



IEEE Guide for Early Detection, Mitigation, Preventative Measures, and Response to Smoke, Fire, and Explosions in Underground Electrical Structures

IEEE Power and Energy Society

Developed by the
Insulated Conductors Committee

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STANDARDS

IEEE Guide for Early Detection, Mitigation, Preventative Measures, and Response to Smoke, Fire, and Explosions in Underground Electrical Structures

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Abstract: Abstract: Failures of underground cables and accessories can result in the release of toxic gases and large amounts of energy. These failures include smoking manholes, manhole fires, and manhole explosions. These failure events can damage underground infrastructure and pose a risk to the maintenance crews and the public. The root causes, prevention, early detection, mitigation, and response to failures of accessories and cable inside, and connected to underground electrical structures (i.e., manholes, vaults, handholes, etc.) are examined. Methods that can help prevent manhole events and methods that can mitigate the severity of manhole events are suggested.

Keywords: Keywords: arcing faults, IEEE 2417™, manhole events, manhole explosion, manhole fire, smoking manhole

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Introduction

This introduction is not part of IEEE Std 2417-2022, IEEE Guide for Early Detection, Mitigation, Preventative Measures, and Response to Smoke, Fire, and Explosions in Underground Electrical Structures.

The guide examines the root causes and methods for prevention, early detection, mitigation, and response to failures of accessories and cable inside, and connected to underground electrical structures (i.e., manholes, vaults, handholes, etc.). Little peer-reviewed information is available regarding the identification of precursor events, time sequences, and the impact of possible solutions.

These failures, often referred to as *manhole events*, can generate toxic and flammable gases, ignite fires inside underground structures, and propel structure covers into the air. Any of these outcomes can expose the public to risk and impact system reliability. The mechanisms behind these events involve electrical, mechanical, and chemical processes oftentimes simultaneously. This guide has been created because there are few easy-to-understand public documents that integrate the electrical, mechanical, and chemical elements into a single document that describe the phenomena, their causes and effects, and actions that can help prevent, detect, identify, and mitigate these potentially dangerous events.

This guide does not reflect the views of any one contributor or source and is not intended for use to advance a specific scientific, public health, security, environmental, or legal position attributed to, or propounded by, any user or third party. While it is impossible to give recognition to all those who have contributed to the content of this guide, the assistance of past and present members of the IEEE PES ICC Manhole Working Group should certainly be acknowledged. The efforts of the Electric Power Research Institute (EPRI) and the National Electric Energy Testing Research and Applications Center (NEETRAC) should also be acknowledged. Much of the work these organizations have performed on this important topic is reflected in this guide.

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1. Overview

1.1 Introduction

Failures of underground cables and accessories can result in the release of flammable and toxic gases and large amounts of energy. The guide examines root causes, prevention methods, early detection, mitigation, and response to failures of cable and cable accessories within underground electrical structures (i.e., manholes, vaults, handholes, etc.). The term *manhole event*, or more precisely *perceivable manhole event (PME)* is used to describe an abnormal condition in an underground structure such as a manhole, vault, handhole, or service box that can originate within the structure itself or in a cable duct between structures. The typical surface-observable manifestation of a minor manhole event is smoke emanating from the underground structure. In a more extreme case, fire in the structure can produce large quantities of smoke and flames extending from the manhole. The worst type of manhole event is an explosion that can lift the top of the structure or displace the manhole cover. In some cases, there are measurable parameters that precede manhole events. Measurement of these parameters and affirmative actions can help avoid or mitigate the evolution of an event from the incipient stage to a PME.

1.2 Scope

This guide deals with smoke, fires, and explosions caused by cables or cable accessories in electrical subsurface structures and duct runs.

1.3 Purpose

The purpose of this guide is to define manhole events and identify the causes of those events. It contains a compilation of methods a practitioner could use to help detect, prevent, mitigate, and respond to manhole events.

1.4 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. Definitions, acronyms, and abbreviations

2.1 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.⁸

cable limiter: An enclosed fuse for disconnecting a faulted cable from a secondary network distribution system and protecting the unfaulted portion of the distribution system from serious thermal damage. Cable limiters do not provide overload protection. They are designed for short-circuit protection only.

combination events: An electrical failure that generates an arc, releasing electrical energy and generating combustible gases in the vicinity of the arc, which, together with any flammable materials present prior to the arc, are then ignited by the arc, generating additional energy.

combustion-driven manhole events: Manhole events where the primary source of energy is the oxidation of byproducts generated by the decomposition of insulation and/or duct materials through plasmalization and/or pyrolysis.

contact voltage: A voltage resulting from electrical faults that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Contact voltage can exist at levels that may be hazardous.

deflagration explosion: Combustion of a substance with a flame-front that propagates with a velocity lower than the local speed of sound.

detonation explosion: Detonation explosions are characterized by blast waves that propagate at least as fast as the speed of sound.

electrically driven events: Manhole events where the primary source of energy is derived from an electrical arc associated with a fault in a cable or accessory. Most manhole events involving primary and transmission voltages are electrically driven.

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

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

⁸IEEE Standards Dictionary Online is available at: <http://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.

explosion: The sudden conversion of energy (chemical, potential, and/or electrical) into kinetic energy with the production and release of gases under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials. In the context of this document, explosions result from the rapid release of chemical energy when a combustible gas ignites and burns and/or when electrical energy is released by an electrical fault. Explosions may be deflagrations, detonations, or both.

fault: A partial or total local failure in the insulation or continuity of a conductor.

fire: One or more of the following phenomena: (1) plasmalization, (2) pyrolysis, (3) oxidative decomposition.

heavier than air (HTA): Gases that are more than twice the density of air at standard temperature and pressure.

imperceivable manhole event (IME): A manhole event where flammable gases and combustion byproducts of a fire in a manhole or a connected duct accumulate before it is perceivable at the surface. An imperceivable manhole event may or may not progress to a perceivable manhole event.

lighter than air (LTA): Gases that are less than half the density of air at standard temperature and pressure.

lower flammability limit (LFL): The concentration of a single flammable substance at a given temperature below which it will not ignite or explode because the fuel-air mixture is too lean to propagate a flame front. The lower flammability limit is also referred to as the lower explosive limit (LEL). *See also: corrected lower flammability limit (CLFL) or corrected lower explosive limit (CLEL) in Annex C.*

manhole event: An abnormal condition in an underground structure such as a manhole, vault, handhole, or service box that can originate within the structure itself or in a cable duct between structures. Manhole events include three categories: *See: imperceivable manhole event (IME), nascent manhole event (NME), and perceivable manhole event (PME).*

manhole explosion: An event that creates over-pressures from either a detonation or deflagration explosion sufficient to raise the internal pressure of the manhole to dislodge the manhole cover and/or roof from its frame or project debris into the air around the manhole. These events are perceivable from outside the structure.

manhole fire: An event in which the cover remains seated in its frame and visible flame escapes from the edge of the cover or from holes in the cover. Internal pressures developed during a manhole fire are not sufficient to dislodge the manhole cover. These events are perceivable from outside the structure.

nascent manhole events (NME): Abnormal conditions in a manhole that can escalate to an imperceivable manhole event (IME) and/or a perceivable manhole event (PME). The abnormal conditions include: (1) third-party sources of combustible gases, (2) hydrogen from aluminum hydroxylation, and (3) aged or damaged cable and components where insulation has failed.

oxidative decomposition: The energy producing (exothermic) reaction of organic materials (e.g., cable and component insulation, conduit polymers, etc.) that generate primarily carbon dioxide and water vapor.

perceivable manhole event (PME): A manhole event where one or more of the following are observable with human senses: (1) smoke, (2) flames, (3) explosion sounds, (4) a displaced manhole cover, (5) flying manhole cover, (6) displaced manhole roof.

plasmalization: The energy absorbing (endothermic) reaction of all matter when exposed to electrical arcs that generate a plasma of the matter's atomic nuclei and free electrons.

pyrolysis: The energy absorbing (endothermic) reaction of organic materials (e.g., cable and component insulation, conduit polymers, etc.) subject to temperatures in excess of about 350 °C achieved by electrical current leakage, oxidative decomposition, or gross circuit overloading. The primary products of pyrolysis

include carbon agglomerates (soot), carbon monoxide, hydrogen gas, and small quantities of various unsaturated hydrocarbons. Pyrolysis often precedes combustion.

smoke: The visible portion of the plume of fire products that results from most fires. Many important fire byproducts described in B.2 are not visible, including carbon dioxide, carbon monoxide, ozone, volatile organic components, oxides of nitrogen, oxides of sulfur, and water vapor above its dew point. These invisible byproducts are almost always accompanied by visible fire products including liquid water droplets (generally condensed from invisible water vapor as the plume cools) and particulates such as agglomerates of carbon and ash.

smoking manhole: A perceivable manhole event in which smoke is visible outside the manhole, but no visible flames escape from the edge of the cover or from holes in the cover.

upper flammable limit (UFL): The concentration of a flammable substance above which it will not ignite or explode because the fuel is too rich. That is, there is insufficient oxygen to support combustion. The upper flammable limit is also referred to as the upper explosive limit (UEL).

2.2 Acronyms and abbreviations

CLEL	corrected lower explosive limit (LEL)
CLFL	corrected lower flammable limit (LFL)
CT	current transformer
HTA	heavier than air
IOT	Internet of Things
IME	imperceivable manhole event
LTA	lighter than air
LEL	lower explosive limit (See Annex C for CLEL)
LFL	lower flammable limit (See Annex C for CLEL)
LSZH	low smoke zero halogen
NME	nascent manhole event
PE	polyethylene
PME	perceivable manhole event
PPE	personal protective equipment
PVC	polyvinyl chloride
RF	radiofrequency
STA	similar to air (gas density)
STP	standard temperature and pressure
UEL	upper explosive limit
UFL	upper flammable limit
VOCs	volatile organic compounds
XLPE	cross-linked polyethylene

3. Background

Manhole events can occur in underground structures including manholes, vaults, handholes, or service boxes. Events can also originate within cable ducts that extend between structures or between structures and building or switchgear service entrances. The severity of events can range from self-extinguishing small fires and their accompanying smoke limited to the interior of the underground structure, to flames and smoke extending into the environment, to explosions of combustible gases or an electrical fault within the structure displacing the manhole cover, or in extreme cases, destructively displacing the roof or walls of the underground structure. Electrically driven events are generally not preceded by the production of any smoke or flames, and they create an over-pressurization of the air that can yield structural damage.

Except for electrical faults at primary and transmission voltages, most perceivable manhole events (PMEs) evolve from imperceivable manhole events (IMEs). IMEs may self-extinguish or may escalate to PMEs. IMEs are far more numerous than PMEs.

There are two possible energy sources for manhole events: oxidative combustion and electrical. There are multiple hydrocarbon-based materials in underground systems that can decompose and create combustible gases. These include cable insulation, insulating oils, and duct materials. Most events involving cables and accessories operating at secondary voltages are combustion-driven events. Although electrical faults in secondary cable in a duct can be the initiating source to produce combustible gases, the manhole event itself is generally combustion driven.

Electrically driven manhole events in primary systems can release a substantial amount of energy during a fault. The current is generally interrupted, and the energy release is mitigated by the system protective equipment. Combustion-driven events generally evolve more slowly. During this evolution, substantial quantities of combustible gases can be generated and accumulate. If the failure is in a duct, the gases and entrained carbon soot flow toward adjacent structures, driven by the solid-to-gas phase change, convective gas flows, and atmospheric pressure differences between structures.

Some events derive their energy from an electrical failure that generates an arc that releases electrical energy. The arc fault is accompanied by the generation of combustible gases in the vicinity of the arc, together with any flammable materials present before the arc, which may then be ignited by the arc and generate additional energy; these are referred to as *combination events*.

Manhole events cannot only release large amounts of energy, but they also can generate substantial quantities of combustible and toxic gases such as hydrogen, volatile organic compounds (VOCs), carbon monoxide, and carbon dioxide (EPRI TR-106394 [B28]; Zhang, et al. [B64]). Burning and the evolution of combustible and toxic materials may continue until the utility and fire department can coordinate activities to extinguish the fire. In some cases, the fire may originate or extend to a structure located in or adjacent to the basement of commercial or residential buildings and smoke may migrate into adjacent buildings.

The distribution of manhole events between different classes of electrical systems depends on a wide variety of variables. These variables are too numerous to list and beyond the scope of this guide. Three of the most important variables are enumerated to allow a handful of generalizations to guide policy makers:

- a) The quantity of cables in the class. For example, if there is much less insulated transmission cable than primary and secondary cables, transmission events are less likely.
- b) The age and condition of the cables in the class. Cables with low service life and/or those that have not encountered high operating temperatures are less likely to fail than cables installed decades ago that have experienced operating conditions likely to shorten their operating life.
- c) The fault tolerance of the system. Circuit protection for transmission and primary distribution cables generally removes power within a few tenths of a second of a fault, while secondary networks may

operate with faults for hours or even days. Such prolonged faults provide energy to create combustible gases.

While an industry-wide accounting of manhole events and classification of those events does not exist, three of the most important variables that determine the frequency and distribution of manhole events support the anecdotal observations that secondary networks are most prone to suffer events. Primary distribution systems follow in a distant second place, and transmission cables suffer the fewest incidents. This discussion ignores the outage impact of each event. For example, a single transmission event can have a much larger impact than a corresponding secondary network event.

The risk to the public from manhole events can be reduced by the early detection of nascent manhole events (NMEs) and imperceivable manhole events (IMEs), limiting the chemical and electrical energy available, ventilating flammable gases to stay below the lower flammable limit (LFL) threshold, and by controlling the energy released if an event occurs.

4. Root causes of manhole events

4.1 Introduction

[Figure 1](#) is a root cause analysis of nascent manhole events (NMEs), imperceivable manhole events (IMEs), and perceivable manhole events (PMEs). This guide focuses primarily on events that are associated with some type of insulation failure. That insulation failure (an NME) can either lead to the generation of combustible gases (an IME) that provide energy or smoke for a PME or can lead to an electrical arc that can be the source of energy for a PME (Bertini “Manhole explosion and its root causes” [B3]; Walsh and Black “Thermodynamic and mechanical analysis of gas explosions” [B60]; Zhang [B63]; Zhang, et al. [B64]). There are two other sources of energy considered: combustible gases from a third-party source and hydrogen from aluminum hydroxylation. The three potential fuel sources for all manhole events are represented as oval-shaped elements 4.2, 4.3, and 4.4 near the bottom left of [Figure 1](#).

The flow of [Figure 1](#) is from root causes within the NME envelope (dashed rectangle) at the bottom to the IME envelope in the middle to the PME envelope at the top. Each of the 21 elements (diamond, rectangle, oval) in [Figure 1](#) is described in 4.2 through 4.22, respectively. Subclauses share the same numbering as [Figure 1](#) elements.

In addition to the 21 elements defining events and their root causes, there are four measurements represented as hexagons and lettered 7.2 to 7.5. These measurements may be used to monitor NMEs and IMEs and thus warn of potential PMEs and the need for preventative maintenance. The numbering of the hexagons corresponds with the like-numbered subclauses in this guide.

Hexagon 7.2. Changes in differential current flow over individual cables may be measured in real time in vault environments to detect faults. See [7.2](#).

Hexagon 7.3. Current from the faulted insulation may follow conductive pathways to the surface and energize street-level objects like sidewalks, roadways, and fences. This is a condition known as *contact voltage*. See [7.3](#).

Hexagon 7.4. Higher fault currents may cause perturbations in the voltage waveform that may appear to customers as flickering lights or other power quality-related issues. More sensitive monitoring equipment may also detect the resultant voltage transients. See [7.4](#).

Hexagon 7.5. Perturbations of environmental variables including combustible gas concentrations, combustion gas byproduct concentrations, particulate concentrations, and temperatures may be measured in real time

in vault environments to detect fires, third-party combustion sources, and hydrogen gas from aluminum hydroxylation. See 7.5.

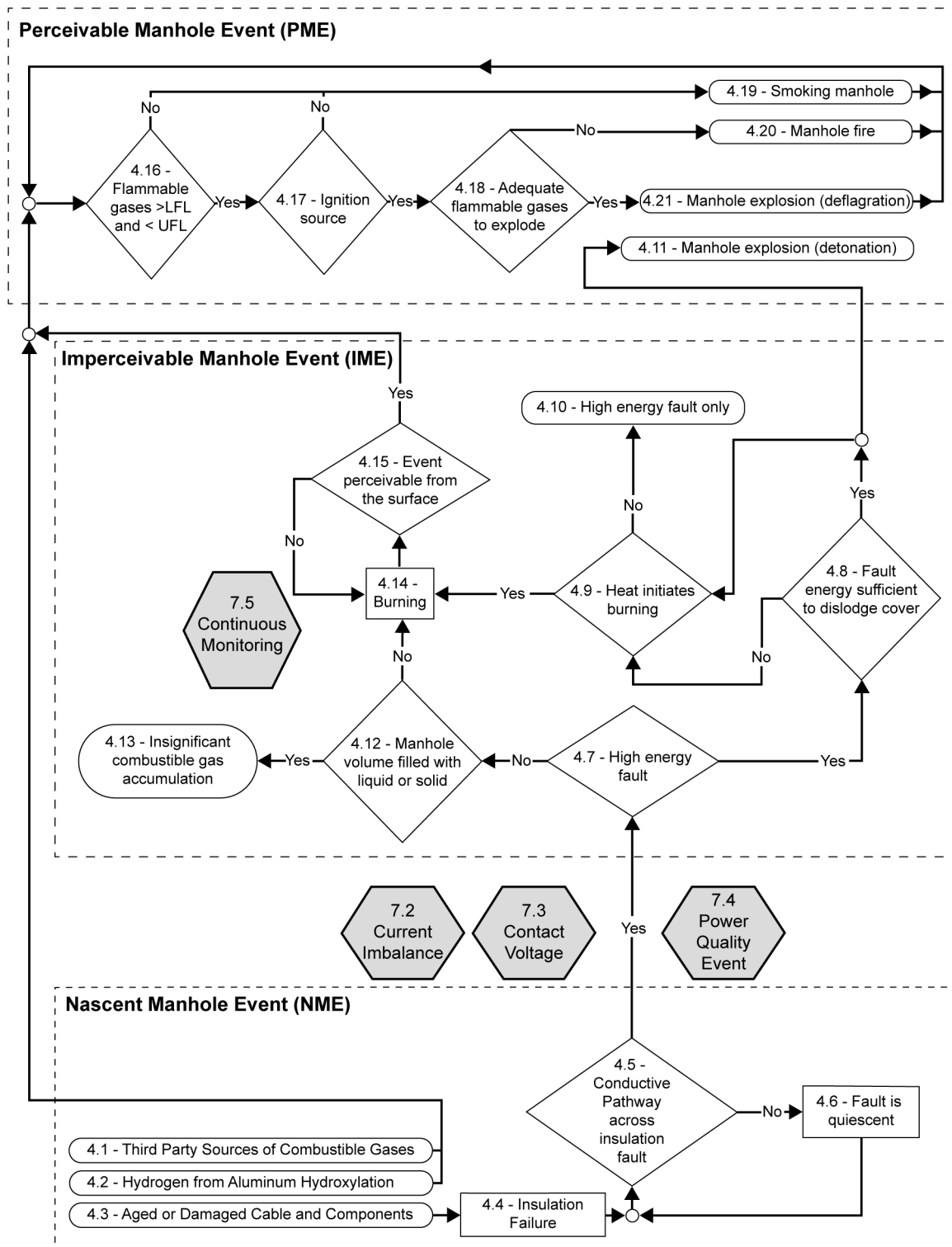


Figure 1—Root causes of manhole events

4.2 Third-party sources of combustible gases

Natural gas leaks, hydrocarbon plumes, and hydrogen-sulfide from the decomposition of organic matter are examples of combustible gases that are not a result of aged or damaged cable and components. This guide provides some insight on how to help prevent or reduce the build-up of such gases in 6.3. The elimination of the sources of such gases is outside the scope of this guide. Referring to Figure 1, if third-party sources of combustible gases are present, proceed to Element 4.17 in the PME envelope.

Third-party sources of combustible gases may be detected with suitable gas sensors represented by Hexagon 7.5 shown in Figure 1. See 7.5.

4.3 Hydrogen from aluminum hydroxylation

Hydrogen generation may occur from aluminum conductors when in contact with water (Kruizinga [B42]; Kruizinga et al. [B43]). The phenomenon occurs in any cable (primary or secondary) where the conductors are aluminum and where liquid water contacts the conductor strands. The reaction forms aluminum hydroxide and hydrogen gas. Water in the conductor strands is not a normal occurrence in a properly operating primary cable circuit. Water can be present in secondary conductors. Water is thermodynamically driven from the strands of operating cables as shown in Bertini “Molecular thermodynamics” [B5]. Evolved hydrogen will transport to nearby terminations and splices and will leak from component-cable interfaces (Luzzi [B44]).

As described in 5.2, hydrogen is not a particularly dangerous gas, but it is often incorrectly blamed for events, so it is included in this discussion for completeness (Neville [B47]). The presence of hydrogen gas may indicate the ongoing deterioration of aluminum conductors. Referring to Figure 1, if hydrogen gas generated by wet aluminum conductors is present, follow the branch to Element 4.17 in the PME envelope.

4.4 Aged or damaged cable and components

4.4.1 Introduction

The aging of cables and associated components is complex and may include mechanical, thermal, and electro-mechanical mechanisms outlined below. When these aging mechanisms result in insulation failure, follow the branch to Element 4.5 of Figure 1 within the NME envelope.

4.4.2 Mechanical

Examples of mechanical aging include:

- Rough handling during installation and maintenance
- Damage from nearby construction activities
- Expansion-contraction stresses with thermal cycling
- Polymer creep, especially at cable-component interfaces
- Animal damage
- Seismic activity, including traffic-induced vibrations

4.4.3 Thermal

Temperature cycling, a direct result of cyclic loads, contributes to the mechanical aging and thermal degradation of insulation materials.

A significant factor that influences the degradation of insulation systems, particularly polymeric insulations, is the exposure of the insulation to high temperatures. All polymers age in the presence of oxygen or other oxidizing compounds. Aging is slowed by the presence of antioxidants, but antioxidants are depleted with time, and they deplete faster at higher temperatures than they do at lower temperatures. With or without antioxidants, oxidation itself is likewise a function of elevated temperatures and duration of exposure.

As the insulation thermally ages, it becomes less flexible and eventually will succumb to cracking as mechanical forces stress the polymer. Cable insulation can be subjected to localized thermal aging because of heating from nearby circuits, steam systems, or other adjacent thermal sources. Other regions of localized elevated temperatures, or hot spots, can be caused by increases in impedance at connection points due to design deficiencies or installation errors of joints and accessories.

Oxidation of cable insulations increases in all polymers as the temperature increases. As a rule-of-thumb, oxidation doubles for each 10 °C increase in insulation temperature. Exudation of volatile components created by oxidation generally triples for each 10 °C. Polymers employed as cable insulations begin to pyrolyze between 310 °C and 540 °C, creating predominately carbon monoxide, hydrogen, and elemental carbon as described in 5.2.2 and 5.2.3. While pyrolysis requires thermal overload, increased oxidation and exudation of combustible gases occurs at all temperatures. A circuit operating at a nominal temperature of 40 °C oxidizes at about twice the rate, and it exudes volatiles at about three times the rate of the same circuit at 30 °C.

4.4.4 Electro-chemical

Underground cables are subject to a variety of electro-chemical phenomena that can damage insulation systems and lead to cable failure. Electro-chemical treeing in primary and transmission cables results in pathways for discharge of current between the conductor and a surface at a different potential.

4.5 Insulation failure

Insulation failure is characterized as a crack or a hole through the insulation and is the endpoint of aging. Referring to Figure 1, follow the branch to Element 4.6 within the NME envelope.

4.6 Conductive pathway

Typical primary and transmission cable fault currents will ionize (i.e., heat to the plasma state) any fluid that occupies the crack or hole through the insulation of a shielded cable. Where cables are not shielded or where voltages are at secondary levels, the presence of an insulation failure is a necessary, but not a sufficient, condition to create a fault.

For current to establish a path, there must be a conductive pathway between the exposed conductor and either a ground or a second exposed conductor at a different potential. At secondary voltage, a dry and untracked surface may not conduct significant current, and hence an exposed conductor is not faulted but rather is quiescent. Referring to Figure 1, follow the “No” branch to Element 4.7.

Weather conditions can exacerbate the symptoms of insulation failures. During wetter seasons, there are measurable increases in low-voltage events. First responders report significant increase in events during periods of snow melt, when salt has been applied to roadways (Sun, Ma, and Boggs [B57]). When the mixture of salt and water contacts energized cables, the failure rate of insulation materials is accelerated.

Referring to Figure 1, if there is a conductive pathway through or across the insulation allowing current to travel from the cable conductor to ground or another conductor at a different potential, depart the NME envelope by following the “Yes” branch to Element 4.8 within the IME envelope.

Current along a conductive pathway may be detected with technology encompassed in one or more of Hexagon 7.2 (see 7.2), Hexagon 7.3 (see 7.3), and Hexagon 7.4 (see 7.4) in Figure 1.