

IEEE Recommended Practice for Applicability of Methods for the Evaluation of Low-Voltage and Medium-Voltage Installed Cable Systems in Nuclear Facilities

IEEE Power and Energy Society

Developed by the
Insulated Conductors Committee

IEEE Std 1186™-2025

IEEE Recommended Practice for Applicability of Methods for the Evaluation of Low-Voltage and Medium-Voltage Installed Cable Systems in Nuclear Facilities

Developed by the

Insulated Conductors Committee
of the
IEEE Power and Energy Society

Approved 19 June 2025

IEEE SA Standards Board

Abstract: Guidance for the application of test methods to evaluate cable systems installed in nuclear facilities is provided in this recommended practice. This document covers low-voltage (2000 V or less) and medium-voltage (2001 V to 46 000 V) cable systems, both shielded and non-shielded cable types.

Keywords: cable condition monitoring, cable system, IEEE 1186™, nuclear, nuclear facility

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2025 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 12 November 2025. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 979-8-8557-2823-1 STD28422
Print: ISBN 979-8-8557-2824-8 STDPD28422

IEEE prohibits discrimination, harassment, and bullying. For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26>.
No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers/>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA, and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE is the approved IEEE standard.

Use by artificial intelligence systems

In no event shall material in any IEEE Standards documents be used for the purpose of creating, training, enhancing, developing, maintaining, or contributing to any artificial intelligence systems without the express, written consent of IEEE SA in advance. “Artificial intelligence” refers to any software, application, or other system that uses artificial intelligence, machine learning, or similar technologies, to analyze, train, process, or generate content. Requests for consent can be submitted using the Contact Us form.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter’s views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and Standards Coordinating Committees are not able to provide an instant response to comments, or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

¹ Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

² Available at: <https://standards.ieee.org/about/contact/>.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for the standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴ Available at: <https://standards.ieee.org/standard/>.

Patents

IEEE Standards are developed in compliance with the [IEEE SA Patent Policy](https://standards.ieee.org/about/sasb/patcom/patents/).⁵

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents/>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

IMPORTANT NOTICE

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. IEEE Standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

⁵ Available at: <https://standards.ieee.org/about/sasb/patcom/patents/>.

Participants

At the time this recommended practice was completed, the Recommended Practice for Applicability of Methods for the Evaluation of Cable Systems in Nuclear Facilities WG_P1186 Working Group had the following membership:

Stephanie Watson, Chair
Andrew Mantey, Vice Chair

Richard Easterling
Timothy Fallesen
Leo Fifield
Craig Goodwin
Steven Graham

Gary Harmon
Paul Knapp
Robert Konnik
Eric Rasmussen
David Rouison

Mohammad Sadollah
Justin Schmidt
Jeffrey Schroeder
Gabriel Taylor
Vataliy Yaroslavskiy

The following members of the individual Standards Association balloting group voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

S. Aggarwal
Saleman Alibhay
Earle Bascom III
Manfred Bawart
Kenneth Bow
Paul Brigandi
Kent Brown
Keith Bush
Suresh Channarasappa
William Chen
Kurniawan Diharja
Donald Dunn
Richard Easterling
Richard Ellis
Tim Fallesen
Leonard Fifield
Carl Fredericks
Kamal Garg
Shubhanker Garg
Craig Goodwin

Dexter Gordon
Steven Graham
Daryl Harmon
Gary Harmon
Hamidreza Heidarisafa
Lee Herron
Lauri Hiivala
Werner Hoelzl
Kenneth Kettle
Henry Kleinfelder
Paul Knapp
Robert Konnik
Thomas Koshy
Jusuf Krvavac
Philip Laudicina
Wang Lei
Andrew Mantey
Rachel Mosier
Arthur Neubauer
Lorraine Padden

James Parham
Bansi Patel
Howard Penrose
Jan Pirrong
Benjamin Quak
Eric Rasmussen
Lakshman Raut
James Reilly
David Rouison
Ryandi Ryandi
Justin Schmidt
Jeffrey Schroeder
Rebecca Steinman
John Vergis
Detlef Wald
Lanyi Wang
Stephanie Watson
Hughes Wike
Wang Xueting
Vitaliy Yaroslavskiy

When the IEEE SA Standards Board approved this recommended practice on 19 June 2025, it had the following membership:

Lei Wang, Chair
Jon Walter Rosdahl, Vice Chair
David J. Law, Past Chair
Alpesh Shah, Secretary

Edward Au
Ted Burse
Xiaofeng (Alfred) Chen
Doug Edwards
Nehad El-Sherif
J. Travis Griffith
Deborah R. Hagar

Guido R. Hiertz
Ronald W. Hotchkiss
Tyler L. Jaynes
Thomas Koshy
Howard Li
Xiaohui Liu
Kevin W. Lu
Hiroshi Mano

Daleep C. Mohla
Annette D. Reilly
Robby Robson
Daniel Sabin
F. Keith Waters
Sha Wei
Luyang (Eric) Zhan

Introduction

This introduction is not part of IEEE Std 1186-2025, IEEE Recommended Practice for Applicability of Methods for the Evaluation of Low-Voltage and Medium-Voltage Installed Cable Systems in Nuclear Facilities.

Currently, there is no guidance or industry consensus for the application of known in situ evaluation techniques for determining the adequacy of installed cables in nuclear facilities, in which the condition of the cable may be called into question due to natural aging, aging in an adverse local environment, or due to some condition that could affect cable reliability. In addition, the acceptability of any installation may be called into question due to 1) absence of historical cable design information, 2) failure to address individual installation recommendations/requirements, or 3) suspected but unconfirmed damage. These techniques include tests performed during cable manufacturing, tests for environmental qualification, post-installation tests for adequacy for energization, and maintenance tests for the suitability for continued operation. This recommended practice is needed to compile the well-known, but sometimes misapplied, condition monitoring tests and accepted practices for in situ testing of station cable systems. The recommended practice is meant to promote the correct application of a chosen test and ensure that test levels, acceptance criteria, and results/conclusions drawn from the tests are consistent across the industry to support cable reliability.

Contents

1. Overview	10
1.1 Scope	11
1.2 Purpose	11
1.3 Word usage	11
2. Normative references.....	11
3. Definitions, acronyms, and abbreviations.....	12
3.1 Definitions	12
3.2 Acronyms and abbreviations	12
4. Background.....	13
5. Cable types	13
5.1 Low-voltage cables.....	14
5.2 Materials: General, insulation, shield, jacket.....	16
5.3 PILC cables degradation mechanism.....	24
6. Test matrix.....	24
Annex A (normative) Test method descriptions.....	31
A.1 Visual inspection.....	32
A.2 Electrical tests	37
A.3 Physio-chemical tests.....	103
A.4 Mechanical tests.....	125
A.5 Summaries for lesser-used/ laboratory tests.....	138
Annex B (informative) Laboratory tests.....	140
B.1 Introduction.....	140
B.2 Internal irregularity test for XLPE and TR-XLPE insulations (hot oil test).....	140
B.3 Microscopic examination (optical).....	145
Annex C (informative) Guide on the provision of test data.....	150
C.1 General.....	150
C.2 Key information to include	150
C.3 Data formatting	150
Annex D (informative) Bibliography	152

IEEE Recommended Practice for Applicability of Methods for the Evaluation of Low-Voltage and Medium-Voltage Installed Cable Systems in Nuclear Facilities

1. Overview

Nuclear facilities rely on cables to provide normal power requirements for the processes required to produce the desired product, whether that be electrical power, radioisotopes for medical applications, radiography equipment, etc. Cables are also required for internal facility electrical distribution systems, emergency power, and emergency safety systems needed to safely shut down, remove decay heat from a nuclear reactor, and keep the fuel (active and spent fuel) cooled.

The number of cables required varies among the applications of nuclear facilities, but in the case of a commercial nuclear power plant, there are as many as 30 000 to 40 000 cables in a single unit. Low-voltage cables are typically managed initially by using visual and tactile techniques to provide qualitative insights into cable condition. If jacket or insulation damage is observed, the degradation of the insulation needs to be qualitatively evaluated at some point. This assessment technique is usually performed (e.g., indenter modulus, elongation at break, insulation resistance, or tangent delta) to better understand if the insulation is degraded.

The guidance provided herein is intended to assist individuals responsible for managing the aging of electrical cables in nuclear facilities. The guidance can be applied to any nuclear facility, but it is of greater importance for those cases where the facility is being operated beyond the initial licensing period. Cables in these facilities have a higher probability of aging, especially those that are in an adverse local environment (ALE). The ability to manage cable aging has many benefits, including avoiding time-based cable replacements, preventing in-service failures that can challenge plant operations, identifying degradation of specific cable types that could allow proactive replacement, etc.

Which technique to apply can vary and is often dictated by polymer type, accessibility of the degraded cable(s), and other factors. This document aims to provide guidance on which method(s) to use for various conditions and insulations. The test methods can be found in [Annex A](#), which provides a description of the test method, how to evaluate the results, acceptance criteria determination, test equipment used, complexity of interpretation, etc. It should be noted that while cables with mineral insulations can be found in some limited high-temperature applications in nuclear facilities, they are not considered in this document due to the lack of a specific test method to monitor their condition.

At present, there is no single test that can definitively specify the remaining life of an insulation, and many times, more than one test method may be needed to better evaluate the cable insulation condition. The use of the tests described in this recommended practice is meant to determine the condition of aged cables, not for the field of factory acceptance testing.

1.1 Scope

This document provides guidance for the application of test methods to evaluate cable systems installed in nuclear facilities. This recommended practice covers low-voltage (2000 V or less) and medium-voltage (2001 V to 46 000 V) cable systems, both shielded and non-shielded cable types.

1.2 Purpose

The purpose of this document is to provide guidance when applying test methods to detect and quantify degradation, manufacturing defects, and installation issues of cable systems. It is not intended to encompass all possible test methods, nor is it intended to exclude test methods that are not discussed.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D3895-19, Standard Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry.⁸

EPRI NP-7348, January 1991, *Cable Indenter Aging Monitor*.⁹

EPRI TR-104075, January 1996, *Evaluation of Cable Polymer Aging through Indenter Testing of In-Plant and Laboratory-Aged Specimens*.¹⁰

EPRI TR-105581, March 1996, *Improved Conventional Testing of Power Plant Cables*.¹¹

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

⁸ ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>).

⁹ This report is publicly available at no charge at <https://www.epri.com/research/products/np-7348>.

¹⁰ This report is publicly available at no charge at <https://www.epri.com/research/products/tr-104075>.

¹¹ This report is publicly available at no charge at <https://www.epri.com/research/products/tr-105581>.

IEEE Std 400™, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above.^{12, 13}

SAND96-0344, *Aging Management Guideline for Commercial Nuclear Power Plants—Electrical Cable and Terminations*, Sandia National Laboratories, September 1966.¹⁴

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁵

adverse local environment (ALE): An area that is more severe than the general environment.

electrical stress: Force created in a dielectric by an electric field.

in situ test: A test run in the field or at the location of the suspected fault or damage.

3.2 Acronyms and abbreviations

ac	alternating current
ALE	adverse local environment
ALEE	adverse local equipment environment
AWG	American Wire Gauge
CPE	chlorinated polyethylene
CR	polychloroprene
CSPE	chlorosulfonated polyethylene
dc	direct current
EPDM	ethylene propylene diene rubber
EPR	ethylene propylene rubber
ETFE	ethylene tetrafluoroethylene
EVA	ethyl vinyl acetate

¹² IEEE publications are available from the Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹³ The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

¹⁴ This document is available from the Nuclear Regulatory Commission at <https://www.nrc.gov/docs/ML0311/ML031140264.pdf>.

¹⁵ *IEEE Standards Dictionary Online* is available at: <https://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

HDPE	high-density polyethylene
LDPE	low-density polyethylene
LSZH	low smoke zero halogen
LV	low voltage
MV	medium voltage
PD	partial discharge
PILC	paper insulated lead covered
PFA	perfluoroalkoxy alkanes
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
PVF	polyvinyl fluoride
TID	total integrated dose
TP-CPE	thermoplastic chlorinated polyethylene
TP-LSZH	thermoplastic low smoke zero halogen
TR-XLPE	tree retardant cross-linked polyethylene
UV	ultraviolet
V_p	velocity of propagation
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin

4. Background

A large variety of electrical cables, in the low- and medium-voltage range, can be found in nuclear facilities. The intent of this document is not to provide a comprehensive description of each cable design. Instead, a general overview of the main cable types is given in the following clauses, followed by a description of the most common polymer compounds and metallic components used in cable construction. The main aging stressors affecting low and medium-voltage cables are also discussed, with a focus on their effects on the long-term performance of the cables.

5. Cable types

Low-voltage cables make up the majority of cables found in nuclear facilities. They can be grouped into three different categories: instrumentation applications (e.g., pressure, temperature, flow instruments), control functions

(breaker open/close circuit power, relay power, relay contacts, etc.), and low-voltage power (distribution transformers, motors, lighting, etc.). Medium-voltage power cables feed similar equipment as does low-voltage power, but typically that equipment is much larger and requires higher voltages to operate. It should be emphasized that the types of cables described in this document are generally manufactured according to international standards. It is not the intent of the information provided in the next subclauses to provide all the construction details found in these standards, but to give a brief overview of the general designs and functions of cables found in nuclear power facilities.

5.1 Low-voltage cables

5.1.1 Instrumentation cables

Instrumentation cables are used to power and communicate with a wide variety of instruments (amplifiers, frequency converters, indicator lamp circuits, etc.) and sensors (temperature, pressure, motion, position, voltage, etc.). Depending on the application, instrumentation cables can be continuously or intermittently energized. While most instrument cables operate at or below 24 Vdc—often in the millivolt range—they are usually rated for 300 V or 600 V. There are a few exceptions, such as radiation sensors, for which the instrument cable operates at a higher potential. In all applications, instrument cables carry low current, which does not result in any appreciable ohmic heating. It should be noted that communication cables, identified by the Telecommunications Industry Association (TCIA) as Category cables, are also considered instrumentation cables.

Instrumentation cables come in a large variety of designs. The most common assemblies consist of a bundle of the following:

- Single insulated conductors
- Twisted pairs of insulated conductors
- Twisted triads of insulated conductors

The most common conductor sizes are 16 AWG (1.5 mm²) and 18 AWG (0.75 mm²). The simplest instrument cable is the twisted pair design that is primarily used by thermocouples for temperature measurement. Due to the nature of the low current and sometimes high frequency signals handled by instrument cables, shielding is often an important part of the cable design. A metallic shield should be applied to the overall cable or on individual twisted pairs or triads. The actual construction of an instrumentation cable is typically driven by the application and operating requirements, including environmental conditions. All instrument cables include individual metallic conductors covered with an electrically insulating material providing isolation from ground and between conductors. For low-voltage cables, the insulation thickness significantly exceeds the required dielectric stress levels. The outer polymeric jacket provides mechanical protection for the cable during installation and operation, and may be used for UV protection and fire retardancy if the insulation does not have these properties. Individual conductors or pairs and triads can also be jacketed for added protection and separation. In addition to these main components, instrument cables can also include a belt, used as a thermal barrier in the event of fire, and binder tape and fibers to maintain the conductors' bundle profile (i.e., roundness). Separator tape used during manufacturing to prevent extruded material from flowing into the conductor or jacket adhesion to the drain wire, armor, and, as noted previously, metallic shield(s). Details about the most common materials used for these components are provided in 5.2.

5.1.2 Control cables

Low-voltage control cables are generally rated for 600 V, with some examples of 1000 V and 250 V ratings. Typical operating voltages include 240 Vac or 120 Vac single phase, 250 Vdc, 125 Vdc, 48 Vdc, or 24 Vdc. The main function of control cables is to change the operating status of control components such as breakers, relays, solenoids, valves, dampers, etc. They can also be used in other applications requiring intermittent operation such as status indicators. Control cables are available in a variety of designs, ranging from individual conductors to multiple individually insulated conductors.

A cable assembly most commonly consists of a bundle of single insulated conductors. Common conductor sizes include 14 AWG (2.5 mm²) and 12 AWG (2 mm²), but larger sizes are also available. Control cables typically do not require shielding, but shielded designs are sometimes used. The actual construction of a control cable is typically driven by the application and operating requirements, including environmental conditions.

All control cables include individual solid or stranded metallic conductors (typically copper) covered with an electrically insulating material providing isolation from ground and between conductors. As noted for instrumentation cables, the insulation thickness exceeds the required dielectric stress levels. The overall polymeric jacket provides mechanical protection for the cable during installation and operation, and is also used for UV protection and fire retardancy.

Control cable designs can also include a belt, used as a thermal barrier in the event of fire, and binder tape and fibers to maintain the conductors' bundle profile. During manufacturing, separator tape is used to help prevent extruded material flow into the conductor or jacket adhesion to the drain wire, armor, and, more rarely, a metallic shield. Details about the most common materials used for these components are provided in the 5.2.

5.1.3 Low-voltage (LV) power cables

Low-voltage power cables are generally rated for 600 V or 1000 V and operate at 480 V or less. They are typically single-conductor or multi-conductor with or without a bare copper ground wire (3- or 4-wire cables). Low-voltage power cables are used primarily to operate equipment in the plant, such as pumps, fans, ventilation, and many other devices.

The design of low-voltage power cables is very similar to that of control cables, with the difference that conductor size can range from 12 AWG (4 mm²) to 1000 kcmil (506.7 mm²), depending on the ampacity requirements of the application. The cables generally include an outer jacket for protection and fire retardancy. Some single-conductor designs do not include an outer jacket and would be used for applications with simple installation requirements (i.e., no complex pulls). As noted in the previous subclauses, the insulation thickness exceeds the required dielectric stress levels.

Low-voltage power cables do not commonly include a metallic shield. Similar to control cables, power cables' designs can also include a belt, binder tape and fibers, separator tape, drain wire, and armor. Some of these components are used for cables with smaller-sized conductors. Details about the most common materials used for these components are provided in 5.2.

5.1.4 Medium-voltage (MV) power cables

Medium-voltage cables are used to operate prime movers, such as large pumps and motors, and to distribute power on sites. They are typically rated between 5 kV and 15 kV, but cables up to 46 kV can be found at nuclear facilities. They are typically single or three-conductor. Similar to low-voltage cables, the construction and design of medium-voltage cables are dictated by the application and related requirements.

The basic elements of a typical medium-voltage cable include the conductor, conductor shield, insulation, insulation shield, metallic shield, and outer polymeric jacket. Some cable designs also include additional tapes or fillers to provide moisture barriers or armor for increased mechanical protection.

For 5 kV and 8 kV rated cables, unshielded designs (i.e., those without a metallic shield) were commonly used in the industry during the original plant construction. These unshielded cables do not always include external jackets. Other medium-voltage cables used in nuclear facilities are typically jacketed for mechanical, UV protection, and fire retardancy. Details about the most common materials used for these components are provided in 5.2. It should be noted that while most cables found in nuclear facilities use polymer materials as insulation and jacket, a few sites still have paper insulated cables.

5.2 Materials: General, insulation, shield, jacket

5.2.1 Low-voltage (LV) cables

5.2.1.1 Insulation

While in service, low-voltage cable insulation experiences low electrical stresses, as was explained in the previous subclauses. As a result, these materials do not have to abide by strict electrical performance requirements. This situation allows the use of a wide variety of base polymers and formulations to meet specific design, environmental, and mechanical conditions. While the intent of this document is not to provide a detailed description of all the insulation compounds found in nuclear facilities (references are included for this purpose), the most common materials are briefly discussed here.

Polymers used for low-voltage insulation fall into two distinct groups: thermoset and thermoplastics. Thermoplastic polymers are materials that can be softened or melted when exposed to high temperatures and harden upon cooling. Thermoset polymers are materials that undergo an irreversible reaction, generally defined as curing or crosslinking, which results in the creation of linkages between all the polymer chains. In this state, the material becomes thermally stable and cannot be softened or melted anymore. In nuclear facilities, the requirements related to design basis accidents, specifically high heat, restrict the use of thermoplastic materials, and most low-voltage cable insulations are thermoset.

Many low-voltage cables used in nuclear facilities currently are either based on crosslinked polyethylene (XLPE) or ethylene propylene rubber (EPR) compounds, including ethylene propylene diene rubber (EPDM). In recent years, the term crosslinked polyolefin (XLPO) has also started being used to refer to a broader family of polyolefin-based materials, which includes XLPE and various blends of crosslinked polyolefins. Polyvinyl chloride (PVC) compounds were also used extensively in a number of earlier plant designs and can therefore still be found. Other thermoset materials found in low-voltage cable insulations include ethyl vinyl acetate (EVA), primarily in Europe, and silicone rubber. For instrumentation cables in high-temperature and high-radiation applications, polyimide film insulation is also used. This last material comes in the form of a film that is applied over the conductor using a special process.

As noted earlier in this section, thermoplastic polymers such as low- and high-density polyethylene (LDPE and HDPE) or thermoplastic PVC are used in nuclear facilities outside of the United States (US), but due to their limitation under high heat conditions and potential for corrosion of primary piping in nuclear containments, they have mostly been removed from those locations in US facilities. Some fluorinated materials with higher temperature ratings, such as ethylene tetrafluoroethylene (ETFE) and polyvinylidene fluoride (PVDF), can also be found in certain applications.

It should be emphasized that these general families of polymers consist of a large variety of material grades, which provide a wide range of properties. In addition, most polymers used in low-voltage cable insulation are compounded (i.e., mixed) with a number of organic and inorganic additives, including fillers, to modify their properties. These additives, which include, but are not limited to, antioxidants, flame retardants, plasticizers, inorganic fillers, and crosslinking agents, will influence the mechanical properties and environmental resistance (i.e., thermal and radiation) of the final compounds. Hence, the common XLPE and EPR materials found in most low-voltage cable insulations can exhibit significant differences in short- and long-term performance based on their formulation.

Among legacy materials found in nuclear facilities, a number of manufacturers applied a thin layer of fire-retardant material over XLPE and EPR insulation compounds. These materials, generally based on PVC, polychloroprene, or chlorosulfonated polyethylene, could be bonded to the underlying insulation.

5.2.1.2 Shields

The use of metallic shields in low-voltage cables is most common for instrumentation cables to provide shielding from electrical interference caused by adjacent equipment or circuits. For this type of cable, shields generally come in the form of metallized polymer tape, metallic tape, or metallic wire braid. Metallized tape is made of a polyester tape with a deposited layer of metal, usually aluminum, on one side. This type of shield cannot be used for grounding of the cable due to the very thin metal layer, and a drain wire is generally included in the cable bundle for that purpose. Shielding is also achieved by using a helically wound metallic tape, generally copper, around the conductors. This type of shield can be used for grounding the cable and provides flexibility in the cable design. The last type of shield relies on the application of a metallic braid over the conductors. In addition to its electrical function, this type of shield also provides mechanical protection to the individual conductors, at the expense of overall flexibility of the cable. This type of braid is usually made of tinned copper wires. As mentioned in earlier subclauses, some multiconductor instrument cables can include individually shielded twisted pairs (or triads). In this configuration, shielding is typically achieved using metallized polymer tape as just described. While less common, some low-voltage power cables can include corrugated metallic shields (copper), like the ones encountered in medium-voltage cables. Finally, some low-voltage cables include a metallic armor, which can provide some level of shielding and grounding even if it is not its primary purpose. These armors are generally made of aluminum.

5.2.1.3 Jacket

The main functions of low-voltage cable jackets are to provide mechanical protection for internal components during installation, protection from the surrounding environment in service, for instance, UV light or external contaminants, and fire retardancy. Because of these requirements, jacket compounds have historically been based on elastomeric compounds, which provide a good combination of flexibility and resistance. The most common thermoset materials found in nuclear facilities are PVC, polychloroprene or neoprene, and chlorosulfonated polyethylene. Other jacket materials include EPR, EPDM, silicone rubber, thermoset chlorinated polyethylene (CPE), and, more recently, XLPO and low smoke zero halogen (LSZH) materials. As was noted in 5.2.1.1, XLPO is a generic term that includes a variety of polyolefin materials. LSZH materials are also generally based on polyolefins, most commonly ethyl vinyl acetate, mixed with a high filler content.

For the same reason mentioned for insulation materials, thermoplastic-based jacket compounds, other than PVC and LSZH, are rarely found in nuclear facilities' cables. However, in some non-safety-related applications, thermoplastic chlorinated polyethylene (TP-CPE), fluorinated polymers, and thermoplastic low smoke zero halogen (TP-LSZH) are sometimes used.

Similar to insulation compounds, jacket compounds include a variety of organic and inorganic additives to tailor their properties to match performance requirements. While the majority of jacket compounds are colored black, cables used in indoor applications can be found to display lighter colors such as yellow or orange.

5.2.2 Medium-voltage (MV) cables

5.2.2.1 Insulation

Insulation materials for medium-voltage cables in nuclear facilities are commonly based on EPR or XLPE compounds. In older facilities, some butyl rubber-insulated cables, generally rated 5 kV or, more rarely, 8 kV, can still be found. This material, broadly used prior to the advent of EPR compounds in the 1960s, was compounded with carbon black and other fillers and additives. However, due to its high dielectric loss, low breakdown strength, and limited thermal and radiation resistance, it was rapidly replaced by EPR and XLPE materials. Butyl rubber cables in ALEs (see 5.2.4) have been typically replaced by EPR or XLPE cables over the years.

Original EPR compounds relied on similar formulations to butyl rubber insulations and contain carbon black as one important component. These insulations, known as "black EPR" in the industry, exhibited more frequent water-

related degradation over time and maintained high dielectric loss. As a result, EPR cable manufacturers began to develop compounds containing lead monoxide, which are known as “pink EPR” (even though they can be pink, red, or orange), that provide improved water resistance. EPR compounds are quite complex and include many additives such as inorganic fillers, coupling agents, curing agents, antioxidants, metallic oxides, oils, and lubricants. Most EPR insulations rely on clay mineral, more specifically kaolin, as their main inorganic filler to improve the physical properties of the material. To enable proper bonding of the clay with the polymer, coupling agents are also added to the compound. Crosslinking of EPR compounds is achieved with peroxides or sulfur-containing chemicals. Peroxide crosslinking has become the preferred approach. Zinc oxide is another commonly used additive that acts as a crosslinking synergist and acid scavenger, and improves the electrical insulating properties of the material. Another type of EPR compound, known as partial discharge (PD) resistant or “brown EPR” (although in some cases it can be grey or even black), can be found in nuclear facilities.

XLPE compounds are considered simpler than EPR compounds because they typically contain only polyethylene as the base polymer. One notable difference is the absence of any inorganic fillers in XLPE insulation. The main additives found in these materials include antioxidants, crosslinking agents and synergists, acid scavengers, and tree retardants. This last category of chemicals, which includes polyethylene glycol, has been shown to reduce the formation and size of water trees. XLPE insulations with such tree-retardant properties are generally marketed as TR-XLPE to distinguish from traditional XLPE compounds. Crosslinking in XLPE material is achieved with peroxides.

While the vast majority of medium-voltage cables in nuclear facilities use EPR and XLPE insulations, a few other materials can be found around the world. These include PVC for applications below 10 kV and PILC cables. For this last family of cable, the insulation is based on layers of oil-impregnated paper wound around the conductor to achieve the desired thickness for that insulation design voltage.

5.2.2.2 Conductor and insulation shields

The conductor shield is used at the conductor-to-insulation interface to reduce the electrical stress concentration in that region. The insulation shield provides a smooth surface over the insulation to control the electrical stress between the insulation and the metallic shield. The conductor and insulation shields are typically semiconductive materials (a non-conductive conductor shield has been used in at least one design). They were originally applied as semiconductive fabric tapes helically wound along the length of the cables.

While these tapes can still be encountered in legacy cables in older facilities, they were progressively replaced by polymeric semiconductive screens extruded over the conductor and the insulation. These materials are thermoset compounds commonly based on polyolefins such as EPR, polyethylene, or EVA. They include many additives similar to those found in insulation compounds, with the addition of carbon black, which provides the semiconductive properties of the materials. The insulation shield typically includes release agents to reduce the bond strength between the shield and the insulation, facilitating the stripping of the material for termination or splice installation.

5.2.2.3 Metallic shield (shielded design only)

The metallic shield in medium-voltage cables is grounded at one or both ends and provides a path to ground for leakage current during normal operation, or for fault current if a failure occurs. This shield comes in different forms, with the most common type in nuclear facilities being the helically wound wide copper tape, known as “tape shield”. This configuration provides higher flexibility to the cable. Other types of metallic shields include concentric neutral wires, narrow thick copper tapes, known as “straps,” and longitudinally corrugated copper shield. For medium-voltage cables, the copper material used for shielding is generally non-treated. A zinc shield tape was also used for a period in the mid-to-late seventies on the PD-resistant cable mentioned earlier.

5.2.2.4 Jacket

The role of the jacket in medium-voltage cables is similar to that of low-voltage cables. Hence, the jacket materials used for medium-voltage cable are commonly based on PVC, neoprene, and chlorosulfonated polyethylene. For further information on these compounds and on other less typical jacket materials, see [5.2.1.3](#).

5.2.3 Extruded cables degradation mechanism

In their installed state, LV and MV cables can be subjected to various stressors, which can be broadly categorized as mechanical, environmental, and electrical stressors. Environmental conditions can stress extruded cables' materials and cause certain degradation mechanisms to occur. Common environmental stressors include exposure to high ambient temperature, ionizing radiation, UV radiation, chemical contaminants, including long-term wetting and submergence, and oxidizing conditions.

Cables can also be subjected to mechanical stresses through contact with sharp edges or excessive compression or tension, and to mechanical stresses during installation, including excessive pull tension and pull force, excessive bending to radii below the minimum bending radius, or damage caused by too high a friction during pulling or being pulled through too tight an area.

Finally, cables can experience electrically induced degradation, such as water-treeing, corona, or partial discharge, because of the presence of defects in the cable construction or due to degradation. Additional electrical failures can be caused by improper splicing and termination of cables. These stressors can affect cables over their entire length, or, as is generally the case, they can be localized to a short section or sections of a cable length. The stressors can lead to changes in the cable dielectric capability, and possibly failure, by affecting the properties of the insulation, and, in the case of MV cables, of the shield and semiconductive screens. The main stressors affecting cables in nuclear generating stations, and their effect on cable materials, are discussed in the following subclauses.

5.2.4 Environmental stressors

5.2.4.1 Thermal

When subjected to high temperature, extruded cable polymeric material, which includes the insulation, the jacket, and the semiconductive screens for MV cables, experiences thermo-oxidative degradation mechanisms that gradually lead to changes in the material's mechanical and electrical properties. Most cable materials will exhibit loss of flexibility with increasing thermal aging, leading to embrittlement and hardening (butyl rubber can soften). The degradation rate is determined by the thermal resistance of the material and by the magnitude of the temperature it is experiencing.

Cable insulations are designed to operate at the rated ampacity in a rated ambient environment (typically 40 °C) for their design life. The actual rated conductor temperature varies depending on the thermal characteristics of the insulation material, with temperature ratings generally in the range of 60 °C to 105 °C. Most cables will operate well within those limits and thus will have a long service life, possibly well beyond the design life if subjected to either low conductor temperature or low ambient temperature. However, the cables' life can also be limited if the temperature experienced by the insulation (and semiconductive screens for MV cables) exceeds its rating, from exposure to high ambient temperature, high conductor temperature, or a combination of both. While high conductor temperature, through excessive ohmic heating, is always a possibility due for instance to erroneous ampacity calculations or imbalanced load, the main concern for thermal aging of cable systems in generation plants is the presence of high ambient temperature, more specifically localized high ambient temperature, referred to as an adverse local equipment environment (ALEE), sometimes referred to as adverse local environment (ALE).

Additionally, cable insulation accessories (terminations and splices) also have temperature ratings that, if not the same as that of the cable ratings, will age and reach the end of life faster than the cable.

As noted, the main concern for plant cables is the presence of thermal ALEEs, which can lead to an early onset of insulation degradation. ALEEs can result from various conditions, and a knowledge of the location and cause of these hot spots is key to understanding how fast or long an insulation will remain useful. Common causes are the proximity of cables to high-temperature process lines that may be uninsulated or poorly insulated. Other causes include inadequate ventilation or dead spaces in the higher room elevations, or cables being located next to radiant heat sources such as high-energy plant lighting.

Since external heat is the major source of cable thermal degradation, the jacket will typically be the first component to exhibit loss of properties. In addition, for most cables, the jacket material is based on elastomeric compounds having lower thermal ratings than the underlying insulation. As such, the jacket can generally be used as a leading indicator of the condition of the underlying insulation.

Certain jacket materials, such as PVC and neoprene, contain plasticizers that will migrate to the surface as the material experiences thermal aging. This migration will cause the material to shrink, to harden, and exhibit a sheen from the plasticizers disassociating and depositing on the jacket surface. Increased plasticizer loss typically results in spontaneous jacket cracking (both radial and axial). Chlorosulfonated polyethylene tends to discolor and harden when thermally degraded, but does not typically crack unless mechanically agitated or bent during handling.

The use of the jacket as a leading indicator of thermal aging for external heat sources is not applicable to jackets bonded to the underlying insulation since initiation of cracks resulting from embrittlement of the jacket can progress through the insulation even if it has still retained good flexibility. This case has been observed in environmental qualification testing where pressure changes in the test chamber required for the qualification profile resulted in this condition, where the expansion of the relatively flexible insulation caused the hardened jacket to crack, leading to insulation failure (exposed conductor) when pressure is reduced, and the insulation expanded faster than the embrittled jacket. This could theoretically occur if aged cables with bonded jackets are over-flexed during manipulation when isolating them for equipment tag outs (electrically isolating them from a power source or the associated equipment they feed) or performing maintenance.

Finally, it is important to consider the effects of other stressors in conjunction with heat exposure that can result in different rates or different modes of aging. The presence of compressive stress, for instance, can lead to softening of certain materials, such as XLPE, when exposed to high temperatures or prolonged thermal exposures to the cable system.

5.2.4.2 Radiation

Ionizing radiation, including gamma rays, neutrons, alpha particles, and beta particles, reacts with the polymers' orbital electrons to form unstable ion pairs, which lead to the rupture of covalent bonds. The resulting highly unstable and reactive species, called free radicals, are then involved in competing termination and propagation reactions that determine the level and type of degradation experienced by the material. The two competing degradation mechanisms are chain scission, which gradually results in a reduction of the molecular weight of the polymer, and crosslinking, which results in an increase in the molecular weight of the polymer.

As was noted for the thermal aging mechanism, the presence of oxygen, more specifically the presence of absorbed oxygen in the material, will result in additional reactions affecting the rate of degradation. Materials have an upper radiation threshold measured in Total Integrated Dose (TID) over time, above which they exhibit detectable damage. This threshold is generally much higher when oxygen is not present.

For most materials used as cable jackets and insulations in nuclear facilities, crosslinking is the dominant mechanism when exposed to radiation. Hence, these materials will experience a gradual loss of flexibility and embrittlement. Among this family of materials, XLPE and EPR insulations in particular exhibit high resistance to radiation with good retention of properties for TID more than 500 kGy (50 MRad) for specially formulated compounds. For some materials, such as butyl rubber and some fluoro-elastomers, chain scission is the dominant reaction leading to gradual softening of the material and associated loss of mechanical properties. These materials generally have a low radiation threshold. In general, operating experience to date for nuclear facilities shows that

cable jackets and insulation degradation have typically been dominated by thermal degradation. There are some radiation-dominated areas, but one study (EPRI Report 3002010403 [B103]) showed that most in-containment areas where cables are installed will not reach the TID levels that will be of concern for aging during plants, even out to 80 years.

As mentioned for thermal aging effects, the existence of local radiation hot spots can lead to localized degradation of cable materials characterized by a gradual loss of mechanical properties. As for thermal aging, in most cases, the jacket can still be used as a leading indicator of insulation degradation as long as the insulation material is known to be more resistant to radiation damage than the jacket.

Finally, it is important to remember to consider the effects of other stressors in conjunction with radiation exposure, which can result in different rates or different modes of aging. For instance, a material exposed to a combination of radiation and tensile strain would experience increased chain scission reactions, which could become the dominant aging mechanism under these conditions. Combined thermal and radiation can stress the insulation in complicated ways as well.

5.2.4.3 Ultraviolet (UV)

The effects of ultraviolet (UV) radiation on cable jacket and insulation are very similar to those described for ionizing radiation. The main difference is that the lower energy UV radiation generally does not achieve a high depth of penetration in these materials. The resulting degradation is characterized by discoloration and embrittlement or softening (depending on the dominant aging mechanism). UV degradation is considered a surface degradation mechanism; however, for thin insulations of single conductor exposed to UV radiation, from artificial lighting, for instance, embrittlement could lead to through-wall cracks exposing the conductor. The formulation of the compounds, especially the type of fillers used, has a strong influence on the UV resistance of the material, with carbon black being a significant contributor to the resistance of jacket materials to the effects of this degradation mechanism. Once again, the presence or absence of oxygen, or of other stressors, can contribute to a different rate and level of degradation.

5.2.4.4 Chemical degradation

Chemical degradation results from the interaction between the cable materials and an external contaminant or chemical. The exposure to the external contaminant can occur following a spill or leak in the plant or from the presence of undesirable chemicals in the soil or water if the cable runs underground.

Such exposure can have various effects on the cable polymeric materials, including the jacket, insulation, and semiconductive screens, such as swelling, dissolution, embrittlement, or growth of chemical trees within the insulation. These various degradation mechanisms can impact the mechanical, physical, and electrical properties of the affected materials, leading to a loss of performance and potentially failure. They can also affect the interaction between the various components making up a cable, and can, for instance, lead to the formation of voids or delamination between the insulation and semiconductive screen and the development of PD activity.

While the jacket often provides a barrier to protect the underlying materials from the external influences of a variety of contaminants, compatibility charts should be used to determine the long-term effects of chemicals on the affected materials. Just because a jacket is affected by a particular chemical attack, it must be determined or have some knowledge of how the underlying screens and insulation are affected. It is also important to consider the ambient conditions at which the exposure occurs since temperature can have a significant influence on the interaction between a chemical and a polymeric compound.

Contamination of MV cables by chemicals or water can also have an influence on the electrical cell activity between the metal neutral and the semi-conductive shield, and can lead to the corrosion and deterioration of the metallic neutral of the cable. Neutral corrosion can lead to failure as a result of voltage imbalances at the cable's outer semi-conductive screen. Such imbalances can cause surface electrical discharges, material erosion, or pitting, and

eventually lead to electrical treeing, resulting in failure. Neutral degradation can also affect the testability of MV cables by increasing the attenuation of the shields (polymer and metal) that limit the effectiveness of high-frequency diagnostic tests.

Chemical and water exposure often affects accessories, particularly due to moisture ingress, contamination ingress, and/or improper interface pressures. These conditions lead to electrical tracking or surface conduction currents, high dielectric loss, and interfacial partial discharge, eventually leading to either internal surface flashover or direct insulation breakdown.

5.2.4.5 Biological degradation

Biological degradation refers to the effects of micro-organisms found in the environment on cable materials. Micro-organisms such as algae, fungi, and bacteria can, under the right conditions, form biofilms on the cable jacket, insulation, or shield. Mold and mildew are common forms of such species, which can also originate in animal droppings, notably birds. The presence of moisture is generally key to the formation of a sustained biological attack on a cable. Other factors influencing its formation and proliferation include the local pH, light, temperature, and presence of nutrients. These micro-organisms can affect the mechanical and electrical properties of the jacket and insulation materials.

While the digestion of the main polymer backbone is a very slow process and unlikely to be observed, lower molecular weight additives present in the materials, such as plasticizers and antioxidants, can be consumed by these organisms, leading to embrittlement or premature aging. In addition, the presence of micro-organisms on the material surface can cause increased hydration, which affects its electrical properties. In some instances, biological organisms can penetrate polymeric materials, leading to a higher rate of degradation through hydration and depletion of additives.

5.2.5 Electrical stress

5.2.5.1 Dry electrical defects

“Dry” electrical defects refer to manufacturing and design deficiencies present in the cable insulation of polymeric cables, which result in local electrical stress enhancement and initiation of partial-discharge activity in MV and HV cables. When allowed to persist, such activity is followed by surface carbonization, material erosion, inception and growth of electrical trees, and eventual dielectric breakdown and failure. The time to the formation of electrical treeing from a partial discharge-inducing defect is unpredictable and depends on a large number of factors (e.g., insulation thickness, applied voltage). However, once electrical treeing has begun, it progresses very quickly (in contrast to water-treeing), with a time span to failure typically ranging from minutes to days after formation for cables operated at higher voltages. In cables, dry electrical aging is primarily caused by manufacturing deficiencies (voids, contaminants, protrusions). Secondary causes include design deficiencies (particularly as relating to insulation shields) and other factors, such as mechanical damage sustained during transport or installation. Dry electrical aging failures in cables are typically more prevalent at the infant-mortality (e.g., post-installation) stage. In accessories, dry electrical aging can occur due to the same factors as stated previously, but poor installation workmanship or natural aging (thermo-mechanical movement at interfaces, material embrittlement, etc.) are more often the primary causes.

5.2.5.2 Treeing

Treeing (electrical or water trees) is the most significant aging mechanism contributing to failures of field-aged polyethylene MV cables. Moisture ingress into the insulation leads to failure through the formation of either electrical trees, large water trees (primarily vented but can also be streamer or bow-tie type), or a high density of small water trees (primarily bow-tie but can also be other types). Both cases of water treeing are associated with a

decrease in insulation strength, with complete insulation breakdown occurring if the water treeing leads to thermal runaway (i.e., as a result of increased dielectric losses) or induces an electrical tree (and the electrical tree grows a channel of sufficient length to fail the insulation). Water-tree growth under service conditions is contingent on many factors and is typically a very slow process, usually taking many years to completely penetrate the insulation from the inside or outside.

Water tree formation initiates at a small void or contaminant present within the insulation, or at the interface between the insulation and semiconductive screens, and in the presence of moisture that diffuses into the material over time, and the level of voltage applied across the insulation to ground. The combination of a voltage on the local stress enhancement and water results in the local degradation of the insulation material. The affected area exhibits an increased water content, which affects the dielectric properties of the insulation. Long-term exposure, or repeated exposures, to water is a prerequisite for the formation of water trees in polyethylene insulated cables. Water treed cables going through dry and wet cycles have been shown to recover dielectric properties as the water present in the insulation, and the water trees, diffuses out of the cable (EPRI 1025263 [B122]). The improvement was based on improved metrics for very low frequency tan delta measurements after the cables were dried.

Modern XLPE insulation types, known as tree resistant XLPE (TR-XLPE), include additives (such as polyethylene glycol) that enhance their resistance to the formation of water trees.

Water tree formulation has also been observed in butyl rubber and all the various EPR types. Butyl rubber and “black” EPR have shown the highest susceptibility to water tree-related degradation and failures. This higher susceptibility has been linked to the use of carbon black in these compounds. Cables with water scavenging ingredients such as lead oxide found in “pink” and “brown” EPRs have shown much lower susceptibility to water tree degradation and failures.

It should be emphasized that water treeing is not observed in low-voltage cables since the electrical stress in the insulation is not sufficient to initiate the degradation mechanism described in the previous paragraphs.

5.2.5.3 Mechanical

LV and MV electrical cables can be subjected to various mechanical stressors throughout their lifecycle. The pulling tensions exerted on cables at the time of installation can result in excessive tensile stress if not properly calculated or if improper procedures are used. Excessive bend radii, exceeding recommended values, can also result in excessive stress to the cable components. Such a condition can result in mechanical damage to the materials and components, for instance metallic shield break, leading to the initiation of electrical degradation once the cable is energized, as noted in previous subclauses.

In their installed state, cables can also be subjected to constant tensile or compressive stress, for instance, at a tight bend or because of contact with a hard surface. As noted in previous subclauses, the presence of such stress can affect the rate of thermal and radiation aging of the materials, resulting in early onset of degradation and premature failure of cables. Excessive localized mechanical stress from sharp edges, from civil structures or cable trays, for example, can also lead to severe indentation or initiation of cracks in the cable materials and electrical faults.

In generation plants, some cables can also be used in dynamic applications to operate equipment. They are generally installed in cable tracks and subjected to repeated bending and stretching. While the actual stress resulting from each cycle is usually not excessive, its repeated application can lead to permanent deformation of the cable, separation of layers, and fatigue-induced damage to the materials. This repeated stress can also affect the rate of thermal and radiation aging of the insulation and jacket materials.

5.2.6 Wildlife

Wildlife, more specifically small animals such as mice, rats, and squirrels, can find their way into electrical junction boxes or within equipment enclosures and chew on cable materials. This situation is mostly encountered with low-

voltage cables of small gauge sizes, which have thinner layers of jacket or insulation materials. Rubber compounds have been observed to be the most prone to such attacks. The localized loss of material can lead to exposed conductors and electrical fault.

5.3 PILC cables degradation mechanism

In PILC cables and accessories, extreme elevation changes or breach of the lead sheath (through cracks, corrosion) can lead to oil migration and dry spots in the insulation. This can lead to PD and localized dielectric heating, paper oxidation, and a decrease in dielectric strength. Damaged lead sheaths are points of moisture ingress. Moisture in the paper can lead to localized or bulk dielectric heating and increased insulation loss. This, in turn, leads to paper oxidation and eventual decrease in dielectric strength.

Tearing, folding, or separation of paper insulation can occur from poor workmanship. These areas cause localized stress enhancements where partial discharge activity can occur. Although PD activity in oil-paper insulation can be tolerated to a degree (unlike typical instances of extruded cables), persistent and increasing PD in PILC cables can lead to paper oxidation, increased dielectric losses, and breakdown.

External electrical issues, limited to external interfaces such as terminations, occur as a result of external surface contamination, material oxidation (i.e., from UV degradation), or external electric stress enhancements (i.e., corona in air due to insufficient clearances or sharp discontinuities). This leads to electrical tracking or surface conduction currents, localized surface material erosion, or high dielectric loss, eventually leading to either internal surface flashover or direct insulation breakdown.

6. Test matrix

Evaluation of the condition of a cable may best be done with multiple tests. This can provide a picture of the health of the cable. In some cases, this will indicate if the cable is in relatively good condition or bad condition. In some cases, the results will not be conclusive. Having multiple tests to provide more evidence can aid in the evaluation. There is no single test that consistently provides all the information needed to conclusively determine the condition of the cable across all stages of installation.

[Table 1](#) provides a summary of the test methods in Annex A. More detailed information on each test method can be found in the annex. Each test method is listed along with columns for material applicability, material function, limit of deterioration, degradation, destructive, in situ, trendable, local, and a comment.

Material applicability relates to limits on the applicability to certain materials or whether it is suitable for any material. Material function specifies the primary application of the test method. In some cases, it will be for insulation, or it may be more specifically for MV insulation. That is not to say that the test method could not be used for low-voltage insulation, as an example, just that it is predominantly used for MV insulation evaluation.

In some cases, there is no limit on the function of the material, but the material must be accessible. Depending on the test method and what is accessible, in a tray, a jacket may be accessible; performing a laboratory test that will require some amount of jacket to be removed may not be desirable. Insulation may be accessible at end devices or not, depending on how it is terminated. If a splice is removed or if there is a terminal block, there may be other access points to the insulation. Where a cable is in a conduit, it would not be accessible.

The limit of degradation gives some idea if the test is for gross deterioration, is only a pass/fail test, or if there is some other limit on what the test can detect. Degradation provides an indication as to what the test is targeted for, such as to find wet degradation, thermal degradation, or radiation degradation, etc. The destructive column indicates if the test is considered destructive, nondestructive, or possibly destructive. Be aware that just because the test is generally not considered to be destructive, it does not mean that the cable may not be damaged just from handling,

disconnecting, reconnecting, etc. Suitable precautions should be taken, and suitable spare cable should be available when doing any testing.

The in situ column indicates if the test can be done in the field or if it has to be done in the lab. Note that just because it can be done in the field does not mean it cannot be done in the lab, using a removed cable sample.

The trendable column indicates whether the test results can be trended or not. In some cases, it may be possible, but that does not mean any meaningful information can be gathered from attempting to trend the data.

The local column indicates if the test is performed in one location or if it applies to the entire length of the cable. Note that if it is local, multiple tests can be run to get other data at other accessible points. Just because the test is meant to be done on the entire length, it does not mean that it is achievable. There may be limitations based on the shield, the power of the equipment, or the resolution of the equipment. See the test method limitations in [Annex A](#).

Finally, the comment column summarizes the typical purpose of the test.

Table 1—Test method applicability matrix

Test Method	Material Applicability	Material Function	Degree of Deterioration	Type of Degradation	Destructive	Treatable	In situ	Local	Comment
A.2 Visual inspection	Accessible Visibility	Accessible Visibility	Gross Deterioration	Visual Damage	Nondestructive	No	In situ	Local	Generally, part of a walkdown and other techniques can be used to evaluate damage.
A.3.1 Insulation resistance	Any	Insulation	Gross Deterioration	Electrical, Wet	Nondestructive	Possibly Treatable	In situ	Global	Determines conductive losses in insulation. Dependence on temperature, humidity, and voltage level can make testing difficult. Good for wet insulation, less reliable for dry, thermally aged insulation.
A.3.2 Polarization Index Test	Any	Insulation	Gross Deterioration	Electrical, Physical, Wet	Nondestructive	No	In situ	Global	Generally, a comparison test.
A.3.3 Time Domain Reflectometry	Any	Insulation	Gross Deterioration	All	Nondestructive	Treatable with baseline	In situ	Global	Used to locate significant changes in impedance, such as a splice or detecting relatively gross conductor or shield damage, near short circuits and impedance discontinuities caused by variation in environment temperature, local aging, or damage to the cable system.
A.3.4 Frequency Domain Reflectometry (FDR)	Any	Insulation	Gross Deterioration	Thermal and Radiation	Nondestructive	Treatable after baseline	In situ	Global	Most useful for local degradation or faults with shielded cable, but may use multiple conductors.
A.3.5 Dielectric Spectroscopy	Any	Insulation	Gross Deterioration	Electrical, Physical, Wet	Nondestructive	Treatable	In situ	Global	Generally, for MV cables and wet applications.
A.3.6 Tan Delta (TD)/Dissipation Factor	Any MV	MV Insulation Shielded	Gross Deterioration	Electrical, Physical, Wet	Possibly Destructive	Treatable	In situ	Global	Typically used as one of the tests to address wet aging of MV cables.
A.3.7 Withstand Voltage Testing at Very Low Frequency (VLF)	Any	MV Insulation	Gross Deterioration	All	Possibly Destructive	No	In situ	Global	Typically used as one of the tests to address wet aging of MV cables.
A.3.8 Offline Partial Discharge Testing	Discharge free insulation	Shielded MV insulation system	Gross Deterioration	All	Possibly Destructive	In situ	Treatable after baseline	Global	One common test for initial acceptance testing and to evaluate possible damage of shielded MV cables, splices, and terminations.

Test Method	Material Applicability	Material Function	Degree of Deterioration	Type of Degradation	Destructive	Treatable	In situ	Local	Comment
A.3.9 Polarization-Depolarization Current	Any	Insulation	Unknown	Any	Possibly Destructive	In situ	Treatable	Global	Shielded best, but can be used with multi-conductor, non-shielded, or single conductors. Current use of this technique in the early adoption stage.
A.3.10 Withstand Voltage Testing at Near Power Frequency	Any	Insulation	Gross Deterioration	Any	Possibly Destructive	In situ	No	Global	Used for factory acceptance and pre-qualification as well as field testing.
A.3.11 Power Frequency AC High Voltage Breakdown Tests	Any	MV Insulation	Gross Deterioration	Electrical, Physical, Wet	Destructive	Lab	Possibly	Global	Not generally used to assess field/cables unless pulling out a larger section to test. May be suitable for additional circuits that would lead to energization of MV cables or in a location to be tested periodically.
A.3.12 Cable Jacket Testing	Any Nonconductive	MV Jacket on shielded cable	Pass/Fail Test	Electrical, Physical, Wet	Nondestructive	In situ	No	Global	Looking for jacket damage.
A.3.13 Coax Impedance	Any	Coaxial/Trial Cable	Unknown	Electrical, Physical, Wet	Nondestructive	In situ	Possibly	Global	May be usable in some cases.
A.3.14 DC Withstand Voltage Testing	Any	New Insulation	Gross Deterioration	Electrical, Physical, Wet	Possibly Destructive	In situ	No	Global	Pass/Fail Test is generally used for new cables, generally MV.
A.3.15 Continuity/Loop Resistance Test	Metal	Conductor and metallic shield	Pass/Fail Test	Electrical continuity	Nondestructive	In situ	No	Global	Pre-service and troubleshooting test.
A.3.16 Infrared Thermography	Any	Any Accessible	Unknown	Thermal	Nondestructive	In situ	No	Local	Looking for Hot Spots: Generally Near Terminations.
A.3.17 Differential Insulation Resistance	Any	MV Insulation	Severe Damage	Wet	Destructive	Lab	No	Local	Locate imperfections in service-aged cable insulation, typically caused by water trees in MV insulation.
A.4.1 Density Test Method	Any	Accessible	Unknown	Thermal and Radiation	Possibly Destructive	Lab	Treatable with baseline	Local	Density may increase or decrease with aging, depending on various parameters. Need baseline specific gravity that may vary by batch and color.
A.4.2 Gel Content (Solubility) and Swelling Ratio Measurements	Crosslinked Polymer	Any Accessible	Unknown	Thermal and Radiation	Possibly Destructive	Lab	Treatable with baseline	Local	Most applicable to cross-linked polymers with minimal additives, such as MV insulation.

Test Method	Material Applicability	Material Function	Degree of Deterioration	Type of Degradation	Destructive	Treatable	In situ	Local	Comment
A.4.3 Oxidation Induction Time/ Temperature Tests	Typically XLPE & EPR	Accessible	Unknown	Thermal and Radiation	Destructive	Lab	Possibly	Local	Measure of loss of antioxidant in material.
A.4.4 Plasticizer Content	Plasticized PVC	Any	Unknown	Thermal	Destructive	Lab	Possibly	Local	When loss of plasticizer is the aging mechanism, this may be correlated to thermal aging.
A.4.5 Fourier Transform Infrared Spectroscopy (FTIR)	Any	Any	Unknown	Thermal and Radiation	Destructive	Lab	Treatable with baseline	Local	Generally used as one test to fingerprint a material. Change in carbonyl peak evaluation correlating to aging is experimental.
A.4.6 Near Infrared Spectroscopy (NIR)	Any light color	Any Accessible	Unknown	Thermal and Radiation	Nondestructive	In situ	Treatable with baseline	Local	Need enough information to determine if it correlates to degradation. Light grey change color of pigment that may not correlate to thermal or radiation damage.
A.4.7 Thermo-gravimetric Analysis (TGA)	PVC	Accessible PVC	Unknown	Thermal and Radiation	Destructive	Lab	Possibly	Local	Evaluation of PVC aging. For strictly thermal aging, plasticizer content may be a more suitable technique.
A.4.8 Thermal Phase Transition	Any	Any	N/A	N/A	Destructive	Lab	No	Local	May be used in forensic investigations. Not much information for amorphous materials, more for crystalline materials.
A.5.1 Elongation at Break/Tensile Strength	Any	Any	Sensitive after initial plateau	Thermal and Radiation	Destructive	Lab	Treatable	Local	Benchmark test for thermal aging.
A.5.2 Indenter Test	Lower crystallinity materials	Jacket or Insulation	Sensitive after initial plateau	Thermal and Radiation	Possibly Destructive	In situ	Treatable with baseline	Local	Generally used to test jacket for local high temperature or radiation to infer where insulation may will be damaged.
A.5.3 Mechanical Hardness	Generally, "softer" materials	Any Accessible	Unknown	Thermal and Radiation	Possibly Destructive	In situ	Treatable with baseline	Local	Similar to indenter, need baseline on specific cable. Likely best for localized thermal or radiation damage from external source.
A.5.4 Micro-Modulus	Any	Any Accessible	Unknown	Thermal and Radiation	Destructive	Lab	Treatable with baseline	Local	Similar to indenter, need baseline on specific cable. Likely best for localized thermal or radiation damage from external source.

Test Method	Material Applicability	Material Function	Degree of Deterioration	Type of Degradation	Destructive	Treatable	In situ	Local	Comment
A.6.1 Acoustic Velocity Testing	Any	Jacket or Insulation	Unknown	Thermal and Radiation	Non-destructive	Lab	Treatable with baseline	Local	Experimental, looks to identify changes in the velocity of propagation caused by the degradation of a polymer.
A.6.2 Gas chromatography mass spectrometry (GC-MS)	Any	Jacket or Insulation	Unknown	N/A	Destructive	Lab	Possibly	Local	An analytical method that combines the features of gas-chromatography and mass spectrometry to identify different substances within a test sample.
A.6.3 Nuclear Magnetic Resonance in Solution	Any	Jacket or Insulation	Unknown	N/A	Destructive	Lab	Possibly	Local	A test that allows assessment of the aging of materials that are partially crystalline such as XLPE. NMR measures changes to polymer or hydrogen atoms in materials. Correlates to the material state changes in hardness from oxidation and cross-linking.
A.6.4 X-ray Fluorescence Spectrometry (XRF)	Any	Jacket or Insulation	Unknown	N/A	Destructive	Lab	Possibly	Local	A method used to determine the concentration of elements (that have greater masses than sodium) in materials through the emission of characteristic “secondary” (or fluorescent) X-rays from a material that is excited by the bombardment with high-energy X-rays.
A.6.5 Scanning Electron Microscopy (SEM)	Any	Jacket or Insulation	Unknown	N/A	Destructive	Lab	Possibly	Local	A test that allows assessment of the aging of materials that are partially crystalline such as XLPE. NMR measures changes to polymer or hydrogen atoms in materials. Correlates to the material state changes in hardness from oxidation and cross-linking.
A.6.6 Creep	Any	Jacket or Insulation	Unknown	N/A	Destructive	Lab	Possibly	Local	A test method for determining the degree of cross-linking via the elongation and creep set after exposure to elevated temperature. Hot Creep/Hot Set corresponds more closely to service conditions than a solvent-extraction procedure.

Test Method	Material Applicability	Material Function	Degree of Deterioration	Type of Degradation	Destructive	Treatable	In situ	Local	Comment
B.2 Internal Irregularity Test for XLPE and TR-XLPE Insulations (Hot Oil Test)	MV XLPE	MV Insulation	Gross Deterioration	Wet	Destructive	Lab	No	Local	Looking for protrusions and voids from water or electrical trees in MV XLPE insulation.
B.3 Microscopic Examination (Optical)	Any	Any	Unknown	Any	Destructive	Lab	No	Local	A first evaluation when the issue is found.

Annex A

(normative)

Test method descriptions

A.1 Overview

This normative annex contains currently practiced test methods for the condition-monitoring of an insulation system in a cable system (complete cable and accessories) to determine if degradation has occurred and, in some cases, to what degree. A variety of tests are available; some of which are commonly used and others that are less frequent. Each test in this annex contains the following sections and references, and further information from each test method will be compiled in [Annex B](#).

1. Title
 - 1.1. Test method name
2. Application
 - 2.1. A discussion on the background of the test.
3. Test description
 - 3.1. A description of the test and procedure.
4. Evaluation of results
 - 4.1. A discussion on how to evaluate the results.
5. Acceptance criteria
 - 5.1. A discussion of the specific criteria used to judge the insulation condition.
6. Material applicability
 - 6.1. A discussion on the usefulness of the test on all insulations, if there are any restrictions on insulations to which the test can only be applied (if any), or if there are any known limitations for using the test.
7. Test nature
 - 7.1. Information is provided on whether the test method is destructive, non-destructive, or semi-destructive.
8. Test equipment necessary
 - 8.1. A discussion on the test equipment required to perform the test.
9. Test considerations
 - 9.1. An explanation of the various factors that must be considered when performing a test (e.g., temperature effects, humidity, cleanliness).
10. Training and experience requirements
 - 10.1. A discussion on the level of training, skill, and experience required to achieve the desired information and not skew test results.
11. Complexity of results interpretation
 - 11.1. A discussion on the difficulty of evaluating the test results.
12. Maturity of the technique
 - 12.1. A short description of the level of maturity of the test.
13. References
 - 13.1. A list of references used for developing the previous information.
14. For further information
 - 14.1. A list of references not used for developing the previous information, but germane to the subject.

A.2 Visual inspection

A.2.1 Application

Visual inspection can be performed in almost all settings on a variety of cable types, cable arrangements, and cable systems, including accessories (splices, joints, separable connectors, and terminations). The limitation is typically the accessibility of the target cables and whether they can be seen with reasonable efforts and means. For example, cables that are installed in underground vaults, conduits, raceways, trenches, elevated cable trays, or otherwise hidden from view by permanent structures are excluded from routine visual inspections and walkdowns. Also excluded are cables in areas where excessive heat, radiation, or other hazards may pose personnel safety concerns, unless opportunities exist when conditions are less restrictive, such as during maintenance or outages. It should be emphasized that cables in such environments are most vulnerable and, as such, should be inspected whenever possible, or alternative methods of remote testing are used to determine cable condition. However, even if the cables themselves are not visible, the structures or raceways that house the cable should be examined for signs of potential degradation. For example, if visible signs of thermal overheating, liquid spots, or buildup of chemical residue are identified on or near the cable tray or conduit, these should be noted for further investigation.

Low-voltage power instrument, and control cables are particularly important to be included in visual inspections since there are limited test methods available to identify and track their aging and degradation. The primary focus of a visual inspection is to develop a qualitative assessment of the condition and health of the cable insulation system through the appearance of the cable jacket or the outermost surface of the cable and connectors. In many cases, cables age and undergo degradation from the external environmental conditions and elements impacting the cable jacket. There are, however, instances where internal cable stressors can cause property changes and potential performance issues. These could be caused by abnormal ohmic heating (internal heat generated due to conductor resistance and high currents), sulfur and chlorine compounds in certain insulations corroding conductors from the inside, water trees, electrical trees, etc. In most cases, these internal cable stressors will eventually manifest themselves into visual indications of changes observable on the external surface.

Most nuclear facilities perform cable systems walkdowns to identify adverse localized equipment environments (ALEE). ALEEs are areas or conditions in a specific location that are significantly more severe than the specified service conditions for which the cable was originally designed. Environmental characteristics such as temperature, radiation, chemical exposure, ultraviolet (UV) rays, and moisture may result in an ALEE. Additionally, situations where a cable is subject to mechanical stress or strain should also be considered as ALEE. Examples of such conditions are sharp edges in cable trays or points of entry and exit of cables in conduits or raceways, bend radius violations, improper vertical cable supports, cable ties unsuitably tightened exerting excessive pressure on jackets, over-filled cable trays, etc. The effects of an ALEE may accelerate the rate of cable aging and degradation.

A.2.2 Test description

Visual inspection starts with a walkdown of plant areas by trained personnel to search for and identify potential ALEEs. There are guidelines published in a variety of documents providing details and methods of identifying and managing ALEEs. Some of these documents are listed in [Clause 2](#). As part of the development of walkdown plans, previous operating experience, observations by plant personnel, EQ zone information (expected zone temperature, radiation, etc.), environmental monitoring data in specific locations (if available), previous walkdown documentation, operating experience (site-specific and industry), and cable routing database should be factored in for an integrated approach.

Examples of conditions and areas that might negatively impact the performance of cables and can be considered ALE (provided cables/connectors are exposed to these conditions) are listed next:

- *High temperature or local hot spots:* Proximity to hot pipes, pipes that are not thermally insulated (temporarily or permanently), areas above heat-producing equipment (e.g., turbines, large motors, diesel generators), space heaters, etc.

- *Radiation zones*: Proximity to reactor vessel, piping, tanks, or other sources of radiation with inadequate shielding or missing shielding (temporarily or permanently).
- *Chemicals and oil contaminations*: Chemical (e.g., boric acid), fuel oil, hydraulic fluids, lube oil leaks, sprays, fumes, areas prone to animal congregation (dropping, excrements containing chemicals such as phosphates and ammonia).
- *Excessive moisture*: High humidity areas, wet/dry cycle areas, stagnant fluid areas, areas subject to flooding, leaks or spills, manholes, underground ducts, trenches, etc.
- *UV exposure*: Direct proximity to high-energy lighting, direct sunlight exposure, etc.
- *Vibration zones*: Proximity to rotating or moving equipment, inducing chronic vibration to nearby structures, conduits, cable trays, buses, etc.
- *Mechanical stress and strain*: Overfilled cable trays, excessive bend radius, sharp edges in cable trays or supports, sharp edges in points of entry and exit (e.g., boxes, conduits, raceways), improper supports on vertical cable runs, over-tightened cable ties/grips or clamps, cuts or installation damages, fretting contact points, foreign material on cable trays or trenches, damage caused by animals (chewing, clawing).
- *Other potential stressors*: Proximity to high traffic and high maintenance activities, previous cable failure sites, previous cable repairs and splices, cables covered with fire retardant compounds.
- *Cables and wires inside field cabinets or enclosures*: Infrequently exposed cables and wires inside MOV compartments, motor compartments, etc., that can be subject to potentially harmful elements such as heat, oil, or contamination.

Upon identification of ALEEs and situations where cables might be subject to environmental stressors beyond normal service conditions, close examination of accessible cables is performed. This activity should include splices, connections, terminations, and accessories. These inspections look for signs of degradation, unusual aging, and physical damage characterized by one or more of the following characteristics:

- Jacket surface anomalies (voids, bumps/blisters, cuts, cracks, etc.) and contamination
- Embrittlement (appearance of stiffness or loss of ductility)
- Discoloration or dullness (some material containing carbon black may not readily show discoloration)
- Cracking
- Melting
- Swelling
- Oozing (typically green plasticizer material from PVC compounds or other material)
- Oily residues
- Chemical residues
- White powder or dust buildup
- Burns or charring
- Blisters
- Bubbles
- Crystal formations (salts)
- Cuts
- Stressed or compressed cable signs (reduced size, flat spots)
- Fraying

- Abrasion or scuffing
- Corrosion (green or brown spots, rust formation, loss of material, etc.)
- Softening
- Cable tie overtightened signs
- Sharp edge damages (at elevation changes, supports, blocks, exit/entry points in conduits, boxes, raceways, etc.)
- Stretch or strain marks (e.g., vertical runs improperly supported)
- Loss of jacket or insulation material (due to peeling, rubbing, animal bites, etc.)

During the inspection, observations are carefully recorded, photographs taken (when possible), measurements made (length of cracks, depth of impressions, etc.), and samples are requested to be based on plant procedures if a need is demonstrated (contaminated material, oozing residues, foreign material, etc.). Anomalies identified during the inspection needing immediate corrective actions are reported to the responsible organization and entered into the corrective action program in accordance with site procedures. The inspection results and the details of the findings are recorded and passed on to the responsible organization for evaluation, trending, as well as determination of any necessary follow-up testing or repairs.

A.2.3 Evaluation of results

The results of the visual inspection are reviewed, compared to previous findings (if applicable), trending performed (if possible), and a qualitative determination is made to determine if follow-up action, testing, and/or repairs are required. Site and industry operating experience, as well as knowledge based on cable manufacturers' information, are useful to assess the condition of the cables.

There are various guides available to assist in evaluation and deciding the amount of acceptable degradation for each type of cable system. This recommended practice provides information on available follow-up testing of cables that may require quantitative determination of the degree of degradation.

A.2.4 Acceptance criteria

Visual inspection is a qualitative, objective test that is useful in determining if a quantifiable test may be warranted to determine cable condition. As such, the acceptance of visual condition requires an individual who understands the cable jacket and insulation types, how they degrade, and how that degradation presents itself visually (discoloration, superficial cracking, stiffening, etc.). An unacceptable criterion is probably best defined as a condition or state that, if left unmanaged, could result in a loss of intended function. In most cases, the logical assumption is that the cable jacket appearance (or the outer insulation in the absence of jacket) and condition are good indications of the status of the underlying layers and overall state of that section of the cable run (some exceptions, such as internal degradations due to treeing, conductor aging, or ohmic heating, could exist).

Cable degradation is typically less than that of the sections located in severe environments than the ALEEs.

A.2.5 Material applicability

The visual inspection method can be employed for all material and cable types, although different cable and jacket material and methods of manufacture will result in different observable characteristics and telltale signs of aging and deterioration. For instance, oozing of plasticizer is typically limited to PVC material, and discoloration of jackets may not apply to material containing carbon black.

A.2.6 Limitations

Visual inspection is a qualitative test. They require trained personnel who are familiar with what stressors cause cable degradation and how that degradation presents itself visually. The value of the evaluation is limited by the knowledge of the person making the final determination of what is not degraded, what is degraded, and whether repairs, replacement, or a qualitative test is required to determine if the cable can still support its design function. Visual inspections can only be done on cables that are observable and considered accessible. Therefore, walkdowns should be supplemented by opportunistic inspections of cables not normally accessible, but are accessible during certain operating conditions or during maintenance that allows observation (such as when a motor-operated valve operator is opened for valve testing, or a bus outage, etc.). Cables should only be manipulated, touched, altered, disturbed, or stressed by qualified personnel and as allowed by safety standards.

A.2.7 Test nature

Visual inspection is nondestructive in nature and is performed in situ.

A.2.8 Test equipment necessary

A few tools and test equipment are commonly needed to perform visual inspections. The following is a list of helpful tools that test personnel should consider using:

- Camera
- Flashlight
- Mirror
- Binoculars
- Magnifying glass
- Thermometer
- Infrared camera
- Remote distance measuring devices (non-conductive and/or electronic measuring tape)
- Sample collection aids (bags, vials, or cotton swabs for sample collection—typically for environmental conditions such as dust, contamination, cable secretions, etc.)
- Infrared thermometer
- Hygrometer borescope

It should be noted that care should be taken while using some of the above tools (e.g., magnifying glass, thermometer, borescope) in close proximity to cables, whether they are energized or not. Further investigations, if needed, may warrant the use of thermography equipment, ultrasound, partial discharge detectors, or other devices on cables that are energized.

A.2.9 Test considerations

Visual inspection is done with no preconditioning, preparation of the cables, or other measures to change the state of the cables from the normal operating conditions. In some cases, it may be necessary to remove surface dust, mud, contaminants, fire-retardant coating (if allowable per site procedures), or other foreign material from cables to be able to observe the jacket material closely and effectively. In such cases, arrangements should be made and proper precautions and safety measures should be taken to perform these tasks. Cables are generally considered energized,

and static charge buildup is a possibility that can lead to shock hazard. Therefore, safe working procedures, voltmeters, and proper protective equipment should be utilized for this purpose.

Resource availability and the window of appropriate time to perform visual inspections can often result in having to prioritize the areas and cable runs to be included in upcoming inspections. Prioritization should consider cable function/load significance (safety and economic attributes), type of cable, and plant/industry operating experience, and interval between inspections. A prudent technique in prioritization is to consider risk. Risk-informed decision making evaluates three parameters known as “risk triplets.” These are: type of failure (what can go wrong), likelihood of failure (estimated probability), and consequence of failure (impact on safety and cost). A prioritization derived by considering risk offers a sound platform to help ensure the best use of limited resources.

A.2.10 Training and experience requirements

Personnel conducting visual tests and walkdowns should understand proper installation practices and the signs of aging. Persons evaluating visual inspection results should be well-versed and experienced in cable polymers, their construction, how the polymers change under various ALEEs, repair methods, and testing to quantitatively assess the level of degradation. Familiarity with the plant layout and features is also required. Inspection teams can be a combination of plant personnel (component engineer, system engineer, electrical and instrument technicians, etc.) and outside consultants/subject matter experts (SMEs). The following skills and knowledge areas are recommended to be considered in the formation of a walkdown team:

- Site specifications for cable procurement
- Cable manufacturer’s technical manual
- Cable construction and material details
- Cable routing and installation methods at the site (cable identification, cable tray and conduit routing, raceway arrangements, underground arrangements, train separation methods, cable supports and blocks, terminations and accessories, etc.)
- Industry applicable standards and guides
- Industry guides on walkdowns, ALE, and visual inspection
- Site procedures and safety practices
- Environmental Qualification (EQ) program

A.2.11 Complexity of results interpretation

Interpretation of results is not considered complicated, but it is subjective, and the results may vary depending on the level of experience and expertise of the person performing the review.

A.2.12 Maturity of technique

Visual inspection can be considered a mature technique due to many decades of experience and a vast industry knowledge base related to cable conditions in a variety of environments and service conditions. By leveraging available industry literature and standards, inspection teams can add tremendous value to the quality of their task, and the plant can benefit from the results in the areas of reliability, safety, and cost.

A.2.13 References

More details on the visual inspection method can be found in the following works:

- IEEE Std 1205™, IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations [B83]
- Guideline for the Management of Adverse Localized Equipment Environments [B67]
- Cable Polymer Material Handbook—Low Voltage Power and Control [B43]
- Plant Engineering: Cable Polymer Material Handbook—Medium Voltage Insulations [B121]
- Plant Engineering: Cable Polymer Material Handbook—Instrument Cable [B120]
- Plant Engineering Electrical Cable Test Applicability Matrix for Nuclear Power Plants [B123]
- Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables [B111]
- Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants [B112]
- Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients [B137]
- Essential Elements of an Electric Cable Condition Monitoring Program [B138]
- Condition-Monitoring Techniques for Electric Cables Used in Nuclear Power Plants [B139]

A.2.14 For further information

None.

A.3 Electrical tests

A.3.1 Insulation resistance

A.3.1.1 Application

Insulation resistance testing is used to determine the resistance of insulation between conductors and ground. The test is useful for detecting gross insulation damage that results in significantly lower insulation resistance values (multiple decades of change). The test is most suitable for evaluating low-voltage and medium-voltage, non-shielded cables in wet environments. This test is not suitable for detecting gradual aging from thermal and radiation aging for any cable insulation, regardless of voltage rating. Comparisons of results from one test to another will require compensation factors if there are significant differences in temperature and humidity at the time of the measurements. It is typical for cable test measurements to be adjusted in terms of MΩ-1000 ft or MΩ-km when used in conjunction with cable acceptance criteria.

A.3.1.2 Test description

The test evaluates the bulk dc resistance of the insulation and includes all materials between the two terminals of the test device, including jackets, insulation, and air gaps. If a section of the conductor is exposed, the success in detecting the problem will be a function of the orientation of the exposed conductor and the length of the tracking/insulation path to the measurement's ground plane. The bulk resistance of the insulation system might be measured from conductor to conductor, from conductor to all other conductors, from conductor to ground or shield, or from conductor to all other conductors grounded. The test may be performed at any voltage from 50 Vdc to 5000 Vdc.

Testing of medium- or high-voltage extruded polymers, such as cross-linked polyethylene (XLPE) and ethylene propylene rubber medium- or high-voltage cables, at voltages $>10,000$ Vdc is not recommended by IEEE standards due to the potential of creating space charges in the insulation. Most tests of low-voltage power and control cables are performed at 500 V, which is considered to provide sufficient electrical stress to identify significant flaws, but which is not overly stressful. The leakage current from the test is converted to ohms. The test is useful for detecting gross imperfections, deterioration, and damage that result in significantly lower insulation resistance values (multiple decades of change). Measurements are generally 1 min to 10 min in duration, with the insulation resistance increasing initially and stabilizing during the test. Decaying insulation resistance values during a measurement or instability in the measurement are indications of an insulation or test equipment problem.

Insulation resistance measurements at 1 min and 10 min are often used to compute a polarization index (PI), which is described separately [see the PI test discussion (A.3.2)].

A.3.1.3 Evaluation of results

A cable, whether medium- or low-voltage, should have an insulation resistance of at least $305\text{ G}\Omega\text{-km}$ ($1\text{ G}\Omega\text{-1000 ft}$), which is required by many manufacturing standards. Test results can be significantly affected by cable routing configuration in trays and conduit. Results might also be significantly different between dry and moist ambient conditions and with changes in ambient temperature, with and without the presence of severe degradation. When insulation resistance values are high (that is, in tens of giga-ohms), changes in one to two decades in results from previous test results may be related to ambient environmental conditions and not be indicative of any significant problem. The differences in ambient temperature and humidity at the time of measurement should be considered. Temperature compensation for insulation resistance measurements can be performed. The cause of a significant change in insulation resistance, such as a decrease to less than $30.5\text{ M}\Omega\text{-km}$ ($100\text{ M}\Omega\text{-1000 ft}$) should be evaluated. Values in the tens of $\text{M}\Omega\text{-1000 ft}$ are indicative of a significant problem for most low-voltage cable types and lengths. Low insulation resistance values and insulation resistances that decrease or fluctuate significantly during the measurement indicate damage or severe degradation of the insulation system.

Insulation resistance values for good cables are often greater than many thousands of $\text{M}\Omega\text{-1000 ft}$. Depending on the nature of a cable damage site and its cleanliness, the insulation resistance might remain high or might decrease to a $\text{M}\Omega\text{-1000 ft}$ or less.

Caution shall be taken when evaluating insulation resistance readings of low-voltage or medium-voltage cables in dry applications. High insulation resistance values may not be a direct indication as to whether a problem exists. Dry, cracked insulation may have high insulation resistance because dry air acts as a good insulator and could mask the degree of insulation degradation. Accordingly, insulation resistance does not always provide an indication of damage and will not necessarily provide a useful trend related to gradual deterioration. However, this test method is useful for detecting and eliminating damage that results in leakage paths across the insulation from conditions such as cuts coupled with high humidity or chemical contamination.

One other method of results evaluation is a comparison of test results of similar cables that are part of the same circuit (such as the three phases of a motor or transformer, or multiple conductors under the same jacket, or other motors for the same system, etc.). Large variations between the insulation resistance values may provide an indication of degradation.

A.3.1.4 Acceptance criteria

EPRI 1020804 [B127] describes compensation of insulation resistance to 1000 ft (km) and recommends $100\text{ M}\Omega\text{-1000 ft}$ ($30.5\text{ M}\Omega\text{-km}$) as the action level for considering that significant degradation has occurred. Cables may continue to operate with such values if the cause is well understood and rapid failure in service has been eliminated through further testing or analysis.

NOTE—If the insulation is chlorosulfonated polyethylene (Hypalon), the as-manufactured insulation resistance is approximately 16–26 MΩs-km (50–80 MΩ-1000 ft). The acceptance criteria for chlorosulfonated polyethylene insulation should be 1.6 MΩ-km (5 MΩ-1000 ft).

Trending of insulation resistance over a period may be difficult because the effect of ambient temperature, moisture, and contamination can greatly impact results from test to test. Still, evaluating the trend in measurements taken over a period may provide insights regarding the condition of the cable and the environment of the cable. However, insulation resistance testing alone will not necessarily provide a direct indication of the state of the cable insulation. Testing of severely degraded insulation located in dry air might produce very high insulation resistance values.

A.3.1.5 Material applicability

The test can be applied to any insulation system.

A.3.1.6 Limitations

Insulation resistance testing should be applied to coaxial and triaxial cables with caution because significant capacitive charges can be accumulated during the test. These charges might adversely affect the instruments used on these circuits if the charge is not fully drained before the circuit is returned to service.

Testing of extruded polymers, such as XLPE and ethylene propylene rubber cables, at higher voltages is not recommended by IEEE standards due to the potential of creating space charges in the insulation.

For other cable types, the voltages used in insulation tests do not impose a significant stress on the insulation system. Therefore, the test might not detect even gross damage unless the damage site is in contact with the return path for the test or has a conducting contaminant, such as moisture, available to complete the return path for the leakage current. An insulation defect might not be detected when exposed to air because air is a good insulator.

A.3.1.7 Test nature

The test is typically nondestructive and performed in situ.

A.3.1.8 Test equipment necessary

An insulation resistance meter, a temperature and humidity measurement device, and an approved grounding method to discharge the cable.

A.3.1.9 Test considerations

The following things need to be considered:

- The cable generally must be disconnected from any devices or switchgear.
- Trending of results will be affected by the bulk temperature of the cable.
- Measurements performed on the same cable at 0 °C and 30 °C (32 °F and 86 °F) might vary by an order of magnitude or more.
- Making measurements under similar ambient environmental conditions will reduce the variability of trending.

- Differences in the physical arrangement of cables within trays and conduits might cause even similar circuits to have different insulation resistance values. However, if the purpose of the test is to identify gross changes in insulation resistance values, these differences in initial values might not matter.
- Insulation resistance tests will not detect gradual radiation and thermally induced aging. However, gross physical damage or deterioration under wet conditions should be detectable.
- Cleanliness of the terminations for medium-voltage cables may influence the insulation resistance values. Dirt or contamination may provide a leakage path to the cable shield and affect the measurement results.

A.3.1.10 Training and experience requirements

The test is straightforward to perform, and only limited training is required.

A.3.1.11 Complexity of results interpretation

To evaluate the test results, one needs to have an understanding of the cable type, application, operating environment, physical layout, and environmental conditions during the testing, which are required for the results to be most useful. Initial values from installation and commissioning are also useful for trending.

As a go/no-go measurement, less experience is necessary.

A.3.1.12 Maturity of technique

The technique is very mature.

A.3.1.13 References

More details on the insulation resistance method can be found in the following works:

- Plant Support Engineering: Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants [\[B127\]](#)

A.3.1.14 For further information

More details on the insulation resistance method can be found in the following works:

- IEEE Std 43, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery [\[B86\]](#)
- IEEE Std 62, IEEE Guide for Field Testing Power Apparatus Insulation [\[B88\]](#)
- ANSI/NETA MTS-2015, Standard for Maintenance Testing Specifications [\[B16\]](#)

A.3.2 Polarization Index test

A.3.2.1 Application

Polarization Index (PI) testing is a derivative test based on the results obtained from a ten-minute dc insulation resistance test measurement. Originally, the test was used on motor and generator insulations; the test method was also used for testing the cable insulation when the motor and feeder cables were not disconnected for testing. If a problem was identified in the combined connected load (motor or generator) and the feeder cables, then the circuits

were separated and tested individually to determine which part of the circuit was degraded. At some point, the test was applied to cables as a diagnostic test to monitor insulation degradation. The use of PI has been effective for motor and generator insulations because good stator winding insulation has a relatively low initial insulation resistance, which improves dramatically as the capacitive and dissipation currents decrease over the 10-minute hold time. However, for cable insulations, there is relatively little change in the capacitive current and the resistive current change is minor (except in cases where the insulation is severely degraded). Regardless, over the course of the test voltage application, the insulation resistance change is minimal.

The application of this test on cable insulation is widespread because of the relative lack of choices for aging management programs that monitor cable insulation degradation for low-voltage control and power cables and medium-voltage unshielded power cables, and it is a long-practiced method. The test has been applied to cable insulations in both dry and wet operating conditions.

A.3.2.2 Test description

PI testing measures the insulation resistance of the test circuit for 10 minutes under dc potential at a value appropriate for the cable voltage rating (for example 16500 V for low voltage power cable, 1000 V for 5 kV, 2500 V for 8 kV and higher cables) is applied to the cable conductor using the station ground or an adjacent conductor for the test circuit return path.¹⁷ The test measure evaluated is the ratio of the ten-minute insulation resistance value divided by the one-minute insulation resistance value. As a ratio, it is somewhat independent of test conditions (as insulation resistance is affected by temperature and humidity). The resulting ratio is the PI, and values for cable insulation should be ≥ 1 for a good cable. Values of $PI < 1$ or values that have decreased from previous measurements are indicative of deteriorated insulation.

A.3.2.3 Evaluation of results

For most cables, the PI will be one or slightly greater than one because the absorption and charging currents decay well within one minute. Long cables and cables with shields might have ratios > 1 . Values < 1 indicate leakage current is increasing during the duration of the test, which is unacceptable.

A.3.2.4 Acceptance criteria

A $PI > 1$ or one that has not significantly changed from historical values are acceptable. PI results < 1 or PI values that have changed by more than 10% of previous readings should be investigated further. Long cables and/or well shielded cables may have a PI ratio > 1 .

A.3.2.5 Material applicability

The test can be applied to any insulation system.

A.3.2.6 Limitations

When using insulation resistance to obtain a PI for coaxial and triaxial instrument cables, it is important to proceed with caution to help ensure that no significant capacitive charges can be allowed to accumulate in the insulation during the test. These charges might adversely affect the instruments to which they are connected if the cable is not grounded for a sufficient time to fully drain any captured charge before the circuit is returned to service (typically 10 min for each minute of applied dc voltage).

¹⁷The values given are examples. Actual values used can vary and are typically based on historical precedence.

PI measurements will only detect gross deterioration of cable insulation, dielectric, or mechanical properties. Low-voltage cable dielectric stress is not typically high enough to cause insulation degradation. PI may be useful to detect severe damage or severe age-related degradation that has progressed since previously performed test results. Electrical properties of low-voltage cable insulation typically change only after gross mechanical property changes caused by excessive cross-linking or chain scissioning, and the changes do not typically result in lower insulation resistance values unless wet. Cables in dry environments may show no change in PI even if the conductor is exposed because no ground path for leakage exists and air is a good dielectric and typically would not arc over to another conductor or ground at the test voltages applied.

Medium-voltage cable insulation, especially at voltages above 4160 operating voltage, is dielectrically stressed. However, the PI will act similarly to a low voltage insulation and not change noticeably in dry conditions but may be observable in the results of cables in wet locations. Regardless, both insulation resistance and PI are much less sensitive compared to other tests, such as very low-frequency tan delta, dielectric spectroscopy, and partial discharge testing, in finding dielectric loss or discharges that can be detected much earlier than PI testing.

A.3.2.7 Test nature

The test is typically nondestructive and performed in situ.

A.3.2.8 Test equipment necessary

An insulation resistance meter, a temperature and humidity measurement device, and an approved grounding method to discharge the cable.

A.3.2.9 Test considerations

The following things need to be considered:

- The cable generally must be disconnected from any devices or switchgear.
- Trending of results will be affected by the bulk temperature of the cable.
- Measurements performed on the same cable at 0 °C and 30 °C (32 °F and 86 °F) might vary by an order of magnitude or more.
- Resistance values should always be temperature corrected to a consistent value [e.g., 25 °C (77 °F)]. See IEEE Std 43 [B86]-temperature correction.
- Making measurements under similar ambient environmental conditions will reduce the variability of trending.

Differences in the physical arrangement of cables within trays and conduits might cause even similar circuits to have different insulation resistance values. However, if the purpose of the test is to identify gross changes in insulation resistance values, these differences in initial values might not matter.

Insulation resistance tests will not detect gradual radiation and thermally induced aging. However, gross physical damage or deterioration under wet conditions should be detectable.

Cleanliness of the terminations for medium-voltage cables may influence the insulation resistance values. Dirt or contamination may provide a leakage path to the cable shield and affect the measurement results.

A.3.2.10 Training and experience requirements

The test is straightforward to perform, and only limited training is required.

A.3.2.11 Complexity of results interpretation

To evaluate the test results, one needs to have an understanding of the cable type, application, operating environment, physical layout, and environmental conditions during the testing to be most useful. Initial values from installation and commissioning are also useful for trending.

A.3.2.12 Maturity of technique

The technique is very mature.

A.3.2.13 Reference

More details on the polarization index test can be found in the following works:

- Plant Support Engineering: Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants [\[B127\]](#)

A.3.2.14 For further information

More details on the polarization index test can be found in the following works:

- IEEE Std 43, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery [\[B86\]](#)
- IEEE Std 62, IEEE Guide for Field Testing Power Apparatus Insulation [\[B88\]](#)
- ANSI/NETA MTS-2015, Standard for Maintenance Testing Specifications [\[B16\]](#)

A.3.3 Time Domain Reflectometry

A.3.3.1 Application

Time Domain Reflectometry (TDR) can be used as a commissioning, maintenance, or troubleshooting test to identify sections of cables with significant impedance differences from the remainder of the cable. These impedance changes might be indicative of corrosion damage of metallic shields (concentric neutral type), mechanical damage, or degraded insulation. It is also used to confirm the presence of splices and detect open circuits in the conductor and shield system. The test will identify the location of the impedance difference along the cable length. The test is nondestructive by nature.

A.3.3.2 Test description

In a TDR test, a low-voltage, narrow pulse, or step waveform is imparted to the terminals of the cable being tested. As the wave travels along the cable, energy is reflected back to the terminals wherever the characteristic impedance of the insulation or conductor system changes. The voltage is reflected back to the point of application of the pulse measured by the TDR system, and a trace is displayed on a monitor.

More advanced methods can also be used where the pulse width and rise time are varied. Varying the pulse characteristics enables the TDR analyst to adapt the test parameters to specific characteristics and features of the cable under test, for instance, its length, or to overcome high attenuation issues caused by a severely degraded shield. This advanced methodology increases the resolution and diagnostic capability of this technology.

The results are displayed as changes in amplitude of the measured reflected voltage versus time. The time axis is directly proportional to the distance from the cable termination where the pulse was applied. Evaluation of the test data allows identification of points of loss of conductor continuity and of severe insulation damage.

Positive location of the cable end can also be performed, where accessible by shorting the tested conductor to ground. Such a condition provides a pronounced signature in the waveform to verify the endpoint. Once obtained, cable length can also be estimated based on the approximate velocity of propagation of the waveform. Travel speeds can vary based on the insulation system and insulation age, which also must be considered in a length estimation.

Simplistic examples of these concepts are provided in [Figure A.1](#).

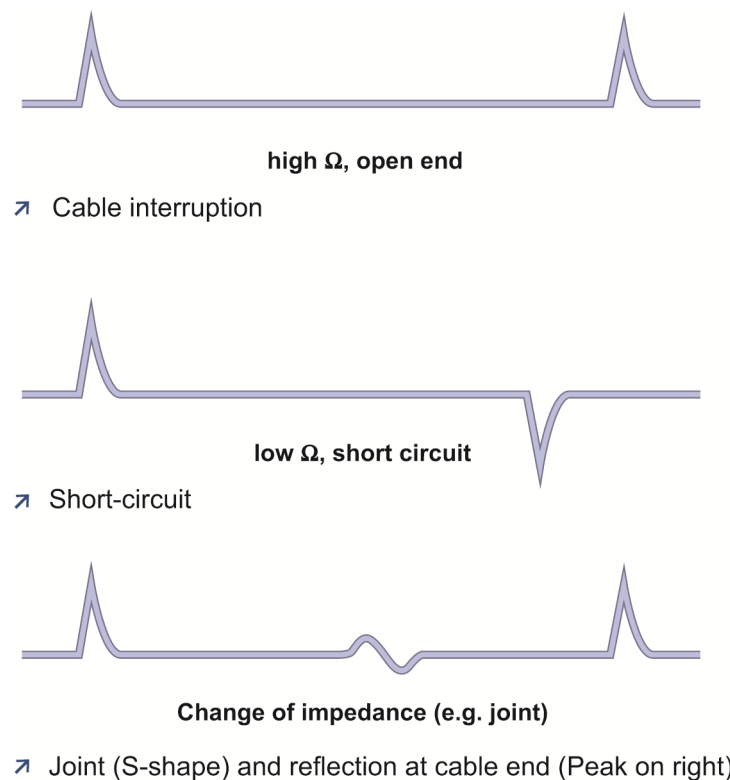
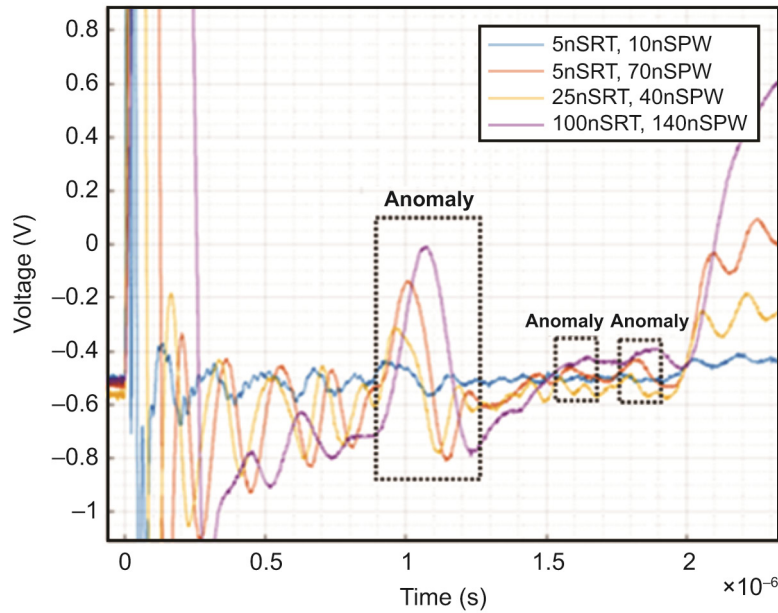


Figure A.1—Demonstration of TDR signal wave forms for cable interruption, short circuit, and joint (splice) impedance changes

A.3.3.3 Evaluation of results

Evaluation and trending of test results require accurate information on the cable system (length and splice locations) and personnel experienced in the evaluation and post-analysis of TDR data. [Figure A.2](#) provides an example of an actual TDR application and interpretation using advanced TDR methods in medium-voltage cable applications. [Figure A.3](#) shows a TDR and how it can be used to identify or locate splices of an MV cable. Note that the further from the injection side (left-hand side), the smaller the reflection of each splice gets due to attenuation and the length of the cable.



NOTE—Inconsistencies in pulse behavior across rise time and pulse width are used to identify potential anomalies for further evaluation or trending.

Figure A.2—Example of Advanced TDR results from distribution class cable test illustrating use of variable pulse characteristics to identify and locate potential defects

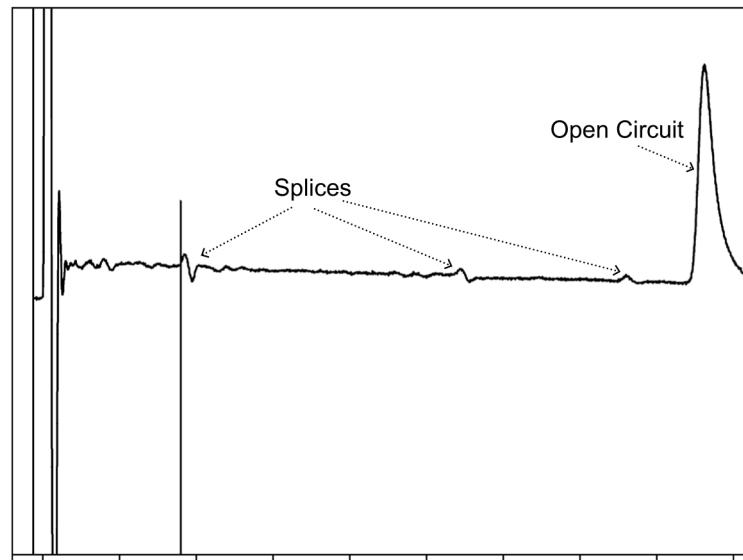


Figure A.3—TDR trace of an MV cable with three splices

A.3.3.4 Acceptance criteria

There are no absolute acceptance criteria.

TDR results are evaluated on the basis of comparison with baseline results, comparison of results with those of parallel circuits, or through detection of impedance changes that are not expected in the circuit being evaluated. The

test is most effective in detecting relatively gross conductor or shield damage, near short circuits, and splices. It can also be used to detect impedance discontinuities caused by local aging or damage to the cable system.

A.3.3.5 Material applicability

The test is applicable to all cable materials.

A.3.3.6 Limitations

The test can be applied to most cable geometries. The cable must be shielded or have multiple conductors for the test to be effective. Higher quality results can be expected from shielded and coaxial/triaxial constructions. Blind spots at the signal injection point exist. Attenuation of signals can also occur, especially with taped metallic shields, and may require more advanced strategies and methods to overcome, such as varying signal pulse width and rise times. In cases where TDR is applied to medium-voltage class cables with tape-wrapped metallic shields, the increase in energy and pulse width may not be sufficient to detect the far-end reflection (which is typically not an issue for low-voltage cables). While a more energetic and wider pulse allows a TDR pulse to propagate further down longer lengths of cable, corrosion of the metallic shield and resultant signal attenuation may decrease the resolution of the TDR measurement. The loss of resolution could affect the TDR's ability to detect and display small, potentially important irregularities in the cable.

A.3.3.7 Test nature

The test is nondestructive and can be performed in situ.

A.3.3.8 Test equipment necessary

A time domain reflectometer (pulse generator and recording oscilloscope) is needed.

A.3.3.9 Test considerations

The test might require isolation of connected equipment from the tested cable to eliminate interference of the signal from the equipment and to allow connection of the test equipment.

Splice points between segments with different insulation systems will be detected (for example, if a circuit has two segments, one with an EPR insulation, and one with XLPE insulation, the differences in insulation characteristics might be detected). Additionally, as cable ages, the velocity of propagation changes, and the time of travel usually reduces the signal speed. Therefore, a knowledge of the cable circuit, its age, and any available records of length is required to facilitate proper interpretation of the results.

The test usually will not detect small defects up to and including through-insulation cuts and cracks if the damage site does not affect impedance significantly (for example, clean, dry through cuts and cracks might not be detected).

A.3.3.10 Training and experience requirements

The test is relatively easy to perform with automated TDR testers; limited training is required. For advanced TDR, which requires the setup of pulse characteristics, experienced users with adequate training are required. The choice of test parameters necessitates a detailed understanding of the cable system design and the impact of aging and degradation on the TDR signal.

A.3.3.11 Complexity of results interpretation

Evaluation of the results requires an engineer or analyst with test experience. Differences in traces can be quite subtle. External factors, such as electromagnetic noise, can affect the results.

A.3.3.12 Maturity of technique

The technique is considered mature.

A.3.3.13 References

More details on the time domain reflectometry method can be found in the following works:

- Diagnostic Testing of Underground Cable Systems (Cable Diagnostic Focused Initiative Phase 1). NEETRAC [B50]
- Diagnostic Testing of Underground Cable Systems (Cable Diagnostic Focused Initiative Phase 2). Chapter 5, Time Domain Reflectometry, NEETRAC [B51]

A.3.3.14 For further information

None.

A.3.4 Frequency Domain Reflectometry

A.3.4.1 Application

The Frequency Domain Reflectometry (FDR) test method is a distributed electrical test that transmits a signal wave down two parallel planes (e.g., cable conductors) to identify and locate impedance changes in a cable circuit, specifically insulation. This technique is sensitive to changes in a cable's physical dimensions [e.g., changes caused by thermal expansion or contraction of the insulation polymer(s)] as well as changes in the electrical permittivity of the cable's insulation material. The speed or velocity of propagation (V_p) of the test signal is dependent on the characteristics of the cable (e.g., capacitance and inductance). As an insulation polymer degrades, its electrical permittivity increases, resulting in the lowering of the cable's characteristic impedance that is measured by the FDR test. These changes in impedance can be due to many variables throughout the cable's ambient environment. For example, a localized "hot spot" near exposed hot piping or a large section of the cable running through a room or building of the plant that contains adverse environmental conditions that could result in polymer aging, or result in dimensional changes due to thermal expansion of the cable's insulating polymer(s).

FDR testing is most suitable for cables that consist of two or more conductors within one jacket or a single conductor with a concentric shield. Single-conductor and unshielded cables may be more challenging to test; these conductors require a continuous conduit or cable tray as the transmission line reference. However, the non-uniformity of the spacing between the conductor and reference transmission line will reduce the ability of FDR or any reflectometry test to accurately identify and locate changes in characteristic impedance along the cable.

A.3.4.2 Test description

FDR test equipment typically consists of a device that can transmit a sinusoidal waveform at a specified voltage and frequency while measuring the incident and reflected signal, similar to a Vector Network Analyzer. The FDR test is versatile, as it can be applied at one end of a cable while the other end remains connected to the load or end device.