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Guidelines for Intelligent Asset Replacement

Volume 3-Underground Distribution Cables

Technical Report

Guidelines for Intelligent Asset Replacement

Volume 3–Underground Distribution Cables

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REPORT SUMMARY

Greater pressure from both customers and regulators to maintain and enhance service reliability, while at the same time controlling costs, has put many utility distribution businesses in a classic dilemma of conflicting objectives. For that reason, asset management has become an increasingly important aspect of corporate business strategies. A significant focus of EPRI's asset management research in recent years has been to develop a rational basis for selecting repair or replacement options for specific classes of equipment by balancing the risks of equipment failure against the costs of continued maintenance or capital replacement. EPRI's *Guidelines for Intelligent Asset Replacement* series provides methods for making decisions about aging assets in electric distribution systems. Volume 3 focuses on underground distribution cables. EPRI plans to continue this research in order to improve the specificity, precision, and scope of these guidelines and to extend them to other classes of assets.

Background

For many utilities, particularly those focusing on the power delivery business, their underground cable inventory represents a substantial asset. Managing this inventory entails significant costs and directly affects the reliability of electric service. Thus, utilities need cost-effective strategies for maintaining their underground distribution assets.

Objective

To provide analytical tools, information, and guidance on developing economic strategies for managing underground distribution cables.

Approach

EPRI has developed a decision framework that enables utilities to generate business cases for asset management policies. This framework takes a life-cycle costing approach that permits corporate financial managers and regulators to assess the multi-year financial impacts of maintaining specific classes of power delivery infrastructure assets, such as underground cables.

The analytical tools presented in this report share a basic framework for decision-making that specifies the evolution of the condition of the asset population over time, various decision alternatives available, including testing, and basic data needed to support the decision model.

The decision framework represents the dynamic process of underground cable deterioration mathematically, using a set of equations that provide a forecast of future deterioration. The dynamic equations describe the evolution of cable condition probabilistically. Given the current cable state, the equations specify the probability distribution of states in which the cable might be observed the next time it is inspected. The model of underground cable condition developed in this report depends upon what types of data are available for decision-making.

Results

This report describes a set of analytical models for dealing with the complexities of underground cable management decisions. This framework is valuable for several reasons, namely it

- Systematically and logically captures the interrelationships among factors that influence the cost-effectiveness of cable management policies
- Identifies key information needed for making good decisions
- Provides an objective way to choose among decision alternatives
- Permits calculation of the cost and performance consequences of cable management policies
- Facilitates evaluation of the benefits of different test protocols

EPRI Perspective

EPRI has been advancing distribution planning since 1992, developing methods, software, and equipment failure data to aid companies in formulating economic asset management strategies. Such strategies must meet customer needs for reliability and power quality at least cost. The goal of this project is to use the information, tools, and experience developed in EPRI's asset management research to deliver general guidelines and strategies for managing specific equipment categories – in this case underground distribution cables – based on knowledge assembled in previous years' work.

Keywords

Asset Management
Distribution Systems
Underground Cables
Aging Assets
Equipment Repair and Replacement
Reliability
Distribution
Reliability Analysis

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INTRODUCTION

Utilities today face the twin challenges of satisfying increasingly high standards for reliability and service quality while at the same time reducing costs and improving earnings. To meet the challenges, utilities are adopting *asset management* as their framework for allocating capital and operation/maintenance budgets. Simply stated, asset management consists of decision-making processes that have the goal of deriving the most value from utility assets within the available budget.

For many utilities, particularly those focusing on the power delivery business, their underground distribution cable inventory represents a substantial asset. Managing this inventory entails significant costs and directly affects the reliability of electric service, since cable failures can lead to lengthy and widespread outages. Thus utilities need cost-effective strategies for maintaining their underground distribution assets. The purpose of this report is to provide analytical tools, information, and guidance on developing economical strategies for managing underground distribution cables.

Among the asset management decisions that arise in dealing with underground cables are the following:

- Choosing the type and size of cable (e.g., PILC, XLPE, XILC; 1000 kcmil, 750 kcmil, 500 kcmil, 1/0, 2/0, etc.) and the initial installation (e.g., direct buried, in cable trays, near other underground utility conduits, etc.) for new underground distribution cable installations;
- Determining how frequently to inspect or test cable segments and what types of inspections or tests to perform (e.g., tan-δ, withstand, etc.);
- Determining which segments to repair and what repairs to apply to individual segments (e.g. silicon injection, etc.);
- Determining when to replace underground cable segments.

Of course, these issues are closely related, so that deciding, for instance, to use a certain type and size of underground cable, and to install the cable in a particular way, can affect the frequency of inspections, tests, repairs, and replacements. Thus, balancing the many factors that influence the overall cost and reliability impacts of underground distribution cable management strategies forms a complex, multi-faceted decision problem.

This report describes a set of analytical models for dealing with these complexities. This framework is valuable for several reasons:

- It systematically and logically captures the interrelationships among the factors that influence the cost effectiveness of underground distribution cable management policies.

- It identifies the key information needed for making good decisions.
- It provides an objective way to choose among decision alternatives.
- It enables calculating the cost and performance consequences of underground distribution cable management policies.

Basic Framework for Decision-Making

The analytical tools presented in this report share a basic framework for decision-making that specifies the evolution of the condition of the cable inventory over time, the various decision alternatives that are available, and the basic data needed to support the decision model. This section summarizes that framework. (Previous EPRI reports also discuss the basic methodology, including *Guidelines for Intelligent Asset Replacement, Vol.1* 1002086, *Guidelines for Intelligent Asset Replacement, Vol.2, Wood Poles* 1002087, and *Cable Reliability Management Strategies* 1002257.) The following are the elements of the decision framework:

- Objective
- State definitions and dynamics
- Test definitions and accuracy
- Decision alternatives and policies
- Data requirements

Objective

The objective in this decision framework is to minimize the lifecycle cost of maintaining the underground cable inventory, subject to serviceability requirements. The lifecycle cost comprises the total of the installation, inspection/test, repair, and replacement costs throughout a multi-year time horizon, all taken on a present value basis. The serviceability requirement means that cables segments that fail or do not meet the minimum standards (e.g. for withstand voltage) must be replaced or repaired.

Dynamic Behavior: Deterioration and Hazard Rates

The dynamic behavior of underground cable is based on the idea of deterioration. Over time, the condition of an individual underground cable *segment*—typically from manhole to manhole—may deteriorate as it experiences thermal loading, environmental damage (including water contact), animal activity, and other factors. The rate of deterioration depends on the cable type, the initial installation, as well as on the occurrence of these influencing factors, and it also can be retarded by some remedial maintenance activities. The decision framework utilized in this report represents the dynamic process of cable deterioration mathematically, using a set of equations that provide a forecast of future cable conditions. The forecast depends on the present condition of the cable segment. For example, the condition of an *extruded* cable is a pair of values that specify the condition of the insulation (e.g., *no degradation, mild degradation, moderate degradation*, *severe degradation*) and the condition of the neutral (*good, moderate loss, severe* *loss*). For *paper-insulted lead cable (PILC)*, only the condition of insulation is modeled. However, the condition of underground cable segments is usually not directly observable, and therefore, although condition influences the value of various decision alternatives, the condition cannot be associated with an individual segment with certainty.

In general, information summarizing what is known about an underground cable segment is called its *state*. The condition is an unobservable part of the state. The state may include other information as well, including the cable's age and the results of any tests performed on the segment. The importance of the state variable is that it contains information about the segment that is sufficient to forecast its future behavior.

In this report, the observable state of an underground cable segment has two components. The first component represents its age. The second component of the observable state is the number of previous failures of the cable segment. These state components have been chosen because, based on prior experience, they provide a reasonable basis for deciding among the various courses of action available for underground distribution cables. Assume that these two components of the state are known at any time for all cable segments.

Generally speaking, with current technology the condition of individual underground cable segments is not monitored continuously. Thus, the decision framework does not represent any formal inspection procedure (in contrast to overhead distribution systems, for which utilities often have regular inspection programs). However, it may be possible to test a cable segment because its observable state suggests that the cable segment may have an elevated risk of failure. Therefore, whether or not to test is a *decision*, a part of the overall asset management policy for underground distribution cables.

Expanding on this idea, the decision framework developed in this report represents the decisions regarding testing, repair, maintenance, and replacement as depending on the state of an underground cable segment. The specification of a decision for each cable state is called a *policy*, so the decision framework develops a *state-dependent policy* that *minimizes the lifecycle cost* of maintaining the cable population.

In general, as noted above, the evolution of the cable state cannot be predicted with certainty; that is, the deterioration of a cable segment is subject to random influences. This fact implies that the dynamic equations must describe the state evolution probabilistically – given the current segment state, there will be a probability distribution of states in which the segment might be observed at some future time. The random evolution of the state results from three factors:

- The insulation and neutral degradation processes proceed randomly. Furthermore, even if the state of an underground cable segment were known with certainty at some point in time, over time these random influences would destroy that knowledge.
- The state does not completely capture the current condition of an underground cable segment because some aspects of the condition cannot be observed directly. For instance, neutral degradation usually has no visible manifestation and testing methods for neutral degradation may not detect it until such degradation is far advanced. This incomplete information results in uncertainty about the current condition that in turn creates uncertainty about the future evolution of the state. If degradation is present but not detected, the probability of failure at

some future moment must include the probability that degradation at some level was present, but not detected, at the present time.

- The state does not necessarily represent all aspects of an underground cable segment's history relevant to predicting its future evolution. That is, choosing a representation of the state is a design decision within this analytical framework. Usually, the amount of information that the state can represent is limited, for two reasons. First, the amount of information in a utility's records is limited for reasons of cost or practicality. For instance, a utility may record only the most recent inspection of a cable segment and not its entire history. Second, a complex definition of the state can make the dynamic equations mathematically intractable. The more information that is encoded in the state, the higher the dimension that is needed in the dynamic equations, a phenomenon called the "curse of dimensionality." For instance, even if one could record the entire history of a cable segment, computing a policy based on this information would be impossibly complicated. With limited information encoded in the state, two segments with the same state might in fact have different histories, and differences in their future condition would appear to be random because the information needed to predict them are not available.

The deterioration of an underground cable segment's condition is represented mathematically by a probability distribution called the *hazard function*. The value of the hazard function at a particular age t, called the *hazard rate*, is the probability that a cable segment that has survived to that age does not survive to age $t+1$. That is, the hazard rate at age t is the probability that it will fail in the next year. Figure 1-1 illustrates the general shape of the hazard functions used to model underground cable segment deterioration.

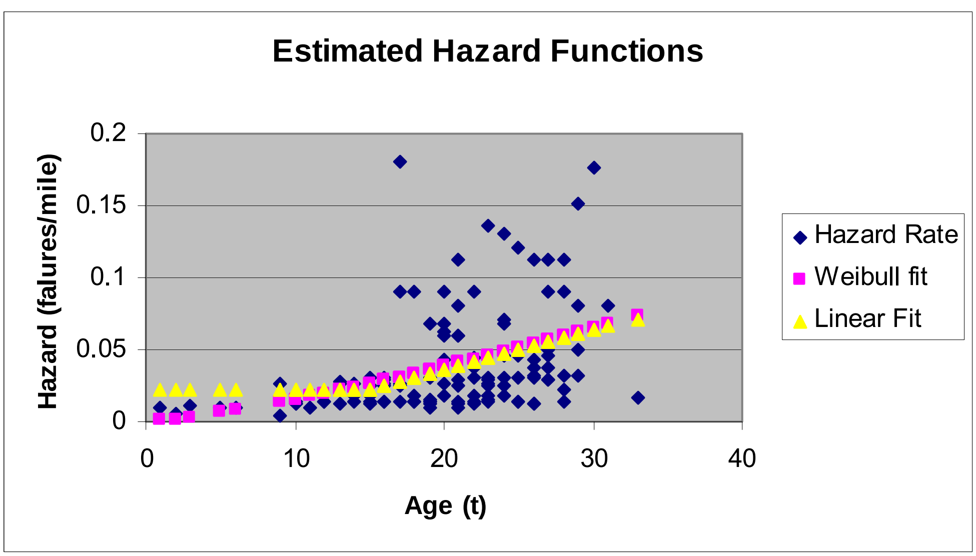

Figure 1-1
Estimated Hazard Functions, Based on Observed Failure Data

The Figure indicates the relationship between the hazard function and the observed data that the function summarizes. The hazard in Figure 1-1 is expressed as the failure rate per mile of cable installed as a function of the age of the cable.

One way to capture the information in the data is to fit the parameters of a hypothesized hazard function to the data. The Figure shows the result of fitting two hazard functions, a piecewise-linear fit, using three parameters—the steady-state hazard rate, the age at onset of burnout, and the burnout rate—and a Weibull function. In this case, both fitted models are relatively close, and they both can only approximate the actual data. Other models that are popular include the exponential hazard function, the lognormal hazard function, and the Normal hazard function. The methodology described in this report can apply any hazard function that the analyst chooses.

In this example, the hazard function exhibits the following plausible behavior. When an underground cable segment is relatively new, the likelihood that it will fail is small and constant. As it ages, it reaches a point at which the failure probability increases more rapidly. This increase continues for the foreseeable future. This behavior has been confirmed by empirical data, as discussed in the report *Medium Voltage Cable Failure Trends*, EPRI 1002256. (In contrast, empirical observations show that other assets, notably wooden poles, experience increasing hazard only to some later age after which the hazard rate levels off again, but at a higher rate than when the asset was new.)

Clearly, the hazard function depends directly on the age of the cable segment, but it also can depend on other components, both observable and unobservable, of the cable's state. Chapters 4 and 5 of this report discuss how to develop good estimates of the failure behavior of underground cable based on observed data.

Unobservable Conditions and Stressors

In addition to observed data, the decision framework permits the analyst to specify two other considerations that affect the failure of underground cables, the dynamics of unobservable condition and the presence of stressors.

Unobservable conditions are levels of deterioration that increase the risk of failure or the cost of maintenance of the underground cable that cannot be directly detected. At present, there are two kinds of unobservable conditions in this analysis, Insulation Degradation Condition (applicable to both PILC and extruded cables) and Loss of Neutral Condition (applicable only to extruded cables). These conditions each have several levels (see Chapter 4, Tables 4-2 and 4-3). In principle, the analyst may specify unobservable conditions arbitrarily, subject to the ability to specify the effect of the unobservable conditions on the hazard function and to specify the likelihood that a cable segment is in any of the condition states as a function of the age of the segment. The main idea here is that the unobservable conditions change over time, and when they change, the hazard rates change. How the unobservable conditions affect the hazard rate can be specified in many ways. The current implementation relies on the ability of the analyst to specify hazard rate multipliers. See Chapter 4, Table 4-4.

Stressors are external influences that may increase the likelihood that an underground cable segment will fail. The definition of a stressor is arbitrary. The present implementation of the decision framework identifies two kinds of stressors, environmental and operational stressors. Generally, environmental stressors represent factors that are beyond the control of the utility, such as moisture or soil conditions, while operational stressors represent factors that are potentially within its control, such as cable loading. Detailed definitions of these stressors are given in Tables 4-5 and 4-6. The analyst must be able to specify the effect of the presence of stressors on the hazard rate. The present implementation expresses this dependency as hazard rate multipliers. See Table 4-7.

Empirical and Judgmental Data

Much of the flexibility and realism of the decision framework used in this report stems from the contributions of expert engineers to its formulation. This expertise is reflected, in particular, in the definitions of the degradation states of cable insulation and neutral, the relationship between degraded conditions and hazard rates, the impacts of stressors on cable degradation and on hazard rates, and the specifications of diagnostic test protocols. These factors represent parameters that must be quantified for use in the decision model. Ideally, one would like to use empirically observed data to estimate statistically the values of the parameters, such as, for instance, the hazard function illustrated in Figure 1-1. However, in many cases, the data that are available are not sufficiently rich to provide a basis for good statistical estimates for many of these parameters.

There are several reasons why existing data may not be sufficient. First, because asset management is a fairly new concept, many utilities did not have a reason collect detailed information to track equipment condition. Even when they did collect data, it was often for other purposes and therefore was not available through integrated databases that facilitate the sorts of analysis required for asset management decision-making. Many utilities are just now converting their legacy data into integrated databases and instituting systematic processes for collecting and validating such data. Second, equipment replacement decisions occur when the equipment reaches the end of its life, and as is apparent from the discussion of hazard functions, equipment behaves quite differently as it approaches that stage than when it is comparatively young. Thus, even though data collection processes are improving, there will be a considerable lag before information tracking the full lifetime of equipment becomes available. Third, gathering certain kinds of data is very costly. For instance, since the condition of an underground cable is not directly observable while it is in service, it would be necessary to decommission a cable and dig it up in order to determine its condition. Furthermore, for the purposes of statistical estimation, it would be necessary to do this for an adequately sized sample of multiple cable segments to give a certain level of statistical precision to the estimates. It would be difficult for most utilities to justify the expense of digging up cables just to provide data for estimating the parameters of a decision model. Finally, the dimensionality of the data increases cost and complexity of the data collection task. Dimensionality means the number of factors that influence a given parameter. For example, consider the hazard rate. It depends on at least the following factors: the cable's age, the number of prior failures, the condition of the insulation and of the neutral (for extruded cable), the presence and degree of one or more stressors, etc. Even with a small number of distinct levels for each of these factors, it is easy to see that dozens of hazard rate estimates would be needed to properly account for all of them. Utility data collection processes are usually not set up to differentiate all of these factors, and even if they were, the required sample sizes would make data collection extremely expensive.

Given the limitations of statistical data analysis to estimate key relationships among parameters of the decision model, use of expert judgment provides an important element of the analysis.

Among the parameters estimated by experts are the differential effects on the hazard rates of the following factors:

- condition states of the cable insulation and the neutral
- environmental and operating stressors
- past failures

In addition, the following parameters have also been estimated by experts:

- the proportion of the cable population in each condition state as a function of age
- the accuracy of test protocols is revealing the true condition of the insulation and neutral.

Essentially, at present, statistical data analysis supports estimating the basic hazard functions with some level of specificity by type; the remainder of the parameters primarily have been estimated by experts. With systematic data collection efforts across the industry, it should be possible in the future to validate the expert judgments with statistical data analysis.

Diagnostic Tests

Diagnostic tests can play an important, though somewhat controversial, role in managing underground distribution cable assets. Because cable condition is not directly observable, diagnostic tests can provide some information about their condition. However, three issues limit the usefulness of tests. First, tests are generally not completely accurate; that is, for instance, a cable segment with no insulation degradation may give a test result indicating some level of degradation and vice versa. It should be noted, however, that even an inaccurate test may provide information useful for asset management decisions (see *Asset Population Management and Testing – Methodology Extensions*, EPRI 1011665). In principle, it should be possible to quantify the level of test accuracy (a subject of on-going research at EPRI), but at present such estimates rely on expert judgment. Second, the relationship between test outcomes and hazard rates is not well established; that is, how much more likely is a 30-year-old cable segment with moderate insulation degradation to fail in the next year than a cable segment of the same age with no insulation degradation? Again, in principle, it should be possible to quantify this relationship (also a subject of on-going research at EPRI), but at present such estimates rely on expert judgment. Finally, testing is costly (and in some cases may cause failure of the equipment). In fact, these three issues are linked together, and the controversy over cable testing is basically a question of whether the value of the information, even if somewhat inaccurate, outweighs the cost of obtaining it. (A fuller discussion of this issue may be found in [1011665].)

The decision framework used in the report models testing using several overall principles. First, whether or not to test is a decision, a part of the overall asset management policy for underground distribution cables. That is, the value of test information depends on the actions one takes based on the test outcome and on the cost savings attainable over acting without doing the tests. Said another way, a test has value only if its outcome would lead to making a different decision, and even then, unless the value exceeds the cost of the test, one should not use the test. Thus, testing is included among the decision alternatives considered by the framework. Second, the decision framework separates specification of the test outcome from the action taken based upon it. This principle stands in contrast to much of the current industry practice, which is to state the test outcome as a recommendation for action, such as, “replace immediately” or “retest in 3 years.” Separating test outcome from recommended action permits optimizing the asset management policy as a function of test outcome, rather than pre-specifying the decision. Third, test outcomes are specified in terms of the condition state they diagnose; that is, test outcomes are reported as, for instance, “the condition of the insulation is moderate degradation.” This specification was chosen because it is fairly easy to understand, it applies across many kinds of tests, and it conforms to another industry practice of rating cable condition on a qualitative scale (typically with 3- or 4-points). Alternatively, one could specify the test outcome as the specific numerical measurement produced by the test; however, it is not clear that this would improve the overall decision model, and it would make it much more complicated. One consequence of this assumption is that test accuracy can be specified as the probability that the test says the condition is X when in fact the true condition is Y, where X and Y represent condition states (see Table 5-11 for the specific way in which test accuracy is specified for the cable condition states). Fourth, the decision framework represents *test protocols*, or test banks, rather than individual tests. A test protocol is a bank of related tests applied to an individual cable segment either at the same time or in succession over a relatively short period of time (say within 2 or 3 years). This representation conforms to current industry practice that takes advantage of the different kinds of information available from different tests (e.g. withstand, partial discharge, reflectometry, etc.) It also allows representing some of the contingent test policies utilities are using, such as retesting within two years to determine how rapidly degradation is progressing. Finally, through the use of test protocols to represent banks of related tests, the decision framework assumes that no other dependence exists among tests done on the same cable segment at different times; that is, the model does not remember the outcome of a previous test bank. This assumption greatly simplifies the state dynamic equations by not requiring them to represent the unobservable state. It is a reasonable assumption under two conditions: i) test intervals are fairly long relative to the speed of degradation, or ii) the action taken as a result of the test changes the cable’s condition so that the previous condition is no longer relevant. However, the representation of test information over time remains an area of possible extension of the decision model, which may have relevance to other kinds of equipment, particularly substation transformers.

Decision Alternatives and Inventory Policies

At any point in time, the methodology assumes that the observable state of a cable segment is known, the unobservable state of the cable is specified by a probability distribution (which is also known), and the asset manager must make a decision about the cable. The methodology permits the choice of the following alternatives:

- *do nothing*, which does not change the state of the cable; doing nothing means that the behavior of the cable is governed by the hazard function given by the current state of the cable—which means that the current state is sufficiently satisfactory so that no intervention need be taken;
- *maintain* the cable, which changes the state of the cable; the single maintenance alternative defined is *rejuvenation*; when a cable is rejuvenated, its unobservable condition is changed favorably; the analyst may define the specific changes; in the present implementation, the probability that the unobservable condition is in the worst state is changed to zero as a result of rejuvenation;

- *repair* the cable, which is mandatory after a failure and which increases the number of prior failures represented in the state; the cost of repair is part of the cost of a failure;
- *test* the cable, which means that further information about the unobservable condition is needed prior to deciding what to do with the cable; the outcome of the test is a claim about the unobservable condition; testing is not perfect, so that the test outcome revises the probability distribution on the unobservable condition, hence the hazard rate is changed, which in turn changes the subsequent decision; the decision is then based on knowledge about the state and the test result;
- *replace* the cable, which means that the present state of the cable was such that the risk of failure was too great to accept (with respect to cost-effectiveness); the cable can be replaced with a like cable or a different cable type; in the present implementation, only a single replacement type is permitted, and a hazard function for that replacement type must be specified if the replacement type differs from the cable under analysis.

By convention, decisions occur at specified points in time during the planning period. In the present implementation, the time between decisions is not a single year. Instead, decisions occur at the beginning of a time period that lasts five years. This is done for two reasons. First, five-year intervals make the computations required for a solution tractable. Second, as a consequence of the fact that there are five years between decisions, we may treat the outcomes of successive applications of the test protocol as independent (note that a test protocol may consist of a bank of individual tests applied during the 5-year period). That is, the outcome of the test bank does not depend on the outcome of the previous application. This has two important consequences. Not only does this make the description of the asset state simpler, because it is not necessary to remember the results of previous test banks, but also it relieves the analyst of the burden of specifying the conditional behavior of a sequence of test banks applied at intervals greater than five years.

A *policy* is a complete specification of what decisions to make at each decision point in the planning period (or, in the present implementation, at the beginning of each five-year interval) as a function of the state of the cable. The methodology determines the least cost policy over the indefinite future that makes the same decision for a cable state regardless of what time in the planning period the decision is taken. This is called a *stationary policy*. The least cost stationary policy is the solution to the asset management problem.

Ideally, the optimal stationary policy would be implemented immediately. The practical consequences of such an implementation typically include replacing a relatively large fraction of the inventory because of its age or previous failure history. These replacements may exceed the available annual budgets. Therefore, the *transient* policy can be followed. The transient policy is a sequence of replacements and other decisions that does not violate the budget constraints and transfers the inventory from its present condition to the optimal steady-state inventory with least exposure to failure consequences. A method to specify a transient policy is presented in the report 1011665.

Specifying a Case for Analysis

In addition to specifying the hazard function, the methodology discussed in this report is based on a collection of user inputs that describe the behavior of underground distribution cables, the economics of underground cable, and the decisions that can be made with respect to the inventory of cable. The inputs are listed and described below.

- Cable Type. A cable type comprises a group of cables that are treated the same way from a modeling perspective; that is they all have the same conditions states, hazard functions and other parameters, the same testing and decision alternatives, and the same costs. The decision model discussed in this report treats a single cable type; multiple cable types require multiple runs of the decision model. Specifying a cable type requires striking a balance between the need to develop different policies for individual kinds of cables and availability of data to differentiate among them. With very limited data, one could treat all underground cables as a single type, but this may mask very important distinctions. Alternatively, treating various combinations of insulation, conductor size, and voltage as different cable types may require either a very rich data set or an elaborate set of expert judgments to create different hazard functions and other parameters. The notion that costs are identical for all cables of the same type also plays a role in the specification of cable types. In the present methodology, failure costs measure the impact of outages both to the utility and the customer, and some analysts may want to distinguish among cables according to the type of customer served. This requires setting different failure costs for different classes of customers. Therefore, the different cable types are specified according to the class of customer served, if such distinctions are important for cable management decisions.
- Inventory. The amount of installed cable (in miles, segments, or feet) as a function of cable age and number of past failures must be specified. In each analysis run, only a single cable type can be considered. The analyst specifies the cable types. Some of the considerations that influence the specification of cable types are the following.
- Hazard Function. The hazard function for the cable inventory must be specified. Often, data is available to help estimate the hazard function.
- Unobservable states must be defined. The effect of the unobservable state on the hazard function is given as a multiplier, which must be specified. The probability distribution on the occurrence of the state as a function of the cable age is required.
- Stressors can be defined as needed. The effect of the presence of stressors on hazard rates is given as a multiplier, which must be specified.
- Tests. Specified tests report on the level of an unobservable condition. The accuracy of the test must be specified as a likelihood function. (See Chapter 4 for further discussion of test likelihoods.)
- Economic data are required.
  - Failure Cost. The cost of a failure, not including the cost of replacing any failed equipment. The failure cost measures the impact of an outage both to the utility and the customer. The failure cost typically includes the direct cost to the utility of a failure, plus any indirect costs that may arise from a failure, as well as the imputed cost to the customers served when an outage occurs (see *Customer Needs for Electric Power*

Reliability and Power Quality: EPRI White Paper. 1000428). Therefore, the failure cost can vary greatly by cable type. It is reasonable to expect that this parameter will be very influential in determining the optimal policy. In particular, with higher failure costs, decisions to replace or refurbish cables would typically occur at younger ages, resulting in a lower annual aggregate number of failures and higher reliability. The analyst will almost surely want to determine the sensitivity of the optimal policy to changes in failure cost.

  – Replacement cost, maintenance cost, testing cost. These are costs associated with their respective decisions. They are each expressed as single amounts.
  – Condition occupancy costs. If the presence of a condition, such as degraded neutral, adds to the operating cost of the inventory, it must be identified. This cost measures the consequences to the utility if the underground cable is in such a condition. In the present implementation, when extruded cable experiences moderate or severe neutral corrosion, there is an added risk of damage if a fault occurs. The cost represents the expected damage should a fault occur. Avoiding or delaying this cost is a benefit provided by the replacement and the maintenance decisions.
  – Discount rate. The methodology minimizes the net present value of the inventory policy.

- Decision Consequences. In general, what a decision does to the state variable must be given.
  – Replace. Provides a new cable, age = 0, past failures=0, unobservable conditions = new.
  – Rejuvenate. Changes unobservable conditions as the analyst specifies. Typically, rejuvenation reduces or eliminates the likelihood of the worst unobservable condition states. Cables are rejuvenated if the neutral conductor is in good condition and water tree degradation is observed by diagnostic testing but there are no detectable local defects, i.e., the insulation degradation is moderate. Rejuvenating cables restores the insulation condition to mild deterioration.
  – Test. Provides further information about the unobservable states. The probability distribution on the unobservable states is revised conditional on the test outcome. The analyst specifies the test accuracy.
  – Do Nothing. No change in the state.

This completes the list of inputs.

Contents of this Report

This introductory Chapter discusses the motivation for developing decision models for managing underground distribution cable assets and provides an overview of the technical approach.

Chapter 2 generally describes the basic components of decision models for managing underground distribution cable assets: how to represent the condition of cable and the outcome of decisions (do nothing, maintain, test, and replace) applied to underground cable.

Chapter 3 describes how to represent mathematically the dynamics of cable degradation and the effects of decisions applied to cables. In this Chapter, the dynamic decision model is formulated.

The decision model describes how the cable state evolves in response to various degradation factors and how decisions affect the cable state.

Chapter 4 discusses estimating the hazard functions used in the dynamic decision model. Procedures are given for estimating piecewise linear and Weibull hazard functions.

Chapter 5 discusses estimating other critical parameters of the decision model using expert judgment.

Chapter 6 presents an example that illustrates the methods discussed in Chapter 4 that can be applied to estimate hazard rates for cable.

Chapter 7 presents representative results using the decision model to develop testing and replacement strategies for underground distribution cables.

Chapter 8 suggests several additional lines of research with the aim of improving the applicability of the methodology discussed in this report to cable management.

Appendix A, written by John Densley of ArborLec Solutions, is a technical description of medium-voltage underground cable, the kind addressed by this model. It describes underground cable types, the failure mechanisms of the cable and the diagnostic tests that can be applied to underground cables to draw inferences about the actual condition of the cable.

2
REPRESENTING UNDERGROUND CABLE CONDITION AND THE RESULTS OF REPLACEMENT, MAINTENANCE, AND TESTING DECISIONS

This Chapter generally describes the basic components of decision models for managing underground distribution cable assets: how to represent the condition of underground cable and the outcome of replacement, maintenance, and testing decisions applied to underground cable.

State Variables for Underground Cables

The *state* of an asset such as an underground cable is the collection of information about the asset that is sufficient to predict the asset's condition in the next time interval. Choosing the definition of states is a design decision within this analysis framework, and there may be a number of useful, alternative definitions. There are four considerations that apply to the definition of the state:

1. First, the state is descriptive. It contains sufficient information about the asset at any time to describe the relevant aspects of its condition at that time. For instance, the underground cable state might include information about the presence of insulation degradation or about the past treatment of the cable segment.
2. Second, the definition of the state is not unique. The choice of state variable depends on several things, including what information is available about the asset's condition, what information is needed to predict the future evolution of the its condition, and how the evolution of condition is represented. That is, given two different mathematical models of asset condition, the same asset can have different state representations.
3. Third, the state is dynamic. The state of an asset such as an underground cable changes over time, as external conditions change or as the asset responds, as it ages, to the external conditions it encounters. For instance, a cable segment that does not reveal evidence of insulation degradation in the current state has a non-zero probability of experiencing insulation degradation the next time it is inspected or tested.
4. Fourth, the entire state of an asset need not be directly observable. In that case, tests and other observations may permit inferring the occurrence of unobservable components of the state as a consequence of what is observed. For example, since insulation degradation is usually not directly observable, a partial discharge test might allow an inspector to infer its presence.

Some asset characteristics do not change with time, such as its location, size, manufacturer, and year installed. These constant characteristics do not need to be represented in the state; rather, a separate decision model is formulated for each subcategory or type of cable. That is, as discussed in the introductory chapter, a cable type comprises a group of cables that are treated the same way from a modeling perspective; that is they all have the same conditions states, hazard functions and other parameters, the same testing and decision alternatives, and the same costs. The dynamic equations treat a single cable type; multiple cable types require multiple runs of the decision model. This separation into cable types reduces the complexity of the state description and the dynamic equations without severely limiting the kinds of testing/ maintenance/ replacement policies that can be considered. Henceforth, it is assumed that the state description and dynamic equations refer to a single type of underground distribution cable, defined by its location, size (#2AWG, 500 kcmil, etc.), voltage, and other installation conditions. If information is not available about these characteristics, then underground cable of all types can be considered together in a single set of dynamic equations.

The simplest, and essential, state variable for a cable segment is its age. If more is known about the cable, then the state can include further information, such as the failure history of the segment. These are observable components of the state, and we restrict the observable state to the pair (age, number of past failures). Thus, we will develop policies that will indicate what action to take if, for example, a 500 kcmil cable is presently age fifteen years and has failed once previously (although we will not capture the time since the most recent failure).

The fundamental modeling assumption associated with the state definition is that *all assets in the same state at a given time evolve the same way in the next time interval*. This assumption does *not* mean that the future state of all cable segments sharing the same initial state will be the same. The future state for any segment is the result of degradation processes that evolve probabilistically. Hence, the current state specifies the *probability distribution* of the future state of a segment. Thus, the fundamental assumption means that the probability distribution of the future state is identical for all cable segments having the same initial state.

This fundamental assumption has implications for the way the states are defined. Characteristics of underground cable that would cause differences in the future evolution of their condition must be captured in the state definition. Conversely, limiting the amount of information contained in the state (which is frequently necessary to make the dynamic equations tractable mathematically) limits the ability of the model to differentiate future condition evolution among cable segments. That limitation is not necessarily a bad thing, since it may reflect the unavailability or costliness of data needed to differentiate condition states. However, it does imply that sound engineering judgment needs to be applied in formulating the model of asset condition evolution, to balance the degree of specificity with the availability of data and the tractability of the calculations.

Managing the population of underground distribution cables requires making decisions about what to do with individual cable segment, such as: do nothing, test, repair, rejuvenate, or replace. The state must contain sufficient information to determine the evolution of the state that results from making a decision about a particular segment. For instance, a state-dependent decision for a segment might take the form "if a 1000 kcmil cable is less than 30 years old and a partial discharge test detects moderate insulation degradation, replace the segment." In addition, the cost of that decision may be a function of the present state. For instance, the cost of rejuvenation might depend on the age of the cable segment. However, such dependency has not been implemented in the present version of the methodology, in part in order to make the data requirements as simple as possible.

The definition of the state thus has fundamental implications for the economic analysis of alternative maintenance policies. The fundamental assumption implies that all cable segments with the same state will be managed the same way; that is, the underground distribution cable management policy is *state-dependent*. Hence, given the dynamic equations governing the evolution of the state and given a cable management decision policy that is a function of the state, the lifecycle costs of the management policy can be calculated. Therefore, in principle, it is possible to find the management policy that has least cost by determining the state dynamics associated with any policy. That idea is fundamental to the methodology presented in this guidebook.

State Dynamics

As discussed in the introduction to this report, it is usually not practical to develop a maintenance policy for each underground cable segment individually. Instead, the dynamic equations represent the evolution of the entire cable inventory. In particular, define an array to represent the population of cable segments as a function of the state variables. Let $X(s)_k$ = underground cable population that is in state s at time k; call the population in a particular state a *cohort*.

The subscript k indexes chronological time, measured in years, during the analysis period, which is can be represented as the interval $\lfloor 0, T_f \rfloor$, for some arbitrary number of years, T_f, called the *planning horizon*. The state s, as discussed above, can be any collection of information that is sufficient to describe the cable and to determine the state evolution in the next period.

The dynamic equations mathematically describe how the cable population evolves over time. The next Chapter discusses the dynamic equations in detail. Generally, there are four important aspects of the formulation. First, the distribution of cable population among the states in the next year is a function of the current distribution. For instance, in the simple case that the state is the segment's age, and underground cable does not fail, the population at age t in year k equals the population at age $t+1$ in year $k+1$

$$X(t+1)_{k+1} = X(t)_k .$$

Second, the migration of underground cable among the states usually occurs probabilistically. Again, let the state s be the age t. Now, if cable segments fail at age t at the rate $h(t)$, then the surviving population of age $t+1$ in year $k+1$ is

$$X(t+1)_{k+1} = [1 - h(t)]X(t)_k$$

The function $h(t)$ is the *hazard rate* for underground cable. The hazard rate is determined empirically, using some generally applicable functional forms. We discuss the estimation process in detail, below (see Chapter 4).

In general, the probability that an underground cable in one state evolves to another state in the next time period is called the *state transition probability*.

Third, the dynamic equations represent the evolution of the entire cable population rather than that of an individual cable segment. In contrast to the dynamic equations that would describe the state evolution of an individual asset, the population dynamics take advantage of the law of large numbers, which states, roughly speaking, that the average behavior of a population that consists of a large number of independent, identical random variables is approximately the average or expected behavior of an individual member of that population. In this case, if the failure probability of an individual cable segment at a given age is $h(t)$, then $h(t)$ is the fraction of the population at that age that will fail and the remaining fraction $1-h(t)$ will survive. (Recognize that the law of large numbers is an approximation, the accuracy of which increases with the size of the population.) Using the population dynamics allows one to compute the state-dependent maintenance policy for the entire population at once, whereas using the individual asset model would require many runs.

Fourth, the migration of underground cable among the states can depend on some *action* taken with respect to a particular segment in a particular state. For instance segments that are to be replaced as a consequence of the state-dependent optimal policy or that have failed may be replaced with new cable, so that the population of new (that is, age 0) segments at the beginning of the next year is the total of the segments of all ages that are replaced in the current period

$$X(0)_{k+1} = \sum_{t>0} h(t)X(t)_k$$

(It may not be obvious that this action, replacement, actually involves a decision. However, a cable segment that is replaced at any period under the optimal policy need not have actually failed in the present period, and even if it failed, it may be repaired rather than replaced. We may interpret the failure rate $h(t)$ in the above equation in two ways, depending on the age of the cable. If the optimal policy indicates that all cable segments of age greater than t^* must be replaced, then $h(t) = 1$ if age $t > t^*$. For segments of age less than t^*, then $h(t)$ is the ordinary failure probability, known as the hazard rate, which we discuss below. Furthermore, another formulation, as noted above, could include a decision to replace or rejuvenate a failed segment, if the number of past failures does not exceed some threshold. The next Chapter discusses the formulation of the mathematical model in greater detail.)

A *decision rule* specifies the action to be taken in a particular state at a given time in the analysis period. Let

$d(s)_k$ represent the decision made at time k for a cable segment that is in state s.

In general, the dynamic equations describe how the underground cable population migrates among the states as a function of the state transition probabilities and state-dependent decision rules. A *policy* is a complete specification of the decision rules used for all possible states s at all times k during the analysis period.

Two kinds of costs can be incurred in implementing a policy, the costs of the decisions themselves and the costs incurred by cable segments in a particular state, called the *occupancy* costs. For example, decision costs could include the costs of underground cable inspection and maintenance. Occupancy costs could arise from handling trouble reports that occur between tests or inspections, which may increase with cable age or changes in cable condition. The dynamic equations determine the costs of implementing a policy.

Inspection, Testing, and Treatment

The purpose of inspection and testing is to determine the condition (that is, the state) of the underground cable segment and thereby decide what maintenance actions to take. In general, the purpose of inspection and testing is to assess the unobservable components of the state of a cable segment. In the present formulation of the methodology, the unobservable components of the state of a segment include the condition of the insulation and the condition of the concentric neutral (for extruded cable). The outcome of a test or a test protocol is assumed to be a claim about the true condition of the cable. The test is imperfect; hence the consequence of the test is to revise the probability distributions on the insulation condition and the condition of the neutral. Prior to inspection and testing, the probability distribution on the unobservable conditions is governed by an age-dependent dynamic process that is specified as part of the input to the methodology.

As the probability distribution of the unobservable components of the state changes, the future behavior of the cable segment changes. In particular, as the insulation condition deteriorates, failure becomes more likely. Therefore, knowledge of the insulation condition can motivate rejuvenation or replacement of the cable. It is the interplay between test results, dynamically changing cable condition, and the costs and consequences of decisions that guides the specification of the optimal underground distribution cable management policy.

There are several modeling and analysis issues that are important considerations with respect to testing. The state description selected must be consistent with the actual test outcomes so that any particular outcome can be expressed as a claim or conclusion about the unobservable state of the cable segment. The typical test result will be a number, perhaps a voltage, or a discharge time, or a power factor, depending on the test. These direct measurements imply something about the condition of the cable. The modeling issue is how best to relate the observed measurement to the state description. In the present implementation, the unobservable state of the cable is assumed to be in one of several qualitative conditions. (More precisely, it is assumed that the cable is in each of the possible states at any age with some probability.) For example, one condition that PILC can be found in is *Mild Insulation Degradation* (see Tables 5-3 and 5-4 for the complete descriptions of the states). For a test that measures degradation, a range of test outcomes must be specified such that if the actual outcome is in that range, then the conclusion of the test is that the cable is in the condition *Mild Insulation Degradation.* Outcome ranges must be specified such that any possible test outcome corresponds to a single cable condition.

The analysis issue is to specify the accuracy of the test. The accuracy of the test is given by its *likelihood function*. The likelihood function of a test is the probability that the test indicates that the cable is in condition X when it is truly in condition Y. This is a conditional probability. The conditional probability of the occurrence of an event X given that the event or condition Y is known is written p{X|Y}. We use the notation {“X”} to indicate the event that the test result indicates that the cable state is X. The notation is adopted to indicate that the test is making a claim or a statement about the condition. Thus, the likelihood function of the test is the collection of probabilities p{“X”|Y} for all possible unobservable cable states X (and Y). In particular, the likelihood p{"X"|X}, which is the probability that the test says the cable is in state X when the cable is actually in state X, is the accuracy of the test. (See Tables 5-10 and 5-11 for the descriptions of the test protocols and there likelihood functions.)

The final analysis issue is to specify the revised state of the cable given a test result. This is the conditional probability p{Y|"X"}, which answers the question "How likely is it that the cable is actually in state Y if the test said it was in state X?". This revised probability is found by an application of Bayes' Theorem, which is a well-known result discussed in virtually any text on probability or decision analysis (see; for example, the books by Ross, Raiffa, and Schlaifer.)

In the present implementation, the analyst is asked to specify the likelihood function for each test. As we discuss below, there are expert default values that are available. These default values have been used in the current version of the methodology.

The costs of inspection, testing, rejuvenation, and replacement vary by utility and must be specified as part of the input data for the analysis.

Stressors

The behavior of underground cable also depends on additional considerations that we collect under the heading of *stressors*. There are two classes of stressors, *environmental* (e.g. water, vibration, heat, etc.) and *operating* (e.g. electrical loading). Stressors are important because it is reasonable to suppose that the presence of a stressor can affect the hazard rate (the probability that a cable will fail), the accuracy of a test, and the degradation rates of unobservable conditions (insulation degradation, loss of neutral).

In the present methodology, the stressors are expressed in the simplest way: the stressor is either present or it is not. The effects of stressors on the hazard rate, test accuracy, and the arrival rate of unobservable conditions are specified as part of the inputs to the methodology.

Policy Specification

As noted above, a policy, which is the solution to the underground distribution cable management problem, is a specification of the decision made with respect to cable segments in each state s at each time k, for all states and all times. A policy that makes the same decision for a given state for all times is called a *stationary* policy. The optimal stationary policy is that set of decisions that minimizes the expected present value of the cost of following the policy for the indefinite future.

For example, a simple policy based on the simple state $s = t$, where t is the age of the cable segment, is to replace a segment when it becomes ten years old and do nothing, not even test, with any cable that is less than ten years old. (Such a policy is almost surely not cost effective, unless underground cables are very likely to fail when they age beyond ten years, and the cost of a failure of a single segment is approximately the same as the cost to replace a segment – neither of which is likely to be the case.) In the present notation, this is the policy

$d(s)_k$ = *replace*, when $s \geq 10$ for all k, and

$d(s)_k$ = *do nothing*, when $s < 10$ for all k.

Notice that in this simple case, the state variable for the underground cable is its age, which means that nothing else need be known for policy analysis. The decision policy is based only on the age of the cable segment. The decision alternatives are the mutually exclusive but not collectively exhaustive actions *replace* and *do nothing*. The policy is stationary, so that the choice is the same for any period k. Note also that this specification of the policy, combined with the appropriate costs, would be sufficient to evaluate the expected present value of the cost of this policy applied to a population of underground cables if one additional aspect of cable behavior were known – the fraction of underground segments of any age (less than ten years old) that will fail in the next year. This fraction is specified by the hazard rate $h(t)$.

In the cases discussed in the rest of this report, the structure of the problem is virtually the same as suggested in this simple example, but the state variables and the decisions can become far more complex.

As an example of a more complex policy, consider the interaction between cable age and the outcome of a test or test protocol on the unobservable condition of the underground cable. The unobservable condition of the underground cable that is of interest is its degree of insulation degradation. When the insulation degradation condition (which can be either *none*, *mild*, *moderate*, or *severe*) falls below a given level for a cable that is sufficiently old, then the underground cable is replaced. Thus, a test that detects, with some probability, the presence of insulation degradation, will provide information that is sufficient to determine policy.

Thus, the observable underground cable state in this situation is the age of the underground cable and the *outcome* of the insulation degradation test, represented by the pair {age, test outcome}. In the present formulation, we suppose that the outcome of the test can be one of four conditions: {No Degradation Detected, Mild Degradation Detected, Moderate Degradation Detected, Severe Degradation Detected}. Note that the test outcomes are similar to the actual conditions.

The test outcomes are claims about the actual condition, which is unobservable. If the test were perfectly accurate, then when the test makes a claim, the claim is identical to the actual condition. But in most real cases, the test is not perfect and so the test outcome does not perfectly indicate the actual condition. Instead, the test outcome revises the probability distribution on the actual condition, as discussed above.

The decision alternatives are {Do Nothing, Rejuvenate, Replace}. The policy specification can be presented in a matrix that indicates which alternative to adopt as a function of the observed state (see Table 2-1). The Table describes policy regions. For example, if the test result is "None" = No Degradation Detected, then the optimal policy is to do nothing, regardless of age. If the test result is "Mild" = Mild Degradation Detected, the optimal policy is to rejuvenate underground cable that is no more than 25 years old and replace cable segments that are at least 26 years old. If the test result is "Moderate" = Moderate Degradation Detected, the optimal policy is to rejuvenate cables no older than 10 years and replace those that are at least 11 years. The same policy applies if the test result is "Severe" = Severe Degradation Detected. Of course, this policy is only an illustration and does not necessarily correspond to a real policy based on analysis.

Table 2-1
Policy Specification as a Function of Observable State (Age) and Cable Insulation Test Outcome

Insulation Condition Test Result	Underground Cable Age							
	0-5	5-10	11-15	16-20	21-25	26-30	31-40	>41
“None”	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
“Mild”	Rejuvenate	Rejuvenate	Rejuvenate	Rejuvenate	Rejuvenate	Replace	Replace	Replace
“Moderate”	Rejuvenate	Rejuvenate	Replace	Replace	Replace	Replace	Replace	Replace
“Severe”	Rejuvenate	Rejuvenate	Replace	Replace	Replace	Replace	Replace	Replace

3
MODELING UNDERGROUND CABLE DYNAMICS AND MANAGEMENT POLICIES

This Chapter describes how to represent mathematically the dynamics of underground cable behavior with respect to failure and degradation, and the effects of maintenance, testing, and replacement decisions applied to an inventory of underground cable. The dynamic behavior of the cable inventory is captured by the changes in the state of the cable and the behavior of the unobservable conditions. The model developed links the dynamic behavior and the decisions made to the costs of the policy specified by the decision rules. These costs are minimized by the optimal policy.

Optimal Policy Model Based on State Variable Dynamics

The purpose of this model is to specify the optimal stationary policy for managing a population of underground cable. A policy is the specification of the decision made for cable segments in each state *s* at each time *k* for all states and all times. A stationary policy makes the same decision for a given state for all times. The optimal stationary policy is that set of decisions that minimizes the expected present value of the cost of following the policy over the indefinite future.

In this model, the observable state of the cable consists of the pair (t, f), where t is the age of the underground cable, and f is the number of past failures the underground cable has experienced since installation. We treat the underground cable population as made up of segments. The segment size is arbitrary. We typically use 500 feet or a tenth of a mile for the segment size. Most utilities report cable inventory in miles of cable by type. It is straightforward to convert miles to segments. The state variable applies to individual segments.

Define the one-period *hazard rate*,

$h(t, f)$ = the probability that an underground cable segment that has survived until age t, and has experienced f failures since installation, does not survive to age $t+1$. Note that the dependence of the hazard rate on both age and failure history is an empirical question. We discuss how to estimate hazard functions in Chapters 4 and 5.

Let

$X(t, f)_k$ = underground cable population (measured in segments) of age t at time k that have experienced f failures since installation. The subscript k indexes chronological time during the planning period. By our conventions, the population is identified at the beginning of period *k*.

Notice that the pair (t, f), which is the state variable s for this model, is sufficient to identify a part, or cohort, of the underground cable population. All members of the cable cohort with the same state behave dynamically in the same way. Therefore, at any time k, the cable population can be represented as a matrix such that each element of the matrix is the number of cable segments in state (t, f) at time *k*, which we denote $[X(t, f)_k]$ with rows representing ages $t > 0$ and the columns representing the failure history, $0 \le f \le f_{\max}$, where $f_{\max}$ is the maximum number of failures that the model considers. The reason that the number of failures in the specification of the state variable reaches a maximum is because the effect of increasing number of failures on the hazard rate diminishes. In the cable model implementation, the maximum number of failures is two. The assumption is that the hazard rate will not change if the number of past failures increases beyond two.

The state dynamics of underground cable are as follows. A cable segment enters the state *(t, f)* at the beginning of period *k* if at the beginning of the previous period (*k-1*) it was in state *(t-1, f-1)* and during the period *k-1* it failed, or if it was in state *(t-1, f)* and did not fail. That is,

$$X(t, f)_k = X(t-1, f-1)_{k-1} h(t-1, f-1) + X(t-1, f)_{k-1} (1 - h(t-1, f)) . \qquad \textbf{Eq 3-1}$$

A policy for underground cable management indicates when cable segments should be replaced. The policy is specified by the stationary (not time-dependent) decision rule $d(s)$. A typical decision rule specifies that cable should be replaced if its age is at least *t** or the cable segment has experienced *f** failures. For such a rule, we find that the number of cable segments that are replaced at the end of period *k-1* (that is, just before the beginning of period *k*)is

$$\sum_{t \ge t^*} \sum_{f \ge f^*} X(t, f)_k = X(0,0)_k \qquad \textbf{Eq 3-2}$$

which we denote as $X(0,0)_k$ because these are new segments put in service at the beginning of period *k*. One way of thinking about such replacements is that the policy prevents a cable segment that would be in state *(t*, f*)* (or worse) in period *k* from being retained in service for that period.

Condition Dynamics and Testing

At any time, a cable segment can be in one of several unobservable conditions. These conditions, as defined in Chapter 2 (see also Table 4-2 and Table 4-3), are levels of insulation degradation, and for extruded cable, levels of neutral corrosion. The presence of these conditions specifies the hazard function.

Let c_j denote the j^{th} condition.

Let $p\{c_j \mid t, f\}$ denote the probability that a cable segment of age *t* that has experienced *f* failures is in condition c_j. These probabilities are input parameters to the model. It is important to note that in this formulation, the condition of the cable is both dynamic and uncertain (in addition to being unobservable). The dependency of condition on cable age and past failures is typically specified by expert judgment rather than recorded data (see chapter 5). Thus, the condition specification is a forecast of an uncertain variable. In the present implementation, it is assumed that the extruded cable insulation and neutral conditions are independent. That is, knowledge that the insulation degradation is at a particular level does not change the prediction (probability distribution) of neutral corrosion, and conversely. Independence assumptions such as this are typical, not unreasonable, and simplify the forecasting task.

Let $h(t, f \mid c_j)$ denote the hazard rate conditional on the cable segment being in condition c_j. These conditional hazard rates are inputs to the model.

Then the unconditional hazard rate, the hazard rate used in (3-1), is given by

$$h(t, f) = \sum_{c_j} p\{c_j \mid t, f\} h(t, f \mid c_j) . \qquad \textbf{Eq 3-3}$$

Therefore, the hazard rate of an underground cable segment depends on the probability distribution on the (unobservable) condition of the cable.

Although it is not possible to observe the condition directly, the cable segment can be tested for the presence of insulation failure or neutral corrosion. The test reports that the cable segment is in a particular condition, but the test is not perfectly accurate. As we noted in the Introduction (p. 1-8 ff.) and Chapter 2 (pp. 2-5 ff.), we describe the accuracy of the test by the likelihood that the test will report that the cable is in condition c_j when it is indeed in that condition, or the probability $p\{"c_j" \mid c_j\}$, which is written to suggest that the test *says* that the condition is c_j. In order to specify completely the behavior of the test, the likelihood function must be given. The likelihood function indicates the chances that the test outcome, in whatever units it is actually observed, will be translated into a conclusion about the condition of the cable, as a function of the actual cable condition. There are two interesting aspects to this question. First, the actual, or directly observed, test outcome must be translated into a statement about the actual cable condition. Second, the uncertainty associated with the test outcome must be specified. This uncertainty can be thought of as the degree to which the test can make a false identification. We write the likelihood that the test concludes that the cable is in condition c_l when the actual condition of the cable is c_j as the probability $p\{"c_l" \mid c_j\}$. Note that when the subscripts are equal, $j=l$, the likelihood is interpreted as the test accuracy, as stated above. All likelihoods must be specified as inputs to the model.

As a result of the test outcome, the probability distribution on condition is revised. This revision is accomplished by application of Bayes' Theorem, which determines the (posterior) probability that the cable is in state c_j given that the test says that it is in any state c_l:

$$p\{c_j \mid "c_l"\} = p\{"c_l" \mid c_j\} p(c_j\} / p\{"c_l"\} . \qquad \textbf{Eq 3-4}$$

This equation, valid for all states *(t,f)* (so the dependence of $p(c_j)$ on *t* and *f* is not shown in this equation), permits the hazard rate to be updated as a result of the test. Therefore, the test-outcome-based hazard rate can be found:

$$h(t,f\,|\,"c_l") = \sum_{c_j} p\{c_j\,|\,"c_l",t,f\}h(t,f\,|\,c_j)\,. \qquad \textbf{Eq 3-5}$$

Dynamic Decision Modeling

These definitions and equations are sufficient to describe the dynamics of the decision model. At the beginning of any period, *k*, a decision is made. The state of the cable at the beginning of the period is the pair *(t,f)* and the unobservable condition is given by the probability distribution $p\{c_j\,|\,t,f\}$. Based on the state of the cable, a decision is made.

Let this decision be denoted $d(t,f,"c")$.

Notice that the decision function has three arguments, the age of the cable, the number of past failures, and the test outcome. At the beginning of the period, the test outcome is unknown, so the value of this argument is null, ϕ. The result of the decision can be either to replace the cable, to maintain it in some way, to test it, or to do nothing. (In the present implementation, the maintenance decision is restricted to *rejuvenate*. The consequences of the *rejuvenate* decision are restricted to changing the probability distribution on the unobservable condition and setting the failure history component of the state to zero, thus re-initializing it. This, in turn, modifies the hazard rate for the cable through (3-3). Therefore, *rejuvenating* a cable segment reduces the probability that it will fail in the next period.) If the decision were to test, then the test outcome *"c_l"* is revealed, and the third argument in the decision function is known. After testing, the possible outcomes of the decision function are to replace the cable, to maintain it in some way (*rejuvenate*), or to do nothing.

If the decision is to do nothing (before or after testing), then the cable segment that is in state *(t,f)* in period *k* either fails and enters state *(t+1, f+1)* or does not fail and enters state *(t+1, f)* in period *k+1*. This behavior is described by (3-1).

The simplest way to represent the effect of the rejuvenation decision is to identify a cable of less age that behaves, going forward in time, identically to a rejuvenated cable. This identification can be done in at least two ways. Either a specific age change is given as in input to the analysis (e.g., a rejuvenated cable behaves as if it were ten years younger) or changes to the observable and unobservable conditions are given as inputs (e.g., the probability distribution of the condition of a rejuvenated cable is modified such that probability that the cable is in the worst condition state goes to zero, and the failure history is set to zero). These considerations introduce the concept of the *effective age* of a cable segment. The actual age of the cable segment does not change, but if the cable segment is rejuvenated, it is, in effect, made younger. Therefore, if the decision is to rejuvenate (before or after testing), then the cable segment that is in state *(t,f)* in period *k* is changed to a cable segment that is in state *(t',0)* in period *k*, where *t'* is the age state that results from rejuvenation applied to a cable segment of age *t*. (The effect of changing the probability distribution on the unobservable state and reinitializing the failure history is represented as a change in cable age. Thus, *rejuvenation* does what it claims to do in this model.) The rejuvenated cable either fails or does not fail, and enters either state *(t'+1, 1)* or *(t'+1, 0)* in period *k+1*. This behavior is described by (3-1).

If the decision is to replace (before or after testing), then the cable segment state is changed to (0,0). This behavior is described by (3-2).

If the decision is to test, then the result of the test is observed, the hazard function is updated [as described by (3-3), (3-4), and (3-5)], and the decision to replace, rejuvenate, or do nothing is specified by $d(t, f, "c")$. Equations (3-1) and (3-2) apply.

This describes the decisions made in a single period. At the end of the period, which is equivalent to the beginning of the next period, the cable segment state *(t,f)* is known and the unobservable condition probabilities are known, so the identical decision process can be applied.

Costs and Objective Function

The costs associated with the underground cable inventory are the replacement cost, the failure cost, the cost of testing, the maintenance (rejuvenation) cost, and operating costs that are associated with the unobservable states. The last category of cost is presently implemented as a cost associated with the occurrence of neutral corrosion. In general, such a cost is based on the probability of the cable segment occupying any of the unobservable conditions.

Let *R* = the cost of replacing a cable segment. Then the cost of replacements in period *k* is

$$R_k = RX(0,0)_k \qquad \textbf{Eq 3-6a}$$

Let *F* = the cost of a cable segment failure. Then the cost of failures in period *k* is

$$F_k = \sum_t \sum_f \sum_{c_l} FX(t, f)_k h(t, f \,|\, "c_l") \,. \qquad \textbf{Eq 3-6b}$$

Note that if there is no test result, because testing was not chosen, then the conditional outcome is null and the hazard function is given by (3-3) instead of (3-5).

Let τ = the cost of testing a cable segment. Then the cost of testing in period *k* is

$$T_k = \sum_t \sum_f \tau X(t, f)_k d(t, f, \phi) \qquad \textbf{Eq 3-6c}$$

where the third argument in the decision function, which is the test outcome, is null.

Let *V* = the cost of maintenance (rejuvenation). Rejuvenation can be chosen before or after a test is done. There are two terms in the cost of rejuvenation. Then the cost of rejuvenation in period *k* is

$$V_k = \sum_t \sum_f VX(t,f)_k d(t,f,\phi) + \sum_t \sum_f \sum_{c_l} VX(t,f)_k d(t,f,"c_l") \quad \textbf{Eq 3-6d}$$

Let O_{c_j} = the operating cost of a cable segment if it is in (unobservable) condition c_j. Then the operating cost in period k is

$$O_k = \sum_t \sum_f \sum_{c_j} O_{c_j} X(t,f)_k \, p(c_j \mid t,f,"c") \quad \textbf{Eq 3-6e}$$

where the probability distribution on the unobservable condition is modified by the test outcome if testing were chosen.

Then, the present worth of the policy that makes decisions $d(t,f,"c")$ is, for annual interest rate r

$$PV_\infty(r,d) = \sum_{k=1}^{\infty} (1+r)^{-k} [R_k + F_k + T_k + V_k + O_k]. \quad \textbf{Eq 3-6f}$$

The decision problem is to choose the decision rule $d(t,f,"c")$ that minimizes the present value of the policy given by (3-6f). The solution to this problem has been implemented.

Data Required to Support the Optimal Policy Model

The essential description of the behavior of underground cable is the hazard rate function *h(t,f)*. Many utilities have data that can be used to estimate these hazard rates. We discuss methods for estimating hazard functions in the next Chapter.

The consequences of decisions such as rejuvenation must be specified with respect to the state variables. This can be done using actual data or provided by expert assessment.

The unobservable conditions are described by probability distributions $p\{c_j \mid t,f\}$. These are usually provided by expert assessment.

Testing accuracy, given by likelihood functions $p\{"c_j" \mid c_j\}$, are usually provided by expert assessment.

The economic data required are the following.

- The cost of replacing a cable segment
- The cost of failure of a cable segment.
- The cost of testing a cable segment.
- The cost of rejuvenating a cable segment.
- The operating cost if a cable segment is in a particular condition.

These costs can be found from utility records or provided by expert assessment.

4
ESTIMATING HAZARD FUNCTIONS

The previous Chapter presented the dynamic decision model that determines the least cost policy to manage a population of underground cables. This Chapter turns to the issues of data. The model described above requires estimates of parameters in order to perform an analysis. Specifying model parameters usually requires a combination of data analysis and expert judgment, with judgment playing an essential role when data is sparse or unavailable.

There is an important relationship between models and data: it is inefficient and misleading to collect data prior to specifying a model. Ideally, modeling requirements should drive data gathering, so that one does not incur the expense of gathering unnecessary or irrelevant data. In reality, of course, utilities usually have existing data sets that were gathered for any number of reasons. Therefore, in practice, modeling is often formulated to conform to existing data or to available judgment; however, this is not the ideal situation. Even in this situation, though, a model can tell an analyst what data to look for within the existing data sets and how to analyze that data.

As discussed in the previous Chapter, the models require three general types of data:

1. Data to describe the dynamic behavior of the cable segment.
2. Data to describe the failure behavior of the cable segment.
3. Data to describe the economic behavior of the cable segment.

The data requirements vary according to the modeling assumptions and cases, which in turn depend on the state description of the cable and the policy alternatives that are to be investigated, as discussed in Chapter 3. The data requirements for describing the dynamic behavior and the economic behavior of cables were discussed in the preceding Chapter. This Chapter focuses on the issue of describing the failure behavior of cables.

Describing the failure behavior of underground cables is essential when applying the dynamic decision model. As noted above, we seek a hazard function, the probability that a cable segment will fail in the next year, given that it has survived until the end of the previous year. We show in this Chapter how event data can be used to estimate the hazard function.

Overview of the Estimation Method

In developing hazard functions from empirical data, it is important to keep in mind two properties of hazard functions that one expects the estimates to obey. First, the hazard rate is an increasing function of age; that is, underground cables are more likely to fail as they get older. Second, the hazard function is relatively smooth; that is, the hazard rates for age t and $t+1$ are not too different from each other. Furthermore, a hazard function of several variables, such as age and failure history $h(t, f)$, should exhibit these two properties in all other dimensions as well.

In practice, purely empirical estimates of failure rates often fail to behave this way, due primarily to natural, random fluctuations in the data (see for instance, Figure 4-1). These fluctuations may become particularly severe when the underlying data is sparse for a particular age or another explanatory variable, because each individual observation carries more weight when there are relatively few of them. The noise in the estimated hazard rates should not be allowed to drive the treatment/replacement decision. Therefore, some means is needed to filter these naturally occurring fluctuations.

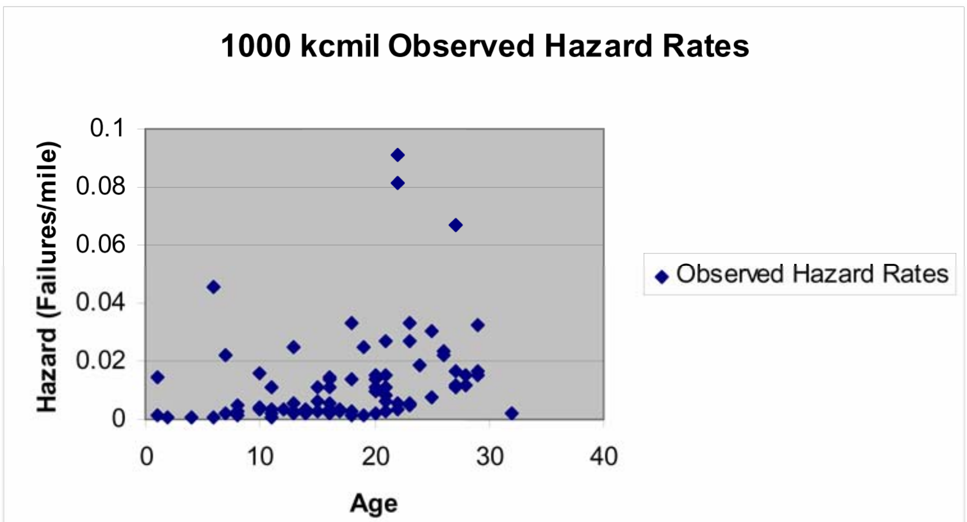

Figure 4-1
Observed Hazard Data for an Inventory of 1000 kcmil Underground Cable

The approach we use to control empirically observed variations is to develop a *model* of the hazard function. An empirical model summarizes the information contained in observed data in a way that is consistent with expectations about the behavior of equipment. In many applications, the observed hazard rate is expressed as a so-called *bathtub curve* (see Figure 4-2). The nature of the hazard rate is that it tends to start out relatively large and decreases during the *burn-in* period, remains constant for an arbitrary time, during the *steady-state* period, and then increase, during the *burnout* period. The burnout period reflects the effect of aging.

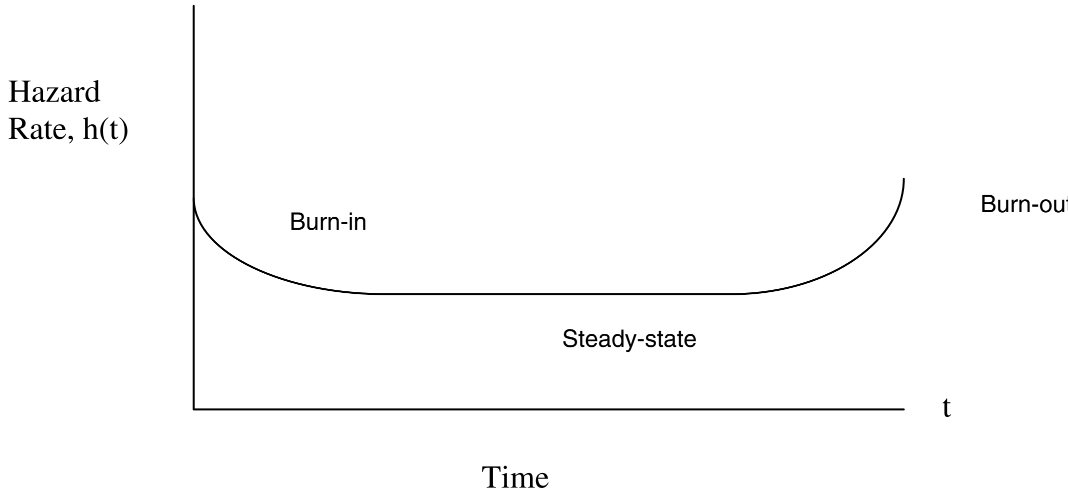

Figure 4-2
Hazard Rate "Bathtub" Curve

Other models specify a functional form for a hazard function that depends on several parameters that can be estimated from the hazard data. Many applications in statistical analysis commonly use a linear regression model, in which a straight line represents the observed data. However, the linear regression model does not represent hazard data very well. We propose alternative approaches, including the use of the piecewise linear model and the Weibull model. These approaches have properties that more closely represent the expected and observed behavior of underground cable failure data.

Cable Failure Models

We distinguish between failure models that are based on statistical life distributions—exponential, normal, lognormal, Weibull, extreme value—and failure models that are purely empirical—the bathtub curve of Figure 4-2 and the piecewise linear hazard rate. The statistical life distributions typically respond to a particular phenomenon or failure mechanism. We begin the discussion with those distributions.

Exponential

The exponential distribution on time to failure is described by the density function $f(t) = \lambda \exp(-\lambda t)$, the cumulative distribution $F(t) = 1 - \exp(-\lambda t)$; and the hazard rate $h(t) = \lambda$. There is one parameter in the exponential model, λ, which is the reciprocal of the average lifetime of the

$$p(k) = \exp(-\lambda t)\,(\lambda t)^k / k!\,, \quad k = 0, 1, 2, \ldots \qquad \textbf{Eq 4-1}$$

where λ is the constant rate of occurrence of peak stresses.

Thus, the equipment will not fail in the interval (0, t) if no peak stresses arrive, which occurs with probability $p(0) = \exp(-\lambda t)$. Hence, F(t), which is the probability that the equipment fails before t, is 1- p(0) which is equal to $1 - \exp(-\lambda t)$, as noted above.

Normal

The Normal distribution is described by the density function $f(t) = (2\pi)^{-1/2} (1/\sigma) \exp(-(t-\mu)^2/ 2\sigma^2)$, which is valid for $-\infty < t < \infty$. The graph of this density function is the familiar so-called bell-shaped curve. The distribution has two parameters, the mean time to failure μ and the variance of the time to failure σ^2. The hazard rate is a monotonically increasing convex function. See Figure 4-3.

The Normal hazard is used to represent the failure of equipment when the number of shocks required to cause failure is greater than one. This is an extension of the exponential distribution. (The mathematical details of this assumption are beyond the scope of this report. Briefly, the main idea here is that another distribution, the gamma distribution, is used to represent the failure time of equipment that fails after receiving r shocks; the gamma is approximated by the Normal; the shocks arrive following a Poisson distribution with parameter λ; and the mean and variance of the approximating Normal are given by the gamma distribution parameters $\mu = r/\lambda$, $\sigma^2 = r/\lambda^2$.)

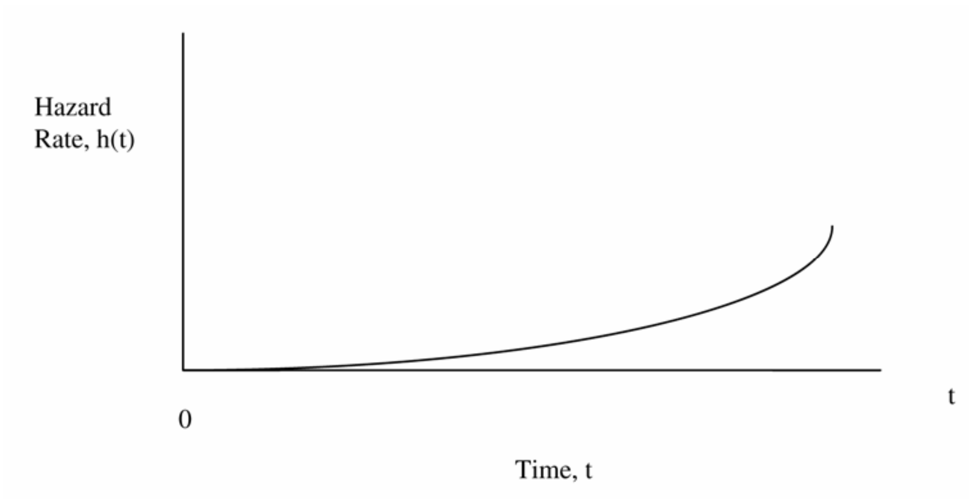

Figure 4-3
Normal Hazard Rate

Lognormal

The lognormal distribution governs a variable the logarithm of which is normally distributed. The distribution is skewed to the right and has a density function that is specified by two parameters, μ, σ, where $f(t) = (2\pi)^{-1/2} (1/\sigma t) \exp(-(\ln(t)-\mu)^2/ 2\sigma^2)$. The mean time to failure is $\mu_{ln} = \exp(\mu + \sigma^2/2)$ and the variance of the time to failure is $\sigma^2_{ln} = \exp(2\mu + \sigma^2) (\exp(\sigma^2) - 1)$.

The usefulness of the lognormal distribution arises from a form of the Central Limit Theorem that states that the product of n independent random variables is lognormally distributed (for large n). The failure process modeled is multiplicative, such that the effect of succeeding shocks on the equipment is proportional to the level of the effect of all preceding shocks. Another application of the lognormal is with respect to repair times, rather than failure times. This is because the hazard function is not monotone and therefore possesses an interior maximum. The lognormal hazard is shown in Figure 4-4.

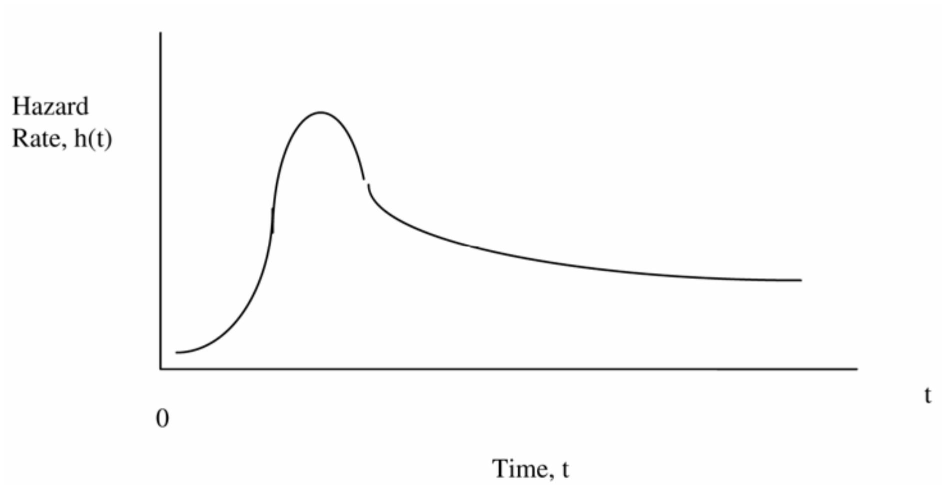

Figure 4-4
Lognormal Hazard Rate

Weibull

The Weibull distribution is given by the density function $f(t) = (\alpha/\beta) (t/\beta)^{\alpha-1} \exp[-(t/\beta)^{\alpha}]$, valid for $t \geq 0$. The cumulative is $F(t) = 1 - \exp[-(t/\beta)^{\alpha}]$. The hazard rate is $h(t) = (\alpha/\beta) (t/\beta)^{\alpha-1}$. The parameters α and β are known as the shape parameter and the scaling parameter respectively. In log-log coordinates, the hazard function is a straight line. Thus, the hazard rate is increasing if $\alpha > 1$, constant if $\alpha = 1$ (and the Weibull becomes an exponential distribution), and decreasing if $\alpha <1$. See Figure 4-5.

The phenomenon modeled by the Weibull is associated with the theory of extreme values. The Weibull is the distribution of the minimum value of a collection of independent observations from a gamma distribution. If a system consists of a collection of components, each of which has a lifetime governed by a gamma distribution (which may be approximated by a normal), and if the system fails when any of its components fail, then the time to failure of the system is the minimum time to failure of any of the components. The Weibull is also robust in that the components may each have somewhat different gamma (normal) parameters, and the minimum is still distributed by the Weibull.

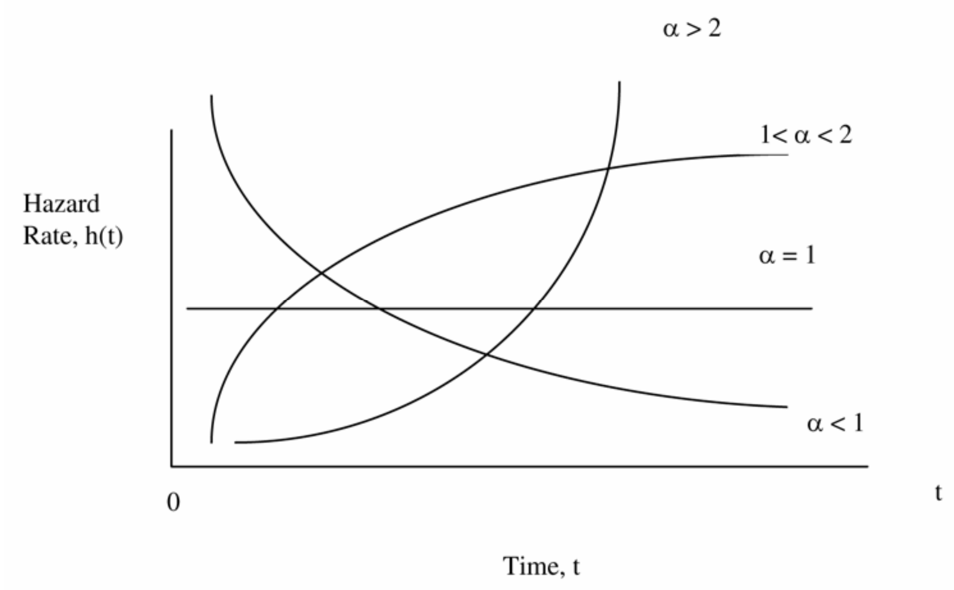

Figure 4-5
Weibull Hazard Rate

Extreme Value Distributions

The Weibull is an example of an extreme value distribution. It is also called a type III asymptotic distribution of minimum values. Also useful are other extreme value distributions, including the type I asymptotic distributions of the maximum and the minimum values. We shall not pursue these distributions in this report. The Weibull appears to provide sufficient modeling capability for capturing the distribution of the minimum. The classic reference for discussion of extreme value distributions is Gumbel (*Statistics of Extre*mes, Columbia University Press, 1958). Abernethy (*The New Weibull Handbook, 2nd Edition,* Dr. Robert B. Abernethy Publisher, North Palm Beach, FL, 1996) provides a good reference for understanding Weibull distributions.

The behavior of the extreme value hazard functions is shown in Figure 4-6. The hazard rate of the asymptotic distribution of the minimum value grows exponentially. The hazard rate of the asymptotic distribution of the maximum value approaches a constant as t approaches infinity.

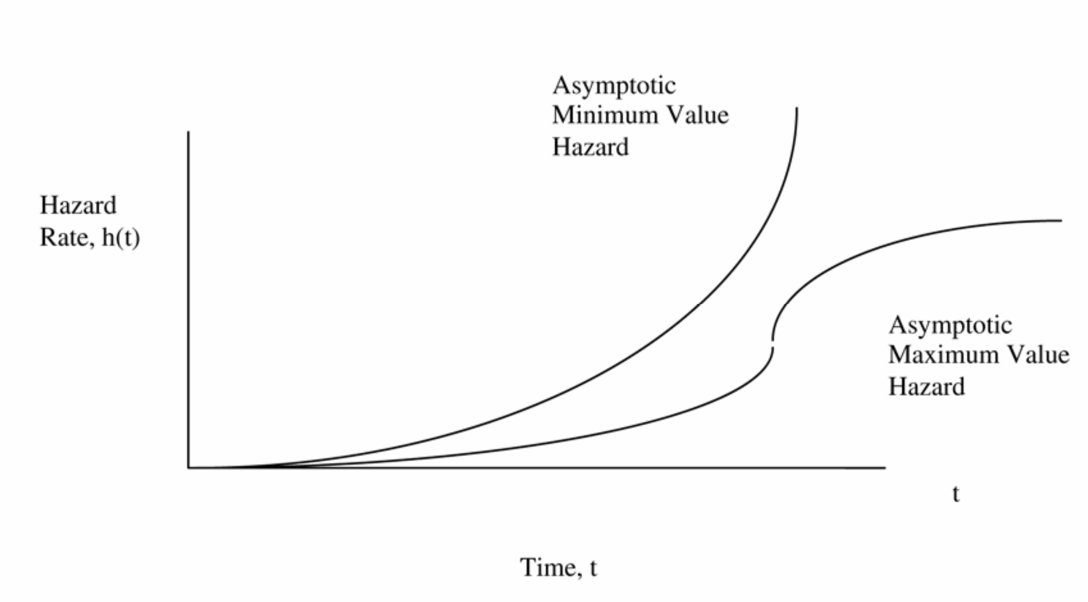

Figure 4-6
Extreme Value Hazard Rate

Empirical Hazard Functions

The empirical hazard functions are not based on any underlying life distribution. (This is a mathematical modeling distinction. The hazard rate is the conditional probability that the asset fails in the next instant of time, given that it survived until the present. If we represent the cumulative probability distribution of the lifetime of as asset by the function F(t), such that the probability that the lifetime is less than t is F(t), then the hazard rate h(t) is given by the equation

$$h(t) = dF(t)/dt[1 - F(t)]^{-1} \quad \textbf{Eq 4-2}$$

where dF(t)/dt = f(t), the probability density of the lifetime of the asset. This implies that the hazard rate is dependent on what is assumed about the life distribution, F(t). The life distributions—exponential, normal, lognormal, Weibull, extreme—are what characterized the hazard functions discussed above, and (4-2) determined h(t). Alternatively, the empirical hazard functions assume a model for the hazard function directly, find the best fit of the data to that model, and then find the life distribution by solving the differential equation (4-2), the solution of which is

$$F(t) = 1 - \exp(\int_0^t h(x)dx). \quad \textbf{Eq 4-3}$$

Bathtub Curve

The bathtub curve, shown in Figure 4-1, is an empirically observed representation of failure for most equipment. The choices for the burn-in and burnout periods are arbitrary. Clearly, the normal, Weibull, or extreme distributions can provide models for the burnout period. Exponential burnout, corresponding to the type I asymptotic distribution of the minimum as shown in Figure 4-6, is a popular form. For underground cable repair/replace studies, we have not found it important to represent the burn-in period. Therefore, we tend not to use the complete bathtub curve model. However, the burnout behavior of the bathtub curve is generally applicable. It is only a matter of choosing the rate of burnout in order to apply the model.

Piecewise Linear Model

A simple approximation to any of the hazard functions described above is the piecewise linear function shown in Figure 4-7. The hazard rate is constant at the steady-state rate h_{ss} until the onset of the burnout period, which begins at age T. After the onset of burnout, the hazard function grows linearly with slope m. Thus, for $t > T$, $h(t) = h_{ss} + m(t-T)$. Therefore, the function is specified by three parameters, h_{ss}, T, and m.

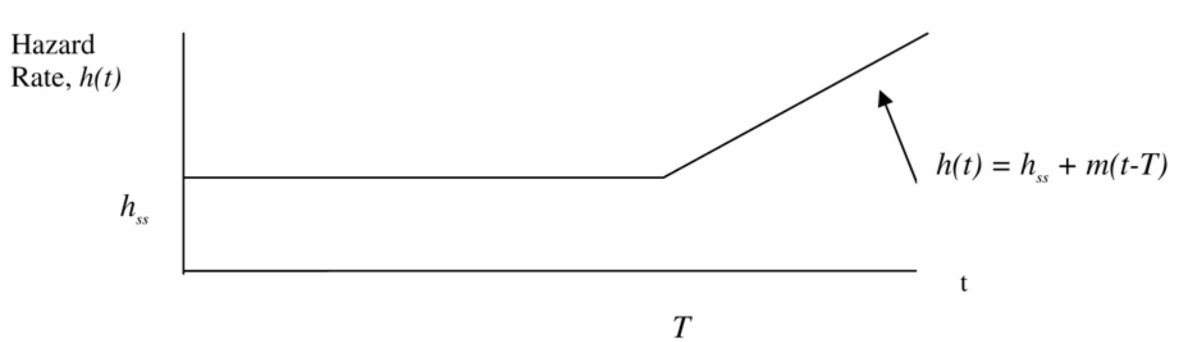

Figure 4-7
Piecewise Linear Hazard Function

Discussion

There are two fundamental ways to interpret the hazard function, as noted above. It can be thought of as a logical consequence of an underlying life distribution, or it can be thought of as the determinant of an empirical life distribution. The mathematical analysis of underground cable does not change depending on which of these interpretations is adopted, but the empirical analysis of utility data can be very different. The difference arises in the role of judgment in the analysis of the data.

The usual procedure for fitting a hazard function derived from a life distribution is to estimate the best values of the parameters by minimizing the sum of the squared errors in the estimate. Thus, a single set of parameter estimates is used for the entire range of data. However, in practice, because of a general paucity of data, it often turns out that the data are not scattered sufficiently over the range of lifetimes to provide a balanced weighting of both the steady-state period and the burnout period. The consequence of this is that the parameter estimates are more responsive to the denser region of the data, typically the earlier or shorter lifetimes, than to the sparser or longer lifetimes. What happens then is that the fit is better where the data is denser. And because the hazard function is completely determined by the parameters, the burnout period may not be accurately represented by the data. In other words, one is stuck with whatever the parameters predict for burnout, but the parameters are determined by the steady-state behavior. This is a weakness that can only be overcome by judgment, whereby the analyst adjusts the hazard function to fit better the actual data, overriding the estimated values of the parameters.

This difficulty tends not to arise in empirically fitted bathtub and piecewise linear hazards. In the piecewise linear case, the analyst typically assigns a value to T, the onset of burnout, and lets the data drive the best estimates of h_{ss} and m, the steady-state hazard and the slope of the burnout period. As we shall see, some form of judgment is required in all cases when the data is extremely sparse.

Estimating the Hazard Function Based on Underground Cable Age

The simplest state description of an underground cable segment is its age. In this case, if age is all that is known about the condition of a cable segment, the state has a very elementary dynamic behavior: the segment ages every year until it is taken out of service. Hence, the basic data for this case is the failure likelihood of a cable segment as a function of its age, that is, a hazard function.

Estimating hazard rates from empirical data in this case uses the following procedure. Identify two time scales in the data, t denoting the age of the cable segment and k denoting the calendar time (e.g., the year 2004). The hazard rate for underground cables of age t observed at time k equals the ratio of the number of cable segment s in service of age t at time k that failed between periods k and $k+1$ divided by the number of segments of age t that are in service at time k. Assuming that the failure process is a stationary one – that is, the hazard rate does not depend on k – then a single snapshot of the cable inventory at a single time k would be sufficient to estimate the hazard function, assuming there are sufficient cable segments of all ages t in the observed snapshot. Generally, however, data can be collected over time, for various times k.

An example of an observed set of hazard rates was given in Figure 4-1. The data presented in the Figure are estimated exactly as described in the paragraph above. Notice that the hazard rates for different ages show considerable variation, not a smooth progression. This variation results from the circumstances that applied in this particular set of underlying failure data, and in particular, the large swings at later ages (20 and beyond) result from the relatively small numbers of underground cables that survive. Therefore, rather than allow these sample-specific fluctuations to drive the analysis, it is preferable to develop a smoother functional representation of the hazard function. One might try to fit a straight line to the hazard data using least squares linear regression. However, the data observed in Figure 4-1 suggests that the hazard function can be better approximated by the two-parameter piecewise linear hazard function described above, shown in Figure 4-7. Another reasonable candidate that summarizes the information in the observed data set might be the Weibull hazard, as shown in Figure 4-5, with parameter $\alpha > 1$.

In the next Chapter, we will provide an example. In the present section, we will describe the steps necessary to estimate a piecewise linear hazard function and a Weibull hazard function from observed data.

Estimating a Piecewise Linear Hazard Function

The estimation problem is the following: given a collection of data describing the failure of underground cable, estimate the three parameters, (h_{ss}, m, T) of a piecewise linear hazard function. We describe the solution in the following steps.

Step 0. Create the data set. The data set will have only two variables for each period k, the age (t) of the cable and the fraction of installed cable of that age that failed in the given year. That fraction may be expressed as failures per foot, or failures per mile, or failures per segment. We may denote this hazard rate as the observed hazard at age t, or $h_{obs}(t)$. As a result of this step, the collection of values $(t, h_{obs}(t))$ are specified. At this point, it is always useful to plot the data, to find a Figure similar to Figure 4-1.

Step 1. Estimate the age at onset of burnout, T. This is estimated by expert judgment and will vary in the analysis until a suitable value is found. A reasonable starting point is approximately 25 years, although the specific data set will suggest a value.

Step 2. Estimate the steady-state value h_{ss} by taking the average of all observed hazards for age $\leq$ T.

Step 3. Subtract h_{ss} from all observed hazards for age greater than T. Subtract T from all observed ages greater than T. These steps create a partial data set that contains all the points observed after onset of burnout. The subtractions express these values as departures from the (*age, hazard*) pair (T, h_{ss}).

Step 4. Estimate the slope m by fitting a straight line to the points with ages greater than T. The straight line must go through the point (0,0) in order to estimate m correctly. (This estimation may be accomplished by using the Excel LINEST command with the restriction that the intercept of the estimated linear function is 0.) This means that the slope found will be the best value of m for the piecewise linear function that goes through the point (T, h_{ss}).

Step 5. Use the parameter estimates to determine the estimated hazard as a function of age. That is, find

$$h_{est}(t; h_{ss}, m, T) = h_{ss} + \max\{0, m(t-T\} \qquad \textbf{Eq 4-4}$$

(where the second term is equal to zero if $t \leq T$ and is equal to $m(t\text{-}T)$ if $T > t$).

Define the estimation error

$$e(t) = h_{est}(t; h_{ss}, m, T) - h_{obs}(t) \qquad \textbf{Eq 4-5}$$

which is the difference between the estimated value of the hazard and the actual observed data. Compute the sum of the squares of the errors, the value $J(T)$, which can be considered a function of the estimated value of T,

$$J(T) = \sum_t e(t)^2 \qquad \textbf{Eq 4-6}$$

J(T) is a measure of the goodness-of-fit of the piecewise linear hazard.

Step 6. Return to step 1. Vary systematically the estimate of *T*. Select *T* that minimizes *J(T).*

Estimating a Weibull Hazard Function

Again, the estimation problem is the following: given a collection of data describing the failure of underground cable estimate the two parameters, (α, β), of a Weibull hazard function. We describe the solution in the following steps. The basis of this procedure is that the Weibull hazard function, $h(t) = (\alpha/\beta)\,(t/\beta)^{\alpha-1}$, can be expressed as $\log h(t) = (\alpha-1)\log t + \delta$, where $\delta=\log \alpha - \alpha \log \beta$. Thus, the logarithm of the hazard rate is a linear function of the logarithm of the cable age. Therefore, the parameters (α, β) can be estimated by the ordinary linear least-squares procedure.

Step 0. Create the data set. This is identical to Step 0 for the piecewise linear hazard function.

Step 1. Apply a logarithmic transformation to the data. Take the logarithm of the age *t* and the logarithm of the observed hazard $h_{obs}(t)$. This creates the data set, the pairs $(\log t, \log h_{obs}(t))$.

Step 2. Estimate the parameters $\alpha-1$ and δ using the linear parameter estimation procedure. (In Excel, this procedure is LINEST.) Find the parameter $\beta = \exp[(\log \alpha - \delta)/\alpha]$.

Step 3. Use the parameter estimates to determine the estimated hazard as a function of age. That is, find

$$h_{est}(t;\alpha,\beta) = (\alpha/\beta)(t/\beta)^{\alpha-1} \qquad \textbf{Eq 4-7}$$

Define the estimation error

$$e(t) = h_{est}(t;\alpha,\beta) - h_{obs}(t) \qquad \textbf{Eq 4-8}$$

which is the difference between the estimated value of the hazard and the actual observed data. Compute the sum of the squares of the errors, the value $J(\alpha, \beta)$,

$$J(\alpha,\beta) = \sum_t e(t)^2 \qquad \textbf{Eq 4-9}$$

$J(\alpha, \beta)$ is a measure of the goodness-of-fit of the Weibull hazard. (If *J* is divided by the number of observations in the data set to create an average, such average values of *J* can be compared to determine relative goodness of fit.)

The Role of Expert Judgment

The state of an underground cable influences the hazard rate. Most utilities will not have extensive failure history for each cable segment. Therefore, the effects of second component of the observable state can generally not be estimated statistically from existing data. Therefore, the effect of failure history on hazard rate must be specified in other ways.

Further, the hazard rate is influenced by the unobservable state variables, the condition variables. Again, most utilities will not have sufficient data on hand to create forecasts for the dynamic process whereby cable condition changes. Nor will data exist that indicates the effect of condition on hazard rate. Therefore, this effect, too, must be specified in other ways.

The approach taken to specifying these additional effects is *expert elicitation*. The process of expert elicitation results in estimates that are not supported by data, and it substitutes for data analysis when data is not present. The next chapter discusses the role of expert elicitation in the methodology.

In particular, the following issues are addressed by expert elicitation.

- The effect of failure history on the hazard rate
- The effect of cable condition on the hazard rate, which includes the definition of the unobservable conditions, the specification of the dynamic process whereby conditions change, and the effect of condition on the parameters of the hazard function
- The effect of stressors on the hazard rate.

Conclusion

This chapter presented methods for estimating piecewise linear and Weibull hazard functions using available event data, that a utility might be expected to have. The methods are based on parameter estimation. The chapter also indicated that the hazard rates also depend upon the other components of the state of the cable, such as the failure history and the condition of the cable (the unobservable state). The expert elicitation that develops these dependencies is discussed in the next chapter. The chapter following the next one presents, in some detail, an example of the procedures for a sample data set.

5
EXPERT ELICITATION

As noted at the end of the previous chapter, the data typically available at a utility is often insufficient to specify the effect of the complete state, both observable and unobservable components, upon the hazard rate. The observable state of an underground cable segment is the pair (age, past failures) = (t,f). It is reasonable to expect that utilities will not have extensive failure history for each cable segment. Therefore, the effect of failure history on hazard rate must be assessed in other ways.

Further, as discussed above the unobservable states must be completely characterized. This characterization includes the following:

- definitions of the unobservable cable conditions
- specification of the dynamics of the unobservable conditions
- effect of the unobservable conditions on the hazard rate.

In addition, because identifying the unobservable condition of a cable segment is the purpose of any test, the accuracy of the applicable tests in terms of the possible unobservable conditions must be specified. Each of these aspects of the unobservable states is assessed by expert judgment.

Also, the specification of various stressors and the effects of the presence of such stressors on the hazard function are assessed by expert judgment.

These results are presented in this chapter.

Expert Elicitation

Most significant decision problems involve dealing with uncertainty. In fact, many decision problems become trivial if uncertainty is removed. The problem of selecting the best policy for dealing with aging assets like underground cable is no exception. If we knew precisely when a cable section would fail, the best policy would be to replace it shortly before failure. Moreover, without uncertainty, there would be no need to test.

The cable-aging problem has inherent uncertainties. Each period, there is uncertainty about failure. There is typically some data for specifying the average hazard function that quantifies this uncertainty; however, there is little data showing how this hazard function changes with different stressors or failure history. Also, there is little data about the uncertainty about the underlying condition of the asset over time and the uncertain test accuracy.

Logical decision-making requires specifying the amount of uncertainty that exists given our current state of information. If we ignore data gaps, we may get the right answer to the wrong problem. If we assume certainty when large uncertainty exists, we may get the wrong answer to the right problem.

A better approach is to fill data gaps with the best expert judgments available, elicited with a transparent, structured process. A significant advantage to quantifying expert judgments is that probability provides an explicit language for communicating about uncertainty. Other experts can see the judgments and replace them with their own if they so choose.

It would be unwise to make a decision without considering all available information before acting. Often, such information resides in the heads of experts. The expert judgments can come in the form of point estimates or explicit probability distributions. If a variable is almost certain and the problem is not sensitive to its value, we obtain a point estimate. However, if the variable is either highly uncertain or the decision is extremely to changes in the value of the variable, then we quantify explicitly the range of uncertainty.

Over the past thirty years, decision analysis has evolved a set of effective procedures for eliciting expert judgments. These procedures minimize certain known biases in the way experts (and indeed all humans) process and communicate information. The expert-elicitation procedure used in the underground cable elicitation was a simplified version of a process designed for EPRI, the Department of Energy and the Nuclear Regulatory Commission [*Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts*," U.S. Department of Energy, NUREG/CR-6372, August 1995]. This expert process, which has become the standard for large public policy studies, has been applied in a large number of applications, including seismic hazard, volcanic hazard, ground water contamination hazard, and nuclear plant risk. The expert elicitation procedure was used to obtain either point estimates or uncertainty ranges for the following variables:

a) Impacts of failure history on hazard

b) Impacts of environmental and operational stressors on hazard

c) Probability of cable conditions over time

d) Test accuracy at detecting cable condition

e) Impact of rejuvenation on the cable's effective age

For variables on which there was significant uncertainty, we elicited the range of the variable, as quantified by the experts' judgments of the 10^{th} and 90^{th} percentiles. For some uncertainties, the results depended on whether the cable was PILC or extruded.

In the present implementation, we engaged in a two-expert elicitation process. The experts were John Densley and Robert Keefe.

Dr. John Densley, P.Eng, IEEE Fellow, the President of ArborLec Solutions Inc. has worked on electrical aging mechanisms and diagnostic techniques in electrical insulation for more than 35 years. He has published over 100 research papers on insulation systems, delivered more than 50 technical presentations, based on his practical and theoretical knowledge of aging and failure mechanisms of insulation systems in high voltage equipment such as medium and high voltage cables, transformers and switchgear.

Robert J. Keefe is the manager of EPRI's Underground Distribution He is also currently the Chair or past Chair of several IEEE Insulated Conductor Committee discussion groups on characteristics of insulating materials. Prior to joining EPRI in 2001, he had worked at General Cable, BICC, and BP Chemicals. There, he had a combined 15 years experience working in materials technology, developing polymeric compounds and manufacturing processes for dielectric and semi-conductive applications.

In some expert elicitations, experts will disagree, in which case the best process is to record and preserve the disagreements. However, in this elicitation, the two experts agreed on all judgments, including the ranges of uncertainty. The results of the expert elicitation are presented below.

The Effect of Failure History

For the piecewise linear hazard, it is natural to ask how increasing number of failures affect the three parameters, (h_{ss}, m, T), of the model. The following Tables (5-1, 5-2) provide the multipliers for PILC and extruded cable, respectively. These multipliers are used to adjust the parameters. For example, referring to Table 5-1, if a PILC cable segment has experienced one previous failure, then the steady-state hazard rate h_{ss} is unchanged, the onset of burnout occurs at 0.9T, and the *doubling time*, the time it takes for the hazard rate to reach 2h_{ss}, decreases to between sixty and eighty percent of the value for the segments with no previous failures. (Doubling time was chosen by the experts as the most natural way to express the effect on m.) This latter condition means that the slope of the burnout period varies between 1.25m and 1.67m. (The relationship is reciprocal: if the doubling time is reduced by one-half, then the slope of the burnout is doubled.) Table 5-2 presents the multipliers found by expert judgment for extruded cable.

Table 5-1
The Effect of Failure History on Piecewise Linear Hazard Rate for PILC

Previous Failures	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
0	1.00	1.00	1.00
1	1.00	0.90	0.60 – 0.80
2+	1.00	0.70	0.40 – 0.6

Table 5-2
The Effect of Failure History on Piecewise Linear Hazard Rate for Extruded Cable

Previous Failures	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
0	1.00	1.00	1.00
1	1.00	0.50	0.50 – 0.70
2+	1.00	0.30	0.10 – 0.50

The Effect of Underground Cable Condition

The fundamental assumptions about underground cable condition are that it is (a) unobservable, (b) uncertain, and (c) dynamic. The first assumption means that it is not possible to learn directly what the actual condition is. The second assumption means that the most appropriate description of the condition state is a probability distribution. The third assumption means that the probability distribution of the condition state changes over time.

Because underground cable condition is unobservable and uncertain, testing provide information about the posterior—after the test result is observed—probability distribution of the unobservable condition. The prior probability distribution is an input to the model, which is described below. The number of different conditions is arbitrary. In the present implementation, there are two kinds of cable, PILC and extruded. For PILC, the only unobservable condition is the level of *insulation degradation*. For extruded cable, the unobservable conditions are the level of *insulation degradation* and the degree of *loss of neutral*.

Condition State Definitions

The two condition states were chosen because they represent the dominant failure modes for underground cables. The levels of these unobservable variables are what diagnostic tests are designed to discover. Therefore, the levels of these unobservable variables are natural descriptors of the actual condition of an underground cable segment. Only two unobservable conditions were chosen because the experts believed that these conditions are sufficient to determine the behavior of the cable (when combined with the observable state) and also because as the number of unobservable variables increases, the analysis, from input to conclusion, becomes increasing difficult. This expert choice reflects a balance between realism and tractability.

As part of the definition of the unobservable state, the measuring scale must be specified. Although it is natural to attempt to define a numerical scale, the experts recognized that such a scale was not readily available, and two qualitative scales were defined instead. The main modeling issues associated with a qualitative scale are to choose the number of different levels and to define each level unambiguously and meaningfully. The levels were chosen to be consistent with utility practices with similar assessment systems, which rate cable condition on a qualitative scale, typically with 3- or 4-points. Insulation Degradation has four levels. Loss of Neutral has three levels.

The definitions of the unobservable states are given in Tables 5-3 and 5-4.

Table 5-3
Definition of Insulation Degradation Condition State Levels

Insulation Degradation Condition State	Description
No Degrade	Insulation good as new
Mild Degrade	Small water trees (WT) (<10% of ins. thick.) or voids in insulation
Mod Degrade	Moderate WT (lengths 10-30% of ins. thick.) or voids in insulation
Severe Degrade	Severe WT (> 30% of ins. thick.), large voids (PD inc. < 1.5 Vo)

Table 5-4
Definition of Insulation Degradation Condition State Levels

Loss of Neutral Condition State	Description
Good Neutral	Greater than 75% neutral remaining
Moderate Loss	25%-75% neutral remaining
Severe Loss	Less than 25% neutral remaining

Dynamics Of Unobservable Conditions

The underlying consideration that guides the specification of the unobservable conditions is that cables degrade over time. Therefore, it is reasonable to expect that the likelihood that a cable segment is at any level of unobservable condition changes over time. The expert specification of these dynamic changes is given in the following tables.

Table 5-5
Dynamics of Insulation Degradation Condition State Levels for PILC

Fraction of Cable in each State

Age	No Degrade	Mild Degrade	Mod Degrade	Severe Degrade
10	95%	4%	1%	0%
20	75%	10%	10%	5%
40	60%	20%	10%	10%
60	50%	20%	20%	10%

Table 5-5 specifies the likelihood that a PILC cable segment will be in an Insulation Condition State as a function of age of the segment. Each row provides the probability distribution on condition for the specified age. Note that the probability that the cable segment experiences no degradation decreases with age, such that at age 60, the forecast indicates that half the segments are expected to experience some degradation. These dynamic distributions are the so-called *prior* (before any testing) distributions on condition.

Tables 5-6 and 5-7 specify the dynamic behavior of the condition states of extruded cable.

Table 5-6
Dynamics of Insulation Degradation Condition State Levels for Extruded Cable

	Fraction of Cable in each State			
Age	**No Degrade**	**Mild Degrade**	**Mod Degrade**	**Severe Degrade**
10	90%	9%	1%	0%
20	60%	20%	10%	10%
40	40%	20%	20%	20%
60	20%	20%	25%	35%

Table 5-7
Dynamics of Concentric Neutral Condition State Levels for Extruded Cable

	Fraction of Cable in each State		
Age	**Good Neutral**	**Moderate Loss**	**Severe Loss**
10	95%	4%	1%
20	60%	30%	10%
40	50%	35%	15%
60	25%	45%	30%

These tables are sufficient to specify the probability distribution on condition state for cable of any age. The tables are interpolated linearly for ages between the specified points.

Effect of Cable Condition on Hazard Rate

The condition state affects the parameters of the hazard rate. Expert assessment resulted in the collection of parameter estimates given in Table 5-8 for PILC and Table 5-9 for extruded cable. In the present implementation, it is assumed that the level of loss of neutral does not influence hazard. (The effect of loss of neutral condition state is counted in the present implementation as a cost, charged in each year that the neutral condition is degraded. When extruded cable experiences moderate or severe neutral corrosion, there is an added risk of damage if a fault occurs. The cost represents the expected damage should a fault occur.) The interpretation of the entries in the Table is similar to those found for failure history. Note that the insulation condition does not affect the steady-state hazard rate.

Table 5-8
The Effect of Insulation Condition State on Piecewise Linear Hazard Rate for PILC

Insulation State	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
Mild Degradation	1.0000	0.50	0.85
Mod Degradation	1.0000	0.35	0.60
Severe Degradation	1.0000	0.15	0.40

Table 5-9
The Effect of Insulation Condition State on Piecewise Linear Hazard Rate for Extruded Cable

Insulation State	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
Mild Degradation	1.0000	0.50	0.85
Mod Degradation	1.0000	0.35	0.60
Severe Degradation	1.0000	0.15	0.40

Test Accuracy

For each cable type, there is a test protocol that is designed to provide information about the cable condition. As discussed above, the tests are uncertain. Therefore, both the test protocol and the accuracy of the protocol are specified by expert judgment.

The description of the test protocol and the likelihood function for the protocol that identifies the level of insulation degradation for PILC is given in Table 5-10a. The conditional likelihoods are given in the rows of Table 5-10b. Note that if the cable is in the No Degrade condition, the test is eighty-five percent accurate. That is, p{"No Degrade"|No Degrade} = 0.85, but the test is only thirty-five percent accurate if the actual condition is Moderate Degradation.

Table 5-10a
Test Protocol for PILC

Description of Insulation Degradation Test Protocol
Withstand or diagnostic test
PD test measures local degradation (tracking, etc)
Damage caused by PD depends on location of PD
Different types of test voltages (DC, 60 Hz, VLF, DAC)
Standards available for some tests (include criteria to assess cable condition)
Bulk degradation measured by tan delta or power factor (extent of WT damage)

Table 5-10b
Test Accuracy for PILC

	Test Protocol Outcome			
Actual Condition	**"No Degrade"**	**"Mild Degrade"**	**"Mod Degrade"**	**"Severe Degrade"**
No Degrade	0.80	0.10	0.05	0.05
Mild Degrade	0.20	0.40	0.30	0.10
Mod Degrade	0.15	0.30	0.35	0.20
Severe Degrade	0.05	0.10	0.15	0.70

Similar results are given for extruded cable in Tables 5-11a, b, c. Extruded cable tests investigate both the insulation degradation and the loss of neutral.

Table 5-11a
Test Protocol for Extruded Cable

Description of Insulation Degradation Test Protocol

Withstand or diagnostic test
PD test measures local degradation (tracking, etc)
Damage caused by PD depends on location of PD
Different types of test voltages (DC, 60 Hz, VLF, DAC)
Standards available for some tests (include criteria to assess cable condition)
Bulk degradation measured by tan delta or power factor (extent of WT damage)

Description of Neutral Condition Test Protocol

Withstand or diagnostic test
PD test measures local degradation (tracking, etc)
Cable will resist PD for many years, PD level of thousands of pC are harmful
Different types of test voltages (DC, 60 Hz, VLF, DAC)
Bulk degradation measured by tan delta or power factor
Standards available for some tests (include criteria to assess cable condition)

Table 5-11b
Test Accuracy for Extruded Cable: Insulation Degradation

	Test Protocol Outcome			
Actual Condition	**"No Degrade"**	**"Mild Degrade"**	**"Mod Degrade"**	**"Severe Degrade"**
No Degrade	0.80	0.10	0.05	0.05
Mild Degrade	0.20	0.40	0.30	0.10
Mod Degrade	0.15	0.30	0.35	0.20
Severe Degrade	0.05	0.10	0.15	0.70

Table 5-11c
Test Accuracy for Extruded Cable: Loss of Neutral

	Test Protocol Outcome		
Actual Condition	"Good Neutral"	"Moderate Loss"	"Severe Loss"
Good Neutral	0.85	0.10	0.05
Moderate Loss	0.15	0.70	0.15
Severe Loss	0.05	0.15	0.80

The Effect Of Stressors

Stressors are external influences that may increase the likelihood that an underground cable segment will fail. The definition of a stressor is arbitrary. In the present implementation, we have identified two kinds of stressors, environmental and operational stressors. The definitions of these stressors are given in the following Tables (5-12 and 5-13). These tables are taken from the EPRI report *Equipment Failure Model and Data for Underground Distribution Cables, 1008560*. There are many ways to define and measure stressors. The present implementation expresses the simplest binary stressor; i.e., the stressor is present or it is not, without consideration of degree. This may be sufficient for many purposes, especially since data on the presence and the effect of stressors is not readily available.

Table 5-12
Environmental Stressors

Environmental	Description
Average environment	Low incidence of fault locating (e.g. because of lightning strikes), typically low seasonal environmental temperatures and humidity leading to low ground temperature (hence cable operating temperature), absence of aggressive soil conditions, and operating below 40 volts per mil
Severe environment	High incidence of fault locating (e.g. because of lightning strikes), typically high seasonal environmental temperatures and humidity leading to high ground (hence cable operating) temperature, or presence of aggressive soil conditions, e.g. high ground moisture level, rocky soil (not for ducted cables), or soils with high acid or alkali levels, or cables operating at above 40 volts per mil.

Table 5-13
Operational Stressors

Operating	Description
Average utilization	Cables operated with a load factor below 75%, and a low incidence of switching transients.
High utilization	Cables operated with a load factor above 75%, or with a high incidence of switching transients.

The effects of the presence of stressors are specified in Table 5-14. The effects were judged to be the same for both PILC and extruded cable. If both stressors are present, the hazard rate parameters will be modified by both effects.

Table 5-14
The Effect of the Presence of Stressors on Piecewise Linear Hazard Function for PILC and Extruded Cable

Stressor	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
Average Op Conditions	1.00	1.00	1.00
Severe environment	1.00 – 2.00	0.50 – 0.70	0.50 – 0.70
High utilization	1.00 – 1.50	0.70	0.70 – 0.90

This concludes the results of the expert elicitation. These results can be used as defaults in the inputs to the methodology. The analyst may freely override these default inputs if he or she believes that other values would represent more realistically the situation at the utility.

6
HAZARD FUNCTION ESTIMATES: AN EXAMPLE

In this Chapter, we solve the estimation problem: given a collection of data describing the failure of underground cable, estimate the hazard function. An example of a data set provided by a utility is the following. The data are ordered by increasing age, *t*.

Table 6-1
Failure Data

Year Installed	Year Failed	Number of Failures	Feet Installed	Age (t)	Hazard Rate h(t)
1997	1998	1	33208	1	3.01132E-05
1995	1996	1	56311	1	1.77585E-05
1996	1997	2	17712	1	0.000112918
1997	1998	1	34240	1	2.92056E-05
1994	1996	1	26891	2	3.71872E-05
1995	1997	3	56311	2	5.32756E-05
1995	1997	1	56311	2	1.77585E-05
1996	1998	1	29117	2	3.43442E-05
1997	1999	2	34240	2	5.84112E-05
1994	1997	1	26891	3	3.71872E-05
1996	1999	1	29117	3	3.43442E-05
1997	2000	1	33208	3	3.01132E-05
1995	1999	1	56311	4	1.77585E-05
1994	1999	1	5375	5	0.000186047
1990	1997	3	7477	7	0.00040123
1991	1998	1	33020	7	3.02847E-05
1989	1997	1	54674	8	1.82902E-05
1991	1999	1	33020	8	3.02847E-05
1990	1999	1	7477	9	0.000133743
1985	2000	1	13329	15	7.50244E-05
1978	1997	1	4160	19	0.000240385
1978	1999	1	4160	21	0.000240385
1978	2000	1	4160	22	0.000240385
1975	1998	1	3416	23	0.00029274

This Table lists the times to failure of an inventory of cable segments. The year the cable was installed is in the first column. The second column is the year in which a failure was observed. The difference between these two times is the age of the cable when it failed. That is shown in column five. The number of failures observed for that cable is listed in column three. The number of feet installed is listed in column four. The ratio of the number of failures observed (column three) to the number of feet installed (column four) is the hazard rate, expressed in failures/foot/year as a function of age. The hazard rate is shown in column six. The last two columns of Table 6-1 comprise the data required for estimating the hazard function. For example, the first row of the Table corresponds to the year 1998. In that year, 1 failure occurred in cable that was 1 year old (the cable was installed in 1997). There were 33,208 feet installed in 1997. Therefore, the hazard rate was 1 failure /33208 feet of cable installed = 3.01132×10^{-5}, as noted in column six. Further, as indicated in the last row of the Table, in 1998 there was one failure of cable installed in 1975. There were 3416 feet installed in 1975, so the hazard rate is 1/3416 failure per feet of cable installed = 2.9274×10^{-4}, as noted in column six.

In order to create Table 6-1, what must be known is the year the cable was installed, the number of feet of cable installed in that year, and the number of failures of that vintage cable in any year. It is important to note that the data in Table 6-1 is not separated by vintage. By combining all vintages of cable into one data set, we make the underlying assumption that vintage does not affect hazard. If that assumption is not true, then the data should be collected separately by vintage. For example, if it is believed that cable installed in the 1970s differs in behavior from cable installed after 1979, and all cable installed after 1979 behaves in the same way, then the data should be separated into two groups. For such data, two hazard functions would be separately estimated. An interesting question would be to ask whether the functions found in that way are really different. This question could be answered using statistical analysis. In the limit, data could be kept separately for each year cable is installed. Regardless of how many different data sets there may be, the hazard functions can be estimated in the same way.

Estimating the Hazard Function

Figure 6-1 presents the data in Table 6-1 graphically. Creating such a plot is a natural first step towards estimating the hazard function.

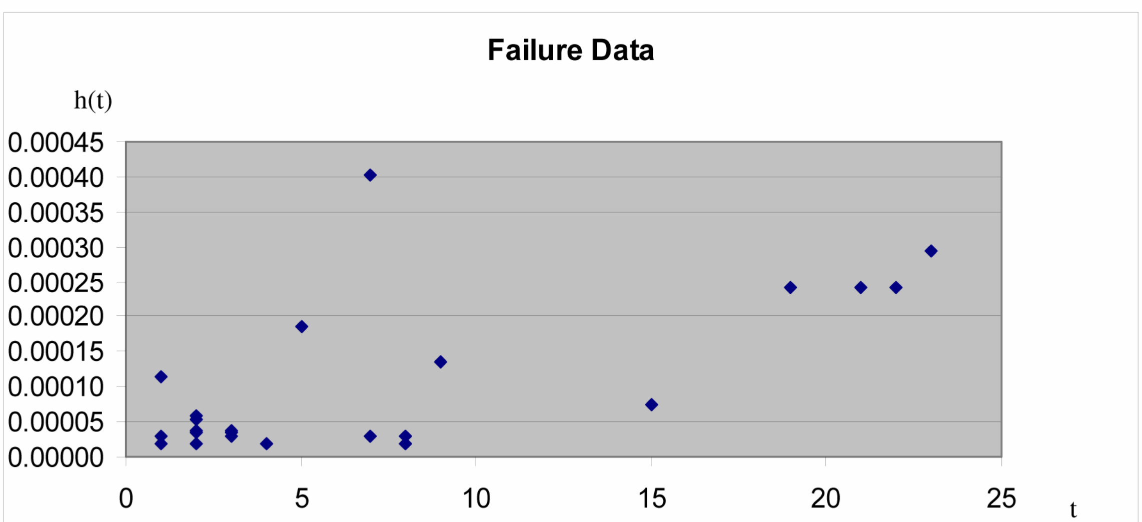

Figure 6-1
Observed Failure Data

It may be reasonable to discern a burnout period that begins at approximately fifteen years in the data shown in Figure 6-1. Appropriate choices for hazard functions appear to be piecewise linear, normal, and Weibull. We restrict our attention to the piecewise linear and Weibull models.

Piecewise Linear Hazard Function

We will apply the procedure specified in Chapter 4 to fit a piecewise linear hazard function to the data in Table 6-1.

Step 0. This has been accomplished by creating Table 6-1.

Step 1. The onset of burnout is uncertain in this data set. It may begin as early as nine years or as late as 15. We will investigate value of T in the range $8 \leq T \leq 16$.

Step 2. The results of the computations are presented in Table 6-2, below. As T varies over the range specified in step 1, several values of h_{ss} are found. The value of h_{ss} increases as T increases because when T =9, the data point (9, 1.33473 x 10^{-4}) is included in the average, and when $T \geq 15$, the data point (15, 7.50244 x 10^{-5}) is included in the average.

Step 3. For example, when T = 15 there are four data points that have t > 15. These values are found in rows 21, 22, 23, and 24 (last four rows) of Table 6-1. Subtracting 15 from each of the ages and subtracting 6.93 x 10^{-5}, the value of h_{ss} for T =15, from each of the observed hazards yields the data set: {(4, 1.711 x 10^{-4}), (6, 1.711 x 10^{-4}), (7, 1.711 x 10^{-4}), (8, 2.235 x 10^{-4})}.

Step 4. The slope of the straight line that fits these four points with minimum sum of squared errors and that also goes through the point (0,0) is m = 2.85 x 10^{-5}.

Step 5. The sum of squared errors when T = 15 is J = 1.572 x 10^{-7}.

Step 6. Varying T and repeating steps 1-5 yields the results in Table 6-2.

Table 6-2
The Effect of Varying Onset of Burnout (T) Upon Parameter Estimates and Goodness-of-Fit (J)

T	hss	m	t2-T	J
8	6.54E-05	1.42E-05	4.62	1.608E-07
9	6.90E-05	1.50E-05	4.60	1.614E-07
10	6.90E-05	1.63E-05	4.23	1.601E-07
11	6.90E-05	1.78E-05	3.86	1.589E-07
12	6.90E-05	1.97E-05	3.50	1.577E-07
13	6.90E-05	2.20E-05	3.14	1.568E-07
14	6.90E-05	2.49E-05	2.77	1.564E-07
15	6.93E-05	2.85E-05	2.43	1.572E-07
16	6.93E-05	3.33E-05	2.08	1.591E-07

The minimum sum of squared errors occurs for $T = 14$. However, the sum of squared errors varies very slowly with respect to changes in T over the interval (12, 15). Any of those values appear to be reasonable. An additional consideration is the slope of the burnout period. The fourth column of Table 6-2 identifies the doubling time, the time it takes for the steady-state hazard rate to double after onset of burnout. This is a parameter of the hazard function that some experts believe is an important characterization of the hazard rate. For the piecewise linear model, the doubling time is the ratio of the steady-state hazard rate to the slope of the burnout period. This value varies over the entire interval of T values. Indeed, there is discernable variation with respect to changes in T over the interval (12, 15). This variation may motivate the choice of a value of T other than the minimizer $T = 14$. For illustrative purposes, we present the result for $T = 14$. See Figure 6-2.

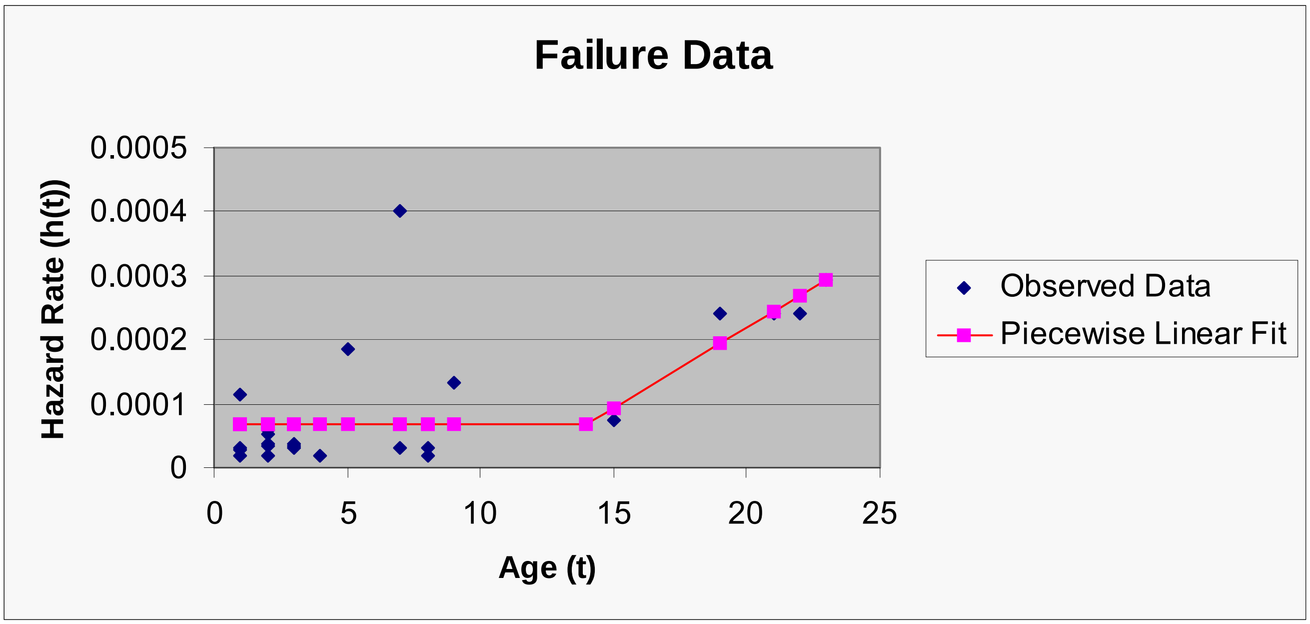

Figure 6-2
Piecewise Linear Hazard Function for *T*=14

Weibull Hazard Function

We will apply the procedure specified in Chapter 4 to fit a Weibull hazard function to the data in Table 6-1.

Step 0. This has been accomplished by creating Table 6-1.

Step 1. The logarithmic transformation of the data in Table 6-1 is shown in Table 6-3. the last two columns of the Table contain the data that are used to fit the logarithm of the Weibull hazard.

Step 2. The estimates of the parameters are $\alpha = 1.5949$ and $\beta = 1025.7$. The sum of squares of the errors of the fit is $J = 1.8370 \times 10^{-7}$, which is somewhat greater than the value of J for the piecewise linear hazard function. The Weibull hazard is shown in Figure 6-3.

Table 6-3
Logarithmic Transformation of Hazard Data

Year Installed	Year Failed	Number of Failures	Feet Installed	Age (t)	Hazard Rate h(t)	Log h(t)	Log t
1997	1998	1	33208	1	3.01132E-05	-10.41054609	0
1995	1996	1	56311	1	1.77585E-05	-10.93864518	0
1996	1997	2	17712	1	0.000112918	-9.088850474	0
1997	1998	1	34240	1	2.92056E-05	-10.44114983	0
1994	1996	1	26891	2	3.71872E-05	-10.19954694	0.693147181
1995	1997	3	56311	2	5.32756E-05	-9.840032888	0.693147181
1995	1997	1	56311	2	1.77585E-05	-10.93864518	0.693147181
1996	1998	1	29117	2	3.43442E-05	-10.27907748	0.693147181
1997	1999	2	34240	2	5.84112E-05	-9.74800265	0.693147181
1994	1997	1	26891	3	3.71872E-05	-10.19954694	1.098612289
1996	1999	1	29117	3	3.43442E-05	-10.27907748	1.098612289
1997	2000	1	33208	3	3.01132E-05	-10.41054609	1.098612289
1995	1999	1	56311	4	1.77585E-05	-10.93864518	1.386294361
1994	1999	1	5375	5	0.000186047	-8.589513853	1.609437912
1990	1997	3	7477	7	0.00040123	-7.820974632	1.945910149
1991	1998	1	33020	7	3.02847E-05	-10.40486872	1.945910149
1989	1997	1	54674	8	1.82902E-05	-10.90914356	2.079441542
1991	1999	1	33020	8	3.02847E-05	-10.40486872	2.079441542
1990	1999	1	7477	9	0.000133743	-8.919586921	2.197224577
1985	2000	1	13329	15	7.50244E-05	-9.497697392	2.708050201
1978	1997	1	4160	19	0.000240385	-8.333270353	2.944438979
1978	1999	1	4160	21	0.000240385	-8.333270353	3.044522438
1978	2000	1	4160	22	0.000240385	-8.333270353	3.091042453
1975	1998	1	3416	23	0.00029274	-8.136225555	3.135494216

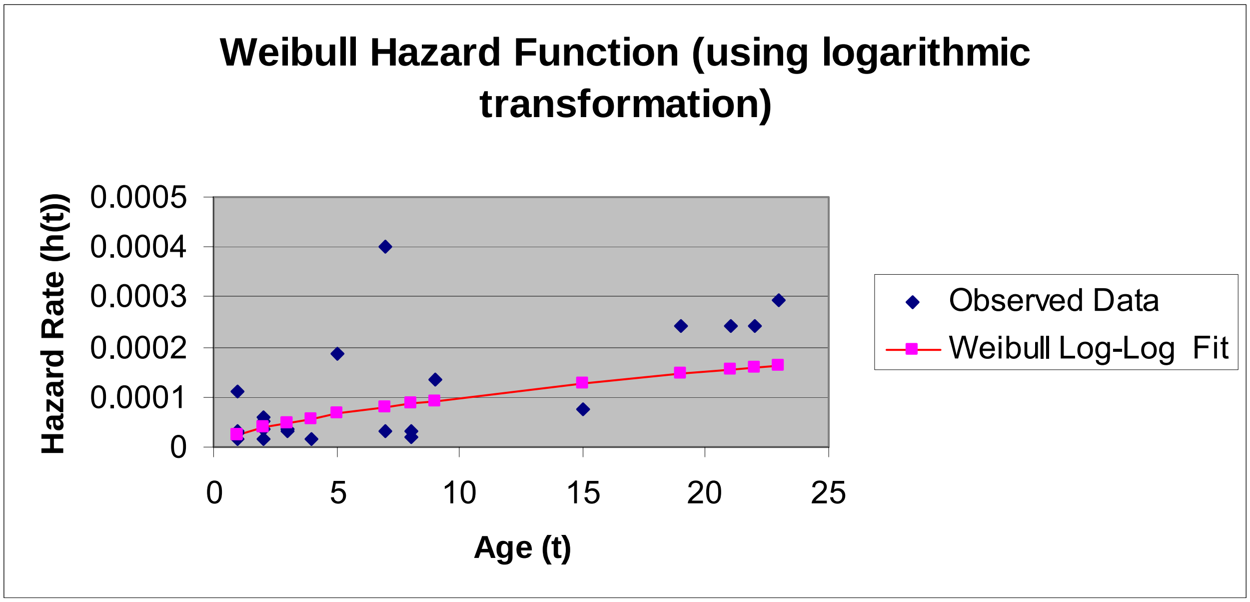

Figure 6-3
Weibull Hazard Function Based on Observed Data, Fit with Logarithmic Transformation

The Importance of Expert Judgment

The Weibull fit obtained in Figure 6-3 illustrates the point made earlier in this report about the density of the data driving the parameter specification. It is clear that for the larger number of data points for the shorter lifetimes, the fitted function attempts to balance the errors, while for the fewer data points at the longer lifetimes, the fitted function is uniformly lower. The uniformity with respect to sign of the estimation error—which is the difference between the observed value (data) and the estimated value (based on the estimated parameters), or $e_t = h_{obs}(t) - (1.5949/1025.7)(t/1025.7)^{0.5949}$, which is positive for longer lifetimes, compared with both positive and negative errors for shorter lifetimes—suggests that the fitting method could introduce bias. This is another situation that suggests the importance of judgment.

In this case, it is straightforward to test various settings of the parameters α and β. The most convenient way to do this testing is graphically. In the present situation, the more important region to represent accurately is the burnout period because that is what typically determines the optimal repair/maintain/replace policy for the underground cable inventory as that inventory ages. Therefore, we developed a manual fit that appears to track the data more accurately than the fit obtained by minimizing the sum of squares of the logarithmic error. The manually fit hazard function does not agree with the data very well in the earlier period. In fact, the sum of squared errors $J = 2.3451 \times 10^{-7}$, somewhat greater than the errors in the other fits shown in this Chapter. The setting of the parameters that we found that seemed most appropriate overall, while emphasizing the agreement with the data in the burnout period, are $\alpha = 4$ and $\beta = 110$. We hasten to say that there can be any number of settings that appear to be reasonable. See Figure 6-4.

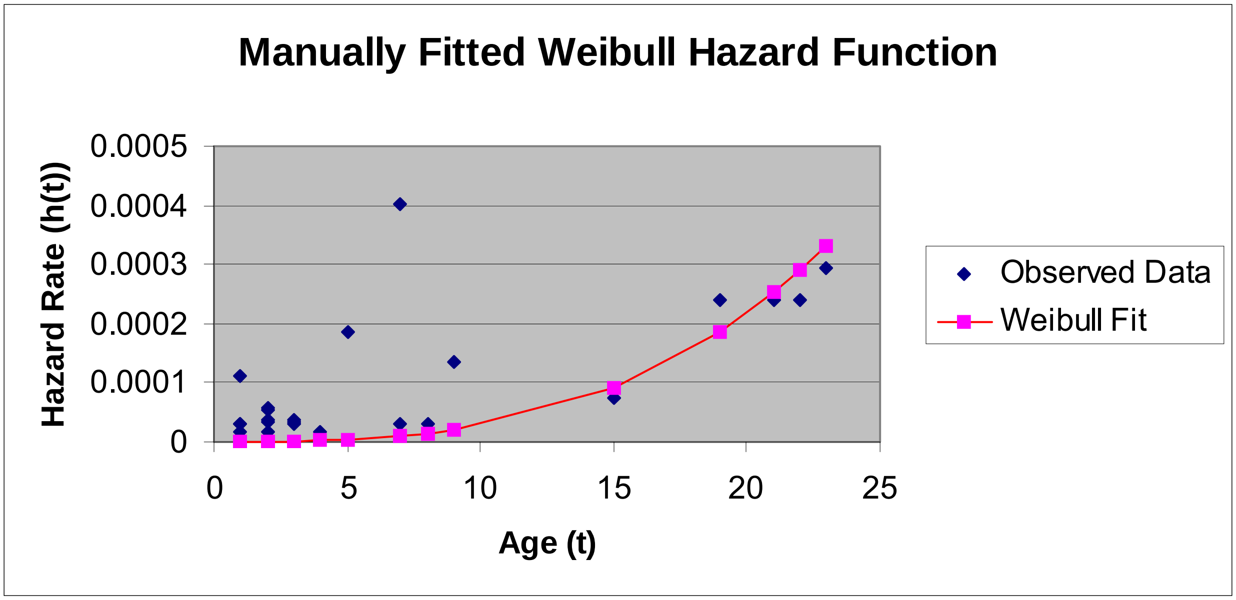

Figure 6-4
Weibull Hazard Function Based on Observed Data Fit Manually

This is one example of how expert judgment can be brought into play in the hazard function estimation process. It is important to recognize that one of the reasons that this problem arises is that there is somewhat less flexibility in a two-parameter analytic function such as a Weibull than there is in an empirical function like a bathtub curve or a piecewise linear hazard. For the Weibull hazard function, the steady-state or earlier behavior is tightly linked to the burnout behavior. For a piecewise linear function or a bathtub curve, the slope of the burnout is generally completely independent of the steady state hazard. The nonlinear burnout behavior of the Weibull is completely determined by the parameter settings of that function, and those parameters are often selected with great dependence on the earlier data, as we have seen in the example above.

Other Models, Including the Bathtub Curve

Although there are many possible life distributions, and therefore many possible hazard functions, the Weibull hazard is perhaps the most popular. There seems to be no compelling reason to adopt the exponential hazard (no burnout), the normal hazard (nonlinear burnout, as in the Weibull), the lognormal, or any other model. The underlying life distribution of the normal hazard indicates a concentration of lifetimes about the mean life. We have no reason to believe that this is appropriate for underground cable. The lognormal seems inappropriate for cables because of its interior maximum hazard. Therefore we propose to adopt either the Weibull hazard, the piecewise linear hazard, or the bathtub curve (Figure 4-2). The main advantage of the bathtub curve is that it combines the nonlinear burnout period of the Weibull with the decoupled burnout period of the piecewise linear.

However, fitting a bathtub curve is an exercise in combining expert judgment with data analysis. The steady-state hazard, as in the piecewise linear case, is simply the horizontal function $h(t)$ =

h_{ss}, for $0 < t < T$. The burnout period ($t > T$) can be represented by any nonlinear monotonic function. Therefore, Weibull burnout can be applied to a bathtub curve, and the data during the burnout period can be used to estimate the Weibull parameter α, which applies only over the burnout period. Therefore, estimating a bathtub curve requires splitting the data into two parts, the steady-state part and the burnout. We ignore burn-in, which appears not to apply to cable. Thus, one sets T using expert judgment. Based on that specification, the data prior to T can be used to estimate h_{ss} by a simple averaging process. Beyond T, expert judgment is required to specify the shape of the burnout hazard rate. Once that shape is specified, then the parameters are selected to minimize the sum of squared errors over the burnout period, in a manner virtually identical to the examples above. If Weibull burnout is assumed, then the logarithmic transformation can be applied to the data over the burnout period. Other functional forms will require other error formulations, but the ideas involved in parameter estimation are identical.

7 REPRESENTATIVE RESULTS

This chapter presents the results of a sample analysis. The inputs to the analysis are completely described, so that any user of the methodology can replicate the results. The results and any conclusions are specific to this example only, certainly not generally applicable, but merely indicate the kinds of analyses that can be performed with the methodology.

Inputs

The inputs to the model include the hazard function, the costs, and the specification of the unobservable conditions. The following inputs were used.

Costs

The costs are given in Table 7-1. Replacement cost is \$23,000 per segment (500 ft), rejuvenation cost is \$15,000 per segment, Failure cost is \$18,500 per occurrence, which includes both utility cost and estimated customer cost, and Testing cost is \$500 per test. The discount factor is 0.05 per year.

Table 7-1
Sample Cost Inputs

Costs	(\$000)
Replace	\$23.0
Rejuvenation	\$15.0
Failure	\$18.5
Test (per test)	\$0.5
Moderate Corrosion Loss (annual)	\$0.0
Severe Corrosion Loss (annual)	\$0.0

Hazard Function

The cable type is extruded. The hazard function used is the function found in the data analysis presented in Chapter 5. This is a piecewise linear hazard with parameters steady-state failure rate h_{ss} = 6.90 x 10^{-5} failures/ft/yr = 0.3642 failures/mile/yr, onset of burnout T = 14 years, and slope of burnout m = 0.361 failures/mile/yr, which is equivalent to setting the doubling time during burnout = 2.77 years. These settings are given in the upper part of Table 7-2. The Table is taken from the input forms of the present implementation of the methodology. The next section of the Table presents the effect on the hazard rate of the insulation condition. Recall that these effects are multipliers. The section of the Table following that is the effect of the presence of stressors. The final section of the table presents the effect of past failures. These entries are based on the expert elicitation described above, in Chapter 5.

Table 7-2
Sample Hazard Function, Including the Effects of Insulation Condition State, the Presence of Stressors, and the Impact of Failure History

BASE CASE HAZARD FUNCTION

	Piecewise Linear Parameters		
Base Case (average)	Steady state hazard (failures/mile/yr)	Onset of burnout	Hazard Rate doubling time during burnout
Hazard Function	0.3643	14	2.77

IMPACT OF INSULATION CONDITION

Insulation State	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
Mild Degradation	1.00	0.54	0.85
Mod Degradation	1.00	0.34	0.60
Severe Degration	1.00	0.14	0.30

IMPACT OF STRESSORS

Stressor	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
Average Op Conditions	1.00	1.00	1.00
Severe environment	1.50	0.60	0.60
High utilization	1.25	0.70	0.80

IMPACT OF FAILURE HISTORY

Previous Failures	Steady state hazard	Onset of burnout	Doubling time
	Multiplier		
0	1.00	1.00	1.00
1	1.00	0.50	0.60
2+	1.00	0.30	0.30

Other Case Settings

In order to complete the specification of a case, additional data must be specified including the presence of stressors, the inventory, and the effect of rejuvenation. These settings are as follows.

- The presence of stressors is set at Average Environment and Utilization.
- The inventory has 20,000 segments, with age and failure history given in Table 7-3. These numbers are for illustrative purposes only and do not correspond to any known population.

Table 7-3
Initial Inventory of Cable Segments, By Age and Failure History

Failures	INITIAL CABLE INVENTORY								
2	0	0	1000	1000	1000	1000	1000	1000	1000
1	0	1000	1000	1000	1000	1000	1000	0	0
0	1000	1000	1000	1000	1000	1000	1000	0	0
Age	0	5	10	15	20	25	30	35	40

- The effect of rejuvenation is to modify the probability distribution on insulation condition as follows.
  - The probability that the cable is in *severe* condition goes to zero. The probability that the cable segment was in severe condition prior to rejuvenation is assigned to the *moderate* state.
  - The probability that the cable is in *mild* condition goes to zero. The probability that the cable segment was in mild condition prior to rejuvenation is assigned to the *no degradation* state.

Condition Dynamics And Testing

The dynamics of the probability distribution on the unobservable conditions are given in Table 7-4 for both insulation condition and neutral condition (recall that this is an example using extruded cable). The likelihood functions for the test protocol are given in Table 7-5. These are based on the expert elicitations described in this report.

Table 7-4
Sample Condition Dynamics for Extruded Cable

EXTRUDED — **INSULATION DEGRADATION STATES**

Fraction of Cable in each State

Age	No Degrade	Mild Degrade	Mod Degrade	Severe Degrade
10	90%	9%	1%	0%
20	60%	20%	10%	10%
40	40%	20%	20%	20%
60	20%	20%	25%	35%

EXTRUDED — **CONCENTRIC NEUTRAL STATES**

Fraction of Cable in each State

Age	Good Neutral	Moderate Loss	Severe Loss
10	80%	20%	0%
20	60%	20%	20%
40	20%	20%	60%
60	0%	20%	80%

Table 7-5
Condition Test Likelihood Functions

INSULATION DEGRADATION TEST

	Test Protocol Outcome			
Actual Condition	**"No Degrade"**	**"Mild Degrade"**	**"Mod Degrade"**	**"Severe Degrade"**
No Degrade	0.80	0.05	0.05	0.10
Mild Degrade	0.20	0.40	0.30	0.10
Mod Degrade	0.15	0.30	0.35	0.20
Severe Degrade	0.05	0.05	0.10	0.80

NEUTRAL CONDITION TEST

	Test Protocol Outcome		
Actual Condition	**"Good Neutral"**	**"Moderate Loss"**	**"Severe Loss"**
Good Neutral	0.80	0.10	0.10
Moderate Loss	0.10	0.80	0.10
Severe Loss	0.10	0.10	0.80

This completes the specification of the inputs.

Base Case Results

The base case optimal policy (without testing) is given in Table 7-6. Note that the optimal policy replaces cable segments that have not failed when the age is 25 years. Rejuvenation is optimal for cable that has failed more than once and is 15 years old.

Table 7-6
Base Case Optimal Policy

OPTIMAL CABLE POLICY

	Failures		
Age	**0**	**1**	**2**
0	No Action		
5	No Action	No Action	
10	No Action	No Action	No Action
15	No Action	No Action	Rejuvenate
20	No Action	Replace	Replace
25	Replace	Replace	Replace
30	Replace	Replace	Replace
35	Replace	Replace	Replace
40	Replace	Replace	Replace

The levelized cost of this policy is \$202.9 x 10^6 every five years, or approximately \$40.6 x 10^6 per year.

The optimal policy with testing is given in Table 7-7. The optimal policy is to test cable when the observable states are {(age, failures)} = {(15, 1), (20,1), (25,2)}. Testing adds value.

The levelized cost of the optimal policy with testing is \$201.3 x 10^6 every five years, or approximately \$40.3 x 10^6 per year.

Therefore, the levelized value of testing is \$1.62 x 10^6 every five years (\$3.24 x 10^5 per year).

Table 7-7
Base Case Optimal Policy With Testing

OPTIMAL CABLE STRATEGY WITH TESTING			
	Failures		
Age	0	1	2
0	No Action		
5	No Action	No Action	
10	No Action	No Action	No Action
15	No Action	Test	Rejuvenate
20	No Action	Test	Replace
25	Test	Replace	Replace
30	Replace	Replace	Replace
35	Replace	Replace	Replace
40	Replace	Replace	Replace

The contingent policy with testing is given in Table 7-8. The Table indicates that the decision changes (from *No Action*) in state (15,1) if the test outcome indicates some degradation, and the decision changes (from *Replace*) in states (20,1) and (25,0) if the test outcome indicates no degradation.

Table 7-8
Contingent Test Strategy

STRATEGY CONTINGENT ON TEST OUTCOME Shaded cells indicate change in policy due to test					
Age	Failures	No Degrade	Mild Degrade	Mod Degrade	Severe Degrade
15	1	No Action	Rejuvenate	Rejuvenate	Rejuvenate
20	1	No Action	Replace	Replace	Replace
25	0	No Action	Replace	Replace	Replace

This completes the solution of the base case.

Sensitivity Analysis

The purpose of sensitivity analysis is to determine whether the base case policy is robust, or relatively unchanging as the values of the parameters change. The present methodology supports virtually any kind of sensitivity analysis. Sensitivity results are shown for failure cost, replacement cost, and the hazard rate parameters.

The sensitivity analysis addresses three outcome variables of interest in each case: (a) the cost of the optimal policy, compared with that of the policy that does not replace aging assets (what is termed the No Action or Repair Only policy); (b) the value of testing; and (c) the replacement age of a cable section that has experienced no previous failures.

Sensitivity With Respect to Changes in Failure Cost

The base case failure cost is $18,500 per outage. This includes the costs to the utility and the costs to the customer. The base case levelized optimal policy cost is $202.9 x 10^6 in each 5-year period ($40.6 x 10^6. per year). The base case levelized *No Action* policy cost is $301.0 x 10^6 in each 5-year period ($60.2 x 10^6. per year).

Figure 7-1a presents the variation in policy cost as a function of the variation in outage cost. Two observations are (1) that the optimal policy cost is less than the *No Action* policy cost, and the difference between them increases as the failure cost increases and (2) the policy cost of the *No Action* policy is more sensitive to changes in failure cost than is the optimal policy cost. (Economists refer to this relationship between the optimal policy cost and the failure cost as an *inelastic* one. The elasticity is the ratio of the percentage changes of the variables. When the elasticity is less than 1, the inelastic case, the percentage change in the dependent variable is less than the percentage change in the independent variable. In this case, the failure cost is the independent variable. When it changes by 50%, the dependent variable, the policy cost, changes by less than 50%.)

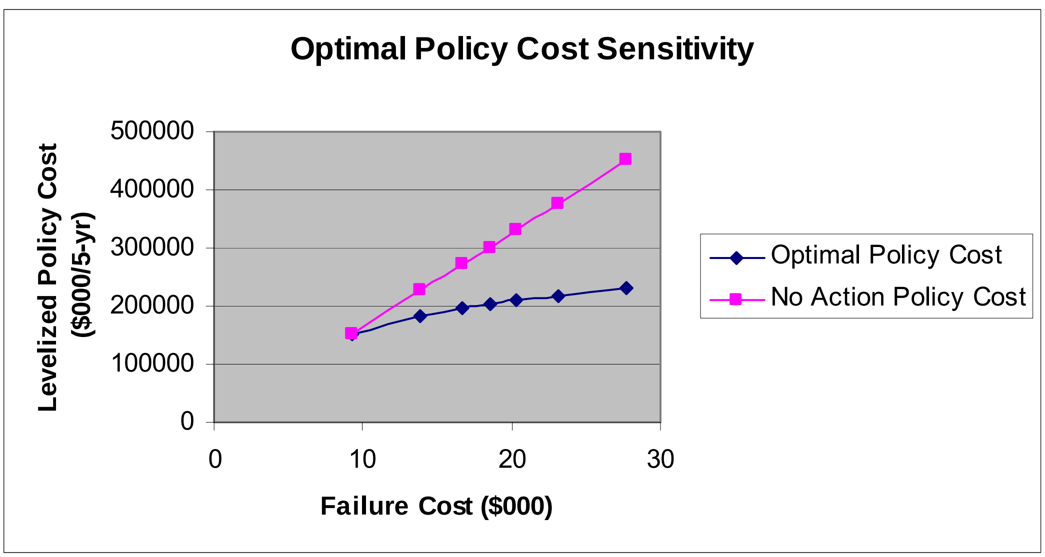

Figure 7-1a
Sensitivity of Policy Cost to Failure Cost

Figure 7-1b presents the sensitivity of the value of testing to changes in failure cost. The base case value of testing is \$1.62 x 10^6 per 5-year period (\$3.24 x 10^5 per year).. The sensitivity of the value of testing is variable. At the low end of the variation in failure cost, there is no value to testing because the policy is the No Action policy, as indicated in Figure 7-1a.

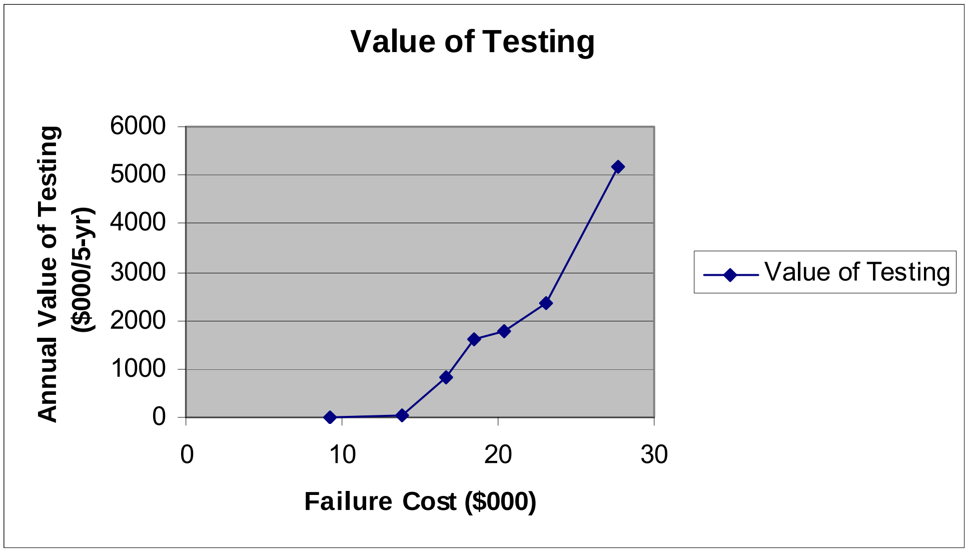

Figure 7-1b
Sensitivity of the Value of Testing to Failure Cost

Figure 7-1c presents the sensitivity of the replacement age to the failure cost. The replacement age is the age at which a cable segment that has no previous failures is replaced. This sensitivity is one way to characterize the overall policy sensitivity. The base case value for the replacement age is 25 years, as indicated in Table 7-6. The replacement age is inelastic.

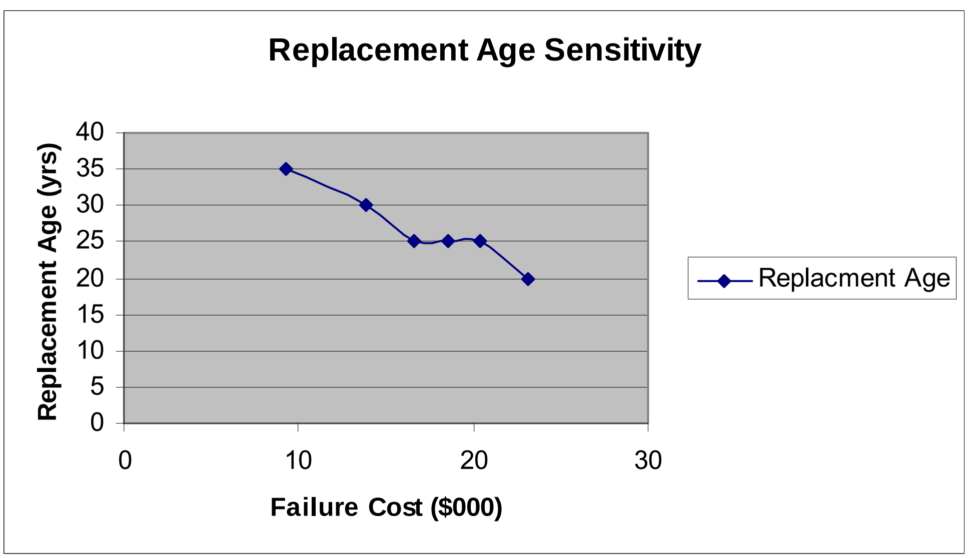

Figure 7-1c
Sensitivity of Replacement Age to Failure Cost

Sensitivity With Respect to Changes in Replacement Cost

The base case replacement cost is $23,000 per cable segment (500 feet).

Figures 7-2a, b, c present the sensitivities with respect to replacement cost.

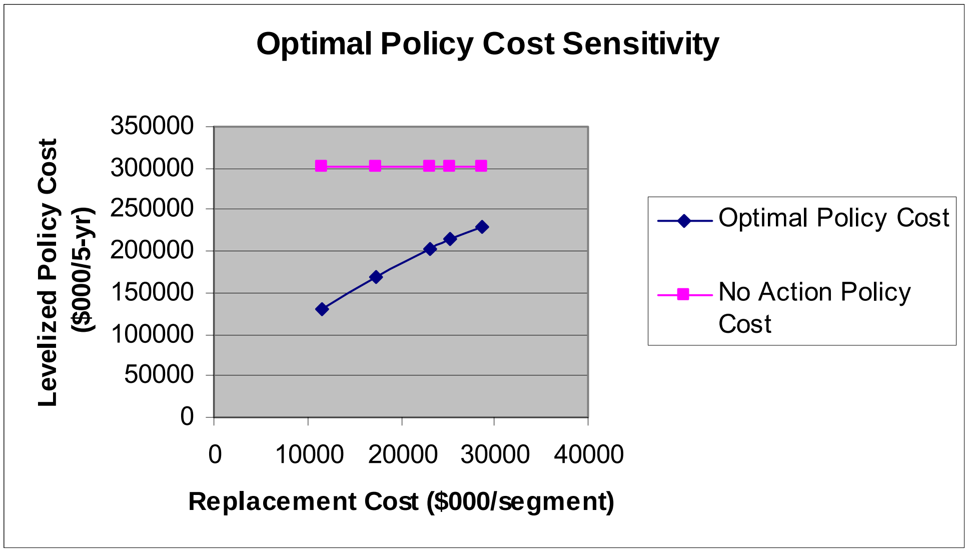

Figure 7-2a
Sensitivity of Policy Cost to Replacement Cost

The *No Action* policy cost is completely inelastic—it does not change with respect to changes in replacement cost. This is because no replacements are made when this policy is adopted. The optimal policy cost is relatively inelastic, although it is sensitive to changes in replacement cost.

Figure 7-2b presents the value of testing as a function of replacement cost. Not only is the value of testing sensitive to changes in replacement cost, it is also not monotone. This is because, in this case, there are policy changes that occur as replacement cost varies and for some policies testing plays a very small role.

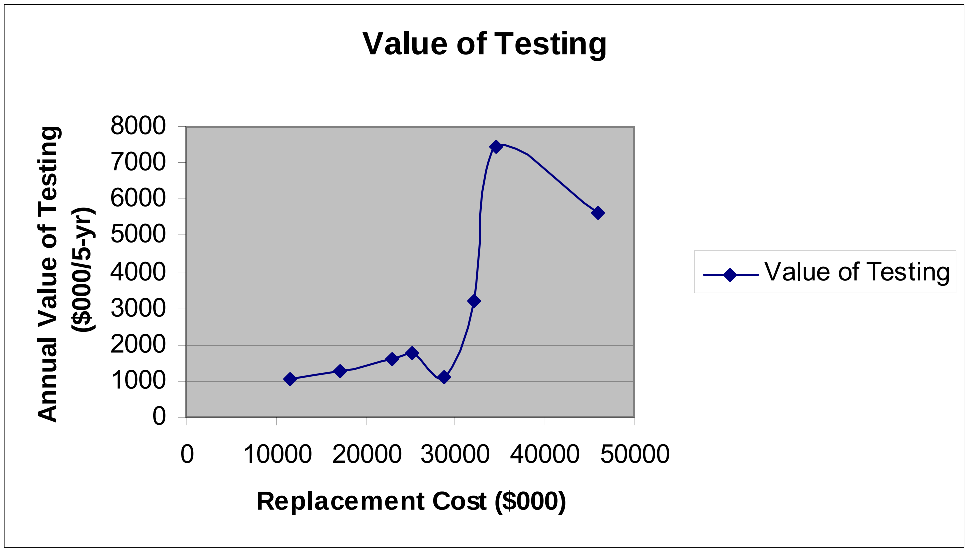

Figure 7-2b
Sensitivity of the Value of Testing to Replacement Cost

Figure 7-2c presents the sensitivity of replacement age to replacement cost. Replacement age is sensitive to increases in replacement cost, relative to the base case, and relatively inelastic for replacement cost decreases.

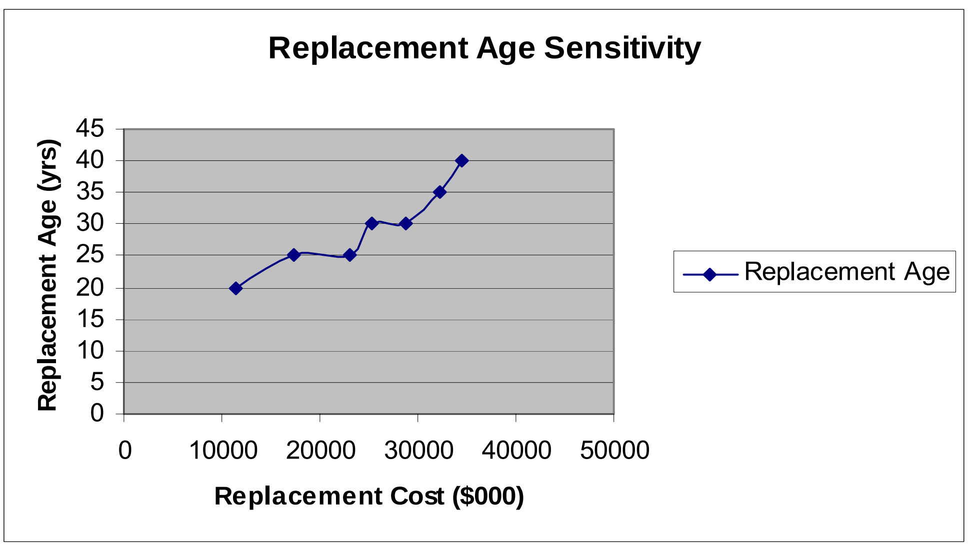

Figure 7-2c
Sensitivity of Replacement Age to Replacement Cost

Sensitivity With Respect to Changes in Hazard Rate Parameters

The piecewise linear hazard function has three parameters. The base case values of the parameters are: steady-state failure rate h_{ss} = 6.90 x 10^{-5} failures/ft/yr = 0.3642 failures/mile/yr, onset of burnout T = 14 years, and slope of burnout m = 0.361 failures/mile/yr, which is equivalent to setting the doubling time during burnout = 2.77 years.

The sensitivities are given in Figures 7-3, 7-4, and 7-5.

The most sensitive parameter appears to be the steady-state hazard rate, although the onset of burnout influences all the dependent variables. The slope of the burnout period is not very sensitive, by comparison. Note that the value of testing is not monotonic in each case. The graphs are appended without further comment.

Sensitivity With Respect to Steady-State Hazard Rate

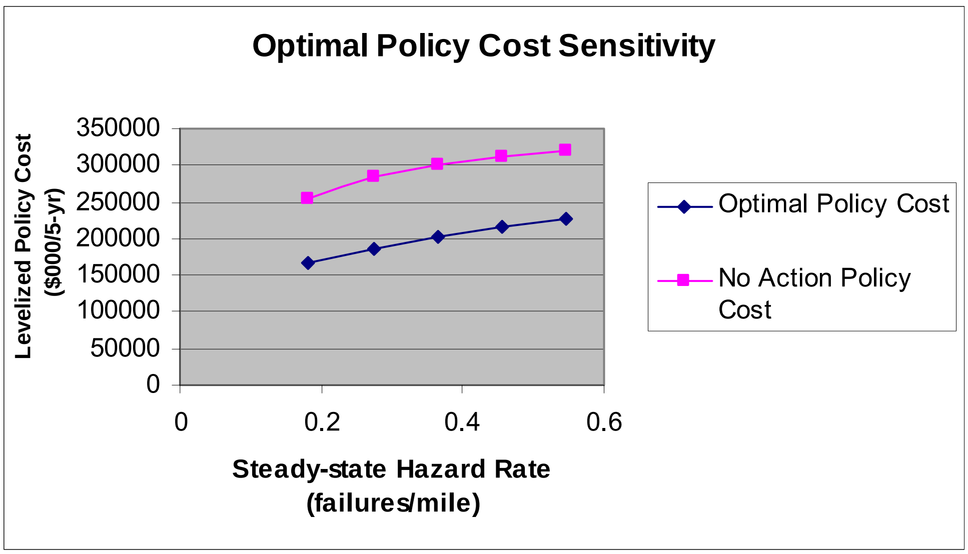

Figure 7-3a
Sensitivity of Policy Cost to Steady-State Hazard Rate

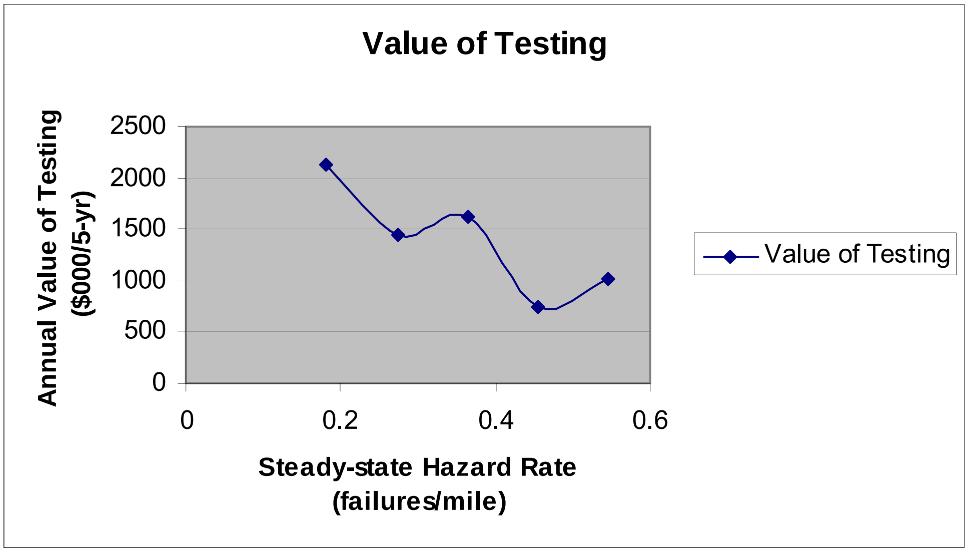

Figure 7-3b
Sensitivity of the Value of Testing to Steady-State Hazard Rate

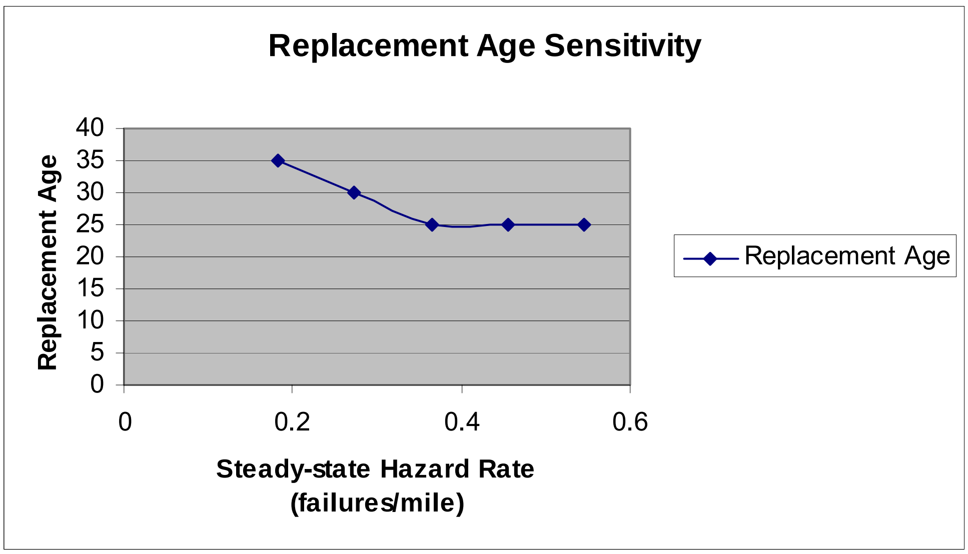

Figure 7-3c
Sensitivity of Replacement Age to Steady-State Hazard Rate

Sensitivity With Respect To Hazard Rate Doubling Time

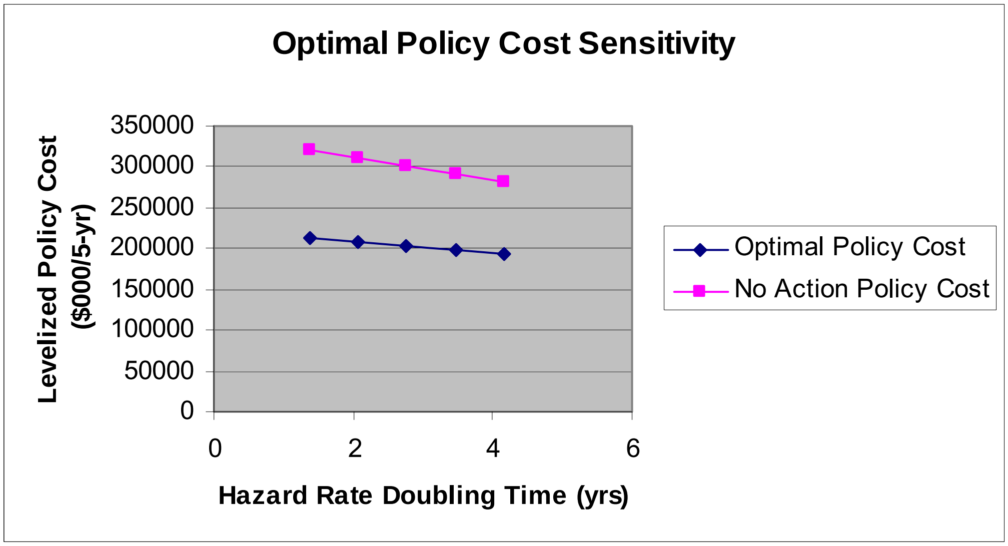

Figure 7-4a
Sensitivity of Policy Cost to Hazard Rate Doubling Time

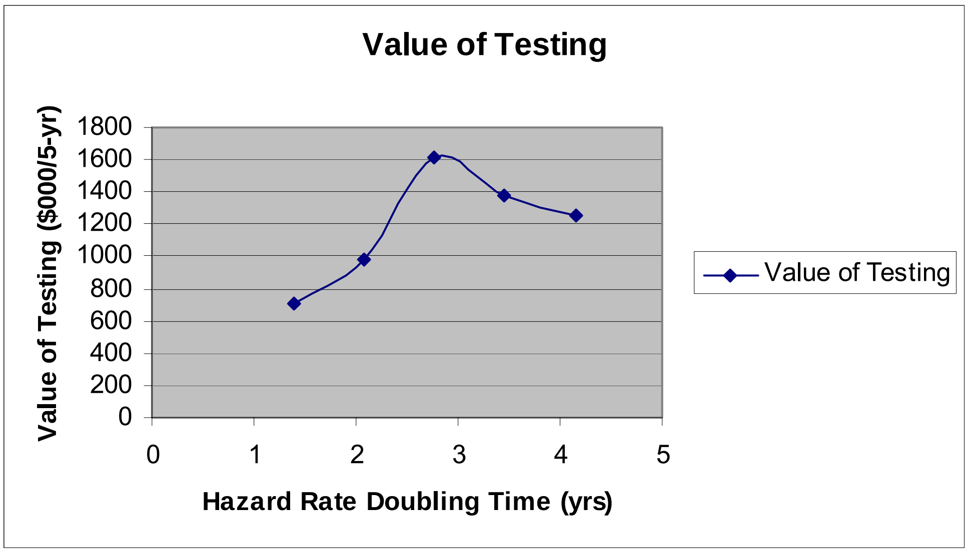

Figure 7-4b
Sensitivity of the Value of Testing to Hazard Rate Doubling Time

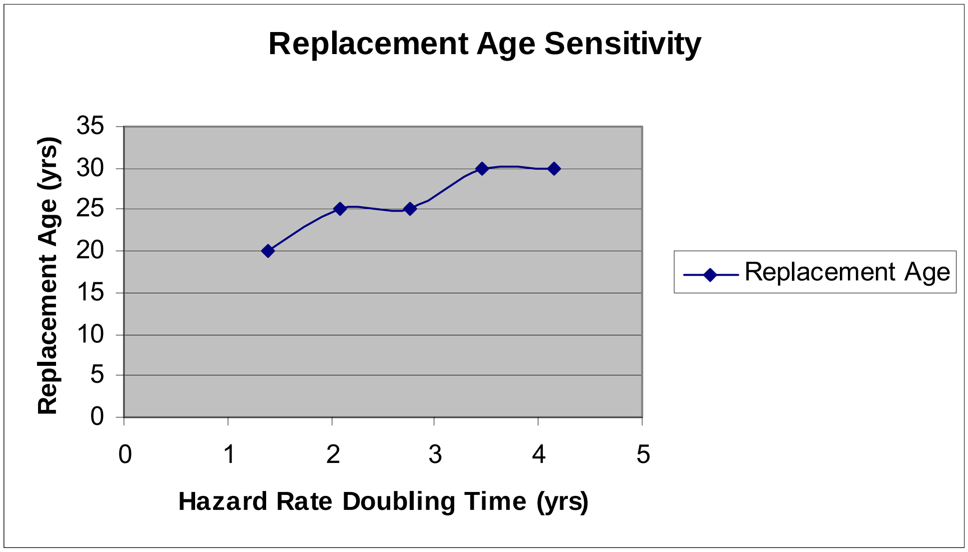

Figure 7-4c
Sensitivity of Replacement Age to Hazard Rate Doubling Time

Sensitivity With Respect to Onset of Burnout

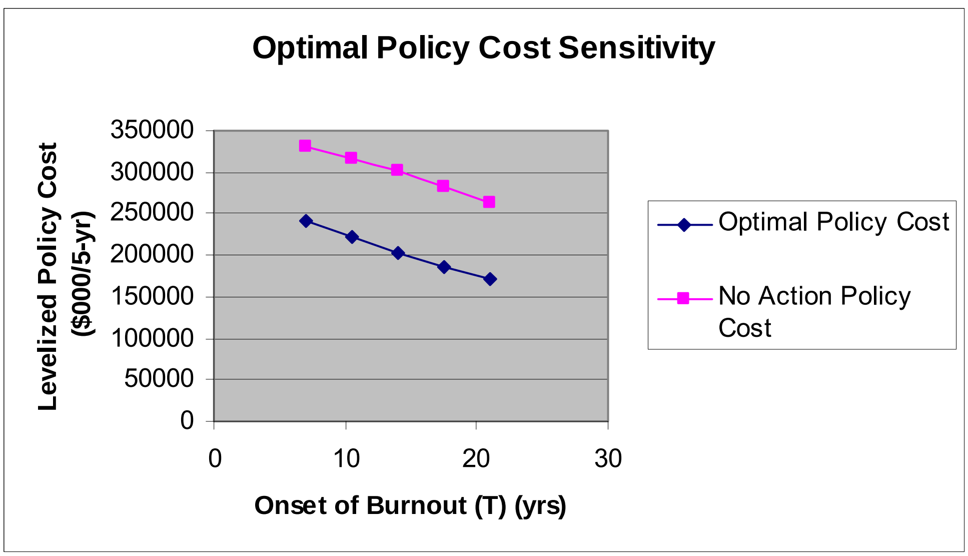

Figure 7-5a
Sensitivity of Policy Cost to Onset of Burnout

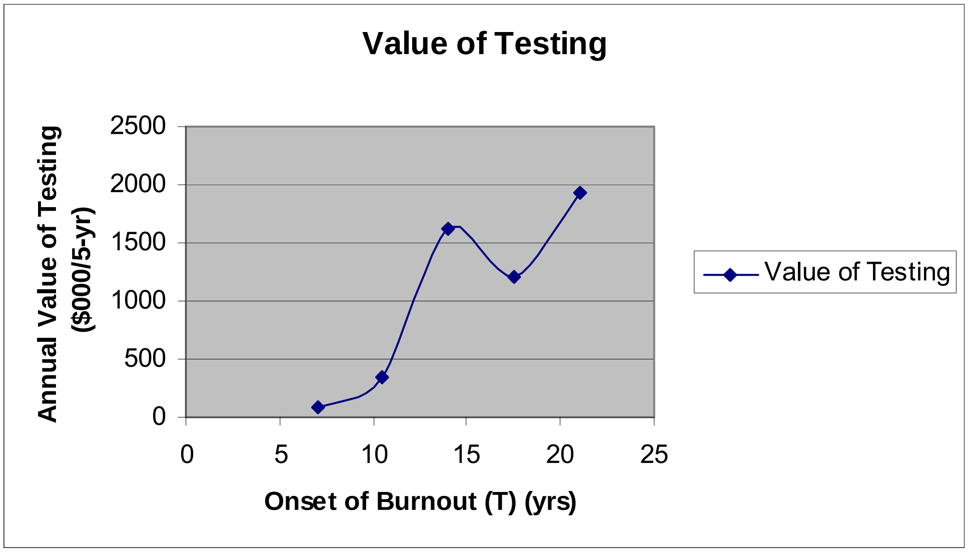

Figure 7-5b
Sensitivity of the Value of Testing to Onset of Burnout

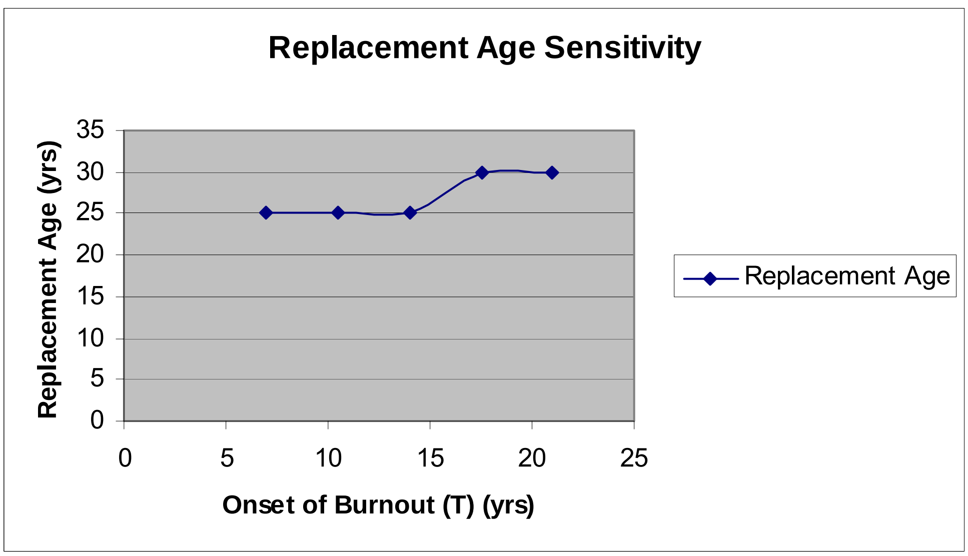

Figure 7-5c
Sensitivity of Replacement Age to Onset of Burnout

This completes the sample analysis.

8 RECOMMENDATIONS

This report presents a method that can be applied to solve the problem of managing a population of underground distribution cables. It follows several prior reports on the general issue of formulating cost-effective asset management policies for aging power delivery infrastructure (EPRI 1000422, 1001703, 1001704, 1001872, 1001873, 1002086, 1002092). Building on that general framework, this report addresses several specific aspects of the problem as it relates to underground cables: definition of cable states, dynamic equations, data analysis, and failure models. The experience reported here suggests several additional lines of research with the aim of improving the applicability of the methodology to cable management:

- Expert Elicitation of Key Parameters
- Data Analysis
- Asset Management Policies

Expert Elicitation of Key Parameters

The decision framework described in this report relies heavily on a number of parameters for which the judgment of experts is currently the best source. These parameters include:

- the differential effects on the hazard rates of the following factors:
  - condition states of the cable insulation and the neutral
  - environmental and operating stressors
  - past failures
- the proportion of the cable population in each condition state as a function of age
- the accuracy of test protocols in revealing the true condition of the insulation and neutral

Essentially, at present, statistical data analysis supports estimating the basic hazard functions with some level of specificity by type; the remainder of the parameters primarily have been estimated by experts.

In the long-run, one needs to calibrate the parameters derived from expert judgment to actual statistical data to the extent possible. These parameters represent the collective, informed judgment of the experts on the panel, but that information needs to be validated by comparing them with empirically derived estimates using actual field and laboratory data. Experience with PM Basis database, reported in EPRI report 1009633, has generally shown reasonable agreement between expert judgment and empirical estimates of failure rates, and it is expected that this experience will also hold true for underground distribution cables. The issues involved with calibrating the equipment failure model parallel those for data analysis generally, which are discussed in the next section.

Furthermore, with systematic efforts across the industry, it should be possible in the future to collect data to validate the expert judgments with statistical analysis. Such efforts are already underway with the EPRI Cable Testing Network (ECTN). In these kinds of collaborative efforts, the decision framework discussed in the report can serve to guide the design of the data collection. The framework defines the parameters of importance in cable asset management decisions. The economic model can also be used, through sensitivity analysis, to identify the parameters that have the greatest impact on the decisions; these parameters should be the primary focus of the data collection effort. Further developments needed for successful industry-wide data analysis include:

- standardizing the definitions of condition states, failure codes, and other dimensions to insure consistent measurement across multiple companies
- establishing data collection procedures utilizing standardized definitions
- calibrating test protocols and developing causal relationships between test outcomes and cable condition
- implementing long-term data collection among a collaborative group of utilities
- conducting on-going failure cause analysis of selected equipment recovered form the field
- undertaking statistical analysis of the data and comparing with the results of expert judgment

Data Analysis

Ideally, the critical parameters of the decision model, particularly the hazard rates, should be determined empirically using actual data on cable maintenance. Chapter 6 presents the results of such an analysis based on data from one utility. Chapters 4 and 6 discuss in detail some of the issues encountered in that data analysis, particularly the noisiness of the data (even in a very large dataset) and the consequent difficulty in distinguishing hazard rates among the various condition states. There are additional issues that also need to be addressed.

Assembling a Dataset for Analysis

The first set of issues relates to assembling a dataset for analysis. As discussed in Chapters 2 and 3, one of the key design decisions in setting up a decision model is the definition of the state, and one of the key limitations on the state definition is the availability of data. For instance, if the state includes information on various degraded conditions, such as the presence of corroded neutral, then data on degraded conditions is needed in order to estimate different hazard rates for different conditions. Similarly, if the state includes information on what prior maintenance a cable segment has received, then data on prior cable maintenance is needed in order to estimate different hazard rates for different maintenance histories. Without such data, meaningful distinctions in the underground distribution cable management policy cannot be made based on cable condition or prior treatments.

In the short run, the decision model a particular utility can use may depend on what data it already has assembled. However, in the longer run, a utility can specify the data it wants to collect and can develop systems and processes for collecting it. In fact, condition assessment studies are frequently a priority need as a utility adopts an asset management philosophy. Thus, the specification of the decision model can provide significant guidance to the data collection by indicating what data is needed to support it. Furthermore, testing the sensitivity of the decision model for variations in the parameters can provide guidance on the relative importance of collecting various kinds of data and on the required accuracy of the estimates.

Does the Dataset Reflect Actual Underground Cable Failure Experience?

The second set of issues relates to determining the extent to which the dataset reflects actual cable failure experience. In particular, if the dataset does not capture certain kinds of failures, then there may be biases in the hazard rate estimates or there may be important aspects of cable condition that are not represented in the state. One issue is completeness of the data, such that all failures of the inventory of cable are counted. Another issue is whether the effects of cable maintenance have been properly accounted for in the dataset.

Validating the Hazard Rate

A third set of issues relates to validating the estimated hazard rate found using the methods presented in this report. The hazard rate represents a prediction about future failures. It would be very valuable for a utility to validate the prediction by tracking the behavior of the cable inventory. Further, if the equipment failure model is available, it can be used to predict overall failure rates that may or may not be consistent with the hazard function. Using the equipment failure model to predict overall cable failure rates entails a bottom-up process of aggregating failure rates from many disparate mechanisms. If the two formulations do not agree, a utility is faced with the task of "debugging" the equipment failure model to determine which of the component degradation mechanisms may be at fault. One way to validate the equipment failure model is to track more detailed information on the condition of cables in the population over time. Most utilities do not keep such information currently; however, as discussed below, as utilities move toward condition-based maintenance of their distribution equipment, the necessary systems and processes for collecting and tracking equipment condition will be put in place. The equipment failure models will play an importance role in defining what condition information needs to be tracked.

What Level of Accuracy Is Necessary to Support the Decision Models?

A fourth set of issues relates to determining the level of accuracy of the hazard rate estimates necessary to support the decision models. Experience has shown that the decisions generated by policy models of the type discussed in the report may not be particularly sensitive to the precision of the failure rate estimates. For example, in the piecewise linear hazard rate model discussed in Chapter 4, it may be sufficient to estimate the steady-state hazard rates within, say, an order of magnitude and the start of the burn-out period within, say, five years. Sensitivity analysis of a similar decision model for underground cable replacement, discussed in the EPRI report *Guidelines for Intelligent Asset Replacement* (1002086), indicates that the most sensitive parameters for those decisions are the steady-state failure rate and the rate of failure acceleration due to prior failures; the time of onset and rate of burn-out are much less sensitive parameters. Performing a sensitivity analysis of a cable decision model, by varying the input parameters and observing the changes in the decisions, is an essential step for determining where to focus efforts to improve the parameter estimates.

Condition-Based Asset Management Policies

Further consideration of the analytical framework discussed in this report suggests that utilities can enhance their management policies by shifting cable management from time-based to condition-based policies.

Although the decision models discussed in Chapter 3 focus on a time-based policies for cable management, the analytical framework used in this report actually has a much more general capability to develop management policies base on cable condition. The decision framework represents the decisions regarding cable management as depending on the cable state, and the state definition can explicitly represent the condition of the cables, such as the presence or extent of insulation degradation. However, the shift from a time-based to a condition-based management strategy represents more than a choice of model formulation; it has profound implications for the maintenance process used by a utility. In particular, it affects the underlying information systems, maintenance management procedures, and crew training and utilization used by the utility. While a complete discussion of these implications is beyond the scope of this report, several observations are in order.

First, using a condition-based management policy requires that information about cable condition be routinely collected and used in dispatching maintenance projects. The utility needs to establish standardized condition codes, capture condition assessments made by field crews, maintain records of test outcomes over time, track condition deterioration over time, and utilize condition information in deciding when and how to maintain the cable inventory. The costs of developing the information systems and gathering the data must be considered in the decision to adopt condition-based management.

As discussed in this report, the decision model establishes what information on cable condition needs to be collected and how it will be used. Furthermore, an equipment failure model provides a framework for condition coding by specifying the important degradation mechanisms and the activities that detect them. Thus, the methodology discussed in this report provides a basis for moving from time-based to condition-based management policies.

Second, condition-based management changes maintenance management. At a macro level, condition-based management may lead to different inspection/testing/maintenance intervals for cables with different service conditions or environmental stressors. For instance, lines in different locations might be maintained on different schedules because their cable deterioration rates differ. At a micro level, cables will not be treated unless the test outcomes indicate certain levels of deterioration. Cable inspections without maintenance might be done more frequently in order to detect the need for maintenance before deterioration proceeds beyond the level at which maintenance is required. Cable testing and testing accuracy may become more important factors in maintenance decisions. Again, the decision models discussed in this report play a significant role, not only in determining what maintenance decisions to make based on cable condition, but also in testing whether a condition-based strategy makes sense from an economic and reliability perspective.

Third, implementing a condition-based cable management policy will require providing specific guidance to the field crews as to what maintenance actions should be undertaken based on cable condition. One needs to recognize that a policy based on an index of cable condition may be difficult to implement if that index is not readily observable in the field. A further concern is that experienced field crews may not readily accept treatment policies based on unfamiliar methods of assessing cable condition. These issues imply that implementing a condition-based management policy will require revising a utility's maintenance standards, maintenance actions, and testing protocols and retraining field crews to conform to those revisions. The costs of doing so must be considered in making the decision to adopt condition-based management.

Conclusions

This report has established a new analytical framework for developing management polices for underground distribution cables. Key features of this framework include:

- The objective in this decision framework is to minimize the lifecycle cost of maintaining the cable inventory, subject to serviceability requirements related to the condition of the cable.
- The decision framework summarizes the condition of a cable by its *state*. The state includes both observable components (age and number of prior failures) and unobservable components (condition of the insulation and the concentric neutral).
- The decision framework represents the dynamic evolution of the state mathematically, using a set of equations that provide a forecast of future condition.
- The decision framework represents the decisions regarding cable management as depending on the cable state. The decision framework develops a *state-dependent policy* that *minimizes the lifecycle cost* of maintaining the cable population.
- The dynamic equations describe the cable state evolution probabilistically – given the current cable state, there will be a probability distribution of states in which the cable might be observed in the next time period.
- Tests can give information about the unobservable components of the state, but testing is not completely accurate, and the relationship between test outcome and future failure rates is not firmly established.
- Testing is costly and so the decision to test depends on the value of the information it provides. Testing strategy with therefore depend on the cable's state, and in some states the value of the information will be too low to justify the expense of testing.
- The dynamic equations represent the evolution of the entire cable *population* rather than that of an individual cable. The population dynamics take advantage of the law of large numbers.
- The deterioration of a cable's condition is represented mathematically by a probability distribution called the *hazard function*. The hazard function depends on both the observable and unobservable components of the state.

- Developing good estimates of the hazard function for underground cables presents a primary challenge in implementing the decision models. This report discusses making these estimates based statistical modeling of failure data. However, much of the dependence of the hazard function on the unobservable state components can only be determined by relying on expert judgment.
- A statistical model specifies a functional form for the hazard function which depends on several parameters that can be estimated from the hazard data. The commonly used linear regression model does not represent hazard data very well. Instead, this report discusses using a piecewise linear model and a Weibull that more closely represent the expected and observed behavior of cable failure data. The report provides examples of the estimation procedure.
- This report also discusses using expert judgment to estimate parameters for which the available data are not sufficient to permit statistical analysis. An equipment failure model defines the various modes of cable deterioration over time, identifies how environmental stressors and service conditions influence deterioration, and quantifies the rates at which deterioration occurs. The model thus permits projecting failure rates for the equipment as a function of the various service conditions and stressors that may be present.

This report concludes with several recommendations for additional lines of research with the aim of improving the applicability of the methodology to cable management:

- Expert Elicitation of Key Parameters
- Data Analysis
- Asset Management Policies

9
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A
UNDERGROUND CABLE TECHNICAL CONSIDERATIONS

Introduction

Medium-voltage cables represent a major asset for electrical utilities. Some medium voltage cable circuits continue to operate successfully after more than sixty years in service, while, on the other hand some vintages of cables have been prone to high failure rates. A high percentage of the installed cables are more than thirty years old and may be considered to be approaching the end of their useful lives. In addition, the high cost of cable replacement, the loss of revenue and customer dissatisfaction when a premature cable circuit failure occurs make the management of the cable assets a very high priority for utilities. This appendix gives the technical background, by describing typical cables and accessories, their aging mechanisms, testing, refurbishment and maintenance.

Cable Systems

Although high voltage cables can be constructed from different materials, they have two basic designs:

a) a coaxial cable which has a single high voltage conductor to carry the load current that is insulated from an outer low voltage conductor , or

b) a three conductor cable which has three high voltage conductors installed inside a low voltage sheath. This design of cable is used in three phase circuits.

The thickness of the insulation between the high and low voltage conductors depends on the type of insulation used and the voltage rating of the cable. Other components are added to the cable to serve specific functions as described below. Cables are joined together by splices or joints and have terminations at the ends (usually called potheads for PILC cables). The conductors are either soldered together or crimped.

There are two main insulation systems used in medium voltage cables, cables insulated with oil impregnated paper and referred to as paper insulated lead covered (PILC) and those having extruded insulation. The extruded insulation may be butyl rubber, low molecular weight polyethylene (LMWPE), cross-linked polyethylene (XLPE), tree retardant XLPE (TRXLPE), and ethylene propylene rubber (EPR). More than 90% of the extruded cables installed today are TRXLPE or EPR.

PILC Cable systems

The earliest PILC cables were installed in Europe in the 1890s, and their design and construction developed over the next thirty to fifty years to essentially the design in use today. This type of cable has given excellent service, with large quantities still in service after more than sixty years. Examples of single and three conductor 15 kV PILC cables are shown in Figure A-1. In Figure A-1, the conductor (A), either aluminum or copper strands, carries the load current. A stranded conductor allows greater flexibility of the cable. In the three conductor cable the conductor may have a sectored shape to reduce the overall diameter of the cable. To reduce the magnitude of the local electric field at the outer strands, carbon impregnated paper tapes (B) are spirally wrapped around the conductor. The main insulation (paper tapes) (C) is then wound spirally over the conductors, the total thickness depending on the voltage rating of the cable. There is a small gap between the turns to allow easier impregnation of the oil and to allow bending of the cable without wrinkling of the paper tapes. The correct paper tension must be used during manufacture and care must be taken to ensure that gaps between the turns are not adjacent to each other in successive layers. An insulation screen (D) consisting of carbon impregnated paper tapes is wrapped over the insulation to maintain the electric field radial within the insulation. In the single conductor cable, Figure A-1a, the lead sheath (E) is then extruded over which a polymer jacket (F) is extruded to prevent mechanical damage and corrosion of the lead. In the three conductor cable, Figure A-1b, a metal tape shield (E) is intercalated with the insulation screens (D) wound over each cable core to ensure good contact between the cores. Impregnated paper fillers (F) are applied to make the cable circular in shape. A binder copper tape (G) keeps the cores together to enable the installation of the lead sheath (H) and the extruded polymer jacket (J). To improve the electrical properties of the paper insulation, it is heated and placed under vacuum to reduce the moisture in the paper, prior to impregnation with oil. It is only when the paper is impregnated with oil that it has the high dielectric strength and low dielectric loss suitable for high voltage cable insulation. In 5 kV and some 8 kV three conductor cables, the insulated conductors do not have individual screens to control the electric field and are surrounded by a paper belt; this type of cable is referred to as belted cables.

Cables are joined together by splices or joints and have terminations at the ends (usually called potheads for PILC cables). The conductors are either soldered together or crimped. For PILC cable splices the insulation is impregnated paper or crepe paper hand wrapped to the necessary thickness according to the voltage rating of the cable. Carbon impregnated paper and metal tapes are then wrapped over the insulation to make a conducting path between the sheaths of the two cables being spliced together. A lead sheath is then installed over the joint and soldered onto the sheath of each cable to prevent the ingress of moisture into the cable circuit. The present trend is use a shrinkable polymer in place of the lead sheath. In potheads, the high voltage cable conductors are connected to connectors of the pothead, which sit on top of porcelain insulators that are on top of a metal enclosure, see Figure A-2. The metal enclosure is filled with bitumen to prevent moisture ingress and give additional insulation. As with the splices, there is a trend to use shrinkable polymer tubing and non-ceramic insulators to replace the metal and porcelain components. Splicing and terminating PILC cables requires considerable expertise. This expertise in utilities is slowly disappearing as PILC cables have been largely superseded by extruded polymeric cables.

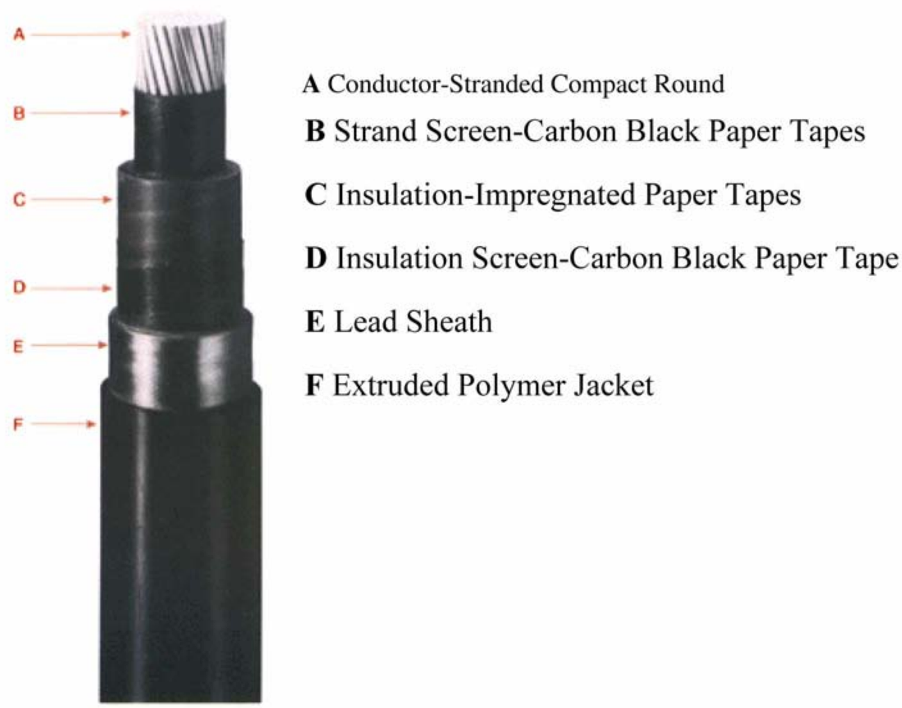

Figure A-1a
Single Conductor 15 kV Paper Insulated Lead Covered Cable (Figure Courtesy of Okonite Cables)

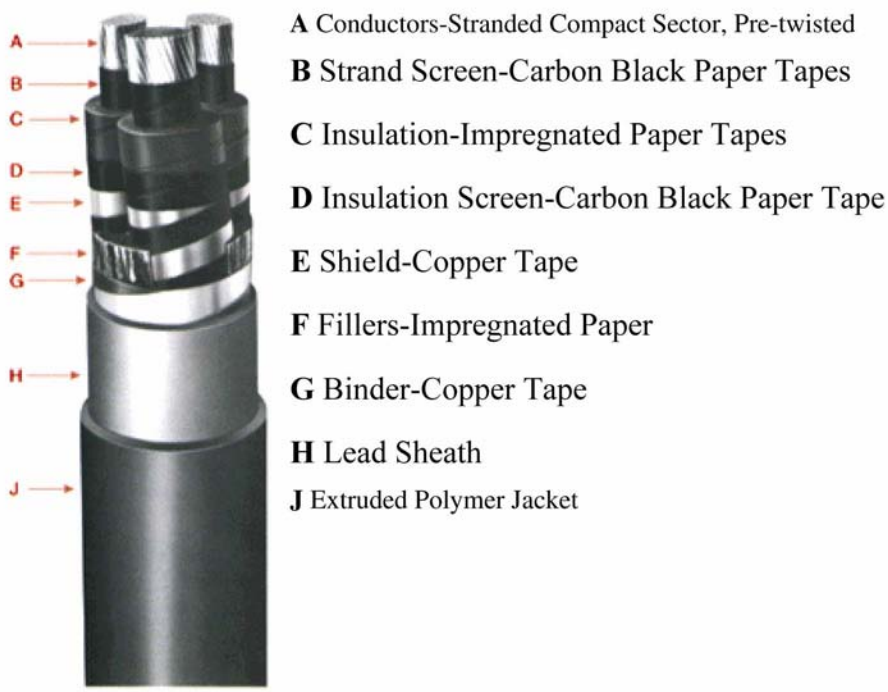

Figure A-1b
Three Conductor 15 kV Paper Insulated Lead Covered Cable (Figure Courtesy of Okonite Cables)

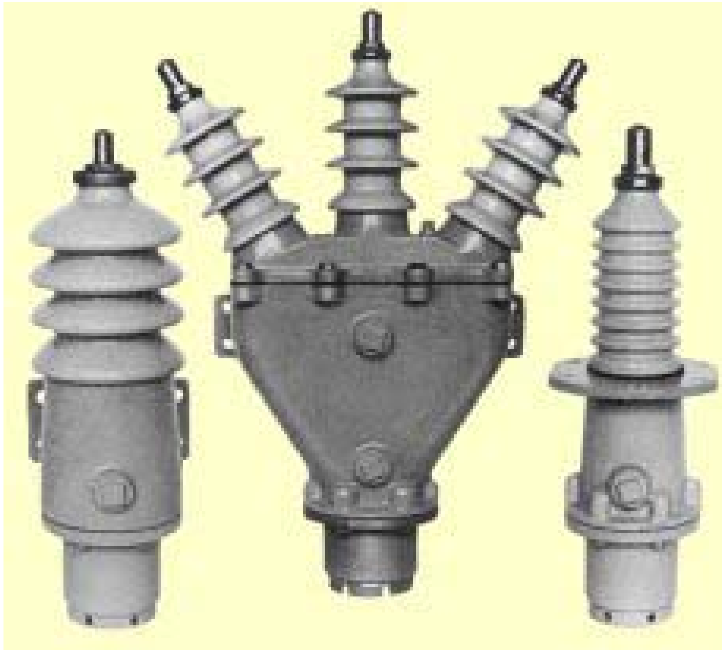

Figure A-2
Examples of Single and Three Conductor PILC Potheads (Photo From G&W Web Site)

Extruded Cable Systems

The first extruded cables were introduced in the 1930s and used rubber as the insulation. Butyl rubber was used as medium voltage cable insulation in the middle of the last century but was largely replaced by ethylene propylene rubber (EPR). The term EPR is used in the cable industry to cover two classes of materials, a cross-linked copolymer of ethylene and propylene, and also a cross-linked terpolymer of ethylene, propylene and a diene, sometimes referred to as EPDM. Another type of extruded cable was introduced in the early 1960s. The insulation was low molecular weight polyethylene (LMWPE).

Figure A-3 shows an example of the typical construction of an extruded medium voltage cable.

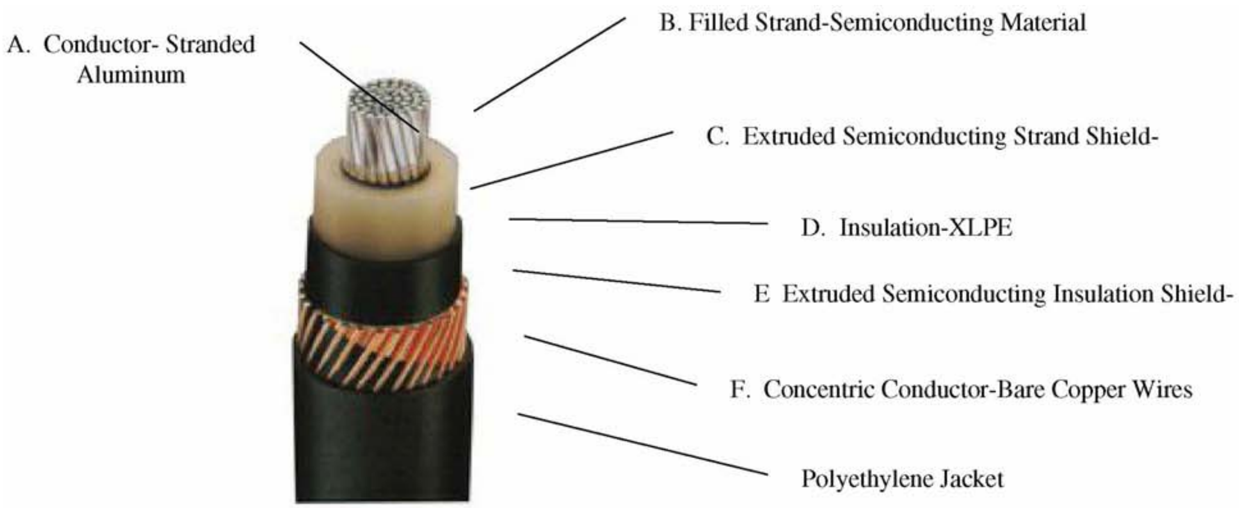

Figure A-3
Typical Present Day Extruded Medium Voltage Cable (XLPE) (Figure Courtesy of Nexans Cables)

The conductor (A) is stranded aluminum or copper, although smaller conductor sizes may be solid. The volume between the strands may or may not be filled with a semiconducting strand fill material (B) to prevent moisture migration along the conductor. A thin semiconducting conductor shield (carbon loaded polymer) is extruded over the conductor to eliminate the increases in electric field due to the conductor strands and to ensure there are no voids between the conductor and the main insulation (D). The main insulations presently in use are tree retardant cross-linked polyethylene (TRXLPE) and ethylene propylene rubber (EPR). These two insulations have largely replaced butyl rubber (used in the 40s and 50s), low molecular weight polyethylene (LMWPE, used in the 60s and 70s), and cross-linked polyethylene (XLPE, used in the late 60s to the late 90s). There are different formulations of TRXLPE and EPR depending on the material supplier and/or cable manufacturer. Another thin semiconducting shield (E) is extruded over the insulation to control the electric field and to ensure that there are no voids between the insulation and the concentric neutral wires (F). The concentric neutral has different forms, spirally wound copper neutral wires, neutral wires with copper tape, copper straps, polymer/metal laminated tapes, longitudinally wound corrugated copper sheath, and extruded lead. The type of neutral depends on the application and installation of a particular cable. Finally an optional insulating or semiconducting polymeric jacket (G) is extruded over the neutral to give the cable additional mechanical protection and to slow the ingress of moisture into the insulation. Early jackets were extruded over the concentric neutral, thus enabling water, which permeated the jacket or entered through cracks or tears, to travel along a cable in the spaces between the neutral conductors underneath the jacket. Encapsulating the neutral wires in the jacket prevents the longitudinal migration of moisture along the cable.

It should be noted that the manufacturing technology to make extruded cables today is significantly improved over that available in the 60s and 70s. For example the shields and insulation of early vintage cables were extruded in separate runs, which allowed contamination of the surface between extrusion runs. Manufacturers in the 60s used a tape for one of the shields. An improvement came in the early 70s with the introduction of the simultaneous extrusion of the conductor shield and the insulation, with the insulation shield applied in a subsequent extrusion. It was not until the late 70s and early 80s that 'true triple" extrusion was widely used, which eliminated potential sources of contamination. During this time there was also a change in the process for cross-linking materials with the replacement of steam curing by dry nitrogen curing. Further significant changes were the introduction of cleaner materials, improved handling and transportation of the materials between the suppliers and the cable manufacturers, and cleaner manufacturing conditions.

The accessories for extruded cables also evolved with the cables. Initial splices and terminations were prepared by hand, using self-amalgamating insulating and semiconducting tapes. These have been replaced by pre-molded stress cones, the use of stress relief materials that have non-linear dielectric properties, cold and heat shrinkable polymers, and the use of separable connectors.

Aging and Degradation

This section describes the aging and degradation mechanisms of PILC and extruded insulation cables.

Aging can be defined as the changes in properties that occur with time due to the stresses (electrical, thermal, mechanical, and environmental) that are applied to the components of cable circuits. Several aging mechanisms may be occurring simultaneously. Oxidation is an example of material aging. Aging can lead to degradation, i.e., permanent damage that may eventually affect the ability of materials or systems to perform their normal functions. Examples of degradation are tracking in PILC cables and electrical treeing in extruded cables. A cable circuit fails when there is an electrical breakdown between the high voltage conductor and ground causing a fault in the system.

The mechanisms of aging leading to failure are statistical in nature, so that there may be considerable variations in how the mechanisms develop and progress (a) along the length of a cable and its accessories, and (b) between identical cable circuits operating in the same environment and under the same conditions. This will result in considerable variation in the times to failure.

PILC Cable Systems

The service experience with PILC cable systems has been excellent. The main mechanisms of aging are:

- Thermal aging at high operating temperatures causing oxidation of the oil/paper insulation. This can lead to eventual embrittlement and tearing of the paper tapes and an overall decrease in the resistance of the insulation. The dielectric loss of the insulation will increase and the dielectric strength will decrease.
- Electrical aging due to partial discharges in voids in the insulation. Repeated thermal expansion and contraction of a cable due to load cycling will cause gas-filled voids to occur in the oil-impregnated insulation, e.g., the butt gapes between adjacent turns. These voids tend to move in the insulation as the temperature changes and the oil migrates filling some

voids and creating others. If the voltage across a void exceeds the breakdown voltage of the gas in the void, the gas will breakdown, and a partial discharge (PD) will occur. Partial discharges generate minute high frequency currents that flow in the cable circuit, and these can be detected, measured, and located by PD detection techniques. As the voids tend to move, the PD also move and do not affect exactly the same region of the paper tapes. In addition, oil-impregnated paper is resistant to partial discharges, so it is not unusual for PILC to operate under continuous PD. However, if the PD become sufficiently localized the paper will eventually become degraded, begins to carbonize, and carbon tracks are formed (tracking). The carbon tracks cause a local increase in the electric field, further increasing the likelihood of partial discharge at that location. The carbon tracks gradually travel between the tapes and can reach up to several meters along the insulation before it bridges the high and low voltage conductors to cause failure. This process usually takes several years. Localization of voids and partial discharges can be due to contaminants in the insulation introduced during manufacture or installation, migration of the oil due to large changes in elevation of the cable, leakage of oil from cracks or holes in the lead sheath, or ingress of moisture into the insulation through cracks or holes in the lead sheath.

- Corrosion of the lead sheath causing a loss of oil and/or the ingress of moisture. The loss of oil will cause ‘dry spots’ in the insulation, which become sources of partial discharges and overheating of the cable. The ingress of moisture will also cause partial discharges, and/or cause an increase in dielectric losses that could lead to thermal runaway. The purpose of the polymer jacket over the lead sheath is to prevent corrosion of the sheath so it is important that the integrity of the jacket is maintained.
- Mechanical fatigue of the metal due to vibrations or at the interfaces between the cable and accessory sheaths can cause cracks, allowing the leaking of oil and the ingress of moisture and setting up conditions for localized electrical aging.
- Movement of the tapes along the cable, for example, due to incorrect tensioning of the tapes during manufacture, to cause ‘soft spots’ in the insulation, which become electrically weak regions and a possible site for partial discharges.

All the above mechanisms become more significant with the age of the cable, i.e., the older the cable circuit, the greater the probability of the occurrence of severe degradation and the higher the risk of failure. Thus older circuits should be checked regularly for leaks and subjected to diagnostic tests. The aging and failure mechanisms described above can be used as diagnostic tools to assess the condition of PILC cable circuit, as will be discussed later.

Extruded Cable Systems

The aging of extruded cable insulations is mainly caused by the action of different stresses on defects in the insulation or in the semiconducting shields such as contaminants, protrusion, and voids (CPVs). These defects are usually introduced during cable or accessory manufacture, storage, transportation, or installation, and many cables manufactured in the 60s, 70s and early 80s contained significant levels of contaminants. Examples of defects are metal or dirt particles, which may be soluble or insoluble in water, particles of semiconductor in the insulation, semiconductor protruding into the insulation, delamination of the semiconductor from the insulation, interfacial voids between the cable and accessory insulations, and gas-filled voids in the insulation.

Early extruded cables installed in the 60s and 70s did not have a jacket, so that the concentric neutral was exposed to soil conditions in direct-buried cable circuits. Water could readily diffuse into the insulation or from the soil or from the conductor if allowed to enter the conductor, for example during installation. Thus older extruded cables were likely to have contaminants in water saturated insulation and shields. However the factory tests on cables at that time, e.g., 1000 hours in a high temperature water bath, did not indicate that the water or level of contaminants would be a problem.

The main mechanisms of aging of extruded cable systems are:

- Partial discharges in voids created by poor adhesion between contaminants and the polymer insulation, and delamination between the shields and the insulation. The poor adhesion may not occur until after some years of repeated thermal cycling of the cables in service. The partial discharges eventually cause erosion and pitting of the void surfaces and lead to electrical treeing. Most polymers are not resistant to partial discharges. However EPR is more resistant than XLPE and TRXLPE to partial discharges, and there are significant differences in partial discharge resistance for different formulations of EPR
- Electrical treeing from contaminants, protrusions, and voids subjected to partial discharges. The electric field at the tips of protrusions or contaminants may be sufficiently high to cause local intrinsic breakdown of the insulation. The breakdown creates a small channel within which partial discharges occur that in turn create additional channels, see Figure A-4. The channels grow relatively rapidly to bridge the conductors and cause failure within days to weeks.

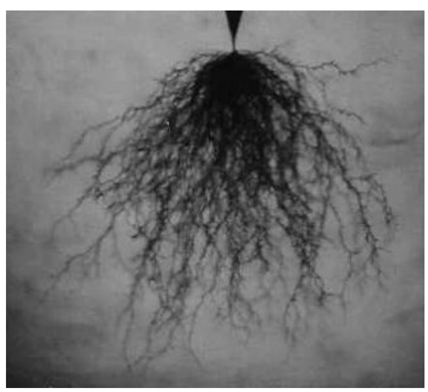

Figure A-4
Example of An Electrical Tree Growing From a Protrusion in XLPE

- Water treeing, which are tree-like structures consisting of water-filled microvoids. The water trees initiate from protrusions at the shield/insulation interface (vented trees) or from water-filled voids or contaminants within in the insulation. Water trees were first observed in the early 70s in field-aged low-molecular-weight polyethylene (LMWPE) and XLPE cables that had been in service for about five years. Figure A-5 shows examples of vented and bow-tie water trees. Water trees grow very slowly with time and may reach a limiting length, particularly bow-tie trees. However water trees from soluble contaminants grow more rapidly and do not tend to reach a limiting length.

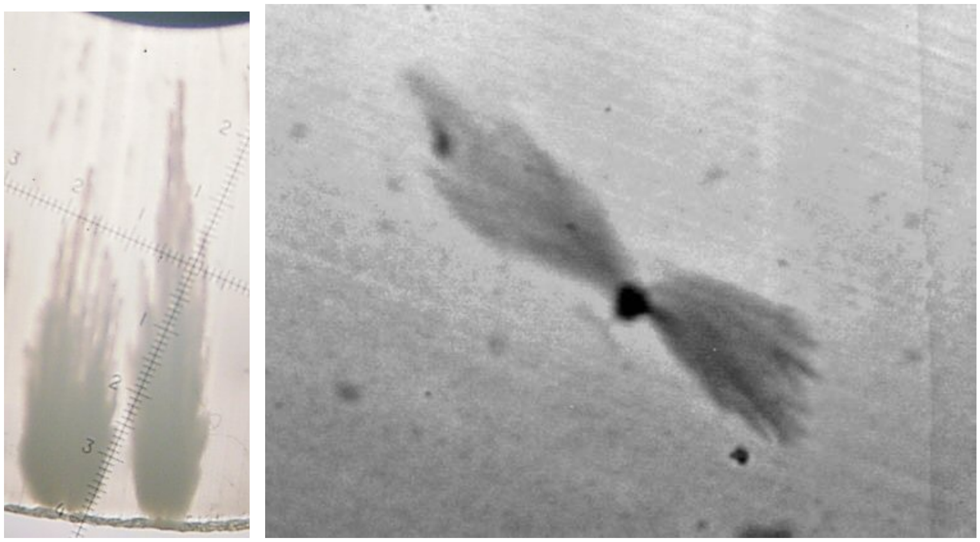

Figure A-5
Examples of Vented and Bow-Tie Water Trees in XLPE Insulation

- Thermal runaway, if the operating temperature is too high. The dielectric loss increases with temperature and, if it later becomes too large, for example at a hot spot where circuits are in close proximity to each other, the losses will keep increasing, raising the temperature even further and creating thermal runaway conditions.
- Concentric neutral corrosion due to the aggressive soil environment. The corrosion eats the concentric neutral wires and causes an increase in the resistance of the concentric neutral. If there is a break in the neutral, the induced voltage between the isolated sections of the neutral may be sufficient to cause discharges along the surface between them. The repeated discharges will eventually erode the insulation shield and penetrate into and through the insulation to cause failure.

Diagnostic Testing

Diagnostic Testing Methods For Extruded Cable Systems

Diagnostic tests are carried out to evaluate and locate aging or degradation that may cause cable and accessory failure. The aging and degradation mechanisms should be known for the different cable and accessory types in order to develop useful diagnostic tests, and also to be able to interpret the data from such tests. Table A-1 lists the main aging mechanisms and the diagnostic techniques that can detect these mechanisms. The test protocols should involve tests to determine the condition of the insulation, tests to verify the integrity of the conductor and neutral (shield) and a visual inspection. The latter can only be performed on the accessible components, such as terminations and splices. Any test to evaluate the insulation that is carried out at voltages above the rated voltage of the cable system increases the risk of failure during the test; the higher the test voltage the greater the risk.

Table A-1
The Main Aging Mechanisms and Diagnostic Techniques for Extruded Cables

Aging Mechanisms	Cause	Detection Method*
Water treeing (WT)	CPVs**, Water, Voltage	Dissipation Factor, recovery voltage, loss currents***
Electrical treeing (ET)	CPVs**, WT, Voltage	PD
Partial discharges (PD)	CPVs*, ET, Voltage	PD
Tracking	Surface contamination, Interfacial voids	PD, visual
Intrinsic breakdown	Lightning	none
Chemical changes, e.g., oxidation, hydrolysis	High temperature or direct contact with aggressive liquids	Dissipation Factor, recovery voltage, loss currents****
Thermomechanical	Current overloading	Visual, PD (if voids form due to mechanical deformation)
Thermal runaway, hot spots	Current overloading, dielectric heating	Visual (signs of overheating) Dissipation Factor, recovery voltage, loss currents****
Hardening/softening of insulation/shields/jackets	High temperatures, exposure to solvents, etc.	Visual, PD if voids form, otherwise none
Concentric neutral corrosion	Water, aggressive chemicals	Time domain reflectometry (TDR), resistance measurement

* An AC withstand test can also be used as a diagnostic test to check for insulation aging
** Not all contaminants, protrusions and voids (CPVs) will result in water trees, electrical trees, or partial discharges
*** High density of water trees necessary
**** Sensitive only if affected length of cable is relatively long

There are two types of diagnostic tests, destructive and non-destructive.

Destructive tests are voltage withstand or high potential (hipot) tests in which a constant test voltage, above the rated voltage V_0,, is applied for a specified time, usually according to an accepted standard or guide, for example IEEE 400.2™-2004 Guide for Field Testing of Shielded Power Cable Using Very Low Frequency)..Typical test voltages are about 3 V_0, and durations applied for up to ~ one hour according to the specific standard or guide. It is a Pass/Fail test. If the cable circuit passes the test, it is put back into service. Data was presented at the Spring 2005 IEEE Insulated Conductors Meeting showing that 97% of the cables that passed a 0.1 Hz withstand voltage of $3V_0$, for one hour remained in service without failure for three years. If the circuit fails the test, i.e., there is a failure, the cable is either repaired and retested or replaced. The test levels are selected from data and experience to weed out weak cables and accessories that would have a high risk of failure in service in a short time, e.g., less than a year, but not too high to cause increased degradation that would cause failure when the cable circuit is returned to service. There are no specific recommendations in IEEE 400.2™-2004 on how often cables should be tested, but although some utilities recommend retesting every three to five years, very few utilities follow this practice.

Non-destructive tests are carried out at lower voltages to reduce the risk of failure, either during or immediately after the test. Non-destructive tests measure properties, other than the breakdown strength, that assess the condition of the circuit and are related to the aging or degradation of cable circuits. Non-destructive tests of the insulation fall into two categories:

- Tests that measure the general or average condition of the whole insulation, e.g., dissipation factor. These tests are not usually sensitive to local variations that may often occur along a length of cable or in an accessory
- Tests which are sensitive to local defects in the insulation, e.g., partial discharges.

Tests to measure the integrity of the metal shield or neutral conductor are also non destructive and require different test equipment to that used to measure the insulation condition. Visual inspection of the terminations and other accessible parts of the cable circuit are useful to determine if problems such as surface degradation, e.g. tracking, overheating of components, or mechanical damage is serious enough to warrant remedial actions.

The advantages and disadvantages of withstand and non-destructive tests are listed in Table A-2.

Different non-destructive tests are sensitive to the different mechanisms of aging and degradation, so that there is no single test that can give a complete diagnosis of any cable circuit. Utilities rarely can afford to perform a full range of tests, so they generally restrict tests to the one or two that are sensitive to the most common aging mechanisms, e.g. partial discharges or water treeing in the insulation and corrosion of the metal shield or neutral..

Older XLPE and some types of EPR cables are located in a wet environment and are susceptible to water tree degradation, which, if widespread along the length of the cable, can be detected by tests that measure the average condition of the whole insulation, These tests include dissipation factor (DF) - sometimes referred to as tan delta or power factor - where the DF can either be measured at a single frequency or over a range of frequencies (dielectric spectroscopy). Dielectric spectroscopy tests are usually more sensitive than single frequency measurements. Other tests that measure the bulk properties are recovery voltage and polarization and depolarization tests. Some criteria to assess the condition of the cable are available for dissipation factor measurements (see IEEE 400.2™). These types of measurements are sensitive to external noise, and certain types of accessories can give data that resemble degraded cable insulation. Thus measurements have to be made with care, and it is essential to know what type of cable and accessories are being tested, as the dissipation factors of XLPE, TRXLPE and EPR are all different. This makes testing of mixed circuits (circuits with cables of different insulations) very difficult to interpret. Diagnostic tests that measure the average condition of the whole circuit are useful on older cables where severe water treeing is suspected and failures may have started to occur. The tests can prioritize which cable circuits or areas need to be replaced first or should be subjected to a rejuvenation program. The advantages and disadvantages of tests to measure the overall condition of the insulation are listed in Table A-3.

DC Hipot tests are not recommended for aged extruded cables, particularly XLPE and TRXLPE cables. Not enough data are available to know how effective DC hipot testing is for EPR cables. The recovery voltage and polarization and depolarization current measurements use high voltage DC to energize the cables under test but the voltage levels are usually restricted to 2 KV or less.

Partial discharge tests locate defects that have initiated partial discharges, for example large water trees from which electrical trees have initiated, large voids such as delaminations of the shield from the insulation, separation of the insulation of an accessory from the cable insulation at interfaces, voids formed by thermomechanical damage, etc. The degradation caused by partial discharges depends on the source and location of the discharges and also the insulation material.

EPR is more resistant to partial discharges than XLPE or TRXLPE so that discharges in EPR cables or accessories are not usually considered as serious as partial discharges in XLPE. The measurements are also sensitive to external noise and special techniques are employed to separate noise from actual partial discharge signals. All partial discharge measurement systems have techniques to locate the discharges. The statistical nature of partial discharges increases the difficulty in assessing the severity of the defect and thus the condition of the cable. Techniques to characterize partial discharge data with the severity of the defect have been developed and are continuously improving as more data are collected. There are no standard test voltage levels for partial discharge testing. Testing at too high a voltage may initiate partial discharges at a defect that would be discharge free at operating voltage and thus not a danger to the insulation. Test voltages on old cables should be limited to 2 V_0, but newer cables may be tested at 2.5 V_0. Partial discharge tests can also be carried out on-line. This has the advantages of testing under actual operating conditions so that the cable is at operating temperature and no outage is required but the inception and extinction voltage of the discharges cannot be determined as can be done in an off-line test. Other advantages and disadvantages of on-line and off-line partial discharge tests are listed in Table A-4. An IEEE guide for partial discharge testing of medium voltage cables in the field is under preparation (IEEE P400.3 IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment). This guide does not give a specific recommendation on how often cables should be retested but does state that periodic testing, e.g., every three to five years, should improve the interpretation of partial discharge test data. At the present time, few utilities perform repeat tests on cable systems.

To evaluate the insulation and metal shield or neutral of a cable circuit, the following procedure is carried out by some utilities. First, a test is performed to determine the condition of the metal tape or neutral (see IEEE draft Guide P 1617, which should be finalized in early 2006). If there is localized damage in direct buried cables, it can be repaired. If the damage is severe, replacement of the cable should be seriously considered. The installation of cathodic protection may be considered if the corrosion is mild or moderate. If the condition of the metal tape or neutral is acceptable, the circuit is subjected to a test that measures the overall condition of the whole insulation e.g., a dissipation factor test (at power frequency or 0.1 Hz) at different test voltages up to less than 2 V_0 to determine the degree of water treeing. Depending on the results (no trees, mild, moderate or severe treeing), the circuit may be returned to service without additional testing, considered for rejuvenation, or replaced. Cables considered for rejuvenation are subjected to a partial discharge test up to $2V_0$ to check for severe defects. Intense partial discharge activity would result in cable replacement or repair. In the absence of partial discharges, the cable would be rejuvenated by the injection of a liquid down the conductor that diffuses into the insulation and effectively neutralizes the water trees present, retarding their further growth. The criteria for deciding which action to follow varies from utility to utility, i.e., no standard has yet been accepted for the magnitudes of the dissipation factor and partial discharges.

Some utilities do not carry out this comprehensive series of tests but restrict themselves to a single test (overall condition measurement or a partial discharge test). Not determining the state of the metal shield or neutral can give misleading results of tests to determine the overall condition of the insulation or partial discharge tests. A severely corroded metal shield or neutral decreases the sensitivity of partial discharge tests and gives erroneous results in the tests that measure the overall condition of the insulation. Other limitations are listed in Tables A-2 and A-3

Table A-2
Advantages and Disadvantages of Withstand and Non-Destructive Tests

Advantages of Withstand Tests
• Test equipment is basically a high voltage supply (DC, power or very low frequency (VLF) as these power supplies are compact and portable). • Standards available for most cable types (IEEE Std 400, (some parts under preparation)). • Tests are relatively easy to perform (constant voltage of ~3 V_o for set time). • Tests are less costly than non-destructive tests. • Test results are easy to interpret (Pass/fail criterion)
Disadvantages of Withstand Tests
• Only gives pass/fail criterion • Not easy to assess trends in cable condition • The sensitivity to detect defects depends on the type of withstand voltage applied • Risk of inducing damage to cable during test that might cause failure a short time after being put back into service (test values recommended in the standards have been chosen, based on experience, to make this risk small). • Outage required for off-line tests.
Advantages of Non-Destructive Tests
• Low risk of failure during test or immediately after being put back into service as test voltages are usually lower (<2 V_o) than those used in withstand tests. • Tests are available to measure global or localized conditions. • Trending can be performed to give a better assessment of the cable system. • Off-line tests can be performed over a range of voltages from 0 to 3 V_o or higher so that trends with voltage can be measured.
Disadvantages of Non-Destructive Tests
• Test equipment is more expensive than that needed for withstand testing. • Some test equipment requires considerable expertise to use equipment and run tests. • Test conditions may adversely affect the data (introduce noise or erroneous data). • Interpretation of data may be prone to error. • Limited criteria developed to assess cable circuit condition. • Outage required for off-line tests.

Table A-3
Advantages and Disadvantages of Global Property Diagnostic Techniques

Advantages of Tests that Measure Global or Bulk Properties of the Insulation
• Measures the average property of the insulation • Accuracy in interpretation of the data is improved if measurements are repeated periodically, i.e., trending • Low risk of failure during the test if tests are limited to a maximum of 2 V_o
Disadvantages of Tests that Measure Global or Bulk Properties of the Insulation
• Considerable expertise needed to make the measurements • Specialized equipment needed that may be costly • Signals to be measured are usually small and affected by external noise • Localized aging cannot be detected • Tests are performed off-line • Interpretation of data may be prone to error. • Corrosion of the neutral/shield or high contact resistance between the neutral/shield and the insulation shield will give artificially high DF vales

Table A-4
Advantage and Disadvantages of Off-line and On-line Tests

Advantages of On-line PD Tests
• No need to take an outage to perform the test • Measurements are carried out at normal operating temperatures of cable circuit components • Periodic testing can give trends
Disadvantages and Limitations of On-line PD Tests
• Cannot measure PDIV, PDEV or voltage trends • May be difficult to identify type of defect • Can only make measurements short cable lengths
Advantages of Off-line PD Tests
• Tests can be performed over a range of voltages from 0 to 2 V_0 or higher so that trends with voltage can be measured • Inception and extinction voltages can be measured • Tests at different voltages may help identify type of defect • Some equipment can measure PD in branched circuits
Disadvantages of Off-line PD Tests
• Have to take an outage that could be expensive • Measurements cannot be made at operating temperatures

Diagnostic Tests for PILC Cable Systems

Diagnostic tests are carried out to evaluate and locate aging or degradation that may cause cable and accessory failure. Diagnostic tests maybe potentially destructive if carried out above the rated voltage V_0. Withstand (hipot) tests are tests carried out at voltage levels above the rated voltage for a specified time according to an accepted standard or guide. Withstand or hipot testing using high direct current voltage (HVDC) has been employed successfully for many years to determine the condition of PILC cable systems. The voltage test levels and the durations of the applied voltage, developed from the data collected over many years of testing, have been chosen to weed out failures that would have soon occurred in service. The leakage current can be monitored during the test, and the resistance of the insulation determined. A significant difference between the resistances of one phase to the other two phases of a three conductor cable may be an indication of possible problem. The latest version of the IEEE Guide for HVDC testing of PILC cables (IEEE 400.1™ Draft Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and above with High Direct Current Voltage) is in its final stages of approval, Acceptance and maintenance test voltage levels and test durations are recommended for cables of different voltage ratings. There is no requirement on how often repeat tests should be carried out on PILC cable systems.

The withstand/hipot test is a Pass/Fail test and is considered to be a destructive test as there is a significant risk of failure during the test due to the high voltage test levels used. Over the last ten years, non-destructive tests have been investigated that use lower test voltages to reduce the risk of failure during the test. These non-destructive tests measure either the overall losses in the insulation, i.e., a bulk measurement or degradation at specific sites by partial discharge testing.

Although the main aging mechanisms for PILC cables have been discussed previously they are included in Table A-5 which also lists the diagnostic techniques that are most sensitive to the specific aging mechanism.

Table A-5
Aging Mechanisms and Diagnostic Methods for PILC Cable Circuits

Aging/Degradation Mechanisms	Cause	Diagnostic Techniques
Partial discharges (PDs) in voids leading to tracking	Voids in the insulation due to oil or tape migration	DC withstand, PD, dissipation factor
Leakage of oil/oil starvation leading to dry spots and partial discharges	Sheath corrosion/fatigue, Cracks at potheads/splices, Mechanical damage	Visual, DC withstand, PD, dissipation factor, recovery voltage, loss currents
Ingress of moisture leading to partial discharge and thermal runaway	Sheath corrosion/fatigue	DC withstand, PD, dissipation factor, recovery voltage, loss currents
Thermal runaway	Insulation overheating due to high losses or load currents	Dissipation factor, recovery voltage, loss currents,

Diagnostic Test Equipment

The equipment needed to perform off-line diagnostic tests has to portable so that it can be transported easily to the test site and robust to withstand the vibration, knocks, and environmental conditions that it is likely to experience in use. The power supplies must have the power rating to be able to energize long lengths of cable.

Typical power supplies that are in use are:

- AC power supplies (60 Hz, 0.005 Hz to 0.1 Hz (VLF), resonant supplies 30 Hz to ~200 Hz)
- DC power supplies
- Damped AC voltage

The diagnostic test equipment in use includes:

- Partial discharge detection (on-line and off-line)
- Dielectric loss measurements
- Dielectric spectroscopy (measure dielectric loss as function of frequency)
- Recovery voltage
- DC leakage (polarization and depolarization) current

Data Interpretation From Diagnostic Tests

How the data from diagnostic tests are interpreted determines the assessment of the condition of cable circuits. The interpretation of withstand test data is more straightforward as the test is a pass/fail test. Either the cable survives the test or it fails. Standards and guides have been written that specify the DC voltage levels for PILC cables and the VLF test voltage levels for extruded cables..

The data from non-destructive tests, particularly from PD tests, are more difficult to interpret. In general it is easier to determine really good or really bad cables. For example, the partial discharge level or the dissipation factor could be very low or high. Even then errors can occur as the measurements may be insensitive due to external noise or there could be a malfunction in the test equipment. The results indicating the possibility of moderately aged cables are the most difficult to interpret. Some of the reasons for this are:

- Statistical nature of the data measured with respect to time, for example, partial discharge data may vary significantly over a period of hours. As a cable approaches failure the statistical variations tend to decrease
- Statistical nature of the breakdown process itself

At the present time there are no criteria established for PD tests, either in terms of PD amplitudes or PD intensity. Also there no specific test voltages or how often repeat tests should be carried out on cables. Equipment is available to carry out PD tests with different frequencies of the applied voltage.. These criteria and test voltage levels may one day be established when more experience and data has been accumulated.

Some utilities have developed a test protocol for extruded cables using PD and dielectric loss measurements (to assess local defects and the global condition of the insulation). In addition, the concentric neutral is checked for corrosion. Depending on the results (the PD and dielectric loss levels measured and the condition of the concentric neutral), no action is taken, the cable or accessory is replaced, or the cable is rejuvenated by injecting the cable with a liquid that reacts with the water and prevents further water tree degradation. Rejuvenation may involve changing the splices to allow the injected liquid to flow along the cable.

Conclusions

- This appendix describes the different types of cables and accessories that are presently in operation in utilities in North America. Some of these cables have been in operation for more than sixty years
- The aging mechanisms of the different types of cables have been discussed along with the factors affect the aging
- The most suitable diagnostic techniques to detect the different types of aging have been discussed so that the best test techniques for a particular type of cable can be selected
- Test protocols have been described. Some of these protocols have been prepared as IEEE standards but others are being performed as agreed between the diagnostic test service provider and the particular utility. There are no recommendations in the guides and standards as to how often repeat tests should be performed on either PILC or extruded cables.

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