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Plant Support Engineering: Failure Models and Data Analysis for Nuclear Plant Medium Voltage Cables for Consideration in Preventive Maintenance and Strategic Replacement

A PM Basis Application

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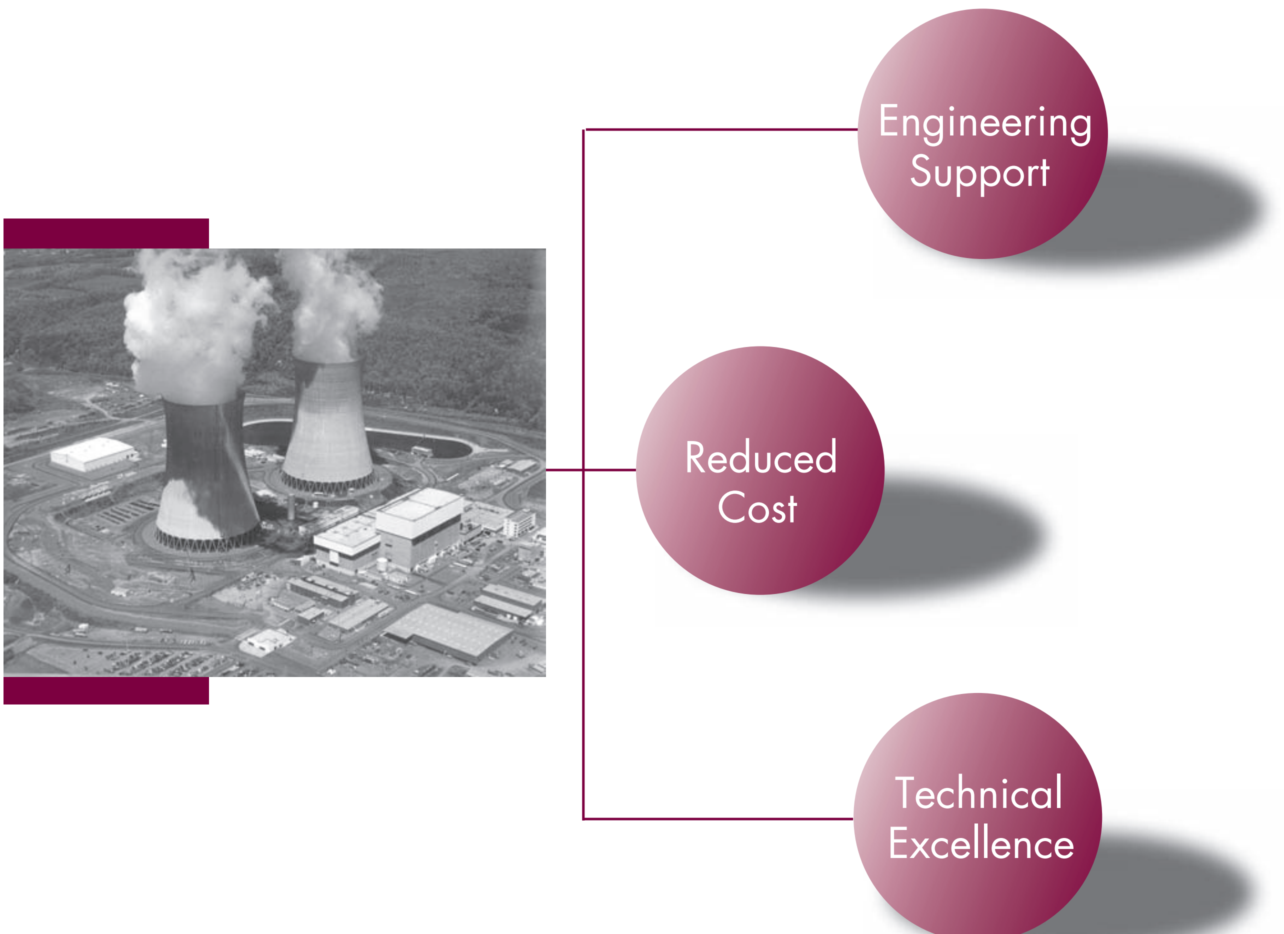

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A PM Basis Application

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PRODUCT DESCRIPTION

Regulatory and management concern regarding the reliability of medium-voltage cable systems at nuclear plants has been increasing for the past 5–10 years. The staff of the Nuclear Regulatory Commission is concerned that wetted medium-voltage cables might be degrading to the point at which multiple cables could fail when called on to perform functions affecting safety. Utility managers are concerned that cables might fail, causing adverse safety consequence and/or plant shutdowns. This report focuses on failure rates and distributions for key types of cables used in nuclear power plants.

The goal of the project was to determine when the failure distribution would indicate the point at which replacement would be more appropriate than performing condition-monitoring tests. Tools in the Electric Power Research Institute (EPRI) *Preventive Maintenance Basis Database* (1010919) and analysis of data indicating the number of installed cables were used to determine failure rate estimates and distributions. Methods for condition monitoring and programmatic guidance will be described in a separate document.

Results and Findings

Rather than identifying a narrow end-of-life failure distribution for medium-voltage cables with an onset of end of life occurring at approximately 30–40 years and a relatively short period (such as 10–15 years) until the entire population has failed or needs to be replaced, the failure distribution for most of the cable types indicates that only a small percentage of cables will have failed at 60 years. Thus, the decision to replace cables should be based on economic analysis rather than on a narrow, peaked failure distribution. In addition to developing failure rates and distributions, the project developed preventive maintenance (PM) basis templates for the various types of cables in use in the nuclear industry and the conditions they are likely to experience as well as recommendations for periodicity of condition testing.

Challenges and Objectives

In most cases, limited failure data exist for nuclear plant components. However, a survey of installed medium-voltage cable types and configurations and medium-voltage wet-condition cable failures performed by the Nuclear Energy Institute in 2004 provided information for determining failure rates for underground nuclear plant cables, allowing a more detailed analysis for the various types of cables used in nuclear plants. In addition, a separate project developed PM basis templates for the basic cable types used in the industry through a group of subject matter experts for medium-voltage distribution cables and published the results in the EPRI report *Security, Quality, Reliability and Availability: Metrics Definition, Progress Report* (1008569). In the present project, these templates were modified to cover the cable designs and conditions for cables used in nuclear plants. These templates and the EPRI PM Basis Database tools were then used to develop failure rates as an alternative means of assessing the expected failure rates for the cables based on a combination of expert judgment and available data.

Application, Value, and Use

This report provides a basis for basic condition assessment periodicity for testable cables (cables with insulation shields) located in wet conditions. It also provides a sound basis for failure rates for the types of medium-voltage cables subject to wet conditions, which indicates that the failures remain random in nature and are not indicative of the onset of a sudden increase in failure rates. This indicates that condition monitoring is a means of determining when cables should be replaced rather than that there is an imminent need to begin replacement programs. The basis for determining the desirability for replacement of cables can be achieved through life cycle management and cost-benefit analysis.

EPRI Perspective

Information gathered for the power plant cables for this report has also been loaded into the EPRI PM Basis Database. The broad objective of the PM Basis Database project is to develop a PM basis for a large number of component types in utility power systems (including nuclear and fossil generating plants and transmission and distribution systems) using information supplied by the industry. This report extends the content of the database by incorporating information for an important category of nuclear plant medium-voltage cables. Furthermore, this report extends the methodology of the database by using it to develop an equipment failure model for plant power cables, which defines how cables deteriorate over time and quantifies the rates at which deterioration occurs. The model thus permits projecting failure rates for the component as a function of the various service conditions and stressors that might be present. One result of these calculations would be to establish failure rate data for use in the asset management decision models. Other uses of the models include establishing condition and failure codes for use in data collection and tracking as well as calibrating failure rates through the use of such data.

Approach

The available installed cable information and the failure data through 2004 were used to perform Weibull analyses for the various types of cables used in wet, medium-voltage cable applications. The results were analyzed for inferences and compared to the failure rates generated by the PM Basis Database tools. The process used to develop a PM basis for a component follows a well-defined sequence of steps and a combination of information developed by a panel of experts and information derived from analyses performed through computerized algorithms resident in the PM Basis Database.

Keywords

Cable failure rates
Component reliability
Maintenance optimization
Medium-voltage cables
Preventive maintenance

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1 INTRODUCTION

1.1 Background

In general, equipment failures accelerate as they age, and at some point, the costs of outages, repairs, and emergency replacements exceed the costs of planned replacements. Both the staff of the Nuclear Regulatory Commission and the management of nuclear power plants have become concerned that medium-voltage cables that are subjected to wet conditions (up to and including submergence) might be approaching their end of life and that a larger number of failures might be expected each year. The bathtub wear-out curve has been described, with the concern that, after a relatively long period of low-level, random failures, the industry will experience a substantial increase in the failure rate and that multiple failures might be experienced and multiple cables can be expected to require replacement in a relatively short period. Utility managers have indicated that the efforts to electrically test cables and to be prepared for replacement if cable test results indicate severe degradation are burdensome. These managers have asked for analyses that indicate when replacement should be scheduled rather than performing tests and responding to the results.

The objective of this report was to evaluate the failure rates and failure distributions for the various types of cables used in wet environments at nuclear plants to determine whether the failure distributions readily indicate when a substantial number of failures can be expected and thereby when replacement becomes an obvious solution to long-term reliability. The thought process behind this concept was driven by the frequently described bathtub failure curve that starts with a number of infant mortalities and then enters a period with a low, random failure rate, followed by the wear-out period in which failure rates increase significantly, indicating end of life. At this point, the remaining population is expected to fail in a short time. However, analysis of the available population and failure data through 2005, published in the *Medium Voltage Underground Cable White Paper* (NEI 06-05) indicates that the failure rates remain constant; rather than experiencing a bathtub end-of-life curve, the wetted cables failure curve resembles a shallow pool with a gentle slope to its edge [1]. Although failures have continued to occur since 2005, the number per year has not increased significantly since that time. An increase in failure rate is possible if a new failure mechanism is identified. Accordingly, repeating this analysis in 5 to 10 years is recommended to verify that the failure rates remain stable.

For underground power cables used at nuclear power plants, about 30 years of operating experience through 2004 has resulted in 50 in-service failures in a total of about 2000 cables subject to a high level of moisture or water in the underground environment, whether the cables are in ducts or are direct-buried. (In 2004, the average age of the U.S. fleet of nuclear plants was

28 years; the oldest unit was 36 years old.) The 50 failures excluded circuits that had failed splices or terminations and concentrated on cable insulation failures. Most of the cables in this group carried electrical loads that are important to either power production or plant safety. Although this proportion of failures is only a few percent, they have been distributed throughout the 30-year period in question. This has raised questions about whether the failures were due only to early-life random events that are expected when new equipment is put into service or could be due to emerging aging issues that will become much more important as the age of the cables increases. The age at failure of these cables was obtained from a survey described in the *Medium Voltage Underground Cable White Paper* (NEI 06-05) [1].

Estimating future equipment failures is a critical challenge to applying the available decision tools. This report uses statistical analyses of the data from the NEI survey of underground cable failures as well as the *Preventive Maintenance Basis Database* (1010919) tools to estimate cable failure rates [2].

1.2 Objective

This report provides a systematic way to estimate failure rates of plant power cables with rated voltages ranging from 5 kV to 35 kV, supported by limited data analysis on a select number and types of cables, using Weibull techniques. In addition to baseline data, the report provides equipment failure models informed by data analysis that enables utilities to adapt those estimates to the particular service conditions that exist in their systems. The intended use of these estimates is to drive asset management decisions regarding the plant power cable inventory, including decisions on testing and maintenance intervals and cable replacement policies. Asset managers and analysts can use this information in development of economic strategies for plant power cable management.

The technical approach used in this report, called *preventive maintenance (PM) basis*, which is described in the next section, also facilitates the development of PM programs; indeed, that is the purpose for which it was developed. The broad objective of the PM basis project is to develop a PM basis for these component types in nuclear and fossil generating plants, using information supplied by the industry [2]. Thus, an important secondary use of this document is to provide a program of PM tasks suitable for application to plant power cables with rated voltages ranging from 5 kV to 35 kV. The PM tasks that are identified represent common practices used by utilities to identify and mitigate the causes and mechanisms that lead to cable degradation and failure. They can be used in conjunction with information and recommendations from other sources to develop a PM program or to improve an existing program. However, they should not be considered recommended practices; each utility must evaluate the cost effectiveness of these practices in light of their own circumstances. Utility managers, supervisors, craft technicians, and training instructors responsible for developing and optimizing PM programs can use this information to assist in those tasks.

Information gathered for plant power cables for this report has also been loaded into the PM Basis Database, which was developed for EPRI's Nuclear Power Division [2]. The tables presented in the remainder of this report represent a combination of the information developed for the equipment failure models, information derived from Weibull analysis of failure times, and information developed by analysis using computerized algorithms in the PM Basis Database [2].

1.3 Technical Approach

The process used to develop a PM basis for a component follows a well-defined sequence of steps. The process uses a combination of the information developed by the original expert panel for buried substation power cables and information derived from analysis performed using computerized algorithms resident in the PM Basis Database [2]. The EPRI PM basis data-gathering protocol assisted the expert group in reaching agreement on the details of the PM template and its supporting basis information. The major process steps were the following:

1. Review maintenance and failure cause data obtained from relevant industry documents to categorize failure types and to gauge the relative effectiveness of current maintenance practices.
2. Subdivide the component type into logical groups by design and by installed environmental characteristics (see Table 1-1). It was determined that nuclear plant power cables are all jacketed and should be divided into 30 cable types, based on the insulator material, the presence or absence of their potential for continuous exposure to moisture for both the cables and their terminations, and the presence or absence of splices. Splices, although also treated as a separate component type, are not designated by any identifying characteristic except to be simply called a splice.

Table 1-1
Plant Power Cable Types by Design and Operational Characteristics

Design Characteristics	Operational Characteristics								
	Voltage Ratings			Cables		Terminations		Splices	
	5–15 kV	5–35 kV	5 kV	Wet	Dry	Outdoor	Dry	Wet	Dry
Black Ethylene Propylene Rubber (EPR), Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X	X	
Black EPR, Jacketed, Unshielded			X	X	X		X	NA	NA
			X	X	X	X		NA	NA
			X	X	X	X		X	X

Table 1-1 (continued)
Plant Power Cable Types by Design and Operational Characteristics

Design Characteristics	Operational Characteristics								
	Voltage Ratings			Cables		Terminations		Splices	
	5–15 kV	5–35 kV	5 kV	Wet	Dry	Outdoor	Dry	Wet	Dry
Brown EPR, Discharge-Resistant (DR), Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X	X	
Brown EPR, DR, Jacketed, Nonshielded			X	X	X		X	NA	NA
			X	X	X	X		NA	NA
			X	X	X	X		X	X
Butyl, Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X	X	
Butyl, Jacketed, Nonshielded			X	X	X		X	NA	NA
			X	X	X	X		NA	NA
			X	X	X	X		X	X
Pink EPR, Discharge-Free (DF), Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X	X	
Pink EPR, DF, Jacketed, Nonshielded			X	X	X		X	NA	NA
			X	X	X	X		NA	NA
			X	X	X	X		X	X
Tree-Resistant Cross-Linked Polyethylene (TR-XLPE), Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X		X
Cross-Linked Polyethylene (XLPE), Jacketed, Shielded	X			X	X		X	NA	NA
	X			X	X	X		NA	NA
		X		X		X	X	X	

3. Define the boundary of cables and splices for the purpose of the database (see Table 1-2). The boundary divides the cable with the termination and the splice from equipment that is attached to them, and it basically represents the components that would ordinarily be included in an inspection and maintenance program. Boundaries for cables are 1) the cable itself, typically a 500-ft (152-m) length and 2) terminations and splices, if present. Lightning arrestors, transformers, ducts, manholes, hand holes, pull boxes, and so on are excluded. Boundaries for the splices are only the splice itself.

Table 1-2
Component Boundary for Plant Power Cables

Boundary for Plant Power Cable Types
The cable itself, typically a 500-ft (152-m) length.
Terminations and splices, if present.
Lightning arrestors, transformers, ducts, manholes, hand holes, pull boxes, and so on are excluded.
Boundary for the Splices
Only the splice itself.

4. Establish the functional importance, service conditions, and duty cycles that influence cable degradation and PM strategies (see Table 1-3).

   In general, *duty cycle* captures stressors on the equipment that result from intensity of use (for example, for a pump, a high duty cycle would indicate continuous use and low duty cycle would indicate occasional use). Therefore, duty cycle itself is one of the most important service stressors, but we label it separately because of its general impact on the degree of wear experienced by the equipment. The term *service condition* captures stresses on the equipment, other than the duty cycle, that result from the operating environment.

Table 1-3
Functional Importance, Duty Cycles, and Service Conditions Definitions for Plant Power Cables, Terminations and Splices

Functional Importance			
Critical	Functionally important, such as in Maintenance Rule scope (safety-related, fire protection, off-site feeds, or important to power production).	**Minor**	Functionally not important but economically important, such as other non-critical feeds and loads.
Duty Cycle Definitions			
High	Cables operated with a load factor (ampacity) of >75% and normally energized.	**Low**	Cables operated with a load factor (ampacity) of <75% or not normally energized.
Service Condition			
Severe	Presence of water or high ground temperatures or poor heat transfer leading to elevated cable operating temperature.	**Mild**	Absence of the severe conditions.

5. Establish a preliminary PM task list (that is, inspections and tests) to assist in defining how failure causes can be discovered.
6. Divide the component into major maintainable subgroups.
7. Establish failure locations. Failure locations are the places on a cable, termination, or splice where degradation can occur (see Tables 1-4 and 1-5).

Table 1-4
Failure Locations for Plant Power Cables

Cable – conductor
Cable – insulation
Cable - insulation shield (cotton tape)
Cable - insulation shield (polymer tape)
Cable - insulation shield (extruded polymer)
Cable - outer jacket
Cable - taped metal shield
Terminations
Splices, if present

Table 1-5
Failure Locations for Plant Power Cable Splices

Splices

8. Determine the degradation processes, the factors that influence the degradation, and the time characteristics of the progression to failure.

   Degradation processes represent the various ways in which a cable deteriorates over time. Each mechanism operates at one or more of the failure locations, and the influences and timing characteristics of a particular mechanism can vary according to failure location. In general, deterioration mechanisms are assumed to proceed independently of one another; for instance, the presence of water trees does not make corrosion more likely, although they might be under a common influence, such as moisture. Degradation processes that affect power plant cables and splices are listed in Tables 1-6 and 1-7, respectively.

Table 1-6
Degradation Processes of Plant Power Cables

Embrittlement leading to loss of jacket integrity
Insulation material degradation
Mechanical damage leading to tracking
Mechanical stress
Mechanical stress (bending)
Overheating from high resistance connection
Partial discharge and tracking
Surface tracking
Thermal damage
Tracking
Voltage stress riser
Water trees caused by water ingress through damaged or degraded jacket
Water trees, severe (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)

Table 1-7
Degradation Processes of Splices in Plant Power Cables

Degraded insulation
Overheating from high resistance connection
Partial discharge and tracking
Tracking

The *influence factors* represent stressors that can accelerate (or perhaps retard) the progression of degradation by a particular mechanism. For instance, moisture influences water-related insulation degradation as well as metal conductor and shield corrosion mechanisms.

The *time characteristic* represents the rate at which deterioration occurs by a particular mechanism under a particular influence. It can be thought of as the expected time until the earliest failures of the equipment occur due to that mechanism. The coding of time characteristics is described more fully in Section 2.

At this point in the process, one has defined an *equipment failure model* for underground cables. That is, the model defines how buried cables deteriorate over time and approximately quantifies the rates at which deterioration occurs. The model thus permits projecting failure rates for the component as a function of the various service conditions and stressors that might be present. One result of these calculations would be to establish failure rate data for use in the asset management models. Other uses of the models include establishing condition and failure codes for use in data collection and tracking as well as calibrating failure rates through the use of such data. Of course, a primary use of the model is to establish a PM basis for the equipment. The remaining steps of the process address that function.

9. List the discovery opportunities for each of the subcomponent failure locations. *Discovery opportunities* are inspections and tests that can be applied to determine the extent of deterioration in a cable. As is well known, most of the tests that can be applied to cables do not unambiguously indicate the extent of deterioration, the true extent of which might be unobservable. For instance, the presence or extent of water trees might not be fully revealed by partial discharge or tan δ testing. Therefore, the effectiveness of each test was also rated by the expert panel.

10. List the final PM strategies and tasks considered by the expert panel to be effective in discovering degradation and preventing the onset of the failure mechanism, or in returning the component to an as-new condition through accepted PM techniques. These PM tasks for underground cables are considered to be common practices in the industry but should not be considered recommended practices; each utility must evaluate the cost effectiveness of these practices in light of their own circumstances.

11. List the effectiveness (high, medium, low) of each PM task for addressing each degradation mechanism.

12. Describe the objective and scope of each PM task.

13. Develop a maintenance template providing PM tasks and task intervals that summarize the information developed in the previous items.
14. Develop a list of recent and relevant industry references.

The recommended template task intervals are moderately conservative values that are intended to be used as default values for cases in which a utility has no basis for its existing task intervals. They are based on a synthesis of current utility experience and might not be suitable for direct application by a given utility without careful consideration of its own service history. It is essential for utilities to continue to adjust intervals based on their own service experience. The information most likely to be useful to assist in this process would be information on as-found equipment condition.

1.4 Organization of This Report

This section explains the approach used to develop the equipment failure model for plant power cables using the EPRI PM Basis Database component process, which was enhanced by data analysis performed using Weibull techniques on a sample of failure data collected by NEI [1]. The remainder of this report consists of the following sections:

- Section 2 presents the theory behind the development and use of the Weibull distribution for the prediction of component failure. Two additional topics are presented: 1) an overview of how to extract the Weibull distribution shape parameters (β, γ, and η) using data on the age of cables when they failed and 2) the failure rate inferences that can be gained from the failure rate algorithms in the PM Basis Database and two ways that they can be used to compare with and to improve the predictions from the data analysis.
- Section 3 contains the failure statistics, analysis, and predictions for four types of medium-voltage power cables typically found in today's power plants. They are generically labeled as black ethylene propylene rubber (EPR), pink (red) EPR, cross-linked polyethylene (XLPE), and butyl.
- Section 4 contains a tabular summary of the equipment failure models for the various types of buried cables, including degradation and failure mechanism information for cables, which was obtained by direct interviews with the expert panel members in a joint workshop format. The data represent the panel's opinions of the factors that influence failure, the PM actions and strategies that can be used to discover or prevent the failure, and the effectiveness of the PM activities.
- Section 5 presents the PM program in a concise format. The PM tasks that are identified represent common practices used by utilities as identified by the expert panel. These common practices should not be considered recommended practices; each utility must evaluate the cost effectiveness of these practices in light of their own circumstances. The selected PM tasks are presented as a template for consistency with the format used with other component types.
- Section 6 provides a list of cited references and relevant research materials related to asset management and equipment failure models and to underground cables.

2
WEIBULL ANALYSIS THEORY AND INFERENCES

2.1 Review of Theory

A Weibull distribution of times to failure represents the time-dependent failure rate as a simple power, beta (β), of an item's age, where the latter is shifted by a location parameter, or minimum life, gamma (γ), and scaled by the characteristic life, eta (η).

$$\lambda(t) = (\beta/\eta)((t-\gamma)/\eta)^{(\beta-1)}$$ **Eq. 2-1**

Because the failure rate changes with age, one can define the average failure rate over the age range 0 to T, which differs from $\lambda(T)$ only by the factor β.

$$AV\lambda(0,T) = (1/\eta)((T-\gamma)/\eta)^{(\beta-1)}$$ **Eq. 2-2**

For cables, we can gauge the rate at which the failure rate increases as the cable ages by considering just the value of β. For example, if $\beta = 3$, the actual value of the failure rate at T is 3 times the average value over (0,T). At $t = \gamma$, $\lambda(t) = 0$ and $AV\lambda(0,\gamma) = 0$.

The failure rate of Equation 2-1 corresponds to a probability density function (pdf) for the times to failure, given by

$$pdf(t) = ((\beta/\eta)[(t-\gamma)/\eta]^{(\beta-1)})\exp[-((t-\gamma)/\eta)^{\beta}]$$ **Eq. 2-3**

The cumulative distribution function (cdf) is then

$$cdf(t) = 1 - \exp[-((t-\gamma)/\eta)^{\beta}]$$ **Eq. 2-4**

The characteristic life, η, is the point within the time-to-failure distribution (the pdf) at which the probability that the item has already failed is 63%. In terms of age of the equipment, the characteristic life is thus $\eta+\gamma$. A similar time shift must also be introduced into the mean and median of the time-to-failure distribution. The mean of the time-to-failure distribution is given by

$$t_{Mean} = \gamma + \eta\Gamma[1 + 1/\beta], \text{ where } \Gamma \text{ is the gamma function}$$ **Eq. 2-5**

The median is given by

$$t_{Median} = \gamma + \eta(\ln 2)^{1/\beta} \quad \textbf{Eq. 2-6}$$

The variance is

$$\text{Variance of failure times} = \eta^2[\,\Gamma(1+2/\beta) - \{\Gamma(1+1/\beta)\}^2] \quad \textbf{Eq. 2-7a}$$

The dependence on β results in a narrow pdf (that is, with small variance) for large values of β because $\Gamma(1) = 1$, and so the term in square brackets tends to zero at large β.

$$\text{Standard deviation of failure times} = (\text{Variance})^{1/2} \quad \textbf{Eq. 2-7b}$$

The following are true for β:

- When β <1 the failure rate decreases with age.
- When $\beta = 1$, the Weibull pdf equates to an exponential distribution of failure times, with constant failure rate, $\lambda = 1/\eta$, independent of time.
- When β >1, the failure rate increases with age.
- When $\beta = 3.44$, the Weibull pdf approximates a normal distribution of failure times, with the mean equal to 0.9η.

In the cable analysis, we will find that the failure rates are of order 0.001 failure per cable per year, which means that the eta (η) parameter is on the order of several hundred to 1000 years. Because we are interested in cables whose age is in the 10–60 year timeframe, it is useful to examine what it means in terms of the pdf and $\lambda(t)$ when $(t/\eta) \ll 1$.

When $t/\eta \ll 1$, the exponent in Equation 2-3 can be ignored (that is, = 1, so cdf = 0) because beta is always positive. The effect of γ can be ignored here because it does not affect the conclusion. In that case

$$\text{cdf}(t, \text{given } (t/\eta) \ll 1) = (t/\eta)^{\beta} \quad \textbf{Eq. 2-8a}$$

$$\text{pdf}(t, \text{given } (t/\eta) \ll 1) = (\beta/\eta)(t/\eta)^{\beta-1} \quad \textbf{Eq. 2-8b}$$

Equation 2-1 shows that this is also equal to $\lambda(t)$, for any values of t and η, so

$$\text{pdf}(t, \text{given } (t/\eta) \ll 1) = \lambda(t) \quad \textbf{Eq. 2-9}$$

This can also be seen from the normal relation between the pdf and λ for any time dependence (when $(t/\eta) \ll 1$, cdf = 0):

$$\lambda(t) = \text{pdf}(t)/[1 - \text{cdf}(t)] \quad \textbf{Eq. 2-10}$$

The Weibull distribution is useful because it can represent a wide variety of time dependence for the failure rate within a single functional form, using only three parameters. If data exist on the times to failure (that is, age at failure) for a set of items, a fit to the data can be used to estimate the Weibull parameters, which can then be used to make predictions about reliability, cumulative failure probability, and remaining life. If the data are split into partitions over separate age ranges, fits to the separate ranges of data might also reveal different individual underlying wear-out processes at work. This is quite useful, but it should also be a warning.

The versatility that has made Weibull analysis famous hides a serious limitation that is frequently ignored. A moment's reflection will show that when you have data only on the first part of the life of a component, no amount of excellent fitting will provide information on its later behavior unless you also assume that no additional wear-out processes come into play at a later age. In other words, you can accurately estimate β, γ, and η, but if their values change at a later time, the predictions of later behavior are worthless. For this reason, publications of Weibull fits almost always extend through the majority of the life of the items being studied. It is frequently possible to be misled by the excellent quality of fit to partial life data, giving narrow confidence bounds on the Weibull parameters, but it is vital to remember that this says little about the quality of projections based on those parameter values at much later times, unless supplemented by additional knowledge, even of a qualitative or semiquantitative kind.

The data on underground power cables in this report cover about the first 30–40 years of life. Only a few percent of the cables in service had failed by this age. The goal is to extend our ability to say something intelligent about the future failure rate and remaining life, despite the limitation just described.

2.2 Parameter Estimation from Failure Times

The complement of the cdf of Equation 2-4, the probability of not being failed at time t, can be manipulated to the following form by twice taking the natural logarithm of each side:

$$1 - \mathrm{cdf}(t) = \exp[-((t-\gamma)/\eta)^{\beta}] \quad \textbf{Eq. 2-11}$$

$$\ln\{\ln[1/(1 - \mathrm{cdf}(t))]\} = \beta.\ln(t-\gamma) - \beta.\ln\eta \quad \textbf{Eq. 2-12}$$

Consequently, a plot of the left side of Equation 2-12 against $\ln(t-\gamma)$ produces a straight line of gradient β, with an intercept such that $\eta = \exp(-\mathrm{Intercept}/\beta)$. For the work in this report, least squares linear regression was used to develop best fits and confidence bounds for β and η. The location parameter, γ, was routinely found by maximizing the r^2 value for goodness of fit. The location parameter simply enables the power law behavior, which would otherwise take effect immediately when an item is placed in service, to be exhibited after a time delay of γ, and thus model wear-out behavior. The location parameter can also represent the earliest time that random failures are experienced.

The fitting procedure followed normal practice in using an approximation to median ranks for the cdf. The y ordinate was thus $\ln\{\ln[1/(1 - \text{Median Rank}_i)]\}$, where

$$cdf(t_i) = \text{Median Rank}_i = ((i-0.3)/(N+0.4)) \qquad \textbf{Eq. 2-13}$$

and i is the rank of the *i*th failure time, t_i, ordered from shortest to longest. Thus, i = 1 to N, where N is the total sample size.

2.3 Inferences from Preventive Maintenance Basis Database Modeling

The PM Basis Database failure rate models estimate the failure rate as a constant average failure rate over long times. However, contributions from wear-out mechanisms that exceed the age of the cable can be excluded, so the result is then the average failure rate from zero to the age of interest. A set of these estimates over a succession of different ages provides the dependence of the average failure rate on the age of the cable. Consequently, Equation 2-2 is the relevant starting point for comparison with PM Basis Database results.

$$AV\lambda(0,t) = \eta^{-\beta}.(t-\gamma)^{(\beta-1)} \qquad \textbf{Eq. 2-14}$$

Taking natural logarithms

$$\ln(AV\lambda(0,t)) = -\beta\ln(\eta) + (\beta-1)\ln(t-\gamma) \qquad \textbf{Eq. 2-15}$$

The logarithm of the average failure rate at a given age, plotted against the logarithm of the age, provides a straight line with gradient equal to $(\beta-1)$ and an intercept equal to $-\beta\ln(\eta)$, from which:

$$\eta = \text{Exp}[-(\text{Intercept})/\beta] \qquad \textbf{Eq. 2-16}$$

However, because the data analysis that follows ultimately showed essentially no aging structure at <50 years of age, this procedure was not used for this report. Instead, if the inference that $\beta = 1$ is taken to be correct up to 50 years of age (which includes the age range of the data), forcing this value during the fitting process can enable better values of η, γ, and constant λ to be found directly from the data, using the following procedure.

Taking natural logarithms of Equation 2-4, where β has been set equal to unity, gives

$$-\ln(1 - cdf) = t/\eta - \gamma/\eta \qquad \textbf{Eq. 2-17}$$

Therefore, a plot of $-\ln(1 - cdf)$ against t yields a straight line of gradient $1/\eta$, with γ recovered from

$$\gamma = -\eta(\text{Intercept}) \qquad \textbf{Eq. 2-18}$$

These fits were also done using linear regression.

3
CABLE FAILURE ANALYSIS

Table 3-1 shows the number of the majority of medium-voltage power cables in service underground at nuclear power plants in the United States, together with the number of cable failures recorded for each type. The installed cable and failure data are from an NEI survey performed in 2005 and reported in NEI 06-05, *Medium Voltage Underground Cable White Paper* [1]. The failures listed are for the cable insulation in underground applications through 2005. Termination and splice failures are not included. A large number of failures in one year at one plant caused by rodents chewing on cables in troughs are also not included. The presumption in this analysis is that, if the cables were underground, the failure was associated with wet aging. The cables were also presumed to be energized for their entire life, which would be required for voltage–water-induced degradation to proceed. The data do not include cables removed from service based on condition monitoring data. However, it is likely that the population of cables removed from service based on condition is not large, given that few plants had implemented condition monitoring programs until very late in the period.

Table 3-1
Numbers of Plant Power Cables of Different Types and Numbers of Failures

Cable Type	Number of Cables			Number of Failures of Wet Cables
	Total	Underground, (Ducted or Direct Buried)	Underground and Wet	
All	8539	2842	1925	50
Butyl	352	168	58	4
Black EPR	2848	968	745	19
Pink EPR	2481	702	559	7
Brown EPR	1468	625	215	0
All XLPE	1341	336	305	12
Filled XLPE	49	43	43	8

The ages of cables that did not experience failures are not recorded, and there is no accurate estimate of the numbers of cable years of in-service experience in the data set. The average age of the U. S. fleet at the time of the survey was 28 years; the oldest plant was 36 years old. The age at failure for each of the 50 cable failures was determined by the industry survey. These 50 values of the age at failure (not listed here) were used in the Weibull analysis reported in this section. For black EPR and XLPE, the entire populations went into service close in time and then were generally replaced with pink EPR if they failed. Although 2842 cables were underground (either in ducts or direct buried) and 1925 of them either were exposed to water or were likely to have been exposed to water, the period of their life during which they were wet could be quite different from the time between their installation and the time of the survey.

3.1 Black Ethylene Propylene Rubber Failure Statistics

The 745 underground or wet cables in the black EPR sample experienced 19 failures over a total number of cable years that was long enough in at least one instance to permit one cable to reach 30 years of age (age at latest failure). The total number of cable years accumulated by the sample has not been determined, but it is likely to be of order 745 × 30 ≈ 22,350. This indicates that the average failure rate is 19/22,350 ≈ 0.00085 failures per cable per year. Cables that failed were mostly replaced by pink EPR, removing them from the black EPR population. Because the fraction that failed was quite small, this will not affect the analysis or the results. Because the fraction of cables that failed is only 2.5% (19/745) we should not expect to develop precise failure rate values from this data set. The Weibull fit to all the age-at-failure data for black EPR cable is shown in Figure 3-1.

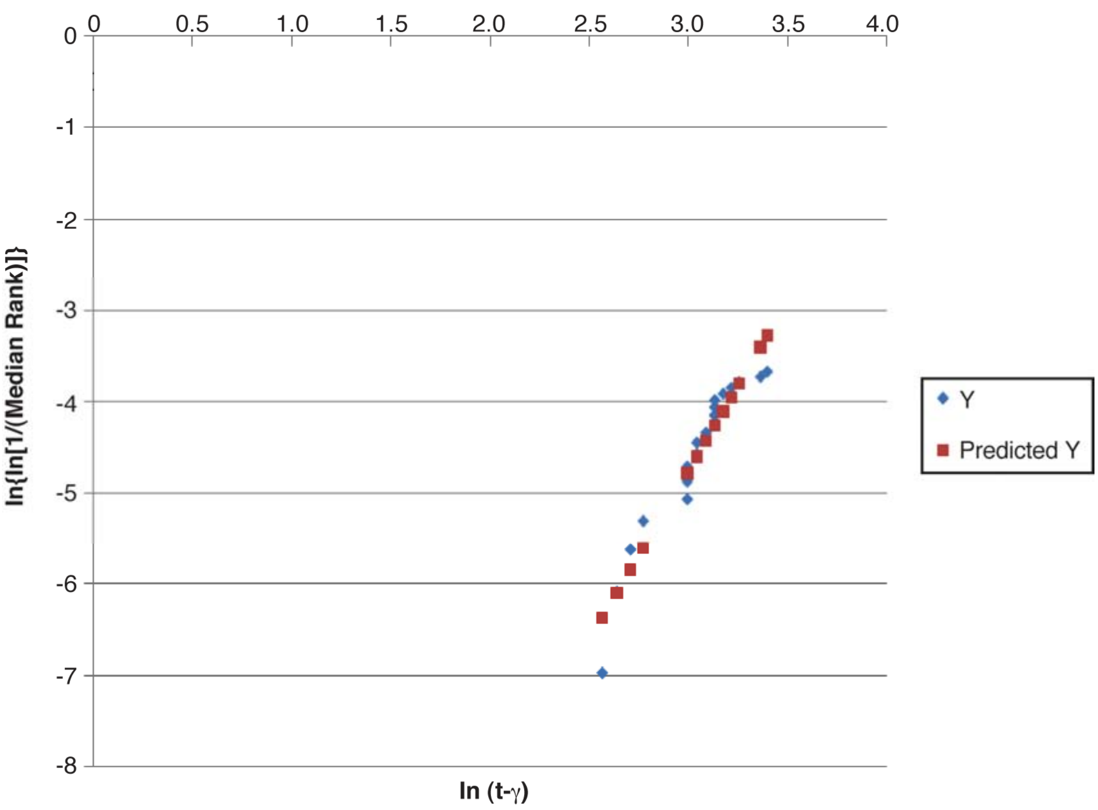

Figure 3-1
Black Ethylene Propylene Rubber Failure Data (All Data, Age at Failure ≤30 Years)

The fit to the limited data is reasonable, but the Weibull parameters are not closely determined, even at 80% confidence, as shown in Table 3-2.

Table 3-2
Weibull Fit to Age-at-Failure Data for Black Ethylene Propylene Rubber (Age at Failure ≤30 Years)

Parameter	Best Fit (r^2=0.924)	80% Confidence Bounds	
		Lower	Upper
Beta	3.7	3.36	4.04
Eta	72.65	153	39
Gamma	0	0	0

The fit can be significantly improved by shifting the time axis to maximize r^2. Figure 3-2 shows the improved fit.

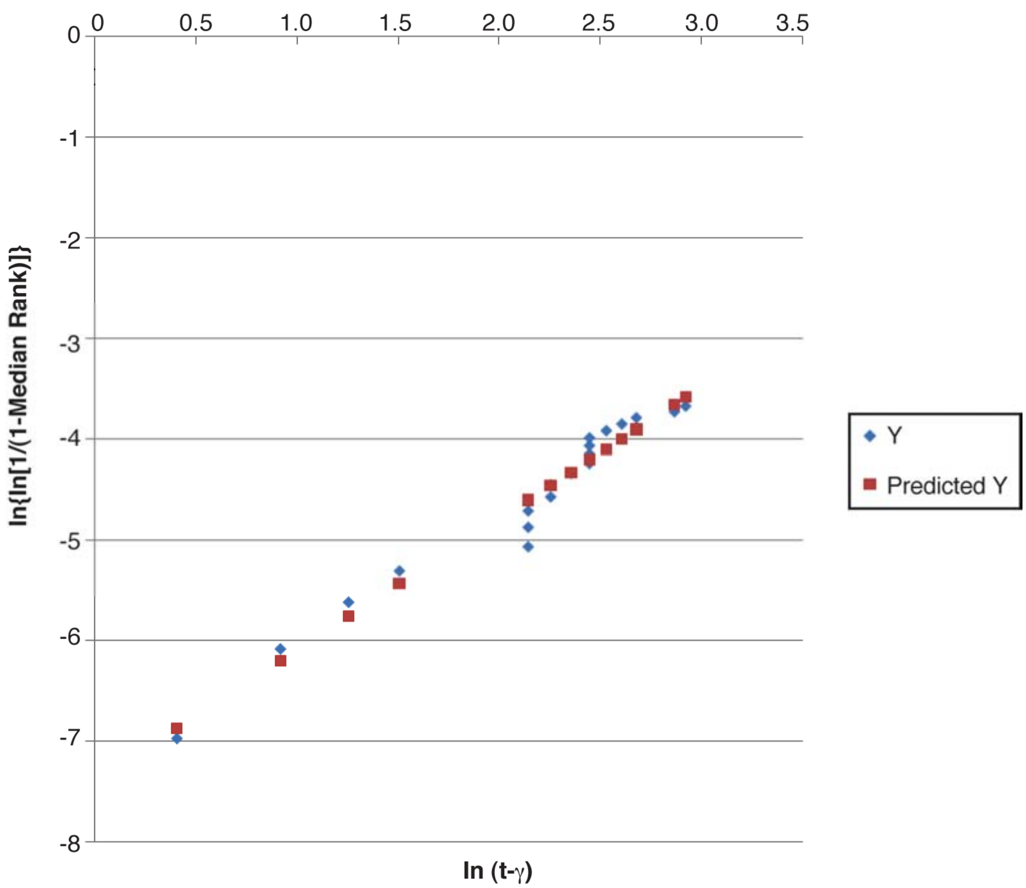

Figure 3-2
Black Ethylene Propylene Rubber Failure Data (All Data, Time Shifted)

The Weibull parameters for the improved fit are shown in Table 3-3.

Table 3-3
Improved Weibull Fit to Age-at-Failure Data for Black Ethylene Propylene Rubber (Age at Failure $\leq$30 Years, Time Shifted)

Parameter	Best Fit (r^2=0.963)	80% Confidence Bounds	
		Lower	Upper
Beta	1.3	1.22	1.39
Eta	286	490	178
Gamma	11.5	11.5	11.5

Using the best-fit values in Equations 2-1 and 2-2 suggests that the average failure rate over the interval 0–30 years is 0.00154 failures per cable per year, with the failure rate at 30 years being 0.0020 failures per cable per year. The value of 30 years has been chosen simply as being a representative age of interest. This estimated average failure rate is about twice our rough expectation of 0.00085 failures per cable per year from the raw numbers of failures. Equation 2-4 gives the probability of being failed after 30 years as 2.8%, to be compared to the actual fraction failed, which was 2.5%. If 0.00154 is taken to be the average failure rate, and 19 failures occurred, this gives an estimate of the number of cable years of experience in the 745-cable data set as 12,338 (19/0.00154), and thus an average age per cable of 16.6 years (12,338/745).

The black EPR cables were all manufactured in the early 1970s, and the last was likely installed no later than 1980. The actual average operating age was therefore likely to have been close to 30 years in 2005 (rather than the estimated average age of 16.6 years). Given the uncertainty in data definition and the fact that the 80% confidence bounds on failure rate differ from the mean by a factor of 1.7, this factor of two discrepancy in estimated average age does not appear to be significant. The only reason for considering it is to perform a sanity check on estimates of age of the cables, because the total number of cable years of operational exposure was not determined by the industry survey.

The characteristic life from this fit is 286 years, and the shape of the failure time distribution is not far from exponential (β=1). The mean failure time is 264 years (Equation 2-5), which is close to 286 years (the mean = η when β=1), and the standard deviation is about 205 years, using Equation 2-7.

There is a suggestion in the data that there is more than one wear-out failure mechanism. This is implied when the data show groupings of data points (diamond points) with a concave-down shape, tentatively revealing two such groups in this case. However, this might simply be the optical interference from two instances in which there are multiple failures in the same year. Nevertheless, the possibility of two mechanisms was investigated. When the data are fitted separately for these two groups, the results are shown in Figures 3-3 and 3-4.

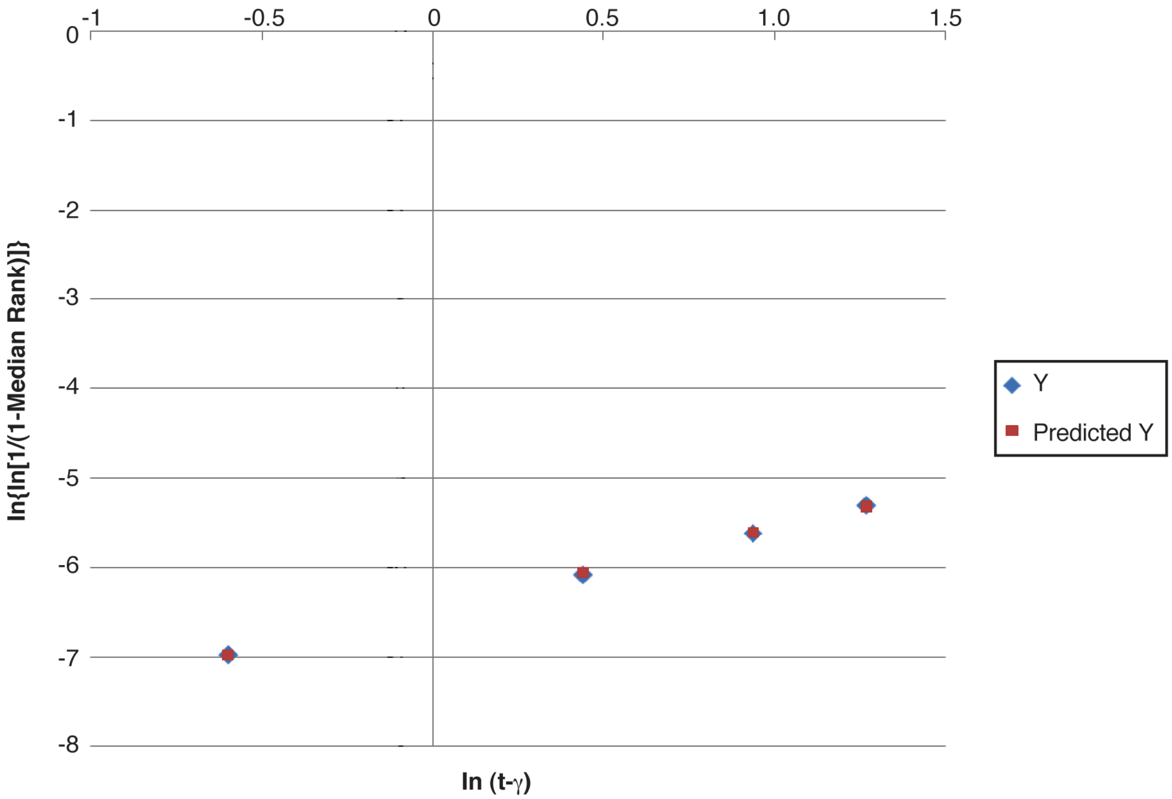

Figure 3-3
Black Ethylene Propylene Rubber Failure Data (Age at Failure ≤16 Years)

The corresponding parameter values show a much improved fit for the first subset (see Table 3-4).

Table 3-4
Weibull Fit to Age-at-Failure Data for Black Ethylene Propylene Rubber (Age at Failure ≤16 Years)

Parameter	Best Fit (r^2=0.999)	80% Confidence Bounds	
		Lower	Upper
Beta	0.89	0.86	0.92
Eta	1,390	1,841	1,068
Gamma	12.45	12.45	12.45

At 80% confidence, β is narrowly confined to a value that suggests that the behavior is not far from having a constant failure rate in this age range.

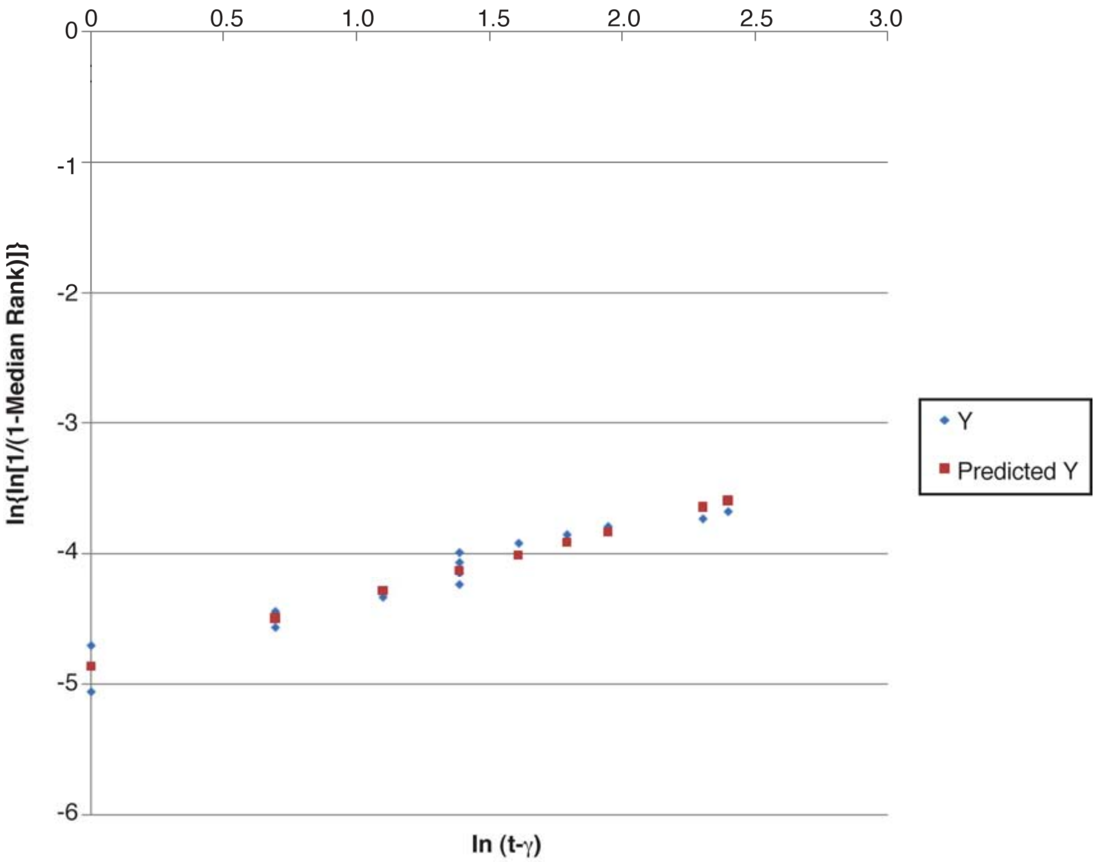

Figure 3-4
Black Ethylene Propylene Rubber Failure Data (Age at Failure 20–30 Years)

The second data subset shown in Figure 3-4 provides only a slightly better fit than when using all the data (see Table 3-5).

Table 3-5
Weibull Fit to Age-at-Failure Data for Black Ethylene Propylene Rubber (Age at Failure 20–30 Years)

Parameter	Best Fit (r^2=0.946)	80% Confidence Bounds	
		Lower	Upper
Beta	0.53	0.48	0.58
Eta	9,497	26,826	3,986
Gamma	19	19	19

These results are not convincing. In both subset cases, β <1, indicating a decreasing failure rate, although it is close to being constant for the first subset. In both cases, η (eta) >1000, in the second case much greater, indicating a characteristic life of approximately 10,000 years that does not seem realistic. The estimated values for η are much less certain than for β.

Assuming that the best result is to include all the data as in Figure 3-2, the best-fit parameters, along with Equations 2-2 and 2-4, provide the apparently good estimates of an overall average failure rate for the period 0–30 years given in Table 3-6.

Table 3-6
Overall Average Failure Rate of Black Ethylene Propylene Rubber

Black EPR	Failure Rate at Age 30 years	Average Failure Rate over the First 30 Years	Failure Rate at Age 40 Years	Failure Rate at Age 60 Years
Data from All Failure Times ≤30 Years	0.0020 (the 80% bounds are higher and lower by a factor of 1.7)	0.0015 (the 80% bounds are higher and lower by a factor of 1.7)	0.0023	0.0027

The data analysis results for black EPR suggest that the average failure rate over the first 30 years of life was approximately 0.0015 failures per cable per year, with a rate that might be increasing slowly through 60 years of age. The estimates for times >30 years use the parameters determined from only the first 30 years of experience with black EPR cables.

The results indicate a predominance of random failures for ages up to 30 years. The evidence for multiple underlying processes is weak from these data because the improvement of fit it produced was minimal and the decrease with time of the implied failure rate for the second process (the β value of 0.53 for that process implies that the failure rate at 30 years was half the average over 30 years) conflicts with the roughly constant failure rate determined from the complete black EPR data set.

3.2 Pink Ethylene Propylene Rubber Failure Statistics

The 559 underground or wet cables in the pink EPR sample experienced 7 failures over a total number of cable years that was long enough in at least one instance to permit one cable to reach 20 years of age (age at latest failure). The total number of cable years accumulated by the sample has not been determined, but it must be of order $559 \times 20 \approx 11{,}000$, given the range of years during which pink EPR cables are known to have been installed. This indicates that the average failure rate is $7/11{,}000 \approx 0.0006$ failures per cable per year. Presumably, cables that failed were replaced, in principle allowing them to fail again, although we would expect few to have done so. Because the fraction of cables that failed is only 1.2% (7/559), we should not expect to develop precise failure rate values from this data set. The Weibull fit to all the age-at-failure data for pink EPR cable is shown in Figure 3-5.

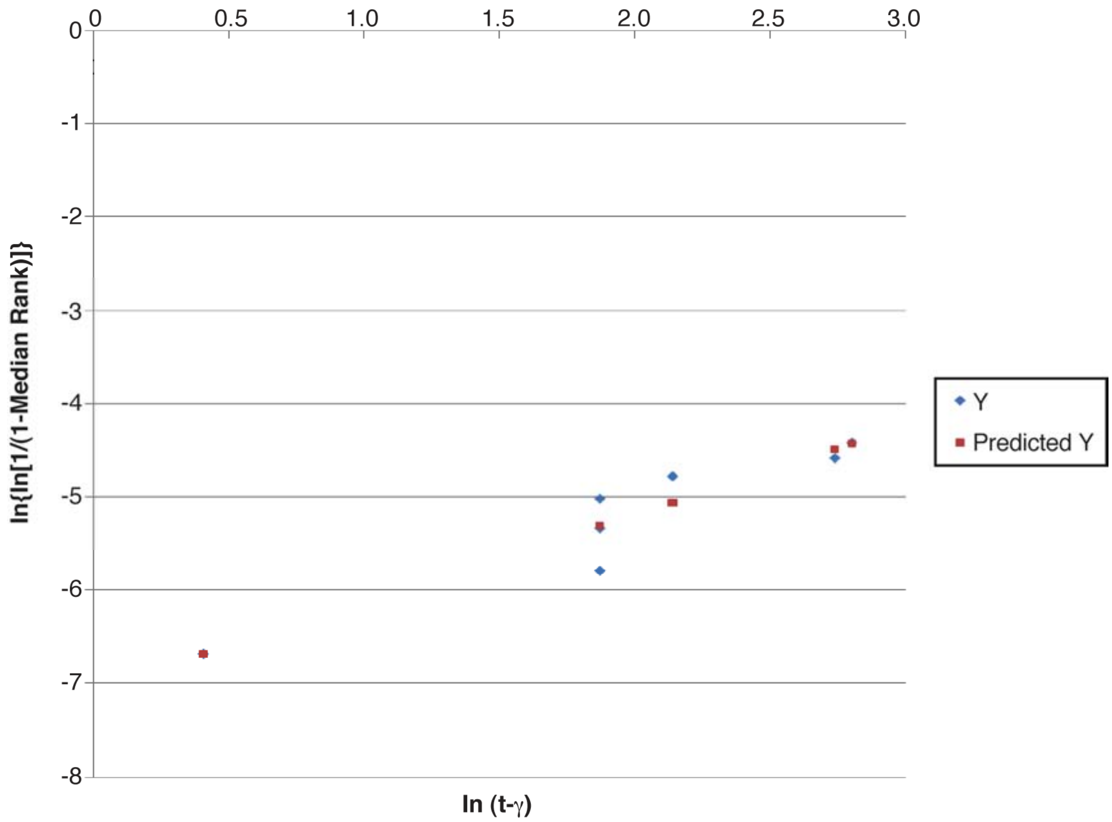

Figure 3-5
Pink Ethylene Propylene Rubber Failure Data (All Data, Age at Failure ≤20 Years)

The fit to the limited data is reasonable, but the Weibull parameters are not closely determined, even at only 80% confidence, as shown in Table 3-7.

Table 3-7
Weibull Fit to Age-at-Failure Data for Pink Ethylene Propylene Rubber (Age at Failure ≤20 years)

Parameter	Best Fit (r^2=0.891)	80% Confidence Bounds	
		Lower	Upper
Beta	0.94	0.72	1.15
Eta	1,829	32,519	302
Gamma	3.5	3.5	3.5

Using the best-fit values in Equations 2-1 and 2-2 suggests that the average failure rate over the interval 0–20 years is 0.00072 failures per cable per year, with the failure rate at 20 years being 0.00068 failures per cable per year, both values being similar owing to β (0.94) indicating an almost constant failure rate. The value of 20 years has been chosen simply as being a representative age of interest. The average failure rate is in accordance with our rough expectations of 0.0006 failures per cable per year from the raw numbers of failures. Because the characteristic life from this fit is 1829 years and the failure rate is almost constant, the mean failure time is close to 0.9 × 1829 = 1646 years, and the standard deviation is of the same order, at 1090 years, using Equation 2-7. Equation 2-4 gives the probability of being failed after 20 years as 1.0%, agreeing well with the actual fraction failed, which was 1.2%. If 0.00072 is taken to be the average failure rate, and seven failures occurred, this gives an estimate of the number of cable years of experience in the 559-cable data set as 9722, and thus an average age per cable of 17.4 years (9722/559). This is in good agreement with a rough estimate of 20–24 years, because many of these cables are for plants from the early 1980s, after the Three Mile Island accident. In fact, Table 3-8 shows that, using the 80% confidence bounds on the failure rate, our inferences from the pink EPR data set have reasonable precision.

Table 3-8
Overall Average Failure Rate of Pink Ethylene Propylene Rubber

Pink EPR	Failure Rate at Age 20 Years	Average Failure Rate over the First 20 Years	Failure Rate at Age 40 Years	Failure Rate at Age 60 Years
Data from All Failure Times ≤20 Years	0.00068 (80% bounds are higher and lower by a factor of 3)	0.00072 (80% bounds are higher and lower by a factor of 3)	0.00065	0.00063

Perhaps the most significant finding from this analysis is that there is no evidence that the failure rate is increasing through the first 20 years, most likely being dominated by random failures. The estimates for longer times use the parameters determined from the first 20 years of experience with pink EPR cables.

3.3 All Cross-Linked Polyethylene Failure Statistics (Including Filled Cross-Linked Polyethylene)

The 305 underground or wet cables in the complete XLPE sample (that is, including 8 failures from 43 filled XLPE cables) experienced 12 failures over a total number of cable years that was long enough in at least one instance to permit one cable to reach 27 years of age (age at latest failure). The total number of cable years accumulated by the sample has not been determined, but it is most likely of order 305 × 25 ≈ 7,500. This indicates that the average failure rate is 12/7500 ≈ 0.0016 failures per cable per year. Cables that failed were mostly replaced by pink EPR, removing them from the XLPE population. Because the fraction that failed was quite small, this will not affect the analysis or the results. Because the fraction of cables that failed is only 3.9% (12/559), we should not expect to develop precise failure rate values from this data set. The Weibull fit to all the age-at-failure data for XLPE cable is shown in Figure 3-6.

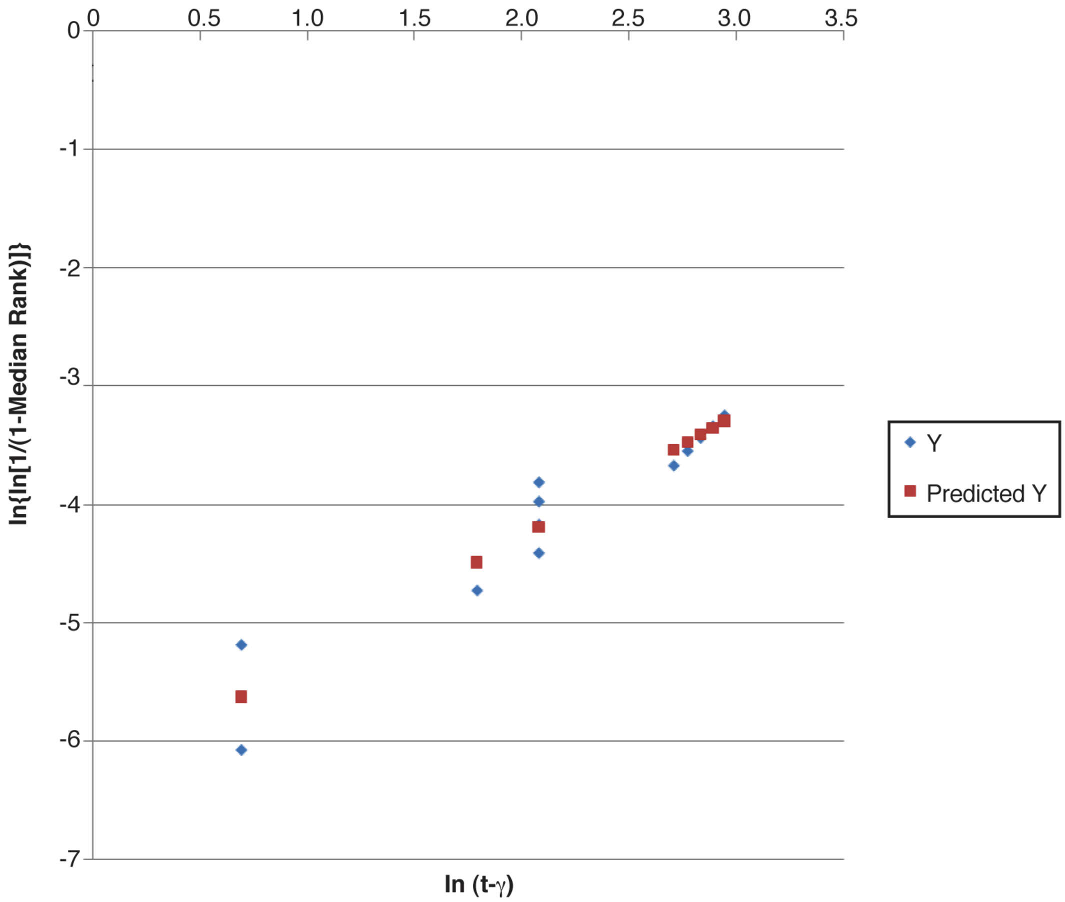

Figure 3-6
Cross-Linked Polyethylene Failure Data (All Data, Age at Failure ≤27 Years)

The fit to the limited data is reasonable, but the Weibull parameters are not closely determined, even at only 80% confidence, as shown in Table 3-9.

Table 3-9
Weibull Fit to Age-at-Failure Data for Cross-Linked Polyethylene (Age at Failure ≤27 Years)

Parameter	Best Fit (r^2=0.910)	80% Confidence Bounds	
		Lower	Upper
Beta	1.03	0.89	1.17
Eta	458	1732	167
Gamma	8	8	8

Using the best-fit values in Equations 2-1 and 2-2 suggests that the average failure rate over the interval 0–30 years is 0.00199 failures per cable per year, with the failure rate at 30 years being 0.00205 failures per cable per year, both values being similar owing to β indicating an almost constant failure rate. The value of 30 years has been chosen simply as being a representative age of interest. The average failure rate is in accordance with our rough expectation of 0.0016 estimated from the raw numbers of failures. If 0.00199 is taken to be the average failure rate and 12 failures occurred, this gives an estimate of the number of cable years of experience in the 305 cable data set as 6030, and thus an average age per cable of 19.8 years (6030/305). This estimate of average age for the XLPE cables is a little lower than an independent estimate of 25 years from knowledge of the range of years during which most of them were installed. This small difference is not significant given the 80% confidence bounds in Table 3-9.

Because the characteristic life from this fit is 458 years and the failure rate is almost constant, the mean failure time is close to $0.9 \times 458 = 412$ years, and the standard deviation is close in value at 439 years (would be the same if $\beta = 1$), using Equation 2-7. Equation 2-4 gives the probability of being failed after 30 years as 4.3%, in good agreement with the actual fraction that failed (3.9%). In fact, Table 3-10 shows that, using the 80% confidence bounds on the failure rate, our inferences from the XLPE data set have reasonable precision.

Table 3-10
Overall Average Failure Rate of Cross-Linked Polyethylene

XLPE	Failure Rate at Age 30 Years	Average Failure Rate over the First 30 Years
Data from All Failure Times ≤30 years	0.002 (80% bounds are higher and lower by a factor of 2.5)	0.002 (80% bounds are higher and lower by a factor of 2.5)

Once again, perhaps the most significant finding from this analysis is that there is no evidence that the failure rate is increasing over the first 30 years, most likely being dominated by random failures. The estimated failure rates at 40 and 60 years are not given in Table 3-10 because they remain essentially constant based on the parameters estimated for the first 25 years of life.

3.4 Filled Cross-Linked Polyethylene Failure Statistics

Eight of the 12 failures recorded and analyzed for XLPE cables occurred at one plant in a specific type of filled XLPE that was only used at that plant. Visual inspection of the failure times shows that the eight failure times for filled XLPE cables were distributed throughout the larger set of 12 failure times. Moreover, a separate Weibull fit to these eight points gave a significantly inferior quality fit ($r^2 = 0.841$ compared to 0.910) than when they were accompanied by the other four failures to provide the results reported for XLPE as a whole. The Weibull parameter values for the filled XLPE subset are shown in Table 3-11 and are still consistent with an almost constant failure rate.

Table 3-11
Weibull Fit to Age-at-Failure Data for Filled Cross-Linked Polyethylene

Parameter	Best Fit (r^2=0.841)	80% Confidence Bounds	
		Lower	Upper
Beta	0.906	0.67	1.14
Eta	110	1127	27.7
Gamma	8	8	8

Table 3-12 shows that, using the 80% confidence bounds on the failure rate, our inferences from the filled XLPE data have a larger uncertainty than when using all XLPE data combined.

Table 3-12
Overall Average Failure Rate of Filled Cross-Linked Polyethylene

Filled XLPE	Failure Rate at Age 30 Years	Average Failure Rate over the First 30 Years	Failure Rate at Age 40 Years	Failure Rate at Age 60 Years
Data from All Failure Times ≤ 30 years	0.0096 (80% bounds are higher and lower by a factor of 4.5)	0.011(80% bounds are higher and lower by a factor of 4.5)	0.0092	0.0088

Once again, the failure rate is nearly constant in time. The average failure rate for the 43 filled XLPE cables is approximately equal to a rough estimate of 0.0074 failures per cable per year, assuming an average age of 25 years per cable (8/(43 × 25)). The four failures experienced by the other 262 XLPE cables (that is, excluding the filled XLPE type), on the same basis, would be expected to have an average failure rate over the first 25 years of life of 0.0006 failures per cable per year (4/(262 × 25)). This is more than an order of magnitude lower than for filled XLPE and about the same as estimated for pink EPR. However, it proved impossible to obtain any fit to these four failures that gave any sensible Weibull parameter values.

3.5 Butyl Rubber Failure Statistics

The 58 underground or wet cables in the butyl sample experienced four failures over a total number of cable years that was long enough in at least one instance to permit one cable to reach 30 years of age (age at latest failure). The total number of cable years accumulated by the sample has not been determined, but it most likely is of order 58 × 30 ≈ 1740. This indicates that the average failure rate is 4/1740 ≈ 0.0023 failures per cable per year. Presumably, cables that failed were replaced predominantly by pink EPR. Because the fraction of cables that failed is only 6.9% (4/58) we should not expect to develop precise failure rate values from this data set. The Weibull fit to all the age-at-failure data for butyl cable is shown in Figure 3-7.

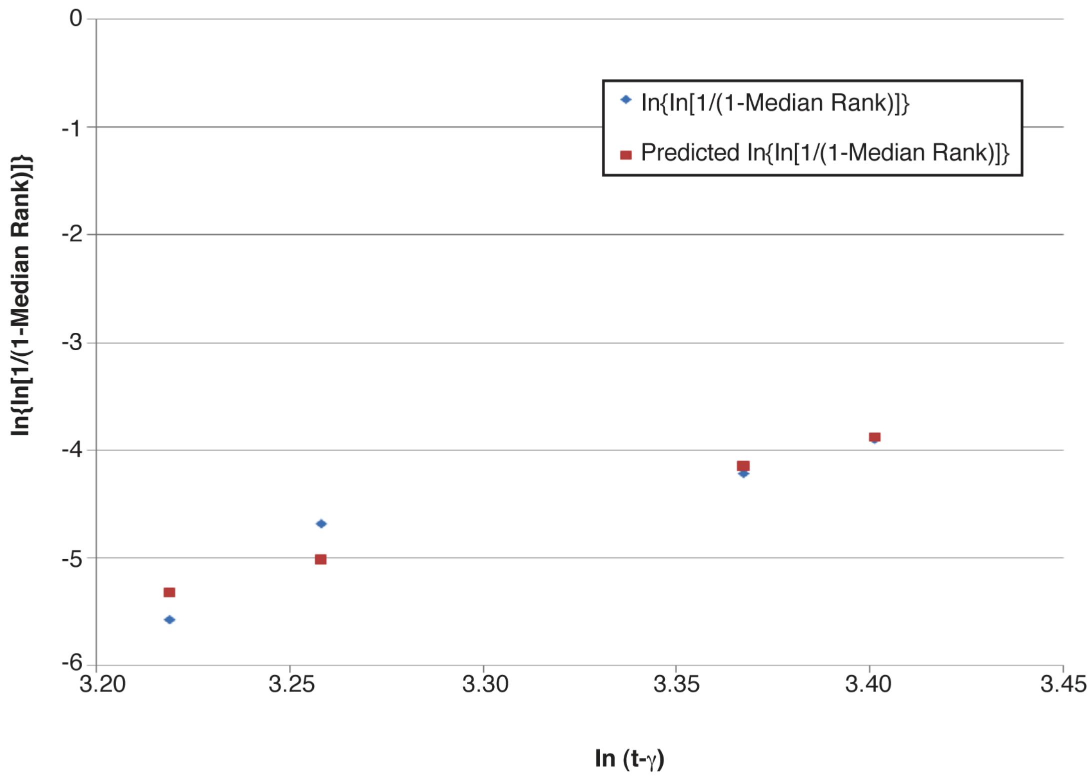

Figure 3-7
Butyl Failure Data (All Data, Age at Failure ≤30 Years)

The fit is not good, with $r^2 = 0.889$. The data points give some indication of being concave down, suggesting that a time shift along the x-axis might improve the fit. This indeed is the case, as is shown in Figure 3-8, where the age at failure has been shifted by 24.5 years to maximize r^2.

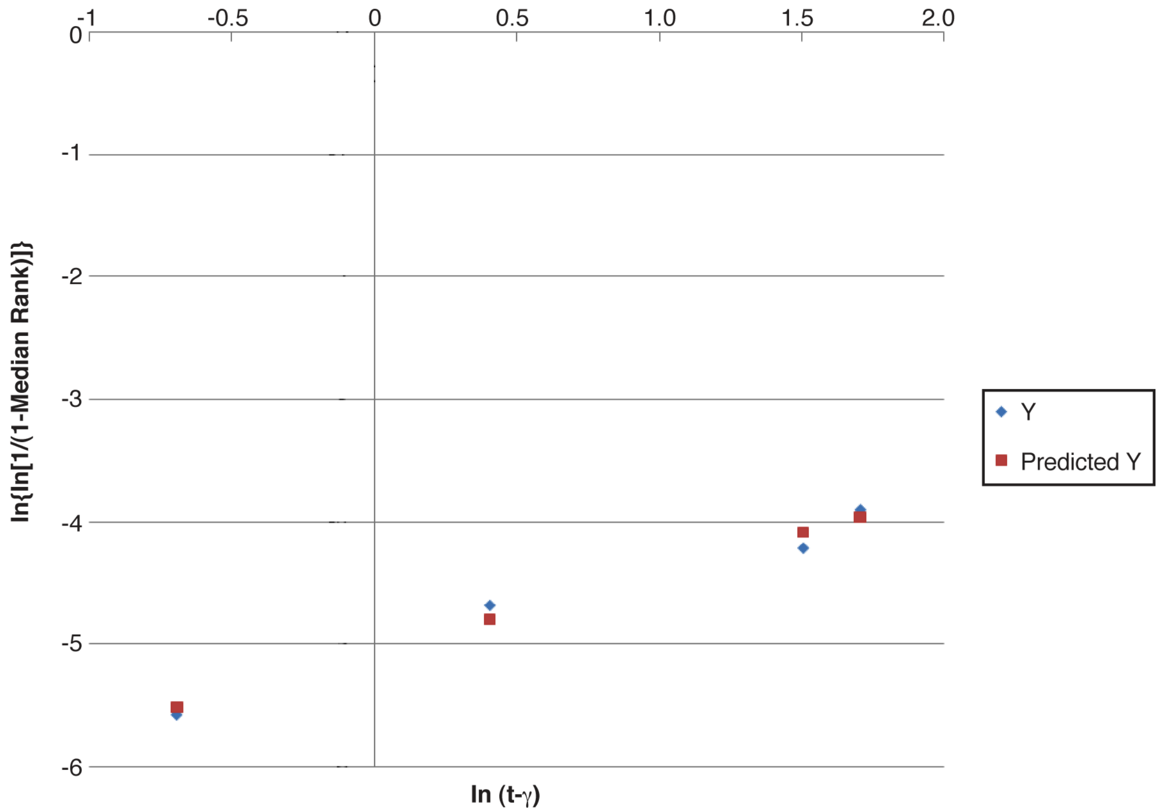

Figure 3-8
Butyl Failure Data (All Data, Age at Failure ≤30 Years, Time Shifted)

The fit to the data is now significantly improved (r^2 = 0.976) but the Weibull parameters are not closely determined, even at 80% confidence, as shown in Table 3-13.

Table 3-13
Improved Weibull Fit to Age-at-Failure Data for Butyl (Age at Failure ≤30 Years, Time Shifted)

Parameter	Best Fit (r^2=0.976)	80% Confidence Bounds	
		Lower	Upper
Beta	0.65	0.52	0.79
Eta	386	2495	113
Gamma	24.5	24.5	24.5

Using the best-fit values in Equations 2-1 and 2-2 suggests that the average failure rate over the interval 0–30 years is 0.011 failures per cable per year, with the failure rate at 30 years being 0.0074 failures per cable per year, indicating a gradually declining failure rate. The value of 30 years has been chosen simply as being a representative age of interest. The average failure rate is not in good agreement with our rough expectations of 0.003 failures per cable per year estimated from the raw numbers of failures. If 0.011 is taken to be the average failure rate, and four failures occurred, this gives an estimate of the number of cable years of experience in the 58 cable data set as 364, and thus an average age per cable of 6.2 years (364/58). This lack of agreement might be due to estimation using only four data points and a limited population. However, at least one plant is known to have replaced all their cables before failure. This might mean that the population size is decreasing over time (probably at least by 25% or more; private communication, G. Toman) rather than that the failure rate is decreasing. The standard deviation is 841 years. Without further assumption regarding the population size, the value of β indicates that the failure time density is decreasing gradually in the range of interest. Equation 2-4 gives the probability of being failed after 30 years as 6.1%, in good agreement with the 6.9% that had actually failed by a tentative average age per cable of 19.7 years.

The inferences from the butyl data set still provide reasonable estimates of the failure rates using the 80% confidence bounds on the failure rate, as shown in Table 3-14.

Table 3-14
Overall Average Failure Rate of Butyl

Butyl	Failure Rate At Age 30 Years	Average Failure Rate over the First 30 Years	Failure Rate at Age 40 Years	Failure Rate at Age 60 Years
Data from All Failure Times $\leq$30 years	0.0073 (80% bounds are higher and lower by a factor of 1.8)	0.011 (80% bounds are higher and lower by a factor of 1.5)	0.005	0.004

Once again, perhaps the most significant finding from this analysis is that there is no evidence that the failure rate is increasing over the first 30 years. Rather, the rate appears to be significantly decreasing, most likely by being dominated by random failures that are becoming less frequent over time. It is also possible that the butyl cable failure rate is constant or increasing in time but appears to decrease because some plants might be replacing all their butyl cable before it fails, producing a decreasing population that is not reflected in the data analysis.

In addition, it is evident that the reliability of butyl cable will be much inferior to that of the other cable types, except for the unusual filled XLPE cable, because the failure rate for butyl is much higher. The average failure rate of butyl cable is similar to that for filled XLPE cable, but its time dependence is much more pronounced.

3.6 Preliminary Conclusions from Data Analysis

Table 3-15 summarizes the best-fit values from the results given in the previous subsections.

Table 3-15
Summary of Failure Rates and Their Trends from the Preceding Weibull Analysis

Cable Type	Average Failure Rate Per Cable Per Year over the Period 0–30 Years	80% Confidence Range Average Failure Rates		Trend in Failure Rate
		Low	High	
Butyl	0.0110	0.0073	0.017	Decreasing or flat, but an increase might be masked by population decrease
XLPE	0.0020	0.0008	0.005	Flat
Black EPR	0.0015	0.00088	0.0025	Slightly increasing
Pink EPR	0.0007	0.00024	0.00216	Flat

These values are all similar within estimated uncertainties. They are all approximately constant over long periods of time. However, at 30 years of age, the average failure rates (and instantaneous rates) display a systematic decrease with the introduction of progressively later cable designs. There have been no failures of wet brown EPR, and one manufacturer of pink EPR has experienced no failures. An estimate of average failure rate for the wet brown EPR at 50% confidence is 0.00016 failures per cable per year, based on an upper one-sided confidence interval (as is customary in the nuclear power industry when no failures have occurred) and an average cable age of 20 years for 215 wet brown EPR cables. On this evidence the pink EPR (and with less certainty, the brown EPR) provide the best performance among all the cable types. Butyl clearly provides the worst failure rate (together with filled XLPE, which is not shown in Table 3-15).

Other uncertainties have not been estimated, including the following:

- The size of the populations
- The homogeneity of the populations with regard to voltage, functional importance of application, and degree of exposure to water
- Censoring of data points due to omissions, premature removals, and so on

Despite these concerns, given the similarity of the results (excepting butyl) in magnitude, uncertainty, and trend over time, it seems reasonable to consider XLPE, black EPR, and pink EPR as part of an overall population with a constant mean failure rate equal to 0.0014 ± 0.0014. These bounds were estimated by adding the squares of the three uncertainty values, dividing by n(n-1) (=6), and taking the square root of the sum. This quadrature procedure is only approximate when the fractional uncertainties are large, as in the current case. Butyl was not included in this average.

It is worth remembering that if the 12 filled XLPE failures are excluded, the failure rate for other XLPE cables is significantly reduced to about the same value as pink EPR. This low value for XLPE has significant uncertainty because of the unknown average age of the cables and inadequate parameter estimation from the four XLPE failures. The apparently good performance of unfilled XLPE interferes to some degree with the neat conclusion of smoothly improving failure rate with later cable design, but it reinforces the low overall value of the combined (XLPE, black EPR, and pink EPR) failure rate—in fact, it reduces it even further.

Thus, on the basis of the analysis of time-to-failure data alone, the significant uncertainties in the failure rates of XLPE, black EPR, and pink EPR and the fact that their estimated failure rates are based on only the first 30 years of life suggest that the industry would benefit from tracking the failure rates going forward and perhaps monitoring the cables for any emerging failure phenomena.

3.7 Insights from the Preventive Maintenance Basis Database

Failure rates were estimated from the PM Basis Database, using the tables of failure mechanisms developed in this project, with no allowance for the benefits of any kind of PM or testing [2]. These estimated values account for all the known mechanisms by which the cables degrade in service, but they are not expected to be more precise than a factor of two, at best. Furthermore, wear-out mechanisms are activated abruptly by the model at the relevant age thresholds, requiring some smoothing to be applied to the time-dependent results.

The PM Basis Database uses a universal value for the contribution of each random failure mechanism, which is 0.000375 failures per year per random mechanism. This value is reasonable based on general experience, and it was optimized in the past in an EPRI project by benchmarking against published reliability data. However, the value is not specifically determined for random mechanisms affecting cables, such as the chance of damaging cable jackets by pulling cables through ductwork during installation. For the cables themselves (that is, excepting failures of terminations and splices) the number of random mechanisms ranges from 13 to 18, providing a constant contribution to the failure rate of 0.0048 to 0.0067 failures per year. Table 3-15 shows that this accounts for the value of the failure rate estimated by the PM Basis Database during the phase of cable life in which only random mechanisms are active.

In all cases, this random phase lasts until the intrinsic life of the cable insulation is reached at 50 to 60 years, depending on the cable and the service conditions. During this random phase, the PM Basis Database overestimates the best-estimate failure rates estimated from the data analysis in Table 3-15 by a factor ranging from 2.5 to 7, but it is within a factor of two to three of the upper 80% bounds.

There is a possibility that conditional wear-out mechanisms that initiate only after a random event has occurred, such as the ingress of water after damage to the cable jacket has been sustained, might all be synchronized in age because the damage would have occurred at the start of service life. However, unless the probability of such random initiating events significantly exceeds the value used in the PM Basis Database, there will be very few of these cases. Such effects, therefore, should not significantly perturb the results and conclusions presented in this report.

Other processes are also present that involve water penetrating the jacket over long periods of time without the jacket specifically being damaged or defective. Some failures of this kind have been observed, although it is not obvious that these effects would be experienced universally, even in wet conditions. In these cases, there is evidence that, even when water has penetrated the jacket, further random defects in the insulation are required to produce failure of the cable. In addition to the presence of water, the random presence of manufacturing defects, voids, contaminants, and ionic impurities leaching from the jacket material might play a role. Consequently the PM Basis Database models contain only the single wear-out of degraded insulation material, initiating at 50 to 60 years, as a universal wear-out phenomenon. All other failure contributions are essentially random in initiation, although several exhibit long-term wear-out behavior after initiation.

According to the PM Basis Database cable models, the additional contribution to the failure rate from wear-out at the end of normal life of the insulation is approximately 0.0048 to 0.0057 failures per year, depending on the type of cable, but this does not begin until an age of 50 to 60 years has been reached. It would almost exactly double the total random failure rate estimated by the PM Basis Database after this age is reached. Aging of butyl insulated cables is expected earlier than for the other types, and it might somewhat more than double the random failure rate estimated by the PM Basis Database (see Table 3-15). Of course, model estimates and projections from them are subject to considerable uncertainty.

If the influence of wear-out of the insulation starting at 50–60 years develops as estimated by the PM Basis Database, it would increase the actual best-estimate current failure rates of the cables (see Table 3-16) by a factor of two to five. In that case, about half the black EPR and XLPE cables will have failed by the sum of random effects plus this insulation wear-out mechanism after an age of about 150–200 years has been reached. Of course, the aging effect will not be experienced sharply at that age threshold as the model depicts, but it will phase in gradually, according to the unknown shape of the failure-time distribution. Although the wear-out shape is not known, Equation 2-7b shows that the cumulative failure probability equals $(t/\eta)^{\beta}$ in the early part of the distribution. Thus, when t is <10% of the characteristic life, $t/\eta < 0.1$. For $\beta > 1$ (wear-out), $(t/\eta)^{\beta}$ becomes rapidly less than 0.1 as β increases. For example, if $\beta = 2$, the probability of failure in the first 10% of the characteristic life will be about 1%. The equivalent failure rate is then only $(\beta/\eta)(t/\eta)^{\beta-1} = 0.2/\eta$. For a wear-out initiating after 50 years, the characteristic life is most unlikely to be less than a few hundred years (we have already seen values of η in this range during the data analysis), meaning that the failure rate will be at most of order $0.2/100 \approx 0.002$ from such a mechanism. This validates our expectation that the failure rate will not increase by much more than a factor of two during the first decade or two of such a wear-out mechanism.

Table 3-16
Average Failure Rates for Shielded and Nonshielded Cable Types Estimated by the *Preventive Maintenance Basis Database* [2]

Cable Type (Ducted Unless Underground)	Average Failure Rate per Year	To Age (Years)	Trend in Failure Rate
Butyl, 5 kV, Nonshielded	0.0047	40	Flat to 40 years, then ~x2.5, flat
Butyl, 5–15 kV	0.0056	40	Flat to 40 years, then ~x2.3, flat
Butyl, 5–35 kV, Underground	0.0067	40	Flat to 40 years, then ~doubles, flat
XLPE, 5–15 kV	0.0051	60	Flat to 60 years, then ~doubles, flat
XLPE, 5–35 kV, Underground	0.0063	60	Flat to 60 years, then ~doubles, flat
TRXLPE, 5–35 kV, Underground	0.0063	60	Flat to 60 years, then ~doubles, flat
Black EPR, 5 kV, Nonshielded	0.0048	50	Flat to 50 years, then ~doubles, flat
Black EPR, 5–15 kV	0.0056	60	Flat to 60 years, then ~doubles, flat
Black EPR, 5–35 kV, Underground	0.0065	50	Flat to 50 years, then ~doubles, flat
Brown EPR, 5 kV, Nonshielded	0.0048	60	Flat to 60 years, then ~doubles, flat
Brown EPR, 5–15 kV	0.0056	60	Flat to 60 years, then ~doubles, flat
Brown EPR, 5–35 kV, Underground	0.0067	60	Flat to 60 years, then ~doubles, flat
Pink EPR, 5 kV, Nonshielded	0.0045	60	Flat to 60 years, then ~doubles, flat
Pink EPR, 5–15 kV	0.0052	60	Flat to 60 years, then ~doubles, flat
Pink EPR, 5–35 kV, Underground	0.0063	60	Flat to 60 years, then ~doubles, flat

3.8 Bayes Inference from the Data Analysis and the PM Basis Database [2]

The PM Basis Database results and the tables of underlying failure mechanisms support the inference from the Weibull data analysis that only random failures are contributing to the failure data at the present age of the cables. The PM Basis Database confirms that this should hold up to an age of 30 years and most probably to twice this age. Given that this is the case, a Bayes inference procedure can be introduced to the Weibull analysis of the data, which can improve the parameter estimates.

This is a standard procedure used when the β value has strong support from independent sources. In this case, we can state that evidence for random failures with no interference from wear-out mechanisms is substantial, and this fixes the value of β at unity for all the cable types in the age range from installation to 50 or 60 years. An example of the quality of fit that is obtained from the failure time data using Equations 2-17 and 2-18 with $\beta = 1$ is provided in Figure 3-9 for black EPR cable.

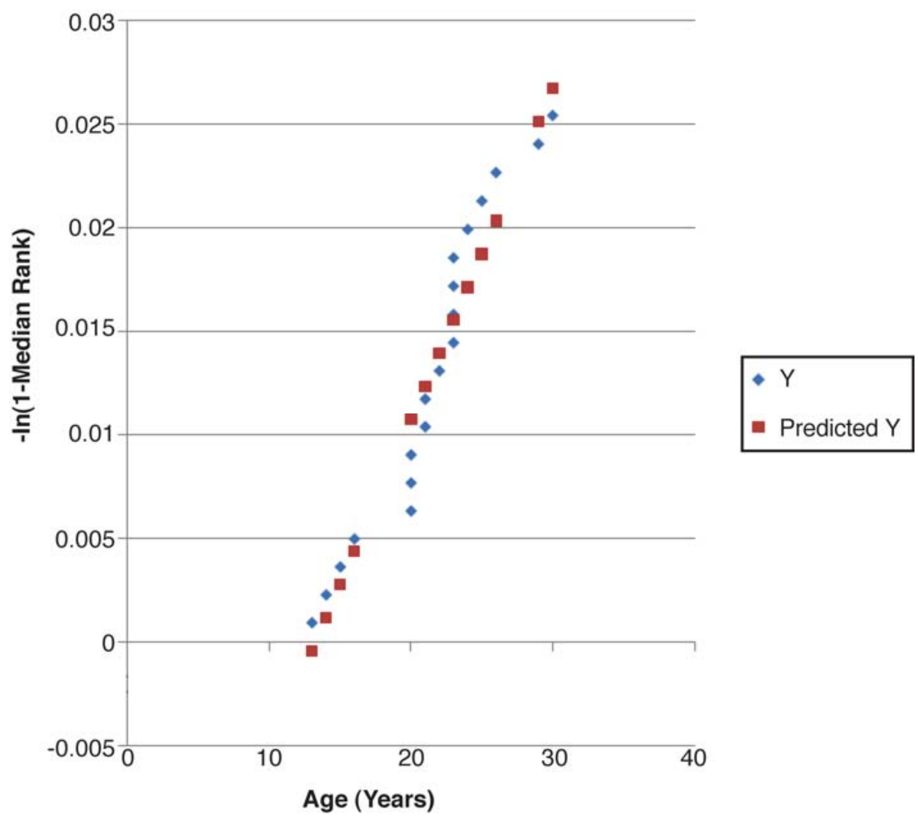

Figure 3-9
Wetted Black Ethylene Propylene Rubber Failure Data (All Data, β=1)

The new fits to the data for the different cable types, enforcing β=1, provide the estimates of constant failure rates shown in Table 3-17.

Table 3-17
Weibull Parameters from Fit to Time-to-Failure Data When Beta Is Fixed at Unity for Wet Cable

Cable Type	r^2	Eta	Gamma	Constant Failure Rate (Per Year ± 80% Confidence Bounds)
Butyl	0.953	106	23.4	0.0094 ± 0.00280
XLPE	0.936	524	7.8	0.0019 ± 0.00020
Black EPR	0.927	628	13.2	0.0016 ± 0.00014
Pink EPR	0.889	1482	2.44	0.0007 ± 0.00017

These values are derived from the same time-to-failure data as were analyzed in Sections 3.1 to 3.6, but because the independent inference about the value of β was added, they are much more precise (by factors of 2 to 15) than when β was being estimated at the same time. This observation brings into question the appropriateness of combining the average values into a grand average, particularly given the persistence of an improving trend in performance for the later cable designs. Notwithstanding this point of view, but bearing in mind our reservations about the effects of uncertainties that have not been taken into account, an average value for the cable failure rate, excepting butyl, is 0.0014 ± 0.0001, the same mean value that was obtained from the data alone and with an 80% confidence bound that is 16% smaller. The latter observation is due to the uncertainty in the grand average being more influenced by the differences between the values than by their individual uncertainties.

The values in Table 3-17 are used in Figures 3-10 and 3-11, which provide plots of reliability and cumulative failure probability over the age range of 0–60 years. Numerical values are provided in Tables 3-18 and 3-19. A reliability of 90% at age 60 years means that there is a 90% probability that the cable will successfully provide its intended function with no failures from the time it is installed up to age 60 years. An unreliability of 10% at 60 years means that there is a 10% probability that the cable will have failed before that age is reached.

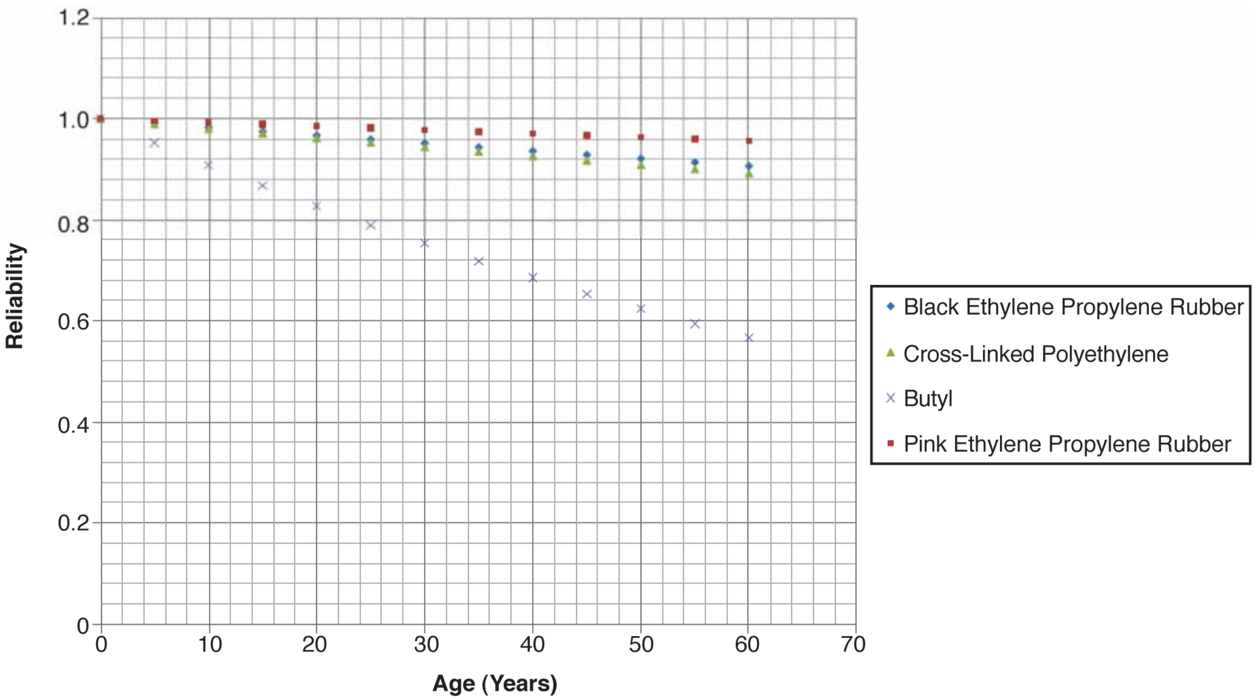

Figure 3-10
Reliability of Wet Cables up to 60 Years of Age

Table 3-18
Reliability of Wet Cables up to 60 Years of Age

Age (Years)	Black Ethylene Propylene Rubber	Pink Ethylene Propylene Rubber	Cross-Linked Polyethylene	Butyl
0	1	1	1	1
5	0.9920	0.9965	0.9905	0.9540
10	0.9841	0.9930	0.9811	0.9102
15	0.9762	0.9895	0.9719	0.8684
20	0.9685	0.9860	0.9627	0.8286
25	0.9607	0.9826	0.9536	0.7905
30	0.9531	0.9792	0.9445	0.7542
35	0.9455	0.9757	0.9356	0.7196
40	0.9380	0.9723	0.9268	0.6866
45	0.9305	0.9689	0.9180	0.6550
50	0.9231	0.9656	0.9093	0.6250
55	0.9157	0.9622	0.9007	0.5963
60	0.9084	0.9588	0.8922	0.5689

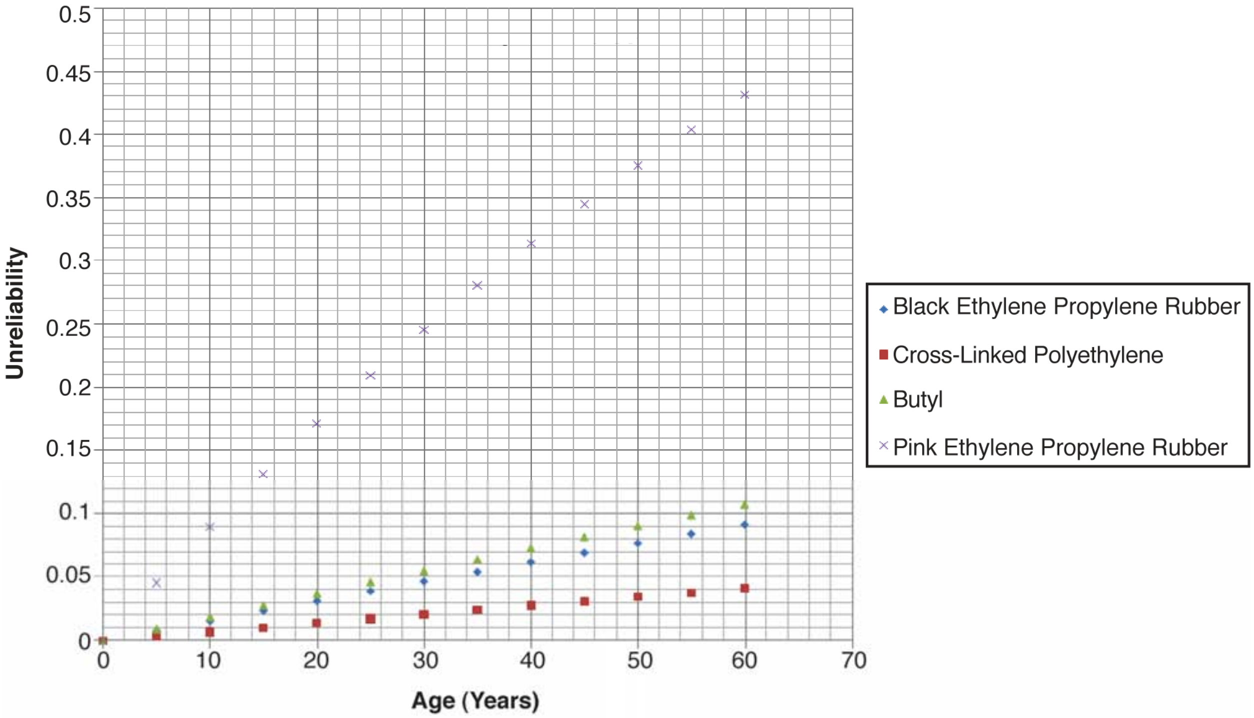

Figure 3-11
Unreliability (Cumulative Failure Probability) of Wet Cables up to 60 Years of Age

Table 3-19
Unreliability (Cumulative Failure Probability) of Wet Cables up to 60 Years of Age

Age (Years)	Black Ethylene Propylene Rubber	Pink Ethylene Propylene Rubber	Cross-Linked Polyethylene	Butyl
0	0	0	0	0
5	0.0079	0.0034	0.0094	0.0459
10	0.0158	0.0069	0.0188	0.0897
15	0.0237	0.0104	0.0280	0.1315
20	0.0314	0.0139	0.0372	0.1713
25	0.0392	0.0173	0.0463	0.2094
30	0.0468	0.0207	0.0554	0.2457
35	0.0544	0.0242	0.0643	0.2803
40	0.0619	0.0276	0.0731	0.3133
45	0.0694	0.0310	0.0819	0.3449
50	0.0768	0.0343	0.0906	0.3749
55	0.0842	0.0377	0.0992	0.4036
60	0.0915	0.0411	0.1077	0.4310

3.9 Conclusions from Analysis of Times to Failure

The conclusions from the quantitative part of this work are the following:

- Failure rates developed by direct Weibull analysis of times to failure show no signs of increasing significantly over the first 30 years of service experience for black EPR, XLPE, and butyl cable types, and show no signs of increasing significantly over the first 20 years of service experience for the pink EPR cable type. These age limits were conservatively estimated from the highest ages at failure, not from known ages of cables that did not fail. Consequently, the conclusion extends to somewhat higher ages than stated, perhaps by 5 to 10 years. The shape factors (β) for all cable types are sufficiently close to unity to suggest that the failure rate is, in fact, exactly constant over time and therefore due only to random failures. A summary of the variation of failure rate over a period, T, is provided by the aging ratio $[\lambda(T) - AV\lambda(0,T)] / [AV\lambda(0,T)] = \beta - 1$, independent of T. These values are shown in Table 3-20.

  Table 3-20
  Aging Ratios of Cable Types

Type of Cable	Aging Ratio	Absolute Error in λ(T)
Black EPR	+30%	±70%
Pink EPR	-6%	±200%
XLPE	+3%	±125%
Butyl	-35%	±80%

  These ratios showing variability of failure rate over the age of the cables are all small, especially when viewed in relation to the uncertainties, which themselves are quite small when compared to uncertainties that are normally encountered for values of failure rates.

- The best estimate values show evidence of a decreasing trend over time in the average failure rates (and in the instantaneous rates) as improved cable designs were introduced, roughly in the order of butyl, XLPE, black EPR, pink EPR, and brown EPR. Butyl cables exhibit a failure rate 5–10 times higher than that of the other cable types. Pink EPR cables exhibit a failure rate 2–3 times lower than that of XLPE and black EPR cables. The XLPE and black EPR cables have equivalent failure rates, although the value for XLPE is probably conservative due to the inclusion of failures of filled XLPE cable from only one plant. When filled XLPE cable failures are excluded, XLPE is inferred to have a failure rate similar to that of pink EPR, but the uncertainty on this result is large. These trends and conclusions persist when the condition of constant failure rate is imposed on the Weibull analysis.

- With the exception of butyl, the results from three-parameter Weibull fits lie within the 80% confidence bounds estimated from the time-to-failure data. These bounds are reasonable but are only at 80% confidence and do not account for all the known sources of uncertainty in the data. Consequently, results for the failure rates of XLPE, black EPR, and pink EPR can best be combined to give an average failure rate of 0.0014 ± 0.0001 per cable per year.

When the condition of constant failure rate, inferred from the time-to-failure data analysis and from PM Basis Database estimates and model content, is imposed on the time-to-failure data analysis, the uncertainties are reduced significantly to the point at which the decreasing trend in failure rate with improving cable design becomes statistically more significant. It is then not as persuasive to consider XLPE, black EPR, and pink EPR as part of a pooled population that is more or less homogeneous in failure rate. Instead, the expectation that the industry has moved in a positive direction in developing and installing improved cable designs over time is well supported by the data.

- The failure models in the PM Basis Database show evidence only of random or randomly initiated wear-out mechanisms up to an age of 40 years for butyl; 60 years for XLPE, pink EPR, and 5–15 kV shielded black EPR; and 50 years for the nonshielded 5 kV black EPR and the shielded 5–35 kV black EPR [2]. Furthermore, over the age range of interest, the average failure rate estimated by the PM Basis Database for all the types of cables is in the range 0.0045–0.0067 failures per cable per year. Values estimated from the data fits were in the range 0.0007–0.011. The PM Basis Database thus lends significant qualitative and quantitative support to the results of the data analysis, but it produces conservative results for the failure rates due to their total dependence on the random contribution to the failure rate that is not well known from previous analysis of active equipment.
- Although it not described in the body of this report and not subjected to data analysis, the inclusion of a splice is estimated by the PM Basis Database to add about 0.0015 failures per year to the failure rate for a cable. About 0.002 failures per year are also added by including a termination. Both of these modifications should also be constant in time. Neither of them is influenced by being in dry or wet conditions unless additional installation errors have occurred.
- The failure models developed for the PM Basis Database also include other wear-out mechanisms that can act over timeframes of 10–30 years, but these either require damage to have occurred to the cable jacket from pulling during installation or from some source of high operating temperature or they are wear-out mechanisms that still have some imperfectly understood dependence on other factors, such as ionic impurities in the cable jacket or additional manufacturing defects. The high-temperature mechanism does not seem to apply to the majority of the nuclear plant underground cables. The typical rate used for random events is approximately 4×10^{-4} per year, a value that is generic, not at all specifically related to power cables, and not well known from prior benchmarking against active equipment dominated by wear-out behavior. However, it is a value that has stood the test of time in providing reasonably accurate estimates of failure rates for the mostly active PM Basis Database equipment.

  According to this random event probability, for the roughly 2000 cables in question, it is not likely that more than a few cables were damaged during installation, even if the random probability were several times larger. Further, there are wear-out mechanisms that on average take many years for moisture to penetrate the jacket, which is followed by progressive damage to the insulation over a similar timeframe that appears to depend on somewhat random initiation by further defects in the insulation. This wear-out behavior is thus weakened by the intermediate random probability. It is also known to take a long time, 10 to 30 years, before the first failures appear, and failures would be expected to continue over an additional 30–90 years so that the number occurring in any year would be small.

It is conceivable that installation of more than one cable at a given plant might be adversely affected by a common cause due to inadequate skill of the installers. However, such an occurrence might be expected to show up in the Weibull analysis. This was not the case, not even for the relatively high incidence of failures of filled XLPE cables at one plant. Those failures resolutely confirmed an almost constant failure rate that was not consistent with a wear-out behavior.

- The only universally applicable wear-out process appearing in the PM Basis Database failure mechanisms for the cables themselves, without any interference by moderating random effects, is due to intrinsic aging of the cable insulation that begins around the age of 40 to 60 years, depending on the type of cable. Failure rate estimates by the PM Basis Database show that this aging process would add about as many failures as are due to the total of random failures. Thus, the failure rate might be expected to approximately double due to normal aging of the insulation over the first decade or two after the first failures due to this wear-out mechanism. This effect would initiate more gradually than estimated by the PM Basis Database because the database just activates it abruptly with full force at the threshold age.

3.10 Summary

The overall conclusion of most significance is that there exists little evidence that the failures of plant underground power cables over the past 30 or so years are due to wear-out (that is, aging processes), even for those cables known or suspected to operate in wet conditions. Further, the values of the failure rates are consistent with a specific set of known, random processes. Finally, it is expected that wear-out will begin to be noticed at an age of 40–60 years due to normal degradation of the cable insulation, which takes place even in the absence of water. Even then, this added source of failures should not lead to a dramatic increase in the failure rates over short periods of time.

Nevertheless, it is recommended that the industry continue to monitor the trend in failure rate with a view to repeating the analysis reported here when more failures have accumulated, perhaps in 10 years. Because the current work shows the absence of time-dependent behavior quite clearly, any significant change to this situation can be expected to be readily discoverable. Before conducting any future industry survey to collect failure time data, it will be worthwhile to carefully consider the data to be gathered so as to maximize the information that can be gleaned from the kind of analysis reported here.

The average failure rates and their uncertainty bounds indicated by the fit-to-failure-time data are projected from goodness of fit considerations and do not themselves imply anything about the values in the future. The intelligence added by the PM Basis Database from considering the possible failure mechanisms is the factor that enables projections to be made about the future. The fact that estimates of the current failure rates by the database are in reasonable agreement with experience adds some confidence that the future projections are reliable.

4
FAILURE MODELS FOR PLANT POWER CABLES, TERMINATIONS, AND SPLICES

This section presents the contents of the failure models in tabular form. These models were developed by adapting the failure models of similar but direct-buried cables used in utility power distribution systems that were developed by utility subject matter experts as part of the PM Basis Database [2]. There is one table for each cable type. Differences in the insulation materials, service environments, and presence or absence of splices are captured in the bodies of the tables. The process was necessarily fairly repetitive to ensure that each set of circumstances (that is, component failure location and degradation mechanism) was given proper consideration.

Using the process described in Section 1, the models identify many failure locations that, in the industry's maintenance experience, are known to occur. This information is supplemented with the leading degradation mechanisms, the main physical influences on the degradation, and the time progression of the degradation for each failure location. For each case, the model includes the time scale after which the degradation would actually become a failure. This information is presented in the first four columns of Tables 4-1 through 4-31. The next four columns in the tables show how effectively specific PM tasks, thermography and diagnostic testing, can detect a significantly degraded condition. Total replacement has been included as a benchmark for comparing PM costs versus the reliability that might be gained from new cables over maintaining older ones. The tables of detailed information presented here can also support utilities wanting to modify the suggested tasks or task intervals to account for their specific conditions.

4.1 Component Degradation Data Table

The data gathered for each component type are presented as a tabular summary of the equipment failure models, including degradation and failure mechanism information. The data obtained represent the factors that influence failure, as follows:

- The locations where failures are most likely to occur
- The degradation mechanisms
- The factors that influence the degradation
- How the degradation progresses over time
- The opportunities to recognize the onset or status of the degradation
- The PM actions and strategies that can be used to discover or prevent the failure from occurring and the effectiveness of these activities

The component degradation data table identifies many subcomponent locations (failure locations) at which, in the industry's maintenance experience, failures are known to occur. This information is supplemented with the leading degradation mechanisms, the main physical influences on the degradation, and the time progression of the degradation for each specific cable type and combination of termination and splice. For each case, the model includes the timeframe after which the degradation would actually become a failure. In addition, service stressors (such as moisture and high temperature) are identified that can be turned on or off, depending on their presence. This information is presented in the first four columns of Tables 4-1 through 4-31.

The rightmost columns in each table describe how effectively specific PM tasks such as diagnostic testing can detect a significantly degraded condition. Task effectiveness for the purpose of the PM Basis Database is defined as high, medium, or low. Each task is rated on how well it can address each degraded condition, as follows:

- H (high) denotes a 97% chance of success in detecting a problem if it exists at the time the task is performed and in preventing the degraded condition from becoming an in-service failure.
- M (medium) denotes an 80% chance of success.
- L (low) denotes no more than a 50% chance of success.

Task effectiveness as described here assumes that the task will be done at the right time. A blank entry in these columns means that the task is not capable of addressing the relevant degraded condition. The tables of detailed information presented here can also support utilities that want to modify the suggested tasks or task intervals to account for their specific conditions.

4.2 Time Codes

The time code columns in the tables represent the rate at which deterioration occurs by the particular mechanism under the influences shown in the preceding columns. It can be thought of as the expected time until the earliest failures of the equipment occur due to that mechanism. The codes are defined as follows:

- A **W** (wear-out) time code shows the time in years that a wear-out mechanism typically takes to lead to the earliest cable failures—an analog of minimum life. A range of years indicates uncertainty in this minimum life. When the **W** is not accompanied by a **U**, it means that the wear-out mechanism is not experienced by every component of this type but must be triggered by the existence of a special condition or by another event taken to be a random occurrence.
- A **UW** (universal wear-out) code indicates a wear-out mechanism that is universally experienced and that starts to degrade the component as soon as it is put into service.
- An **R** (random) code indicates a randomly occurring degradation mechanism. Normally, the random mechanisms individually do not exert a strong influence on the failure rate unless no universal wear-out processes are active, which is the case in the early life of cables, but their random occurrence pattern makes them hard to avert unless PM tasks are performed quite frequently.

4.3 Service Stressors

Service stressors (that is, stressor groups as labeled in the component degradation tables) modify the stated time codes to adjust the earliest time to first failure that an impacted degradation mechanism will exhibit. The use or non-use of service stressors is up to the individual utility and can be switched on if it is felt that the stressed condition exists at that particular plant. The adjustment to the time code is handled automatically by the PM Basis Database. In brief, when a stressor is applied, the different time codes are modified in the following fashion:

- The **W** (wear-out) codes are simply activated at the stated time. (W10, normally treated as having a small, essentially random influence on the failure rate will now look like a UW10 beginning its wear-out period at 10 years.)
- The **UW** (universal wear-out) codes are approximately halved in time. (UW10 becomes UW5, so the earliest time to first failure or the failure-free period is shortened to 5 years instead of 10.)
- The **R** (random) codes, which normally contribute little (approximately 4×10^{-4}) to the failure rate now contribute approximately 4×10^{-2}.

The stressor codes available for use on power plant cables are the following:

- **D** (high duty cycle) represents a condition in which the cable is normally energized and operated with a load factor (ampacity) >75% rated.
- **M** (moisture) indicates the continual presence of moisture or water.
- **T** (temperature) indicates that the cable almost always experiences elevated temperatures greater than rated.
- **B** (biological) indicates buried cables where rodents, such as woodchucks, can cause cable damage.

The stressor codes can be combined, such as DT, indicating that duty cycle or temperature or both can affect the time code’s stated value. The stressor codes have their effect only when 1) the influence of the stressor is quite significant and 2) the stressor acts as a necessary and sufficient condition in promoting degradation of the condition. In most cases in the tables in this section, the effects of the stressors have been already included in the time codes, because the printed version of the tables will be used in circumstances in which the user will not be able to turn the stressors on and off as they could if the data were used within the PM Basis Database software. This is particularly true for the effects of moisture and is responsible for the proliferation of similar tables presenting alternative combinations of, for example, wet or dry terminations.

4.4 Tables of Failure Locations, Degradation Mechanisms, and Preventive Maintenance Strategies

Table 4-1
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-1 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random, but if highly loaded or otherwise hot, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-1 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W25_30	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H
Cable Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		R	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H

Table 4-1 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W20_30	Random	Loss of continuity or tracking		H	H
Terminations, Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H

Table 4-1 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Dry	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations, Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-2
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices)	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-2 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices)	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random, but if highly loaded or otherwise hot, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-2 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices)	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W25_30	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H
Cable - Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		R	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H

Table 4-2 (continued)
Black Ethylene Propylene Rubber, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices)	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W20_30	Random	Loss of continuity, tracking		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge, Inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-3
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-3 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random, but if wet and damaged by high loading or high temperatures expect first failures only after 20 to 30 years	None			H

Table 4-3 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W25_30	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge (local)		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography, or partial discharge (local)	H	L	H

Table 4-3 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography (local)	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge, Inspection (local)		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-4
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-4 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling	DT	W20_30	Random, but if highly loaded or otherwise hot, expect first failures only after 20 to 30 years	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)		W10_12	Random	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	None			H

Table 4-4 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)		W25_30	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge (local)		H	H
Terminations, Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H

Table 4-4 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Dry	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge (local), Inspection		H	H
Terminations, Dry	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-5
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-5 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W25_30	Random	None			H

Table 4-5 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random, but if highly loaded or otherwise hot, expect first failures only after 20 to 30 years	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H

Table 4-5 (continued)
Black Ethylene Propylene Rubber, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local), Inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-6
Black Ethylene Propylene Rubber, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW50	Expect first failures after 50 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-6 (continued)
Black Ethylene Propylene Rubber, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random, but if highly loaded or otherwise hot, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W20_24	Random	Power factor or dissipation factor (tan delta)		M	H

Table 4-6 (continued)
Black Ethylene Propylene Rubber, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W20_30	Random; when wet and damaged due to high loading or high ambient temperature, expect first failures only after 20 to 30 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W24_30	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H
Cable Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		R	Random	Partial discharge		M	H

Table 4-6 (continued)
Black Ethylene Propylene Rubber, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection (only if visible)			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection (only if visible)			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection (only if visible)			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W20_30	Random	Loss of continuity, tracking		H	H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H

Table 4-6 (continued)
Black Ethylene Propylene Rubber, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Surface tracking	Moisture, contamination, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H
Terminations, Outdoor or Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-7
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-7 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	H

Table 4-7 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations, Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H

Table 4-7 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Dry	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations, Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-8
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	Partial discharge		L	
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			

Table 4-8 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	

Table 4-8 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge		H	
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	

Table 4-8 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	

Table 4-9
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-9 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H

Table 4-9 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge (local)		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge (local)	H	L	H

Table 4-9 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-10
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-10 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H

Table 4-10 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge (local)		H	H
Terminations, Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H

Table 4-10 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Dry	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge (local) or inspection		H	H
Terminations, Dry	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-11
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-11 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H

Table 4-11 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H

Table 4-11 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-12
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W10_15	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-12 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H

Table 4-12 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H

Table 4-12 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection (only if visible)			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection (only if visible)			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection (only if visible)			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W20_24	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H

Table 4-12 (continued)
Brown Ethylene Propylene Rubber, Discharge-Resistant, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Surface tracking	Moisture, contamination, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H
Terminations, Outdoor or Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-13
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-13 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		R	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-13 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H

Table 4-13 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-14
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		UW60	Expect first failures after 60 years	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		W10_15	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		W20_25	Random	None			H

Table 4-14 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W15_30	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)		R	Random	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		R	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		R	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W5_10	Random	Partial discharge		M	H

Table 4-14 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		W10	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)		R	Random	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		UW30	Expect first failures after 30 years	Loss of continuity or tracking		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		R	Random	Partial discharge		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		UW60	Expect first failures after 60 years	Partial discharge or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H

Table 4-14 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		W10_15	Random	Partial discharge or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Partial discharge		H	H

Table 4-15
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-15 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-15 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge (local)		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge (local)	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H

Table 4-15 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-16
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		W15_20	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		R	Random	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		W10_15	Random	None			H

Table 4-16 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W20_25	Random	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		R	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-16 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)		R	Random	Inspection			H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		R	Random	Partial discharge (local)		H	H
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		W30	Random	Partial discharge (local)		H	H

Table 4-16 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Surface tracking	Moisture, especially at higher voltages		R	Random	Partial discharge (local) or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-17
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-17 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-17 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local), Inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-18
Pink Ethylene Propylene Rubber, Discharge-Free, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-18 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		R	Random	Partial discharge		M	H

Table 4-18 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H

Table 4-18 (continued)
Pink Ethylene Propylene Rubber, Discharge-Free, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Surface tracking	Moisture, contamination, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H

Table 4-19
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-19 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H

Table 4-19 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Neutral (Concentric or Taped Only)	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H

Table 4-19 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-20
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-20 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H

Table 4-20 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Neutral (Concentric or Taped Only)	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge		H	H

Table 4-20 (continued)
Butyl, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-21
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-21 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H

Table 4-21 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random	Inspection			H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random, but if wet expect first failures only after 10 to 12 years	Partial discharge (local)		H	H

Table 4-21 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and Wet or Dry Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge (local)	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-22
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-22 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-22 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge (local)		H	H
Terminations, Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Dry	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge (local) or inspection		H	H
Terminations, Dry	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-23
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Corona - partial discharge	Design - no shield present		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	None			H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	None			H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H

Table 4-23 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	None			H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	None			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-23 (continued)
Butyl, 5 kV, Jacketed, Nonshielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge (local) or thermography	H	L	H
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge (local)		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge (local) or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge (local)		H	H

Table 4-24
Butyl, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W8_12	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW40	Expect first failures after 40 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H

Table 4-24 (continued)
Butyl, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W10_15	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W20_24	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H

Table 4-24 (continued)
Butyl, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_24	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H
Cable Insulation Shield (Polymer Tape)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Neutral (Concentric or Taped Only)	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H

Table 4-24 (continued)
Butyl, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W20_24	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-24 (continued)
Butyl, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Surface tracking	Moisture, contamination, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H
Terminations, Outdoor or Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-25
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-25 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W20_25	Random	Power factor or dissipation factor (tan delta)		M	H

Table 4-25 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H

Table 4-25 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-26
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-26 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H

Table 4-26 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H

Table 4-26 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-27
Tree-Resistant Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W15_20	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-27 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H
Cable Insulation	Thermal damage	High-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		L	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H

Table 4-27 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Extruded Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H

Table 4-27 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H

Table 4-27 (continued)
Tree-Resistant Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Surface tracking	Moisture, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H
Terminations, Outdoor or Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-28
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W5_10	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-28 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H

Table 4-28 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H

Table 4-28 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Dry Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations	Surface tracking	Moisture, especially at higher voltages		W15	Random	Partial discharge or inspection		H	H
Terminations	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-29
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W5_10	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H

Table 4-29 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H

Table 4-29 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation Shield (Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Terminations, Outdoor	Degraded insulation	Installation error allowing ingress of moisture		W10	Random	Partial discharge		H	H
Terminations, Outdoor	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H

Table 4-29 (continued)
Cross-Linked Polyethylene, 5–15 kV, Jacketed, Shielded, in Duct or Conduit or Tray with Wet or Dry Cables, Outdoor Terminations, and No Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor	Surface tracking	Moisture, especially at higher voltages		UW30	Expect first failures after 30 years	Partial discharge or inspection		H	H
Terminations, Outdoor	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-30
Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Conductor	Corrosion (aluminum-stranded, unfilled only)	Water ingress, chemistry		R	Random	None			H
Cable Conductor	Mechanical stress (bending)	Too small a bending radius		R	Random	None			H
Cable Insulation	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Insulation	Electrical trees	Lightning		R	Random	Partial discharge		M	H
Cable Insulation	Electrical trees	Manufacturing defect (voids and protrusions or contaminants in insulation)		W5_10	Random	Partial discharge		L	H
Cable Insulation	Material degradation	Normal life (that is, remaining dry)		UW60	Expect first failures after 60 years	Power factor or dissipation factor (tan delta)		M	H

Table 4-30 (continued)
Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Mechanical damage leading to tracking	Improper transportation, handling, or installation (such as knife cuts or improper cutback)		R	Random	None			H
Cable Insulation	Mechanical stress	Improper pulling technique - depends on degree		W13_18	Random	None			H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Damaged by foreign material or protrusions in the duct during pulling		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation	Water trees caused by water ingress through damaged jacket	Embrittlement of jacket due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	R	Random and significantly enhanced if highly loaded or otherwise hot	Power factor or dissipation factor (tan delta)		M	H

Table 4-30 (continued)
Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Insulation	Water trees (that is, those that lead to electrical trees, mainly water trees that exceed 30% of the insulation thickness)	Water ingress in the presence of voltage, especially in the presence of manufacturing defects (voids, contaminants, ionic impurities).		W10_12	Random	Power factor or dissipation factor (tan delta)		M	H
Cable Insulation Shield (Cotton Tape)	Voltage stress riser	Cotton fiber penetration into insulation		R	Random	Partial discharge		L	H
Cable Insulation Shield (Polymer)	Electrical discharge	Gaps between insulation and insulation shield - possibly installation damage		W15_30	Random	Partial discharge		M	H
Cable Outer Jacket	Animal damage	Squirrels and other rodents	B	R	Random and significantly enhanced by the known presence of rodents	Inspection (only if visible)			H
Cable Outer Jacket	Damaged	Foreign material or protrusions in the duct		R	Random	Inspection			H

Table 4-30 (continued)
Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Circulating currents in neutral		R	Random	Inspection			H
Cable Outer Jacket	Embrittlement, leads to loss of jacket integrity	Thermal aging due to high-temperature operation (high load factor, bad heat transfer, high ambient temperature)	DT	W15_30	Random, but if highly loaded or otherwise hot, expect first failures only after 15 to 30 years	Inspection			H
Cable Taped Metal Shield	Corrosion	Water ingress, chemistry		W5_10	Random	Loss of continuity or tracking		H	H
Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge		H	H
Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H
Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-30 (continued)
Cross-Linked Polyethylene, 5–35 kV, Jacketed, Shielded, Underground Direct-Buried with Wet Cables, Outdoor or Dry Terminations, and Wet Splices

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography of Terminations and Splices	Diagnostic Testing	Total Replacement
Terminations, Outdoor or Dry	Degraded insulation	Installation error allowing ingress of moisture		W5	Random	Partial discharge		H	H
Terminations, Outdoor or Dry	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Partial discharge or thermography	H	L	H
Terminations, Outdoor or Dry	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations, Outdoor or dry	Surface tracking	Moisture, especially at higher voltages	MC	W5	Random, but if wet or contaminated, expect first failures only after 5 years, especially at higher voltages	Partial discharge or inspection		H	H
Terminations, Outdoor or Dry	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

Table 4-31
Terminations and Splices, All Types, 5–15 kV

Failure Location	Degradation Mechanism	Degradation Influence	Stressor Group	Time Code	Failure Timing	Discovery Prevention Opportunity	Thermography	Diagnostic Testing	Total Replacement
Terminations or Splices	Degraded insulation	Installation error allowing ingress of moisture		W10_12	Random	Partial discharge		H	H
Terminations or Splices	Overheating from high-resistance connection	Improperly installed, corrosion		R	Random	Thermography or partial discharge	H	L	H
Terminations or Splices	Partial discharge and tracking	Installation error (such as poor cutbacks, voids, nicks, or contamination)		R	Random	Partial discharge		H	H
Terminations or Splices	Tracking	Manufacturing defect		R	Random	Partial discharge		H	H

5 PREVENTIVE MAINTENANCE TEMPLATES

This section presents the PM program in a concise format. The PM tasks that are identified represent common practices used by utilities as identified by the expert panel; however, they should not be considered recommended practices. Each utility must evaluate the cost effectiveness of these practices in light of their own circumstances. The selected PM tasks are presented as a template to be consistent with the format used with other component types. Explanatory notes expand on the rationale, definition, and usage of each PM task.

5.1 Preventive Maintenance Templates and Task Descriptions

The template tabulates the recommended tasks and task intervals for a range of functional importance, duty cycle, and service conditions. Each template consists of eight columns, each of which represents one of the eight possible combinations (often called *categories*) of functional criticality (critical or minor), duty cycle (high or low), and service condition (severe or mild).

For each PM task, a task interval is usually provided for each of the eight possible combinations. (Section 5.4 describes how a task interval is derived and should be applied.) The intervals represent the suggested best time that a particular task should be performed when the component is best described by one of the eight template categories. The intervals usually consist of a number and a single letter, indicating the time in months or years (for example, 3M indicates 3 months, 2Y indicates 2 years, and so forth). Two additional interval representations that can appear are NA (not applicable; no PM task is recommended for this template category), and AR (as required; the expert group could not recommend a specific best interval or felt that the task was to be performed as an on-condition task).

Table 5-1 is the PM template for cables, and Table 5-2 is the PM template for terminations and splices.

Table 5-1
Preventive Maintenance Template, Cables (All Cable Types)

	Critical Functional Importance				Minor Functional Importance			
Duty Cycle	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Service Condition	**Severe**	**Severe**	**Mild**	**Mild**	**Severe**	**Severe**	**Mild**	**Mild**
Thermography of Terminations and Splices	3Y	3Y	3Y	3Y	AR	AR	AR	AR
Diagnostic Testing	6Y	6Y	6Y	6Y	AR	AR	AR	AR
Total Replacement	AR	AR	AR	AR	AR	AR	AR	AR

Y, years; AR, as required. Refer to specific application notes for each PM task.

Table 5-2
Preventive Maintenance Template, Terminations and Splices

	Critical Functional Importance				Minor Functional Importance			
Duty Cycle	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Service Condition	**Severe**	**Severe**	**Mild**	**Mild**	**Severe**	**Severe**	**Mild**	**Mild**
Thermography	3Y	3Y	3Y	3Y	AR	AR	AR	AR
Diagnostic Testing	6Y	6Y	6Y	6Y	AR	AR	AR	AR
Total Replacement	AR	AR	AR	AR	AR	AR	AR	AR

Y, years; AR, as required. Refer to specific application notes for each PM task.

5.2 General Precautions

The PM Basis Database program assumes that the cables are initially in nominally good condition. Cables that have not been serviced for a long time might require that an inspection be performed and remedial action be taken before this program is applied.

The expert panel felt that there was sufficient cause to perform tasks with intervals as close as possible to the intervals indicated in the template unless specific means are used to add confidence that a more extended interval can be used (such as visual inspection, maintenance history, or as-found conditions). Deferral of any task requires an evaluation. One evaluation method would be to compare, using a sampling process, the candidate cable’s maintenance history and as-found condition to those of other cables with similar specifications and operating conditions. If the component operates in severe service conditions, the specific conditions must be considered in order to select appropriate intervals.

If there are specific conditions (that is, one or more columns) for which no PM task is appropriate, it is considered to be run-to-failure. Run-to-failure is a maintenance option for only those noncritical cables that meet all the following conditions:

- The cable is not required for vital system redundancy.
- The cable's failure does not promote failure of other components.
- It is more cost-effective to repair or replace the cable after failure than to do PM.
- There is no simple, cost-effective task to maintain the cable.

Existing regulatory requirements should always be followed. If the recommendations in this section differ from regulations, the more conservative approach should be followed.

5.3 Use of Vendor Recommendations

The information and recommendations contained in this report should be used in conjunction with recommendations provided by the original cable vendor. The basis for departures from vendor recommendations must be carefully considered and documented. The information in this report should enable decisions involving departures from those recommendations to be made with a greater awareness of the specific failure causes that are involved and the indications of degradation that can show whether the decision was appropriate as time passes. A specific PM task might address many failure causes that are also addressed by other tasks. This can provide for overlapping between tasks that can make such decisions less critical by the adoption of compensating actions.

5.4 Determination of Task Intervals

The general PM task intervals suggested in this report should be determined and adjusted by each utility based on individual experience and vendor recommendations. Intervals provided in the template are suggested starting points for this process, although in general, if these tasks are already being performed, the existing intervals could be used as the starting point if a basis exists for them. Such a basis could be constructed from condition assessment data, past inspection data, failure history, and information in this document.

It is prudent to change time-directed intervals in the search for intervals that are short enough to protect against unacceptable equipment deterioration but not so short as to waste maintenance resources or to introduce unnecessary sources of maintenance error. When selecting time intervals for intrusive PM tasks, it is not necessarily conservative to select shorter rather than longer time intervals in a possible range. Shorter intervals expose the equipment to more opportunities for maintenance error and to the potential for maintenance-induced damage.

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