS, SPLICES

With respect to wet or dry aging, splices and terminations are expected to have very long lives if they are made in accordance with manufacturers' recommended procedures. This means that crimps and bolted connections have been made properly and that the tapes have been properly applied to the correct thickness and with the appropriate tension, or that heat-shrink materials have been properly applied and completely shrunk in place. Given that no voids exist, the splice and termination insulation is thicker than that of the cable and generally has ratings equal or exceeding the insulation on the cable.

Generally, when splices or terminations fail, it is because of an installation error. Errors include inadequate removal of semiconducting layers, cuts to the insulation under the splice, voids from inadequate taping or heat shrinking practices, and the presence of dirt in the splice layers. Most of the failures do not occur upon initial energization and may take as much as 30 years to manifest themselves, even under wet conditions.

Because of the bulk of medium-voltage cables, lengths that could be shipped on a reel often dictated that splices were necessary in long runs. Therefore, plants are identifying splices in cables to intake structures and other long runs that were previously thought not to exist.

The main concern for power connections is that a high-resistance connection does not occur. Visual inspections and thermography are used to determine whether connection problems exist. The most critical connection issue relates to aluminum-to-copper cable connections. A few plants use aluminum field cables for power circuits. Spring-loaded connections are required to prevent the aluminum from cold flowing and to prevent a high-resistance connection from occurring. If one does occur, overheating can cause the insulation to degrade or the connection to burn open over time.

10. RECOMMENDATIONS AND CONCLUSIONS

The previous sections have discussed in some detail the prevalent degradation modes and concerns for different cable insulation materials in different environments for nuclear power plants A variety of environmental stressors in NPPs, such as temperature, radiation, moisture/humidity, vibration, chemical spray, mechanical stress, and the oxygen present in the surrounding gaseous environment (usually air), can influence the degradation of low and medium electrical power and instrumentation and control (I&C) cables and their insulation. Over time these stressors can lead to degradation, which, if not appropriately managed, could lead to insulation failure of the associated components, and potentially resulting in cables being unable to perform their intended safety function.

In the context of this report, low-voltage cables have ratings below 2,000 volt (V) and generally operate at voltages of 525V alternating current (ac) or below 250 V direct current (dc). Medium-voltage cables are rated at 46 kilovolts (kV) and below. Most in-plant and underground cables are rated at up to 15 kV and are operated at 13 kV or less. Most safety-related medium-voltage cables rated at 5 kV are operated at 4,160 V. Some plants have short lengths of cable with operating voltages between 100 and 230 kV; these are plant-specific cables and are often not insulated with a polymer. As such, unique plant-specific cables are not covered by this report. Furthermore, high-voltage cables are not covered by this report. The details of the assessment of cables and cable insulation are found in Volume 5 of this report.

10.1 SPECIFICS OF PIRT PROCESS FOR CABLE AND CABLE INSULATION PANEL

The cable system expert panel used the PIRT process described above to identify safety-relevant phenomena, assess their importance, and identify and prioritize research needs. Five panelists provided scoring on a variety of issues and environments. The PIRT process followed by this specific panel consisted of the following steps:

1. A list of relevant insulation materials was developed, along with a hierarchical identification of the various degradation modes and environments that could affect each of the insulation materials and their performance. A consensus of the issues to be assessed was obtained through discussions among the members of the panel. Crosscutting issues were identified. A total of 44 different scoring categories were considered.

2. A database was developed, containing the independent scoring for each of the above PIRT criteria by each panelist for each insulation material and their related degradation modes. The panel then discussed the individual scoring, and each panelist was provided the opportunity to keep or revise their original scores based on this discussion.

3. Based on the final set of scores, the mean, median, and standard deviation were determined for each potential degradation mode/mechanism.

For I&C cables, the degradation for polymers is highly dependent on the material and the environment. Although the PIRT assessment divides the cable insulations based on the base material, the particular degradation phenomena vary depending on the formulation of the insulation. For example, one XLPO insulation may behave differently from another XLPO insulation, depending on the additives (pigments, plasticizers, anti-oxidants, etc.). Furthermore, the PIRT assessments were performed using the insulation material in a range of environmental conditions in order to assess the insulation in a variety of environments as the insulation material could be used in different areas of a NPP. Since the major stressors to insulation are temperature and radiation, the environmental conditions are considered with a temperature and radiation dose range. For I&C cables, the study did not include wet environments.

10.2 KEY FINDINGS FOR CABLE AND CABLE INSULATION PANEL

The panelists used the PIRT process to prioritize the different material/environmental concerns (the PIRT scores are shown in Appendix A). There are several notable trends in the data. First, the panelists were in agreement as to the present levels of knowledge and overall aging-related susceptibility of cable insulation materials, as demonstrated by the uniformity of the Knowledge and Susceptibility scores. Further, there were very few material/mode combinations where Susceptibility was ranked above “2” with the generic Susceptibility increasing with increasing severity in environment conditions. The Knowledge ranking was either 2 or 3 for all materials, environments, and conditions considered. This is likely a reflection on the 40 years of information on generic aging although this may not extend to specific plant locations/conditions as noted above.

The main area of uncertainty for extending NPP operation beyond 60 years relates to the pre-aging carried out during the equipment quantification (EQ) process and whether it can adequately predict aging over that time scale. However, most concerns are based on the premise that cables will be exposed to the operating and design basis environments (temperature, radiation, humidity, chemical spray, and other environmental factors) that were used in the equipment quantification process. The current understanding, based on general opinion and utility experience, is that most cables are exposed to environments that are considerably less severe than the design environment. Actual environmental conditions should be quantified by measurement and analysis so that the temperatures and dose rates to which different types of cable are exposed are quantified over their qualified life.

Recommendations and conclusions for cable use beyond 60 years are provided below:

1. A reassessment may be made to determine the number of circuits and types of cable that are in the high-radiation zones [i.e., 70 Mrad over 80 years (up to 1 Gy/hr) between 45 to 55 °C (113 to 131 °F)].

2. Measurements of the operating temperatures of cables in plant are needed, particularly for those cable groups that are subjected to EQ, to quantify the actual temperatures to which cables are exposed.

3. If, as expected, environmental information demonstrates that thermal aging is the dominant process for nearly all cables in U.S. NPPs, then it is important that the activation energy for the specific cable materials used, under specific environment, be estimated with increased confidence level. This is because the actual value of activation energy plays a major role in behavior prediction model over time at a given environment. Experiments conducted to estimate activation-energy should be conducted at temperatures close to service temperatures using techniques such as oxygen consumption that have the ability to cover wide temperature ranges. This ability allows one to use the oxygen consumption results to confirm a correlation (same activation energy) with the mechanical properties (e.g.,

elongation) at the higher temperatures and to use low temperature oxygen consumption results to probe any changes in activation energy in the low temperature extrapolation region.

4. Inverse temperature effects need to be understood better if semi-crystalline materials, such as some XLPE/XLPO and EPR insulations, are determined from plant assessment (item 1 above) to be exposed to radiation in-plant dose rates that exceed 0.1 Gy/h (10 rad/h). At that level of radiation dose rate, significant degradation may be observed after 60 years for temperatures <50 °C (122 °F).

5. Little is known regarding the consequences of long-term wetting of both low- and medium-voltage cables. Research in that area would enable safety significance assessments of long-term submerged cables.

6. For loss of coolant accident simulations, this research has identified oxygen concentration in the atmosphere during a loss-of-coolant accident to be important, needing a consideration of this aspect in engineering simulations.

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APPENDIX A

PIRT RESULTS AND TABLES

A.1 PIRT PROCESS AND ORGANIZATION

For I&C cables, the degradation for polymers is highly dependent on the material and the environment. Although the PIRT assessment divides the cable insulations based on the base material, it is important to note that particular degradation phenomena may vary depending on the formulation of the insulation. For example, one XLPO insulation may behave differently from another XLPO insulation, depending on the additives (pigments, plasticizers, anti-oxidants, etc.). Furthermore, the PIRT assessments are performed using the insulation material in a range of environmental conditions in order to assess the insulation in a variety of environments as the insulation material could be used in different areas of a NPP. Since the major stressors to insulation are temperature and radiation, the environmental conditions are considered with a temperature and radiation dose range, as listed below. For I&C cables, the study did not include wet environments.

<u>I&C cables</u>

1. up to 35 °C (95 °F), effectively 0 dose rate
2. 35–50 °C (95–122 °F), up to 1 rad/hr (0.01 Gy/hr) (outside containment)
3. 45–55 °C (81–131 °F), 1–10 rad/hr (0.01 to 0.1 Gy/hr) (containment)
4. 45–55 °C (81–131 °F), 10–100 rad/hr (0.1 to 1 Gy/hr) (containment)
5. 60–90 °C (140–194 °F), little rad (<1 rad/hr) (localized hot spot).

After the scoring matrix was developed, panelists independently scored the degradation scored the degradation scenarios in three categories that were originally used in the PMDA report: Susceptibility, Confidence, and Knowledge. The Susceptibility score rates the likelihood that degradation will occur, on a scale from 0 (not considered to be an issue) to 3 (demonstrated, compelling evidence for occurrence, or multiple plant observations). This panel used a susceptibility of 0 to indicate that there was no susceptibility of the material in the particular environment. The Knowledge score rates the expert's current belief of how adequately the relevant dependencies have been quantified through laboratory studies and/or operating experience, on a scale from 1 (poor understanding, little and/or low-confidence data) to 3 (extensive, consistent data covering all dependencies relevant to the component). Finally, the Confidence score measures the expert's *personal* confidence in his or her judgment of Susceptibility, on a scale from 1 (low) to 3 (high).

After completion of scoring and identification of "outliers," the panels were reassembled for discussion of the scoring. In most panels, this was done in a face-to-face meeting, but this was not required in all cases. During this discussion, each degradation mode and related scoring was discussed with the "outliers" being of highest priority. In these discussions, the scoring panelist presented rationale for any scores that differed from the average. The objective was not to develop a consensus score or force conformity among the panelists. The primary goal of this discussion was to foster debate and exchange differing points of view. This debate and discussion among panelists was an important part of the process to ensure all points of view were considered, including consideration of any new information on the subject area which was not previously considered, and accounted for in the final scoring. After compiling any changes in scoring following this debate, the PIRT scoring was tabulated to determine relative needs and priorities.

After compiling any changes in scoring following this debate, the PIRT scoring was tabulated to determine relative needs and priorities. In this process, the average Susceptibility and average Knowledge scores were plotted versus each other on a simple plot. An example plot of Knowledge versus Susceptibility is shown in Figure A.1. The left side of the plot with the lighter shading is indicative of low Knowledge, while the darker shading on the right side of the plot is indicative of high Knowledge. The labeled areas in the corners of the plot indicate the high Knowledge, low Susceptibility; high Knowledge, high Susceptibility; and low Knowledge, high Susceptibility areas discussed above. Moving from upper right to lower left can be accomplished via additional research and development to understand and predict key forms of degradation. The different domains of these plots highlight key areas of concern, including:

- Low Knowledge, high Susceptibility degradation modes are indicated by the pink shading in Figure A.1 and represent modes of degradation that could be detrimental to service with high Susceptibility scores (>2) and low Knowledge scores (<2). These scores indicate gaps in understanding for degradation modes that have been demonstrated in service. Low Knowledge and moderate Susceptibility also indicate gaps in knowledge, although with lower consequences. These scoring regions are useful in identifying potential knowledge gaps and areas requiring further research into mechanisms and underlying causes to predict occurrence.

- High Knowledge, high Susceptibility degradation modes are shown in red in Figure A.1 and represent areas that could be detrimental to service with high Susceptibility scores (>2) and high Knowledge scores (>2). These modes of degradation are well understood and have likely been observed in service. While there may be some mechanistic understanding of the underlying causes, re-confirmation for extended service and research into mitigation or detection technologies may be warranted.

- High Knowledge, low Susceptibility degradation modes (dark green in Figure A.1) are those that are relatively well understood and of low consequence to service with low Susceptibility scores (<1) and high Knowledge scores (>2). These modes of degradation are adequately understood and may been observed in service. Mitigation and maintenance can currently manage this form of degradation. Research on these modes of degradation is a lower priority.

Other combinations of Knowledge and Susceptibility are of course possible and fit between the cases listed above in terms of priority.

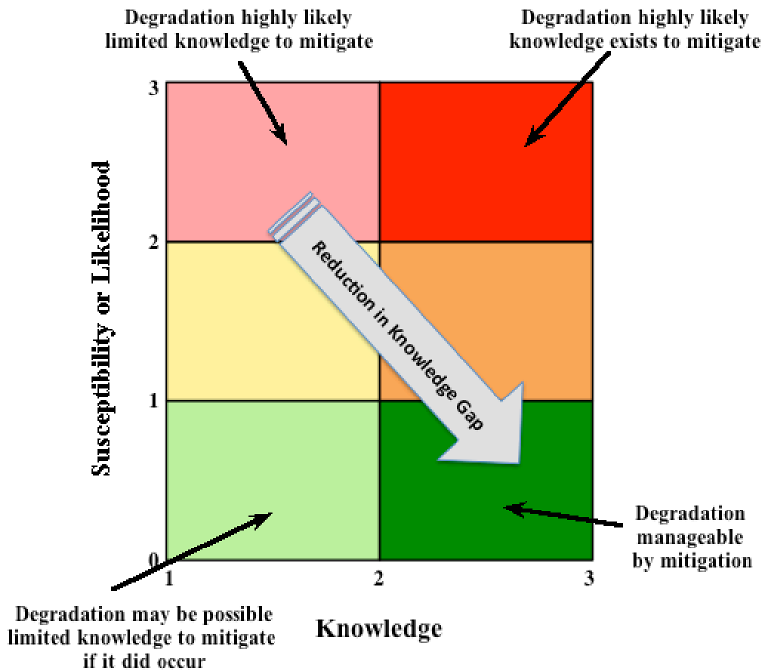

Figure A.1. Schematic illustrating the combinations of Susceptibility and Knowledge scores suggesting various life management responses.

A.2 PIRT RESULTS

The PIRT scoring is tabulated below for each of the main areas considered. The numbers listed in each table represent individual panelist scores. For example, 0,0,0,0,0 means 5 separate anelists gave a ranking of 0. Rainbow charts are also provided for each subsection

A.2.1 Findings for Cables up to 35 °C (95 °F) with No Irradiation

Table A.1. Summary of PIRT scores for cables up to 35 °C (95 °F), effectively 0 dose rate

Up to 35 °C (95 °F), effectively 0 dose rate			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPO	0,0,0,0,0	3,3,3,3,3	
EPR-FR	0,0,0,0,0	3,3,3,3,3	
EPR/neoprene	2, 0-2, 2, 2, 2	3,3,3,3,3	Dependent on the formulation
EPR/CSPE	0,0,0,0,0	3,3,3,3,3	
SiR	0,0,0,0,0	3,3,3,3,3	
Neoprene	2, 0-2, 2, 2, 2	3,3,3,3,3	Dependent on the formulation
CSPE	0,0,0,0,0	3,3,3,3,3	

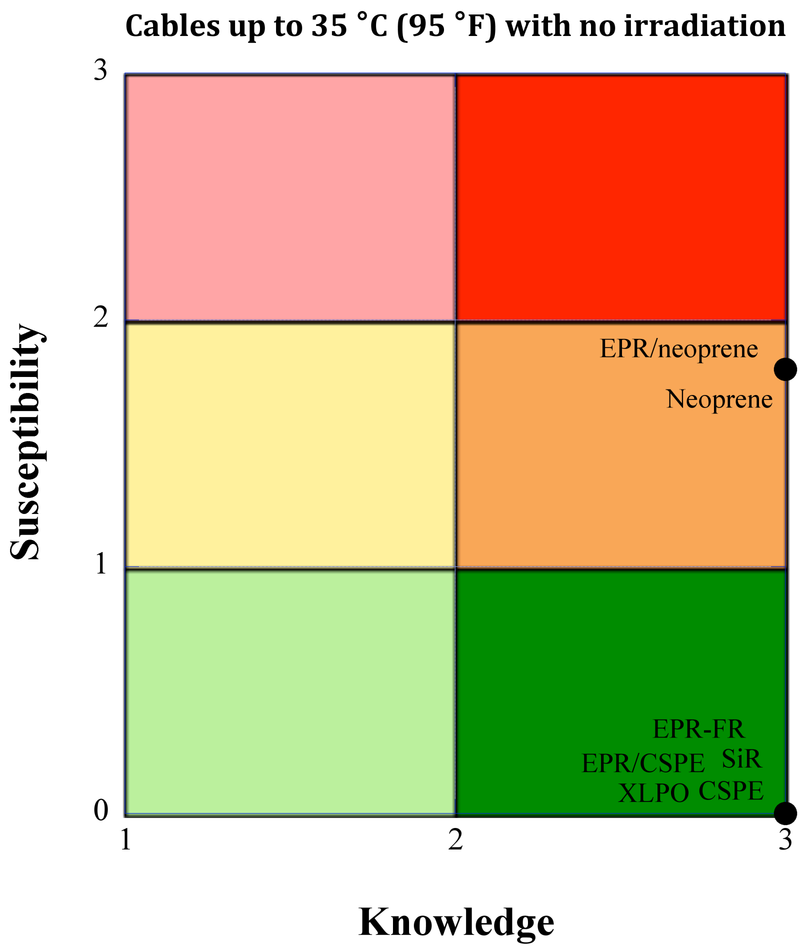

Figure A.2. Susceptibility–Knowledge plot for cables at up to 35 °C (95 °F) with no irradiation.

A.2.2 Findings for Cables at 35–50 °C (95–122 °F) and up to 0.01 Gy/hr (1 rad/hr)

Table A.2. Summary of PIRT scores for cables at 35–50 °C (95–122 °F) and up to 0.01Gy/hr (1 rad/hr)

35–50 °C (95–122 °F) and up to 0.01Gy/hr (1 rad/hr) (outside containment)			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPO	0,0,0,0,1	3,3,3,3,2	Some formulations may have inverse temperature effect
EPR-FR	0,0,0,0,0	3,3,3,3,3	
EPR/neoprene	3, 3, 3, 3, 2	3,3,3,3,3	Dependent on the formulation
EPR/CSPE	0,0,0,0,1	3,3,3,3,3	Formulation dependent
SiR	0,0,0,0,1	3,3,3,3,2	Radiation only concerns, formulation dependent
Neoprene	3, 3, 3, 3, 2	3,3,3,3,3	Dependent on the formulation
CSPE	0,0,0,0,1	3,3,3,3,3	Formulation dependent

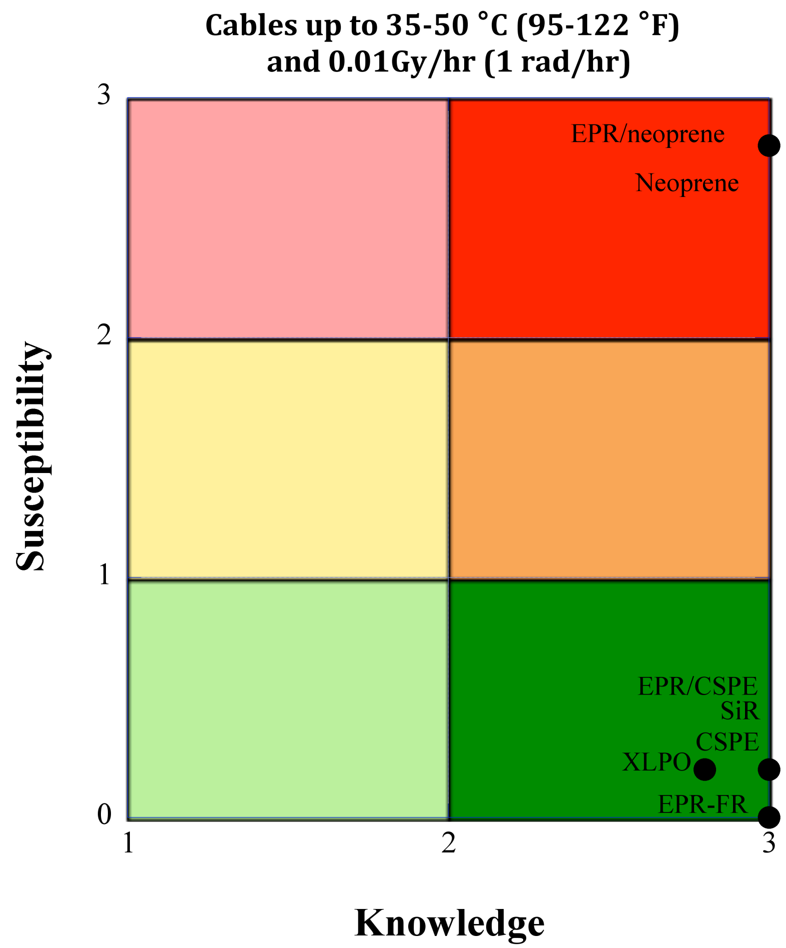

Figure A.3. Susceptibility–Knowledge plot for cables at 35–50 °C (95–122 °F) and up to 0.01Gy/hr (1 rad/hr).

A.2.3 Findings for Cables at 45–55 °C (81–131 °F) and 0.1–0.01 Gy/hr (1–10 rad/hr) (Inside Containment)

Table A.3. Summary of PIRT scores for cables at 45–55 °C (81–131 °F) and 0.1–0.01 Gy/hr (1–10 rad/hr) (inside containment)

45–55 °C (81–131 °F) and 0.1–0.01 Gy/hr (1–10 rad/hr) (inside containment)			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPO	2, 0,1,0,1-2	2,3,3,3,2	Inverse temperature effects
EPR-FR	2,2,2,0,2	2,2,2,3,2	Inverse temperature effects
EPR/neoprene	2.5,3,3,3,3	2,3,3,3,3	Inverse temperature effects
EPR/CSPE	2.5,2,2,2,2	2,2,2,3,2	Inverse temperature effects, formulation dependent
SiR	2,1,1,0,2	2,2,2,3,2	Formulation dependent, radiation concerns
Neoprene	3,3,3,3,3	3,3,3,3,3	
CSPE	2.5,2,2,2,2	3,2,2,3,2	Formulation specific

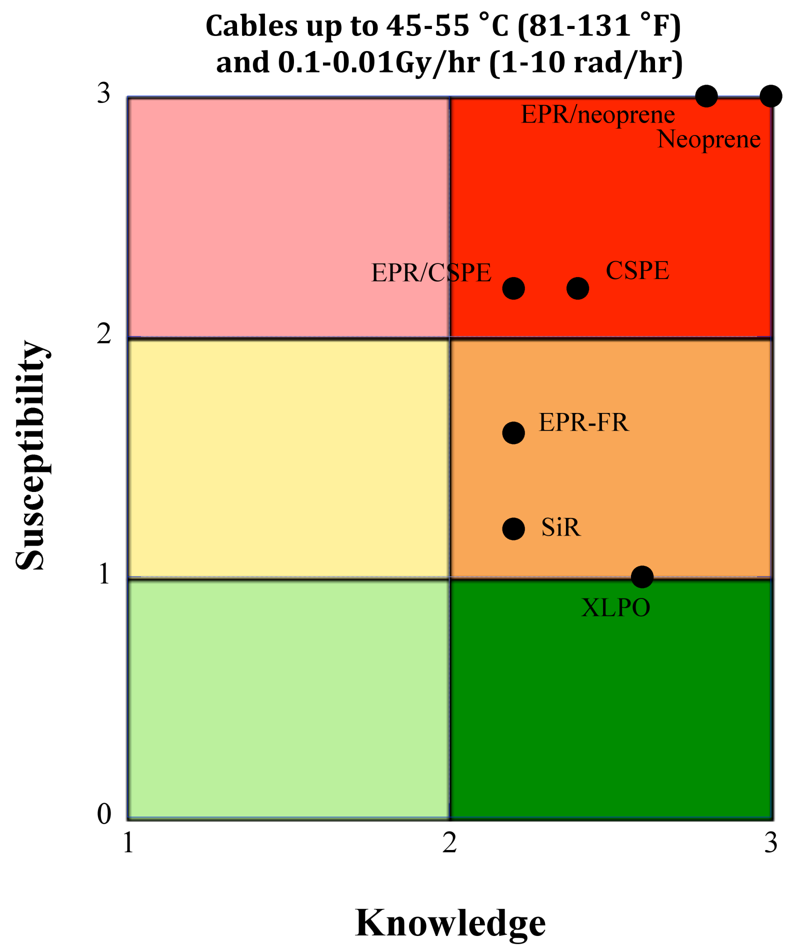

Figure A.4. Susceptibility-Knowledge plot for cables at 45–55 °C (81–131 °F) and 0.1–0.01 Gy/hr (1–10 rad/hr) (inside containment).

A.2.4 Findings for Cables at 45–55 °C (81–131 °F) and 0.1 to 1 Gy/hr (10–100 rad/hr) (inside containment)

Table A.4. Summary of PIRT scores for cables at 45–55 °C (81-131 °F) and 0.1 to 1 Gy/hr (10–100 rad/hr) (inside containment)

45–55 °C (81–131 °F) and 0.1 to 1 Gy/hr (10–100 rad/hr) (inside containment)			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPO	2,2,2,1,2	2,2,2,3,2	Inverse temperature effects, formulation dependent
EPR-FR	2,2,2,1,2	2,2,2,2,2	Inverse temperature effects, formulation dependent
EPR/neoprene	3,3,3,3,3	3,3,3,3,3	
EPR/CSPE	3,2,3,3,3	3,2,3,3,3	
SiR	3,2,2,2,3	2,2,2,2,3	Formulation dependent
Neoprene	3,3,3,3,3	3,3,3,3,3	
CSPE	3,2,2,3,3	3,2,2,3,3	Formulation dependent

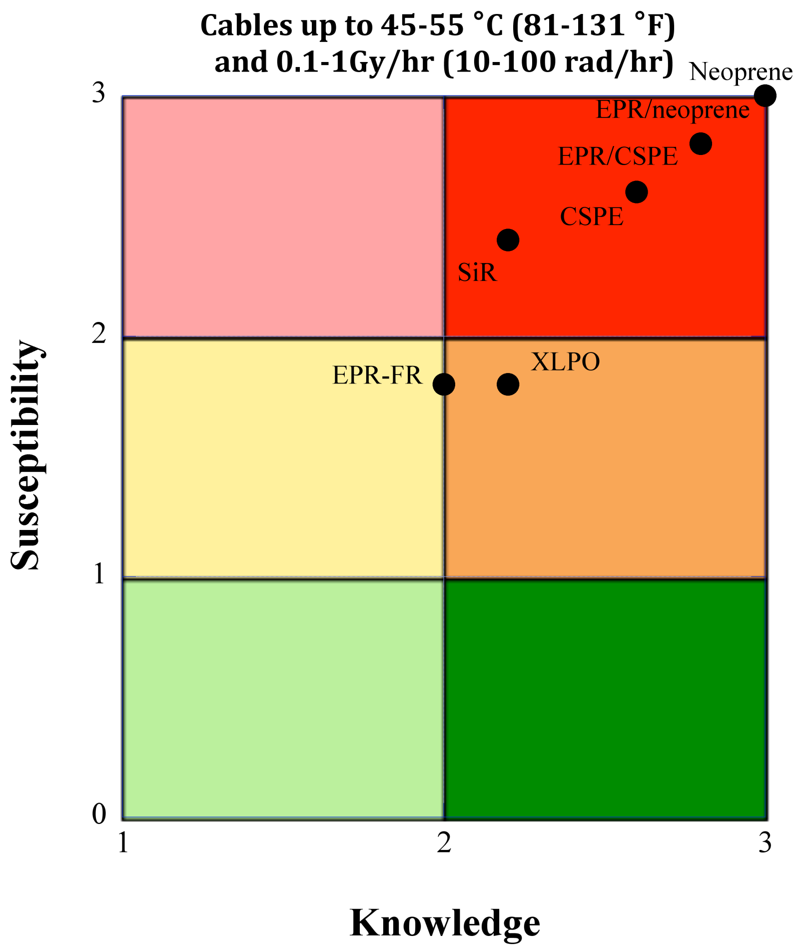

Figure A.5. Susceptibility–Knowledge plot for cables at 45–55 °C (81–131 °F) and 0.1 to 1 Gy/hr (10–100 rad/hr) (inside containment).

A.2.5 Findings for Cables at 60–90 °C (140–194 °F) with No Irradiation

Table A.5. Summary of PIRT scores for cables at 60–90 °C (140–194 °F) with no irradiation

60–90 °C (140–194 °F), little rad (<1 rad/hr) (localized hot spot)			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPO	2,2,2,1,2	3,3,3,3,2	Formulation dependent, uncertainty on accelerated aging
EPR-FR	2,3,3,1,3	3,3,3,2,3	Formulation dependent
EPR/neoprene	3,3,3,3,3	3,3,3,3,3	
EPR/CSPE	3,3,3,3,3	3,3,3,3,3	
SiR	2,1,1,2,2	2,2,2,2,2	Formulation dependent
Neoprene	3,3,3,3,3	3,3,3,3,3	
CSPE	3,3,3,3,3	3,3,3,3,3	

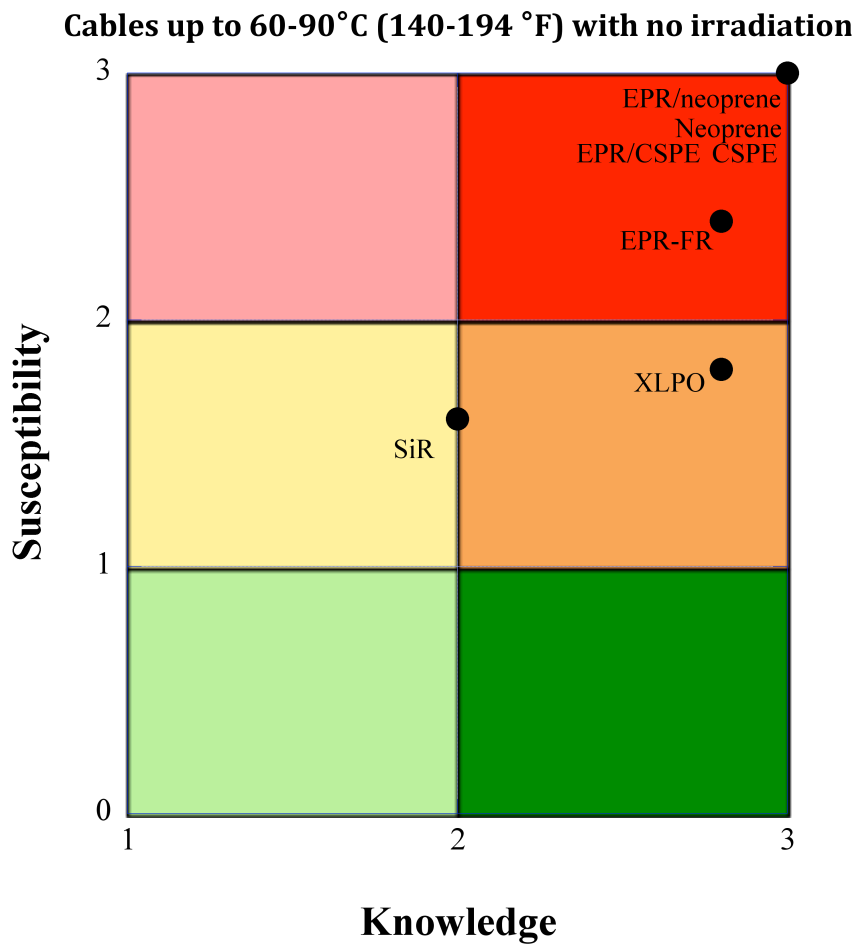

Figure A.6. Susceptibility-Knowledge plot for cables at 60–90 °C (140–194 °F) with no irradiation.

As noted above, the panelists were in agreement as to the present levels of knowledge and overall aging-related susceptibility of cable insulation materials, as demonstrated by the uniformity of the knowledge and susceptibility scores. Further, there were very few material/mode combinations where susceptibility was ranked above “3” with the generic susceptibility increasing with increasing severity in environment conditions. The knowledge ranking was either 2 or 3 for all materials, environments, and conditions considered. This is likely a reflection on the 40 years of information on generic aging although this may not extend to specific plant locations/conditions as noted above.

A.2.6 Findings for Medium Voltage Cables in Long-Term Wet Conditions

The panel consisted of two members that had knowledge on medium-voltage cables. As discussed in Section 8, medium-voltage cables are not located inside containment and are rarely used in radiation zones of significance with respect to cable longevity. With the exception of elevated temperature conditions or exposure to oils, hydraulic fluid, or chemicals, medium-voltage cables are expected to have a very long life under dry conditions. The PIRT assessment scores medium-voltage cables under long-term wet conditions, which is the aging concern for long-term operation.

Table A.6. Summary of PIRT scores for medium-voltage cables in long-term wet conditions

Medium voltage, long-term wet conditions			
Material	**Susceptibility**	**Knowledge**	**Notes**
XLPE	3,3	3,3	
Modern TR XLPE	2,2	3,3	
Black EPR	3,3	3,3	
Pink EPR	1,1	2,2	Onset of first failure is likely to be >50 yr, expected to be replacements
Brown EPR	1,1	3,3	Onset of first failure is likely to be >50 yr, expected to be replacements
Butyl rubber	3,3	3,3	
neoprene			Importance of jacket is plant-specific and circuit-specific, failure of jacket not cause failure of insulation due to moisture
CSPE			Importance of jacket is plant-specific and circuit-specific, failure of jacket not cause failure of insulation due to moisture
CPE			Importance of jacket is plant-specific and circuit-specific, failure of jacket not cause failure of insulation due to moisture

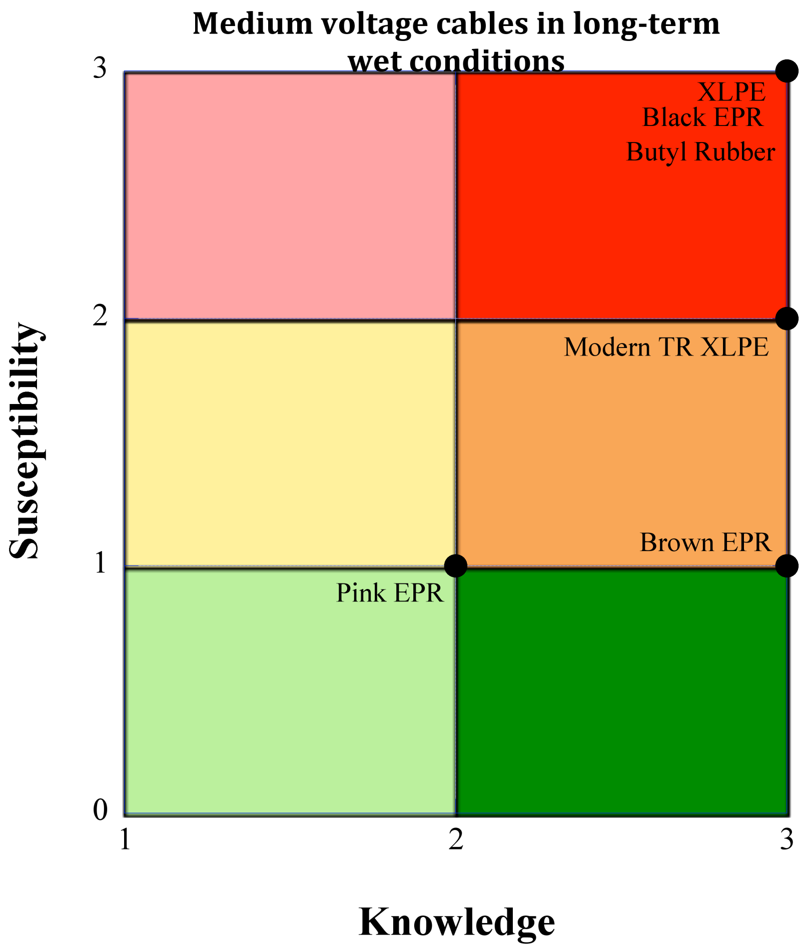

Figure A.7. Susceptibility–Knowledge plot for medium-voltage cables in long-term wet conditions.

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BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)
Most nuclear power plants in the United States are currently licensed for up to 60 years of operation. The nuclear industry is assessing the feasibility of operation for up to 80 years. The U.S. Nuclear Regulatory Commission (NRC) and U.S. Department of Energy (DOE) co-sponsored the Expanded Materials Degradation Assessment (EMDA) to identify information gaps and research priorities for aging related degradation of reactor components for up to 80 years. Expert panels were convened to examine four main component groups using the phenomena identification and ranking technique: reactor core internals and piping systems, the reactor pressure vessel, concrete and civil structures, and electrical cables. Panelists included participants from NRC, DOE national laboratories, industry, academia, and international organizations. The EMDA reports include a ranking of degradation scenarios according to the probability of occurrence and level of knowledge, along with a summary of the current state of knowledge for each component group.

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