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REPORT SUMMARY

This report applies research done to identify and develop methods for making decisions about aging assets in electric distribution systems. This is the first report on guidelines for asset replacement. EPRI plans to continue this research in future in order to improve the specificity, precision, and scope of these guidelines.

Background

The problem of aging assets has become more important because of the increasing emphasis on reliability and customer service. Distribution assets, such as distribution circuits, overhead and underground conductors, line equipment, and hardware, as well as substation transformers, and breakers are subject to failure. The probability of failure is dependent upon at least four factors: loading, age, maintenance, and external conditions. The decisions that asset managers must make regarding distribution facilities include when to replace an asset, when to repair or overhaul an asset, when to maintain an asset and when to do nothing. The optimal decision depends on the four factors listed above, plus other information on the condition of the asset and the costs of various alternatives. Responding to suggestions by member utilities at the annual distribution planning workshop, which was held November 2002, EPRI began a study to discover whether it is possible to design generic guidelines for repairing or replacing distribution equipment, including underground cables, poles, substation transformers, and breakers. Other kinds of equipment may be of interest as well. This report describes what has been learned to date.

Objective

To apply the methods of asset replacement analysis to distribution system assets in order to design generic guidelines for repair/replace of key equipment types.

Approach

Using methodologies developed in earlier work (EPRI report 1000424), the project team developed tentative generic guidelines for repair/replacement decisions on underground cable and breakers. The team studied how best to represent the dynamic processes of failure and repair of equipment, how to modify the failure and repair processes to account for aging of equipment, and how to combine the economics of failure and repair of equipment with the economics and constraints of utility service to customers.

Results

The key findings of this research to date are in three categories: policy guidelines, sensitivity guidelines, and data collection guidelines. Policy guidelines describe both the structure of the optimal policy in general and the specifications of the optimal policy in particular situations. Sensitivity guidelines identify which of the parameters that describe an inventory of aging assets

are most important to specify accurately. The data collection guidelines identify which data are important to gather and use in the analysis of aging assets. Some representative findings:

- The optimal policy for aging assets is generally to replace an asset after some amount of service time has elapsed or some number of failures has occurred. As an example, this study recommends replacing a particular type of underground cable after 30 years or 2 failures, whichever comes first—specific service time and number of failures for replacing other types of assets will depend on the factors cited above. It is generally not optimal to continue to repair an asset regardless of the asset's elapsed time in service or failure history.
- The most sensitive parameter in the description of the probability of failure of aging equipment is the steady-state failure rate. It is important to estimate this value accurately.
- Certain kinds of assets, such as the underground cables discussed in this report, experience failure acceleration. That is, a failure increases the likelihood of future failures. The optimal policy is very sensitive with respect to acceleration of failures.
- The optimal policy is only somewhat sensitive with respect to customer outage costs. That is, over a relatively wide range of customer costs, the best policy does not change. This is an interesting result because a great deal of effort has been spent on adding precision to the estimates of these costs.
- It is essential to collect at least the following data: type of asset (including such information as size and configuration or treatments that affect performance) and number of units. Vintage, or date the asset was first placed in service, is also an important item. It may be possible to proceed to an analysis with just this level of knowledge about the inventory.

EPRI Perspective

EPRI has been developing methods for distribution planning since 1992. At that time, research directed at the concept of distributed resources led to further consideration of distribution planning in general. The distribution planning problem is to determine the least-cost expansion plan under load growth uncertainty. Electric utility restructuring and emphasis on competitive performance have increased the importance of the relationship between cost and reliability. Distribution planning must now include reliability/cost tradeoffs explicitly.

Keywords

Distribution system
Aging assets
Repair and replacement
Reliability
Distribution
Reliability analysis

ABSTRACT

This report applies research done to identify and develop methods for making decisions about aging assets in electric distribution systems. The problem of aging assets has become more important because of the increasing emphasis on reliability and customer service. Distribution assets, such as substation transformers, feeders, poles, wires, breakers and other equipment are subject to failure. The probability of failure is dependent upon at least four factors: loading, age, maintenance, and external conditions. The decisions that distribution system asset managers must make include when to replace an asset, when to repair or overhaul an asset, when to maintain an asset and when to do nothing. The optimal decision depends on the four factors listed above, plus other descriptors of the condition of the asset, combined with the costs of various alternatives.

The purpose of this research is to apply the methods of asset replacement analysis to distribution system assets in order to design generic guidelines for repair/replace of key equipment types, including substation breakers and underground cables. These guidelines will indicate the broad conditions that are necessary to justify replacement.

Key findings are highlighted at the beginning of this report.

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KEY FINDINGS

This report applies research done to identify and develop methods for making decisions about aging assets in electric distribution systems. The problem of aging assets has become more important because of the increasing emphasis on reliability and customer service. Distribution assets, such as substation transformers, feeders, poles, wires, breakers and other equipment are subject to failure. The probability of failure is dependent upon at least four factors: loading, age, maintenance, and external conditions. The decisions that distribution system asset managers must make include when to replace an asset, when to repair or overhaul an asset, when to maintain an asset and when to do nothing. The optimal decision depends on the four factors listed above, plus other descriptors of the condition of the asset, combined with the costs of various alternatives.

The purpose of this research is to apply the methods of asset replacement analysis to distribution system assets in order to design generic guidelines for repair/replace of key equipment types, including substation breakers and underground cables. These guidelines will indicate the broad conditions that are necessary to justify replacement.

The key findings of this research to date are in three categories: policy guidelines, sensitivity guidelines, and data collection guidelines. Policy guidelines describe both the structure of the optimal policy in general and the specifications of the optimal policy in particular situations. Sensitivity guidelines identify which of the parameters that describe an inventory of aging assets are the ones that are most important to specify accurately. The data collection guidelines identify which data are important to gather and use in the analysis of aging assets. The key findings are based on a relatively limited set of studies and on the general structure of the theory of the behavior of aging assets. EPRI plans to continue this research in future in order to improve the specificity, precision, and scope of these guidelines.

Policy Guidelines

- Perhaps the most important finding of this research is that the optimal policy for aging assets is to replace an asset after some amount of service time has elapsed or some number of failures has occurred. An example of such a policy is to replace a particular type of underground cable after 30 years or 2 failures, whichever comes first. Thus, it is not optimal to continue to repair an asset regardless of the asset's elapsed time in service or failure history. At some point short of irreversible failure, the asset should be replaced.
- We compare, in particular, two policies. One is the policy of repeated repair and life extension of an existing asset, or the policy of non-replacement. The other is the optimal replacement policy described above. In all cases**,** the annual costs of the non-replacement policy begin somewhat lower than the optimal policy. But after some number of years, the

non-replacement policy costs greatly exceed those of the optimal policy. Therefore the cost consequences of the non-replacement policy are not apparent until some time in the future; but those consequences are large and persistent.

- It may be optimal to switch to new technology as quickly as possible. This is not generally true, but conditions under which it appears optimal to switch to new technology include: most installed assets using older technology; difficult to replace with older technology; limited capability to refurbish older technology; newer technology has lower steady-state hazard rate; catastrophic failure mode exists for older technology.

Sensitivity Guidelines

- The purpose of sensitivity analysis is to determine how the optimal policy changes as a result of changing the values of the parameters. Sensitive attributes are those that cause changes in policy as the value of the attribute varies.
- The most sensitive parameter in the description of the probability of failure of aging equipment is the steady-state failure rate. It is important to estimate this value accurately.
- Certain kinds of assets, such as the underground cables discussed in this report, experience failure acceleration. That is, a failure increases the likelihood of future failures. This phenomenon may result from a weakening of the asset as a result of a failure, or it may simply reveal information about the internal state of the asset that indicates otherwise unobserved weaknesses. In any case, failure acceleration, that is the rate at which the failure likelihood increases with succeeding failures, is a very sensitive parameter in determining the optimal policy. It is important to measure the consequences of past failures accurately.
- The onset of burnout (that is, increasing failure likelihood resulting from age alone) and the rate of burnout are important parameters, but not as sensitive as the two noted above.
- The optimal policy is only somewhat sensitive with respect to customer outage costs. That is, over a relatively wide range of customer costs, the policy does not change. The point here is that although customer costs surely influence the policy, changing customer costs does not appreciably alter the policy. This is an interesting result because a great deal of effort has been spent on adding precision to the estimates of these costs.

Data Collection Guidelines

- It is essential to collect at least the following data: type of asset (including such information as size and configuration or treatments that affect performance) and number of units. Vintage, or date the asset was first placed in service, is an important item. It may be possible to proceed to an analysis with just that level of knowledge about the inventory.
- Required performance data begins with a description of the asset performance states. This can be as simple as *failed* or *not failed*, or as complex as necessary.
- The minimal data required to estimate the probability that an asset will fail when it is a given age is the number of failures observed in any year. This provides only a very approximate estimate. To get a more accurate estimate, the data should include number of failures by type of asset by year the asset was first placed in service.

- Required cost data include cost of a failure, to both the utility and customer; cost of occupying each condition the asset can be in; replacement cost for a new asset; repair cost for each kind of repair; maintenance cost for each kind of maintenance. The minimal data required are the costs associated with each asset condition and each action.

2

INTRODUCTION

This is the first report on guidelines for asset replacement. These guidelines are based on the theory and methods developed in other projects, and documented in several reports cited in the references on the subject of managing aging distribution system assets.

The theory developed in these reports has been successfully applied at several electric utilities. Those studies[1] investigated how best to manage aging populations of underground cables, substation transformer breakers, and wood poles.

Responding to suggestions by member utilities at the annual distribution planning workshop, which was held November 2002, EPRI began a study to discover whether it is possible to design generic guidelines for repairing or replacing distribution equipment, including underground cables, poles, substation transformers, and breakers. Other kinds of equipment may be of interest as well. This report describes what has been learned to date.

This report begins with a review of the theory and methods that apply to the analysis of aging assets. These methods analyze the problem of asset replacement with particular attention to the specific issues of electric distribution systems, where assets have been in place for long periods, subject to random shocks and other conditions, and have been maintained in varying ways depending upon the practices of the utility. Knowledge of the theory and methods places the guidelines in a context, and we believe that it is important to understand the context in order to judge the worthiness of the guidelines.

Theory and Methods

The problem of specifying methods for managing aging assets requires consideration of three distinct phenomena. The first consideration is how best to represent the dynamic processes of failure and repair of equipment. The second consideration is how to modify the failure and repair processes to account for aging of equipment. The third consideration is how to combine the economics of failure and repair of equipment with the economics and constraints of utility service to customers.

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[1] In most cases, the specific results are considered proprietary by the companies involved, but generally applicable results are reported here.

The State of an Asset

The dynamic process of failure of equipment can be represented mathematically and that representation provides a forecast of the behavior of the equipment. Clearly, the knowledge of the present condition of an aging asset is essential for forecasting the behavior of that asset. The mathematical description that summarizes that present condition is known as the *state* of the asset. The specification of an asset's state, similar to that used in thermodynamics, is specific to an asset or class of assets. Now, as the past history of the asset varies, the present state varies. It is this variation that our methods investigate in order to determine a policy for an aging asset. The policies we develop for controlling aging assets are *state-dependent* policies; the policy varies by state. In principle, if the state of an asset were known with precision, then the policy would be known as well. However, three facts about the state of an aging asset make the problem of determining the best policy, and therefore guidelines for treating aging assets, a challenging one.

First, there is no single description of asset state that is valid for all classes of aging assets. Nor is there a single description of a given asset's state that is necessarily uniformly applicable by all utilities (or asset managers). That is, the information that one person chooses to use to describe an asset (age, manufacturer, past peak loading, …) may be different from the information another person might use; and there is no single correct answer. Much of the description of state depends on what is known. Clearly, it is of limited value to base an aging asset policy on the variable *manufacturer* if the manufacturer of the particular piece of equipment is unknown.

Second, even if, at one time, all the information that comprises the state of an asset were known for a single piece of equipment, over time the knowledge of the true state of an asset becomes more uncertain. This is because the process of aging has consequences that are themselves uncertain.

Third, some important components of the state description are unobservable. Important components are those whose values can cause the policy to change. Unobservable states can be inferred based on the outcome of diagnostic tests or other observations. This process of inference adds to the uncertainty in the state.

Therefore, the problem of specifying the state of an asset is itself an interesting problem. The methods we have created require specification of the state before any analysis can be done. In response to the facts stated above, the methods permit virtually any description of a state for any asset. It is important to recognize the centrality of the concept of state because virtually all of the guidelines for asset replacement are derived from state variable considerations and state-dependent policies.

Failure and Repair

Methods for analysis of failure and repair of equipment have been developed. A previous EPRI report, *Reliability of Electric Utility Distribution Systems: EPRI White Paper (1000424)*, addressed the methodology issue. The most popular models in the literature represent the failure and repair of equipment as a Markov process. These Markov models provide a useful perspective on the key issues, so we will provide a brief summary here.

The Markov process identifies various asset states (e.g., “up”, “down”), as discussed above, that characterize the condition of equipment. The transitions from state to state are governed by probability distributions. The typical assumptions made include specification of constant transition rates. This defines a *stationary* Markov model, the solution of which, for an arbitrary number of states, is well understood (Barlow (1965), Billinton (1983)).

An essential idea underlying the applicability of the stationary Markov model is the assumption that the *hazard rate* is constant. The *reliability* of an asset is defined as the probability that it survives (does not fail) at least up until some arbitrary time. The hazard rate is the conditional probability that the asset fails in the next instant of time given that it survived until the present.

The concept of the hazard rate is interesting for several reasons. First, the hazard rate can be empirically observed and is most often expressed as a so-called *bathtub curve.* (See Figure 2-1.) Observed data on failures combined with expert judgment about asset behavior can be used to estimate the parameters of the bathtub curve or any other hazard function. The actual methods are outside the scope of this report. We discuss estimation methods and identify several hazard functions that may be applicable for underground cables in the report *Medium Voltage Cable Failure Trends: Research Status Report,* EPRI, Palo Alto, CA: 2003 {1002256}.

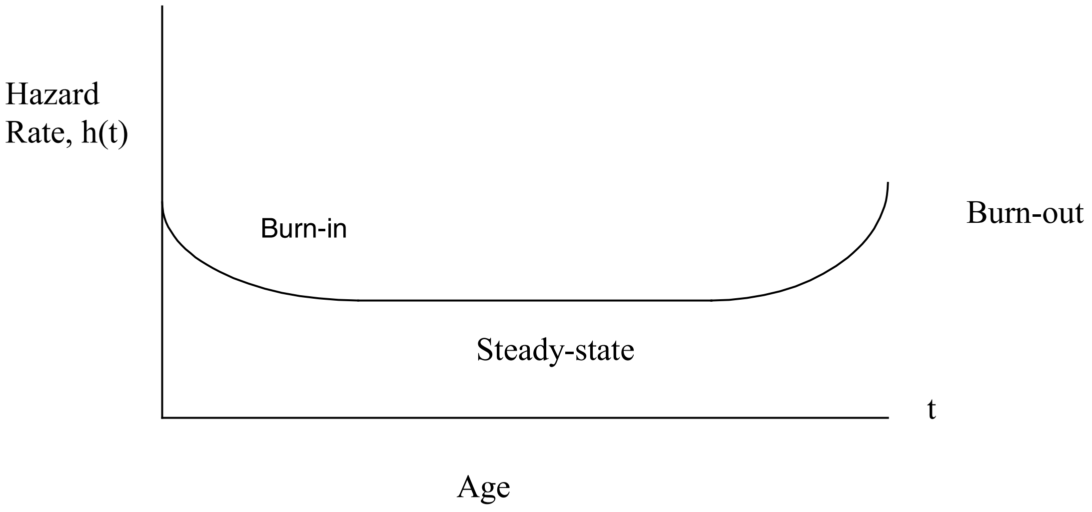

Figure 2-1
Hazard Rate “Bathtub” Curve

The nature of the hazard rate is that it tends to start out relatively large and decrease, during the *burn-in* period, remains constant for an arbitrary time, during the *steady-state* period, and then increases, during the *burnout* period. Second, the burnout period reflects the effect of aging. Hence, we are motivated to consider the behavior of the hazard rate as a fundamental modeling issue for the study of aging assets. Third, the stationary Markov model applies in the steady-state period. Since the hazard rate is constant, reliability is exponential, and the reciprocal of the hazard rate is the mean time to failure. It is important to note that these specifications are generally not valid for aging distribution assets.

For aging assets, it is natural to address the effect of hazard rate directly. We use a nonstationary Markov approach that permits variable transition rates. This method is described below and has been successfully applied in several case studies. The essential characteristic of the method is that it applies nonstationary hazard rates directly, as a function of age and other components of the current state of the asset. That dependence appears to be fundamental to capturing failure and repair of aging assets, and combines the increasing hazard rate and Markov modeling concepts.

Equipment Aging

One aspect of the phenomenon of equipment aging was discussed above. That is, the burnout period associated with aging indicates that as an asset ages it is not appropriate to apply stationary failure probabilities to represent failure dynamics. Other considerations are important to address as well. These include derating, quality of service, and technological change.

As equipment ages, it is important to determine whether the older equipment can perform the function for which it was originally installed. Performance is often measured with respect to capacity (MW), the transmission or distribution peak capability. It is natural to expect that aging may reduce this capability; hence aging suggests the need to derate the capacity of an asset. Moreover, as a decision variable, derating may be useful as life-extension alternative, based on the effect of peak loading on aging of the asset.

Quality of service is becoming a more important issue than it had been in the past. It is possible that aging may interfere with the ability of an asset to provide service at the quality intended. This concept is perhaps somewhat less precise than derating. Nevertheless, deterioration with respect to quality may be an important phenomenon to consider. However, the major effect on quality of service is outage rate and duration. The tradeoff between cost of outages and cost of repair/replace alternatives is precisely what we address in our models.

Technological change is a classic consideration in the analysis of replacement of aging assets (Bellman (1955)). Technological change entails several phenomena related to aging. First, as technology improves, the benefit of replacing an aging asset that embodies the older, presumably inferior, technology by a new, superior asset increases. Second, technological change may offer improved operating techniques that may increase the future value of an aging asset. Third, the salvage or trade-in value of an aging asset tends to decrease more rapidly than otherwise as the technology improves. These effects have all been considered in our case studies, and one of the interesting aspects of the guidelines is the specification of conditions such that it is optimal to replace old technology with new technology immediately.

Economic Considerations

It is natural to formulate the problem of managing aging assets as a cost minimization problem, assuming that the asset is constrained to provide a fixed level of service. In addition to the costs of failure and repair, the problem of managing aging assets suggests consideration of other costs, including (a) operating and maintenance costs, (b) salvage value, (c) lost revenue due to deteriorating quality or derating, and (d) replacement costs. Each of these costs is represented in the analysis of aging assets. In particular, we consider the effects of both calendar time, which permits modeling the effect of technological change or other kinds of learning, and the age of an asset.

Operating and maintenance costs tend to increase as an asset ages. In addition, the qualitative nature of the maintenance performed may change as an asset ages. Further, the consequences of various maintenance policies may differ as technology changes, since technological improvements can enhance the effect of maintenance. It is reasonable to suppose that there are differing economic consequences of alternative maintenance policies. These differences are captured in the methods we apply to this problem.

Salvage value measures the worth of an asset when it is retired from service. Salvage value tends to be a decreasing function of age. The rate of decrease can be accelerated as technological improvement occurs. Clearly, optimal replacement time depends on how rapidly the value of an asset depreciates.

It may be important to measure the consequences of aging by assessing the losses in revenue associated with deteriorating quality or derating. As the aging asset performs less well, costs may accrue. Such costs might include performance penalties or additional expenses the utility must incur as the aging asset remains in operation.

Replacement costs are an important consideration in management of aging assets. As technology changes, replacement costs will also change, although the direction of such changes may be uncertain. Such uncertainty is clearly an important consideration in the management of aging assets. The standard approaches to the problem tend to treat replacement costs as relatively deterministic. This may not be sufficient in the present environment. Our approach permits an analysis based on uncertainty in replacement costs.

Data

The guidelines include specification of the data required to support a complete analysis. Based on our experience, it is reasonable to suppose that utilities may not currently capture all the data that could be needed for a complete analysis.

We are guided by two fundamental concepts about data. First, analytic methods should strive to replace exhaustive data sets with analysis. This is one of the defining characteristics of the methods that we develop. Many alternate approaches rely on statistical analyses of vast databases. But the most successful approaches substitute structure for data and allow logic to identify best policies.

Second, we believe that methodological considerations and data requirements are linked. Indeed, we recognize that the appropriate data to collect is a direct consequence of the design of the methodology that will use the data. To be sure, there is an important feedback loop in the linkage, such that the methodology must be designed subject to availability of data. Nevertheless, unless it is infeasible to collect the required information, the best approaches begin with a methodology that captures problem understanding and then use this methodology to drive the data collection. Therefore, our data collection guidelines have been developed only after the model design has been created. As the model design evolves, it may be that different data are required.

The basic idea here is that modeling logic and analysis should be used to establish the scope of the data gathering. It is often the case that the modeling logic implies that precise measurement of many data elements is not necessary for decision making. In practice, we consider methodology design and data availability simultaneously. We have found that it is important to guide data collection, because we have observed that current data is insufficient to serve as a complete set of inputs for the methodology. The methodology has been adapted to accommodate existing data inputs.

Description of Report

This report contains three additional chapters. In the next chapter, we present two methods that we have applied to the problem of managing aging assets. We discuss the methodology in general and two examples in particular. In chapter 4, we summarize what we have learned from our methodology applications. The summary is in the form of guidelines that address three aspects of the management problem: what data to gather, which parameters are most important to understand with greatest accuracy (the so-called sensitive parameters), and what general policy guidelines can be formulated based on the studies done to date. Chapter 5 states the conclusions of the report. The references consulted in preparing this report are listed in Appendix A.

3

APPROACHES TO ANALYSIS OF AGING ASSETS

This chapter describes two methods for determining the least cost policy for managing aging assets. The first method is an implementation of the general approach known as *stochastic dynamic programming* (Hillier (1986)). The virtue of this approach is that it can capture both the effects of uncertain outcomes on the state of an asset and the value of an arbitrary collection of decision alternatives. This method is well suited to determine the optimal strategy for a single aging asset.

The second method is an implementation of *dynamic systems analysis* (Luenberger (1979)). This method determines the least cost replacement policy for a population of assets using a restricted form of the state variable, as described below. We are presently working on aggregation methods that will combine both approaches into a unified methodology.

At present, these two methods are distinct, although they are conceptually related. The first method is designed to apply all the information available about an asset in order to craft a policy to manage that asset. In particular, the first method is designed to permit the policy to depend on the result of diagnostic tests that reveal information about the state of the asset. The second method is designed to identify the best aggregate policy for controlling an inventory of aging assets. There is no policy dependence on the result of individual tests and individual conditions. The only state variable in the second analysis is age (or more precisely, the *effective* age, such that the age of the asset is modified depending on the past failure behavior of the asset). The purpose of the second method is to forecast the cash flows associated with managing an inventory of aging assets.

Control of a Single Asset: Motivating Example - Air Breakers

EPRI solicited utility members to provide actual examples of aging asset problems. The following problem is one that came in response to that solicitation. We develop this example in some detail in order to present the methodology we apply and to illustrate the model parameters that must be specified, using either data or judgment.

Problem Description

We consider the condition of a collection of air breakers installed in a utility's 138—230—500 kV transmission system. There are either 25 or 26 air breakers installed in the part of the system under study. (It may be of some interest to note that the exact number of breakers installed is not known.) The breakers are all approximately 30 years old. None has failed yet.

The technology is old, the utility expertise with respect to this technology and how to attend to these breakers is departing for many reasons (this appears to be a not uncommon phenomenon at present), the breakers require attention, and the maintenance costs are uncertain.

There are two failure modes for these breakers. The breaker is a fiberglass-encapsulated device that contains a pressurized porcelain tube that can literally blow up and shatter, scattering parts up to 700 feet away. This is the *catastrophic* failure mode. In the *non-catastrophic* mode, the breaker can develop air leaks (in either 500psi or 2000psi systems), which will induce a compressor failure (because the compressor must run continually to overcome the leak). This failure will cause the breaker to open and can cause an interruption. Such interruptions usually occur during cold weather. The cause of this failure mode is worn parts, such as aging gaskets. The critical time for this failure mode is dependent on asset age, and appears to be in the range 8-10 years old. When a non-catastrophic failure occurs, the breaker is taken out of service.

The impact of a failure on customers is variable. Some failures impact no customers, some impact some customers (exactly how many is uncertain) and in some cases—the catastrophic failure mode—all customers could be interrupted for more than 4 hours. Further, when a breaker fails there can be some environmental impacts, particularly a release of SF_6 gas (which is a 3.5 times better insulator than air; and the gas is not toxic).

The current maintenance cycle includes yearly inspection and maintenance. In addition, there are special procedures every three, four, six, and nine years. In particular, current policy calls for a *field rebuild* every nine years. The maintenance is costly and labor intensive.

The decision alternatives are (1) maintain the breaker without rebuilding it; (2) rebuild the breaker in place, which costs approximately $150,000; (3) refurbish the breaker in a shop (which, although a well-defined alternative, requires identifying a shop that is able to do the work); and (4) purchase a new breaker, which costs approximately $300,000.

Uncertainties (and relevant parameters describing the uncertainties) that are associated with these alternatives include the following: (1) the failure rate of breakers as a function of age; (2) the failure rate of breakers as a function of time since last maintenance; (3) the failure rate of breakers since rebuild time (which describes whether a rebuilt breaker is "good as new"); (4) the probability of catastrophic failure as a function of age and maintenance history.

Problem Formulation

Decisions

The problem formulation begins with the decision alternatives. We permit three alternatives {Maintain, Rebuild, Replace}. That is, at any decision point, it is possible either to maintain the breaker, to rebuild it in place, or to replace it with a new breaker. We suppress the alternative to refurbish the breaker because no shop has been found that can do the work. We further assume that if the breaker is replaced, the new breaker technology performs differently than the current breaker technology.

States

In this instance, the *age* of a breaker is measured in periods of three years each, although the formation would allow for periods of any length. In addition to characterizing the age of the breaker, we also characterize the *performance state* of the breaker. We will specify that, prior to making a decision, the breaker can be found to be in one of four distinct performance states representing its condition: (1) *good*; (2) *problem*, which is an unspecified condition different than good but not failed; (3) *failure*, which means that some work must be undertaken to restore the breaker to operating condition; and (4) *catastrophic failure (c-failure)*, as discussed above. The combination of age and performance state comprises the state of the breaker.

Transition Probabilities and State Dynamics

The performance state of the breaker is uncertain and is assumed to be conditional on the previous performance state of the breaker as well as the age of the breaker. (This formulation does not address explicitly the dependence of performance state on maintenance history. The relationship is implicit only.) We assume that if the prior performance state were *good* then the current performance state can be any of the four states, depending on the age of the equipment. Hence a probability distribution on the performance state must be determined.

Similarly, if the prior performance state were *problem*, then the current performance state can also be any one of the four states. The probability distribution ought to reflect whatever remedies might be applied in response to a problem. Further, one would naturally expect that the probability distributions would differ based on the prior state.

If the prior performance state were either of the failure states, then a specific remedy must be applied that returns the breaker to the *good* state. We also assume that a catastrophic failure requires replacement and adoption, therefore, of a new technology. Hence, probability distributions on performance state vary by technology as well.

These probability distributions are inputs in this formulation. There are four sets of such inputs, corresponding to the two kinds of technologies and the prior state, either *good* or *problem.* The distributions used in this example are given by the matrices in displayed in Tables 3-1 through 3-4 below. Note that these failure probabilities were developed through expert judgment, due to a paucity of data on actual failures in this case. Developing such data remains a critical need for application of this approach.

These matrices present the state transition probability distributions for five time periods (of three years each). There is no restriction with respect to number of periods. Table 3-2, for example, indicates that if the previous state were problem, then a breaker that is 4 periods old will enter the good state with probability 0, remain in the problem state with probability 0.55 fail with probability 0.35 and fail catastrophically with probability 0.10. Note that all columns must sum to one. These probabilities are denoted p(i, s, τ, t), where i denotes the current performance state (*good, problem*), s denotes the future performance state (*good, problem, failure, catastrophic failure*), τ denotes the technology type (old, new), and t denotes the age of the breaker (time since installation or rebuild).

Table 3-1
Technology Performance State Probability Matrix (Original Technology, Prior State = *good*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0.85	0.75	0.60	0.41	0.28
Problem	0.10	0.15	0.20	0.30	0.35
Failure	0.05	0.07	0.15	0.20	0.25
C-failure	0.00	0.03	0.05	0.09	0.12

Table 3-2
Technology Performance State Probability Matrix (Original Technology, Prior State = *problem*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0.00	0.00	0.00	0.00	0.00
Problem	0.70	0.67	0.62	0.55	0.47
Failure	0.25	0.27	0.30	0.35	0.40
C-failure	0.05	0.06	0.08	0.10	0.13

Table 3-3
Technology Performance State Probability Matrix (New Technology, Prior State = *good*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0.95	0.99	0.98	0.97	0.96
Problem	0.05	0.01	0.02	0.03	0.04
Failure	0.00	0.00	0.00	0.00	0.00
C-failure	0.00	0.00	0.00	0.00	0.00

Table 3-4
Technology Performance State Probability Matrix (New Technology, Prior State = *problem*)

	Breaker Age				
Perf. State	**1**	**2**	**3**	**4**	**5**
Good	0.80	0.78	0.75	0.74	0.72
Problem	0.15	0.17	0.19	0.20	0.21
Failure	0.05	0.05	0.06	0.06	0.07
C-failure	0.00	0.00	0.00	0.00	0.00

Estimating Transition Probabilities

The probabilities in the transition matrices are specified by a combination of expert judgment, data analysis, and mathematical modeling. In this case, we relied on expert judgment to determine the probabilities. If data were available, it would be straightforward to estimate the transition probabilities.

If a hazard function were available, then the mathematical derivation of the transition probabilities is based on assuming that the hazard rate, denoted h(t) (see Figure 2-1), is the parameter of a time-varying Poisson distribution that governs the occurrence of failure events. In that case, the survival probability of an asset that is age t, that is the probability that no failure occurs in a period that is one year long, is

$$p(0; t) = e^{-h(t)}. \qquad \textbf{Eq. 3-1}$$

This follows from the definition of the Poisson process, such that the probability that k failures—more generally, k occurrences of an event that could cause a failure—occur in the period of length T is given by the Poisson probability

$$p(k) = \exp(-\lambda T)\ (\lambda T)^{k}/k!\ ,\ k =0,\ 1,\ 2,\ \ldots \qquad \textbf{Eq. 3-2}$$

where λ is the constant rate of occurrence of peak stresses. We identify the parameter λ with the hazard rate h(t), for an asset that is age t. The complement of p(0;t), $1- e^{-h(t)}$ is the probability that the asset makes the transition from the good state to the failed state in one year. (In cases where the period is defined as some interval other than one year, the survival probabilities compound.) The other transition rates in the matrices above can be similarly derived. The point here is that there are methods available for estimating these transition rates for any asset.

Costs

In this formulation, two sets of costs must be specified. First, we require a set of technology decision costs, which are the costs associated with making a decision (maintain, rebuild, replace) for each technology (old, new). These costs may vary with time, and are denoted K(d, y), where d represents the decision and y represents time in the planning period.

Second, we require a set of technology performance costs. These are the costs associated with being in a performance state for each technology type. For example, these costs may include routine inspection and maintenance of the breaker, of running the compressor to maintain pressure, or costs incurred by customers as a result of one of the failure modes. These costs may vary with age of the breaker and time, and are denoted $C(\tau, t, y, s)$, where, as above, τ represents the technology, t represents the age of the breaker, y represents the time in the planning period, and we have introduced the notation that s is the performance state. In the simplest version of the model, the costs are completely stationary and vary with technology only. These costs are shown in the Tables 3-5 and 3-6 below.

Table 3-5
Technology Decision Costs ($Thousand)

	Technology	
Decision	**Original Technology**	**New Technology**
Maintain	0	0
Rebuild	100	Not allowed
Replace	350 (replace with new)	350

Table 3-6
Technology Performance Costs ($Thousands per Period)

	Technology	
Performance	**Original Technology**	**New Technology**
Good	50	30
Problem	50	50
Failure	250	250
C-Failure	1000	950

With these inputs, the solution to the problem is found by solving Bellman's equation:

$$V(i, \tau, t, y) \\ = \min_d\{[K(d, y) + \Sigma_s p(i, s, \tau(d), t(d))\ [C(\tau(d),t(d),y, s) + (1/1+\rho)V(s, \tau(d), t(d), y+1)]\} \quad \textbf{Eq. 3-3}$$

where

$V(i, \tau, t, y)$ = minimum cost to go given that the current performance state is i, the current technology is τ, the current breaker is age t, and that the time in the planning period is y.

i = current performance state

t = current breaker age

d = decision

y = time in the planning period

s = subsequent performance state

$\tau(d)$ = technology selected by decision d

$t(d)$ = age of breaker determined by decision d
(note $t(d) = t+1$ if d = maintain and $t(d) = 1$ if d=rebuild or replace).

ρ = discount rate.

Bellman's equation is fundamental to determining the optimal repair/replacement strategy under uncertainty. Equation 3-3 is interpreted as follows:

- The cost V of following the optimal policy
  - starting in current performance state i, with current technology τ, current breaker age t, at time y in the planning period
- is determined by choosing the decision d that minimizes
- the direct cost K of choosing d at time y
- plus the expected value, over all subsequent performance states s, of
- the cost C of being in performance state s,
  - which depends on the technology τ selected by decision d and the age of the breaker t that results from the decision d,
- plus the discounted cost V of following the optimal policy
  - starting in subsequent performance state s, with chosen technology τ(d), breaker age t(d) resulting from decision d, one period later at time y+1.

The model has been implemented in the EPRI Aging Assets software (v. 1.5) released in 2003. The optimal solution to the problem for three decision stages, each stage of three years duration, is shown in a tabular format, in Table 3-7 below (stage 4 is the terminal stage, at which no decision is made). (For the purpose of this explanation, the columns are numbered in the top row of this table.) (Note that because of the length of the table, rows carried forward from the previous page are indicated by light shading on subsequent pages.) The policy unfolds in the form of a "tree" depicted in tabular form in Table 3-7. Each decision gives rise to a set of "branches" representing the possible next states of the asset, which in turn require decisions that themselves give rise to further branches, until the last period is reached, where "leaves" represent the terminal costs that are assessed. The policy illustrated is conditional on the state of the asset.

Starting at the top left of the table (columns 2, 3, and 4), if the asset is "Old" technology and the current state is "Good" and 0 years old, then the optimal decision at stage 1 is to Maintain the existing asset. This is highlighted in column 5. Then, the occurrence of the next state (columns 6, 7, and 8) is governed by the transition probabilities in the first column of Table 3-1, such that the probability that the next state is "Good" is 0.85, the probability that the next state is "Problem" is 0.10, and the probability that the next state is "Failure" is 0.5, as shown in column 7. Since the transition probability from the initial state (Old, Good, 0) to "Catastrophic Failure" is 0, Table 3-7 does not show this state.

If the next state is indeed "Good", as indicated in the seventh column of Table 3-7, then the optimal decision at stage 2 is to Maintain the asset. This is shown in the ninth column of the table. Continuing down the seventh column, if the next state is "Problem" then the optimal decision at stage 2 is to Rebuild the asset. If the next state is "Failure" then the optimal decision at stage 2 is to Replace the asset (which, in this case, is required). Returning to the top of column nine, if an asset that is (Old, Good, 3) is Maintained, then the probability distribution on the next state is given by column 2 in Table 3-1, which yields the probability distribution (0.75, 0.15, 0.07, and 0.03). The corresponding states are (Old, Good, 6), (Old, Problem, 6), (Old, Failure, 6), and (Old, C-Failure, 6), shown in columns 10, 11, and 12.

Table 3-7
Optimal Policy

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stage 1					Stage 2				Stage 3				Stage 4			Terminal
	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Cost
	Old	Good $192.788 p=1.00	0 years	Maintain $242.86												
					Old	Good $222.823 p=0.85	3 years	Maintain $217.71								
									Old	Good $151.214 p=0.75	6 years	Maintain $127.50				
													Old	Good p=0.60	9 years	$50.00
													Old	Problem p=0.20	9 years	$50.00
													Old	Failure p=0.15	9 years	$250.00
													Old	C-Failure p=0.05	9 years	$1,000.00
									Old	Problem $177.013 p=0.15	6 years	Rebuild $160.0				
													Old	Good p=0.85	3 years	$150.00
													Old	Problem p=0.10	3 years	$150.00
													Old	Failure p=0.05	3 years	$350.00
									Old	Failure $552.450 p=0.07	6 years	Replace $381.0				
													New	Good p=0.95	3 years	$380.00
													New	Problem p=0.05	3 years	$400.00

Table 3-7
Optimal Policy (Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stage 1					Stage 2				Stage 3				Stage 4			Terminal
	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Cost
	Old	Good $192.788 p=1.00	0 years	Maintain $242.86												
					Old	Good $222.823 p=0.85	3 years	Maintain $217.71								
									Old	C-Failure $1,302.450 p=0.03	6 years	Replace $381.0				
													New	Good p=0.95	3 years	$380.00
													New	Problem p=0.05	3 years	$400.00
					Old	Problem $248.648 p=0.10	3 years	Rebuild $250.24								
									Old	Good $223.429 p=0.85	3 years	Maintain $0.0				
													Old	Good p=0.75	6 years	$50.00
													Old	Problem p=0.15	6 years	$50.00
													Old	Failure p=0.07	6 years	$250.00
													Old	C-Failure p=0.03	6 years	$1,000.00
									Old	Problem $277.013 p=0.10	3 years	Rebuild $0.0				
													Old	Good p=0.85	3 years	$150.00
													Old	Problem p=0.10	3 years	$150.00
													Old	Failure p=0.05	3 years	$350.00

Table 3-7
Optimal Policy (Continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stage 1					Stage 2				Stage 3				Stage 4			Terminal
	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Decision	Tech	State	Age	Cost
	Old	Good $192.788 p=1.00	0 years	Maintain $242.86												
					Old	Problem $248.648 p=0.10	3 years	Rebuild $250.24								
									Old	Failure $652.450 p=0.05	3 years	Replace $0.0				
													New	Good p=0.95	3 years	$380.00
													New	Problem p=0.05	3 years	$400.00
					Old	Failure $571.850 p=0.05	3 years	Replace $405.44								
									New	Good $403.974 p=0.95	3 years	Maintain $0.0				
													New	Good p=0.99	6 years	$30.00
													New	Problem p=0.01	6 years	$50.00
									New	Problem $433.262 p=0.05	3 years	Maintain $0.0				
													New	Good p=0.78	6 years	$30.00
													New	Problem p=0.17	6 years	$50.00
													New	Failure p=0.05	6 years	$200.00

For purposes of illustration of the computation, let us follow the path that corresponds to occupying the state (Old, Good, 6). The optimal decision at stage 3 is Maintain (column 13), and the subsequent states (columns 14, 15, and 16) are reached with probabilities (0.60, 0.20, 0.15, 0.05), as given in the column 3 of Table 3-1. This is the terminal stage of the analysis.

There is no decision at this terminal stage. The costs associated with being in these terminal states are given in column 17 (see Table 3-6). The expected cost of Maintaining the asset at stage 3 when it is in state (Old, Good, 6) is then the cost of maintenance, which is zero (Table 3-5) plus the expected value of the probability distribution on costs, or $0 + 0.60(50) + 0.20(50) + 0.15(250) + 0.05(1000) = 127.50$, as noted in column 13. This expected cost is discounted three years at the rate 8% (an input parameter) back to the previous period, or $127.50/(1.08)^3 = 101.21$. Then, the cost of occupying the state "Good" is added to this amount, just as in Equation 3-3, to get the cost $101.21 + 50 = 151.21$, as shown in column 11. There are three other costs in column 11 that correspond to the other states possible in stage 3 (columns 10-12).

Repeating this logic a stage 2, the expected cost of Maintaining the asset when it is in state (Old, Good, 3) is then the cost of maintenance, which is zero (Table 3-5) plus the expected value of the probability distribution on costs, or $0 + 0.75(151.214) + 0.15(177.013) + 0.07(552.450) + 0.03(1302.45) = 217.71$, as shown in column 9. The expected cost-to-go at stage 2 from the state (Old, Good, 3) is the cost of occupying the state (50) plus the discounted expected value of the costs of the succeeding states, $(1/(1.08)^3)$ [217.71] or 222.823, as shown in column 7. Similar computations give the costs-to-go for the other states at stage 2 (column 7).

Using the same logic at stage 1 gives the cost of Maintaining the asset in state (Old, Good, 0) as the cost of maintenance, 0, plus the expected cost of the subsequent states $0.85(222.823) + 0.10(248.648) + 0.05(571.850) = 242.86$, as shown in column 5. And the cost-to-go of the asset in state (Old, Good, 0), the initial condition, is $(1/(1.08)^3)\ 242.86 = 192.788$ as shown in column 3 (note that the cost of occupying the initial state, which is 50, is not included in this calculation since it is regarded as a sunk, or unavoidable, cost).

It is worth noting again that the optimal policy depends on the state of the asset. For example, looking down column 13, the optimal policy at stage 3 is to Maintain if the state is (Old, Good, 6), but if the state is (Old, Problem, 6), then the optimal policy is to Rebuild. If the state is (Old, Failure, 6) or (Old, C-Failure, 6) then the optimal policy is to Replace. This completes the example.

Discussion

The structure of this formulation is sufficiently general to permit solution of many aging assets problems. However, it is still early in its development and there are many issues yet to be resolved in applying this approach. In particular, we need to determine whether the data required for the methodology is readily available. We also need to know whether the data required for the methodology captures the essential issues with respect to the behavior of aging assets. If the parameters are available, then the solution to any problem can be presented in the form of Table 3-7 (with potentially many more stages). The solution is a state-contingent policy that yields the least cost associated with an asset of a given age and condition at the beginning of the analysis period. It is worth emphasizing that the purpose of this formulation is to control a single asset and craft a policy that responds to the unique past performance of that asset.

Control of a Population of Aging Assets: Motivating Example - Underground Cable

In response to EPRI's solicitation to utility members to provide actual examples of aging asset problems, we were presented with the problem of controlling a population of aging distribution system underground cable.

Problem Description

The distribution system under study contains approximately 8600 phase-miles of cable. Some of the cable is at least 40 years old. Currently, the company is replacing only about 0.01% of the cable per year. The company is not sure what the life expectancy of cable is but they believe that the 0.01% replacement rate is not consistent with any reasonable estimate of remaining life. The company feels that a more proactive policy is needed to:

- avoid having to replace a large quantity of cable in a short period,
- avoid degradation in reliability due to increasing cable related outages,
- avoid potential, very high cost, double contingency outages in looped cable areas,
- minimize the life-cycle cost of their underground cable system.

The problem is to determine the least-cost strategy for repair/replace of the cable assets, and to develop a ten-year expenditure forecast associated with implementation of the strategy. In order to answer these questions we developed additional methodology, described below.

Data Requirements

The following data requirements are specified for a complete policy analysis. In the present example, much of the required data was not available. Therefore, we constructed the policy based only on what could be provided.

1. Types of cable: Provide a list of the types of cable in the system, and for each type, provide a table that lists the number of miles by age. The list should provide descriptors of the size and type of conductor, insulation materials and any other relevant information that potentially impacts cable life expectancy.

2. Tests: Provide a list of the diagnostic tests used to assess cable conditions.

3. Test outcomes: For each test, provide a list of the possible test outcomes that are indicative of cable condition (state).

4. Failure rates: For each type of cable, provide an assessment of failure rates by age and any other descriptors that may affect failure rate (for example jacketed compared with not jacketed).

5. Failure modes: For each type of cable, provide a list of the underlying conditions that can lead to failure.

6. Costs: For each type of cable, provide estimates of (1) replacement cost per mile, (2) O&M costs associated with an outage, (3) customer costs associated with an outage. Note whether different local conditions or type of cable asset result in different costs, and, if so, provide the costs for specific conditions and cable assets.

In particular, because of limitations in its database, the host utility could only supply items 1, 4, and 6. Therefore, we made deterministic forecasts of both behavior and costs in this study.

The state of the cable consists of three elements:

- cable type—2AWG, 1/0, 2/0, 4/0, 500, 750; in addition, cables installed prior to 1984, called “old” cables, are not tree retardant, whereas those installed later, called “new” cables, are tree retardant.
- cable vintage—measured by the year the cable was installed.
- number of failures in a cable segment—where a segment is the unit of cable length that is replaced.

As in the previous case, the optimal policy depends upon the state of the cable. For example, the optimal policy for 2AWG cable that was installed prior to 1984 is to replace a segment when it has failed two times. The model discussed here provides analogous optimal policies for all cable types.

Data

The data collected in this study is presented in the form of a matrix, such that the columns of the matrix represent the various cable types and the row represents the year it was installed (vintage). The matrix elements are the miles of cable by type and vintage. (We suppress the actual data in this report; the data is company proprietary, but the specific values are unimportant for this report.)

Additional inputs are the observed failures by cable type and install year in each calendar year. Also, we require costs for cable replacement ($/mile) and cable repair, as a function of cable type. Further, each failure has associated with it a cost to the utility, which is the cost of repair, and a cost to the customer, which reflects the losses a customer incurs as a result of a failure. Therefore, the sum of these costs is an estimate of the amount of money it is worth to avoid the failure.

The Hazard Function

We assume that the behavior of each cable type can be represented by a hazard function. The hazard function is shown in Figure 3-1, below. The independent variable is t, the age of the cable. The dependent variable is h(t), the hazard rate for a cable t years old. The hazard rate in this formulation is the expected number of failures per unit length of installed cable per year. We represent the hazard function as a piecewise linear function that 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}, m, and T.

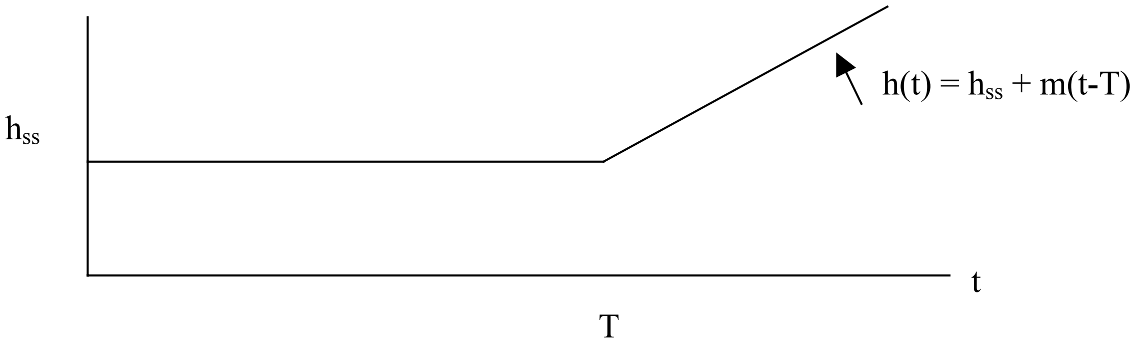

Figure 3-1
The Hazard Function

The hazard function is estimated from the failure data. We describe two procedures for using data to estimate the piecewise linear hazard function for underground cable data in the report *Medium Voltage Cable Failure Trends: Research Status Report,* EPRI, Palo Alto, CA: 2003 (1002256). The methods applied depend on the data available. If a complete distribution of failures by age is known, then it is possible to estimate the three parameters such that the sum of the squared prediction errors is minimized. In order to do this, we define an estimated value of the hazard as a function of the parameters (h_{ss}, m, T) such that for each age t, the estimated value is

$$h_{est}(t; h_{ss}, m, T) = h_{ss} + \max\{0, m(t-T)\} \qquad \textbf{Eq. 3-4}$$

(where the second term is zero if $t \leq T$ and m(t-T) if $T > t$). Now, define the error, e, at age t, as the difference between the observed hazard h(t) given by the data and the estimated value, or

$$e(t, h(t); h_{ss}, m, T) = h(t) - h_{est}(t; h_{ss}, m, T). \qquad \textbf{Eq. 3-5}$$

The parameters (h_{ss}, m, T) are selected to minimize the sum of the squared errors over the entire data set, or

$$\min Q(h_{ss}, m, T) = \Sigma_t\, e^2((t, h(t); h_{ss}, m, T). \qquad \textbf{Eq. 3-6}$$

However, if a complete distribution of failures by age is not known, expert judgment must substitute for data. In the present example, to estimate the hazard function, we assumed a cable failure model. These assumptions, or others similar to them, are necessary because of the paucity of the data. These specific assumptions are particular to this case and we do not suggest that these assumptions are generally applicable. We provide these details to illustrate how one may go about estimating a hazard function using a combination of expert judgment and data. Every assumption made in this example was offered by the utility experts attempting to solve the problem or was a direct consequence of observed data.

The failure model assumes that each failure occurs in a segment of cable that is 0.1 mile long (i.e. about 500 feet). (For 500 and 750 kcmil cable, we set the segment length to 0.3 miles (about 1500 feet).) When cable is replaced because of repeated failure, the replacement involves only the segment that repeatedly failed.

It is possible that a given segment can experience more than one failure in a given year. It is assumed that the expected number of segments that experience a second failure in a given year is one-tenth the number of failed segments. For example, if there are 500 miles of a cable that has a hazard rate of 0.03, then expected number of failures is 15, occurring in 15 segments each 0.1 miles long. Further, one tenth of those failed segments, or 1.5 segments, are expected to experience a second failure. Thus, it is expected that 13.5 segments experience one failure, 1.5 segments experience two failures, and the total expected number of failures is 16.5. It is assumed that the number of repeat failures cannot exceed two in a given year.

It is assumed, based on expert judgment, that old cable, installed prior to 1984, experiences onset of burnout at 25 years. It is assumed that new cable, installed after 1983, experiences onset of burnout at 35 years. This is because the older cable is not tree retardant, while the newer cable is tree retardant.

It is also assumed, based on expert judgment, that old cable has a hazard rate that will double compared with the steady-state rate at five years after onset of burnout. Thus, $m = 0.2h_{ss}$ for old cable. It is assumed that new cable has a hazard rate that will double compared with the steady-state rate at ten years after onset of burnout. Thus, $m = 0.1h_{ss}$ for new cable.

As a consequence of these assumptions, one observes that the hazard function has only one remaining unknown, the steady-state rate h_{ss}. It is straightforward to estimate h_{ss} from the failure data. Values for this example are shown in the Table 3-8. These are failures rates per mile of installed cable.

We made an additional assumption that to capture the phenomenon of accelerated aging with repeated failure. Ordinarily, one measures the independent variable of the hazard function using the so-called *effective age*, which replaces the vintage with an index number that is supposed to measure more accurately the history of any specific cable segment. Since data is not available that enables constructing an effective age index, it is assumed that the failure rates double as a consequence of repeated failure. Thus, if a segment of age t has failed once, the failure rate is doubled, and set at 2h(t). If a segment of age t has failed twice, the failure rate is doubled again, and set at 4h(t). We capped the effect of multiple failures at quadrupling the rate. Therefore, the failure rate for a segment of age t that has failed more than twice is 4h(t).

Table 3-8
Steady-State Failure Rates

Cable Type	SS Failure Rate Pre 1984	SS Failure Rate Post 1983
2AWG	0.1964	0.0336
1/0	0.1948	0.0056
2/0	1.3679	0.4888
3/0	0.0483	0.0043
4/0	0.0483	0.0043
350	0.2144	0.0141
500	0.2144	0.0141
750	0.2144	0.0141

Model Structure

The model structure is described in the following flow chart, Figure 3-2. The equations that describe the cable population dynamics are given below.

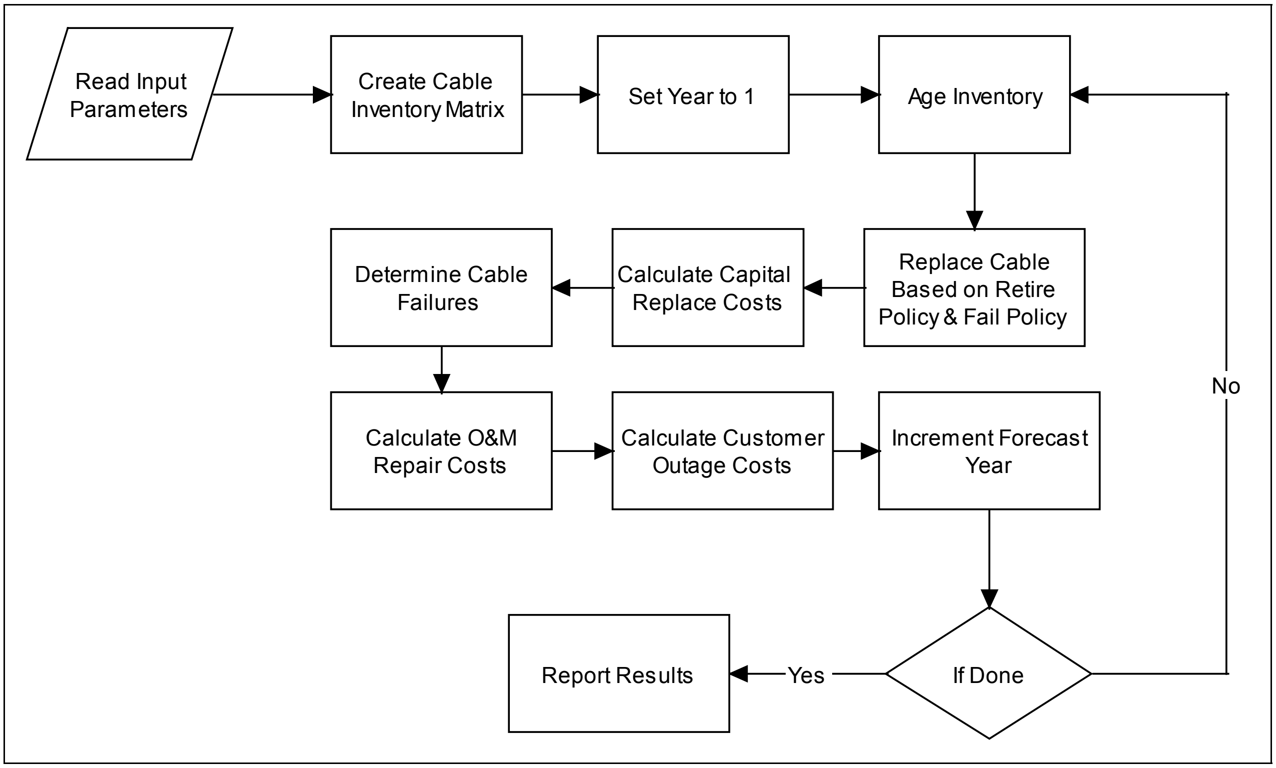

Figure 3-2
Model Flow Chart

Cable Population Dynamics

The equations that govern the population dynamics can be specified as follows.

Consider a single cohort of cables (that is a set of cables of the same vintage). Define the following notation:

$v_f(t) =$ feet of cable with f failures at age t. This is the cable inventory. If the failure history is not known, set $f = 0$.

$h(t) =$ hazard rate, expected number of failures per foot of cable at age t.

$r =$ repeat failure rate, expected number of repeat failures in a year per foot of cable (in this example, $r = 0.1$). This parameter of the model can be determined by data or can be specified by expert judgment. It is the rate at which multiple failures can occur in a failed segment in a single year. If it is known that, say, 100 feet failed in a year, then $100r$ of them will experience a second failure in that year.

$m_f =$ hazard rate multiplier for f previous failures (in this example, $m_1 = 2$, and $m_2 = m_3 = 4$).

$N(t) =$ expected number of failures at age t.

We assume that we do not count failures beyond three. Therefore, we need expressions for $\{v_f(t+1): f = 0,1,2,3\}$ based on the corresponding values for age t.

Note that this model, in contrast to that used in the previous case, works with expected values rather than probabilities.

It is simplest to express the transition equations in vector-matrix form. Let $A(t)$ be the 4 x 4 transition matrix at age t

$$A(t) = \begin{bmatrix} 1-h(t) & 0 & 0 & 0 \\ (1-r)h(t) & 1-m_1h(t) & 0 & 0 \\ rh(t) & (1-r)m_1h(t) & 1-m_2h(t) & 0 \\ 0 & rm_1h(t) & m_2h(t) & 1 \end{bmatrix} \qquad \textbf{Eq. 3-7}$$

and define the state vector of this cohort at age t as

$$v(t) = \begin{bmatrix} v_0(t) \\ v_1(t) \\ v_2(t) \\ v_3(t) \end{bmatrix}$$

The matrix $A(t)$ can be interpreted as the matrix of transition rates from the number of failures associated with the column at age t to the number of failures associated with the row at age t+1. (It may be worth noting that the expression 1 – $h(t)$, the entry in the first row, first column, is the rate at which a foot of cable that had not failed up to age t will survive (i.e. not fail) by age t+1; and this is 1 minus the mean of the probability discussed above, $e^{-h(t)}$, in Equation 3-1). Thus, for example, $(1\text{-}r)m_1 h(t)$, the entry in column 2, row 3, is the fraction of cable that has experienced one failure by age t (column 2) that will experience two failures by age t + 1 (row 3). Then the state of this cohort evolves according to the linear system

$$v(t+1) = A(t)v(t)$$

Eq. 3-8

or

$$\begin{bmatrix} \mathrm{v}_0(\mathrm{t}+1) \\ \mathrm{v}_1(\mathrm{t}+1) \\ \mathrm{v}_2(\mathrm{t}+1) \\ \mathrm{v}_3(\mathrm{t}+1) \end{bmatrix} = \begin{bmatrix} (1-\mathrm{h}(\mathrm{t}))\mathrm{v}_0(\mathrm{t}) \\ (1-\mathrm{r})\mathrm{h}(\mathrm{t})\mathrm{v}_0(\mathrm{t}) + (1-\mathrm{h}(\mathrm{t})\mathrm{m}_1)\mathrm{v}_1(\mathrm{t}) \\ \mathrm{rh}(\mathrm{t})\mathrm{v}_0(\mathrm{t}) + (1-\mathrm{r})\mathrm{h}(\mathrm{t})\mathrm{m}_1\mathrm{v}_1(\mathrm{t}) + (1-\mathrm{h}(\mathrm{t})\mathrm{m}_2)\mathrm{v}_2(\mathrm{t}) \\ \mathrm{rm}_1\mathrm{h}(\mathrm{t})\mathrm{v}_1(\mathrm{t}) + \mathrm{m}_2\mathrm{h}(\mathrm{t})\mathrm{v}_2(\mathrm{t}) + \mathrm{v}_3(\mathrm{t}) \end{bmatrix}$$

Eq. 3-9

Eq. 3-10

which determines the population dynamics.

For example, the first Equation 3-9 indicates that the expected number of feet that have not failed by age t+1 is a fraction of those that have not failed by age t. The remainder, $h(t)v_0(t)$, will have failed either once $((1-r)h(t)v_0(t))$ or twice $(rh(t)v_0(t))$ by age t+1. These two terms are found in the second and third equations, as defined by the second and third rows of the matrix $A(t)$, which specify $v_1(t+1)$ and $v_2(t+1)$, respectively. The fourth Equation 3-10 indicates that the expected number of feet that have failed three times by age t+1 is the number of feet that had failed once by age t and that failed twice more in the next year plus the number of feet that had failed twice by age t and failed (at least) once in the next year plus the number of feet that had failed three times by age t. Recall that for simplicity we are not counting past failures beyond three.

The expected number of failures occurring in this cohort at age t is then

$$N(t) = (1+r)h(t)[v_0(t) + m_1 v_1(t) + m_2 v_2(t) + m_3 v_3(t)]$$

Eq. 3-11

Now in a given year y there will be cables of various ages in various states. Thus, define

$v_f(t,y)=$ feet of cable with f failures attaining age t in year y.

For a given year y the set of vectors $v_f(t,y)$ for all ages $t \geq 1$ is called the age profile in that year. Then the age profile evolves according to the state dynamics equations given above:

$$\begin{bmatrix} v_0(t+1,y+1) \\ v_1(t+1,y+1) \\ v_2(t+1,y+1) \\ v_3(t+1,y+1) \end{bmatrix} = \begin{bmatrix} (1-h(t))v_0(t,y) \\ (1-r)h(t)v_0(t,y)+(1-h(t)m_1)v_1(t,y) \\ rh(t)v_0(t,y)+(1-r)h(t)m_1v_1(t,y)+(1-h(t)m_2)v_2(t,y) \\ rm_1h(t)v_1(t,y)+m_2h(t)v_2(t,y)+v_3(t,y) \end{bmatrix}$$

Representing Replacement Policies

In this model, there are only two descriptors of policy for each type of cable: age and observed number of failures. Therefore, we are seeking the combination of age- and performance-based replacement policies that provide the minimum expected present worth of the costs of replacing the existing inventory. We assume that we do not know if any of the cable has experienced failures prior to this analysis, since the data are incomplete on this information. This assumption is almost surely false, but it provides a lower bound on the cost of the solution that would be found if some prior failure distribution were assumed for the existing inventory.

The policy costs and cable system behavior are based solely on the current inventory of cable. In particular, we are making aggregate estimates only and we are not distinguishing cable by anything other than size, vintage and whether or not it is tree retardant. Further, we assume that there is no testing information available for this forecast.

Suppose that the replacement policy is to replace a failed segment after 3 failures (denote the number of failures prior to replacement by f^*). Then the transition equations above are modified as follows: All segments experiencing a third failure are replaced with new cable so

$$v_3(t+1,y+1)=0$$

$$v_0(0,y+1)=\sum_{t\geq 1}\left[rm_1h(t)v_1(t,y)+m_2h(t)v_2(t,y)\right]=$$ the expected feet of cable replaced in year y

Analogous modifications are made for policies that replace a segment after $f^*=2$ failures or after $f^*=1$ failure.

Suppose that the replacement policy is to replace a segment after it reaches age t^* regardless of the number of failures it has experienced. Then the dynamic equations above are modified as follows

$$v_0(0, y+1) = \sum_{f \geq 0} \left[v_0(t^*, y) + v_1(t^*, y) + v_2(t^*, y) + v_3(t^*, y) \right]$$

= the expected feet of cable replaced in year y

$$v_f(t^* + 1, y+1) = 0 \text{ for } f = 0, 1, 2, \text{ or } 3$$

The number of failures occurring in year y is then

$$\sum_{t \geq 1} (1+r) h(t) \left[v_0(t, y) + m_1 v_1(t, y) + m_2 v_2(t, y) + m_3 v_3(t, y) \right]$$

The optimal policy is that policy that minimizes the present worth of the expected costs of failure and cable replacement.

The cash flows associated with failure and replacement of cable in any year y have three components: capital cost of replaced cable, denoted as k_y; utility failure costs representing repairs, denoted as u_y; and customer failure costs, representing outage consequences, denoted as c_y. Since $v_0(0, y+1)$ equals the expected feet of cable replaced in year y under both policies, and the utility and customer failure costs are proportional to the number of failures, the present worth of the expected costs of failure and cable replacement under the chosen policy is given by the expression

$$PV = \sum_{y=1}^{20} (1+\rho)^{-y} \left\{ \begin{aligned} & k_y v_0(0, y+1) \\ & + \left[u_y + c_y \right] \sum_{t \geq 1} (1+r) h(t) \left[v_0(t, y) + m_1 v_1(t, y) + m_2 v_2(t, y) + m_3 v_3(t, y) \right] \end{aligned} \right\}$$

Eq. 3-12

where $\rho =$ the discount rate. Note that this expression depends on the replacement policy through the age/state transition equations.

PV can be evaluated for all the possible combinations of replacement age t^* and prior failures f^* in a straightforward manner and the policy with the lowest PV is then the optimal policy.

Sample Results

The results of the model are presented in the following Table 3-9. For each cable type, which is described by size and whether or not it is tree retardant (which means that it was installed either after 1983 or prior to 1984), the optimal policy is listed. Also shown is the present value of the policy in 2002 dollars. To find this present value, we discounted all cash flows by 3%, real, and treated capital costs, utility failure costs, and customer failure costs as additive, as noted in Equation 3-12.

Table 3-9
Optimal Policies

Cable Type	Policy—Older Cable (Prior to 1984)	Policy—Newer Cable (after 1983)	Present Value of Least Cost Policy ($M)
2AWG	2 failures	3 failures	49.5+1.4
1/0	2 failures	3 failures	22.3+0.6
2/0	29 yrs, 2 failures	3 failures	6.4+0.9
4/0	3 failures	3 failures	8.9+0.4
500	2 failures	3 failures	7.8+0.1
750	30 yrs, 2 failures	3 failures	19.3+0.8

The table indicates that the optimal policy for all old (pre-1984) cable is to replace the cable after two failures, with one exception. Because the failure rate for the 4/0 cable appears to be somewhat smaller than that of the other types (see Table 3-8), old 4/0 cable may be allowed to fail three times before replacement. Also, 2/0 and 750 kcmil cable ought to be replaced, prior to 2 failures, at 29 years and 30 years of service, respectively. The table indicates that the optimal policy for all new (post-1984) cable is to replace segments that have failed three times. The costs for old and new cable, respectively, are presented as the two terms of the sum in the final column of the table.

The table is presented here to indicate the kind of policy results available from the model described above. Recall that these results are for a population of assets. We will discuss the solution for one cable type in some more detail.

2AWG Cable

The optimal policy for 2AWG cable that is installed prior to 1984, denoted as 2AWG-Old in the following tables and graphs, is to replace all cable segments that have failed two times. This is also indicated in Table 3-9, above. There are over 2000 miles of this cable type installed in the system studied.

The present values of the costs of policies that replace cable at various replacement ages, as well as cable segments that have failed twice, from 20 years to 60 years, are shown in the next graph, Figure 3-3. Notice that as the replacement age increases, the present value of the replacement cost decreases, while the present values of the repair cost and customer cost increase. The sum of these costs, the top curve in the graph, typically has a unimodal or u-shape, with a unique minimum at some time. However, in this case, the minimum value is at (or beyond) 60 years, which indicates that cable should not be replaced because it has reached a certain age. The optimal replacement policy depends only on number of failures.

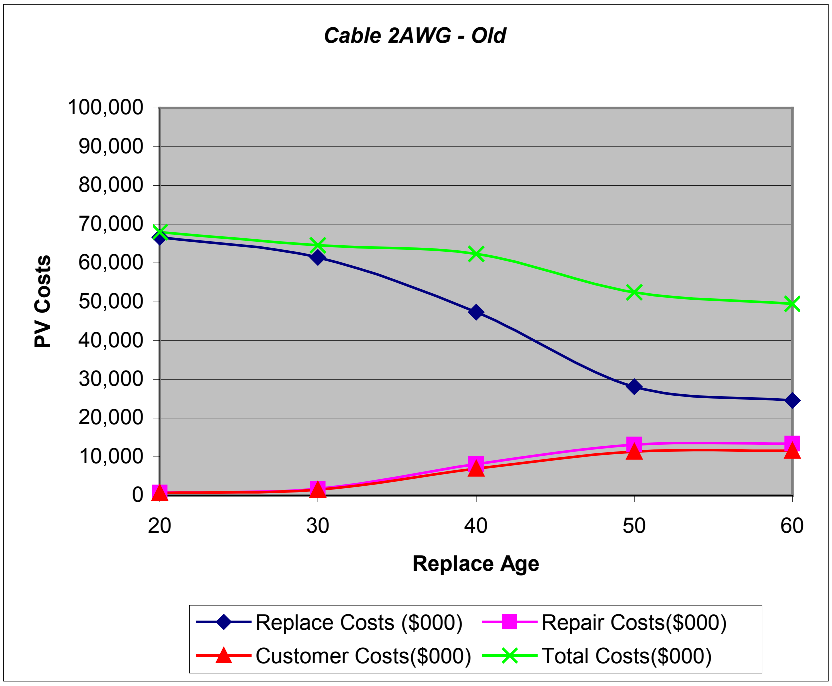

Figure 3-3
Present Value of Replacement Policies—2AWG Old

The cash flows over the twenty-year planning period associated with this policy are presented in the following Table 3-10. In addition, a policy that never replaces cable as it ages, but instead repairs failed segments, is also shown in the table. Figure 3-4 indicates the time variation of these cash flows graphically. One interpretation of these graphs is that the optimal policy requires greater initial cash flows but avoids large cash flows anticipated under the policy of non-replacement.

This interpretation appears to be one of the important findings of this study. At the beginning of the analysis period, we assume that no segment of cable has yet failed. This assumption is based on lack of information about past history of the cable inventory. Therefore, all cable appears in the model as if it were pristine. Now, as cable ages and fails, segments with greater propensity to fail are identified and under the optimal policy are taken out of service. Under the non-replacement policy, such segments are not culled from the population and the result is greater repair costs. Because the model assumes zero failures as the initial state of each cable segment, it considers only repair costs that occur in future years – in particular, there are no repair costs in the initial year, and any repair costs in the past would be sunk costs ignored by the model. This assumption thus almost certainly underestimates the short-term repair costs under the non-replacement policy. Nevertheless, even with this underestimation, the optimal policy is not the policy of non-replacement. Rather the present worth of the cash flows is less under the optimal policy than under the non-replacement policy.

It is interesting to note that most utilities are currently operating under what is essentially a non-replacement policy. What this result reveals is that the non-replacement policy, although in the near term not very costly, can be expected to lead to large costs in the not too distant future. Every example we have examined exhibits this behavior.

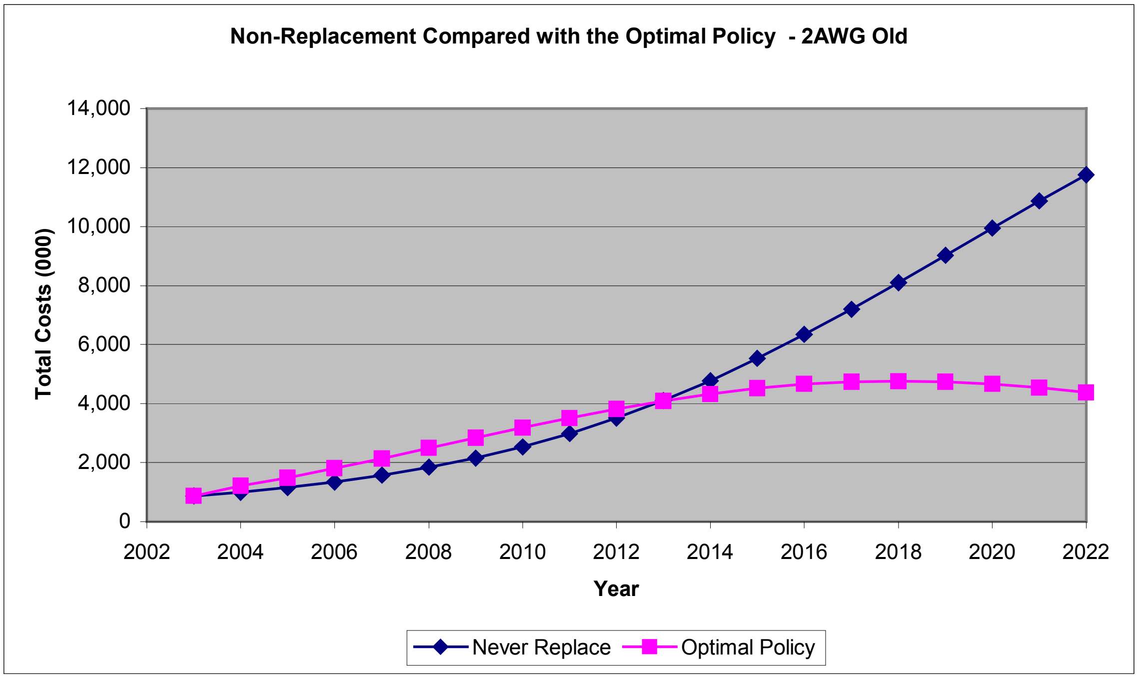

Figure 3-4
Comparison of Optimal Policy and Non-Replacement: Cash Flows Over the Planning Period—2AWG Old

Conclusions

The purpose of this chapter is to present analytic methods for determining policies for managing aging assets and results discovered while applying those methods to two problems, (1) analysis of a population of breakers as the breakers age and as new technology becomes available and (2) analysis of a population of underground cable. At present, there are two methods that solve two related, but different, problems. The first problem is how best to manage a single asset, with particular attention to asset state. The policy is contingent on the state. The second problem is how best to manage a population of assets, with particular attention to failure history and age.

We hasten to note that the specific results presented—change to new technology under specific conditions in the first problem and replace after two failures in the second problem—need not be generally applicable. There are, however, some generally applicable ideas that have been identified as a result of these and other studies. We turn to these ideas in the next chapter.

Table 3-10
Comparison of Optimal Policy and Non-Replacement—2AWG Old

	Non-Replacement					Optimal Policy				
Year	Miles Replaced	Replace Costs ($000)	Utility Failure Costs ($000)	Customer Failure Costs ($000)	Total Costs ($000)	Miles Replaced	Replace Costs ($000)	Utility Failure Costs ($000)	Customer Failure Costs ($000)	Total Costs ($000)
2003	0.0	0	470	405	874	0.0	0	470	405	874
2004	0.0	0	538	463	1,001	3.6	215	531	457	1,203
2005	0.0	0	619	533	1,153	6.3	380	595	512	1,487
2006	0.0	0	721	621	1,341	9.5	568	663	571	1,803
2007	0.0	0	842	725	1,567	13.0	780	732	630	2,142
2008	0.0	0	986	850	1,836	16.7	1,004	799	688	2,491
2009	0.0	0	1,160	999	2,159	20.6	1,237	863	743	2,843
2010	0.0	0	1,365	1,175	2,540	24.6	1,475	921	794	3,190
2011	0.0	0	1,605	1,382	2,987	28.4	1,706	973	838	3,518
2012	0.0	0	1,884	1,623	3,507	32.1	1,928	1,018	877	3,822
2013	0.0	0	2,206	1,900	4,106	35.6	2,134	1,054	908	4,096
2014	0.0	0	2,570	2,214	4,784	38.7	2,319	1,081	931	4,331
2015	0.0	0	2,974	2,562	5,535	41.3	2,479	1,097	945	4,521
2016	0.0	0	3,410	2,937	6,348	43.5	2,608	1,102	949	4,659
2017	0.0	0	3,871	3,334	7,205	45.0	2,700	1,096	944	4,739
2018	0.0	0	4,353	3,749	8,102	45.9	2,755	1,079	929	4,764
2019	0.0	0	4,848	4,176	9,024	46.3	2,775	1,053	907	4,736
2020	0.0	0	5,346	4,604	9,950	46.0	2,762	1,019	878	4,658
2021	0.0	0	5,838	5,028	10,866	45.3	2,715	977	842	4,534
2022	0.0	0	6,316	5,440	11,756	44.0	2,641	929	800	4,371
PV Totals	0.0	0	35,171	30,294	65,466	586.4	24,538	13,390	11,534	49,462

4

GUIDELINES

The guidelines that are presented in this section are based on a limited number of studies performed to date. The guidelines identify the kind of data to collect, the sensitivity of the policy to estimated parameters (which indicates what data to collect or which assessments to refine), and the attributes of policies for aging assets. EPRI expects to continue this research in future in order to make these guidelines more specific and more precise.

Data Collection Guidelines

The data required for analysis of aging assets is classified as follows.

1. Inventory – this is data that describes the collection of aging assets under study.
2. Performance – this is data that describes how assets behave, typically expressed in terms of failure. This data may also include a description of changes in quality of asset behavior as a consequence of asset aging.
3. Cost – this is data that describes the economic consequences of performance of the asset as well as the costs associated with various policy alternatives.
4. Technology – this is data that describes the availability of alternative, typically improved, technology that could replace the asset under study.

Inventory

We have found that the inventory data available varies greatly among utilities and within a utility, across asset types. It is essential to collect the following data: type of asset (including such information as size and configuration or treatments that affect performance) and number of units. Vintage, or date the asset was first placed in service, is an important item. It is usually possible to proceed to an analysis with just that level of knowledge about the inventory.

However, there may be important variations with respect to such variables as manufacturer, service location, and number and type of customers served.

Performance

Required performance data begins with a description of the asset performance states. This can be as simple as *failed* or *not failed*, or as complex as necessary. If the state is either failed or not failed, then it is necessary to estimate a hazard function, either in the form of a function as described in Figure 3-1, above, or as a set of time-varying transition probabilities as described in Tables 3-1 through 3-4.

The minimal data required to estimate the hazard function is the number of failures observed in any year. This provides only a very approximate estimate. To get a more accurate estimate, the data should include number of failures by type of asset by year the asset was first placed in service. The data required to estimate the time-varying transition probabilities is number of failures by asset age.

Additional data required to represent performance include asset loading history, asset maintenance history (or some characterization of it), and the results of any tests done to diagnose the condition of the asset. These additional data permit a more elaborate representation of performance and would provide a more detailed policy that could exploit the value of this additional data. For example, two assets of the same age and same failure history may vary greatly in estimated remaining life based on different test outcomes. In that case, knowledge of the test outcomes is valuable. Treatment of diagnostics tests in the analytical models remains a challenge for this research.

Cost

Required cost data include cost of a failure, to both the utility and customer; cost of each performance state; replacement cost for a new asset; repair cost for each kind of repair; maintenance cost for each kind of maintenance, and costs of diagnostic tests. The minimal data required are the costs associated with each state and each action.

Technology

Technology data is required to determine whether it is optimal to shift from the present technology to a newer technology. Technology data can be based on either existing alternatives or estimates of future technological improvements. A complete specification of costs and performance is required in order to analyze the consequences of changes in technology.

Sensitivity Guidelines

The purpose of sensitivity analysis is to determine how the optimal policy changes as a result of changing the values of the parameters. A policy is said to be *robust* if it is relatively insensitive to changes in parameters. Therefore, identifying both robust policies and sensitive parameters are part of the specification of asset management guidelines.

We consider the following parameters:

- T, the onset of burnout in the hazard function (in the example discussed, set to 25 years for old cable and 35 years for newer cable; see Figure 3-1)
- m, the slope of the burnout in the hazard function (currently set to 0.2 for old cable and 0.1 for new cable; see Figure 3-1)
- h_{ss}, the steady-state hazard rate (currently variable by cable type; estimated by existing data; see Figure 3-1)
- r, the repeat failure rate (currently set to 0.1, see Equations 3-1 and 3-2) the effect of accelerating failure rates (which measures the effect on failure rate of past failures, currently set to double the failure rate with each successive failure)
- customer outage cost

We note the following results.

1. T is not a very sensitive parameter, within the range of changes we have investigated (±5 years). This is true because older the cable repeatedly fails during the burnout period in any case.
2. The slope m of the burnout period is not very sensitive. For a 100% change in slope, changing from m=0.2 to m=0.4, one observes no more than approximately a 5% change in cost. Economists call such changes *inelastic*. This is true because any effect of the slope is dominated by the acceleration due to repeated failures (see point 6, below).
3. The steady-state failure rate, h_{ss}, is a somewhat sensitive parameter. There are some changes in optimal policy as a function of changes in h_{ss}, the steady-state hazard rate of the hazard function. However, in terms of cost differences, these changes are not appreciable if the steady-state rate increases. For a 50% increase in steady-state hazard rate, one observes no more than approximately a 4% change in cost. If the steady-state rate decreases, then somewhat larger changes are observed. For a 50% decrease in steady-state hazard rate, a change in optimal policy can achieve approximately an 8% change in cost.
4. To summarize, the most sensitive parameter of the hazard function is the steady-state hazard rate. The sensitivity is more pronounced in the direction of decreasing hazard rate than increasing hazard rate. The change in cost is relatively inelastic, however, so that the value of specifying the steady-state rate with great precision is limited. The optimal policy is somewhat sensitive to whether the burnout rate is close to doubling in five years compared with a faster rate. Similarly, the change in cost is relatively inelastic, so the value of the information about burnout rate is limited. There is relatively little sensitivity with respect to the time to onset of burnout. Therefore, if the base case hazard function estimates seem reasonable, expensive efforts aimed at further precision appear not to be justified by anticipated changes in present value of policy costs.
5. One of the modeling assumptions made in the analysis is that in any year a segment that has failed may experience a second failure. The simplest way to capture this possibility is to set a deterministic rate of repeated failure. This is done in Equations 3-1 and 3-2, above. The repeat failure rate is 0.1 in the base case of the underground cable analysis. This means that one-tenth of all failed segments will experience a second failure in any year.

The parameter r, as it changes by factors of one-half and three-halves, or ± 50%, is not a sensitive parameter. Within this range, the optimal policy does not change.

6. The optimal policy is very sensitive with respect to acceleration of failures. The base case assumption is that the failure rates double as a consequence of repeated failure. Thus, if a segment of age t has failed once, the failure rate is doubled, and set at 2h(t). If a segment of age t has failed twice, the failure rate is doubled again, and set at 4h(t). We capped the effect of multiple failures at quadrupling the rate. Therefore, the failure rate for a segment of age t that has failed more than twice is 4h(t).

   It is important to measure this acceleration effect with greater precision. There are at least two approaches to representing this effect. First, one can assess multipliers that increase the hazard rate, as has been done in the present example. Second, one can assess an increase in effective age, the independent variable of the hazard function, that is achieved as a consequence of past failures. Of course, any estimation procedure will require the supporting data to be gathered.

   The sensitivity with respect to failure acceleration also indicates the potential value of diagnostic tests. Just as past failures increase the likelihood of future failures, diagnostic tests also produce information bearing on the likelihood of future failures. Policies that are sensitive to the increasing likelihood of future failures will therefore also be sensitive to the information produced by a test. The nature of this sensitivity depends on the characteristics of the test, particularly the correlation of the test outcomes with future failures. Further investigation of this topic is planned.

7. The optimal policy is only somewhat sensitive with respect to customer outage costs. Changes in customer outage costs of approximately ±50% induce policy cost changes of less than 5% and the policy itself does not change. Clearly, as customer costs decrease it may be optimal to wait for more failures or longer service times before replacing an asset. But the effect is not as great as one might have thought. It is not that customer costs are unimportant. It is that the policy is not sensitive to changes in these costs, unless the costs themselves change by very large amounts. This suggests that precise estimates of customer costs are not required to determine the correct policy.

8. The summary conclusion is that a reasonable specification of a base case set of parameters yields a robust policy. That policy is most sensitive to the steady-state failure rate, h_{ss}, and the acceleration of the hazard rate. Somewhat less sensitive, but still important, is the cost of a failure to a customer. The two most sensitive parameters are perhaps the easiest to observe and estimate from data, but this requires that the appropriate data—failure by segment, repeated failure on that same segment in a given year—be collected. The cost of a failure to the customer has been estimated and industry-wide values are available. A reasonable way to proceed might be to compare the base case costs with other values found in the literature and revise, if necessary, the base case assessments.

Policy Guidelines

Policy Structure

The minimal policy specification is to specify asset repair and replacement after some numbers of years, for each alternative. (For example, repair every 3 years, replace after 25 years.) This is a classical engineering-economic result. We expand on this policy structure to include the number of failures as a criterion. Clearly, if more data were available, the policy could be as complex as one might imagine. Especially interesting is the collection of policy recommendations as a function of the outcome of diagnostic tests. We have been unable to identify a case with test performance data, so this policy specification is not available at present. For a complex policy structure, dependent on the setting of many observed variables, we would present the result in a decision tree format similar to Table 3-7. This table clearly indicates which decision, of a discrete set, is chosen for a given collection of prior conditions.

Aging

The optimal policy typically reflects the useful engineering life of an asset. This life is known with varying degrees of precision. As a guideline, however, we believe that age is insufficient. What is critical is the combination of age, failure history, and maintenance policy. These three combine to construct the effective age of the asset, which is then used as the independent variable in the hazard function. There is no single, generally applicable relationship that determines effective age from these three variables. Two assets of identical age can have far different future lives if the failure and maintenance histories are different.

Derating

The policy of derating is based on achieving the life-extension benefits of reducing load on an asset. If an asset is operating in the steady-state condition (service time less than T, the time of the onset of burnout, or accelerating failure rates do not apply), then derating may not be a good alternative, unless it is known to reduce the steady-state failure rate. Derating may be useful if the asset has failed in the past, accelerating failure rates apply, and derating reduces the acceleration. However, it may be optimal to replace such an asset rather than derate it.

Quality of Service

As we have modeled it, quality of service conditions refer to customer cost of failures. Clearly, if the customer costs are relatively high and accelerating failure rates apply, then it is optimal to replace assets after very few failures.

Technological Change

The breaker case indicates that it is optimal to switch to new technology as quickly as possible. We do not expect this to be generally true, but if the following conditions hold, then switching to new technology appears to be optimal. Conditions under which it appears optimal to switch to new technology include: most installed assets using older technology; difficult to replace with older technology; limited capability to refurbish older technology; newer technology has lower steady-state hazard rate; catastrophic failure mode exists for older technology.

5
CONCLUSIONS

The purpose of this report is to present guidelines for managing aging assets based on two approaches. The first approach uses a dynamic probabilistic modeling approach to determine the contingent policy that minimizes the costs of operating an aging asset. In the example studied, the decisions concern when to replace an existing asset and what to do with that asset prior to replacement. The second approach uses a dynamic deterministic approach to identify the least cost policy for managing a population of aging assets and to forecast the costs of that policy. In the example studied, management means repairing and replacing cable segments according to an appropriate policy. The policy variables considered here are replacement interval based on age and replacement based on number of failures experienced by a segment. In the example, a fundamental conclusion is that the optimal policy can avoid large cash flows due to frequent failure of older cable in the future. The main idea behind the optimal policy is to identify weak or poorly performing segments of cable and remove them from the system before their failure incurs large costs. This appears to be a generally applicable conclusion.

This report summarizes the results of several studies in a set of guidelines that indicate what data to collect; which variables are the most sensitive ones, or which variables have the greatest influence on the specification of the optimal policy; and what consequences for policy follow from these studies. Perhaps the most important finding is that the policy of non-replacement, which means continually repairing the asset, is generally not optimal. We have learned that the optimal policy suggests replacement of the asset after a certain age or after a certain number of failures have occurred. The difference in cash flows between these two policies can be very large, but the differences do not appear until some time in the future.

Other important conclusions are that aging asset decisions can be supported by generally applicable and reusable methodology and data, and that the methodology can offer utilities guidance about what data to collect. We also propose to continue this research and make the guidelines more useful.

A
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