Technical Letter Report
TLR-RES/DE 2025-08
PNNL-37317

Addressing Expanded Materials Degradation Assessment (EMDA) Knowledge Gaps for Continued Use of Electrical Cables in Long-term Operation

July 2025

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Task Order Number: 31310024S0025

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Summary

The “Expanded Materials Degradation Assessment Volume 5: Aging of Cables and Cable Systems (EMDA)” (NUREG/CR-7153, Vol.5) [1], published October 2014, was a collaboration between the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) that utilized a panel of industry experts to consider the continued use of electrical cables in nuclear power plants (NPPs) beyond initial plant license renewal. Electrical cables that are important to safety in NPPs (10 CFR § 50.49) were commonly environmentally qualified for at least 40 years, corresponding to the initial reactor license period. Elements of conservatism in that process have been relied upon to justify continued use of cables up to 60 years in initial license renewals and up to 80 years in subsequent license renewals. The EMDA documents a focused consideration of the state of knowledge and risks for cable materials in extended operation. It identified several gaps in understanding related to the historical qualification process and to continued use of cables beyond their initial qualified life. Identified gaps include variable activation energy, diffusion limited oxidation (heterogeneous degradation), dose rate effects, effects of sequence of exposure or synergism in thermal and radiation aging, inverse temperature effects, moisture effects and submerged cables, actual versus conservatively estimated NPP environments, and monitoring of cable condition. Suggestions were made in the EMDA of potential courses of action to address these topics.

This document considers progress and approaches that have been reported in the decade following publication of the EMDA toward closing the identified knowledge gaps and increasing confidence in decisions regarding continued use of qualified cables beyond their original qualified life. The NRC, DOE national laboratories, the Electric Power Research Institute (EPRI), and other entities both inside and outside of the U.S. have published research and developments related to the knowledge gaps. The inherent characteristics of the historic approach to time-based environmental qualification, which often relied heavily on margin and conservatism to overcome the uncertainties in qualified life, have been acknowledged. Alternative methods have been proposed to incorporate information gained from subsequent research. Actual in-plant service conditions in operating boiling water and pressurized water reactors have been more accurately determined. Susceptibility of certain cables to moisture damage and practical methods to ensure reliable performance of potentially wetted cables have been proposed, such as dewatering of manholes and periodic tangent delta testing. Consensus-based standard development groups, including IEEE, have updated their guidance on cable qualification with regards to information presented in the EMDA since the initial 1970’s versions of those documents [2], [3]. The NRC has updated regulatory guidance to support revised standards for qualification of cables considering the uncertainties documented in the EMDA, including NRC Regulatory Guide 1.211 “Qualification of Safety-Related Cables and Field Splices for Nuclear Power Plants”, issued April 2009 [4] and NRC Regulatory Guide 1.89, Revision 2 “Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants”, issued April 2023 [5]. The NRC “Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report, Draft Report for Comment” (NUREG-2191) [6], [7] document and subsequent license renewal guidance have been updated to acknowledge potential aging mechanisms identified in the EMDA and to require cable aging management practices to mitigate potential risks not fully appreciated in historic license guidance.

Acronyms and Abbreviations

AC	alternating current
AEIC	Association of Edison Illuminating Companies
ANSI	American National Standards Institute
BWR	boiling water reactor
CBQ	condition-based qualification
CFR	Code of Federal Regulations
CSPE	chlorosulphonated polyethylene
DBE	design basis event
DC	direct current
DED	dose to equivalent damage
DLO	diffusion limited oxidation
DOE	U.S. Department of Energy
DRE	dose rate effect
E_a	activation energy
EAB	elongation at break
EMDA	Expanded Materials Degradation Assessment
EPDM	ethylene-propylene-diene type-M rubber
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
EQ	environmental qualification/environmentally qualified
EVA	ethylene vinyl acetate
FTIR	Fourier transform infrared spectroscopy
GALL	Generic Aging Lessons Learned
GL	Generic Letter
Gy	Gray (unit of absorbed radiation dose)
HELB	high energy line break
Hz	Hertz (unit of frequency), per second
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IN	Information Notice
IPCEA	Insulated Power Cable Engineers Association (now ICEA)
ITE	inverse temperature effect
kV	kiloVolt (1000 V)
kGy/h	kiloGray per hour
LOCA	loss of coolant accident
mil	0.001 inch

Mrad	Megarad (10^6 rad)
MV	medium voltage (>2 kV and <45 kV)
NMR	nuclear magnetic resonance
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OE	operating experience
OIT	oxygen induction time
OITp	oxygen induction temperature
PE	polyethylene
PIRT	phenomena identification and ranking technique
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
R&T	concurrent gamma radiation and elevated temperature exposure
R→T	gamma radiation exposure followed by elevated temperature exposure
RG	Regulatory Guide
SLR	subsequent license renewal
Std	standard
T→R	elevated temperature exposure followed by gamma radiation exposure
tan δ	tangent delta, tan delta, or dissipation factor
TGA	thermogravimetric analysis
V	Volts
VVER	water-water energy reactor, a Russian pressurized water reactor
XLPE	crosslinked polyethylene
XLPO	crosslinked polyolefin

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1.0 Introduction

The fifth volume of the NUREG/CR 7153, the “Expanded Materials Degradation Assessment, Aging of Cables and Cable Systems (EMDA)” report [1] describes an expansion of the NUREG/CR-6923, “Expert Panel Report on Proactive Materials Degradation Assessment,” [8] consideration of nuclear power plant (NPP) materials degradation to include electrical cable materials and cable use in service environments beyond current license periods. Electrical cables important to safety in NPPs [9] were environmentally qualified for at least 40 years corresponding to the initial reactor license period. Elements of conservatism in that process have been used to justify continued use of cables up to 60 years in license renewal and up to 80 years in subsequent license renewal. Consideration of continued use of cables beyond current license periods prompted an intentional and documented consideration of the state of knowledge and risks of continued cable material use. The EMDA used a phenomena identification and ranking technique (PIRT) approach to rank potential degradation scenarios according to the judgement of experts on material susceptibility and the state of knowledge at the time. The PIRT approach of the EMDA identified the current knowledge base of electrical cable and cable system materials, gaps in knowledge for cables in need of further research, potential new forms of degradation, and prioritized research needs.

In the EMDA PIRT process, expert panelists were in general agreement on levels of knowledge at the time and overall aging-related susceptibility of cable materials. Very few materials and aging condition combinations were identified for which a susceptibility ranking of ‘high’ (on a scale of ‘low-1’, medium-2’, ‘high-3’) was given. The susceptibility ranking of a material increased with increasing severity of environmental conditions including higher aging temperatures and higher gamma radiation dose rates. Knowledge of material aging ranked as ‘medium-2’ or ‘high-3’ for all materials and environments considered, reflecting the significant existing extent of generic polymer aging research findings apart from specific plant locations and conditions.

The EMDA report documents several gaps in knowledge related to the historical qualification process and the continued use of cables, originally qualified for 40 years of operation, in extended operation. The main area of uncertainty identified by the EMDA panelists relates to the pre-aging (accelerated aging) carried out during the environmental qualification process and the equivalence of that accelerated aging to the long-term service aging it was intended to simulate. Identified gaps include variable activation energy, diffusion limited oxidation (heterogeneous degradation), dose rate effects, effects of sequence of exposure or synergism in thermal and radiation aging, inverse temperature effects, moisture effects and submerged cables, actual NPP environments, and methods for condition monitoring. Concerns over the uncertainty raised by these identified phenomena relate to the ability of environmentally qualified (EQ) cables to survive heat, radiation, humidity, chemical spray, and other environmental factors associated with design basis events (DBE) during their qualified time of service. In addition to uncertainty regarding the ability of the historic pre-aging methods to simulate extended time in service, uncertainty was also identified in the actual temperatures and gamma radiation doses to which fielded cables are exposed to during their qualified life. That is, according to the EMDA, not only does uncertainty exist related to the process of replicating long term service conditions through accelerated aging in the laboratory, but there is also uncertainty regarding the current understanding of the long-term environmental service conditions to be replicated. Suggestions were made in the EMDA strategies for actions to address these topics.

The Nuclear Regulatory Commission (NRC), U.S. Department of Energy (DOE) national laboratories, the Electric Power Research Institute (EPRI), and other entities both inside and outside of the U.S. have published research and developments related to the knowledge gaps. Uncertainties in the time-based approach to EQ have been acknowledged, and improved methods to account for them have been proposed. Actual in-plant service conditions in operating boiling water and pressurized water reactors have been more accurately determined. Susceptibility of cables to moisture damage and practical methods to ensure reliable performance of potentially wetted cables have been established and implemented.

Consensus-based standard development groups, including IEEE, have updated their guidance on the cable qualification process considering information presented in the EMDA. The NRC has updated regulatory guidance to support revised standards for qualification of cables considering the uncertainties documented in the EMDA, per NRC Regulatory Guide 1.89, Revision 2 “Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants”, issued April 2023 [5]. The NRC’s “Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report, Draft Report for Comment” (NUREG-2191) [6], [7], and subsequent license renewal guidance have been updated to acknowledge potential aging mechanisms identified in the EMDA and to require cable aging management practices to mitigate potential risks not fully appreciated in previous historic license guidance.

This report considers progress and approaches that have been reported in the decade following publication of the EMDA to close the identified knowledge gaps and to increase confidence in decisions regarding continued use of qualified cables beyond their original qualified life. Each of the knowledge gaps will be discussed individually in Section 2.0, including the location of their mention in the EMDA document, published progress on the topic since the EMDA was released, and conclusions regarding the updated status of the identified topic of concern. A summary of the EMDA knowledge gaps is provided in Section 2.1, followed by topics related to cable qualification in Section 2.2, and consideration of moisture effects in Section 2.3. Section 3.0 reviews the evolution and status of technical standards and regulatory guidance relevant to cable environmental qualification. Section 4.0 contains a discussion of changes to cable qualification and aging management since the EMDA was published and updated guidance on reassessment of qualified cables for use beyond their original qualified life. Finally, Section 5.0 provides concluding remarks considering progress on EDMA knowledge gaps since the publication of the EMDA in 2014.

2.0 Knowledge Gaps Identified in the Expanded Materials Degradation Assessment

2.1 Summary of EMDA Knowledge Gaps

The summary input of experts documented in the EMDA described several specific knowledge gaps or topics of uncertainty related to continued use of installed cables in reactors in extended operation. These topics included concerns with the methodology used to environmentally qualify safety-related cables, limited knowledge of actual in-plant service conditions for cables, and the unanticipated long-term degradation mechanisms of moisture exposure (such as insulation failures due to water-treeing) even for cables designed for submerged conditions. Each of the knowledge gaps will be discussed individually below, including the location of its mention in the EMDA document, published progress on the topic since the EMDA was released, and conclusions regarding the updated status of the knowledge gap.

2.2 Qualification Related Knowledge Gaps

Several of the potential concerns raised in the EMDA relate to the methodology historically used to meet the EQ requirements for safety-related cables. The U.S. Atomic Energy Commission (the predecessor to the U.S. Nuclear Regulatory Commission [NRC]) first published the “Qualification of Class 1E Equipment for Nuclear Power Plants” Regulatory Guide 1.89 (Regulatory Guide [RG] 1.89) in 1974, which described “a method acceptable to the Regulatory staff for complying with the Commission's regulations with regard to design verification of Class 1E equipment for service in light-water-cooled … nuclear power plants”[10]. That first RG 1.89 edition found the basic procedures for qualifying Class 1E equipment described in the IEEE Standard (Std) 323-1974, "IEEE Standard for Qualifying Class IE Equipment for Nuclear Power Generating Stations,”[2] to be generally acceptable and to provide an adequate basis for complying with design verification requirements of such equipment outlined in the NRC Regulations Title 10 portion of the Code of Federal Regulations (CFR) (Criterion III of Appendix B to 10 CFR Part 50 [11]), “Requirements binding on all persons and organizations who receive a license from NRC to use nuclear materials or operate nuclear facilities”. Class 1E or safety-related electrical equipment, including cables, must conform to established industry performance standards to promote confidence in reliably safe function in the nuclear reactor environment. Generally, these standards require cable manufacturers to ensure products maintain performance requirements throughout their design life, even after DBEs [12]. This assurance has usually been met by accelerated aging of the components (e.g., applying the Arrhenius method or the equal dose–equal damage approach) using either thermal, radiation, or a combination of stressors, to simulate the accumulated stress of their qualified life (e.g., 40 years, 60 years, etc.) prior to subjecting the pre-aged components to a design basis (e.g., loss of coolant accident [LOCA], high energy line break [HELB]) exposure simulation. Components that successfully perform following this process are deemed ‘environmentally qualified’. Most installed EQ cables have been qualified for a lifetime of at least 40 years, corresponding to the initial license period of NPPs. The points of concern with the qualification process presented in the EMDA mostly involve the methods used in the pre-aging step, in which the equivalence of 40 years of service aging was meant to be imparted to a component prior to testing its capacity to pass a DBE simulation.

2.2.1 Actual Nuclear Power Plant Environments

To understand the effects of aging equivalent to 40 years on a component in the service environment (to provide reasonable assurance whether a 40-year-old component will pass the DBE simulation), the conditions of the service environment must be used as an input. At the beginning of the nuclear electric power industry, operating experience and knowledge of the effects of service environment conditions on cable system materials was limited. Conservative assumptions were made about the average service temperature, such as 50ºC or even 90ºC, and the average accumulated gamma dose, such as 50 megarad (Mrad [10^6 rad]) or 500 kGray (kGy), that a safety-related cable may be subject to over 40 years of operation. Knowing that they would be conservative, such values were used to robustly qualify cables for confidence in the ability of the cables to perform their safety function throughout the 40-year life of the reactor (corresponding to its initial license period). As the need and desire arose for continued use of existing reactors beyond 40 years, it became important to understand exactly how conservative those original service condition estimates were and consequently, to seek to better understand how much longer than the initial operating license a qualified component might be expected to reliably perform [13]. Chapter 5.9.5 of the EMDA mentions the knowledge gap relating to actual in-service conditions of nuclear power plant electrical components.

EPRI produced a report that addresses the knowledge gap of actual in-service conditions for NPP cables [14]. It describes and discusses measured thermal and radiation data for a representative boiling water reactor (BWR), a representative pressurized water reactor (PWR), and a Russian PWR [the water-water energy reactor (VVER)]. This data can be extrapolated to estimate approximate actual conditions over 40, 60, or 80 years of reactor operation. Key findings from the report are that:

- “In the overwhelming majority of cases radiation levels were often two (2) or more orders of magnitude less than design values used for environmental qualification”, and
- “Thermal environments are typically less than design values (for Westinghouse PWR monitored, one location was 12ºF (7ºC) higher than design while the remaining 54 monitors were 5ºF to 50ºF (2.8ºC to 28ºC) less than design values).”

2.2.2 Non-Arrhenius Behavior and Non-Constant Activation Energy

2.2.2.1 Understanding of Non-Arrhenius Behavior and Non-Constant Activation Energy at the Time of the Expanded Materials Degradation Assessment

Chapter 5.1 of the EMDA document identifies “activation energy values used for thermal aging” as a potential concern in qualification methodology and hence a gap in knowledge for extension of qualification results to expected performance in long-term operation. The process for accelerated aging of cables to the equivalence of the license period (e.g., 40 years) prior to exposing the cable to a DBE simulation involved the assumption that exposure to a higher temperature for a shorter time produces aging equivalent to a longer period at a lower temperature. Specifically, that the rate of the aging reaction depends on the temperature according to the Arrhenius relationship. A material property that tracks aging is selected, such as tensile elongation at break (EAB) of the cable insulation polymer material, an endpoint is selected for the reaction, such as EAB = 50% of the original value, and the exposure time to endpoint at each temperature is determined for a series of temperatures. The activation energy (E_a) of the degradation reaction is derived from the slope of the Arrhenius plot (such as time to EAB endpoint versus the reciprocal absolute temperature). If the natural log of the rate of change is linear with the reciprocal absolute temperature, and the slope of the line (the E_a) is constant over the range of temperatures considered, then the relationship is described as exhibiting Arrhenius behavior. Chapter 5 in the EMDA listed a few publications that reported observation of non-Arrhenius behavior in polymers, or a change in E_a of the polymers in different temperature ranges. Chapter 5.1 of the EMDA elaborated on the reduction in E_a as the temperature was lowered from the accelerated aging condition to the service condition. The potential concern is that if an E_a value calculated using greatly elevated temperatures is significantly higher than the E_a that would be calculated using temperatures near the actual service temperature, then the robustness (i.e., the ability to perform the intended safety function) of the cable at service temperatures may be overestimated.

In Chapter 5.1 of the EMDA, the authors concluded that some of the limitations of use of the Arrhenius equation as a basis for accelerated thermal aging needed to be [better] “appreciated.” For example, the Arrhenius model is only applicable if the same balance of degradation reactions occurs at both the elevated accelerated aging temperatures and at service temperatures.

Chapter 5.9.1 in the EMDA on Activation Energies suggests that derivation of Arrhenius activation energies with reduced uncertainty at low temperatures (close to service temperatures) using sensitive measurement techniques (such as oxygen consumption rather than tensile EAB), and conditions that avoid other aging artifacts (such as use of thin samples to avoid diffusion limited oxidation [DLO]) would provide needed data for improved analytical simulation of thermal aging (see Section 2.2.3 below for additional discussion).

A key finding of the expert panel assembled in the EMDA process is reproduced here:

> “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 [a] specific environment, be estimated with increased confidence level. This is because the actual value of activation energy plays a major role in behavior prediction [modelling] 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” (EMDA Chapter 10.2) [1].

Thus, the EMDA authors bring attention to the fact that E_a values can vary with temperature and E_a values used in predicting cable material behavior over time in service should be determined for the temperature range of the service environment.

2.2.2.2 Research on Activation Energy Reported Since Publication of the Expanded Materials Degradation Assessment

The Arrhenius methodology has been used in many fields to describe the temperature dependance of polymer degradation, but only as an empirical model, with limited predictive power. Using both EAB and oxygen consumption measurements, a reduction in E_a at lower temperatures was experimentally observed for many cable materials, including those used as cable insulation and jacket material [15], [16], [17]. Measuring E_a at a temperature as close to the service temperature as possible is key to improving the accuracy of lifetime estimation. Near the service temperatures, where EAB does not change within months of aging in the laboratory environment, oxygen consumption was reported as one of the few tests sensitive enough to provide a reliable E_a value. E_a values at low temperatures (below 100°C) were reported when other degradative stressors (e.g., gamma or ultraviolet radiation) were present using markers of polymer aging including loss in elasticity, as determined by tensile EAB [18], [19], and rise in chemical oxidation, as tracked by absorbance in the carbonyl region of the infrared spectra observed using Fourier transform infrared spectroscopy (FTIR) [20], [21]. In addition to supporting the determination of E_a and DLO modeling, the accumulated oxygen consumption (or the "oxidation level") was also used to represent the progress of degradation, essentially replacing a "time-temperature superposition" framework with an "oxygen consumption-temperature superposition" framework [22], [23].

The choice of endpoint and the "aging indicator" metric were reported to affect the value of E_a [19], [24], [25]. There was also a desire to use thermogravimetric analysis (TGA) data at different ramp rates to calculate E_a [26], [27], [28]. As has been pointed out in a review of the subject [29], the E_a values calculated from TGA data were focused on the "degradation chemistry pathways that for most polymers are too far removed from the mechanisms that are relevant for the usual application conditions." Similarly, attention should be paid to the relevance of the process used for E_a determination and the degradation process happening in the service condition of cables when using other techniques to calculate E_a.

A numerical method was proposed using two processes, each with its own E_a, to describe degradation of ethylene-propylene-diene type-M rubber (EPDM) characterized by EAB, oxygen consumption, compressive stress relaxation and decay in sealing force [30]. The idea was similar to using two competing processes to explain non-Arrhenius behavior [31] but used different approaches to deconvolute the two processes and arrive at different E_a values. In the model of Zaghdoudi, E_a was dependent on degradation rate, while in the model of Celina and Gillen, E_a was temperature controlled.

2.2.2.3 Impact of Non-Constant Activation Energy on Qualified Life

The impact of non-constant E_a in cable qualification is that it changes the estimated time to endpoint in cable pre-aging (accelerated aging) to the qualification period prior to DBE simulation. If E_a was lower at the service temperature compared to the E_a obtained from accelerated aging studies at significantly higher temperatures, the Arrhenius model would overestimate the time at service temperature represented by the pre-aging. For example, heating cable over a few weeks at elevated temperature to induce degradation representing 40 years of aging at service temperature might represent less than the equivalent of 40 years of aging if the E_a of degradation at service temperature is lower than E_a at the accelerated aging temperature. The amount of overestimation scales with the amount of change in E_a $(E_a - E_a')$, the measured time to endpoint at the accelerated conditions (t_1), and depends on the temperature at which the E_a value varies (T_3). Specifically, if the E_a was constant for the temperature range bracketing the accelerated temperature (T_1) and the service temperature (T_2), then the estimated time to endpoint at the service condition (t_2) would be

$$t_2 = t_1 \times \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

where t_1 is the measured time to endpoint at the accelerated temperature (T_1). If the activation energy value decreased to E_a' at an intermediate temperature (T_3), then the new estimated time to endpoint (t_2') would be

$$t_2' = t_2 \times \exp\left[-\frac{E_a - E_a'}{R}\left(\frac{1}{T_2} - \frac{1}{T_3}\right)\right]$$

$$= t_1 \times \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \times \exp\left[-\frac{E_a - E_a'}{R}\left(\frac{1}{T_2} - \frac{1}{T_3}\right)\right].$$

A comparison between the estimated time to endpoint (t_2) and the actual time to endpoint (t_2') considering the lowering of *E*a was demonstrated in Figure 1, where the actual time to endpoint was 80%, 50% and 90% of the estimated time in the three hypothetical scenarios. Figure 1 is a modified version of Fig. 2 of Celina in [29] that illustrates non-linearity in response to accelerated aging.

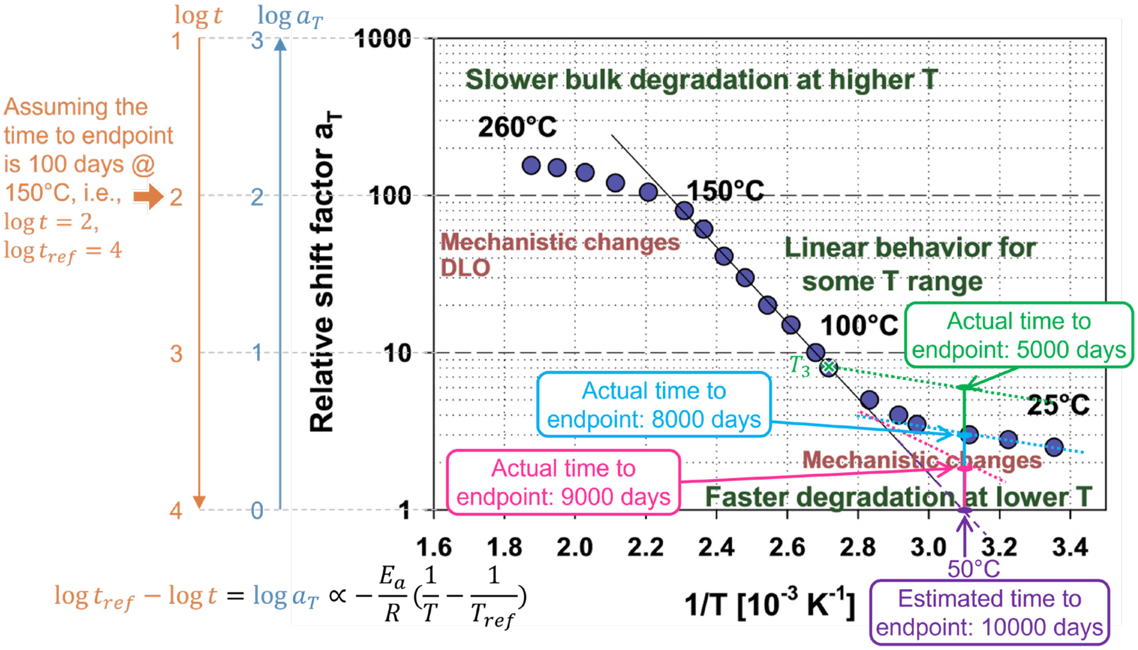


Figure 1. Schematic demonstration of the mismatch between estimated time to endpoint (without *E*a change) and the actual time to endpoint when the *E*a (slope) changes at lower temperatures. Modified from Fig. 2 of [29]. Respectively, the blue, green and pink symbols represent the actual time to endpoint (with a lowering in *E*a) being 80%, 50% and 90% of the estimated time to endpoint (assuming a constant *E*a).

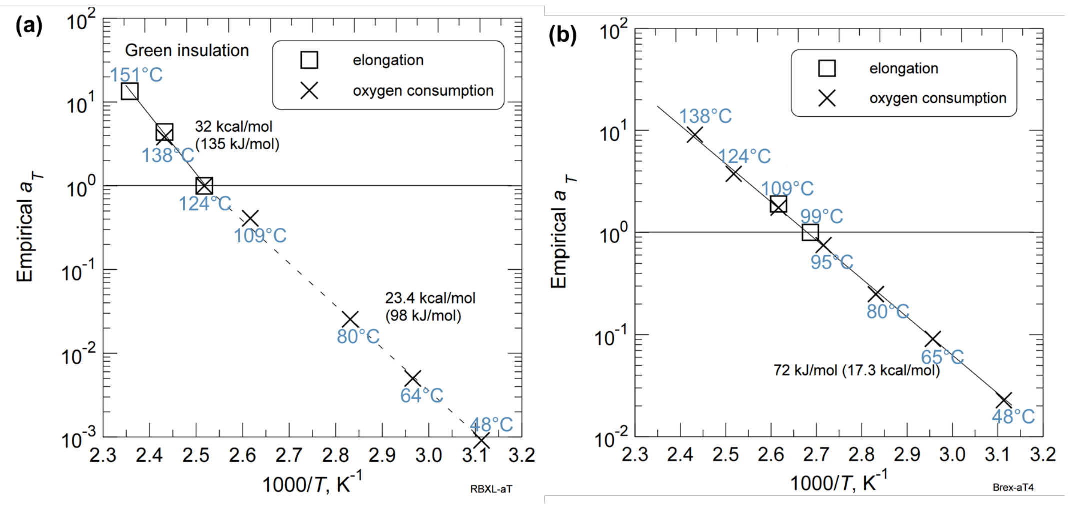


Figure 2. (a) A change in E_a at 124°C observed for a crosslinked polyolefin (XLPO) material. (b) Constant E_a for a different XLPO material. Figures are modified from (a) Figure IV-40 and (b) Figure IV-32 of [32].

A lower E_a value at lower temperature has been reported for a variety of polymers. For example, Figure 2(a) showed the change in E_a for a crosslinked polyolefin (XLPO) material (labeled as “green insulation XLPO-05” in the original report [32]) from 135 kJ/mol (124°C to 151°C) to 98 kJ/mol (48°C to 124°C) and the transition happened at 124°C. In this example, the ratio of the actual time to endpoint and the estimated time to endpoint at 48°C would be

$$\frac{t_2'}{t_2} = \exp\left[-\frac{E_a - E_a'}{R}\left(\frac{1}{T_2} - \frac{1}{T_3}\right)\right]$$

$$= \exp\left[-\frac{(135-98)\times 1000}{8.314}\left(\frac{1}{48+273.15} - \frac{1}{124+273.15}\right)\right] = \exp(-2.65) = 0.07,$$

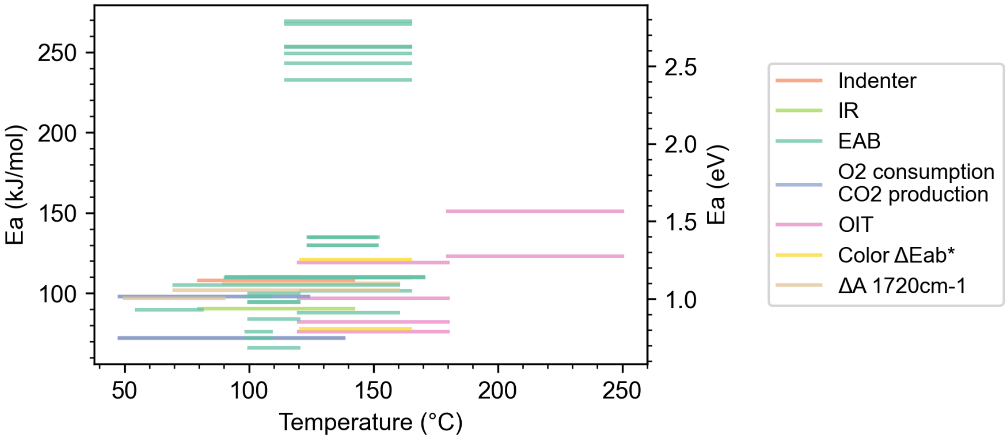
which means the time to endpoint was only 7% of the time to endpoint for the higher E_a value. If the E_a or E_a’ were of a different value, or if the changeover happened at a different temperature, the ratio (t_2'/t_2) would be different as listed in Table 1. It should be noted that not all XLPO materials exhibited a decrease in E_a with temperature. For a different XLPO (labeled as “XLPO-02B” in the original document [32]), as shown in Figure 2(b), the E_a was constant over the temperature range of 48°C to 138°C, which would not lead to overestimation of time to endpoint if accelerated aging was performed at or below 138°C and if the service temperature was at 48°C or above.

Table 1. Ratio of the actual time to endpoint (with a lowering in E_a) and estimated time to endpoint (without considering the lowering in E_a) at different hypothetical situations when estimating the time to endpoint at 48°C.

High-temperature E_a (kJ/mol)	**Low-temperature E_a' (kJ/mol)**	**Change-over temperature, T_3 (°C)**	**Ratio of times to endpoint, t_2'/t_2 (%)**
135	98	124	7
120	98	124	21
135	98	64	52
120	98	64	68

Literature E_a values for crosslinked polyethylene (XLPE)/XLPO and EPR/EPDM types of materials are compiled in Figure 3, where the horizontal lines represent the E_a value calculated based on the isotherms obtained in the corresponding temperature range. E_a values for other polymers reported in literature are listed in the Appendix. As shown in Figure 3, E_a values vary with the test method and the temperature range when the base polymer is in the same material category. As the values were obtained from different references, the test specimens would have different formulations, which may also contribute to the variability of E_a values. A possible explanation for why the E_a values vary between different testing methods is that the different methods probe different stages of aging where the predominant aging mechanism could be associated with different E_a values. For example, OIT is correlated with loss of antioxidants, which occurs at an early stage of degradation. Color change (including yellowing due to the conjugated species produced during aging), and the absorption peaks ΔA at 1720 cm^{-1} and 1714 cm^{-1} (in the carbonyl region), were related to the formation of new chemical structures (e.g., carbonyls). Chemical changes typically happen at much earlier stages than mechanical embrittlement as measured by a decrease in EAB.

(a) XLPE/XLPO



(b) EPR/EPMD

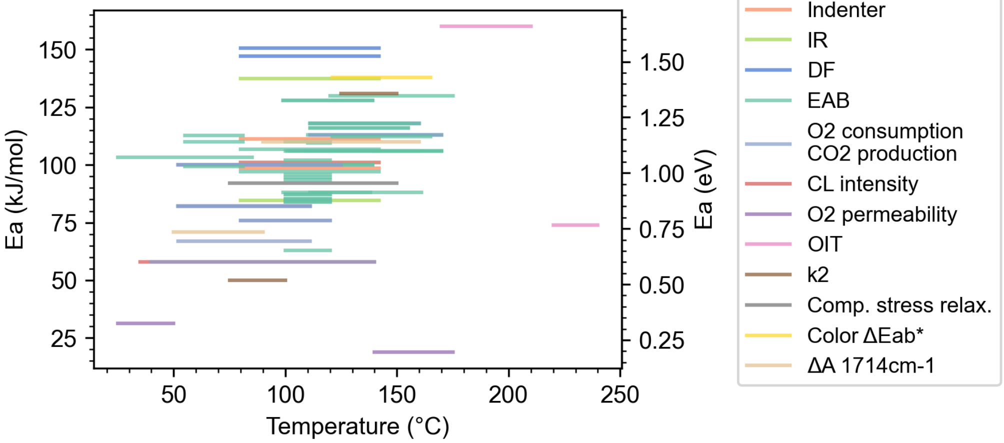


Figure 3. E_a values obtained from different temperature ranges (x-axis) based on different testing methods (legend) for (a) XLPE/XLPO-based and (b) EPR/EPDM-based materials. (Data sources may be found in the Appendix).

2.2.3 Diffusion Limited Oxidation

2.2.3.1 Understanding of Diffusion Limited Oxidation at the Time of the Expanded Materials Degradation Assessment

Diffusion limited oxidation (DLO) was discussed in detail in Chapter 5.2 of the EMDA. Under extreme accelerated aging conditions such as at highly elevated temperatures, oxygen permeating in the polymeric cable insulation material can be consumed in the oxidation reaction with the polymer faster than the oxygen can be replenished by diffusion into the polymer matrix from the surrounding atmosphere. This phenomenon can artificially protect the center of polymer sample from oxidative aging through rapid formation of an aged layer of the surface of the sample with significantly reduced oxygen permeability, such that oxygen is prevented from reaching and reacting with polymer at the center of the sample. DLO may be detected by through-thickness profiling techniques, such as modulus profiling, as demonstrated in Figure 5.5 of the EMDA, where the modulus of a 1.3 mm thick chlorosulphonated polyethylene (CSPE) sample was lower in the center of the sample thickness than the modulus was on the outside air-exposed surfaces. According to Chapter 5.2 of the EMDA, presence of DLO “may overestimate cable insulation lifetimes.” However, the discussion in Chapter 5.2.1 of EMDA for the CSPE sample showing DLO pointed out that the tensile elongation of the subject sample was not affected by DLO, as the local hardening on sample surface could quickly result in bulk failure from crack initiation, indicating that lifetime to the endpoint of a EAB reduction might not be affected by the presence of DLO.

Chapter 5.2.1 of EMDA gave the equation for the critical sample thickness below which DLO is insignificant as a function of oxygen partial pressure, oxygen permeation rate and oxygen consumption rate. Chapter 5.9.2 suggested measuring these parameters and developing 2-D finite element models for DLO on the cable cross-sections.

2.2.3.2 Research on DLO Reported Since Publication of the Expanded Materials Degradation Assessment

Simulation of DLO through finite element modeling has been pursued [33], [34], [35], enabling the visualization of the effects of modeled parameters as a function of oxygen concentration and of sample thickness. The limiting thickness of a sample at which the oxidation rate at the center of the sample closely approximates the oxidation rate at the surface of the sample is a function of the oxygen pressure in the surrounding atmosphere, the oxygen permeability of the polymer, the solubility of oxygen in the polymer, and the oxidation rate of the reaction. These values are not only material dependent but are temperature dependent and evolve during the oxidation reaction. The gradient of transition of highest oxidation of the surface of cable polymers to the lowest extent of oxidation within the sample thickness for polymers exhibiting DLO in the above works seems to be on the order of 0.2 mm to 0.5 mm such that, when present, DLO might be expected to be a factor for samples around 0.5 mm or thicker for those exposed to air on one side only during oxidation and 1 mm or thicker for those exposed to air on both sides during oxidation.

In addition to modulus profiling mentioned in EMDA Chapter 5.2, other profiling methods have been performed to detect DLO including color change [36], FTIR-detected carbonyl bond generation [37], [38], [39], [40], [41], [42], nuclear magnetic resonance (NMR) T2 relaxation time [41], oxidation induction time (OIT) [43], and tensile testing of dumbbell samples cut from different locations through the sample thickness [42]. Among these, the analytical characterizations, such as FTIR and NMR, were able to separate the different pathways leading to the overall degradation of mechanical properties. Pourmand and collaborators reported three mechanisms giving rise to the increase in the indenter modulus of an EPDM after thermal aging. The three mechanisms were oxidation-induced crosslinking, migration of low molar mass species, and anaerobic crosslinking [41], [44]. Others used FTIR profiling to study the concentration and distribution of antioxidant molecules [40] and oxidative products such as carboxylic acid and hydroperoxides through the polymer sample thickness [39], [45].

Another study by Wei et al. examined the fracture propagation of polyamide 6 with the observed DLO [46]. After thermal aging, the sample formed a "skin-core" structure, with the oxidation layer on the surface, and the crack could be arrested by the interface between the oxidized skin and the unoxidized core through plastic deformation. The arrested crack propagated through the unoxidized sample by necking, leading to a constant EAB of approximately 25% when the aging time varied from 1 hour to 24 hours at 180°C. Within 1 hour and after 24 hours, the EAB decreased with aging time [46].

2.2.3.3 Impact of DLO on Qualified Life

Presence of DLO can lead to a decrease in overall degradation rate at extremely accelerated conditions (e.g., above 150°C) [15], [29]. If the E_a obtained from a DLO-present high-temperature scenario using an affected material property was used to estimate the time to endpoint, then the time to endpoint would be underestimated, as shown in Figure 4(a), which does not impair conservativeness. However, if the larger E_a obtained from the lower temperature range was used to back-calculate the aging time needed at the high temperature to achieve an extended time to endpoint, then a longer aging time would be required at the high temperature if DLO is present, as demonstrated in Figure 4(b). One method to quantify the effect of DLO on the time to endpoint is to use the equations listed in Section 2.2.2.3, those involving the two activation energies (E_a, E_a') and the crossover temperature (T_3), if a deviation from linear behavior (associated with E_a) was observed in the DLO-affected region (associated with E_a'). It should be noted that the treatment of DLO effect as a change in E_a is only a simplified mathematical treatment and is not derived from reaction kinetics. The amount of change in E_a due to DLO depends on the material property or the degradation indicator used for E_a determination. For the common degradation indicators, EAB is insensitive to DLO since the crack initiated on the surface can rapidly propagate through the entire cross-section [15], [40]. Localized indicators such as carbonyl index (CI, measured by ATR-FTIR) and indentation modulus (IM) will show different values through the thickness, revealing the oxidation profile, while the CI and IM on the surface represent the most degraded condition. The dielectric permittivity (ε' and ε") measures the polarizability of all molecules through the sample thickness collectively, and trends with the average carbonyl index, meaning it is affected by DLO but cannot be used to detect the oxidation profile through the thickness [47], [48].

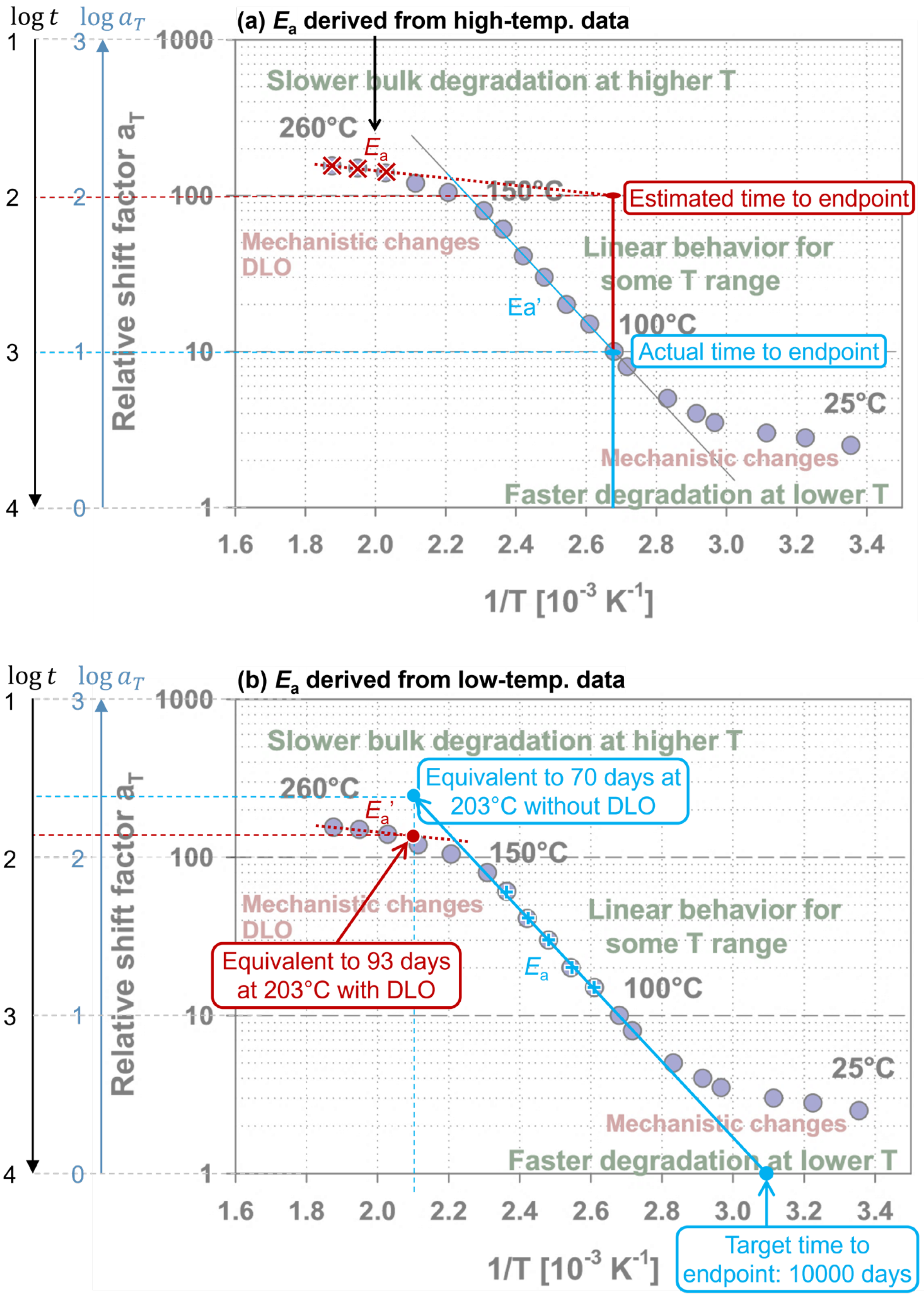


Figure 4. Schematic demonstration of the effects of DLO on qualified life, including (a) the underestimation of time to endpoint when extrapolating the DLO-affected high-temperature data using the E_a calculated from the high temperatures (red crosses) (b) a longer pre-aging time needed to accommodate a lowering in E_a due to DLO, if the pre-aging time was calculated based on the E_a derived from low-temperature data (blue pluses).

2.2.4 Dose Rate Effects

2.2.4.1 Understanding of Dose Rate Effects at the Time of the Expanded Materials Degradation Assessment

Dose rate effects (DRE), as discussed in Chapter 5.3 of the EMDA, represent exceptions to “equal dose, equal damage” behavior in the degradation of cable insulation polymers with exposure to gamma radiation. DRE are cases in which degradation depends not only on total dose, but on how quickly that dose is delivered. In the pre-aging step of cable qualification, the conservatively estimated gamma dose expected to be received by a cable over 40 years of service was applied all at once, within hours. The concern raised in the EMDA is that a significant difference may exist between the effects of a lifetime dose (e.g., 50 Mrad [500kGy]) applied slowly over 40 years to those of a lifetime dose applied over several hours. High dose rate exposure may lead to DLO or other artificial aging behavior that may result in overestimation of cable performance when translated to service conditions. As discussed in the EMDA, the risks associated with DRE include: (1) DRE being commonly found in most of the insulation and jacket materials; and (2) “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.”

Two types of DRE were delineated in EMDA Chapter 5.3:

(1) In the low-dose-rate regime, the thermally induced degradation becomes more dominant (while the proportion of radiation-induced degradation decreases) as the dose rate is lowered; and

(2) “True chemical DRE,” which includes (2-1) heterogeneous oxidation (or DLO as discussed in EMDA Chapter 2.2.2) the high-dose-rate regime, resulting from degradation being bounded by oxygen diffusion rate; and (2-2) other chemical DRE in the radiation-dominant regime.

EMDA Chapter 5.3 also noted that the DRE observed in the same dose rate value ranges can be of different types for different materials. For example, at the combined aging condition of 50°C and 0.1 to 0.5 Gy/h, Neoprene and CSPE jacket materials showed type (1) apparent DRE (Figures 5.8 and 5.9 in EMDA), whereas a crosslinked polyethylene (XLPE) insulation material, which falls in the radiation-dominant region at the same aging condition, showed type (2-2) chemical DRE (Figure 5.10 in EMDA).

DRE was mentioned in the summary Chapter 5.9.2 in EMDA together with DLO, perhaps because of the co-existence of DRE, which are phenomena, and DLO, which is the mechanism behind the type [2-1] DRE phenomena.

Data showing DRE for different polymers can be found in a review paper published in 1993 titled, “Predictive Aging Results in Radiation Environments,” by K. T. Gillen and R. L. Clough [49], which was cited in the EMDA report (reference 89). The different types of DRE were illustrated in a figure of that work (recreated with labels as Figure 5 below), including the type (1) apparent DRE due to a shift towards thermal-dominant degradation and the type (2-1) chemical DRE because of DLO. The paper also discussed additional mechanisms for type (2-2) chemical DRE observed at intermediate dose rates, including the slow reaction of long-lived radicals such as those trapped in the crystalline regions of semi-crystalline polymers. Another mechanism is the rate-determining breakdown of intermediate hydroperoxide species.

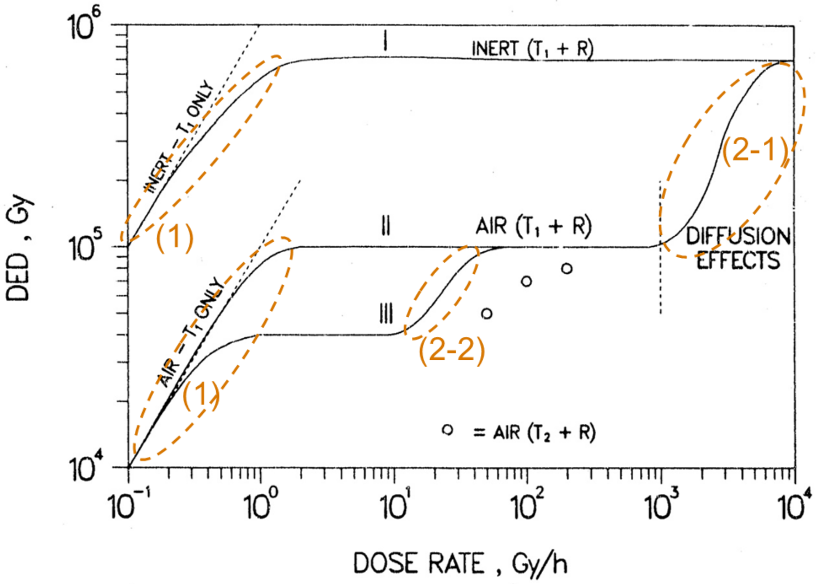


Figure 5. Schematic illustration of different types of dose rate effects (DRE) under inert (curve I) and aerobic (curves II and III) atmospheres. On the dose to equivalent damage (DED) vs. dose rate plot, the sloped portions (circled) indicate the presence of DRE. The figure was reproduced from Gillen and Clough, 1993 [49].

Based on the proposed mechanisms, it could be deduced that type (2-2) may be material-specific, while type (1) and (2-1) DRE are likely to be observed for all polymers but at material-specific dose rate ranges. Polymers that are more resistant to thermal aging might exhibit the type (1) apparent DRE at lower dose rates.

2.2.4.2 Research on Dose Rate Effects Reported Since the Expanded Materials Degradation Assessment was Published

Most research on DRE of cable materials published after 2012 arrived at the same conclusions as mentioned in EMDA Chapter 5.3 [18], [22], [25], [37], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61]. The topics of these publications include direct observation of DRE in cable materials, the molecular-level evidence supporting proposed DRE mechanisms, and model development incorporating the proposed mechanisms into degradation kinetics. The datasets cited in EMDA Chapter 5.3 were mainly mechanical properties, especially tensile EAB. Additional properties were measured to examine if DRE could be detected using other testing methods. DRE were observed using dielectric permittivity (ε’, ε”) [47], [62], dissipation factor (tan δ) [63], [64], resistivity [64], density [47], [64], swelling ratio [51], gel fraction [51], oxidation induction temperature (OITp) [51], gas analysis including O_2 consumption, CO_2 and H_2 evolution [65], [66], and FTIR signals in the carbonyl wavenumber range [67], [68]. Electron paramagnetic resonance results of irradiated XLPE and EPR revealed the presence of long-lived polyenyl, allyl and peroxyl radicals [52], which supports the proposed mechanisms for type (2-2) DRE. The yields of these free radicals were found to be dose-rate dependent [52].

Exhibition of DRE was found to be dependent on material formulation [66]. For example, based on gas analysis data, an XLPE with a specific antioxidant did not show DRE when the specimens were irradiated at 5 and 40 Gy/h, while the other XLPE samples studied without that antioxidant did show DRE [66].

Models based on autoxidation kinetics were developed to describe the type (1) apparent DRE with the asymptotic behavior at low dose rates [23], [69], [70]. Fuse's model also predicted another DRE at higher dose rates caused by antioxidant depletion [69].

2.2.4.3 Impact of Dose Rate Effects on Qualified Life

Based on Figure 6, the same total dose level does not generate the same damage when DRE is present (i.e., DED was not constant). IEEE Std 383-1974 specified a total dose of 50 Mrad (500 kGy) at a dose rate below 1 Mrad/h (10 kGy/h) for radiation pre-aging before LOCA simulation testing. If DRE existed, the 50 Mrad dose delivered at the high dose rate used during qualification would be equivalent to a total dose smaller than 50 Mrad at a low dose rate in the service condition. It should be noted that this hypothetical non-conservative case due to the presence of DRE could be mitigated by the two-orders-of-magnitude overestimation in 50 Mrad compared to actual NPP conditions discussed in 2.2.1 [14]. It is possible that the equivalent total dose, considering a lowered value due to DRE, may still exceed the actual dose that most insulated cables receive during service. No cases have been identified that provide documented evidence of DRE in cables removed from service.

To quantify the impact of DRE, a hypothetical non-conservative case due to DRE is illustrated in in Figure 6, where the 50 Mrad at approximately 4200 Gy/h (accelerated condition) is equivalent to 8 Mrad at 1 Gy/h (service condition, entering temperature-dominant regime), following the DED curve II. In this case, if the target total dose at the service condition is 50 Mrad, then 50 ÷ 8 × 50 = 312.5 Mrad would be needed reach equivalent damage at 4200 Gy/h. Alternatively, the dose rate at the accelerated condition should be carefully chosen to avoid DRE (e.g., between 2 Gy/h and 1000 Gy/h where the curve II is flat). However, the equivalent total dose at the service dose rate needs to be determined from the DED curve for the specific material, which could be challenging due to lack of DED data for most materials, especially at low dose rates. Although models might help provide DED data at low dose rates, model predictions need to be compared to experimental data for validation. The DED curve data available in the literature are typically interpolated from EAB data, which could limit its relevance if the dose to equivalent reduction in dielectric properties is of interest.

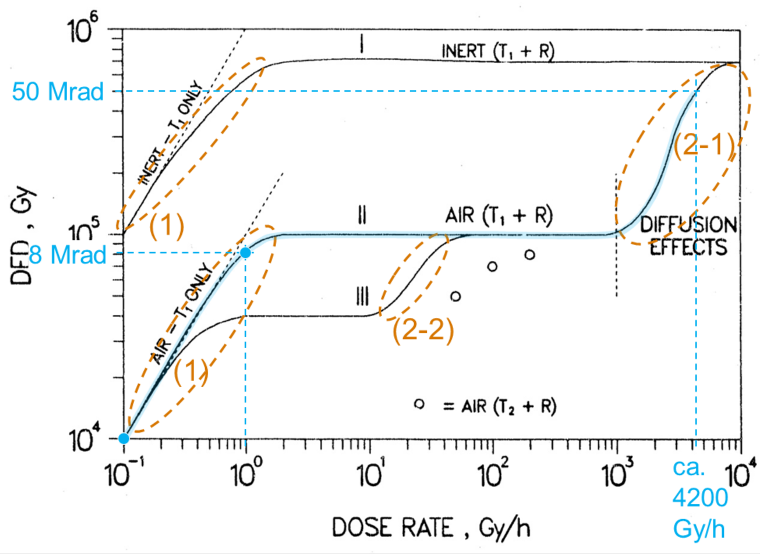


Figure 6. Demonstration of using DED curve to find the equivalent dose at two different dose rates for samples showing dose rate effects.

2.2.5 Sequential vs. Concurrent and Synergistic Aging Effects

2.2.5.1 Understanding of Exposure Order and Synergistic Effects in the Expanded Materials Degradation Assessment

Synergistic effects, or non-additive aging behavior of cable materials exposed to both elevated temperature and gamma radiation at the same time, were discussed in Chapter 5.4 of the EMDA, while a discussion of sequential vs. concurrent aging was briefly provided in Chapter 5.5 of the EMDA. The concern associated with whether materials age differently based on order of exposure to heat and radiation involves recreating service aging behavior during the accelerated pre-aging of the qualification process. An in-service Class 1E cable located in the containment building of a reactor may be exposed to gamma radiation and to thermal stress during the years of its service, while a cable to be type-tested in the qualification process may be exposed to 40-years-service-temperature-equivalent heat exposure at one service provider before being transferred to another location to have 40-years-equivalent gamma dose applied. If the degradation mechanisms are additive, then the accelerated aging might well represent the service aging. If, however, different mechanisms of degradation occur when the material is exposed to elevated temperatures and to gamma radiation concurrently, then the accelerated aging of the material to be qualified may lead to overestimation of the longevity of the material when translated into the service environment. In Chapter 5.5 of the EMDA, its authors declare that “degradation is most severe in concurrent aging and least severe in sequential aging where the thermal aging is carried out before radiation aging.” It should be noted that although the basis for this statement was theoretically robust, the validity of the statement is highly dependent on material formulation, with instances of experimental data revealing exceptions, such as inverse temperature effects for certain cable materials.

Chapter 5.4 of the EMDA also called attention to variation in values of thermal-resistivity and radiation-resistivity in different polymers. This knowledge would be helpful in determining if the material under normal operational conditions (50°C and 0.5 Gy/h, as suggested in EMDA) would be subjected to thermal-dominant or radiation-dominant degradation.

The EMDA Chapter 5.4 also mentioned “another type of synergistic effect” arising from “interactions between the different materials” in a cable assembly, so that aging the complete assembly might give different results than observed from aging of components separately. In the case of bonded cable insulation, for example, when a second layer of insulation or jacketing material is strongly adhered to the insulation of a cable, the less stable of the two materials may reduce the stability of the other material through creation of additional stresses upon aging. In another example, reactive chemical species may volatilize from one material as it ages and induce aging in a nearby material. In cases where qualification was performed on intact cable assemblies, interactions between components could be considered as captured in the qualification process.

2.2.5.2 Research on Order of Aging and Synergistic Effects Reported Since the Expanded Materials Degradation Assessment

As discussed in Chapter 5.5 of the EMDA, the concurrent aging scenario was believed to be the most degradative, as the slowest step in a high-temperature thermal degradation is the initiation of free radicals and radiation could largely accelerate radical generation rate. With the same reasoning, radiation followed by thermal aging is more degradative than the converse, since a large quantity of free radicals produced in the radiation aging step can react with other radical species or oxygen to cause degradation in the subsequent thermal aging step [55], [71]. This trend was confirmed for a silicone rubber material aged at elevated thermal (205°C) and at radiation (1 kGy/h at 100°C) conditions simultaneously (concurrent gamma radiation and elevated temperature exposure [R&T]), sequentially (thermal followed by radiation, T→R), and in the reverse order (radiation followed by thermal, R→T) [72]. The reduction in EAB and tensile strength and increase in modulus, indicating embrittlement, was the most severe under the simultaneous aging condition [72]. The reversed condition (R→T) was slightly more degradative than sequential condition (T→R) but the difference was not significant [72]. The more pronounced degradation in the simultaneous condition was attributed to higher radical yield upon radiation at temperatures above 120°C [72].

Simultaneous aging has not always been observed to be more degradative than sequential or reversed aging (radiation than heat). In a study of EPR materials aged at 155°C and 1 kGy/h, the EAB performance was found to decrease most rapidly under the reversed (R→T) condition and the least rapidly under the sequential condition (T→R), while the reduction in EAB under the simultaneous condition (R&T) depended on the type of antioxidant in the material system [73].

In another study, the relative severity of the simultaneous, sequential, and reversed conditions was found to be dependent on the material properties tested. Fifield et al. reported the EAB results of an EPDM insulation aged at 300 Gy/h and 150°C in which the samples degraded fastest under the reversed order (R→T) and the slowest under the sequential condition (T→R) [74]. The same trend was observed for the indenter modulus behavior of the EPDM [74]. In contrast, the carbonyl index and density data for the same material showed that degradation after simultaneous (R&T) and reversed (R→T) aging conditions were identical and were significantly faster than the sequential (T→R) condition [74], which was consistent with the trend indicated in examples presented in the EMDA. Bortoletto et al. studied the degradation of a cable sheath “made of a halogen-free flame-retardant compound” irradiated at 100°C and under two dose rates, 0.87-1.31 kGy/h and 4.7-5.8 kGy/h [75]. The reduction in EAB after the sequential (T→R) and combined (R&T) aging conditions were of the same level and were much more severe than under the reversed condition (R→T) [75]. But the OIT of the same cable sheath reduced faster at the sequential (T→R) and reversed (R→T) conditions than the concurrent (R&T) aging condition.

One study of XLPE aged at 150°C and 300 Gy/h showed that the sequential (T→R) condition was the most degradative, based on the EAB results, perhaps because inverse temperature effects (ITE) (see Chapter 2.2.6 below) were present in the second radiation step [74]. EAB reduced the least in the reversed (R→T) condition [74]. The carbonyl index of XLPE showed a different trend wherein the simultaneous aging (R&T) degraded faster than the other two aging conditions.

2.2.5.3 Impact of Order of Aging and Synergistic Effects on Qualified Life

For materials exhibiting synergistic effects, meaning degradation induced by heat and radiation was not simply additive, the estimated qualified life would be inaccurate because the time to endpoint estimation assumes that thermal and radiation aging effects are independent. From reported data, the answer of which scenario among the three (R&T, T→R, R→T) is the most severe depends on the polymer type and formulation. The aging procedure in IEEE Std 383-1974 was T→R, which is the most conservative when the material exhibits inverse temperature effects (ITE) but not necessarily the most conservative for all polymers. In a later version, IEEE Std 383-2003, endorsed by NRC in RG 1.211, removed proscription of the order of aging by specifying “age conditioning pertains to temperature and radiation, applied either simultaneously or sequentially, in an accelerated manner." Revised language in the 2003 edition is quoted below.

> "Where substantial service-related synergistic… 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. … 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." [76]

2.2.6 Inverse Temperature Effects

2.2.6.1 Understanding of Inverse Temperature Effects in Cable Materials at the Time of the Expanded Materials Degradation Assessment

Inverse temperature effects (ITE) are mentioned in EMDA Chapter 5.5.1, as a subsection of the "sequential vs concurrent aging" topic. ITE have been observed in the combined thermal and radiation scenario, where the degradation rate was counterintuitively observed to be faster at lower temperatures (50°C to 60°C) than at elevated aging temperatures with common concurrent radiation dose rate. ITE had been observed for many, but not all, insulation materials including XLPE, XLPO, EPR, and EPDM. The accelerated aging conditions of the qualification process inherently utilize higher temperatures than those experienced by cables in long-term service. The concern associated with ITE is that the predicted time to endpoint for materials that exhibit ITE, using existing aging models, might overestimate the actual time to endpoint at the service conditions. That is, if degradation from gamma exposure proceeds more rapidly at the lower temperatures associated with service conditions, then prediction of cable longevity from results of gamma exposure under accelerated, higher temperature conditions will overestimate cable long-term performance. The ITE phenomenon has been explained to result from the localized chain scission of tie molecules in the amorphous region in semi-crystalline polymers, which is less severe at higher temperatures when the chain mobility and oxygen diffusion rate in the crystalline region are higher. In Chapter 5.9.3 of the EMDA, it was suggested that cable materials susceptible to ITE should be identified and suitable accelerated aging should be developed for them.

2.2.6.2 Research on ITE Reported Since the Expanded Materials Degradation Assessment was Published

Similar ITE mechanisms to those discussed in the EMDA Chapter 5.5.1 have been reported in multiple publications [54], [61], [77]. Emphasis has been placed on the observation of ITE below 60°C (the onset of melting of ethylene crystals), detected by EAB, and accompanied by chain scission as evidenced by a decrease in gel content and an increase in density. Two published reviews point out the correlation between chain scission in the amorphous region and lowered EAB based on the re-crystallization of the broken chain ends that causes embrittlement [22], [55]. How the re-crystallization might affect dielectric properties is not clear. The proposed re-crystallization mechanism is consistent with the observation in the same study that ITE was found in mechanical data but not in other material properties. For example, Liu et al. observed ITE of EPDM below 50 °C from EAB and tensile strength data, but not from gas yield or solvent swelling data [78]. Similarly, Fifield et al. reported ITE for an XLPE material below 50 °C as evidenced by EAB but not by yellowing or FTIR carbonyl index [79]. On the contrary, Verardi reported ITE of an ethylene vinyl acetate (EVA) material (a semicrystalline polymer consisting of ethylene segments) detected by OITp, dielectric permittivity, and gel fraction, although their EAB data did not show ITE [80, p. 201], [81].

With experimental confirmation of ITE reported by many research groups, screening of ITE-susceptible materials was suggested to be performed before accelerated aging [60], [82]. Specifically, for the ethylene-based semi-crystalline insulation materials of interest, it was suggested to perform irradiation at room temperature to check if ITE exists, granted that the timeframe to reach an EAB endpoint would be attainable due to ITE. If radiation aging during the qualification process is conducted at ambient temperature, screening of ITE-susceptible materials might be implemented following radiation aging at ambient temperature.

2.2.6.3 Impact of ITE on Qualified Life

The non-conservative case is that the material showing ITE was qualified for 40 years based on the high-temperature test data, but it embrittled shortly after exposure to radiation at mild temperature. This situation may have been mitigated in IEEE Std 383-2003 by involving both aged and unaged samples in radiation exposure during DBE, if the radiation exposure during DBE was sufficient to distinguish the ITE-susceptible material. Otherwise, documenting the “threshold dose” for ITE-susceptible material might be needed to know the dose limit when using the material. The threshold dose could be obtained by exposing the sample to radiation-only aging at mild temperature and no subsequent thermal aging until the EAB reached the endpoint. For cables already installed, the following checklist (Figure 7) can be used to check if there is an ITE-related concern.

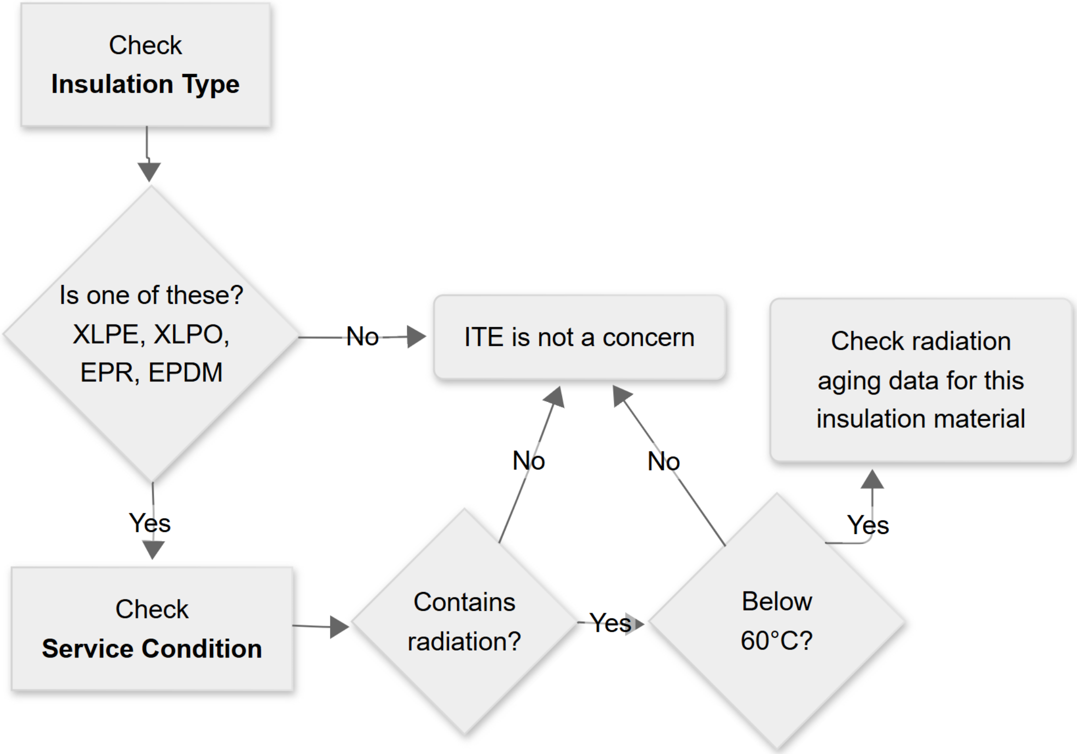


Figure 7. Steps for determining if inverse temperature effects (ITE) are of concern.

2.2.7 Pre-Aging of Semi-Crystalline Materials

2.2.7.1 Description in Expanded Materials Degradation Assessment

Chapter 5.6 of EMDA specifically discussed semi-crystalline cable insulation polymers, especially XLPE, because their melting temperatures lie between their accelerated aging temperatures and their service temperatures. Associated concerns include the change in E_a, the susceptibility to ITE, and the presence of DLO, which have been discussed in Sections 2.2.2, 2.2.6, and 2.2.3 respectively. The EMDA discussion of pre-aging attempted to use a power law dependence between the dose to equivalent damage (DED) and the dose rate (D), $DED \propto D^n$, for time to endpoint estimation for materials subjected to ITE from DED obtained at high dose rates. However, the power law approach may underestimate the time to endpoint of an XLPE insulation at 20°C without radiation aging, since the transitional dose rate below which thermal aging became dominant was not known.

2.2.8 Impact of the Knowledge Gaps on Operation Status

As discussed, the identified knowledge gaps listed in Section 2.2 are situations where the model assumptions for lifetime estimation do not hold. Their local effects on the estimated “qualified life” at the service condition depend on how much the model assumptions deviate from the actual conditions, as discussed in Sections 2.2.2.3, 2.2.3.3, 2.2.4.3, 2.2.5.3, 2.2.6.3 for each corresponding knowledge gaps. The global impact of the knowledge gaps is illustrated in Figure 8, where there might still be enough conservativeness beyond the qualified life and the built-in safety margin until reaching cable operational capacity (e.g., failing LOCA). The margin and the extra conservatism (as illustrated by the blue shaded segment in Figure 8) can mitigate uncertainty in the service condition qualified life associated with identified knowledge gaps.

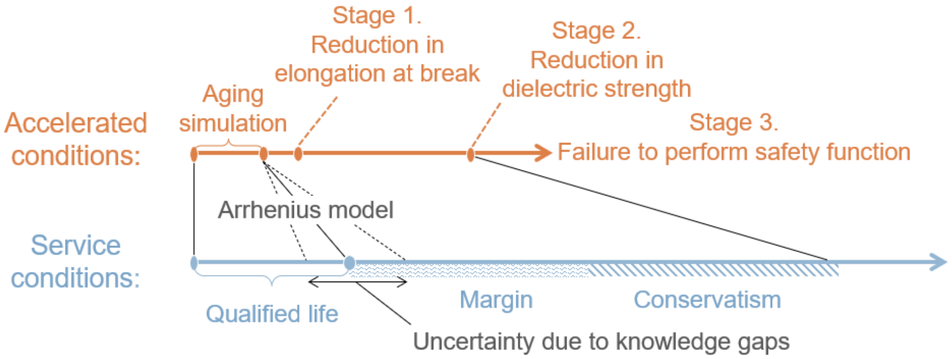


Figure 8. Cable degradation indicators progress toward functional failure. The length of the line segments between different stages of degradation is for illustration and is not to scale. Margin and conservatism mitigate significant uncertainty of the service conditions and the effects of accelerated aging.

A method to estimate additional conservatism is to consider the times required to reach earlier stages of degradation than loss of cable qualified condition. For example, in Figure 8, reduction in tensile EAB and dielectric strength are set as ‘Stage 1’ and ‘Stage 2’ and occur before functional failure of the cable. The sequence of the two stages considers the case where embrittlement of the insulation leads to cracking and subsequent conductor contact or moisture intrusion resulting in electrical shorting. The time to reach the first stage, significant EAB reduction, may be measurable at the accelerated condition. However, a low EAB does not directly indicate functional failure since many cables with a low EAB still pass LOCA testing [83],

[84]. Therefore, additional conservatism may still exist beyond the 'Stage 1' in Figure 8. Dielectric properties are more directly related to the functional performance of cable insulation and its safety function, but the time to reach a 'Stage 2' of severely degraded dielectric strength would likely take a long time even at the accelerated aging condition, potentially making it a lagging indicator that passes a threshold of concern at much longer aging times than EAB [85], [86], [87]. Data has been reported in which both EAB and dielectric performance were measured for the same materials aged at the same conditions. As plotted in Figure 9, the measured dielectric performance (IR, capacitance) did not change during the considered aging period for the two EPR-type insulation materials subjected to combined thermal and radiation condition at 81°C, 0% RH and 69 Gy/h [25]. For both materials, EAB results showed a monotonically decreasing trend, while IR and capacitance (C) fluctuated with aging time [25]. Data for EPDM and XLPE materials are plotted in Figure 10, where the IR did not change except for the EPMD cable aged at 142°C which showed a decreasing trend [88]. To be able to see orders-of-magnitude decrease in IR, the samples would typically be subjected to LOCA testing especially heat and steam exposure [84]. It was also possible that the IR did not decrease after LOCA, or even recovered, as shown in Figure 11.

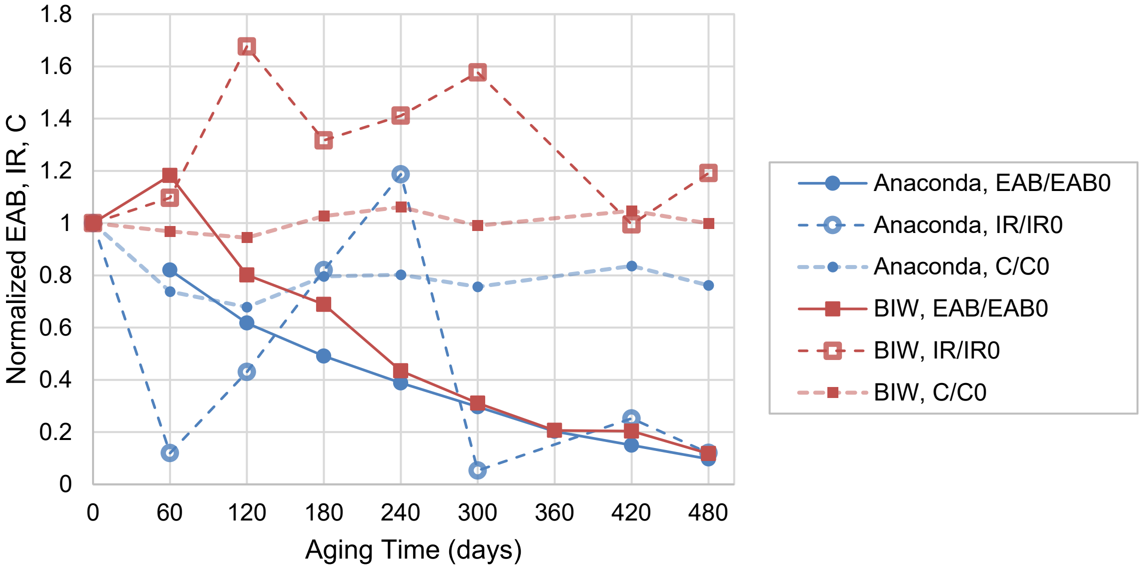


Figure 9. Normalized elongation at break (EAB), insulation resistance (IR) and capacitance (C) with respect to the baseline values (unaged samples) of Anaconda and BIW insulations subjected to 81°C, 0% RH and 69 Gy/h aging up to 480 days. The data were taken from tables in Appendix A of Watson, et al. [25].

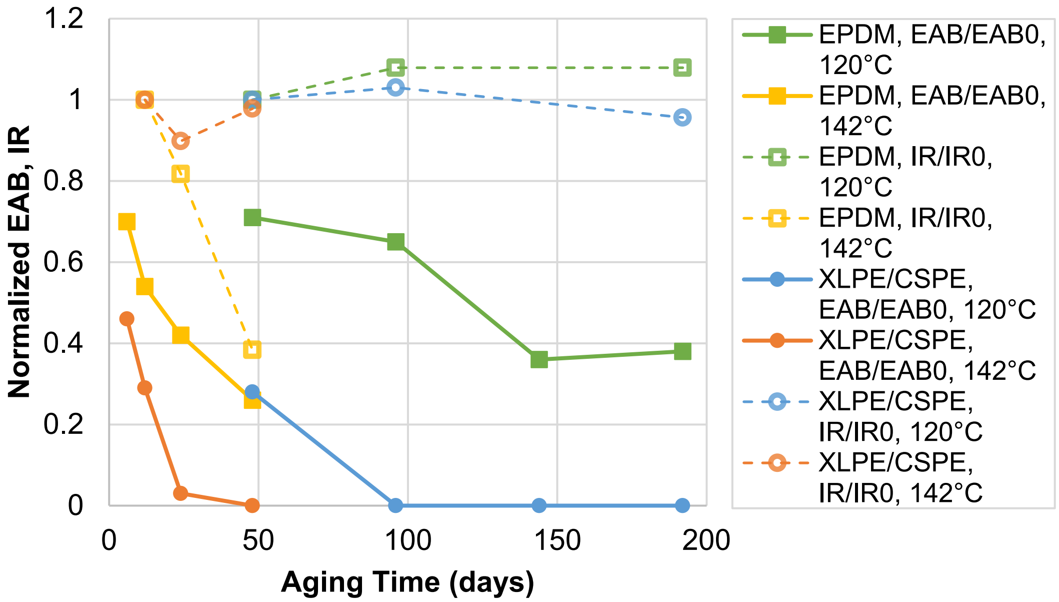


Figure 10. Normalized elongation at break (EAB) and insulation resistance (IR) of an EPDM insulation/EPDM jacket cable and an XLPE insulation/CSPE jacket cable, subjected to 120°C and 142°C aging. The data were taken from tables in Spaang et al. [88].

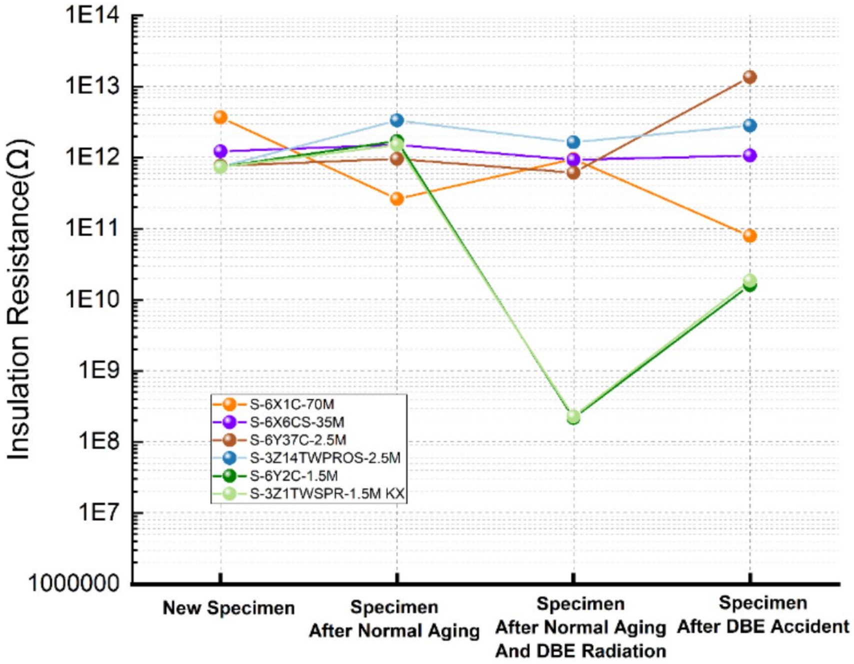


Figure 11. Insulation resistance (IR) of XLPO-type cables before and after design basis event (DBE; e.g., LOCA) simulation. The plot was taken from reference [83].

Difficulty in estimating the time to reach ‘Stage 2’ in Figure 8 leads to uncertainty in the operation status of the cable beyond the qualified life (e.g., whether the cable is still within the ‘additional conservatism’ region). Efforts have been made to improve the accuracy of time-based qualified life calculation, for example, by measuring the E_a at low temperatures from oxygen consumption experiments. Even in an ideal case where the time to endpoint can be estimated with total accuracy, entering the period of unknown status is inevitable when the time of operation exceeds the target endpoint. To understand the operational status evolution of a cable over its entire degradation curve, the cable needs to be aged and tested periodically until it fails a LOCA simulation. Since LOCA failures typically initiate from localized defects and can differ from one cable to another subjected to the same aging condition [89], the full-lifecycle test would require many replicates to establish statistical reliability, which could be an expensive enterprise. Alternatively, a more cost-effective approach may be to correlate the unknown status (the ability of passing LOCA) to a measurable material property (i.e., a “condition indicator” or “condition monitor” in EMDA Vol. 5) and monitor that material property during operation to determine whether the status corresponds to that of a cable able to pass. This approach may still require full testing (including the condition indicator and LOCA with replicates) to establish correlation information.

2.3 Moisture Effects Related Knowledge Gap

2.3.1 Understanding of Moisture Effects at the Time of the Expanded Materials Degradation Assessment

As relayed in Chapter 7 of the EMDA, industry responses to generic letter (GL) summary report, “Generic Letter 2007-01: Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients,” [90] indicated that water intrusion and/or water treeing in the presence of electrical stress is the most significant failure mechanism in the medium-voltage (MV) cable category (rated ≥ 5,000 V) [90] [1]. The GL responses revealed that for low-voltage cables (rated < 2,000 V), general or age-related degradation is the most significant failure mechanism followed by physical/mechanical damage and water/moisture intrusion [1]. It was noted in the GL that, overall, the presence of water or moisture appears to be the predominant factor contributing to MV cable failures.

Chapter 8 of the EMDA mentions that wet or submerged conditions are an aging concern for energized medium voltage cables, especially for early cable designs. Operating experience had shown that certain XLPE-type insulation materials from the early 1970s were more prone to developing water trees and degradation from flaws or inclusions in the material. Water treeing may lead to partial discharge or reduced dielectric strength and potential dielectric breakdown at operating voltages. This behavior was observed after decades of aging but was not uniform and many older cables continued to perform successfully. XLPE quality has improved and tree-retardant XLPE has been developed, but pink EPR has generally been employed as a replacement for moisture-susceptible XLPE cable [91].

In 2008, participants in an NRC - DOE Workshop on Nuclear Power Plant Life Extension Research and Development [92] recommended that future research be considered to investigate 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 [93], as a follow-up to IN 2002-12, Submerged Safety-Related Electrical Cables [94], to inform licensees of updated operating experience on submerged cables. IN 2010-26 stated that the NRC expects licensees to identify conditions which could potentially affect the quality of cables exposed to long-term submergence in water. Upon discovery of a submerged condition, the licensee should take prompt corrective actions to restore the local cable environmental conditions to those within the cable 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. Measures such as design changes to manholes and periodic inspection ensure that cables are not subjected to wetting or submergence.

The effects of long-term wetting of low-voltage cables were not well understood at the time of the EMDA. Results were 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 was available for MV EPR cables used in NPPs. EPRI performed failure mechanism research on EPR cables removed from NPPs after failure or recognition of aging through testing. EPRI technical documents 1015070 [95], 1018777 [96], 1021069 [97], 1022965 [98], 1024894 [99], 3002000554 [100], 3002002993 [101], 3003005323 [102], and 3003007991 [103] describe those results.

2.3.2 Research on Moisture Effects Reported Since the Expanded Materials Degradation Assessment

While thermal and radiation aging mainly affect mechanical properties, moisture is more relevant to dielectric function, which is a concern for the higher electrical stress of MV, especially underground and/or submerged cable [22]. Loss of dielectric function is often initiated by charge generation near impurities, such as particulate inclusions in the formulation, degradation products, voids, defects, and moisture. Moisture degradation is of particular concern for submerged and/or underground MV cables. Charge accumulation can be identified by changes in dielectric properties, such as an increase in dissipation factor (tan δ) or decrease in insulation resistance. The tan δ measurement is particularly sensitive to early-stage moisture-related aging. Unlike thermal and radiation aging that follows a free radical degradation mechanism and can be approximately described by phenomenological models, the effect of moisture has not been captured by a widely accepted model with sufficient predictive power. In SAND-2015-1794 [91], a thorough literature review was performed on the mechanisms of moisture-related aging of MV cables and on relevant condition monitoring techniques. The review concluded that “there is no uniformly accepted methodology, mechanistic model, or empirical model that can predict lifetimes or performance changes as a function of time [for submerged cable degradation]” and that “there is no simple path forward to obtain a more comprehensive model due to the complexity [of a variety of environmental stressors involving] water, ions, voltage, temperature and other factors” [91].

A Nuclear Energy University Program project led by University of Minnesota Duluth focused on a “mechanistic, predictive understanding of aqueous impact on ageing” of MV and LV cables [104]. Several topics related to a mechanistic understanding were separately studied with the following conclusions:

- The water vapor permeability of polyethylene (PE) films increased with oxidation.
- PE films doped with gold nanoparticles were synthesized with the assumption that the nanoparticles would occupy voids during dielectric breakdown and help visualize pore structures.
- Polypropylene and PE samples aged at dry, submerged, and cyclic dry-rewetting conditions in water and ionic salt solutions, all at 90°C, showed no significant differences in terms of carbonyl index, elastic modulus, or yield strength.
- Capacitance increased with water tree length gradually, while resistance decreased rapidly as the water tree tip approached the conductor.

- No increase in partial discharge was detected during the two-year aging of harvested MV power cables at 60 Hertz (Hz), 90°C, and elevated voltages (30 kilovolt [kV] for XLPE and 12 kV for EPR cables).

Research conducted by EPRI concluded that water trees are one of the leading degradation mechanisms that contribute to the loss of dielectric insulation strength in MV cable materials in wet or submerged environments. The electrochemical reactions are caused by the combined effect of the presence of water and high electrical stress. The relative importance of these causal stressors can vary among cable installations and are not specifically measured in most cases. Records of cable failures provided by nuclear plant operators confirm the reliability concern for MV cables in wet or submerged environments and serve as a basis for developing the EPRI test program. Practical management of this kind of damage is based on performance tests. EPRI dissipation factor or Tan Delta (tan δ) testing guidelines and acceptance criteria have been adopted by most NPP operators as the primary tool for evaluation of MV cables. EPRI collected member data from 2009 to 2012 to analyze and validate the EPRI-developed acceptance criteria guidelines [105], [106], [107], [108] and to support forensic research on causes of insulation degradation and failure. The guidelines advise tan δ testing every six years if test result values are in the “good” or green range and every two years if test result values fall into the “further study” or yellow range. Guideline values are insulation material specific and may not be available for all cable insulation materials. Pacific Northwest National Laboratory (PNNL) performed a statistical review of the EPRI reports and the associated data with specific plant information redacted. The PNNL analysis found the EPRI guideline thresholds appropriate, as documented in the PNNL-28542-1 report [109]. The NRC review of this data agreed with the conclusions but did not endorse the shortened test interval “due to the limited data/test results for some categories of cable types and material, as well as reported cases of multiple test results for the same cables. These data do not support consistent and reliable interpretation of trend results” [110]. Available test data from which to make confident conclusions regarding the appropriateness of the EPRI criteria were particularly lacking for XLPE and for brown EPR cable types.

There is no single or simple test to accurately predict remaining useful cable life following submergence or water exposure for nuclear cables. Support for detailed studies of moisture damage is waning in favor of simply adopting a testing-based reliability program that involves periodic or even online testing. EPRI has established tan δ test criteria that are used to manage cable reliability and to guide decisions such increasing test frequency when cable test data indicates degradation and repair, mitigation, or replacement when test data indicates ‘action required’ according to the EPRI acceptance criteria [107]. As part of license renewal, utilities agree to establish a cable aging management program that includes regular testing of some or all safety critical cables [111]. Cable testing intervals are typically six to ten years for undamaged insulation, and as low as two years for cables that are degraded. Ongoing testing is performed to ensure continued acceptability and to establish trending data of degradation progression.

3.0 Updates on Cable Qualification Standards and Regulatory Guides

NPP electrical cables are commonly qualified following procedures in IEEE Std 383 [3], [76], [112]. Type testing, demonstrating that representative samples of cables can meet performance requirements under service conditions including normal and DBE environments [2], has been the preferred method for qualification. The IEEE Std 383 supplements IEEE Std 323, which describes general guidelines and basic requirements for environmental qualification. Nuclear plants have been operating for more than 55 years in the United States with no systematic problems. Initial qualifications of cables may be been done prior to aging being required, but this was quickly corrected, and IEEE standards have been updated periodically. IEEE 383 was initially issued in 1974 [3] and reaffirmed in 1992, and then updated in 2003 [76], 2015 [112], and 2023 [119]. Versions of the applicable standards are shown below in Table 2, where the four-digit number after dash "-" represents the release year. Selected versions of IEEE Std 323 and IEEE Std 383 have been endorsed by NRC in regulatory guides (RG), including:

- RG 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants" [5], [10], [113].
- RG 1.131, "Qualification Tests of Electric Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants (for Comment)" (withdrawn) [114].
- RG 1.211, "Qualification of Safety-Related Cables and Field Splices for Nuclear Power Plants" [4].

Table 2. IEEE Std 323 and IEEE Std 383 releases and endorsements by the NRC.

Standards	Endorsement
IEEE 323-1971, trial-use [115]	Applies to NPPs with construction permit prior to July 1, 1974, per NUREG-0588
IEEE 323-1974 [2]	Endorsed in RG 1.89, Rev. 0, November 1974, and in RG 1.89, Rev. 1, June 1984
IEEE 323-1983 [116]	Endorsed in RG 1.209 for mild environment qualification of computer-based instrumentation
IEEE 323-2003 [117]	Not endorsed
IEEE / International Electrotechnical Commission (IEC) 60780-323-2016 [118]	Endorsed in RG 1.89, Rev. 2, April 2023
IEEE 383-1974 [3]	Endorsed in RG 1.131, Rev. 0, August 1977, for comment (RG 1.131 is withdrawn in April 2009)
IEEE 383-2003 [76]	Endorsed in RG 1.211, Rev. 0, April 2009
IEEE 383-2015 [112]	Not endorsed
IEEE 383-2023 [119]	Not endorsed

Considering the construction permit issue year for NPPs currently in need of SLR, the IEEE standards relevant to the historical qualification of those NPPs are listed below:

- IEEE Std 323-1971, "IEEE Trial-Use Standard: General Guide for Qualifying Class 1 Electric Equipment for Nuclear Power Generating Stations" [115]. Note that aging was not listed as a part of type test procedure.
- IEEE Std 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations" [2]. Section 6.3.2 in the standard lists aging as a step in the type test procedure to simulate the expected end-of-qualified-life condition. Appendix A2 suggested the

following aging sequence: (i) aging, including but not limited to accelerated thermal aging, (ii) radiation, and (iii) vibration. Aged equipment should be operated while exposed to DBE and safety functions monitored.

- IEEE Std 383-1974, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations" [3]. The standard was more specific to type testing of cables. Aging was involved in two examples of type tests: (i) testing to qualify for normal operation and (ii) testing for operation during DBE. Procedures of these two examples are depicted in Figure 12 and Figure 13, respectively.

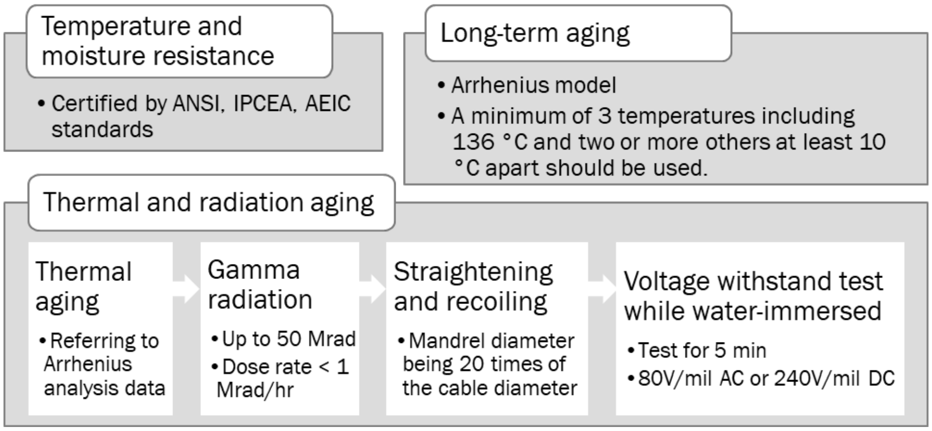


Figure 12. Type testing to qualify for normal operation described in IEEE Std 383-1974. AC = alternating current, AEIC = Association of Edison Illuminating Companies, ANSI = American National Standards Institute, DC = direct current, IPCEA = Insulated Power Cable Engineers Association (now ICEA), mil = 0.001 inch,

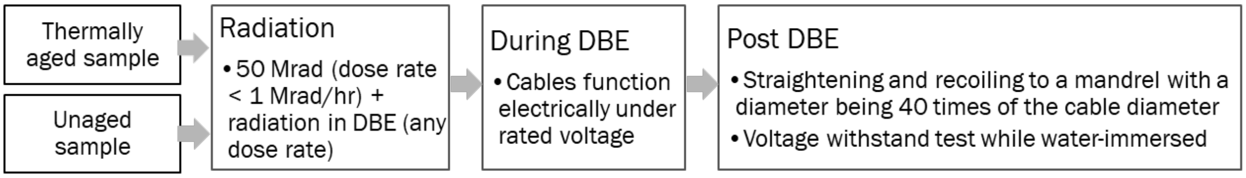


Figure 13. Type testing for operation during DBE described in IEEE Std 383-1974.

3.1 Knowledge Gaps Addressed in IEEE Standards and NRC Publications

Later versions of the qualification standards released in the early 1970s mentioned the knowledge gaps discussed in EMDA Vol. 5, including but not limited to the following statements.

- IEEE Std 383-2003, section 6.3:

> "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 and 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." (emphasis added)

As Chapter 4.4 of the EMDA mentions, the 2003 release of the IEEE 383 standard addresses many of the shortcomings of the 1974 version that form the basis of the EMDA Knowledge Gaps as quoted in the preceding and following paragraphs.

> "Reference [in the updated version] is made to IEEE standards on Arrhenius behavior that have also been updated over the years [[76], [120], [121], [122]]. 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."

- IEEE/IEC 60780-323-2016, section 7.4.1.9.3: "This process involves applying simulated in-service stresses, typically thermal, moisture, radiation, wear and vibration at magnitudes or rates that are more severe than expected in-service levels, **but less severe than levels that cause ageing mechanisms not present in normal service**… The sequence of age conditioning should consider **sequential, simultaneous, and synergistic effects** in order to achieve the worst state of degradation expected… The risk of overestimation of qualified life or qualified condition due to **diffusion limited oxidation effects** of application of excessive temperatures or dose rates depends on the materials involved." (emphasis added)

Therefore, the uncertainties in qualified life or status due to the knowledge gaps might be considered less of a concern for NPPs which followed IEEE Std 383-2003 or later versions for the initial cable qualifications.

In addition to the IEEE standards, the following documents published by NRC have also recognized concerns highlighted in the EMDA, including synergistic and dose rate effects.

- NUREG-0588, Rev. 1 (July 1981), Interim Staff Position on Environmental Qualification of Safety-Related Electrical Equipment, Including Staff Responses to Public Comments: "The staff is aware that some equipment important to safety may contain materials whose aging effects from combined environments (applied either concurrently or sequentially) are more severe than the sum of the effects of each environmental parameter applied separately. Identifying the most limiting combination of environmental parameters in order to establish a qualified life through research programs, however, may be a long-term, on-going process. Therefore, in lieu of research programs, the qualification program should: (1) Identify potentially significant **synergistic effects** through a literature search and account for those effects through testing or analysis when establishing a qualified life, or (2) Establish through a literature search or operating experience the basis for omitting synergistic considerations. For equipment where, for example, significant radiation and temperature environments may be present (and in lieu of contrary information determined through items 1 or 2), **the synergistic effects** to these parameters should **be considered during the simulated aging portion** of the overall test sequence. The testing sequence used to age the equipment (or material) should be justified and the basis documented in the qualification report. For equipment where thermal aging evaluation has been conducted prior to issuance of this document on non-irradiated equipment or materials, the adequacy of the assumptions made and the conclusions reached will be evaluated on a case-by-case basis. Other methods designed to address synergisms (such as ongoing surveillance with additional qualification testing) may also be found acceptable and will be evaluated on a case-by-case basis." (emphasis added)

- RG 1.89, Rev. 1 (June 1984): “5. Section 6.3.3, "Aging," of IEEE Std 323-1974 and paragraph 50.49(e)(5) should be supplemented with the following: a. If synergistic effects have been identified prior to the initiation of qualification, they should be accounted for in the qualification program. Synergistic effects known at this time are **dose rate effects** and effects resulting from the different **sequence of applying radiation and (elevated) temperature**. … Periodic surveillance and testing programs are acceptable to account for uncertainties regarding age-related degradation that could affect the functional capability of equipment. Results of such programs will be acceptable as ongoing qualification to modify designated life (or qualified life) of equipment and should be incorporated into the maintenance and refurbishment/replacement schedules.” (emphasis added)

3.2 Example Environmental Qualification Reports for Cables

To better understand whether and how the knowledge gaps were addressed in the EQ process, seven EQ documents of Class 1E cables used in NPPs were reviewed. Since the purpose of this section is not to comment on the specific EQ processes, the tradenames and manufacturers of the cables are withheld. The conclusion in this section was drawn from only seven reports and should not be generalized to all EQ efforts.

3.2.1 Recognition of Synergistic Effects and Dose Rate Effects

Among the seven available documents, one was dated in 1986, four in 1991, one in 2005 and one was undated. Three document packages dated in 1991 included a comprehensive questionnaire and a list of documents including the original EQ reports dated in 1976, 1981 and 1984. The questionnaire seems to have been added when the document package was collected and bound together in 1991. One section of the questionnaire asked if there were any known synergistic effects that could affect the equipment performance and if the report had addressed the synergistic effects, and the answers to these questions were ‘no’. A paragraph was included to further discuss both dose rate effects and sequential vs. concurrent aging effects since both were considered as synergistic effects in RG 1.89 Rev. 1. Similarly, in the fourth document dated in 1991, a section titled “known synergistic effects” also discussed these two knowledge gaps and concluded no need to address them during EQ.

The document dated in 2005 selected the most degradative sequence to be 50 Mrad radiation → thermal → 150 Mrad radiation aging (DBE dose), by comparing the retention in mechanical properties after thermal and radiation aging in different orders.

The document dated in 1986 did not directly discuss the need of addressing the two knowledge gaps but mentioned “the most severe postulated conditions being constructional extreme” for “possible synergistic effects upon the electrical, chemical and mechanical performance”. Their EQ process (Figure 14) involved IR measurement for unaged samples, for samples after 150°C followed by 200 Mrad aging (DBE dose), and before and after LOCA, which could be compared to additional IR data obtained from a separate research program on synergistic effects and dose rate effects.

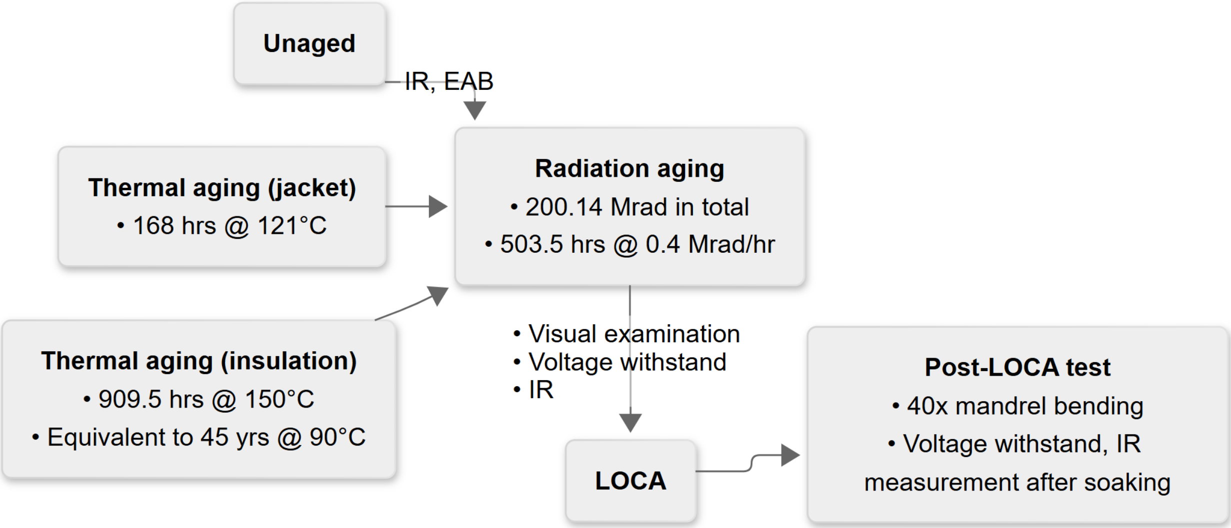


Figure 14. EQ process of crosslinked polyethylene (XLPE) insulation in a report from 1986.

3.2.2 Recognition of Non-Constant E_a

Although the non-Arrhenius behavior and non-constant E_a had not been raised as a concern in the reviewed reports, the phenomenon was recognized, as shown in Figure 15, where the slope changed at 121°C and 150°C. In the EQ report dated in 1991, the slope change was correctly attributed to “two different rate controlling mechanisms.” The other EQ report also correctly pointed out that “the Arrhenius technique is valid if only one chemical reaction is controlling the insulation aging process.” In both EQ reports, the slope obtained from the two lowest temperatures (i.e., 113°C and 121°C in Figure 15(a), 127°C and 150°C in Figure 15(b)), was used for E_a calculation.

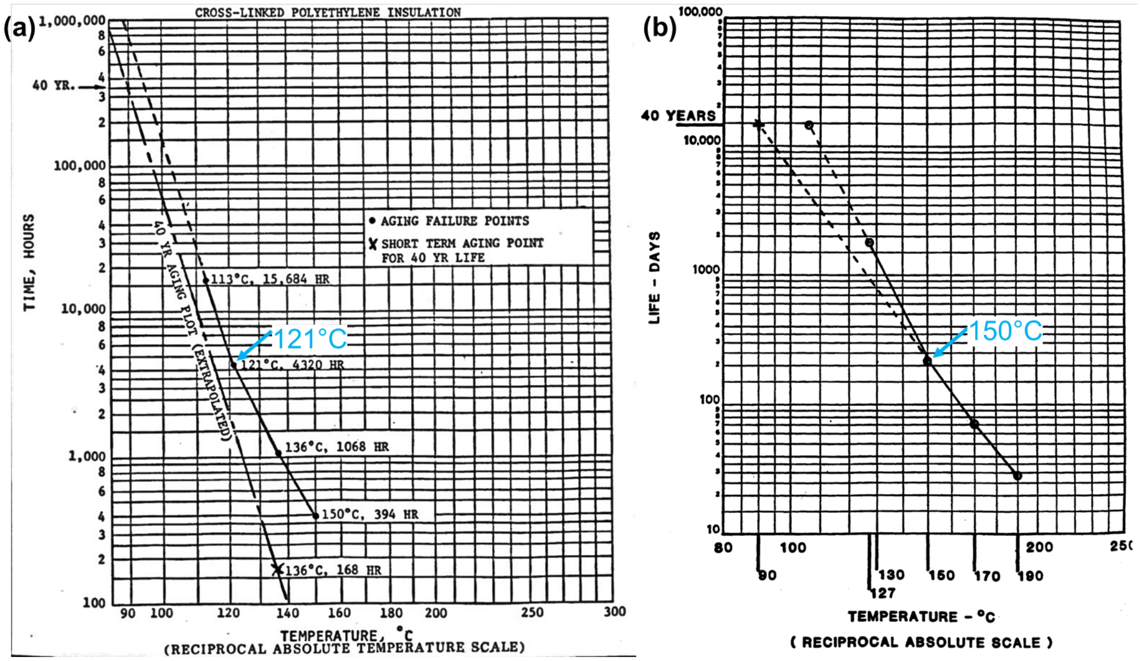


Figure 15. A change in slope on the Arrhenius plot recognized in two EQ reports, one with no date (a), and one dated in 1991 (b).

As shown in Table 3, all seven representative EQ reports have been checked for the E_a values obtained, the criteria to pick the endpoint and the temperatures for E_a determination. One report showed different E_a values for three formulations, and therefore a total of nine E_a values are listed in Table 3. In addition to the commonly recognized EAB, the voltage withstand capability was also used as a failure criterion for two XLPE cables. The service temperature was 90°C in some reports and 49°C in others. The difference in the assumed service temperature and E_a values led to the large variation in pre-aging time and temperature conditions.

Table 3. Activation energy (E_a), pre-aging time and temperature and the corresponding time to endpoint at the service condition from seven EQ documents.

Polymer	**E_a (eV)**	**E_a endpoint**	**Temperature for E_a determination (°C)**	**Pre-aging time and temperature**
XLPE	1.35	60% retention of elongation	121, 136, 150	909.5 h @ 150°C
XLPE	2.11*	crack after 8x mandrel bend, or fail within 5 min to withstand 4 kV-AC immersed in 1% NaCl (aq.) solution	113, 121	168 h @ 136°C
EPR	1.14	50% retention of elongation	121, 150	1440 h @ 155°C
EPR	1.15	40% retention of elongation	121, 136, 150, 165, 180	504 h @ 150°C; 336 h @ 165°C
EPR	1.13	50% retention of elongation	136, 150, 165, 175	
EPR	1.32†	50% retention of elongation	136, 150, 165, 175	
EPDM	1.31	N/A	N/A	168 h @ 121°C
EPR	1.69‡	50% retention of elongation	121, 135, 150‡	168 h @ 150°C
XLPE	1.36	voltage withstand test at 3.0 kV for 1 min	127, 150	168 h @ 150°C

* The E_a value was not listed in the original EQ report but calculated using the data provided in the EQ report.

† The E_a value listed in the original EQ report was 1.32 eV, but it was found to be 1.23 eV when re-calculated using the data provided in the EQ report.

‡ Using the data provided in the EQ report, the E_a was re-calculated to be 1.51 eV from three temperatures or 1.84 eV from the two lowest temperatures.

4.0 Discussion of Status and Potential Paths Forward

4.1 What has Changed Since the Expanded Materials Degradation Assessment was Published?

The EMDA highlighted several points of uncertainty and potential concern regarding continued use of qualified cables in long-term operation, beyond their original 40-year qualified life. Several of these points relate to assumptions that were made in the methodology of the original time-based qualification process and its accuracy in predicting cable performance over many decades of service. Accelerated aging of a representative cable under elevated conditions was used in qualification to represent the aging expected to occur on similar cables installed in an operating plant over the 40-year operating license period. The equivalency of short term accelerated aging effects and long-term service aging effects in the aged cable was noted in the EMDA to be challenged by several aspects of the accelerated aging process. The uncertainty of actual plant conditions was also identified in the EMDA. Finally, concerns regarding performance of cables not originally qualified for wet service, but located in a long-term wetted NPP environment, were also raised. These EMDA gaps surround the question of whether the controls and administrative limitations for use of cables important to safety in long-term operation are sufficiently conservative to provide reasonable assurance of reliable performance.

Prior to publication of the EMDA and the communication of the concerns raised therein, the nuclear cable community has taken action to address the EMDA-identified issues in revisions of the IEEE 323-1974 [2] and 383-1974 [3], notably in the 2003 revisions [76], [117] and the 2015 / 2016 revisions [112], [118]. As discussed in Section 2.0 of this report, the NRC, EPRI, and DOE researchers, as well as industry and academic entities, have performed further aging and testing research on cable materials to investigate issues such as calculation of E_a, diffusion limited oxidation, synergistic effects of combined thermal and radiation aging, inverse temperature effects, and aging due to moisture. These entities have also developed new technologies and methods for condition monitoring of aging cables and further determined correlations between test results and cable status. EPRI has worked with its members to demonstrate testing options in operating NPPs and to obtain measured in-plant conditions for cable locations in PWRs and BWRs.

International consensus-based standards organizations that develop cable qualification guidance have updated standards to include improved guidance regarding the limitations of accelerated aging (i.e., time period extrapolation, synergy between effects of temperature and radiation, dose rate effects, etc.) [118]. EPRI continues to update its cable aging management guidance based on new research results and operating experience (OE) [123]. The NRC has acknowledged and endorsed updated qualification standards [5]. The potential for moisture damage to cables has also been acknowledged [6], [7] and methods to verify cable integrity have been or are being established [110].

Updated NRC guidance in RG 1.89 [5] endorses the international standard IEC/IEEE 60780-323-2016 [118] for qualification of electrical equipment important for safety in nuclear facilities. This standard is an update of earlier IEEE-323 standards and directly reflects an appreciation of the concerns raised in the EMDA.

4.2 How to Manage Cables Past their Qualified Life?

The concerns raised in the EMDA largely relate to the question of confidence for continued use of qualified cables beyond their qualified life. The updated and endorsed IEC/IEEE 60780-323-2016 document [118] directly answers this question with a section entitled “Reassessing qualified life,” which addresses achieving qualified status for cables with anticipated service life beyond their EQ-yielded qualified life. This may refer to cables beyond their original qualified life or cables for which, due to limitations of accelerated aging and material or environment knowledge (such as those raised in the EMDA), have significant uncertainty in relation to their appropriate qualified life. Options available for reassessing qualified life for cables that fit this description as delineated in the standard [118] are listed below. Qualified cable reassessment is a natural part of a cable aging management program and, following current guidance, appreciates the potential concerns raised in the EMDA.

4.2.1 Use Conservatism

The EMDA knowledge gaps represent sources of uncertainty in cable qualified life that may contribute to a reduction in the conservatism of the historic qualification process. Re-analysis of original EQ methodologies to utilize built-in conservatism and safety margin has been the primary method used by industry to extend qualified life beyond original periods. Understanding the assumptions of the original EQ methodology and limitations of the accelerated aging factors used may result in an opportunity to account for those limitations and aging artifacts to arrive, with proper verification, at aging models that can provide a sufficiently conservative qualified life.

4.2.2 Type Test on Aged Samples from the Nuclear Power Plant

Extension of the qualified life of a cable may also be achieved through removal from service of a qualified cable prior to the end of its qualified life, further aging of the sample using accelerated means, and demonstration of the ability of the cable to perform during a simulated DBE. Similar cables in identical service conditions might then be apportioned the extended qualified life, representing service life plus the added period.

4.2.3 Perform Type Testing for Longer Qualified Life

Qualified life may be extended (e.g., from 40 years) by re-qualifying an existing or new cable artificially aged to a longer period representing the desired qualified life (e.g., to 80 years) prior to demonstrating performance or the cable following a DBE simulation.

4.2.4 Replace Components

Aging components may be replaced with new components to extend the qualified life of the system if the component is accessible to replace, and if the replacement process does not adversely affect the ability of the system to perform its safety-related function.

4.2.5 Pursue Condition-based Qualification

An alternative option to the time-based approach for qualifying cables that has historically been used by the nuclear industry in the U.S., in which the desired qualification life is imparted to a material before it is demonstrated to pass a DBE simulation, is to verify through testing that the condition of the cable is consistent with a condition in which it can conservatively be expected to perform its safety-related function during a DBE [83], [124]. Condition-based qualification (CBQ) justifies continued use of a qualified cable based on test results that establish the cable condition along a degradation profile that has been matched to a qualification program, where a representative sample cable continues to perform its safety function following a DBE. The key to performing CBQ is to find a suitable condition indicator (or a group of complementary indicators) that monotonically tracks with aging and can be measured nondestructively. A list of test methods probing the chemical, thermal, mechanical, and dielectric properties of cable insulations have been surveyed for their applicability as condition monitoring techniques, where no single condition monitoring method was found to be suitable for CBQ for all cable types [25], [32], [83], [84], [125]. The well-established EAB trends with aging [25], [84], but it is a destructive method. IM and OIT have been shown to trend with certain jackets and insulation materials [25], [83], [84]. Non-destructive techniques that could potentially be used for condition monitoring include reflectometry, dielectric spectroscopy, dielectric loss (tan δ), polarization/depolarization current, monitored withstand, interdigital capacitance, or other methods that provide a value that monotonically changes as the cable insulation sample degrades in response to normal operating stresses or elevated temperature and radiation exposure for accelerated aging.

5.0 Conclusion

While re-analysis of the original 40-year cable qualification data was largely successful in supporting extension of plant operating licenses to 60 years, when it became apparent that there was a need and desire to continue to operate NPPs in the U.S. beyond their first license renewal, it was prudent to consider material aging issues that may arise during operation beyond the original 60 years and up to the 80 years of a second license renewal. The EMDA process convened nuclear cable experts to consider the state of knowledge of cable materials and aging concerns in the context of such extended operation. That effort resulted in the highlighting of several knowledge gaps and topics of potential concern related to the methodology historically used for cable qualification, the environmental conditions of cables in the service environment, and the long-term effects of moisture on cables not originally anticipated to be wetted in service. The earliest standards for cable qualification did not adequately address these concerns, and the phenomena identified contributed to uncertainty in the expected safety-related performance of qualified cables in DBE conditions, particularly as the cables continued to age past their original qualified life.

Following publication of the EMDA in 2014 [1] and communication of the EMDA topics within the nuclear cable community, much research has been done to consider and address the identified knowledge gaps. Technical standards, industry practice, and regulatory guidance have all been updated since the initial version to account for the issues summarized in the EMDA. Following these accomplishments, new cables are qualified according to a process that minimizes aging artifacts and considers the limitations of artificial aging in recreating NPP service aging. Several options have been developed to reassess the qualified life of installed cables with either anticipated service lives that will exceed their qualified life or for which uncertainty exists regarding their qualified life. These methods may be used to establish a technical basis for extending the qualified life of existing, aged cables.

Condition monitoring of cables has advanced, especially for cables in wet environments using tan δ testing. Research continues by EPRI and others to develop more advanced non-destructive testing methodologies that can be used for cables in dry environments [126]. An additional option for providing confidence in the reliability of cables that are ‘important to safety’ is CBQ. This option requires development of correlation between cable test results and the ability of a cable to perform its safety function during and after a DBE. CBQ could provide a technical and conservative basis for continued use of a cable in verifiable good condition indefinitely, while not being limited to the original qualified life or hampered by potential uncertainties and inadequate conservatism associated with a time-based qualification method.

The EMDA has served an important role in bringing cable material aging concerns relevant to long-term operations to light for the broader nuclear cable community. Since the initial days of qualification, the community has responded to concerns such as those raised in the EMDA by taking action to improve methods for developing technical bases for reliable safety-related cable use, as reflected in updated and endorsed qualification standards. Operating experience has demonstrated that service environments of most plant cables are much less severe in terms of dose rate and temperature than the conservative conditions used as boundaries in initial qualification methodologies. With advancements in understanding of the points identified in the EMDA, the industry has the tools it needs to confidently use new and existing nuclear cables in new construction and in existing reactors.

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7.0 Appendix

Table 4. Activation energy (E_a) values reported in literature.

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
96.30		43 to 110	PVC	EAB	e/e0=0.4, dose rate 0.1-100 Gy/h	[127]
87.92		70 to 140	Neoprene	EAB		[128]
121.56		115	EPR	EAB	in-plant aged	[129]
145.68		115	Silicone	EAB	in-plant aged	
128.32		132	XLPO	EAB	in-plant aged	
92.62		132	Viton	EAB	in-plant aged	
115.78		132	Viton	EAB	in-plant aged	
109.50		132	EPR	EAB	in-plant aged	
88.76		132	Nitrile	EAB	in-plant aged	
89.73		80 to 142	CSPE	Indenter		[130]
98.02		80 to 142	CSPE	EAB		
98.51		80 to 142	EPDM	Indenter		
84.52		80 to 142	EPDM	IR		
147.04		80 to 142	EPDM	DF 60 Hz		
101.11		80 to 142	EPDM	DF 1 kHz		
101.11		80 to 142	EPDM	Indenter		
96.96		80 to 142	EPDM	EAB		
137.48		80 to 142	EPDM	IR		
150.51		80 to 142	EPDM	DF 1 kHz		
105.55		80 to 142	CSPE	Indenter		
98.02		80 to 142	CSPE	EAB		
107.96		80 to 142	XLPO/XLPE	Indenter		
90.50		80 to 142	XLPO/XLPE	IR		
27.59		80 to 142	XLPO/XLPE	DF 60 Hz		
79.31		80 to 142	FPM	Indenter		
86.45		80 to 142	FPM	EAB		
111.14		80 to 142	EPDM	Indenter		
106.80		80 to 142	EPDM	EAB		
92.00		64.5 to 125	Nitrile	surface modulus		[131]
149.00		110 to 150	PP	CL induction time	CL: chemiluminescence	[132]
113.00		110 to 150	PP	CL time to maximum		
120.00		110 to 150	PP	CL oxidation time	time to max - induction time	
83.74	8.4	23 to 96	Nitrile	O2 consumption		[133]
87.92	8.4	23 to 96	Nitrile	O2 consumption		
121.42	8.4	52 to 96	Nitrile	CO2 production		
91.27	8.4	64.5 to 125	Nitrile	EAB		
92.11	8.4	64.5 to 125	Nitrile	surface modulus		
90.43	8.4	23 to 125	Neoprene	O2 consumption		
90.43	8.4	71.5 to 125	Neoprene	CO2 production		
90.02	8.4	120.6 to 149.4	Neoprene	EAB		
92.11	8.4	100.1 to 149.4	Neoprene	surface modulus		
94.20	8.4	111 to 125	Neoprene	O2 consumption induction time		
109.99		80	CSPE	EAB	e=0.5	[134]

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
130.25		91	EPDM	EAB	e/e0=0.6	[134] Cont.
115.78		135	EPR	EAB	e=0.5	
91.66		148	ETFE	EAB	e=0.5	
90.69		80	Neoprene	EAB	e=0.5	
95.52		120	PVC	electrical failure		
173.66		136	Silicone	EAB	e/e0=0.5	
112.88		200	Viton	EAB	e=0.5	
119.64		150	XLPE/XLPO	EAB	e/e0=0.6	
119.64		150	XLPE			[135]
96.48		150	Neoprene			
106.13		98	EPR			
100.34		98	CSPE			
110.95		98	EPDM			
119.64		98	CSPE			
113.85		150	EPR			
87.92		45	XLPE			[136]
87.92		45	CSPE			
104.67		45	CSPE			
100.48		45	CSPE			
87.92		45	ETFE			
96.30		45	PVC			
87.92		45	Silicone			
66.99		45	PE			
87.92		45	Neoprene			
84.00		23 to 96	Nitrile	O2 consumption		[137]
92.00		64.5 to 125	Nitrile	EAB, surface modulus		
113.00		111 to 170	EPR	EAB, surface modulus		
67.00		52 to 111	EPR	O2 consumption		
190.07		215	XLPE	OIT		[138]
181.38		215	XLPE	OIT		
199.71		215	XLPE	OIT		
157.26		225	XLPE	OIT		
157.26		225	XLPE	OIT		
161.12		225	XLPE	OIT		
101.30		200	XLPE	OIT		
138.93		200	XLPE	OIT		
166.91		200	XLPE	OIT		
176.56		210	EPR	OIT		
181.38		185	EPR	OIT		
130.25		170	EPR	OIT		
142.79		170	EPR	OIT		
140.86		170	EPR	OIT		
164.02		220	EPR	OIT		
158.23		220	EPR	OIT		
76.22		65 to 85	CSPE	microcalorimetry heat flow	unaged	[88]
101.30		65 to 85	CSPE	microcalorimetry heat flow	aged 95°C, 384 days	
91.66		65 to 85	CSPE	microcalorimetry heat flow	aged 142°C, 48 days	
84.90		65 to 85	CSPE	microcalorimetry heat flow	LOCA-aged	

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
79.11		65 to 85	EPDM	microcalorimetry heat flow	unaged	[88] Cont.
96.48		65 to 85	EPDM	microcalorimetry heat flow	aged 142°C, 48 days	
77.18		65 to 85	XLPE	microcalorimetry heat flow	unaged	
91.66		65 to 85	XLPE	microcalorimetry heat flow	aged 142°C, 48 days	
90.00		23 to 120	Nitrile	O2 consumption, EAB, surface modulus		[139]
118.00		111 to 160	EPDM	O2 consumption, EAB, surface modulus, force decay, density		
82.00		52 to 111	EPDM	O2 consumption		
118.00		111 to 160	EPDM	O2 consumption, EAB, surface modulus, force decay, density		[140]
82.00		52 to 111	EPDM	O2 consumption		
125.00		100 to 140	Nitrile	IR-carbonyl	Unfilled NBR	[141]
124.00		100 to 140	Nitrile	Edge modulus	Unfilled NBR	
134.00		100 to 140	Nitrile	O_2 consumption	Unfilled NBR	
179.00		100 to 140	Nitrile	CO_2 formation	Unfilled NBR	
158.00		100 to 140	Nitrile	CO formation	Unfilled NBR	
92.00		100 to 140	Nitrile	Elongation, Edge modulus	Carbon-black-filled NBR	
88.00		100 to 140	Nitrile	O_2 consumption	Carbon-black-filled NBR	
120.00		100 to 140	Nitrile	CO_2 formation, CO formation	Carbon-black-filled NBR	
90.00		64.5 to 125	Nitrile	EAB		[142]
118.00		111 to 160	EPDM	O2 consumption, EAB, surface modulus, force decay, density		
82.00		52 to 111	EPDM	O2 consumption		
84.00		80 to 125	Butyl	Compression stress relaxation		[143]
76.00		80 to 120	EPDM	O2 consumption, CO2 formation		[144]
58.00		35 to 140	EPR	CL intensity		
113.46			EPR/CSPE	from qualification report	AIW	[89]
113.46			EPR/CSPE	from qualification report	Anaconda	
138.95			EPR/CSPE	from qualification report	Okonite	
131.22			EPDM/CSPE	from qualification report	Samuel Moore	
128.34			XLPE/Neoprene	from qualification report	Rockbestos	
88.00		64.5 to 125	Nitrile	EAB, O2 consumption		[145]
101.50		80 to 111.5	Butyl	Force decay, O2 consumption		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
75.00		25 to 80	Butyl	O2 consumption		[145] Cont.
110.00		91 to 170	XLPO	EAB		[32]
98.00		80 to 110	Neoprene	EAB		
107.00		100 to 150	CSPE	EAB		
112.00		109 to 138	CPE	EAB		
106.00		100.9 to 170	EPR	EAB		
100.00		52 to 139	EPR	EAB within induction period, O2 consumption		
128.00		99 to 139	EPR	EAB induction time		
106.00		109 to 160	EPR	EAB		
88.00		99 to 138	EPR	EAB		
76.00		99 to 109	XLPO	EAB		
130.00		124 to 151	XLPO	EAB		
96.00		80 to 110	Neoprene	EAB, O2 consumption		
76.00		25 to 80	Neoprene	O2 consumption		
72.00		48 to 138	XLPO	EAB, O2 consumption		
119.00		80 to 120	PU	thermal degradation, from reference		[31]
65.00		20 to 50	PU	thermal degradation, from reference		
127.00		130 to 160	EPDM	from reference		
78.00		50 to 120	EPDM	from reference		
100.00		60 to 110	Butyl	from reference		
60.00		25 to 50	Butyl	from reference		
107.00		100 to 155	PP	from reference		
41.00		40 to 70	PP	from reference		
156.00		100 to 130	PP	from reference		
36.00		50 to 80	PP	from reference		
121.00		100 to 140	PP	from reference		
49.00		40 to 70	PP	from reference		
146.00		85 to 105	PP	from reference		
41.00		35 to 60	PP	from reference		
218.00		150	XLPE			
144.00		to 150	XLPE			
115.00		110	EPDM			
75.00		to 110	EPDM			
120.00		70	PU			
70.00		to 70	PU			
100.00		80	Butyl			
75.00		to 80	Butyl			
89.00		70	Neoprene			
71.00		to 70	Neoprene			
102.00		100	CSPE			
31.40		25 to 50	EPDM	O2 permeability		[146]
18.90		140 to 175	EPDM	O2 permeability		
56.20		25 to 50	Viton	O2 permeability		
17.40		175 to 220	Viton	O2 permeability		
37.80		25 to 50	Neoprene	O2 permeability		
25.60		95 to 125	Neoprene	O2 permeability		
26.90		25 to 50	PU	O2 permeability		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
13.70		85 to 115	PU	O2 permeability		[146] Cont.
54.10		25 to 40	butyl	O2 permeability		
30.30		85 to 105	butyl	O2 permeability		
42.50		25 to 50	nitrile	O2 permeability		
21.60		86 to 125	nitrile	O2 permeability		
-32.00		150 to 240	Epoxy	TOL	F655-2, TOL=thickness of oxidation layer	[147]
16.00		150 to 240	Epoxy	O2 diffusion	F655-2	
80.00		150 to 240	Epoxy	O2 consumption	F655-2	
-30.00		150 to 240	Epoxy	TOL	977-2	
18.00		150 to 240	Epoxy	O2 diffusion	977-2	
78.00		150 to 240	Epoxy	O2 consumption	977-2	
-23.00		150 to 240	CF/epoxy	TOL, direction 1	T800H/F655-2	
-14.00		150 to 240	CF/epoxy	TOL, direction 2 or 3	T800H/F655-2	
35.00		150 to 240	CF/epoxy	O2 diffusion, direction 1	T800H/F655-2	
53.00		150 to 240	CF/epoxy	O2 diffusion, direction 2 or 3	T800H/F655-2	
-38.00		150 to 240	CF/epoxy	TOL, direction 1	IM7/977-2	
-14.00		150 to 240	CF/epoxy	TOL, direction 2 or 3	IM7/977-2	
3.00		150 to 240	CF/epoxy	O2 diffusion, direction 1	IM7/977-2	
50.00		150 to 240	CF/epoxy	O2 diffusion, direction 2 or 3	IM7/977-2	
90.00		150 to 240	Epoxy	Crack propagation	IM7/977-2	
94.39		130	Neoprene	TGA		[148]
88.00			CSPE	EAB, from reference		[149]
105.00			CSPE	EAB, from reference		
88.00			Silicone	EAB, from reference		
109.69			XLPO	EAB, from reference		
87.92			XLPO	EAB, from reference		
88.00			ETFE	EAB, from reference		
88.00			EPR	EAB, from reference		
92.04			Neoprene	EAB, from reference		
117.71			EPDM	EAB, from reference		
129.00		unaged	PVC	OIT	1-15K/min	[150]
128.00		unaged	PVC	OIT	180-250°C	
111.00		120 to 180	PVC	OIT	50% decrease	
114.00		120 to 180	PVC	EAB	50% decrease	
107.00		120 to 180	PVC	TS	50% decrease	
103.00		120 to 180	PVC	Stiffness	50% decrease	
113.00		120 to 180	PVC	color	50% decrease	
123.00		unaged	XLPE	OIT	1-15K/min	
123.00		unaged	XLPE	OIT	180-250°C	
97.00		120 to 180	XLPE	OIT	50% decrease	
104.00		120 to 180	XLPE	EAB	50% decrease	
119.00		120 to 180	XLPE	Stiffness	50% decrease	
130.00		120 to 180	XLPE	color	50% decrease	
125.00		unaged	PVC	OIT	1-15K/min	
116.00		120 to 180	PVC	OIT	50% decrease	
104.00		120 to 180	PVC	EAB	50% decrease	

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
119.00		120 to 180	PVC	Stiffness	50% decrease	[150] Cont.
146.00		120 to 180	PVC	color	50% decrease	
114.00		unaged	PVC	OIT	1-15K/min	
121.00		120 to 180	PVC	OIT	50% decrease	
116.00		120 to 180	PVC	Stiffness	50% decrease	
154.00		unaged	XLPE	OIT	1-15K/min	
151.00		unaged	XLPE	OIT	180-250°C	
82.00		120 to 180	XLPE	OIT	50% decrease	
81.00		120 to 180	XLPE	color	50% decrease	
164.00		120	XLPE	OIT	1-15K/min	
119.00		120 to 180	XLPE	OIT	50% decrease	
127.00		120 to 180	XLPE	Stiffness	50% decrease	
113.00		120 to 180	XLPE	color	50% decrease	
124.00		unaged	XLPE	OIT	1-15K/min	
76.00		120 to 180	XLPE	OIT	50% decrease	
152.00		120 to 180	XLPE	Stiffness	50% decrease	
109.00		unaged	PVC	OIT	1-15K/min	
130.00		unaged	PVC	OIT	180-250°C	
104.00		120 to 180	PVC	OIT	50% decrease	
90.00		120 to 180	PVC	Stiffness	50% decrease	
91.00		120 to 180	PVC	OIT	50% decrease	
117.00		120 to 180	PVC	Stiffness	50% decrease	
109.00		120 to 180	PVC	color	50% decrease	
95.00		120 to 180	PVC	OIT	50% decrease	
103.00		120 to 180	PVC	Stiffness	50% decrease	
119.00		120 to 180	PVC	color	50% decrease	
125.00		120 to 180	PVC	OIT	50% decrease	
105.00		120 to 180	PVC	Stiffness	50% decrease	
115.00		120 to 180	PVC	color	50% decrease	
96.00		unaged	PVC	OIT	1-15K/min	
118.00		unaged	PVC	OIT	180-250°C	
113.00		120 to 180	PVC	EAB	50% decrease	
113.00		120 to 180	PVC	TS	50% decrease	
139.00		120 to 180	PVC	OIT	50% decrease	
115.00		120 to 180	PVC	EAB	50% decrease	
107.00		120 to 180	PVC	TS	50% decrease	
103.00		120 to 180	PVC	Stiffness	50% decrease	
217.10	20	unaged	PVC	TGA	1-15K/min	[28]
192.80	19	unaged	PVC	TGA	1-15K/min	
174.60	17	unaged	PVC	TGA	1-15K/min	
106.13		140 to 170	EPR	EAB		[151]
124.46		unaged	EPR	TGA	5-20°C/min	
84.90		LOCA	EPR	TGA	5-20°C/min	
128.32			XLPE	from qualification report		[152]
104.20		110 to 120	Hypalon	EAB		[153]
109.50		110 to 120	EPR/CSPE	EAB, IM		
104.20		110 to 120	CSPE	IM		
109.50		110 to 120	Kerite	EAB, IM		
87.00	27		Epoxy resin	from reference		[154]
115.00	66		Epoxy	from reference		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
141.00	55		Epoxy-glass	from reference		[154] Cont.
104.00	10	unaged	Epoxy, BPA	TGA, 200-350°C	degradation stage 1	
72.00	10	unaged	Epoxy, BPA	TGA, 200-350°C	degradation stage 2	
85.00	12	irradiated 135 kGy	Epoxy, BPA	TGA, 200-350°C	degradation stage 1	
77.00	21	irradiated 135 kGy	Epoxy, BPA	TGA, 200-350°C	degradation stage 2	
90.00	12	unaged	Epoxy, Cycloaliphatic	TGA, 150-225°C	degradation stage 1	
92.00	14	unaged	Epoxy, Cycloaliphatic	TGA, 150-225°C	degradation stage 2	
107.00		irradiated 135 kGy	Epoxy, Cycloaliphatic	TGA, 150-225°C	degradation stage 1	
100.00		irradiated 135 kGy	Epoxy, Cycloaliphatic	TGA, 150-225°C	degradation stage 2	
89.00		70 to 131	Neoprene	EAB		[82]
71.00		24 to 70	Neoprene	EAB		
96.00		80 to 110	Neoprene	EAB, O2 consumption		
76.00		25 to 80	Neoprene	O2 consumption		
107.00		100 to 150	CSPE	EAB, O2 consumption		
91.00		37 to 100	CSPE	O2 consumption		
106.00		100 to 170	EPR	EAB		
100.00		52 to 125	EPR	O2 consumption		
88.00		99 to 139	EPR	EAB		
100.00		99 to 139	EPR	EAB	early degradation	
128.00		99 to 139	EPR	EAB	late degradation	
72.00		48 to 138	XLPO	EAB, O2 consumption		
110.00		91 to 170	XLPO	EAB		
128.32		120 to 160	XLPE	EAB		[155]
106.13		120 to 160	EPR	EAB		
202.61		120 to 160	Silicone	EAB		
130.00		120 to 175	EPR	EAB		[156]
63.00		100 to 120	EPR	EAB		
115.00	15	120 to 150	PE, EPR, CSPE, PVC	from reference		[71]
65.00	5	100	PE, EPR, CSPE, PVC	from reference		
41.90		100	Silicone	from reference		
97.00	13	110 to 120	EPR	from reference		
130.00		120	EPR	from reference		
62.80		to 100	EPR	from reference		
76.00		80 to 120	EPDM	O2 consumption		
58.00		40 to 140	EPR	O2 consumption		
110.00		100 to 120	XLPE	EAB		[157]
100.00		100 to 120	XLPE	EAB		
66.10		100 to 120	XLPE	EAB		
83.80		100 to 120	XLPE	EAB		
94.50		100 to 120	XLPE	EAB		
94.50		100 to 120	EPR	EAB		
110.00		100 to 120	EPR	EAB		
102.00		100 to 120	EPR	EAB		
95.90		100 to 120	EPR	EAB		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
84.00		100 to 120	EPR	EAB		[157] Cont.
85.10		100 to 120	EPR	EAB		
87.30		100 to 120	EPR	EAB		
87.20		100 to 120	EPR	EAB		
83.80		100 to 120	EPR	EAB		
85.40		100 to 120	EPR	EAB		
47.10		135 to 175	Silicone	EAB		
41.50		135 to 175	Silicone	EAB		
50.40		135 to 175	Silicone	EAB		
72.20		100 to 120	PVC	EAB		
71.20		100 to 120	PVC	EAB		
71.90		100 to 120	PVC	EAB		
89.00		100 to 120	PVC	EAB		
160.00		170 to 210	EPDM	induction time, 1% weight loss		[29]
113.00		110 to 170	EPDM	EAB		
91.00		50 to 100	CSPE	EAB, O2 consumption		[61]
107.00		100 to 150	CSPE	EAB		
106.00		104 to 170	EPR	EAB		
100.00		52 to 125	EPR	O2 consumption		
98.00		48 to 124	XLPO	O2 consumption		
135.00		124 to 151	XLPO	EAB, O2 consumption		
55.00		135 to 175	Silicone	from reference		[72]
58.00		175 to 235	Silicone	from reference		
37.90		40 to 70	PP	FTIR CI induction period	with UV	[21]
42.40		40 to 70	PP	FTIR CI induction period	with UV	
57.80		40 to 70	PP	FTIR CI induction period	with UV	
116.00		111 to 155	EPDM	induction time of EAB, density, modulus, force decay		[15]
82.00		52 to 111	EPDM	O2 consumption		
90.00		64.5 to 125	Nitrile	EAB, surface modulus		
80.00		23 to 64.5	Nitrile	O2 consumption		
71.00		24 to 70	Neoprene	EAB		
89.00		70 to 121	Neoprene	EAB		
107.00		104 to 150	CSPE	EAB		
91.00		40 to 104	CSPE	O2 consumption		
80.00		72 to 127	Butyl	Sealing force		
105.00		82 to 127	Butyl	Sealing force		
135.00		125 to 152	XLPO	EAB		
98.00		99 to 109	XLPO	EAB		
96.00		100 to 138	PA	TS		
30.00		37 to 138	PA	TS		
21.00		20 to 50	Silicone	water sorption		
16.00		20 to 50	Silicone	water sorption		
18.00		20 to 50	Silicone	water sorption		
89.00		50 to 97	PU	water sorption		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
116.00		111.5 to 161.6	EPDM	Tensile Elongation, Density, Modulus, Force Decay		[16]
118.00		111 to 161.6	EPDM	Elongation, Density, Oxygen Consumption		
82.00		49.4 to 111	EPDM	Oxygen Consumption		
90.00		64.5 to 125	Nitrile	Elongation, Surface Modulus		
80.00		21 to 64.5	Nitrile	Oxygen Consumption		
89.00		70 to 121	Neoprene	Ultimate Tensile Elongation		
71.00		24 to 70	Neoprene	Ultimate Tensile Elongation		
107.00		97.2 to 161.6	CSPE	Elongation, Oxygen Consumption		
91.00		39.4 to 97.2	CSPE	Elongation, Oxygen Consumption		
80.00		71.7 to 126.9	Butyl	Time to 75% Force Loss		
105.00		80.2 to 126.9	Butyl	Time to 50% Loss in Sealing Force		
96.00		100 to 138	PA	Tensile Strength		
30.00		37 to 100	PA	Tensile Strength		
109.99			CSPE	from reference		[158]
130.25			EPDM	from reference		
115.78			EPR	from reference		
86.83			ETFE	from reference		
90.69			Neoprene	from reference		
95.52			PVC	from reference		
173.66			Silicone	from reference		
112.88			Viton	from reference		
119.64			XLPE/XLPO	from reference		
106.13			EPR	from reference		
109.99			Neoprene	from reference		
130.25			XLPE/XLPO	from reference		
89.00		70 to 161	Neoprene	EAB		[58]
107.00		100 to 150	CSPE	EAB		
91.00		37 to 100	CSPE	O2 consumption		
86.00		37 to 80	Neoprene	O2 consumption		
115.78		190	PEEK	from manufacturer		[159]
106.13		135	XLPO	from manufacturer		
116.74		135	EPR	from manufacturer		
130.25		120	EVA	from manufacturer		
83.26		190	Silicone	from manufacturer		
139.90		190	Silicone	from manufacturer		
130.25		135	XLPE	from reference		
107.09		120	CSPE	from reference		
121.66		135	EPR	from manufacturer		
121.18		135	EPR	from manufacturer		
120.60		135	XLPO	from manufacturer		
103.23		25 to 85	EPDM	EAB	with irradiation	[18]
94.57		100 to 120	XLPE	EAB		[160]

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
93.52		100 to 120	EPR	EAB		[160] Cont.
253.04		115 to 165	XLPE	EAB		[161]
232.76		115 to 165	XLPE	EAB		
267.52		115 to 165	XLPE	EAB		
269.11		115 to 165	XLPE	EAB		
249.12		115 to 165	XLPE	EAB		
242.95		115 to 165	XLPE	EAB		
253.49		115 to 165	XLPE	EAB		
113.00		111 to 170	EPDM	O2 consumption, surface modulus, EAB		[162]
89.00		70 to 161	Neoprene	EAB		
85.80		28 to 120	CSPE	Oxidation rate		[23]
76.00		28 to 120	CSPE	Oxidation rate		
14.20		28 to 120	CSPE	Oxidation rate		
79.00		28 to 120	CSPE	Oxidation rate		
90.70		37 to 108	CSPE	Oxidation levels		
91.30		37 to 108	CSPE	Oxidation levels		
148.68		70 to 100	natural rubber(50%)/ butadiene rubber(50%)	EAB	e/e0 = 0.55	[19]
119.01		70 to 100	natural rubber(50%)/ butadiene rubber(50%)	EAB	e/e0 = 0.65	
89.34		70 to 100	natural rubber(50%)/ butadiene rubber(50%)	EAB	e/e0 = 0.75	
59.67		70 to 100	natural rubber(50%)/ butadiene rubber(50%)	EAB	e/e0 = 0.85	
89.00		70 to 161	Neoprene	EAB		[17]
71.00		24 to 70	Neoprene	EAB		
105.00		100.4 to 149.5	CSPE	EAB		
91.00		60 to 100.4	CSPE	EAB		
50.00		75 to 100	EPDM	Compression stress relaxation		[30]
131.00		125 to 150	EPDM	Compression stress relaxation		
78.00		75 to 100	EPDM	EAB, O2 consumption		
127.00		125 to 150	EPDM	EAB, O2 consumption		
92.00		75 to 150	EPDM	Sealing force		
71.00		24	Neoprene	from reference		[54]
98.00		25	Neoprene	from reference		
107.00		100	CSPE	from reference		
112.00		109	CPE	from reference		
106.00		50	EPR	from reference		
128.00		50	EPR	from reference		
88.00		50	EPR	from reference		

E_a (kJ/mol)	±	Temperature range (°C)	Polymer*	Dataset†	Notes	Ref.
106.00		50	EPR	from reference		[54] Cont.
110.00		50	XLPO	from reference		
130.00		50	XLPO	from reference		
112.20	7.1	121 to 165	EPR	EAB		[24]
138.00	19	121 to 165	EPR	ΔEab*		
109.60	9.8	121 to 165	XLPE	EAB		
78.00	12	121 to 165	XLPE	ΔEab*		
101.40	13	121 to 165	XLPE	EAB		
121.00	18	121 to 165	XLPE	ΔEab*		
112.88	2.9	55 to 81	EPR	EAB	50% abs. EAB	[25]
99.37	11	55 to 81	EPR	EAB	50% abs. EAB	
109.99	13	55 to 81	EPR	EAB	50% abs. EAB	
89.73	18	55 to 81	XLPE	EAB	50% abs. EAB	
106.00	2	90 to 160	XLPE	Absorbance 1720cm-1		[20]
97.00	1	50 to 90	XLPE	Absorbance 1720cm-1		
110.00	2	90 to 160	EPR	Absorbance 1714cm-1		
71.00	1	50 to 90	EPR	Absorbance 1714cm-1		
105.00	3	70 to 160	XLPE	EAB		
42.70	4.2	unaged	PE	TGA	10-50°C/min, N_2	[27]
40.10	2	unaged	PE	TGA	10-50°C/min, O_2	
72.80	4.6	60kGy	PE	TGA	10-50°C/min, N_2	
67.00	1.7	250kGy	PE	TGA	10-50°C/min, N_2	
51.40	3.4	60kGy	PE	TGA	10-50°C/min, O_2	
112.50	12	250kGy	PE	TGA	10-50°C/min, O_2	
269.38		unaged	XLPE	TGA	Coast Redfern integral method	[26]
181.59		15 yr service life	XLPE	TGA	Coast Redfern integral method	
167.44		30 yr service life	XLPE	TGA	Coast Redfern integral method	
126.00			XLPO	from reference		[126]
125.42			EPR	from reference		[163]
98.30	3.3	75 to 105	PVC	TGA	plasticizer desorption	[164]

* PVC = polyvinyl chloride ; neoprene = polychloroprene ; XLPO = crosslinked polyolefin; Viton = FPM = fluorocarbon elastomer; nitrile = NBR = nitrile butadiene rubber; CSPE = chlorosulphonated polyethylene; EPDM = ethylene propylene diene M-type rubber; XLPE = crosslinked polyethylene; EPR = ethylene propylene rubber; PP = polypropylene; ETFE = ethylene tetrafluoroethylene; butyl = IIR = butyl rubber; PU = polyurethane; BPA = bisphenol A; PA = polyamide = nylon; PEEK = polyetheretherketone

† EAB = elongation at break; IR = insulation resistance; DF = dissipation factor = tangent delta; CL = chemiluminescence; OIT = oxygen induce time; IR – carbonyl = Fourier transform infrared spectroscopy (FTIR)-determined carbonyl index; TOL = TGA = thermogravimetric analysis; IM = indenter = indenter modulus; TS = tensile strength

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