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Light Water Reactor Sustainability Program

First Phase Consensus Roadmap for Development of Condition-Based Cable Reliability Assurance

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Pacific Northwest National Laboratory

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Light Water Reactor Sustainability (LWRS) Program
Materials Research Pathway

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EXECUTIVE SUMMARY

The objective of this work was to develop a first phase consensus roadmap for condition-based qualification (CBQ) of electrical cables. With CBQ, qualification of Class 1E electrical cables moves from a time-based approach to a condition-based approach, which is anticipated to be safer in terms of reliability and conservatism, and more cost effective in the long run. However, due to barriers, the CBQ approach has not yet been adopted by U.S. nuclear power plants (NPPs).

Based upon a review of current work evaluating CBQ, the limitation of available condition monitoring technology seems to be the largest barrier. The importance of condition monitoring, or more specifically selecting appropriate condition indicators, during CBQ cannot be understated. However, selecting appropriate condition indicators is challenged by techniques that are destructive and only evaluate cable degradation locally. Further, arguably, no one identified condition indicator fully establishes cable condition. Thus, additional work is necessary to evaluate potential condition indicators towards CBQ. In addition to the requirements of IEC/IEEE Std. 60780-323, ideal condition indicators should include a) both destructive and non-destructive approaches, b) both local and global measurements, c) real-time (i.e., online) monitoring that trends with degradation, d) enable correlation with qualified levels of degradation, and e) be established within a repository of condition indicators with applicable materials and/or components and their acceptance criteria.

Additional work is needed in development of technology and methodology prior to adoption of CBQ, especially for extending qualified life of installed components. Education and early experience by the industry and regulators will be required for this change in approach as an alternative to re-analysis. A series of workshops that bring together stakeholders to identify and address gaps will be needed. The longstanding cooperative working group of cable researchers from the U.S. Department of Energy, the Electric Power Research Institute, and the Nuclear Regulatory Commission forms a valuable starting point for development of a consensus roadmap to condition-based qualification approach as a viable options for qualification of cable systems in U.S. light water reactors.

ACKNOWLEDGEMENTS

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ACRONYMS

AMP	aging management program
ASTM	American Society for Testing and Materials
CBQ	condition-based qualification
CI	condition indicator
CM	condition monitoring
CSPE	chlorosulfonated polyethylene
DBE	design-basis accident event
DLO	diffusion limited oxidation
DOE	Department of Energy
DMA	dynamic mechanical analysis
DRE	dose-rate effects
DS	dielectric spectroscopy
DTF	distance-to-fault
EAB	elongation at break
EPR	ethylene propylene rubber
EMDA	Expanded Materials Degradation Assessment
EPRI	Electric Power Research Institute
EQ	environmental qualification
ETFE	ethylene tetrafluoroethylene
FDR	frequency domain reflectometry
FFT	fast Fourier transform
FTIR	Fourier-transform infrared
GALL	generic aging lessons learned
HELB	high energy line break
HTK	high-temperature Kerite
IAEA	International Atomic Energy Agency
ICEA	Insulated Cable Engineers Association
IDC	interdigital capacitor
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	indenter modulus
IR	insulation resistance
ITE	inverse temperature effects

LCR	inductance, capacitance, resistance
LOCA	loss-of-coolant accident
LWRS	Light Water Reactor Sustainability Program
MCR	multicarrier reflectometry
MSR	mixed signal reflectometry
NDE	nondestructive evaluation
NIR	near infrared
NMR	nuclear magnetic resonance
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OIT	oxidation induction time
PD	partial discharge
PE	polyethylene
PN	pseudo-random-noise
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
QLD	qualified level of degradation
QM	qualification monitoring
RTD	resistance temperature detector
SLR	subsequent license renewal
SNL	Sandia National Laboratory
SR	silicone rubber
SS	spread spectrum
SSTDR	spread spectrum time domain reflectometry
S/SSTDR	sequence/spread spectrum time domain reflectometry
SWR	standing wave reflectometry
TDR	time domain reflectometry
TGA	thermalgravimetric analysis
UV-vis	ultraviolet-visible
VNA	vector network analyzer
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin
XRD	X-ray diffraction analysis

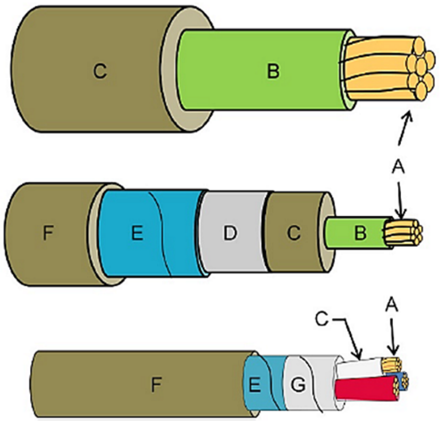
1. INTRODUCTION

This report is submitted in fulfillment of the deliverable for the LWRS milestone (M2LW-24OR0404015) for the Cable Aging and Gap Analysis task of the Materials Research Pathway. This work is part of an effort to develop a technical basis for assessing the level and impact of aging of electrical cables and their components in nuclear power plants (NPPs). The sustainable operation of existing NPPs is supported by development of practical methods to ensure the safety and reliability of installed electrical cable systems. Safety-related installed in hazardous operating environments must be environmentally qualified to provide confidence that they will perform their safety function when needed throughout the entire license period of the reactor in which they are installed. Historically, U.S. plants have utilized a time-based qualification of cables in which confidence in performance throughout the license period is established by applying accelerated aging equivalent to the license period of representative cables and simulating a design basis event to confirm that the aged cables can survive the event and still perform their safety function. Challenges for this approach include the difficulty in effectively replicating extended service life through accelerated aging and the extension of an established qualified life (e.g., 40 years) to an extended license period (e.g., 60 years or 80 years). An alternative approach to establishing confidence in the reliability of cables is to test cables and correlate measured cable condition with the ability of a cable with that condition level to perform its function following a safety-related event. Condition-based qualification has been an option for a cable reliability assurance basis but has not been widely pursued in the U.S. nuclear industry. As the U.S. fleet continues to age and operators seek to continue to extend the license periods of their plants, beyond cable qualification lifetimes, a transition to testing for continued reliability assurance rather than re-analysis of simulated reliable lifetime may be warranted. The primary goal of this task is to support industry consideration of condition-based qualification as a path forward through identification of the value proposition and steps needed to achieve that goal. Input from stakeholders is essential and consensus in priorities and goals is sought.

The following is the initial step toward establishing a roadmap toward condition-based qualification for nuclear cables in existing U.S. nuclear power plants. The roadmap is being pursued by the U.S. Department of Energy (DOE) Light Water Reactor Sustainability program in conjunction with longstanding cable research working group collaborators from the Electric Power Research Institute (EPRI) and the Nuclear Regulatory Commission (NRC). These entities have been coordinating and collaborating on research to address technical knowledge gaps related to cable qualification since approximately 2013 (NRC 2014). In that time, we have improved our understanding of the gaps associated with time-based qualification but have seen the appeal of transition to a condition-based qualification, especially as a strategy for maintaining qualification of installed cables beyond their original qualified life. Following several discussions over the last couple of years, in 2023 the DOE/EPRI/NRC working group planned an initial workshop to bring together key stakeholders in the nuclear cable industry to consider transition to condition-based qualification from diverse perspectives. This workshop was held at the EPRI location in Washington, D.C. in January 2024 and its participants began to identify key elements of the change management process that may be required to implement this alternative approach to cable qualification. It is anticipated that additional workshops in the coming months and years will continue to identify relevant stakeholders, the value proposition, and the gaps and challenges in transition to CBQ. By establishing and maintaining a roadmap that identifies gaps and solutions, DOE Cable researchers can support the sustainability of light water reactors with increased options for efficient and effective management of aging electrical cables in U.S. plant operation beyond their initial license periods.

2. CLASS 1E ELECTRICAL CABLES

Class 1E NPP electrical cables installed in harsh environments must be environmentally qualified (EQ) to maintain their safety related function following a design basis event. This qualification process is discussed in Section 3. NPP cable designs typically include a conductor to carry power, instrumentation, or control signals, and an insulating cover layer to isolate the conductor (see Figure 2-1). They may include more than one insulated conductor within an assembly. Other components that may be associated with the overall cable design include a semiconductor screen (for medium-voltage (MV) cables), a shield over each conductor and/or over all conductors, binder tape, and a jacket. While the insulation provides electrical isolation, in jacketed cable configurations the jacket serves to provide mechanical protection during installation and may provide fire or moisture resistance depending on the cable construction. MV cables comprise a small portion of the population of EQ cables, most are low-voltage (LV).



A. Uncoated copper conductor
B. Semiconducting screen
C. Insulation
D. Insulation screen extruded semiconductor
E. Shielding copper tape with or without drain wire
F. Jacket
G. Helically applied binder tape

Figure 2-1. Configurations of typical cable designs used in NPPs (Glass et al. 2017).

Table 1. Common groupings of cable categories with safety related cables in bold; adopted from (Glass et al. 2016).

Voltage	Application	Environment	Design
Low (< 2 kV)	Power Control Instrumentation Communication Thermocouple Specialty Configuration **Safety Related / EQ** Non-Safety Related	Normal Operating Temperature High Temperature High Radiation Fire/Flame Retardant Submerged – Water Aggressive Solvents	Single/Multi-Conductor Shielded/Unshielded Coaxial Thermocouple Alloys Special Jacket
Medium (2 – 46 kV)	Power **Safety Related / EQ** Non-Safety Related	Normal Operating Temperature High Temperature High Radiation Fire/Flame Retardant Submerged – Water Aggressive Solvents	Single Conductor Shielded/Unshielded Armoring
High (> 46 kV)	Power Non-Safety Related	Normal Operating Temperature High Temperature Submerged – Water Aggressive Solvents	Single Conductor Shielded

Electrical cables are commonly categorized as low-, medium-, or high-voltage as shown in Table 1. Within U.S. NPPs, LV electrical cables may comprise up to 80% of all cables (Groeger, Brown, and Esselman 2017). Within harsh environments, such as in nuclear containment, where degradation and aging of Class 1E electrical cables may occur, a vast majority of cables are LV (NRC 1990). Examples of circuits connected to LV cables may include those supplying power to motor-operated valves, controlling solenoid valves and switches, or instrumentation such as transmitters (e.g., pressure, flow), temperature (e.g., thermocouples, resistance temperature detectors or RTDs), or radiation monitors (Gazdzinski et al. 1996). MV cables are commonly found in connections between MV buses and feeders, large pump and fan motors, and emergency power supplies (Gazdzinski et al. 1996). High-voltage (HV) cables are rarely found in U.S. NPPs. It should be noted that industrial definitions for voltage ranges vary. For example, Nuclear Regulatory Commission (NRC) NUREG-2191 Chapter VI-A specifies typical operating voltage of MV power cables to be 2 kV to 35 kV (NRC 2017). However, within Institute of Electrical and Electronics Engineers (IEEE) Std 690-2018, a standard for cable systems for Class 1E circuits, MV power cables are defined as "designed to supply power to devices of plant systems rated 2 kV to 15 kV" (IEEE 2018). In addition, Insulated Cable Engineers Association S-94-649 specifies "medium voltage shielded power cables" as "rated 5 kV to 46 kV" (ICEA 2021). Lastly, EPRI TR 3002005322 specifies MV as 5 kV to 46 kV and LV power cable as lower than 2 kV (EPRI 2015a).

Table 2. Common insulation material types used in U.S. NPPs (Gazdzinski et al. 1996).

Material	Percent of Total (%)	Material	Percentage of Total (%)
XLPE	36	ETFE	3
EPDM/EPR	36	Flame Resistant	3
SR	5	CSPE	2
Kerite	5	Butyl Rubber	2
Polyethylene	5	All others	Each ≤ 1%

XLPE = cross-linked polyethylene; EPDM = ethylene-propylene-diene elastomer; EPR = ethylene-propylene rubber; SR = silicone rubber; ETFE = ethylene tetrafluoroethylene; CSPE = chlorosulfonated polyethylene.

Table 3. Common insulation and jacket material types within U.S. nuclear containment (Bustard and Holzman 1994).

Material	Percent of Units (%)	Material	Percentage of Units (%)
XLPE	90	PVC	7
EPDM/EPR	75	PE	3
SR	27	Neoprene	3
CSPE	24	Polyimide	3
ETFE	15	Polyalkene	2

XLPE = cross-linked polyethylene; EPDM = ethylene-propylene-diene elastomer; EPR = ethylene-propylene rubber; SR = silicone rubber; CSPE = chlorosulfonated polyethylene; ETFE = ethylene tetrafluoroethylene; PVC = polyvinyl chloride; PE = polyethylene.

Table 4. Sort of the most common manufactures of cables found within NPPs (Bustard and Holzman 1994).

Manufacturer	Insulation	Number of Plants	Manufacturer	Insulation	Number of Plants
Rockbestos	Firewall III XLPE	61	Rockbestos	Coaxial XLPE	24
Anaconda	EPR	35	Raychem	XLPE	23
Brand-Rex	XLPE	30	Samuel Moore	EPR	19
Okonite	EPR	26	BIW	Bostrad 7E EPR	19
Kerite	HTK	25	Kerite	FR EPR	13

XLPE = cross-linked polyethylene; EPR = ethylene-propylene rubber; HTK = high-temperature Kerite.

The materials for cable components are chosen based on their use environment, such as wet, dry, radiation, or sunlit conditions, and the application, such as for power or instrumentation. Conductors, made from copper, aluminum, or tin, are relatively insensitive to age related damage compared to polymer materials of the insulation or jacket. Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) compose most insulation materials in the nuclear industry as shown in Table 2 (over 70% of materials), with silicone rubber (SR) also being of interest. XLPE and EPR are also the most common Class 1E electrical cable insulation materials within nuclear containment as shown in Table 3. In addition, approximately 30 different manufacturers have previously been identified as supplying electrical cables to NPPs as shown in Table 4 (here, the top 10 manufacturers are shown). The most significant jacket materials are chlorosulfonated polyethylene (CSPE – also known as Hypalon® which is a registered trademark of DuPont), polychloroprene (also known as neoprene), and polyvinyl chloride (PVC). While installed cables with intact insulation may well be able to continue to provide safe operation with degraded jacket material, the tendency of jacketing materials to degrade more readily than insulation materials enables their use as leading indicators for local stress prior to insulation degradation and failure, see Section 5.

Cable layouts in typical NPPs are not designed to facilitate direct access and inspection of much of the cable length. Cable trays and conduits are designed to protect cables from environmental stressors as well as from accidental damage from workers and equipment that may be moving either inside containment, auxiliary buildings, or control buildings. While cable ends are generally accessible at termination boxes and control panels, many cables are grouped together in trays that do not follow personnel access pathways, pass-through penetration pipes and conduits that may be buried in concrete, are buried underground, or even pass through areas that may be flooded (see Figure 2-2).

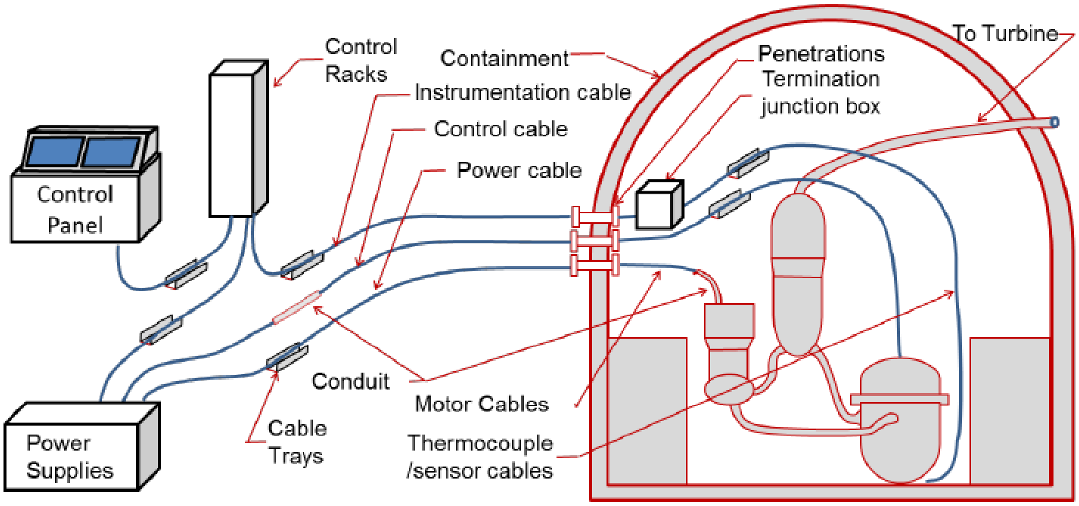


Figure 2-2. Typical cable layout allows access at control racks and termination junction boxes but much of the cable is protected within cable trays and conduits thereby limiting access for local inspections (Glass et al. 2016).

3. HISTORICAL QUALIFICATION OF ELECTRICAL CABLES

Due to the inherent susceptibility of materials to degrade or age over time and to promote the safe function of NPPs, Class 1E electrical equipment, including cables, must conform to established industry performance standards. Generally, these standards require cable manufacturers to ensure products maintain performance requirements throughout their designed life, even after design-basis accident events (DBE). In many cases, this requires accelerated aging of the components, e.g., by applying the Arrhenius method (NRC 1996), using either thermal, radiation, or a combination of stressors to simulate the accumulated stress of their qualified life prior to subjecting the pre-aged components to a DBE such as a loss of coolant accident (LOCA) or high energy line break (HELB) exposure simulation. Components that successfully perform following this process are considered environmentally qualified (EQ). Most currently installed EQ cables have been qualified to a lifetime of at least 40 years. Below, the aging of electrical cables is first briefly discussed, followed by Class 1E cable qualification procedures and qualification standards.

3.1 Aging of Electrical Cables

Aging, which has been defined as the "cumulative effects that occur with the passage of time to a component," (NRC 1990) has the potential to degrade materials past viability. Polymeric materials are generally more susceptible to aging than metals (ASTM 2021) and are commonly found in electrical cables, splice kits, and other components in NPPs. NPP electrical cables may age due to exposure to a number of stressors, such as elevated temperature, thermal cycling, radiation, oxidation, mechanical damage, vibration, dust, moisture, humidity, workmanship, and more. A summary of common stressors, their effects on materials in cables, and corresponding work in literature are shown in Table 5. The effects of aging are potentially significant and can lead to failure of cables and connected devices, plant shutdowns, electrical transients, or other issues (Villaran and Lofaro 2002; NRC 2012). Of particular interest is aging of the cable insulation as its failure can lead to loss of electrical isolation. Therefore, investigations into the response of cables to harsh NPP environments have mainly focused on aging of the insulation (Burnay 2001; Celina, Gillen, and Assink 2005; Wise, Gillen, and Clough 1997; Celina et al. 2000). In addition, thermal and radiation stressors, see Section 3.1.1, are of primary significance in the NPP environment.

Table 5. Potential aging effects for some of the most common materials within cables with the primary stressors of interest in bold; adopted from (Gazdzinski et al. 1996; Villaran and Lofaro 2002).

Component	Most Common Materials	Stressors	Aging Mechanisms	Aging Effects	Qualification Concerns
Insulation	XLPE, EPR	**Thermal**, **radiation**, fatigue, vibration, electrical transients, high voltage, moisture	Embrittlement, cracking, mechanical wear, treeing, wetting	Decrease in dielectric strength, increase in leakage currents, eventual failure	DLO, ITE, DRE, Synergistic (NRC 2014)
Jacket	CSPE, Neoprene, PVC	(as above)	(as above), evaporation of plasticizers	(as above)	(as above)
Splices	EPR, EPDM, SR, PVC, Polyolefins	(as above) workmanship, thermal cycling, vibration	(as above), electrical stress, loss of dielectric isolation, loosening connections	High resistance, eventual failure	Splices on age-embrittled cables (NRC 2009)

XLPE = cross-linked polyethylene; EPR = ethylene-propylene rubber; CSPE = chlorosulfonated polyethylene; EPDM = ethylene-propylene-diene elastomer; SR = silicone rubber; PVC = polyvinyl chloride; DLO = diffusion limited oxidation; ITE = inverse temperature effects; DRE = dose-rate effects.

3.1.1 Thermal and Radiation Aging of Polymers

Thermal and radiative stressors have been observed to primarily be associated with Class 1E electrical cable degradation, with other stressors benign in comparison (NRC 1990). Whenever thermal or radiative degradation occurs in an oxygenated environment these mechanisms become known as thermal-oxidation or photo-oxidation, and oxidative reactions dominate the degradative reaction pathways. Most polymers are thought to undergo oxidative degradation under thermal and/or radiative conditions by an autocatalytic process known as auto-oxidation. G. Bolland et al. were first to establish the classically understood mechanism of polymer auto-oxidation that has become the contemporary theory (Gillen, Wise, and Clough 1995; Gryn'ova, Hodgson, and Coote 2011). This process is described in several steps including initiation, chain propagation, chain branching, and termination, as shown in Figure 3. Initiation (Figure 3, (1)) occurs as weak C-H bonds break (due to the applied thermal or radiative stressor), leading to the formation of free radicals (R·). These free radicals can then rearrange (Figure 3, (2)) without terminating the degradation reaction. Generated radicals quickly react with oxygen to form peroxyl radicals (RO2·) which then quickly stabilize into hydro-peroxides (ROOH) through propagation reactions (Figure 3, (3, 4)). Generated hydro-peroxides can decompose to form RO· and HO· which results in chain branching reactions (Figure 3, (5-8)). Generated radicals ultimately form inactive products such as carbonyl groups or unsaturated groups through termination reactions (Figure 3, (9-11)), which may lead to a loss of performance or aging for the polymer in question.

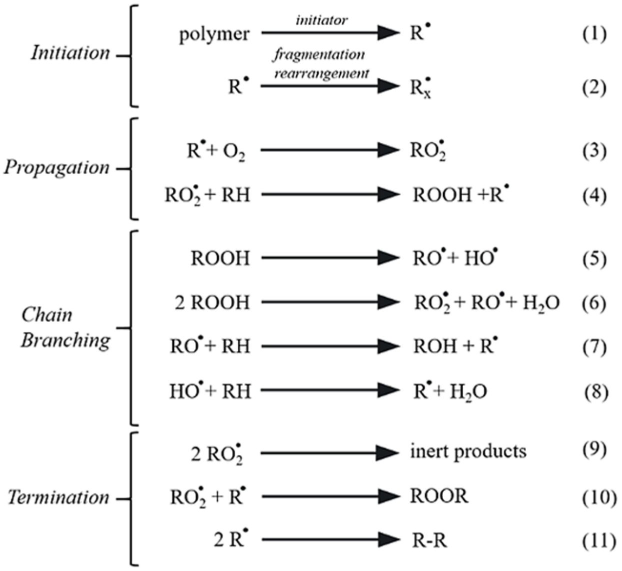


Figure 3-1. The basic auto-oxidation scheme (Gryn'ova, Hodgson, and Coote 2011).

3.2 Class 1E Electrical Cable Qualification

During the license period of a NPP, safety-related equipment or any equipment that could limit safety functions, such as Class 1E electrical cables located in harsh environments and designated as EQ, must be able to perform its safety-related function even during and following a DBE. As such, a series of IEEE standards have been released describing procedures established to cover the process of qualifying equipment as Class 1E. Historically, IEEE Std. 323-1974 has been followed for qualifying Class 1E electrical cables, with IEEE Std. 383-1974 used as a supplement during type testing. Type testing refers to qualification performed on actual equipment to be used in service conditions, the preferred approach to Class 1E cable qualification, as discussed below, and has been used to qualify most relevant equipment within NPPs. More details regarding the evolution of Class 1E standards are discussed in Section 3.3.

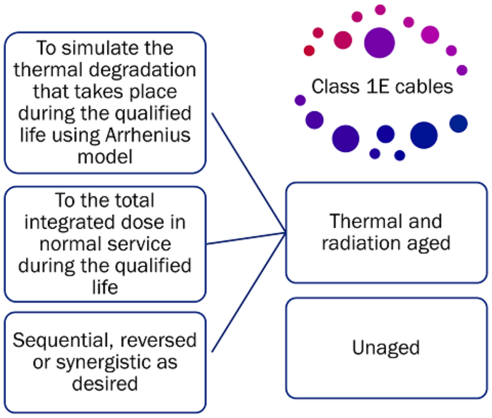


Figure 3-2. Pre-aging of Class 1E electrical cables following IEEE Std. 323 and 383.

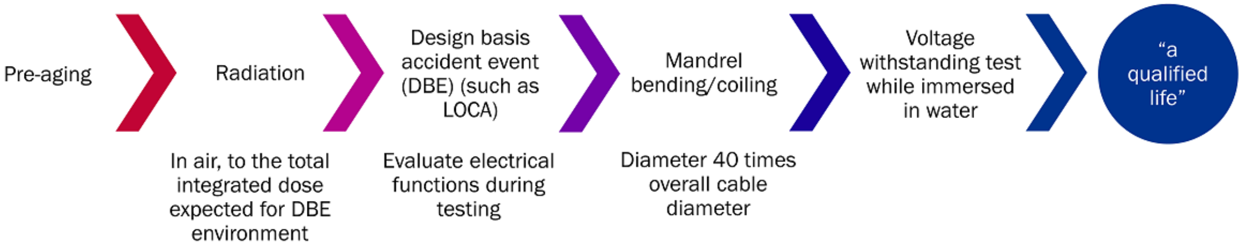
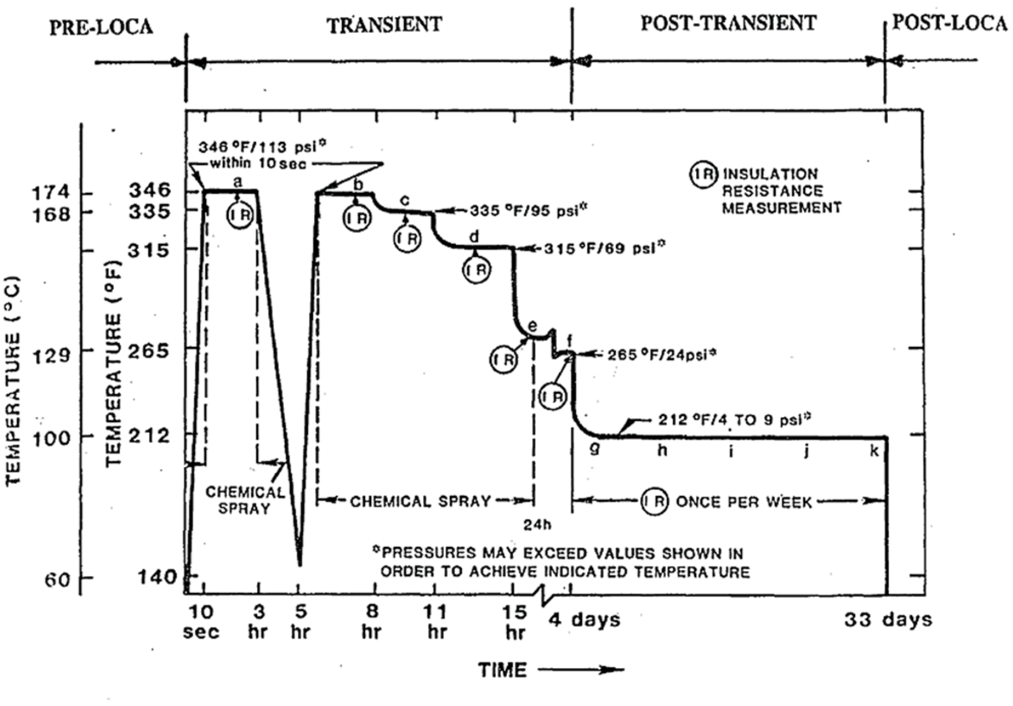


Figure 3-3. Class 1E electrical cable type testing accident exposure following IEEE Std. 323 and 383.

As discussed in Section 3.1, aging may lead to a loss of performance affecting safety function. Such potential loss of performance is a concern for electrical cables within nuclear containment, those used to control the safe shutdown of nuclear reactors, or those located in harsh environments (Giuliano, Duckworth, and Cunningham 2021). Much work has been conducted to ensure continued performance of electrical cables, even under LOCA or other DBE, through EQ. During EQ, electrical cables are first artificially aged, commonly using accelerated aging with a thermal and/or radiation stressor (and all the potential issues associated with it (NRC 2014)), to simulate the design life of a NPP (IEEE Std. 383 1974). This aging is referred to as pre-aging (see Figure 3-2) and primarily induces degradation in the polymeric components, such as the insulation and jacket, which can deteriorate significantly over the lifetime of a NPP and limit reliability of the cable system (NRC 1996). Therefore, pre-aging of Class 1E electrical cables is conducted to ensure such aging is conservative with respect to expected actual in-plant aging.

Following pre-aging, accident exposure testing is conducted as shown Figure 3-3. With accident exposure, electrical cables are exposed to the maximum total cumulative radiation dosage expected over the installed life (if not already included in pre-aging) plus one LOCA exposure to radiation (IEEE 1974a, 1974b), typically up to 200 Mrad (50 Mrad for installed life plus 150 Mrad for LOCA) using a Cobalt-60 source (NRC 1996). Afterwards, a LOCA simulation is conducted which consists of "exposure to hot gases or vapors (for example steam) and a spray or jet of water, chemical solution, or other fluids" (IEEE 1974a). Previous work has identified failure under accident conditions to be primarily moisture-related from steam environments in an accident (NRC 1990). Heat from steam release and pressure buildup are considered dominant stresses in the accident simulation rather than gases or chemical exposure in post-LOCA flooding. In addition, LOCA simulations require electrical cables to be electrically loaded during testing. A typical 1970s LOCA profile is shown in Figure 3-4; however, it should be noted that specific LOCA environmental conditions differ significantly between reactors and between locations in the plant (NRC 1996). After LOCA simulation, electrical cables must be recoiled around a mandrel with a diameter approximately 40 times the overall cable diameter and immersed in tap water at room temperature while also being electrically loaded without shorting (IEEE 1974b). Electrical cables that pass this process are considered to be EQ.



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

Figure 3-4. Typical temperature/pressure profiles for LOCA simulations used by SNL (NRC 1996).

3.3 Class 1E Electrical Cable Qualification Standards

Class 1E electrical cables must conform to IEEE industry standards 323 and 383. Evolution of these standards are shown in Table 6 and discussed below, with historical standards used during qualification bolded. Selected versions of IEEE Std. 323 and IEEE Std. 383 have been endorsed by the NRC in regulatory guides (RG) as shown in Table 7.

Table 6. IEEE standards related to EQ of electrical cables, with historical standards used for qualification in bold.

Standard	Endorsement and Applicability	Reference
IEEE 323-1971, Trial-use	Applies to NPPs with construction permit prior to July 1, 1974, per NUREG-0588	(IEEE 1971)
IEEE 323-1974	Endorsed in RG 1.89, Rev 0, November 1974, and in RG 1.89, Rev 1, June 1984	(IEEE 1974a)
IEEE 323-1983	Not endorsed	(IEEE 1983)
IEEE 323-2003	Not endorsed	(IEEE 2003b)
IEC/IEEE 60780-323-2016	Endorsed in RG 1.89, Rev 2, April 2023	(IEC/IEEE 2016)
IEEE 383-1974	Endorsed in RG 1.131, Rev 0, August 1977, for comment (RG 1.131 was withdrawn in April 2009)	(IEEE 1974b)
IEEE 383-2003	Endorsed in RG 1.211, Rev 0, April 2009	(IEEE 2003a)
IEEE 383-2015	Not endorsed	(IEEE 2015)

Table 7. Latest NRC regulatory guides related to cable aging and condition monitoring.

Year	Title	Regulatory Guide	Standard
2023	Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants (NRC 2023a)	1.89	IEC/IEEE Std. 60780-323-2016 (IEC/IEEE 2016)
2009	Qualification of Safety-Related Cables and Field Splices for Nuclear Power Plants (NRC 2009)	1.211	IEEE Std. 383-2003 (IEEE 2003a)
2012	Condition-Monitoring Techniques for Electric Cables Used in Nuclear Power Plants (NRC 2012)	1.218	Provides Guidance

The IEEE Std. 323 was originally released in 1971 for trial-use for the qualification of safety critical NPP equipment, without the requirement for pre-aging (IEEE 1971). The historical IEEE Std. 323 used for Class 1E electrical cable qualification was released in 1974, which was updated to include qualified life and aging (IEEE 1974a). An update to IEEE Std. 323 was released in 1983 that included a revision to the definition of qualified life and also in-service test conditions but was not endorsed by the NRC (IEEE 1983). Another update to IEEE Std. 323 was released in 2003 (IEEE 2003b) focusing on requirements for margins, aging, and maintaining documentation. This version is the one most U.S. NPPs are licensed too and was endorsed by the NRC for computer-based instrumentation and control systems in 2007 (NRC 2007). The latest version of IEEE Std. 323, which has been endorsed by the NRC (NRC 2023a), was combined with International Electrotechnical Commission (IEC) 60780, which was released in 2016, forming IEC/IEEE Std. 60780-323 (IEC/IEEE 2016); this update included approaches on condition-based qualification, particularly during license renewal periods.

The IEEE Std. 383 was originally released in 1974 as a supplement to IEEE Std. 323 and focused on type testing (IEEE 1974b). An update to IEEE Std. 383 was released in 2003 and removed details regarding flame test methods (instead referring to IEEE 1202 (IEEE 2023)), further emphasized alternatives to type testing, such as past operating experience, ongoing qualification, and qualification by analysis, and removed connections from the scope (IEEE 2003a). The latest revision to IEEE Std. 383 was released in 2015, which has not been endorsed by the NRC, and includes lessons learned from past qualification and research experiences (IEEE 2015).

4. CONDITION-BASED QUALIFICATION OF ELECTRICAL CABLES

The Expanded Materials Degradation Assessment (EMDA) vol. 5 discusses an alternate approach to the time-based electrical cable qualification process described above based upon continued evaluation of cable condition (NRC 2014). While NPP operating experience has suggested that cable failure is rare (Spencer, Elen, and Fifield 2023), there is a growing desire for development of a condition-based qualification (CBQ) approach to ensure readiness of Class 1E cables during a DBE, independent of knowledge of cable history. Such an approach to ensuring cable reliability is being driven in part due to:

1) Electrical cables in subsequent license renewal periods being used far longer than originally anticipated;
2) Uncertainty in environments over the long history of NPPs and the potential for changes in local cable environments; and
3) Retain, repair, and replace decisions, as well as re-test intervals, might be best made based upon current cable condition.

Further, in support of CBQ, the International Atomic Energy Agency (IAEA) has stated:

> "…from the point of view of preserving EQ during the lifetime of a NPP, condition-based qualification is considered more appropriate than the current practice adopted by utilities, which is mainly limited to the monitoring of environmental conditions. The measured values of temperature and radiation dose are used to demonstrate that operational conditions are within the enveloping conditions used for pre-ageing in the original EQ. Using only environmental monitoring does not provide any information on the cable condition or performance. This is considered insufficient to use as a basis for cable qualification preservation or the extension of the qualified lifetime of cable. Utilities are encouraged to adopt a broader approach that includes both environmental and cable condition monitoring within the condition-based qualification process" (IAEA 2012).

4.1 Condition-based Qualification Approach

CBQ is an approach to electrical cable EQ to establish a condition-based qualified life, as opposed to a time-based qualified life as shown in Figure 4-1, and can supply enhanced confidence of safety-related equipment performance through continued evaluation. The approach to CBQ is summarized in Figure 4-2 where the blue line represents degradation of a generalized polymer or component (i.e., "degradation curve"), which implies performance capability is decreasing with time. IEC/IEEE Std. 60780-323 discusses CBQ, although this process has yet to be adopted by U.S. NPPs (EPRI 2023). To successfully accomplish CBQ, qualification monitoring (QM) is necessary to ensure the qualified state of Class 1E electrical cables (IAEA 2012). QM might include both environmental monitoring and cable condition monitoring (CM). During environmental monitoring, temperature, radiation dose, and radiation dose rate are typically recorded, in addition to other potential degradation sources, such as water, steam, etc., to evaluate actual exposure conditions. With CM, condition indicators (CIs), see Section 5, are measured incrementally during pre-aging. These CIs are then used periodically to confirm the qualified state of the cable.

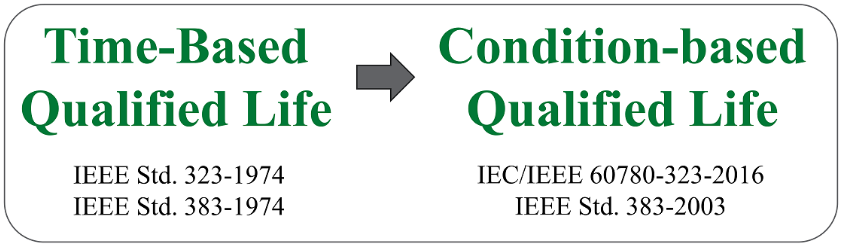


Figure 4-1. CBQ is based upon the concept of 'condition-based' as opposed to 'time-based' qualification.

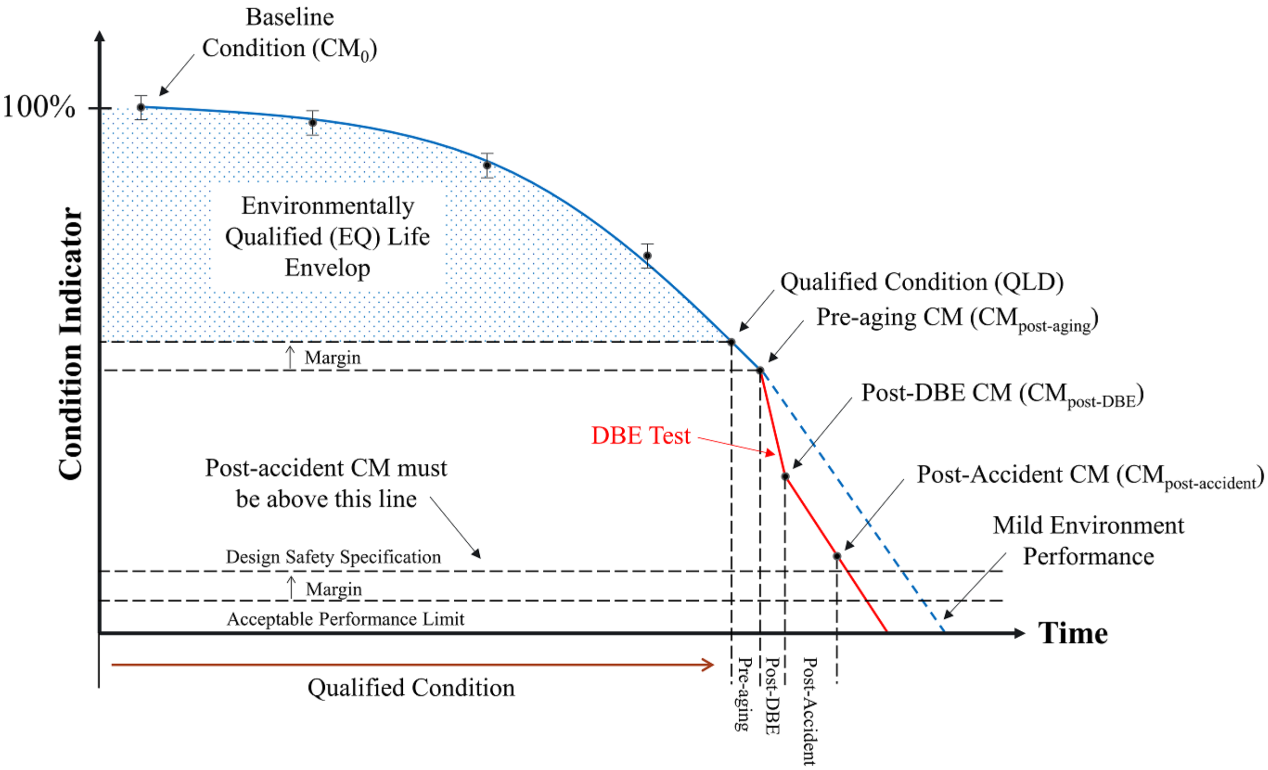


Figure 4-2. Condition-based qualification methodology for Class 1E electrical cables; adopted from (IAEA 2012).

Class 1E electrical cable qualification requires pre-aging as discussed in Section 3.2. The purpose of pre-aging is to conservatively stress the cable to end-of-life prior to accident exposure. During this process for CBQ, CIs are collected incrementally as shown by the data points along the degradation curve in Figure 4-2. One or more CIs may be collected during pre-aging and the shape of the degradation curve may vary between CIs. In addition, the measurement frequency of the CI needs to be determined prior to qualification and be sufficient to ensure the full degradation curve is established. After pre-aging, the CI value is recorded ($CM_{post\text{-}aging}$) and a margin is applied. The qualified condition or qualified level of degradation (QLD) is then determined based upon this end-of-life condition with an established margin. Assuming successful completion of the DBE simulation, *the QLD value represents the value against which future condition monitoring (CM) measurements are compared, to ensure the cable is within its qualified life*. Therefore, if CIs are above the QLD-value (lesser degree of degradation) during inspection (as shown by the blue region in Figure 4-2), the cable is assumed to be able to withstand a DBE. With a DBE, degradation is increased as shown by the red line in Figure 4-2. During DBE simulation, additional CM data points should be collected to establish CIs during the post-accident period. It is important that CIs do not fall below the design safety specification during a DBE, which is established by the acceptable performance limit and relevant margin (as given by the bottom dashed lines in Figure 4-2). To assist with evaluation of CIs during plant operation, test cables samples may be located in accessible regions with elevated stressors for the purpose of destructive and/or non-destructive measurements, or online methods may be incorporated (see Section 5 for more details).

Another approach to CBQ, as outlined in IAEA NP-T-3.6-2012, is incremental qualification. With incremental qualification, qualification is conducted in increments for increasing aging time points (e.g., 20 years, 25 years, 30 years, etc.). For each time increment, the QLD is established for the selected CI. As indicated, “the QLD becomes the degradation management limit for actual plant applications. The QLD point is then the performance capability indicator that will closely reflect and account for the historic environmental effects at the plant” (IAEA 2012). Such an approach is also advantageous for life extension of electrical cables.

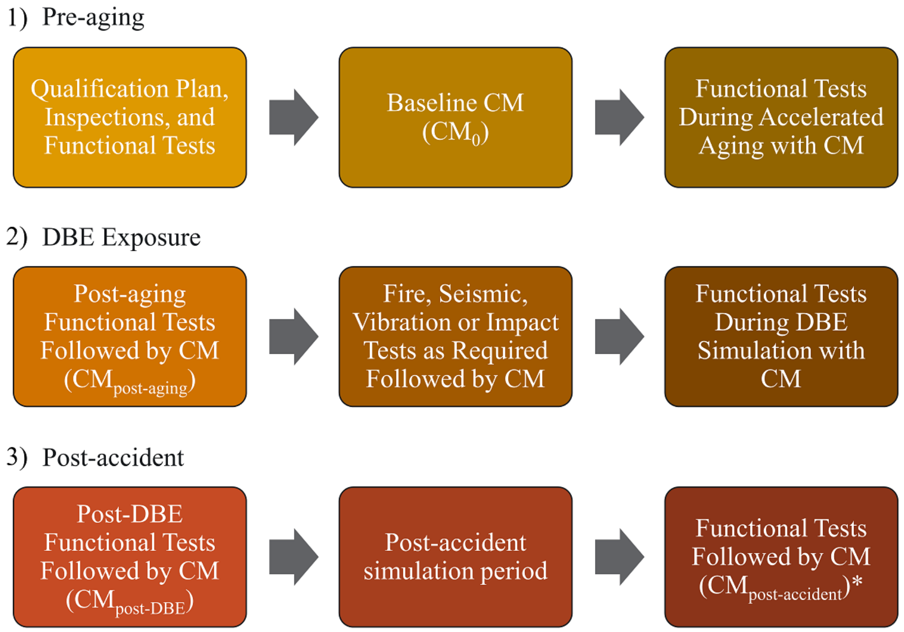
4.1.1 Condition-based Qualification Margins

The margins shown in Figure 4-2 are test margins meant to account for variations in production and test equipment. Therefore, these margins represent a safety factor for in-service conditions compared to qualification conditions. Common margins to include during CBQ are (IAEA 2012):

- Peak temperature: + 8°C
- Peak pressure: ± 10% of gauge
- Radiation: + 10% of accident dose
- Power supply voltage: ± 10% (within cable limits)
- Frequency: + 5%
- Vibration: + 10% acceleration
- Time: + 10% of minimum required duration plus one hour

4.1.2 General Condition-based Qualification Process

A general CBQ process, based upon the methodology of Figure 4-2 and Figure 3.2 in IAEA NP-T-3.6-2012, is outlined in Figure 4-3.



*Must be above design safety specification

Figure 4-3. A generalized condition-based qualification process; adopted from (IAEA 2012).

4.2 Example of CBQ

The Shanghai Nuclear Engineering Research and Design Institute (SNERDI) worked with EPRI to evaluate CBQ for a LV power and instrumentation cable meant for in-containment application (EPRI 2023). The cable had a low smoke, halogen free, dual cross-linked polyolefin (XLPO) insulation and a low smoke, halogen free, flame retardant XLPO jacket. The CBQ process followed is summarized in Figure 4-4. Three pre-aging conditions were investigated, including thermal aging only (165°C), two-stage radiation aging only (1 kGy/h up to 311 kGy followed by less than 12 kGy/h up to 600 kGy), and sequential radiation aging (1 kGy/h up to 250 kGy or 311 kGy) followed by thermal aging (155°C). The selected temperatures and dose rates were high and aimed at depletion of the qualified life (up to 80 years). To conduct CBQ, elongation at break was used as the reference CI and correlation was made between the elongation at break of the jacket and that of the insulation. Indenter modulus, oxidation induction time, thermogravimetric analysis, time/frequency domain reflectometry, and Fourier-transform infrared spectroscopy were also selected as CIs. After CBQ it was noted that while costs and approach were similar to historical time-based qualification, CBQ provided a constraint for cable replacement, which most cables will not reach due to the severity of the qualification process compared to in-plant conditions. Further, it was noted that the CBQ process does not require requalification costs associated with subsequent license renewal. In terms of CIs, elongation at break was found to produce a useful reference curve for CM due to a monotonic trend and provided the best end-of-life evaluation. In addition, indenter modulus was found to be useful for certain insulation materials, such as EPR, SR, and XLPO, and may also be a good leading indicator, particularly for correlating jacket degradation to insulation degradation. Lastly, detailed encoding or nomenclature rules were required to track CM due to complexity of the process.

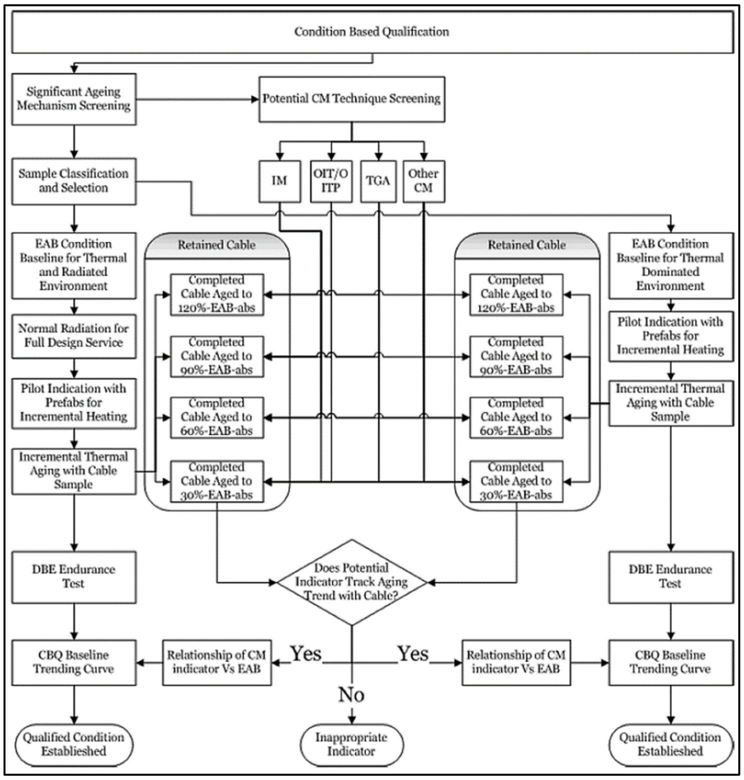


Figure 4-4. Process used to implement and establish CBQ (EPRI 2023).

4.3 CBQ Value Proposition

If successful, CBQ may enable: 1) improved understanding of actual cable conditions within NPPs and also provide additional confidence for re-analysis in license renewal; 2) enhanced regulatory confidence based upon actual data rather than re-analysis for license renewal or subsequent license renewal; and 3) optimized value of initial qualification for new and existing NPPs (EPRI 2024).

4.4 Stakeholders

Identified stakeholders for CBQ include regulators (e.g., NRC), NPP licensees (e.g., plant operators, owners group), service providers, qualification facilities, standards bodies (e.g., IEEE, IEC, ASTM, etc.), research bodies (e.g., EPRI, DOE, etc.), consulting engineering firms, and the nuclear stream supply system (NSSS) vendors (EPRI 2024).

4.5 CBQ Barriers

Potential barriers to transition to CBQ are listed below.

- Condition indicators
    - Need for CI data to accelerate CBQ implementation
    - How to obtain samples for CI development (i.e., harvesting)
    - Testing criteria beyond indenter modulus for non-destructive testing (non-destructive methods are preferred over destructive)
    - Understanding of CIs for different materials and environments
    - Relation of CM and associated CIs to original time-based qualification
    - Lack of specimens and data on older cables and how to resolve to create a CI
    - Establishing a technical basis for CI implementation
- Business case
    - What are the needs and opportunities?
    - Cost benefit analysis and business case for industry
    - Buy-in from stakeholders
    - Case studies to demonstrate value of CM development
    - What are the potential costs?
- Aging management
    - Creation of a universally understandable CBQ framework guide for use in developing standards, regulatory guidance, etc.
    - Challenges or resistance for industry implementation (e.g., testing difficulty, outage management challenges, etc.)
    - Impact to aging management program (AMP) in licensing basis
    - Logistics of implementing CM task in containment
    - Management of value and need to harvest cables to support CBQ
    - How to ensure a repeatable process for testing methodology and collected data
    - Hesitancy to collect environmental data which may support CBQ CM and/or CIs
- Regulation
    - Concerns with regulatory involvement and endorsement inhibiting licensee willingness to test regardless of results
    - Cultural shift for paradigm change in methodology
    - Acceptance of results that differ from current qualification basis
    - How to reconcile acceptability of CM, CIs, and CBQ implementation of a new program between regulator and licensee
    - Proof that CM methods are consistent and repeatable
- Demonstration
    - U.S. industry demonstration case for a first of a kind CBQ
    - Validation of methods and development to show applicability to in-plant conditions
    - Having enough data to use CM/CIs by applying them across a class of cable types (e.g., XLPE, EPR, etc.) to optimize implementation costs versus different formulation or manufacturer

5. CONDITION INDICATORS

CBQ makes use of CIs to ensure Class 1E electrical cables are within their qualified life. CIs are physical measurements, such as elongation at break (EAB) (IEC/IEEE 2012) or indenter modulus (IM) (IEC/IEEE 2011), that trend with equipment aging and that are collected during the qualification process, see Figure 4-2. It is critical that appropriate CIs are selected during qualification planning. As discussed in IEC/IEEE 60780-323-2016, CIs shall be "leading indicators of adverse change in condition directly related to the ability of equipment to function and directly related to the degree of ageing performed in the program." To establish CIs, non-destructive and non-intrusive test methods are preferred. In addition, as appropriate for the aging of concern, one or more CIs may be used to determine if a cable remains in a qualified condition. Per IEC/IEEE 60780-323-2016, CIs are required to be:

1) Measurable, repeatable, and accurate;
2) Monotonically varying with time;
3) Trend consistently from unaged through the qualified pre-accident condition;
4) Linked to electrical cable degradation; and
5) Correlated to the safety function of the cable under DBE events.

The response of the CI to environmental stressors is determined during pre-aging as discussed in Section 3.2 or during aging on similar equipment undergoing the same aging conditions. Specifically, CIs shall be collected at time increments during pre-aging to establish data for comparison during service. It is important that the CI response is established at the conclusion of pre-aging, prior to accident exposure. If qualification has already been completed, incremental CI measurements can be made on replicate equipment. The incremental response of the CI needs to be such to allow "distinguishing the degree of aging and … consistent enough to establish a qualified condition" (IEC/IEEE 2016). With CBQ, qualified equipment remains qualified until the CI reaches the pre-accident exposure response, accounting for margin (QLD as shown in Figure 4-2).

A list of potential CIs that have been observed to be associated with cable degradation are shown in Table 8; more details regarding CIs can be found in literature (IAEA 2012; NRC 2012, 2014; EPRI 2023). First, the type of test is important to identify which mechanism(s) are under evaluation; for example, indicators of structural integrity and electric function are desirable for electrical cables (NRC 2014). Second, the location of the test is also important as lab-based techniques are not usable during normal operation, not usable in areas of limited access, and may require disturbance of the cables. Third, destructive test methods require portions of the cable to be destroyed during CM, which may not be possible or desirable, particularly if a cable repository was not established. As many CIs are heavily dependent upon technology, care also needs to be taken that measurement of the CI does not disturb the cable-under-test nor is intrusive. Fourth, the ability of the CI to detect degradation along the cable-under-test is also desirable, which is indicated as full-length (F); however, it should be noted that full-length CM techniques may or may not measure the distance to a detected anomaly. Fifth, as CIs do not necessarily trend with different insulation and/or jacket materials, care needs to be taken to ensure that CIs track with polymeric aging, particularly during early aging to provide adequate time for corrective action. Lastly, online CIs enable CM without disturbing cables and/or disconnecting equipment, are usable during normal operation, may be usable in limited access areas, and can be cost-effective (NRC 2014). Additional guidance regarding CIs is being developed in IEEE P1186 to assist with applying test methods and quantifying degradation.

In terms of the CIs shown in Table 8, prior work (EPRI 2023; NRC 2023b) has observed EAB trends best with polymeric cable degradation, particularly near end-of-life. In addition, IM has demonstrated large trends with aging for many material types, shown to produce correlation between jacket and insulation aging, and is also non-destructive and non-intrusive. Lastly, reflectometry approaches enable online distance-to-fault detection, which is advantageous when coupled with local CI test methods.

Table 8. Potential CIs for CBQ of Class 1E electrical cables; adopted from (IAEA 2012).

CI	Type	Test Location	Destructive/ Intrusive	Local or Full-length	Example Materials	Online
Density	Chemical	Lab	Microsample	L	EPR, XLPE (minor)	No
FTIR	Chemical	Both	Maybe/No	L	All (primarily polar)	No
Gel Fraction	Chemical	Lab	Microsample	L	Not SIR	No
Infrared	Chemical	Lab	Yes/Yes	L	EPR, PE, XLPE, PVC	No
NIR	Chemical	Both	No/No	L	EPR, PE	No
NMR	Chemical	Lab	Microsample	L	All	No
O_2 Consumption	Chemical	Lab	Microsample	L	All	No
OIT	Chemical	Lab	Microsample	L	EPR, PE, XLPE, PVC	No
Surface Energy	Chemical	Lab	Yes/Yes	L	All	No
TGA	Chemical	Lab	Microsample	L	PVC, CSPE, EPR	No
UV-vis	Chemical	Lab	Microsample	L	All	No
XRD	Chemical	Lab	Microsample	L	All	No
AC Breakdown	Electrical	Lab	Yes	F	All	No
Tan Delta	Electrical	Both	No/Maybe	F	All	Maybe
FDR	Electrical	Both	No/Maybe	F	All	Yes
IDC	Electrical	Both	No/Maybe	L	All	Yes
IR	Electrical	Both	No/Maybe	F	All	Maybe
LCR	Electrical	Both	No/Maybe	F	All	Maybe
Partial Discharge	Electrical	Both	No/Yes	F	All	No
SSTDR	Electrical	Both	No/Maybe	F	All	Yes
Surface Wave	Electrical	Both	No/Maybe	L	All	Yes
TDR	Electrical	Both	No/Maybe	F	All	Yes
DMA	Physical	Lab	Yes/Yes	L	All	No
EAB	Physical	Lab	Yes/Yes	L	All	No
Hardness	Physical	Lab	Microsample	L	Most	No
IM	Physical	Both	No/No	L	PVC, CSPE, EPR	No
Relaxation	Physical	Both	No/No	L	All	No
Borescope	Visual	Field	No/Yes	L	All	No
Color	Visual	Both	No/No	L	Not dark colored	No
Inspection	Visual	Field	No/No	L	All	No
Thermography	Visual	Field	No/No	L	All	No

FTIR = Fourier-transform infrared; NIR = near infrared reflectance; NMR = nuclear magnetic resonance; OIT = oxygen induction time; TGA = thermogravimetric analysis; UV-vis = ultraviolet-visible; XRD = X-ray diffraction analysis; DS = dielectric spectroscopy; FDR = frequency domain reflectometry; IDC = interdigital capacitor; IR = insulation resistance; LCR = inductance, capacitance, resistance; SSTDR = spread-spectrum time domain reflectometry; TDR = time domain reflectometry; EAB = elongation at break; IM = indenter modulus.

5.1 Condition Monitoring of Electrical Cables

To further understanding of "leading indicators of adverse change" for the aging of electrical cables and to support CBQ, continued development of cable CM technology is crucial, particularly of emerging online techniques. The ability to foresee imminent cable demise through accurate CM provides the opportunity to plan for repair or replacement, or to accept the risk of failure with clear information. While CM techniques have seen growth in options and improvement in diagnostics and fault detection, practical implementation of CM has a few limitations. First, there is no single CM method (or CI) to comprehensively evaluate cable performance and safety, and therefore a combination of multiple full-length and/or local tests may be required to collectively provide a high reliability assessment of performance. Second, most of the diagnostic CM techniques (reflectometry, dielectric spectroscopy, tan delta, etc.) require cables to be powered down and/or disconnected on at least one end to implement the test, which can disturb the cable and also result in higher operation and maintenance (O&M) costs. Consequently, to improve the efficiency and cost-effectiveness of cable testing, in addition to industry acceptance of CBQ, alternative ways to implement fewer and more robust CM techniques for assessment is desired. Two burgeoning initiatives that are expected to help manage time and costs are 1) online monitoring (i.e., CM on live or energized cables) and 2) employing CM techniques that can be implemented even with a connection (i.e., a motor) attached (e.g., EPRI 2019). The transition to online monitoring for real-time assessment can lower costs associated with significant down time caused by de-energizing and disconnecting systems to perform testing and also enable real-time CI measurement, which avoids issues with measurement frequency. In addition, implementing CM tests that can be performed while leaving devices connected will help minimize time and costs associated with disconnection and re-connection. In this context, research studies and pilot-scale evaluation of the efficacy of fledgling CM technologies (e.g., Glass et al. 2024) that exhibit potential for reduced costs and higher efficiency are invaluable steps towards future implementation of these technologies in NPPs for CBQ.

The advantages and disadvantages of selected local and full-length CIs are shown in Table 9 and Table 10, respectively. With full-length measurement, electrical characteristics that are tied to function can be tested non-destructively. In addition, full-length techniques evaluate the entire cable assembly, and some can even identify damage locations (e.g., time domain reflectometry, frequency domain reflectometry, etc.). On the other hand, local measurement techniques provide quantitative information regarding the status of health but are limited to accessible cable portions or cable deposits. Below, focus is given to non-destructive, full-length electrical CM approaches as these methods are generally applied for in-situ evaluation of cables, able to evaluate cable function, potentially online, and are expected to be attractive for CBQ (Villaran and Lofaro 2002).

Table 9. Local CI measurement approaches for CM of cables (Glass et al. 2015).

Method	Advantages	Disadvantages
Infrared Spectroscopy	Sensitive to chemical changes on the jacket and outer surface (e.g., the presence of dirt, oil, etc.).	May over-predict jacket or surface damage not indicative of bulk condition. Also sensitive to surface condition.
Visual Walk-downs	Simple and low-cost test method.	Not quantitative and subjective.
EAB	Strongest direct indication of aging damage and classically used in EQ.	Destructive method.
IM	Simple test that is broadly accepted.	Issues when testing some materials, such as XLPE. Limited to accessible external surface (e.g., jacket).
DMA	Promising technique and potential for broader application than indenter.	Currently used in laboratory settings.

EAB = elongation at break; IM = indenter modulus; DMA = dynamic mechanical analysis.

Table 10. Full-length CI measurement approaches for CM of cables (Glass et al. 2015).

Method	Advantages	Disadvantages
TDR	Commonly used for locating defects where full-length cables are relatively inaccessible. Test uses low voltages and is completely nondestructive.	Intrusive – requires disconnecting at least one end of the cable to perform the test if conducted offline. Not particularly sensitive to insulation damage.
FDR	LV, tests full cable including insulation, can identify flaw location. More sensitive than TDR.	Intrusive – requires disconnect if performed offline. Data interpretation can be challenging due to noise.
Partial Discharge	Stepped HV test that identifies cable weakness to point of insulation break-down.	May damage weak or compromised cables and can cause noise and damage in near-by circuits. Applicable to MV and HV, not LV cables.
IR	Commonly performed in industry to determine the condition of the cable insulation – primarily as a screening for other tests.	Inconsistent readings weaken broad acceptance of this test.
DS	Determines dielectric impedance as a function of applied voltage at frequencies apart from power frequencies.	Intrusive, requires decoupling both ends. No information regarding degradation location. Loss metrics trends over time may be needed to interpret individual measurements.
Tan δ	Measures insulation degradation associated with increased resistive current. Stability of value and change in value with applied voltage form actionable metrics. Combination with withstand can prevent in-service failures.	Intrusive, historically has required decoupling of both ends and application of high voltage.

TDR = time-domain reflectometry; FDR = frequency-domain reflectometry; PD = partial discharge; IR = insulation resistance; DS = dielectric spectroscopy; Tan δ = tangent delta.

5.1.1 Online Condition Monitoring

Online CM refers to approaches where the evaluated cable is online and energized – the cable does not need to be disconnected, which can lead to significant cost savings and simplification of the CBQ process. In addition, online methods enable capturing of transients, which may enable improved detection and forensics of events of interest. Online CM is a relatively new approach to CM within NPPs, with SSTDR being a technology that has primarily been investigated (Glass et al. 2022). However, most electrical-based reflectometry approaches are anticipated to be amenable to online measurements. It is noted that, to date, online condition monitoring methods are in early stages of development and have yet to be fully demonstrated, established, or deployed.

Electrical reflectometry CM techniques are non-destructive methods based on the reflection of electromagnetic waves at surfaces and/or interfaces to locate changes and characterize various objects. Within the realm of material characterization, reflectometry techniques may be applied to non-destructively conduct distance-to-fault (DTF) measurements on electrical cables and components. Based on the type of input signal used and the method for analysis of the reflected signal, reflectometry techniques applied for cable evaluations may be broadly categorized as frequency domain reflectometry (FDR) or time domain reflectometry (TDR). For FDR measurements, the steady-state amplitude and phase of the reflected signal is built up over numerous discrete frequencies, while for TDR signals, the reflected signal is measured at discrete moments in time. A study performed in 2006 (Furse et al. 2006) compared several types of reflectometry systems focusing on aircraft wiring networks. The systems reviewed are summarized in Table

11. In addition to electrical reflectometry, electrical approaches to CM include partial discharge (PD), insulation resistance (IR), dielectric spectroscopy (DS) or tan delta as discussed below.

Table 11. Comparison of reflectometry methods (Glass et al. 2021).

Wire Fault Sensor	Accuracy (in)	Min. Length (in)	Max. Length (ft)	Computation	Network Topology Recognition
TDR (Megger. 2020)	6-12	5	100+	Edge Identification	Yes
FDR (Furse et al. 2003)	2	4	50+	FFT; Peak Identification	Yes
SSTDR (Furse et al. 2005)	1	4	70+	Peak Identification	Yes
Capacitance (Chung et al. 2009)	1	1	100+	Linear Curve Fit	No

TDR = time domain reflectometry; FDR = frequency domain reflectometry; SSTDR = spread-spectrum time domain reflectometry; FFT = fast Fourier transform.

5.1.1.1 Time Domain Reflectometry

TDR measures reflections of a stepped or impulse signal along a single conductor to detect and locate any changes in the conductor or insulation impedance. A TDR pulse is usually less than 10 volts and is primarily in the higher frequency range (> 1 kHz), so the pulse has little or no effect on low frequency signals or on 50/60 Hz power excitation. TDR transmits an incident signal into the conductor and listens for signal reflections. If the conductor is a uniform impedance network and is terminated to a matching impedance, then there will be no reflections and the transmitted signal will be completely absorbed at the far end by the termination. Instead, if there are impedance variations as in a short or open circuit at the cable end, a damaged or reduced cross-sectional area, or a splice with a higher resistance along the conductor, then some fraction of the incident signal will be reflected to the source. The polarity of the reflection contains information about the reflector. An open cable end will reflect “in-phase” with the excitation and a short will reflect as an inverted signal. This reflected signal is measured at a point in time on the TDR instrument that is proportional to the signal propagation velocity in the cable and the distance along the cable, thereby allowing assessment of the location of any reflector observed. The amplitude of the reflected signal coupled with the inherent cable attenuation characteristics also allows an estimate of the magnitude of the impedance change. An example TDR plot is shown in Figure 5-1.

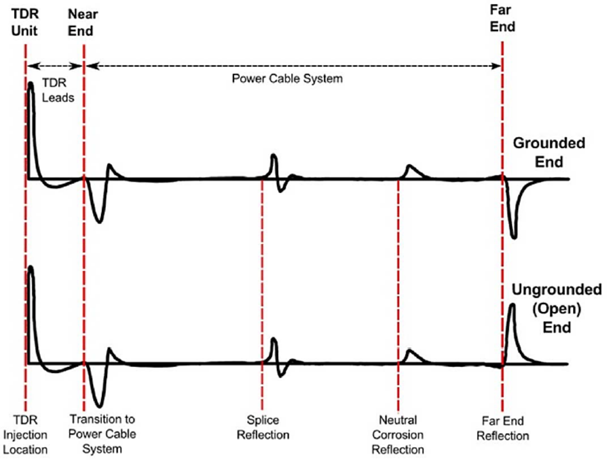


Figure 5-1. Typical test plot of TDR applied to a cable with a splice (Hernandez-Mejia 2016). The effect of grounding the cable is also shown.

Several enhancements to the traditional TDR measurement are available today for locating electrical faults based on reflectometry concepts. These include standing wave reflectometry (SWR), mixed signal reflectometry (MSR) (Tsai et al. 2005), multicarrier reflectometry (MCR) (Naik et al. 2006) and sequence/spread spectrum time domain reflectometry (S/SSTDR). For online applications, S/SSTDR has been most fully exploited in the aircraft industry and the rail industry where low-cost ASIC-based instruments have been developed for online monitoring of control and power circuits up to 1000 volts.

5.1.1.2 Spread-Spectrum Time Domain Reflectometry

SSTDR is a combination of spread spectrum (SS) and TDR techniques. SSTDR shows promise as a robust online cable monitoring technique owing to its ability to operate on energized cable systems. This feature is in sharp contrast with traditional reflectometry methods that have historically required cables to be de-energized and de-terminated prior to testing. Similar to conventional reflectometry, SSTDR sends an excitation signal down the length of the cable and an analysis of the reflected signal is carried out to identify impedance discontinuities in the cable corresponding to faults and anomalies. The key difference lies in the type of signal used in SSTDR testing. SSTDR uses a high frequency pseudo-random-noise (PN) coded excitation signal, which reflects off impedance discontinuities in the cable. The PN code effectively distributes the energy of the input signal across a broad spectrum (hence the name, spread spectrum), resulting in the signal traveling through the cable with little to no interference at any individual frequency in an energized cable. The reflected signal is then cross correlated with the input signal to produce a reflectometry spectrum. While SSTDR has found application in aircraft and railway industry, the technology is in the developmental stages for application in the NPP industry. Evaluation of SSTDR performance against trusted cable monitoring technologies is critical for further development and eventual application of SSTDR to monitor energized cables in service and for CBQ. A typical SSTDR test plot is shown in Figure 5-2.

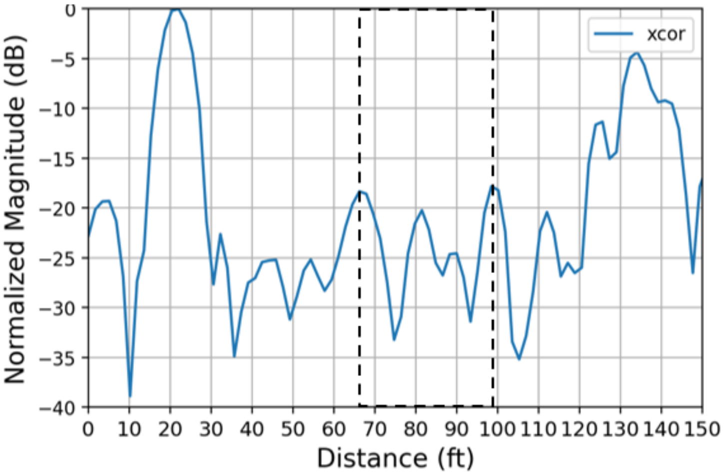


Figure 5-2. SSTDR response for an electrical cable thermally aged at 140°C for 62 days (data collected at the Pacific Northwest National Laboratory).

5.1.1.3 Frequency Domain Reflectometry

FDR is a nondestructive electrical inspection technique used to detect, localize, and characterize subtle impedance changes in power and communication system conductors and insulation materials along the length of a cable from a single connection point. FDR is based on the interaction of electromagnetic waves with conductors and dielectric materials as the waves propagate along the cable, similar to TDR. The technique uses the principles of transmission line theory to locate and quantify impedance changes in the cable circuit. These impedance changes can result from connections, faults in the conductors, or degradation in polymeric materials. Two conductors in the cable system are treated as the transmission line through which a LV swept-frequency waveform is propagated. A linearly increasing "chirp" sinusoidal waveform is the typical excitation signal used in the FDR technique. The excitation signal can be generated for transmission into the cable using an analog circuit, such as a voltage-controlled oscillator, or using a digital circuit such as a direct digital synthesizer. As the excitation signal is swept over the frequency range and the associated electromagnetic wave travels down the cable, the impedance response, or more specifically the reflected complex voltage, is recorded at each frequency to characterize wave interaction with the conductors and surrounding dielectric materials. The remote end of the cable can be terminated in an arbitrary impedance different from the cable characteristic impedance but is often grounded or open-circuited during testing. Because the applied signal is LV, the test is nondestructive and poses no special safety concerns to operators assuming that routine electrical safety procedures are followed. The distance-to-fault of a typical FDR plot is shown in Figure 5-3.

The FDR technique can potentially yield better sensitivity to cable degradations than traditional TDR, which is better suited for identifying open and short circuit conditions in the conductors. For example, FDR is less susceptible to electrical noise and interference due to the availability of filtering and noise-lowering algorithms in the frequency domain, which can lead to increased sensitivity and accuracy. In addition, TDR pulses may have difficulty continuing in the forward direction after several significant reflections or multiple reflections. This may complicate the correlation between the impedance change and the corresponding location on the reflectometry waveform. Conversely, FDR has a high dynamic range and is better suited for identifying and characterizing a series of multiple degradations in long cables, although there can be issues with teasing out multiple, close proximity degradations. Current work at the Pacific Northwest National Laboratory is demonstrating the usage of FDR online to detect cable anomalies.

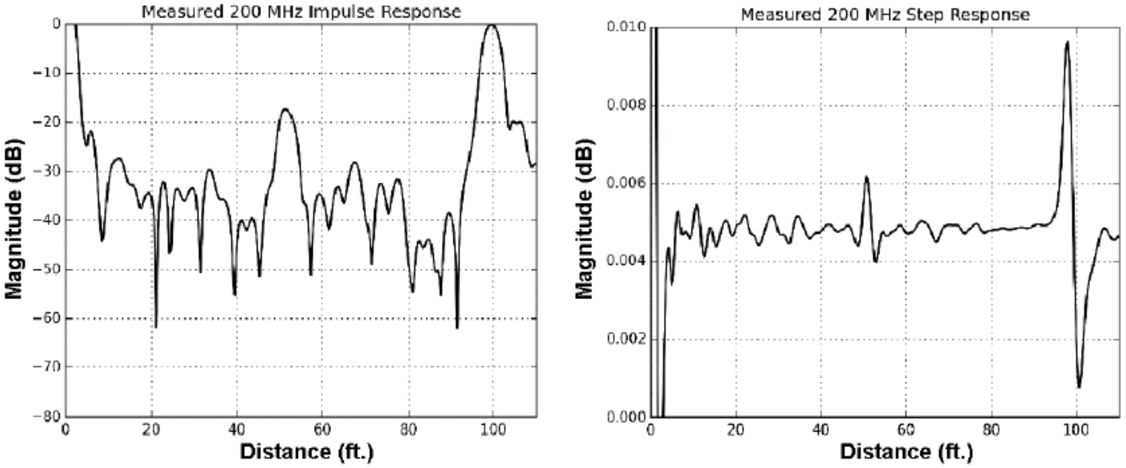


Figure 5-3. Measured FDR response for a shielded triad cable with mechanically damaged defect at mid-point: (left) impulse response and (right) step response (Glass et al. 2016).

5.1.1.4 Partial Discharge

PD are electrical discharges that can result from charge build up at inclusions or defects in MV or HV solid insulation. PDs do not bridge the whole insulation (i.e., they do not extend from conductor to ground) but can lead to material failure. A PD takes place in a nanosecond and causes high-frequency currents, which are measurable by PD detection equipment. After a discharge, both positive and negative charges are deposited on the surfaces of the voids or tree channels. These charges change the localized electric field, thereby controlling the time when the next PD will take place along with changes in the applied sinusoidal voltage. The net result is a pattern of PDs of various magnitudes, repetition rates, and phase angles relative to the applied voltage. During testing in which the voltage is slowly raised, the voltage at which discharges are observed in each cycle are known as the PD inception voltage. On decreasing the voltage slowly from above the PD inception voltage value, the voltage at which PD ceases to occur is referred to as the PD extinction voltage. PD will often become intermittent before complete extinction occurs. Because of the deposition of charges on the surfaces of the voids caused by PD, the PD extinction voltage can theoretically be as low as 50 percent of the inception voltage. In practice, the difference is between 10 and 25 percent. To ensure that a cable is discharge-free at the operating voltage, it is necessary to test for PD at levels up to twice the operating voltage. Decrease in the PD inception voltage is an indication of significant degradation of the insulation material. A cable that has PD at operating voltage or within 1.5 times the operating voltage is generally significantly deteriorated and may fail soon. Cables that have no significant PD at levels up to twice the operating voltage have no immediate expectation of failure from PD and will operate satisfactorily for a significant period. An example PD plot is shown in Figure 5-4.

Modern PD detection equipment can provide three-dimensional plots showing the phase, magnitude, and number of PDs. From the characteristics of these plots, it may be possible to identify the source of the PD (e.g., from spherical or flat cavities or voids, electrical trees, or interfaces). The PD test is potentially damaging because the discharges induced can cause degradation of the insulation over time from localized overheating. This test has limitations for use in the field because it requires relatively high voltages to be applied to the cable, which would be a concern due to the potential for damaging the cable or surrounding equipment. PD is typically performed on MV cables that are de-energized and disconnected. Additionally, nearby operating electrical equipment in a plant environment could interfere with the test because of noise interference, so this test is most successful on shielded cables.

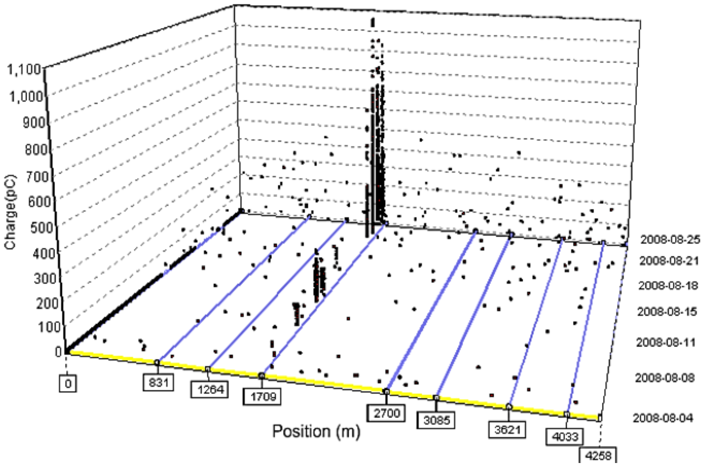


Figure 5-4. 3D plot of online developing PDs in a flawed joint with a crimped connector running hot at 1678 m (Cuppen et al. 2010).

5.1.1.5 Insulation Resistance

Arguably the most straight forward bulk CM technique, IR measures the resistance of insulation within cable systems. In many cases, IR can be measured using a simple multimeter. As polymers are typically electrical insulators, IR can be used to identify phases that have failed or are faulty. With damage and aging, IR readings typically trend downward over time. While IR does not identify the location of damage, it is commonly used as a starting point to identify anomalies. A typical IR plot is shown in Figure 5-5.

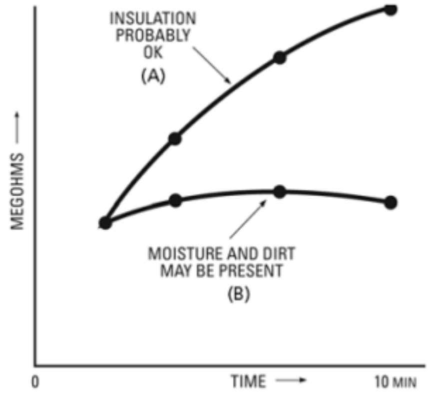


Figure 5-5. IR response for moisture or contaminated insulation (Megger 2006).

5.1.1.6 Dielectric Spectroscopy

As reviewed by (Glass et al. 2019), the dielectric spectroscopy (DS) test is described in (EPRI 2011) as a current passing through the cable insulation in response to a step change in voltage. This current can pass between the cable conductor and a shield or between two conductors in a multi-conductor cable assembly. The current response to voltage is transformed to arrive at dielectric impedance as a function of frequency. The variation in impedance is primarily due to bulk cable capacitance and conductance. The real and imaginary parts of the permittivity, the change in the real permittivity, and the tan δ or loss tangent (ratio of the imaginary part of the complex permittivity to the real part) are evaluated with respect to voltage and frequency change. At each applied voltage, a frequency sweep is performed and the permittivity and tan δ parameters are evaluated.

The following four behaviors have been defined:

1. *Low-loss, linear permittivity*: The response for new or non-water tree deteriorated cables. The results are nearly frequency-independent, the loss is low and has a very weak frequency dependence, and the real and imaginary parts of the permittivity are independent of applied voltage.
2. *Voltage-dependent permittivity:* An indication of water treeing that is significant but has not yet penetrated the whole of the insulation, in which the real and imaginary parts of the permittivity are voltage-dependent.
3. *Transition to leakage current:* An indication that the water trees penetrate through the wall of the insulation and that the breakdown strength of the insulation is significantly reduced. The transition is indicated by an increased loss at the time of applied voltage. In other words, the second measurement at a specific voltage level has a higher loss than the initial measurement.
4. *Leakage current*: An indication that water trees penetrate the whole of the insulation and the cable has very low breakdown strength. Leakage current is observed at low voltages, loss increases with decreasing frequency, and the real part of the permittivity shows a voltage-dependent response. (Glass et al. 2019)

One of the values of DS testing is that it can be performed at frequencies other than power frequencies. A representative DS plot of tan δ versus frequency for series of aged cables is provided in Figure 5-6.

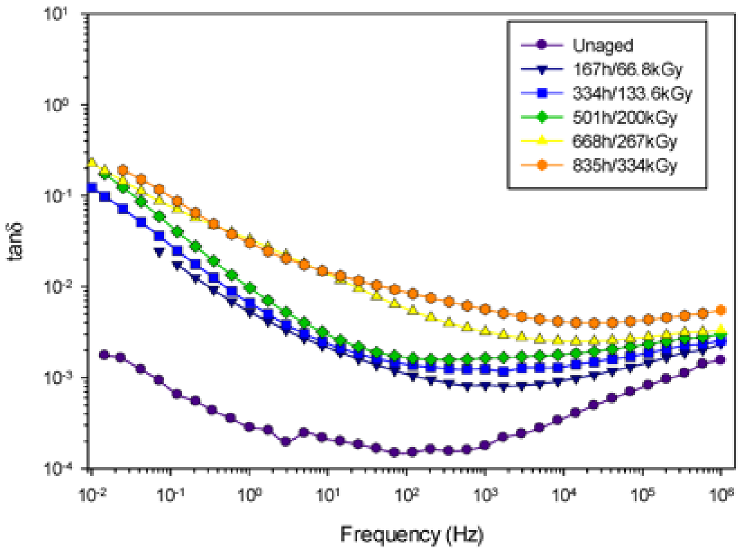


Figure 5-6. Dielectric spectroscopy plot showing tan δ response for a twisted pair cable undergoing radiation aging at different aging time points (Suraci et al. 2022).

5.1.1.7 Tan Delta and Withstand

In contrast to DS, the so-called tan delta (tan δ) technique is usually performed at a single frequency, such as a very low frequency (VLF) value of 0.01 Hz to 0.1 Hz. The concept of the tan δ test is described in (EPRI 2105b), which considers that a cable in good condition acts as a capacitor. The charging current of the capacitor (I_C) is 90° out of phase with the voltage applied across the cable insulation, such as between the cable conductor and a cable shield. Degraded insulation has a resistive current component (I_R) that is in phase with the applied voltage. Tan δ is the angle created by the vector equivalent current ($I_C + I_R$) and the y-axis depicted in Figure 5-7. An increasing I_R is an indication of cable insulation degradation, which is manifested by an increased magnitude of tan δ. Delta tan δ, or the increase of tan δ value with increasing applied voltage, is used as an indicator of the presence of an ionization potential. The stability of tan δ during each applied voltage step is equivalent to percent standard deviation, which is used to evaluate the degree of degradation of the ionization potential.

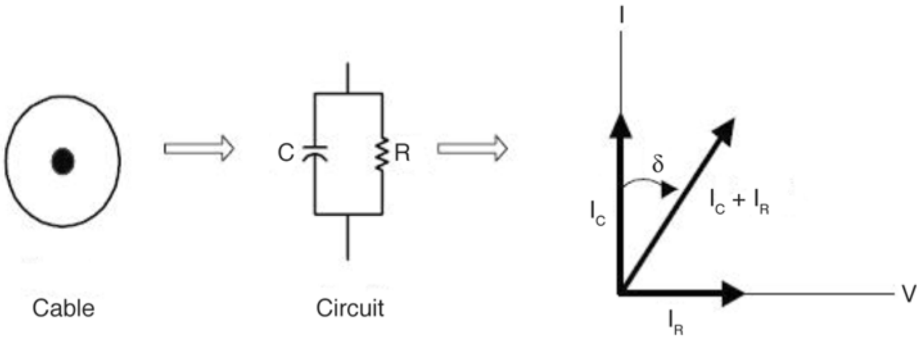


Figure 5-7. Tan δ depiction of loss angle from (EPRI 2015b).

The tan δ test method applies [test voltages] in three or four increasing voltage steps. Test voltages are defined as a fraction of cable line-to-ground operating voltage (U_0). The voltage steps are done in 3 to 4 min increments at values of 0.5 U_0, 1.0 U_0, and 1.5 U_0. Historically, the fourth step was 2.0 U_0, but recently it has often been replaced with the (IEEE 2013) recommended withstand voltage and duration. EPRI has developed recommended guidance for acceptance thresholds for some cables (EPRI 2015b), but sensitivity and reliability are best if used as a regular periodic test where results can be compared to reference data and trended.

This withstand test combined with the tan δ is known as a monitored tan δ withstand test, or just monitored withstand test. The final test voltage is held for 15 to 60 min with 30 min the commonly used time. The monitored withstand test combines the diagnostic capability of tan δ and the intent of the withstand test, which is to prevent the masking of a single large insulation defect that may be caused by the circuit configuration, such as a bad splice, termination, or the longer length of the cable. (The same defect on a short cable will be smaller in magnitude on a long cable). A monitored withstand test combines the bulk insulation condition evaluation of tan δ with the ability of the withstand test to prevent in-service failure caused by a large single defect. (EPRI 2015b)

5.2 Condition Indicator Acceptance Criteria

Since mechanical durability and dielectric insulation properties are the material properties that matter to the safety functions of electrical cables, the importance of EAB might not be replaced by any other chemical or mechanical properties. Practical cable aging management based on condition monitoring data relies on acceptance criteria with easily interpreted test outcomes, such as corresponding to ‘reliable’, ‘test again soon’, or ‘not reliable’ cable status. For each cable testing method, therefore, sufficient understanding of the correlation between the test results and the material state is required. In the absence of established acceptance criteria, many test methods trend well with aging, but are less useful for single snapshot measurements. New test methods often must be developed in consensus-based standards (e.g., IEEE) prior to endorsed usage (e.g., by the regulator). Examples of a few common acceptance criteria are shown in Table 12.

Table 12. Common acceptance criteria for select condition indicators; adopted from (IAEA 2012).

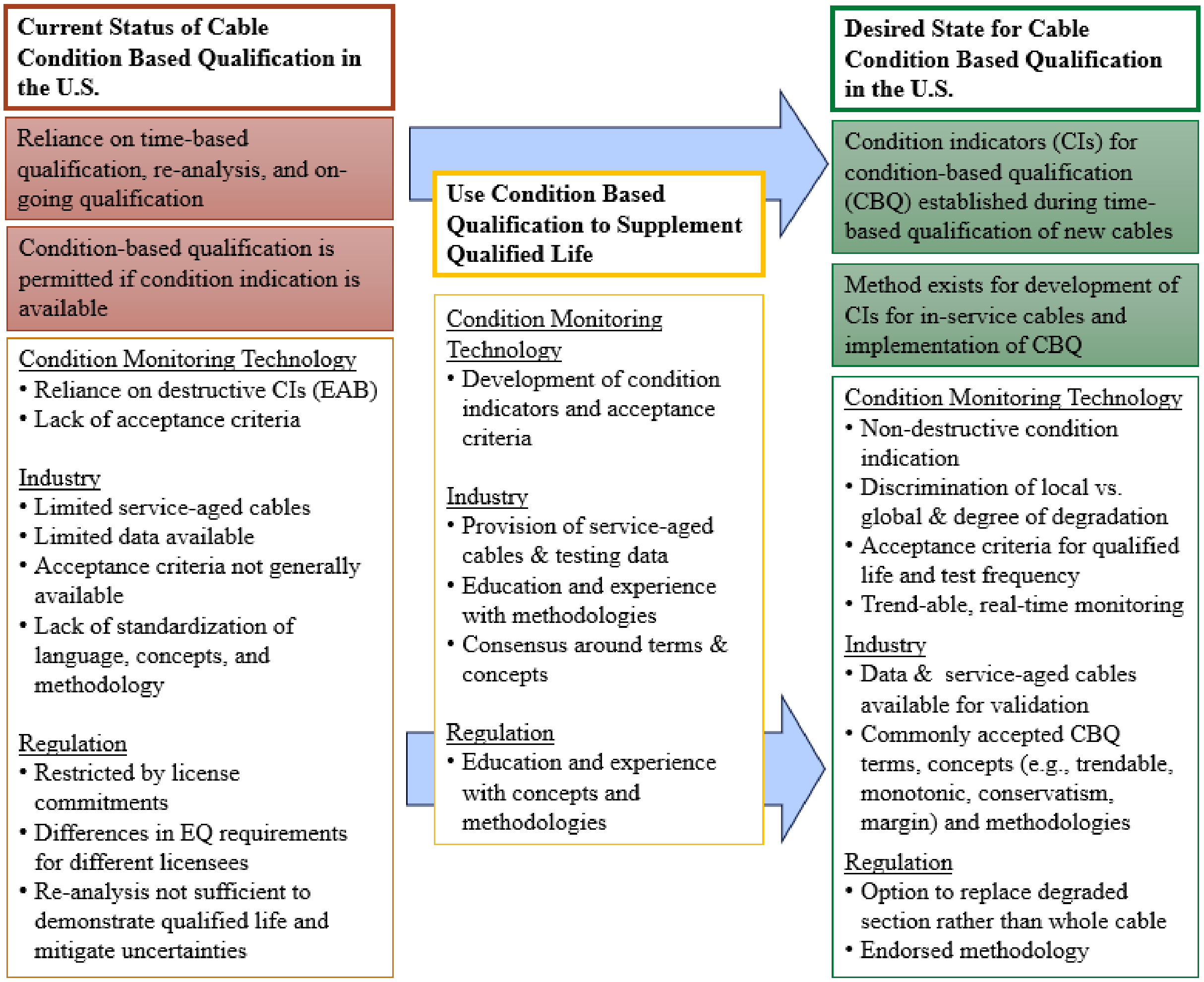
CI	**New Cable**	**After Pre-aging**	**During/After DBE**
EAB	No variation from specification	> 50% absolute	Not specified
IR	No variation from specification, $\geq 10^8$ Ω-m	Within one order of magnitude of specification, $\geq 10^8$ Ω-m	Within four orders of magnitude of specification, $\geq 10^8$ Ω-m
LCR	No variation from specification	No variation from specification	No variation from specification
Tan δ	See (EPRI 2013)	See (EPRI 2013)	Not specified
EAB = elongation at break; IR = insulation resistance; LCR = inductance, capacitance, resistance.			

6. CONSENSUS-BASED QUALIFICATION ROADMAP

Condition-based qualification is an alternative to the time-based qualification approach that has been used exclusively in the U.S. nuclear industry. With CBQ, the assurance of equipment reliability based on simulated performance over a designated period (e.g., 40 or 60 years) is instead based on actual equipment condition. Further, an enhanced understanding of safety-related equipment condition is possible with CBQ, which is arguably safer and potentially more cost effective than traditional qualification, especially with online CM approaches. However, many questions remain regarding implementing CBQ as discussed in Section 4.5, especially in transitioning from a time to a condition qualification basis for cables in existing plants. Below, a path forward for a consensus-based approach to CBQ is discussed.

6.1 Tentative Path Forward

An initial workshop on CBQ was planned by the DOE/EPRI/NRC cable research working group in 2023 held at the EPRI location in Washington, D.C. in January 2024. The event brought together key stakeholders with a diverse set of perspectives. The workshop considered what might be the desired state of CBQ in practice and what are the gaps between the current state and that desired state (EPRI 2024). The tentative roadmap basis discussed at the workshop is summarized in Figure 6-1.



Current Status of Cable Condition Based Qualification in the U.S.

Reliance on time-based qualification, re-analysis, and on-going qualification

Condition-based qualification is permitted if condition indication is available

Condition Monitoring Technology
- Reliance on destructive CIs (EAB)
- Lack of acceptance criteria

Industry
- Limited service-aged cables
- Limited data available
- Acceptance criteria not generally available
- Lack of standardization of language, concepts, and methodology

Regulation
- Restricted by license commitments
- Differences in EQ requirements for different licensees
- Re-analysis not sufficient to demonstrate qualified life and mitigate uncertainties

Use Condition Based Qualification to Supplement Qualified Life

Condition Monitoring Technology
- Development of condition indicators and acceptance criteria

Industry
- Provision of service-aged cables & testing data
- Education and experience with methodologies
- Consensus around terms & concepts

Regulation
- Education and experience with concepts and methodologies

Desired State for Cable Condition Based Qualification in the U.S.

Condition indicators (CIs) for condition-based qualification (CBQ) established during time-based qualification of new cables

Method exists for development of CIs for in-service cables and implementation of CBQ

Condition Monitoring Technology
- Non-destructive condition indication
- Discrimination of local vs. global & degree of degradation
- Acceptance criteria for qualified life and test frequency
- Trend-able, real-time monitoring

Industry
- Data & service-aged cables available for validation
- Commonly accepted CBQ terms, concepts (e.g., trendable, monotonic, conservatism, margin) and methodologies

Regulation
- Option to replace degraded section rather than whole cable
- Endorsed methodology

Figure 6-1. Initial consideration of how we get from here to there – a CBQ roadmap from current to desired future state; adopted from (EPRI 2024).

Naturally, due to schedules, etc. many relevant stakeholders were not available to participate in that first event and the several key aspects of the significant topic were only able to be briefly introduced during the two days of the event. In future workshops additional experts and perspectives on the historic cable qualification practice will be sought and those interested in and affected by pursuit of transition to CBQ.

This initial first phase of the CBQ roadmap has focused on the current state of nuclear cable environmental qualification. The roadmap will next be expanded to include details on the potential future state, the challenges in that transition, and potential solutions to those challenges. A consensus approach considering diverse stakeholder opinions will be most valuable in creating an impactful guide for the industry. Development of improved condition indicators and pilot demonstrations are examples of advancements that will be needed toward implementation.

7. SUMMARY

The objective of this work was to develop a first phase consensus roadmap for condition-based qualification (CBQ) of electrical cables. With CBQ, qualification of Class 1E electrical cables moves from a time-based approach to a condition-based approach, which is anticipated to be safer and more cost effective. However, due to barriers, the CBQ approach has not yet been adopted by U.S. NPPs. In collaboration with EPRI and NRC colleagues, DOE researchers have produced this initial roadmap toward a guide for industry pursuing transition to a condition-based approach for extending qualified life of installed cables. Additional work is needed to evaluate condition indicators, establish the value proposition of CBQ, determine how to conduct aging management, establish regulation, and demonstrate CBQ at U.S. NPPs. Thus, additional workshops are required to identify details and timelines for the roadmap, with inputs from relevant stakeholders. For example, such a workshop could be co-located with the annual EPRI-sponsored user group meeting on cables and activities could include (EPRI 2024):

1) Reaching out to stakeholders (see Section 4.4) to discuss effort, determine interested parties, and obtain input to initial steps (e.g., value proposition statements, barriers to condition-based qualification, etc.); and
2) Meeting with stakeholders to discuss and plan for addressing barriers and determination of a timeline for implementation of condition-based qualification.

Based upon a review of current work evaluating CBQ, limitations of condition monitoring technology was identified as the largest barrier. The importance of condition monitoring, or more specifically selecting appropriate condition indicators, during CBQ cannot be understated. However, selecting appropriate condition indicators is challenged by techniques that are destructive and only evaluate cable degradation locally. Further, arguably, no single condition indicator by itself fully establishes cable condition. Thus, additional work is necessary to evaluate potential condition indicators towards CBQ. In addition to the requirements of IEC/IEEE Std. 60780-323, ideal condition indicators should include a) non-destructive approaches, b) both local and global measurements, c) real-time (i.e., online) monitoring that trends with degradation, d) enable correlation with QLD, and e) be established within a repository of condition indicators with applicable materials and/or components and their acceptance criteria. These needs could well form the basis of future research focus.

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