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Utility Vegetation Management: Use of Reliability-Centered Maintenance Concepts to Improve Performance

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EPRI Project Manager
J. Goodrich-Mahoney

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Environmental Consultants, Inc.

BioCompliance Consulting, Inc.

Maintenance & Test Engineering

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This report was prepared by

Environmental Consultants, Inc.
Address 520 Business Park Circle
Stoughton, WI 53589

Principal Investigator
Ed Cunningham

BioCompliance Consulting, Inc.
7710 196th Ave NE
Redmond, WA 98053

Principal Investigator
John W. Goodfellow

Maintenance & Test Engineering
2037 North Berry Street
Olympia, WA 98506

Principal Investigator
John Skog, PE

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PRODUCT DESCRIPTION

This document describes the approach taken to adapt and apply the principles of Reliability Centered Maintenance (RCM) to Vegetation Management (VM) activities on an overhead electric distribution system. The project included a review of relevant literature, production of an RCM primer for vegetation managers, development of VM-specific Failure Mode and Effect Analysis (FMEA) methods, and production of a structured process and information tool useful in completing an RCM-based assessment of a distribution system vegetation management program.

RCM provides a structured decision -making process for completing an assessment of maintenance needs focused on preserving the reliability of system function. The industry's traditional approach to maintaining vegetation free of distribution lines has been to emphasize maintenance of fixed clearances on a periodic system-wide basis. This is accomplished through the use of fixed-interval preventive maintenance cycles. Examples of an RCM-based approach may include subsystem-specific preventative maintenance tasks and the integration of condition assessment techniques resulting in a modified cycle period.

Results and Findings

This project provides a utility vegetation manager with the opportunity to apply a structured methodology for applying RCM-based analysis to their current VM program. Insight gained in working through the analysis provides the user with a clear understanding of the manner in which trees pose risks to distribution systems, the relative degree of risk for varying types of distribution lines and tree failure, and maintenance task options for mitigating unacceptable levels of risk and consequences.

The project also includes a high level assessment of the user's current practices compared to what are considered industry best management practices.

Challenges and Objectives

This report will be useful to vegetation management personnel in both asset management and field service provider roles. Maintenance tasks within an RCM-based VM program are focused on mitigating the consequence of failures. This may be a combination of reducing the frequency and/or mitigating the effects of failures. In either case, there is a clear relationship between risks, the consequences of failures, and maintenance tasks, which in turn drives cost efficiency and effectiveness.

Applications, Values, and Use

An automated version of the RCM Analysis Tool (the Tool) has been developed as part of this project, and will be available in early 2010. A user workshop introducing the RCM analysis and the Tool to vegetation managers will be conducted during 2010. A proof–of-concept demonstration project has been proposed, the purpose of which would be to make a direct comparison of traditional and RCM-based VM maintenance practices on an in-service distribution system.

EPRI Perspective

EPRI is in the unique position of being able to facilitate the transfer of techniques and technologies from discrete disciplines and segments within the utility industry. This project is a good example of that crossover. It successfully combines expertise in VM with distribution engineering, line operations, and system overcurrent protection. It also leverages EPRI's twenty-five year history of involvement with applications to RCM within the industry. The result is the creation of an analytical method for addressing one of the main causes of interruptions on the distribution system (trees), and for optimizing one of the largest single line items in a utility's O&M budget (vegetation management).

Approach

The goal of this project was to develop a means of adapting RCM methods to distribution system vegetation management programs. This was accomplished by providing potential users with a foundation in RCM, and by producing a structured decision process that walks a user through RCM analysis as it applies to vegetation maintenance.

Keywords

Failure Mode and Effect Analysis (FMEA)
Reliability Centered Maintenance (RCM)
Tree-Caused Interruptions
Vegetation Management (VM)
Vegetation Maintenance

ABSTRACT

This project involved development of methods for applying reliability centered maintenance techniques for the analysis of Vegetation Management (VM) programs on overhead electric distribution utility systems. Reliability Centered Maintenance (RCM) was initially developed as a means of developing preventative maintenance programs in applications with high reliability requirements, even in the absence of extensive operating data. EPRI has led efforts to transfer RCM techniques to the utility industry, first in nuclear and fossil fuel generating stations, and more recently to substations, transmission, and distribution systems. More recently EPRI made a conceptual assessment of the potential to apply RCM constructs to VM. Application of RCM to vegetation management was a logical next step.

This RCM-based study effectively integrated several bodies of work related to trees and their interaction with overhead lines, creating the opportunity to develop a state-of-the-art, reliability-driven VM program. Reliability data and the operational experience of a cooperating utility were used to develop and demonstrate the RCM methods and processes specific to vegetation maintenance.

The RCM project used a systems, rather than component, approach. Systems and subsystems relevant to vegetation maintenance were defined. RCM-based Failure Mode and Effectiveness Analysis (FMEA) methods focusing on the manners in which trees pose risks to overhead distribution lines were developed. The project resulted in an RCM model and templates that can be adapted to and applied at other utilities, making it possible for them to create their own reliability-driven solutions.

Some broad themes have been identified, as a result of the project. They represent significant shifts in maintenance management philosophy, and include the following:

- A shift in orientation from a focus on achieving and maintaining tree-conductor clearance to one focusing on preserving system function (reliability).
- Recognition that while reducing risk and preventing failures is important, there is a need to consider mitigating the consequences (effects) of failures as well.
- A shift from a bias employing a standard approach to vegetation maintenance applied uniformly across the distribution system to recognition of the opportunity to create subsystem-specific maintenance prescriptions. One size does not fit all.
- A shift from age (cycle period) as the exclusive driver of maintenance schedules to one that also includes considers condition assessment and “on-condition” maintenance.

These changes also require increasingly sophisticated VM programs. The value of each change needs to be weighed against the cost of incorporating these new paradigms into a utility’s existing distribution VM program.

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1
PROJECT SCOPE AND BACKGROUND

This project involved the development of a method for applying principles of Reliability Centered Maintenance (RCM) analysis to traditional Vegetation Management (VM) programs. This work is a logical extension of EPRI's long-standing commitment to RCM beginning with nuclear and fossil fuel generation, substations, and Transmission and Distribution (T&D) systems. It effectively leverages EPRI's on-going investment in RCM.

The project specifically focused on vegetation maintenance practices on electric distribution systems. This work typically involves the pruning and removal of trees in close proximity to overhead distribution lines operating at voltages up to 35kV. Both overhead primary and secondary class lines including services to customers were included in the definition of electric distribution used in this project

Trees continue to be a leading cause of service interruptions on electric distribution systems throughout North America. This is in spite of the fact that preventive maintenance of vegetation that interacts with overhead distribution lines is the single largest O&M expense for electric utilities. While numerous refinements have been made in vegetation management practices in past decades, much of the change has been driven by financial and productivity considerations.

While numerous refinements have been made in vegetation management practices in past decades, much of the change has been driven by financial and productivity considerations.

Less innovation has occurred in aligning vegetation maintenance tasks with the actual risks trees pose to distribution system reliability. The traditional approach to mitigating tree-related risk to distribution system reliability has been to apply a fixed standard for clearance between trees and overhead conductors, and to schedule preventive maintenance on a fixed-interval cyclical basis.

More recently a number of studies have been conducted that have led to development of a conceptual model for understanding tree-caused interruptions. This model provided a new understanding of the risk trees pose to reliability. This project draws on several bodies of important work related to the risks trees pose to overhead distribution lines. It incorporates work related to both the electrical and mechanical modes of tree-initiated interruptions. The application of RCM analysis also provided an opportunity to draw from the collective wisdom and experience of practitioners from several disciplines. The resulting RCM analysis method provides a practical means of developing a logical and cohesive integrated vegetation maintenance strategy.

The project included five tasks. Each is described in greater detail later in this report. The tasks included:

1. A review of engineering and arboricultural literature related to RCM, distribution system reliability and vegetation maintenance practices.
2. Creation of a general reference describing RCM constructs. This primer is intended as a basic introduction to RCM principles, methods, and processes for vegetation managers.
3. Creation of RCM-based Failure Mode and Effect (FMEA) analysis tables developed specifically for VM that define the risks trees pose to an overhead electric distribution system.
4. Creation of an RCM-based method providing a structured process and templates for completing RCM analysis of distribution vegetation management programs. This included the creation of an RCM Analysis Tool.

The project also created an opportunity to develop a simple means of conducting a best practices gap assessment.

The project included the participation of a host utility. Access to “real world” data made it possible to evaluate various approaches to vegetation maintenance, and enabled the team to create a durable approach with practical application. In return, the project included a specific assessment of the existing VM program at the cooperating utility and the development of specific recommendations for reliability-driven enhancements to their existing VM program.

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LITERATURE REVIEW

The initial task for the project involved a review of relevant literature. Two main bodies of work were reviewed. Literature related to VM on distribution systems was found predominantly in the Journal of Arboriculture and Urban Forestry and in industry trade publications. Relevant literature related to distribution system functions, engineering and performance was typically found in IEEE Transactions.

Abstracts of potentially useful articles were reviewed. Full copies of papers that appeared to be useful were then obtained and reviewed. Papers deemed to be useful to the project were then re-summarized in abstract form. Twenty-two project-specific abstracts of the cited references appear in Appendix A-1, listed in alphabetical order. The main themes useful to the project are discussed below, and include the number of the abstract from which observations are drawn.

Faults on an overhead distribution system can typically be categorized into two types. The majority of faults are permanent or temporary, rather than intermittent. Repair actions are required for restoration of permanent interruptions. Intermittent faults, in contrast, may not require any repair of damage to overhead infrastructure (1). The manner in which the overcurrent protection system operates plays a major role in determining whether a fault results in a permanent interruption and customer outage. The selection of either "fuse blow" or "fuse save" protection schemes is used by utilities as a means of managing the consequence of tree-initiated faults on system reliability (6, 19).

Altering the existing energy delivery infrastructure can also mitigate the risk of tree-initiated faults. Examples such as replacing bare conductors with coated wire systems (e.g., "tree wire" and spacer cable), relocating the line, and converting overhead lines to underground are possibilities (12). However, the cost of converting existing infrastructure to an alternative type of construction is rarely justified on the basis of tree-related reliability concerns or avoided cost of future tree maintenance and repair. An exception may be adding fuses to lateral tap lines, which often is a cost-effective way to isolate faults (19) and minimize the failure effect.

The risk posed by trees is largely due to their potential for structural failure. The majority of incidental tree contacts on the distribution system remains as high impedance/low current faults that will not result in an interruption, and represent low risk to public safety (9, 10). There are two modes of tree-caused interruptions on the distribution system. (9, 10). A mechanical mode of failure occurs when the tree fails and causes physical damage to distribution infrastructure. The electrical mode of failure occurs when a tree or branch provides a fault pathway between areas of unequal electrical potential. A large percentage of tree-caused faults are due to trees outside of traditionally maintained clearances. It is estimated that 66-95% of tree-caused outages are due to the structural failure of trees and branches coming into contact with distribution lines

(13, 18). A periodic inspection (condition assessment) of overhead distribution lines is an effective means of reducing tree caused faults (1).

One of the ways in which utilities manage the risk of tree failure is to focus on the removal of obviously hazardous trees and branches in the vicinity of utility corridors (17). In some cases, a discrete hazard tree risk management initiative is conducted on portions of distribution circuits exposed to the greatest consequence of failure, and targets trees with elevated risks of failure (16). There is, however, evidence that the majority of trees that fail do not exhibit readily apparent outward signs of impending failure (13). This can be explained in part by the role site features and exposure play in influencing the potential for tree failures.

A fixed interval vegetation maintenance cycle has traditionally been considered a preferred approach to VM on distribution systems (14). An alternative is to adopt a modified means of maintenance scheduling based on criteria that include line voltage, customer density, tree density and predominant species (15). Other factors considered in the determination of vegetation maintenance on overhead distribution feeders include the tree fault rate, wind, climate and exposure (14).

It is recognized that the risks and consequences of tree-caused faults are not uniformly and randomly distributed across the system. Factors such as line segment length, line type, system protection, risk potential and exposure all need to be considered in assessing the reliability of a circuit and any of its parts (8). This recognition is then applied to maintenance expenditures. One method of prescribing maintenance that is referred to as "optimized cherry picking" involves selecting an approach but not carrying it through in application to the entire system. For example, performing vegetation maintenance work on key portions of a circuit including feeder trunks and major lateral lines will achieve the majority of the potential reliability improvement possible (21).

Another consideration in determining vegetation maintenance schedules is tree re-growth following vegetation maintenance pruning. An exaggerated re-growth response was shown to occur following pruning. The re-growth response was greatest in the growing season following pruning. The growth response stimulated by pruning diminished in subsequent growing seasons (11). The cost of line clearance pruning was shown to increase significantly with time as branches grow into close association with conductors and the volume of pruning residue increases with time (5).

There are limited references to the application of RCM to electric distribution systems, and little in the way of references to its application specifically to vegetation management. This is likely due to a lack of familiarity with the method. It may also be due to both an acceptance of some level of interruptions on distribution systems. Finally, difficulty in quantifying the benefits of improvement in reliability due to preventive maintenance tasks to electric distribution systems may have contributed to the slow migration of RCM to this segment of the industry (2, 3). Most applications of RCM to distributions systems focus on the individual equipment components and devices that make up a distribution system (2, 3).

Significant limitations in the type and quality of reliability-related data are widely recognized. Inconsistencies exist within the industry in data availability, data definitions, and in the data collection process (20). Differences in data collection processes and utility system characteristics make development of universally applicable standard metric values, and comparisons between utilities using such metrics, difficult at best. The use of intra-organizational metrics based on historical performance represents a practical means of measuring performance (7). Using longer period averages, such as five to ten years, can identify poor-performing feeders, as long as these feeders have not significantly changed over the period of consideration (4).

3
RCM PRIMER FOR VEGETATION MANAGERS

Introduction to Reliability Centered Maintenance for Vegetation Managers

The purpose of this section is to provide utility vegetation management personnel with a basic understanding of the principle of RCM and the process required to complete an RCM-based analysis of maintenance needs. Subsequent sections provide detailed information on how the project team adapted RCM techniques for application to distribution system vegetation management.

Utility Vegetation Management on Distribution Systems

Utility vegetation management is largely a traditional discipline within a traditional industry. The change process is characteristically slow and incremental in nature. While the utility industry's trend has been toward adoption of RCM, there is little evidence of its successful application in refining vegetation maintenance programs.

The traditional approach to VM has been to emphasize achievement of a standard level of conductor-tree clearance across the distribution system. This has typically been achieved on a fixed-interval, cyclical basis. This was based on the premise that there was a "right age" at which to complete line clearance pruning necessary to ensure safety and operational reliability. It also assumed that a uniform clearance standard applied consistently across the entire distribution system, and that this was the optimal approach to managing preventive maintenance.

The recognition that the relationship between age and the need for maintenance is not so simple or straightforward is leading vegetation managers to re-evaluate the concepts of traditionally scheduled maintenance. Recent work is demonstrating that tree-conductor clearance on distribution systems is "one step removed" from reliability. Trees generally do not cause interruptions in the distribution system by simply growing into contact with conductors. Tree and branch deflection and failure represent the major risks to reliability. The development of proper pruning practices that reduce the risk of branch failure, and more recently a focus on hazard tree identification and risk mitigations, are outcomes of this realization.

RCM-like revisions to traditional vegetation management practices are beginning to occur in the industry. An informal review of RCM applications to utility vegetation management and maintenance of overhead distribution systems in general reveals that while reference to RCM is being made, very little evidence would suggest that RCM is actually being used in managing distribution maintenance programs. In short, references to "RCM" are beginning to be made in relation to distribution VM, but we know of no comprehensive application of RCM to overhead distribution vegetation maintenance programs.

Uncertainty due to deregulation (and re-regulation) and competition is placing increasing demand for distribution system performance while simultaneously limiting the availability of maintenance resources. RCM is a useful tool in bringing renewed focus on the reliable operation of distribution infrastructure. The timing of an RCM initiative appears consistent with the need to develop a contemporary model for effectively managing distribution system maintenance programs. It is also a logical extension of EPRI's earlier efforts.

Budget allocations to utility VM are commonly recognized as a major component of a utility's transmission and distribution (T&D) maintenance program. RCM has a track record of significantly improving maintenance program effectiveness. Even small adjustments will generate substantial improvements in reliability and maintenance resource allocation.

An investigation in VM and in distribution system maintenance in general, would help assess resource allocation across a wide range of T&D maintenance programs and support a marginal analysis of the most effective application of limited maintenance dollars.

History of RCM

RCM was initially developed in the late 1960's in the commercial aviation industry as a means of optimizing maintenance activities for jet-propelled aircraft. This was then successfully applied to a new aircraft during the design stage, the Boeing 747 "jumbo jet". It was driven by a need to develop preventive maintenance programs in the absence of detailed quantitative data on historical performance. The initial application proved to be successful in achieving the desired level of reliability at reduced cost. In fact, it was so successful that in 1975 the US Department of Commerce further refined the concept and adopted RCM as a procurement requirement of major military systems.

RCM then migrated through other industries with high reliability needs. In 1984, EPRI sponsored an RCM pilot project for nuclear power, and by 1987 RCM had become a mandatory requirement at nuclear generating stations. By the early 1990's, RCM had made its way from utility generation to the T&D system. This too was an effort led by EPRI, completing RCM work in the area of substation maintenance. It is important to note that in each of these applications, RCM methods were developed to optimize the maintenance of a system with high reliability requirements at a time when there was little historical failure data available to guide traditional analysis. Most recently there has been interest in applying RCM methods to the distribution system. In 2003 EPRI, completed an assessment[1] of the potential for RCM application to utility VM.

At the same time, RCM was being developed outside the industry, maintenance programs within the utility industry were beginning to evolve. The 1970's represented a period of development, as utilities were enhancing old programs and developing new programs based on manufacturer's

[1] "Utility Vegetation Management – Use of Reliability Centered Maintenance Concepts to Improve Performance", EPRI, Palo Alto, CA, and ECI, Stoughton, WI: 2003. 1008859.

recommendations and their own experiences with interruptions. The 1980's marked a period of normalization for utility preventive maintenance programs. Approaches to maintenance and levels of intensity varied from one utility to the next. Benchmarking led to a degree of consensus and normalization between programs.

In the 1990's, focus shifted to efficiency improvements. Early adopters attempted to apply RCM philosophies to T&D maintenance programs. Unfortunately, many utilities used RCM to justify their existing programs, or as a rationale to reduce or in some cases eliminate preventive maintenance work without making complete use of the RCM analysis process. It is also important to acknowledge that in many applications where RCM was applied to complex systems in other industries, there was a sense that the system of interest was being over-maintained, and significant cost savings were generated by engaging in RCM. The notion of excessive maintenance is not commonly associated with overhead distribution system maintenance. While cost reductions may be possible, it is more likely that RCM will yield greater efficiency in the allocation and use of already limited resources. Not surprisingly, many of the early attempts at applying RCM to distribution systems did not achieve the hoped-for reductions in costs or improvements in reliability. As a result of these false starts, misconceptions and apprehension developed, and the benefits of RCM were not fully realized.

In the first decade of the 2000's, asset management emerged as a leading principle within the utility industry. Maintenance is now viewed as more than just performing the right tasks, it also includes managing the life cycle of an asset and ensuring the asset and the maintenance program performs in a manner that the economic, reliability, availability, regulatory and safety goals of the utility are met. As such, a more structured approach to the total maintenance process is necessary to ensure that continuous improvement takes place.

RCM has proven to be useful in some very rigorous applications that all shared some common characteristics, as follows:

- Industries where reliability is critical
- Industries where quantitative data regarding historical performance and failures are limited
- Industries that may have extensive regulatory requirements

These same characteristics are similar to those encountered in the utility VM industry. Emphasis on reliability is a central theme common to both RCM and the desire of vegetation managers. Secondly, performance data available to utility vegetation managers typically are very limited and are known to contain errors and omissions. Finally, the industry is clearly facing increased regulatory scrutiny. All these factors point to the potential for the full application of RCM to the maintenance of vegetation on overhead distribution systems.

The desire to increase the overall effectiveness of maintenance resources by optimizing the use of routine maintenance has resulted in many utilities turning to RCM. In particular, RCM techniques have been employed because of their successful track record in other competitive industries and because of the technical, unbiased, practical and logical approach to maintenance. A utility's desire to emphasize the application of predictive maintenance techniques is fundamentally supported by RCM. The preventive actions identified through RCM analysis are focused on preserving the fundamental functions of the system and are based on predicting and preserving reliable operations, not on merely achieving a predefined schedule.

It should be noted that the criticality of overhead distribution systems is generally lower than that found in the aviation and nuclear power industries with a longer history with RCM. On distribution systems there is an acceptance of some level of failures (interruptions) both in terms of frequency and duration of system failures. This would not be the case in either aviation or nuclear power applications. Another significant difference is that the relationship between system availability and the opportunity to earn additional revenue is less direct, and the potential economic gain is smaller. The lack of significant additional revenue to be gained from improvements in reliability also reduces the justification for developing sophisticated reliability and maintenance management protocols on simple overhead radial distribution systems.

RCM as a Method and Philosophy

RCM is often described as organized common sense. The method is both logical and systematic. Once understood, the method becomes intuitive and subtle in its elegance. RCM makes use of both quantitative observations and the collective experience of the organization, including a wide range of technical subject matter experts and craftsmen. A well-executed RCM study brings together the collective wisdom of the organization. Its real value is the effective integration of maintenance practices and resources into a logical and cohesive whole.

RCM is a highly adaptable analytical tool and is flexible enough to support analyses of varying intensities, from conceptual to rigorous. RCM is not a "cookbook" process, but is best described as a philosophy and way of thinking. Nor should RCM be thought of as a focused study of finite period and scope. In actual practice it can take a number of forms. State-of-the-art thinking recognizes that RCM is a way of managing maintenance. The initial RCM study establishes a baseline understanding of optimal maintenance practices and resource allocations. Initial findings are tested and refined as the program is implemented and managed. State-of-the-art RCM embraces the notion of continuous improvement. In a sense, the RCM process is never completed, but continues to be refined over time.

RCM analysis focuses attention on understanding risks to reliability and on mitigation of the consequence of failure. Failures that jeopardize safety are prevented. The assumption is that all other failures result in consequences that may be tolerable, and the value of preventive maintenance can be measured in terms of consequence mitigation. In short, the driving element in all non-safety maintenance decisions is valuing the consequence of the failure. Within this context, it is then possible to develop an efficient maintenance program.

One of the challenges typically faced in developing maintenance programs is the lack of statistically valid operating and failure information. RCM provides analytical methods for working though the process even when data are limited or unavailable.

RCM Analysis Process

As previously discussed, RCM provides a structured process and decision logic to assessing maintenance options. The following sections of this chapter are intended to give vegetation management personnel a generic understanding of the process. The remaining chapters describe how generic RCM constructs were adapted specifically to an analysis of vegetation maintenance tasks and the creations of an RCM-based VM plan and program.

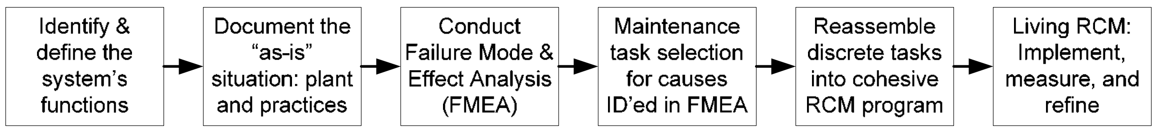

Figure 3-1
Generic application of an RCM analysis process

Defining the System

The first step of an RCM analysis is to reduce the project into logical and workable elements. This is accomplished by defining discrete elements of operationally significant "systems". In the context of RCM, the system is defined by its critical functions. RCM is based on the fundamental premise that the inherent reliability of a system is a function of its design, and that the purpose of preventative maintenance is to preserve the intended level of reliability that the design is capable of achieving.

While all RCM analysis is focused on preserving system function, analysis can be conducted at either at a system or component level. A distribution system can be considered as either an interconnected assembly of components or subsystems. The component approach involves developing maintenance requirements for individual pieces of equipment. The alternative approach is to treat the system as a composite of subsystems rather than components. The authors believe that the system/subsystem approach is more useful in conducting an RCM assessment of VM. It reflects the fact that the functions and potential for failure being studied are relatively less complex than many of challenges addressed through RCM analysis in other segments of the utility industry.

In either case, RCM considers preservation of critical system functions as the primary reason for preventive maintenance. By focusing attention on system function(s) that are important, RCM-driven analysis applies an effective filter for identifying unnecessary tasks and associated costs. Potential maintenance task are evaluated as to their efficacy at preserving system functions. Because RCM focuses attention on preserving system function, a number of strategies not traditionally considered as 'maintenance' might be included in the maintenance prescription.

Define the Current "As Is" Situation

Once the relatively general definitions of systems and subsystems are developed and critical functions identified, attention turns to applying these definitions to the actual installed plant for which the maintenance program is being developed. This step typically involves cataloging or describing the system and subsystems in terms of installed infrastructure. This may also include defining the environment in which the system is deployed.

RCM techniques were initially developed for use in developing preventive maintenance programs in advance of the actual deployment of a system, as in the case of a new airliner. However, more often it is being applied to an assessment of existing systems that are currently receiving some form of maintenance. In these cases it is common to add a detailed characterization of current maintenance practices.

Failure Mode & Effect Analysis

The next step of RCM analysis involves conducting the FMEA. An FMEA is conducted for each subsystem. Functional failures are the basic building blocks of the FMEA. FMEAs are typically created with the input and participation of an interdisciplinary team, representing a broad cross-section of expertise and experience.

Functional failures define the ways in which the subsystem fails to meet functional expectations and requirements. By definition, a functional failure is an unsatisfactory condition involving the inability of a subsystem to adequately perform one or more critical functions. An effective way to identify functional failures is to think about how the function could fail by reviewing the scope of possibilities such as:

- Fails to perform its mission.
- Improper performance of its mission.
- An inadvertent malfunction.

At this point in the process the cause of the failure is not important. It is considered later in the FMEA process.

Modes of Failure

The FMEA process begins by cataloging failure modes. In performing any RCM evaluation, the analyst must identify the likely failure modes for each subsystem of interest. A failure mode describes the general manner in which a failure is initiated, subsequently leading to a functional failure. Said another way, the failure mode defines the way a failure occurs or “how”, but not why a failure occurs. The tendency of first-time users of RCM methods is to move quickly though this step and on to a focus on the consequences of failure. This is a mistake. The analytical process of systematically breaking each functional failure down into a basic statement of mode provides one with important insight that establishes a foundation for the remainder of the RCM process.

Effects of Failure

Once failure modes are established, attention turns to defining the likely effects or consequences of each failure mode. RCM defines failure effect in terms of loss of system functions. RCM uses a structured decision logic that focuses on defining the consequences of failure. Once defined, failure consequences are the focus in selecting cost-effective preventative maintenance tasks.

The effects of failures are typically defined in terms of safety, and other operational consequences such as availability, reliability and cost. The actual failure effects used in the FMEA may vary and are defined by the user. Here again, the approach involves breaking each failure effect down into basic statements.

Figure 3-2 identifies some of the typical criteria used to define the effects of a failure. Defining the physical and operational effects of a failure allows the user to quantify the failure effects in functional and economic terms.

- Availability
  - Frequency of loss of function
  - Duration of loss of function
- Cost of loss of function
  - Revenue loss
  - Cost of repair and restoration of function
  - Customer affects, users of the system's functional outputs or outcomes
- Environmental affects
- Political affects
- Litigation affects

Figure 3-2
Metrics commonly used to define the effects of functional failures of RCM systems

The scope of the effect is defined by the mode, which ultimately ties back to system function. It is not uncommon for failure effects to be created in a somewhat hierarchical fashion with an initial general statement and then a specific statement. This occurs when the user sees the need to refine the initial failure effect statement in more specific and useful terms.

Figure 3-3 offers an example of a generic FMEA for a typical overhead distribution line. It illustrates the hierarchical structure used in this phase of the RCM analysis process. It also offers a sense of the working definition of key terms such as system, function, mode, effect, and cause in actual application.

System: Overhead primary distribution line.

Function: Provide continuous supply of energy to distribution transformers, and ultimately end use to customers.

Failure Modes:

- Fails to conduct
- Fails to provide steady state insulation
- Fails to provide regulatory clearance

Failure Effects:

- Loss of supply to transformer or service entrance
- Voltage instability
- Violation of regulatory requirements

Failure Causes:

- Mechanical failure of conductor
- Mechanical failure of supporting structure
- Electrical failure of insulator
- Contact with foreign object
- Phase displacement or deflection

Figure 3-3
Example of FMEA performed for an overhead primary distribution line

At the conclusion of this step, an FMEA will have been created for each subsystem. It will list all the failure modes and effects that might occur, causing the loss of a system function. At this point a streamlined approach to RCM is often applied. Applying some manner of pragmatic screening criteria focuses attention on the most important failures. Two examples of screening criteria include criticality and dominance. Critical failures are failures involving a loss of an important function. Criticality is an assignment of a relative rating of the affect a failure has on the system. Dominant failures are failures that have a high frequency occurrence. It should also be recognized that if, during the FMEA process, a failure modes is determined to have only benign failure effects, the mode and possibly the supporting function is of low consequence.

Failure Causes

Once the FMEA has established the important modes and effects of system failure defined as loss of function, attention turns to determining the probable cause of each. The failure cause describes why the failure occurred. Failure causes provide the link between failure modes and effects, and the selection of appropriate/cost-effective maintenance tasks. In order to select preventive maintenance tasks, the analyst must first identify reasonable causes of failure. Failure causes are typically an area of keen initial interest. Once again caution is counseled: it is important to work systematically through the FMEA process. Once modes and effects are appropriately defined and prioritized, the determination of the cause of each can be clearly and succinctly defined.

Addressing Data Deficiencies

One of the strengths of RCM is the ability to conduct a systematic assessment of maintenance needs in the absence of complete or accurate data. This characteristic is directly related to the genesis of RCM. The introduction of an entirely new aircraft, the Boeing 747, meant there were little or no data related to failure histories for many of the new systems used in it. There was no operating history, yet a preventive maintenance program had to be designed at the onset that would yield a very high level of reliability.

There are two broad strategies incorporated within RCM that allow systematic analysis regardless of whether failure data are available. The first is reliance on formally structured decision logic. As has been described, this begins with defining important system functions, and then the modes, effects, and causes of failures that occur or could occur. The structured process relies on more than data. This is why it is important to take the necessary time to do a thorough job in developing FMEA's for each subsystem. It allows the user to include failures both known to have occurred (for which data may be available) and those that in the opinion of the expert group could occur (for which there may be only related data or no historical data).

The second way in which RCM analysis overcomes data limitations is through reliance on both the technical knowledge of subject matter experts and the practical experience of the maintenance organization. FMEA analysis typically is completed by an interdisciplinary team, and makes use of both quantitative observations and qualitative experience. RCM analysis also commonly makes use of Delphi Analysis[2] techniques. This involves an iterative review cycle where a subject matter expert or small expert group conducts an initial analysis. The draft work product is then vetted and validated by a larger group of informed stakeholders. The result is a systematic assessment that draws from a variety of data sources, some formal and others less so. It is intended to draw on the experience and collective wisdom of stakeholders.

[2] The Delphi Method involves a structured process used to collect and distill the knowledge of a group of subject matter experts. It uses an iterative process of feedback and refinement. The method recognizes the value of human experience and judgment, and structures it into a useful form. The technique is attributed to the Rand Corporation.

Maintenance Task Selection

As a result of completing the logical and structured FMEA process, the user now has a clear understanding of areas requiring maintenance in order to preserve system function. The next step in RCM analysis involves the selection of maintenance tasks that best address the failure causes and consequences of concern.

At this point, it is important to remember that RCM is based on the assumption that reliability is an inherent design characteristic of a system, and is related to the system's ability to maintain functionality when used as specified. In this context, reliability can be thought of as the probability that a system functions properly, to a level of performance it was designed to achieve and has performed at that level when in proper condition. Reliability can be further delineated, reflecting the failure effects used in the FMEA, such as availability, frequency and cost to name a few.

The other tenet of RCM that is used in the maintenance task selection process is that the primary goal of maintenance is to either reduce or contain the failure rate within some predetermined reliability bounds. Maintenance is focused on preservation of key system functions.

Maintenance task selection involves the identification of appropriate tasks that address the causes of dominant failure modes identified as a result of the FMEA process. During the selection process the evaluator identifies applicable and cost-effective approaches to maintenance that are best suited to preserving system functions. Here too, RCM analysis uses standardized task selection logic. RCM's task selection logic enables the evaluator to systematically evaluate the effectiveness of maintenance options and resource requirements, and provides opportunities to evaluate multiple alternatives to addressing the causes of critical failure modes.

The selection of maintenance tasks using task selection logic is typically limited to functional failures of the system deemed critical, based on the results of an FMEA evaluation. These maintenance tasks are intended to prevent failure consequences identified in the system evaluation. In some cases, the development of maintenance tasks for non-critical failure modes is also appropriate. Adding maintenance tasks for non-critical failures is largely a matter of discretion or economics. Such discretion should be exercised with caution to avoid adding unnecessary tasks that defeat the original intent of RCM, that being to optimize the preventive maintenance program for the system.

There is an implied hierarchy in the maintenance task selection process. The decision logic is intended to lead the user systematically through a series of basic questions that test the cost-effectiveness of each potential maintenance task option in addressing the identified threat to system function (from FMEA: mode/effect/cause). Several versions of the RCM task selection process have been used in various applications. The version described here is a generic and hybridized version created by the authors, based on the basic RCM construct. By design it does not include all task selection considerations that can be used in RCM. This was done intentionally to restrict the discussion to those concepts that are relevant to VM. The RCM task selection process leads the user to the selection of a basic maintenance strategy. The user specifies the actual maintenance details to be performed.

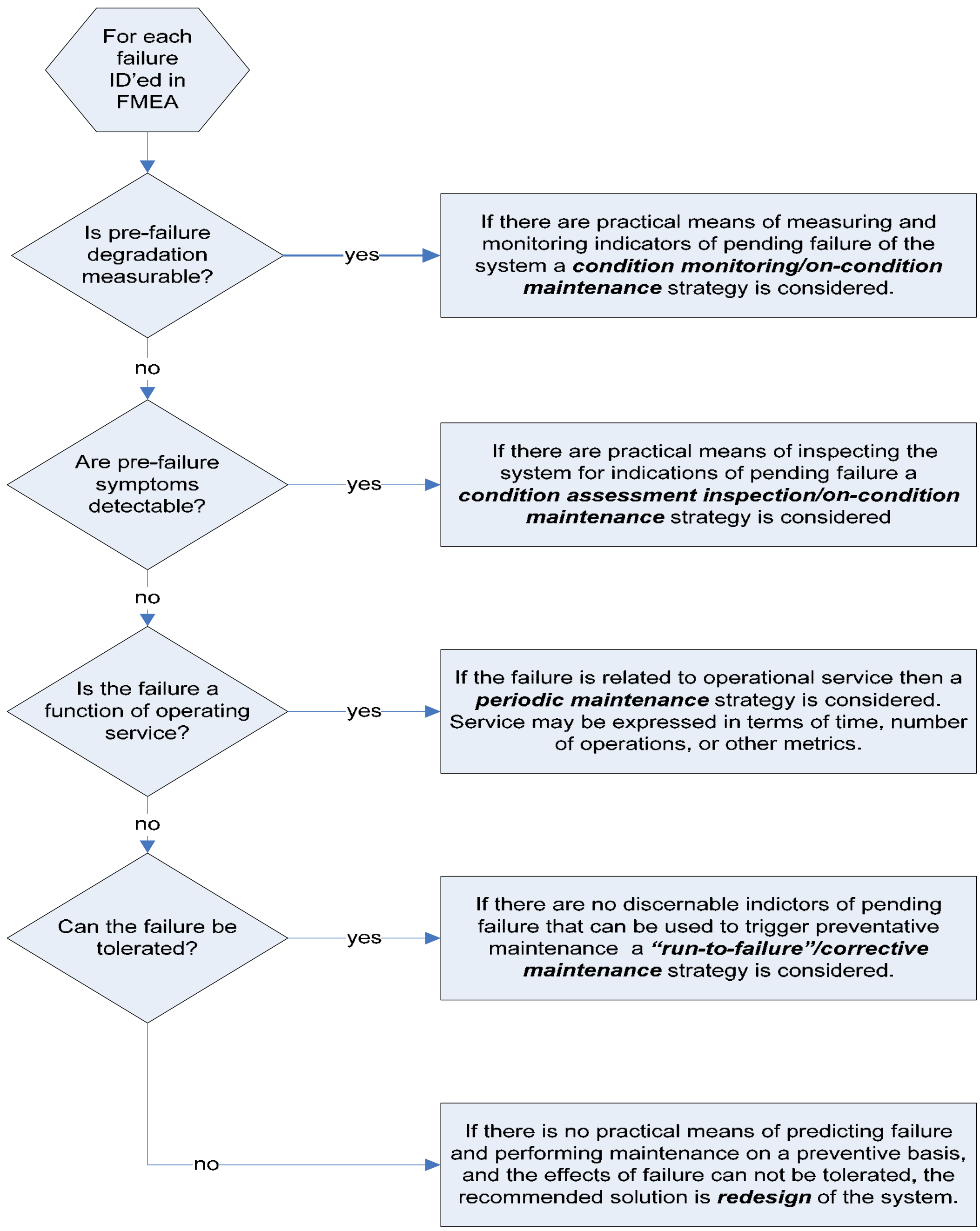

Figure 3-4
Hierarchical maintenance strategy decision process

Typically, the first consideration is whether the risk of potential failure can be detected in advance of the actual failure. If the answer is yes, there are two basic approaches to preventive maintenance that may apply. First, if technology exists to monitor conditions in real time, the user determines if that is a cost effective and practical solution. If so, the solution is real time monitoring of conditions. When monitored conditions degrade and failure is determined to be imminent, preventive maintenance is performed. If real time monitoring is not possible or is impractical, the alternative is to consider some form of condition assessment inspection to detect increased risk of failure. In this case, maintenance tasks are based on scheduled inspections designed to detect potential failures. If the onset of a failure is detected during an inspection, an on-condition preventive maintenance task is scheduled. In either case, if the risk of potential failure can be detected prior to occurrence, preventive maintenance is scheduled on an "on-condition" basis.

If the risk of failure cannot be determined with reasonable certainty prior to the occurrence of a failure, the next consideration is whether the failure is a function of system service. Service may be expressed in terms of criteria such as total time, use time, frequency of use, operations, load factor, etc. If a measurable criterion can be identified, RCM analysis leads the user through a determination of whether it would be cost-effective to schedule preventive maintenance on a fixed-interval basis.

Most failures on the electric distribution utility systems are brought to the immediate attention of operations, since they routinely result in the immediate loss of electrical service to a customer. Some types of functional failures, however, may occur that are not immediately apparent to the system operator. These are known as hidden failures. An example of this kind of failure would be the failure to meet regulatory line clearance requirements. A violation of clearance requirements can occur without an obvious or immediately apparent affect.

The next broad approach to maintenance requires the user to reconsider the criticality of the functional failure being considered. If there are neither diagnostic nor condition assessment opportunities, nor any service-related criteria, then the failure being evaluated is considered to effectively be unpredictable. This means that opportunities for employing a preventive maintenance strategy are limited. In this case, RCM asks the user to re-evaluate the determination made in the FMEA as to whether the failure is critical. The question really is whether the failure can be tolerated. If so the solution is to run the system to failure and conduct corrective maintenance repairing damage and restoring system function. The "run-to-failure" maintenance strategy means that a conscious decision is made to allow a failure to take place and to make corrective repairs after the failure is identified. Also note that if the failure can be tolerated, RCM asks if the failure would be readily apparent. If the failure is not readily apparent, then a failure finding approach is also considered.

Finally, if condition monitoring or assessment, fixed interval, and corrective maintenance strategies are determined to be unacceptable, the task selection process leads to what is referred to as "redesign". Recall that RCM considers system reliability to be a function of design. Basically, at this point in the task selection process, the conclusion is that maintenance in the traditional sense of the word will not deliver the desired level of reliability. The solution then is to consider redesign of the system. The redesign option is typically quite expensive. It may include consideration of tasks such as adding redundancy, changes in system components and infrastructure, relocation, and changes in the configuration of the system to name a few options. At this point, it is not uncommon for the user to cycle back through a reconsideration of other approaches to maintaining system functions.

RCM-based Maintenance Management Program

Upon completion of the maintenance task selection process, a comprehensive list of maintenance strategies and a series of technically and economically effective discrete maintenance tasks will have been created. Some of these tasks can be performed while the item is in service, some may require the item to be out of service, and some require specialized crews and equipment. At this point, the list is reviewed and organized into logical groupings. The intent of this exercise is to optimize the implementation of these tasks.

Logical grouping takes advantage of synergies between tasks and maintenance resources. For each logical group, there generally will be one key or lead task that is used to determine scheduling. Once this lead task is identified, a task frequency can be set with the remaining tasks being performed coincidently with the lead task. The process is repeated for each of the remaining lead tasks. RCM does not provide any structured decision-making process for reassembling the individual tasks into a cohesive and logical whole. This is a management exercise involving proper allocations and scheduling of maintenance resources. Once reassembled, the composite tasks form the basis of an RCM-based maintenance program.

Living RCM

The application of RCM analysis techniques at this point will have led to the establishment of a new baseline understanding of the need for maintenance. Recall that RCM was created as a means of performing a thorough and systematic assessment of maintenance needs in the absence of complete performance data. The structured analysis will also have led to the identification of important metrics and measurement points. “Living RCM” refers to the notion that the process never really ends. As the new program is implemented experience will be gained, and the maintenance manager will have an opportunity to acquire relevant data. These data are used to test, refine, validate, and revise findings the initial RCM study. It is also important to consider the dynamic nature of some systems; as changes occur, this may create the need for re-analysis. In either case, an RCM based preventive maintenance program will include the use of performance indicators, which are used to reassess system performance and adjust maintenance practices.

4

APPLYING RCM ANALYSIS TO DISTRIBUTION SYSTEM VEGETATION MANAGEMENT

The objective of this project was to develop a means of applying RCM-based processes and techniques to the analysis of vegetation maintenance practices on overhead electric distribution systems. The previous sections of this report were intended to give utility VM personnel a basic understanding of RCM.

This section of the report describes the manner in which the authors adapted basic RCM constructs to the development of VM-specific analytical methods. The goal was to develop an approach that, while specific to VM, would be flexible enough to accommodate variants found in the industry.

Basic Approach and Assumptions

The authors have previous experience with RCM analysis on substation, transmission and distribution systems. The authors also have substantial subject matter expertise on contemporary utility VM practices. At the highest level, the basic approach was simply to adopt a generic version of RCM analysis. The previous section of this report discussed the basic tasks that are central to RCM.

The authors also relied on information beyond their expertise and experience. As previously described, a review of the literature was conducted. The authors also had access to internal reference materials from Environmental Consultants, Inc.'s extensive involvement in the utility VM industry. Finally, the project team included a host utility partner, Kansas City Power & Light (KCP&L). The KCP&L vegetation program and distribution system was used to develop and test concepts. This included conducting a Delphi workshop with various stakeholder groups within the utility.

Once the basic structure was established, work turned to adapting each step of the RCM process for specific application to VM programs. This can be thought of as translating RCM's engineering references to terms familiar to vegetation managers. Examples of this include describing failure modes and effects in terms that have direct "line of sight" relationships with the way in which trees present risk to overhead distribution systems. There are several other examples of these adaptive translations. Each is presented in detail in the step-by-step discussion of the RCM process found later in this section of the report. In summary, our basic approach was to attempt a pragmatic application of RCM for the practitioner.

A fundamental goal reflected in the design of this project is that the resulting work products create real value for the user in applying the process. Much is gained in working through each step of the process of analysis. In fact, insights gained in working through the analysis can be as valuable as the results. The user can expect to gain a deeper understanding of the manner in which trees pose risks to the reliability of overhead distribution lines.

Another underlying assumption reflected in the design of this project is that the RCM methods presented here are intended to aid the user in making informed decisions. They are not intended as a means of automated decision-making. In the final analysis the vegetation manager will select the maintenance task that in their informed opinion is best suited to their particular needs at the time. In the process of applying the structured decision logic inherent to RCM, the user will have gained a well-defined basis for making these informed decisions.

Nor is RCM intended as a means of estimating costs and creating budgets. RCM is not a budget tool. Costs are used in the analysis, but they should be considered as a means of comparing the relative cost-effectiveness of various maintenance options. In other words, the model uses relative rather than absolute costs.

Our intent was to create methods that would have wide application across the industry. At several steps, we provide default assumptions and values for use if the user has no other information. The user can substitute values specific to their situation and program, if they are available.

Finally, it should be noted that this work has resulted in development of both the basic analytical methods and the creation of an RCM Analysis Tool (the Tool). The Tool is intended to provide a basic structure that facilitates the user’s progression through an RCM-based evaluation of their VM program.

Characterizing Vegetation Maintenance and Management

Trees are a leading cause of electric service interruptions. VM budgets therefore typically represent the largest single line item in a utility’s O&M budget.

Utility vegetation management activities on overhead electric distribution lines typically involve the pruning and removal of trees in conflict with conductors. The primary purpose of the work is to reduce risk, defined in terms of reliability and safety. Some tasks are also intended to reduce the volume of workload in the future.

The vegetation maintenance work is almost exclusively performed by a contract service provider. Contract specifications commonly establish tree-conductor clearance requirements and related work practices. The general consensus in the industry is that preventive maintenance “line clearance” work is most efficiently performed on a cyclical basis, usually based on a fixed time period.

In some cases, regulations require either mandatory clearance distances or mandatory maintenance cycle intervals.

Defining RCM Systems and Subsystems in the Context of Vegetation Management

Utilities operate extensive energy delivery networks or grids. The portion of the network that distributes energy from substations to end-use customers is commonly referred to as the distribution system. The word "system" as used in this context typically refers to the entire installed plant, and can include hundreds or thousands of circuits. In the context of RCM, a system is defined by function, and becomes the focus of maintenance. Therefore, the definition of systems selected for this analysis is based on the individual distribution circuit. Two fundamental types of RCM-defined systems were identified, differentiated by function. The first can be thought of as a hybrid distribution circuit that functions in a manner that is similar to transmission lines, the primary purpose of which is moving energy between load centers. The other is the ubiquitous distribution circuit, the function of which is to distribute energy to end-use customers. Table 4-1 details the two types of systems used in this application of RCM to VM.

Table 4-1
RCM-based systems and subsystems used in assessment of distribution vegetation management

<table>
<tr><th>RCM System</th><th>Subsystem</th></tr>
<tr><td>Sub-Transmission/High Voltage Distribution Circuit. This is 34.5kV 3Ø, protected by substation breaker. Functions as inter-tie between load centers and substations.</td><td>Not Applicable - There is no need for an RCM subsystem.</td></tr>
<tr><td rowspan="7">Standard Distribution Circuit. Function is to supply energy to distribution transformers, and ultimately to end-use customers.</td><td>3Ø feeder protected by a substation breaker, this is the main backbone of the distribution system.</td></tr>
<tr><td>3Ø feeder protected by a line recloser. This is the remainder of the main backbone</td></tr>
<tr><td>Other multi-phase protected by line fuse</td></tr>
<tr><td>Single-Ø laterals. Protected by line fuses. Mostly armless, but there is some on X-arms</td></tr>
<tr><td>Uninsulated secondary, bare, open wire protected by X-former fuse. Often as underbuild, but occasionally as standalone runs</td></tr>
<tr><td>Insulated Secondary, “triplex” or “quadraplex”, protected by X-former fuse. Often as underbuild, but occasionally as standalone runs</td></tr>
<tr><td>Individual overhead services</td></tr>
</table>

RCM typically is conducted on either a component or subsystem basis. The component approach focuses on equipment performance, as it affects system functionality. The subsystem approach breaks the system down into like elements, and analysis is conducted at the subsystem level. The subsystem approach was determined to be better suited for an RCM analysis of VM. Table 4-1 defines the discrete subsystem elements that were identified as being useful. Note that it was necessary to apply a subsystem approach on one of the two RCM systems. It was felt that the Sub-Transmission/High Voltage Distribution Circuit was uniform enough not to warrant further segmentation.

The subsystems defined within the Standard Distribution Circuit are based predominantly on overcurrent protection and infrastructure considerations. This is a slight departure from RCM’s focus on system function, but this adjustment reflects the important implications of each in terms of reliability and performance. Also note that in this application the working definitions of a system for RCM VM by inference includes the environment in which it is deployed, trees being the focus of VM. This is another example of a modification made to traditional RCM methods.

The systems and subsystems identified are intended to be sufficiently generic to have broad application in the industry. The user may redefine or add additional systems and/or subsystems that are deemed important to their specific application.

Defining the Current "As Is" Situation and Vegetation Management Practices

This phase of the project involved establishing methods for characterizing the asset requiring maintenance. Time was also spent defining historical practices and system performance. As previously stated, RCM was initially developed in an effort to create an optimized maintenance program prior to the systems being placed in service. However, in this application of RCM to VM, we have the benefit of years of experience managing vegetation along distribution lines.

Existing Plant

This task involved creating a standard template of system and subsystem attributes that would be useful in conducting further analysis. Information is collected to the subsystem for each of the subsystems. Table 4-2 defines the basic information that is included in a template developed for this purpose.

Table 4-2
Attributes used to describe the physical characterisitics of each system and subsystem

Attribute Used To Describe Existing Plant	Rationale
Overhead line miles	Expression of total installed overhead infrastructure
Site type (urban, rural)	Expression of customer exposure and VM task restrictions
Site access to equipment (with & without)	Expression of physical exposure and VM workload
Stocking (trees/mile)	Expression of physical exposure and VM workload

Each of these attributes has bearing on the risk exposure, failure consequence, and cost of maintenance. We believe that most utilities have data that would enable the user to describe the in-serve distribution plant in terms of these four attributes, at least as they pertain to the overall distribution network. These attributes, however, are also important at the subsystem level. Availability of quantitative data to that level of detail is less certain. The method developed anticipated that, and provides the user with a means of allocating values to the system and subsystem levels, if they are not available. Practically speaking, lacking other data, an experienced vegetation manager should be able to offer an educated qualitative estimate of these values, and as has been repeatedly stated: RCM is designed to accommodate both quantitative and qualitative observations such as these.

Historical Performance

This task involved creating a standard template to collect system performance attributes. As in the case of plant-related attributes, the data related to the attributes selected to describe system performance should be commonly available for each utility. Table 4-3 provides basic information on what is included in the RCM template:

Table 4-3
Attributes used to describe the historical performance of function of each system and subsystem

Functional Attribute	Rationale
Frequency of interruptions	The frequency of tree-caused outages is directly related to the structural failure of trees, which are the focus of vegetation maintenance.
Customer Minutes Interrupted (CMI)	Duration metrics have an indirect relationship with tree failure rates, yet are important considerations. CMI is a broad and widely used metric.
Cost of restoration and repairs	The cost of repairing the damage to distribution infrastructure is quantifiable and can be significant.

Values for each of these attributes are required for each subsystem. The approach created for this step of the VM RCM project anticipates that this will be a challenge for some utilities. The RCM methods adapted for analysis of VM provide a means of allocating observations that may be available at the system level to subsystems. In the case of repair costs, the adaptive approach is to offer the user a table of standard default cost if the actual cost of repair is not available.

It should be noted that several other reliability metrics are also commonly used in the industry to measure both outage frequency and duration in terms of the loss of system function on customers. CMI was selected because of its inclusive scope and the belief that these data would be available to most utilities. In reality, the RCM VM method that has been developed may accommodate substitution of other metrics.

Current Practices

A battery of questions was developed as a means of defining the utility's current approach to vegetation maintenance and management. The user is asked to select answers that best describe current practices. While an extensive list, the questions were designed to be relatively easy to answer quickly.

This exercise also created an opportunity to include a performance gap analysis as a value-added aspect of the project. It was possible to establish a Best Practice response for many of the questions. The Best Practice response is not identified for the user as they move through the survey. The intent in this design is that at the conclusion of a VM RCM study, the user is also provided with a rudimentary gap analysis, which provides a comparison of their current practices to what would be considered a Best Practice.

The questions are divided into three broad areas. Each is described in the following subsections of this report. An abridged copy of the three-part survey tool containing the questions is included as Appendix B-1.

VM Program

The first series of questions focuses on defining current practices, and includes a series of twenty-three questions that focus on the overarching vegetation management program. These are high-level questions that ask the user to characterize their current maintenance management philosophies and strategies. The survey also includes questions that are intended to determine the types and levels of data used to manage the program.

Vegetation Maintenance Specifications

The second series of questions focuses on vegetation maintenance tactics. The fifteen questions in this section are intended to define the manner in which vegetation maintenance currently is being carried out and what kinds of tasks are found in actual practice.

Vegetation Maintenance Tasks

This final series of questions are focused on specific maintenance tasks. Five of the questions in this tab are similar to those in the other two series in that they include multiple-choice answers. The remaining twelve questions require the user to enter a value. The questions included in this tab have a direct relationship with the RCM-based maintenance task selection module described later in this report.

Cost of Vegetation Maintenance

A different approach was taken in establishing a means of determining the cost of vegetation maintenance work. An extensive module detailing the cost for various maintenance task options is used in a later step of the RCM analysis process. This module contains industry average cost information. The decision was made to also use this module to gather current cost information.

There are many more tasks and cost options included in this module than would be needed to define the costs of current maintenance tasks in an individual company's VM program. This is by design. First, the cost table is intended to represent the broad industry. Second, it includes RCM-driven tasks that are not commonly used in most programs today.

The user is asked to review and validate the standard costs tables. They are given two options for adjusting the standard cost to their actual experience. First, they can simply over-write the standard values with their own. The second option recognizes that the cost of vegetation maintenance work is largely influenced by the cost of labor and equipment. The user is asked to enter cost data for their typical vegetation maintenance crew. The model compares actual to standard VM crew costs, and uses this ratio to adjust the standard reference cost for each maintenance task accordingly.

The cost model makes further adjustments for stocking density (trees/mile), site type (urban vs. rural), and for tasks performed with and without the aid of a bucket truck. An abridged version of the vegetation maintenance cost module is included as Appendix D-1.

VM-Specific FMEA

A critical step in the project was the modification of the generic RCM FMEA process for specific application to vegetation maintenance. This work involved iterative revisions of the basic form until the resulting FMEA process became intuitive to VM personnel. A tabular depiction of the process used is presented in AppendixC-1.

As a result of these efforts, it became clear that the most useful working definitions of failure cause were framed in terms of tree failure. Likewise, failure effect was defined in terms of the affect of the tree failure on distribution infrastructure. Data and information were drawn from several sources including findings from post-interruption investigations into tree failures. A Delphi-like process was used in this phase of the project. The expert team created an initial draft. It was refined and then presented to a larger group of stakeholders, including personnel from the cooperating utility. These stakeholder groups represented a variety of interests and experience both within and beyond the vegetation management program. Table 4-4 presents an example of the relationship between tree failure types and the damage they cause on the single-phase subsystem. Note that the table includes both narrative observations and numeric estimates of allocation of the likely affect of each tree failure on an overhead distribution line. The RCM VM method developed in this project includes a similar table for each system and subsystem being studied.

Table 4-4
Example of table establishing the relationship between tree failures (cause) and the effect on the single-phase subsystem in narrative terms

Tree Failure	Broken Pole	Broken X-arm	Broken conductor	Floating Conductor	Electrical Fault
Uprooting failure	Yes	Yes w/ arms, otherwise N/A	Yes	More likely to cause greater damage	Phase -neutral, tree hangs up
Stem failure	Yes	Yes w/ arms, otherwise N/A	Yes	More likely to cause greater damage	Phase -neutral, tree hangs up
Crown failure	Yes	Yes w/ arms, otherwise N/A	Yes	Yes	Phase -neutral, tree hangs up
Branch failure	Not likely	Yes w/ arms, otherwise N/A	Possible	Yes	Maybe, Ø to neutral faults
Branch deflection	No	No	No	Possible	Maybe, Ø to neutral faults
In-growth	No	No	No	No	Maybe, Ø to neutral faults

Qualitative references similar to Table 4-4 above were created for each subsystem. These were then converted into quantitative references, as can be seen in the example in Table 4-5. The percent values in each row allocate the damage caused by each of the types of tree failure to overhead distribution system infrastructure.

Table 4-5
Example of table establishing the relationship between tree failures (cause) and the effect on the single-phase subsystem translated into quantitative terms

Tree Failure	Broken Pole	Broken X-arm	Broken conductor	Floating Conductor	Electrical Fault	Sum, all types of damage
Uprooting failure	25%	5%	55%	10%	5%	100%
Stem failure	25%	5%	55%	10%	5%	100%
Crown failure	20%	5%	60%	10%	5%	100%
Branch failure	5%	2%	35%	23%	35%	100%
Branch deflection	0%	0%	0%	10%	90%	100%
In-growth	0%	0%	0%	0%	100%	100%

It should be acknowledged that while we believe that the types of tree failures used in the RCM VM analysis tool accurately define the nature of the risk, they will likely present a challenge in terms of availability of quantitative data. The outage cause codes commonly in use in the industry typically assign a single, or in some cases a few cause codes to trees. Many utilities are beginning to conduct post-interruption site investigations. Data from these investigations may be more useful. In any case, the adoption of these six tree failure codes will require the users to rely on their experience to accurately define conditions on their respective systems. These new codes should also be used to acquire data as an RCM-based VM program is implemented and refined.

These tables provide structure to the FMEA process. They generally describe the effect of the failure on subsystem infrastructure. However, additional work is required. The failure effect then needs to be translated into quantitative terms.

Three failure effects were selected for inclusion in the model:

1. The number of functional failures (interruption frequency).
2. The duration of functional failures (CMI).
3. The cost of the functional failures.

Each of these failure effects is considered at the subsystem level. Templates were developed to facilitate data acquisition. It is unlikely that a utility will have readily available data in each of these areas to the level of detail (subsystem) required. Information on both frequency and duration, however, should be available at a composite system level. This information was previously covered in the discussion of historical performance of the current program. The model provides a means of accepting auto-allocations based on embedded decision rules and standard references. The user is also able to overwrite the default values, if they choose.

Establishing the cost of functional failures required an additional step. A matrix of estimated labor, equipment, and material resources required for the restoration and repair of tree-caused damage to distribution infrastructure was created. As in the case of the other elements of the project, this module includes a tab for each subsystem. It is also similar to the previously described vegetation maintenance task cost module in that there are adjustment factors for site type, site access, and variations in the cost of a line repair crew. An abridged version of the cost of damage repair module is presented as Appendix E-1.

The final step of the FMEA process is to assemble all the quantitative and qualitative observations and summarize them. Essentially the effects (frequency, CM, cost) of each failure cause (tree failure type) and failure consequence (infrastructure damage) are presented. There are six different tree failure types considered and nine discrete systems and subsystems used in the analysis. The result is that there are a total of 56 possible scenarios. In actuality, some of the tree cause types have little or no effect on some systems (e.g., incidental grow-in contacts on insulated secondary triplex), so the actual number of possibilities is somewhat less. In any case, in final form there is an FMEA for each subsystem that defines the effects of tree-related failures in terms of frequency, CMI, and cost. The Tool that has been developed has the capability to present the results of the FMEA analysis in graphic format, using each of the three effects. This provides a quick and easy means of identifying areas of greatest risk and consequence. The graphic displays present the range of outcomes in terms of relative ranking and quartile. The suggested decision rules are that top quartile effects must be addressed. Fourth quartile effects may be considered for a “run-to-failure” approach, and second and third quartile effects should be evaluated in more detail.

Vegetation Maintenance Task Selection

The last major step in developing an application of RCM analysis for vegetation management was the development of a systematic process for use in the selection of maintenance tasks. The premise is that once the risks trees pose to system reliability have been clearly defined, it becomes easier to identify maintenance tasks that reduce the consequence of the loss of system function. One approach would have been to not specify maintenance task options, and allow the user to create a unique solution to each problem. The authors, however, have been developing preventive maintenance concepts based on RCM thinking for some time and have extensive experience. Based on this, the decision was made to design the task selection process around maintenance task pick-lists. This approach provides structure and greatly facilitates the final step of the RCM analysis process.

Defining Vegetation Maintenance Task Options

The task selection hierarchy used by classical RCM has been previously presented as shown in Figure 3-4. The first step was to consider which of these maintenance strategies had the potential for practical application to VM. A range of vegetation maintenance tasks was developed. The choices offered are intended to represent a continuum of options generally ranging from high to low intensity. It is important to remember that the intent of this step in the RCM analysis process is to select the most cost effective approach to preventive maintenance. While we are referring to the choices as “tasks” they really represent maintenance strategies in that they are not prescriptive. They do not include specific details as to the actual tasks that would be undertaken in the field. Table 4-6 presents the results these efforts.

Table 4-6
Comparison of classic RCM strategies to those developed specifically for application to vegetation maintenance

Classic RCM Strategy	Apply to VM?	RCM-based Vegetation Maintenance Strategy
Real time monitoring	No	**None.** No condition monitoring technology currently available.
Condition Assessment (inspection) and on-condition maintenance	Yes	**Conduct dedicated Hazard Tree risk assessmen**t and risk mitigation work as a separate initiative. Focus on sites and exposures that increase risk.
	Yes	**Conduct a mid-cycle** risk assessment inspection and complete risk mitigation tree removal or height reduction work reducing risk.
Periodic fixed interval maintenance	Yes	**Increase efforts** during routine VM PM placing greater emphasis (+10%) on identification and mitigation of risk factor (cause, tree failure). This will increase the VM workload on a project.
	Yes	**Shorten PM Interval,** perform VM focusing on managing the risk of tree caused failures more frequently (assume -1 yr).
	Yes	**Revise specification.** Refocus work efforts during routine VM PM on reducing risk. This will result in a reallocation of effort, but should not increase workload on a project.
	Yes	**Continue current Distribution -VM practices** regarding managing tree related risk, make no change.
	Yes	**Lengthen PM Interval.** Perform VM focusing on managing risk of tree failures less frequently (assume +1 yr).
	Yes	**Reduce** the current level of VM tasks related to managing the risk of tree failures. Reduced cost.
Run-to-failure	Yes	**Eliminate** current VM tasks related to managing the risk
Redesign	Limited application	**Alternations and additions** to existing infrastructure including: changes to overcurrent protection system, re-conductoring, re-locations, and conversions from OH to UG.

Currently, there are no practical means of conducting real-time monitoring of tree conditions and the risk they pose to distribution lines. There are, however, opportunities to employ condition assessment inspections and to conduct on-condition vegetation maintenance. The traditional approach to vegetation maintenance involves a fixed period cycle schedule, which is consistent with a maintenance approach included in classical RCM. The VM task selection pick list allows the user to consider altering the cycle period approach. The option of doing no preventative maintenance is offered, which in the vernacular of RCM is referred to as "run-to-failure".

Finally, the decision was made not to include a redesign option in the task selection pick list. This was not because it is not a legitimate strategy. It tends to be an option with very limited application to very specific problems, rather than an option one would apply to an entire subsystem. It was felt that inclusion of a redesign option would create a distraction. The redesign option, however, should be something vegetation managers are aware of. A practical example of redesign that should be routinely considered includes the application of fuses on un-fused lateral taps, particularly those connected to the feeder. Another example would be a deliberate application of either a "fuse save" or "fuse blow" overcurrent protection strategy on specific circuits based on tree conditions.

Defining Vegetation Maintenance Task Cost and Efficacy

Once the maintenance task option pick list was established, a module was developed to facilitate its use. The approach taken is similar to the other models that have been previously described, in that there is a tab for each of the nine systems and subsystems under consideration. Next, standard costs for each task were established. Many of these costs had already been established in the previously described VM cost model. Simple decision rules were also developed. The most complex problem was establishing a means of defining the relationship between cycle period, cost, and reliability. This required that an interval adjustment module be developed. The relationship between time and cost was based on Environmental Consultants Inc.'s history of work[3] on this topic. Figure 3-1 is a conceptual example of the cost model.

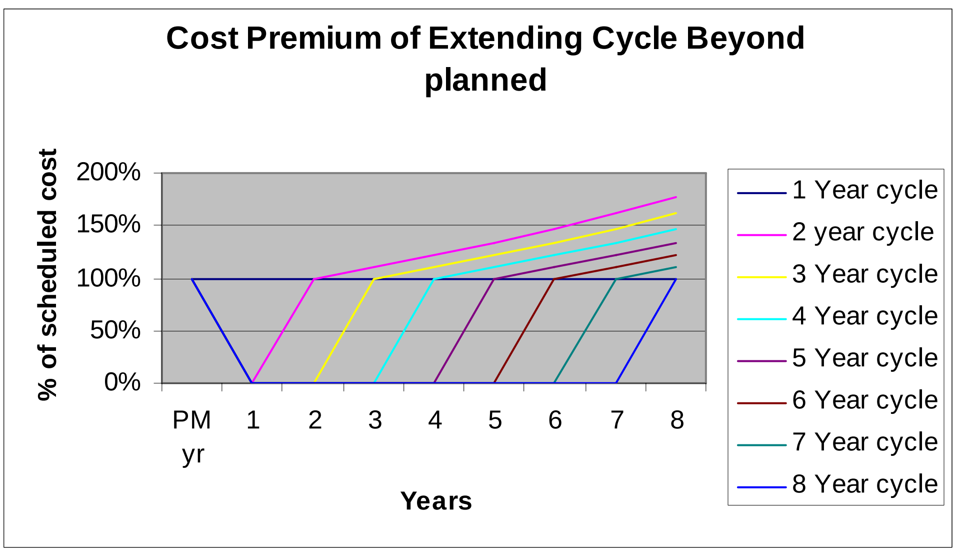

Figure 4-1
Conceptualized graphic depiction of the relationship between adjustments in preventive vegetation maintenance cycle period and cost

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[3] Browning, Mark, and H.V Wiant. "The economic impacts of deferring electric utility tree maintenance", Journal of Arboriculture, May 1997 23(3) pp.106-112.

Finally, standard assumptions of efficacy for each vegetation maintenance task on the pick list were developed using data from a wide range of sources. Efficacy is expressed in terms of the relative change from the as-is historical experience. The relationship between reliability changing preventive cycle period was based on Environmental Consultants, Inc.'s involvement in industry VM program assessments, and in direct involvement in managing VM programs. Figure 4-2 is a conceptual example of the reliability model.

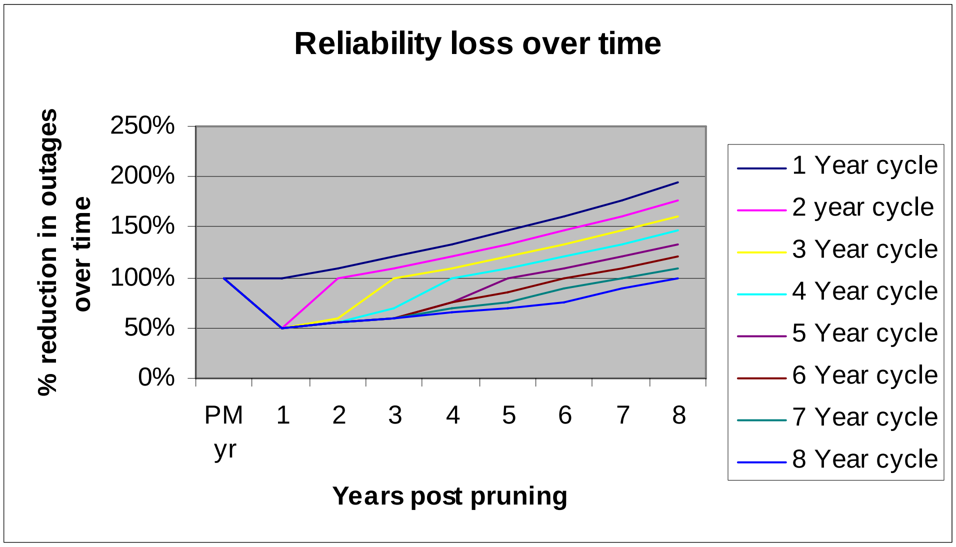

Figure 4-2
Conceptualized graphic depiction of the relationship between adjustments in preventive vegetation maintenance cycle period and reliability

The user is given the choice of using the standard values or may overwrite them and use their own assumptions. An abridged example of the vegetation maintenance task selection module is included as Appendix F-1.

Decision Process and Logic

At this point, the VM RCM application of the process leads the user through the selection of a maintenance task that best addresses the statements of failure cause and effect described in the FMEA. This is an iterative process.

The RCM tool does not make the determination as to which maintenance option represents the best solution. Having moved step by step through the entire process of RCM analysis, the user now has enhanced insight into the risks and consequence of tree-related system failure, and a reasonably quantifiable basis for making an informed choice. The tool that has been developed as part of this project is intended to support and facilitate the decision making process, and allows the user to test different options. But in the final analysis it is the user who selects the appropriate form of maintenance for their specific situation.

It should also be noted that a streamlined approach is supported by the version of RCM that has been adapted for use in analyzing vegetation maintenance requirements. As previously stated in the discussion of the FMEA process, the outcome is a relative ranking of risk and consequence. It is generally not necessary to consider all possibilities. The reality is that in many cases the lesser risks are addressed by the same actions that focus on major risks.

RCM-Based VM Plan

The final steps in the process are actually performed beyond the bounds of RCM. They involve development of specific maintenance actions and specifications, and the integration of the discrete tasks that have been selected into a cohesive preventive maintenance strategy. This is both a technical and management exercise. Insights gained in working through the RCM process should be very useful in revising existing and creating new maintenance specifications. Through the process of task integration it should be possible to capture synergies in maintenance resource allocations and scheduling.

The FMEA and supporting materials provide a basis for establishing VM performance metrics, both in terms what and where to measure results. This is a vital part of the "living RCM" program going forward. It is important that the many assumptions made are tested and validated. It is very unlikely that the first application of RCM will result in an optimal solution. The program should be refined as operational experience and performance data are monitored.

Best Practice Gap Analysis

As previously mentioned, the approach taken to define the existing VM program also afforded the opportunity to do a simple gap analysis. The user's response to questions established current practice. Best practice solutions were included among the possible answers to most of the questions. This made it possible to provide the user with some added value beyond the RCM project. The RCM tool includes an output that provides the user with a simple comparison of their practices to what would be considered a best practice.

5 FUTURE WORK

As with the case of living RCM, the project should include some additional work that refines and adds to the utility of the methods that have been developed.

RCM VM Analysis Tool

The project included the development of an RCM Analysis Tool. The Tool provides vegetation managers with an automated structure for completing an RMC study of their VM program. The tool has been described in this report. It requires a separate EPRI submission process, and the Tool will be released in early 2010.

RCM Tool Workshop

An RCM workshop is planned for 2010. The purpose of the workshop would be to introduce vegetation managers to RCM, and more specifically to facilitate their use of the Tool. This workshop would train participants in use of the processes, templates and analysis contained in the Tool.

Field Validation

The project as originally proposed included the design and implementation of a pilot project at a cooperating utility. The pilot is intended to demonstrate the benefits realized by adopting an RCM-based, reliability-driven distribution VM program. This phase of the project would involve conducting an RCM study of the current VM program at a host utility or utilities. The results of the study would then be implemented.

The intent is to make actual application of the RCM method on an actual system(s) and to track and evaluate results. A comparative study with experimental and control group circuits would be tracked over the course of a preventive maintenance cycle, with interim assessments conducted annually. The concept is to select some peer pair substations and circuits for comparison. The control group would continue to be maintained in the traditional manner. The experimental group would be maintained using RCM-based VM practices.

RCM VM Analysis Tool Enhancements

The project team offers three general recommendations for future enhancements to the RCM VM process and Tool that was developed as an outcome of this project, as follows:

Update the Tool

Experience gained with the Tool as it is used will identify opportunities to refine its form and function. The project team expects that while this first version is functional, it is very likely that relatively simple revisions can be made to increase its practical application and ease of use. It is recommended that the Tool be evaluated and updated after three different applications of the Tool by different users.

Add the Redesign Maintenance Task Option

The approach in this project was to simplify and focus RCM analysis on vegetation maintenance activities. While "redesign" is a legitimate maintenance task option found in RCM, the decision was made to exclude it from this version of the Tool. In this case, redesign refers to alterations of the system, such as making changes to the overcurrent protection system and alterations to distribution infrastructure. The decision to not include redesign was made based on the realization that while it can be an effective solution, it generally only makes sense in very specific circumstances, and that the decision is typically beyond the decision-making authority of the vegetation manager. The project team believes that an effective method can be developed for inclusion of re-design in a future revision to the process and Tool.

Add Additional Failure Cost Considerations

Only the direct cost of restoring the outage and repairing the damage caused by a tree failure is considered as a failure effect. Other costs of functional failure, such as the cost of lost revenue, and the indirect cost of the event to end-use customers should be considered. This could be accomplished by using CMI to determine the amount of energy that was not delivered. This then is discounted by a load factor that recognizes that some loss is actually an offset in time, but will be "made up" when service is restored. Finally, the lost revenue is calculated for the discounted energy loss, using an appropriate value ($/ kWh). This same approach can be used to assess the indirect cost of functional failure using industry standard references of the cost of outages on end-use customers.

6 SUMMARY

The project resulted in development of methods for applying RCM techniques to analysis of VM programs on overhead electric distribution utility systems. This RCM-based study effectively integrated several bodies of work related to trees and their interaction with overhead lines, creating the opportunity to develop a state-of-the-art, reliability-driven VM program.

The project made use of a systems-, rather than component-based approach to RCM. Systems and subsystems relevant to vegetation maintenance were defined. RCM-based FMEA methods focusing on the manners in which trees pose risks to overhead distribution lines were developed.

The resulting work products will support a practicing vegetation manager in applying RCM concepts and techniques to a study of the vegetation program for which they are responsible. It makes use of both quantitative and qualitative data that should be available to most utilities. The RCM model that was developed uses templates that include standard references that can be used directly or adapted by individual utilities.

Some broad themes have been identified as a result of the project. They represent significant shifts in maintenance management philosophy, and include the following:

- A shift in orientation from a focus on achieving and maintaining tree clearance to one of focusing on preserving system function (reliability).
- Recognition that while reducing risk and preventing failures is important, there is a need to consider mitigating the consequences (effects) of failures as well.
- A shift from a bias to a standard approach to vegetation maintenance applied uniformly across the distribution system to a recognition of the opportunity to create specific subsystem-specific maintenance prescriptions. One size does not fit all.
- A shift from age (cycle period) as the exclusive driver to maintenance schedules to one that also includes condition assessment and “on-condition” maintenance.

The newly developed methods of analysis are now ready for testing, validation, and refinement.

A

SUMMARY ABSTRACTS FROM A REVIEW OF THE ENGINEERING AND VEGETATION MANAGEMENT LITERATURE

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1. Benner, C.L., B.D. Russell, and A, Sundaram, A. ***"Feeder Interruptions Caused by Recurring Faults on Distribution Feeders: Faults You Don't Know About".*** 61st **Annual Conference for Protective Relay Engineers, Conference Proceedings 1(3) pp. 584 – 590, April 2008.**

Abstract: This paper discusses types of recurrent faults and interruptions, including their causes and consequences. It also identifies events that cause poor power quality and/or reliability after a significant period in which a degraded condition produces electrical warning signs.

Distribution feeders are exposed to a wide variety of damage scenarios that cause faults, and subsequently interruptions and outages. The affect of weather, equipment failure, and contact by foreign objects are considered. The paper also states that most faults are either permanent or truly temporary. Restoration of permanent faults requires repair of the damage. In contrast, temporary faults do not involve damage or impairment of the distribution system.

Periodic inspection of overhead lines can greatly reduce the number of tree-caused failures. Inspection frequency and mitigation actions are a function of risk tolerance. The authors note instances in which vegetation has caused multiple momentary interruptions over periods of hours to weeks without causing sustained outages.

The authors also note that while analytical techniques are available, they are not routinely put into practice. The reasons given for this are lack of data and reluctance to apply theoretical tools to practical maintenance planning.

2. Bertling, Lina. ***"RCM for Electric Distribution Systems"*** **Ph.D. Dissertation, Dept. Of Electrical Engineering, Royal Institute of Technology (KTH). Stockholm, Sweden, 2002.**

Abstract: This paper described an application of RCM methods to electric distribution systems. The project involved establishing a quantitative relationship between distribution system components, reliability, and cost. The system was designed and intended for general application to distribution systems, and considered the cost of RCM-based maintenance solutions.

The author notes that the criticality of distribution systems is generally lower than that associated with the traditional applications of RCM, such as in aviation and nuclear power applications. There is some acceptance of failures (interruptions) on the distribution system both in term of frequency and duration. This would not be the case in either aviation or nuclear power applications. It was determined that there is little in the way of additional revenue to be gained in developing sophisticated reliability measures for simple overhead radial distribution systems.

3. Bertling, Lina, Ron Allan, and Roland Eriksson. ***"A Reliability-Centered Asset Maintenance Method for Assessing the Impact of Maintenance in Power Distribution Systems".*** **IEEE Transactions on Power Systems, Vol. 20, No. 1, February 2005, pp. 75-82.**

Abstract: This paper describes an enhanced application of reliability-centered asset maintenance (RCAM) methods, which provides a quantitative relationship between preventive maintenance of individual assets and the total cost of maintenance of the system. . The method is developed from RCM principles, and focuses on the relationship between maintenance cost and reliability of the system.

The first step involves defining the system and evaluating critical components affecting system reliability. The second step analyzes the components within the system in detail and, with the support of appropriate data input, defines the quantitative relationship between reliability and preventive maintenance measures. In this application of RCM, the focus is on the individual devices and components as individual elements of the distribution system rather than conducting the analysis based on a systems approach. Like traditional RCM, the approach includes identifying failure causes by failure modes, and defining failure rates.

The third step of the project involves conducting reliability vs. cost/benefit analysis. It involved evaluating both the cost and effect of various maintenance task options on system reliability.

4. Brown, R.E., M.V. Engel, J.H. Spare. ***"Making Sense of Worst-Performing Feeders".*** **IEEE Transactions on Power Systems, May 2005 20(2) pp. 1173-1178.**

Abstract: This paper reports findings from a comprehensive assessment of worst-performing feeders on a utility distribution system using nine years of data. The paper shows that historical data are able to reflect expected reliability but raises serious questions as to the usefulness of assessments based on short interval data. Determinations based on a single year of data are of questionable use. Using two-year or three-year average values to identify worst-performing feeders was shown to be only marginally better, with most of poor performance depending on other factors. Longer period averages, such as five to ten years, can identify poor-performing feeders, as long as these feeders have not significantly changed over the period of consideration.

5. Browning, Mark, and H.V Wiant. ***"The Economic Impacts of Deferring Electric Utility Tree Maintenance".*** **Journal of Arboriculture, May 1997 23(3) pp. 106-112.**

Abstract: This paper discusses findings from a study of the cost implications of deferring vegetation maintenance line clearance pruning on distribution systems. The cost of pruning was shown to increase significantly with time of deferral, as branches grow into close association with conductors. Additionally, the volume of pruning residue and subsequent cost of disposal increases with time. The study did not address the affect of deferring line clearance pruning on service reliability or the cost of corrective maintenance including the cost of repairing damages.

6. Burke, J and C.A. O'Meally. ***"The Impact of a "Fuse Blow" Scheme on Overhead Distribution System Reliability and Power Quality".*** **IEEE Rural Electric Power Conference Presentation. April 2009.**

Abstract: This presentation describes the affect of a "fuse blow" overcurrent protection philosophy on long lines commonly found in rural electric utilities. It also addresses shorter lines as a characteristic of urban distribution systems.

The "fuse save" approach attempts to minimize customer interruption time (reduce SAIDI) by attempting to open the breaker or recloser faster than it takes to melt the fuse. This saves the fuse and allows a simple momentary interruption: a blink. The authors state that "for most systems, this works pretty well". In high short-circuit areas; it may not be possible to make this approach work since the clearing time of the fuse may be faster than the breaker.

The fuse blow approach eliminates the fast trip of the breaker or recloser in favor of having the fuse operate for all permanent and temporary faults. The purpose of this scheme is solely and entirely to minimize momentary interruptions (reduce MAIFI). This scheme is very successful in high short circuit areas where a "fuse save" approach didn't work anyway. The downside of the "Fuse Blow" concept is that it increases SAIDI, i.e., in an effort to increase power quality (reduce momentaries); we decrease reliability (increase SAIDI).

Many utilities use both schemes. The following examples are given:

- Fuse Save is used on overhead laterals and Fuse Blow on underground taps
- Fuse Save is used in rural areas and Fuse Blow in urban areas.
- Fuse Save is used on stormy days and Fuse Blow on nice days.

The authors also note that the use of a mid-circuit recloser and downstream fuse saving may also be used to increase distribution reliability with minor affect, if any, on power quality (momentaries).

7. Chowdhury, AA and D.O. Koval, *"Considerations of Relevant Factors in Setting Distribution System Reliability Standards"*. 2004 IEEE Power Engineering Society General Meeting Proceedings. June 2004, pp. 9-15.

Abstract: This paper presented factors that need to be considered in understanding comparative distribution system reliability performance metrics. The authors argue that there are too many differences between data collection processes and utility systems characteristics to make development of universally applicable standard metric values and comparisons against such standard metric values valid. Rather, the development of uniform standard metric values, which utilities compare to their own historical performance, is more practical.

If cross-comparisons between utilities are desirable, a number of issues and factors associated with individual utilities must be taken into consideration in establishing distribution reliability standards. Major factors and issues that need special considerations in setting reliability standards include: geography, system design, operating and maintenance practices, weather conditions, physical age of electrical equipment, restoration practices, rural versus urban systems, high load density versus low load density systems, overhead versus underground systems, manual outage data collection versus automated outage data collection schemes, major event exclusion or inclusion, definition of terms of different indices and their calculations, variation in major event definitions, etc.

8. Gilligan, S.R. *"A Method for Estimating the Reliability of Distribution Circuits"*. IEEE Transactions on Power Delivery, Apr 1992, 7(2) pp. 694-698.

Abstract: This paper describes a means of estimating the relative expected reliability performance of primary distribution circuits, and notes that reliability is a function of circuit configuration and exposure. The model considers segment length, line type, system protection, risk potential and exposure and calculates the expected reliability for the entire circuit or any of its parts. These indices are then used as guides for selecting circuits for improvement and for highlighting the parts of the circuit to improve. This method has two important advantages: it does not require historical data (which may not be valid or even available), and it identifies specific locations requiring corrective action.

The model considers tree stocking density, assigning a weighting factor of 0.15 for zero trees per mile, rising exponentially to 1.0 at 200 trees per mile. The model attempts to quantify the user's intuition and experience regarding the risks and affects of service interruptions on customers.

9. Goodfellow, John W., "*Investigating Tree-Caused Faults*". Nov 1, 2005, Transmission and Distribution World, Penton Media, Inc., New York, NY

Abstract: The article summarizes research into the modes and causes of tree-initiated faults. Two failure modes are defined:

- The mechanical mode of failure involves physical damage to the energy delivery system due to trees.
- The electrical mode of failure occurs when the tree or branch provides a short circuit fault pathway between areas of unequal electrical potential.

This work has led to a new understanding of the way in which trees cause service interruptions on overhead electric utility distribution systems, and subsequently to more efficient methods to identify and mitigate the risks trees pose to the reliability of overhead distribution systems.

10. Goodfellow, John W. *"Overhead Distribution Vegetation Challenges: Touch Voltage Potential at Ground Level and Aloft in Trees Contacting Energized Distribution Conductors"*. December 2008. Electric Power Research Institute Technical Report EP-P29163/C13792.

Abstract: It is not uncommon for overhead distribution conductors to make contact with trees. These incidental contacts can be either intermittent or relatively persistent, are typically not detectable by overcurrent protection systems, and do not result in interruptions on distribution circuits.

This report focuses on the levels of fault currents and voltage gradients found along the fault pathway provided by trees from point of contact to earth. The purpose of this investigation was to measure the voltages and currents found in the main trunks of trees in contact with a conductor energized at a common electric distribution voltage level. The experimental investigation involved creating and monitoring tree-conductor contacts at 7.6kV and 19.9kV under field conditions. The work included simulated human contacts on the ground and aloft as a tree climber.

Ground level exposure of the general public to touch potential voltages associated with tree-conductor contacts involving small twigs and branches in the outer crown at voltages associated with 15kV class distribution circuits was shown to be very low. The potential risks associated with these incidental contacts were shown to be minimal. This was the case for simulated incidental contacts with both deciduous and coniferous trees.

Touch potential voltage exposure of persons in likely climbing positions within the crown of a tree in which small twigs or branches in the outer crown are in contact with energized distribution conductors, while higher than that of persons on the ground, was also found to represent low risk.

Levels of observed voltages and currents flowing within the test trees increased with shortening distance between the point of contact and earth, and with increasing branch diameter. However touch potential risk on the surface of the bark was shown to be insignificant even in cases of contact with larger branches in the mid-crown.

The high level of impedance across the sheath of bark was shown to play a significant role in reducing the risk of exposure to adverse levels of touch potential. Simulated precipitation did not significantly alter the risk of adverse touch potential exposure.

Tree contact faults at 19.9kV resulted in large increases in voltage gradients and fault currents with the tree. However, touch potential risk was shown to be relatively small for simulated tree contact with conductors energized at 19.9kV. This is thought to be due to bark impedance.

11. Goodfellow, John W., B. Blumreich and G. Nowacki. August 1987. *"Tree Growth Response to Line Clearance Pruning".* Journal of Arboriculture 13(8): pp. 196 – 200.

Abstract: Branch and sprout growth response of six species of street trees following electric line clearance pruning was studied. Differences in tree re-growth were observed after three and four growing seasons. An exaggerated re-growth response was shown to occur following pruning. The re-growth response was greatest in the growing season following pruning. The growth response stimulated by pruning diminished in subsequent growing seasons.

Results varied by species, pruning methods, and crown positions at which the pruning had occurred. Top pruning re-growth rates generally exceeded side re-growth rates. Re-growth associated with natural (lateral/drop crotch) pruning was less than that associated with inter-nodal "round over" pruning cuts. Greater variability in re-growth rates was associated with trees having been round-over pruned.

12. Goodfellow, John W., *"Engineering & Construction Alternatives to Line Clearance Tree Work".* January 1995. Journal of Arboriculture, 21 (1): pp. 41-49

Abstract: This article describes alternative types of overhead and underground distribution system infrastructure to bare overhead conductors. Each may reduce the affect of electric utility lines on trees and may improve reliability. The greatest opportunities for incorporating alternative utility designs into the urban forest come at the time of original construction or when changes are made to the existing utility infrastructure. The author notes that only in exceptional cases can the costs of converting an existing system to an alternative type of construction are justified on the basis of reliability or avoided cost of future tree maintenance and repair.

13. Guggenmoos, Siegfried. *"Managing Tree-caused Electric Service Interruptions".* UAA Quarterly 17(4) August 2009. pp. 5-9

Abstract: The author reports that between 2-15% of tree-caused outages are directly attributable to tree growth. The implication of this finding is that the remainder (85-92%) of outages must then be due to "tree fall-in" (structural failures). The author also notes that post-outage site investigations at two utilities revealed that between 55-70% of the trees that failed exhibited no discernable defects.

14. Kuntz, P.A., R.D Christie. and S.S.Venkata. ***"Optimal Vegetation Maintenance Scheduling Of Overhead Electric Power Distribution Systems".*** **IEEE Transactions on Power Delivery Oct. 2002 17(4) pp. 1164-1160.**

Abstract: This paper presents a quantitatively-derived means of scheduling reliability centered vegetation maintenance on overhead distribution systems. The algorithm that was developed determines when and where to perform maintenance, subject to constraints on reliability, cost, and crew availability. This is compared to the industry's traditional approach of scheduling vegetation maintenance on a fixed-interval basis.

The maintenance scheduling tool determines the optimal location and time for performing vegetation maintenance on overhead distribution feeders. Several factors are considered by the model in predicting the tree caused failure rate; these include the tree fault rate, wind, climate and tree exposure (stocking density). A vegetation failure rate model was developed that quantifies the affect of the maintenance schedule on the reliability of a distribution system.

The maintenance schedules devised by using the maintenance scheduling algorithm were then compared with a traditional fixed-time interval preventive maintenance schedule. Based on application to a real utility distribution system, the maintenance-scheduling algorithm was shown to be more effective both in terms of reliability and cost in scheduling vegetation maintenance tasks than the traditional fixed interval approach to vegetation maintenance scheduling.

15. Miller, Charles H. ***"Crew Organization, Utilization and Location".*** **1981. Journal of Arboriculture 7(2): 76 – 79.**

Abstract: The author, writing nearly thirty years ago, notes that there had been few major advances in the efficiency of line clearance work since the development of the bucket truck and chipper. The article advocates the scheduling of vegetation maintenance work based on criteria including line voltage, customer density, tree density and predominant species. Scheduling vegetation management work on a corrective maintenance basis (a.k.a. "hot spotting") was found to be more costly, resulting in a reduction in service reliability, and only has application as a temporary measure to address an immediate problem.

16. National Grid. June 2008. ***"Distribution Vegetation Management Strategies".*** **National Grid Internal Strategy Document filed with New Hampshire Public Service Commission in response to 2008 Ice Storm discovery. 14 pp.**

Abstract: This NH PSC filing provides an overview of National Grid's strategy to improve distribution reliability through an application of contemporary VM principles. The strategy employs both systematic cycle-based pruning and a discrete hazard tree risk management initiative. The hazard tree initiative is conducted on portions of distribution circuits exposed to the greatest consequence of failure, and targets trees with an elevated risk of failure.

17. Orr, James. *Introduction and Editorial Opinion*, Vegetation **Management Supplement. July 01, 2007. Transmission & Distribution World. Penton Media, Inc., New York, NY.**

Abstract: This citation appeared as a summary introduction to contemporary VM practices in a supplement featuring VM in a leading industry trade publication. The author, writing as President of the Utility Arborist Association, is a highly regarded and experienced subject matter expert. The article concludes that "improvements in reliability may be achieved by changing specifications to include the removal of obviously hazardous trees and branches in the vicinity of utility corridors." The point is that contemporary thinking is shifting from exclusive focus on tree-conductor clearances to one to that includes identifying and mitigating the risks trees pose to service reliability.

18. Peterson, Ward. *"Electric Reliability and Outages",* Nov 01, 2005, Transmission & Distribution World, Penton Media, Inc., New York, NY.

Abstract: The author reported that several studies have shown that trees growing into power lines actually caused less than 14% of the outages for all utilities contacted. Further, that trees falling into the overhead lines, often from outside of the rights of way, have been shown to cause 66% to 94% of outages.

The author also reports that recent research suggests that the trees causing outages are in clusters in specific areas along specific circuits. They are not uniformly spread across the system. In addition, relatively few species cause most of the outages. In one such study, the author reports that four species caused 72% of the outages.

19. Short, T.A. and C.H. Perry. *"Overcurrent Protection Approaches to Improving Distribution Reliability".* Transmission and Distribution Conference and Exhibition 2005/3006 IEEE PES. Conference Proceedings, May 2006 pp. 1233-1238.

Abstract: This paper discusses several approaches to overcurrent protection design and their effect on distribution reliability. Adding protective devices and ensuring that they are properly coordinated ensures that the fewest customers possible are interrupted and makes fault-finding easier. Adding fusing, particularly at unused tap locations, is discussed as an inexpensive way to isolate faults.

Applications of both "fuse blowing" and "fuse saving" protection philosophies are also considered. Neither is described as the best choice for all applications. The best choice depends on many factors, including fusing practices, wire type, the mix and location of customers on a circuit, and the utility philosophy. The authors note that it is useful to review the overcurrent protection system, even on a circuit-by-circuit basis, because many situations may be better served by specific rather than standardized designs.

20. Werner, V.G, D.F. Hall, R.L. Robinson, and C.A. Warren. ***"Collecting and Categorizing Information Related to Electric Power Distribution Interruption Events: Data Consistency and Categorization for Benchmarking Surveys".*** **IEEE Transactions on Power Delivery, Jan 2006. 21(1) pp. 480-483.**

> Abstract: Results of a 1998 nationwide survey of utilities identified significant inconsistencies in the date used to calculate distribution reliability indices. This is due to differences in the data definitions and the collection processes used within the industry. This paper presents a minimal set of data definitions and a categorization structure that, when used in combination with IEEE Std. 1366, will promote consistency in how the industry collects data for the purpose of benchmarking distribution system performance. The intent of this effort is to address common errors introduced by inconsistencies in data definitions and data collection methods. Other factors of concern are differences in system design and operation, and differences in the environments in which different systems operate.

21. Willis, H. Lee, PE. ***"Balancing Reliability And Cost: Optimizing SAIDI And SAIFI",*** **Electric Energy, Lester Publications, LLC, Gainesville, FL 32605.**

Abstract: This paper discusses an approach to optimize expenditures on distribution system reliability. The author refers to it as "optimized cherry picking". This approach involves picking a reliability task from a variety of approaches. The task is selectively implemented and is seldom completely applied to all sites. The example given related to VM suggests that performing vegetation maintenance work on key portions of a circuit including feeder trunks and major branches will achieve the majority of the potential reliability improvement possible.

B

SURVEY OF CURRENT VEGETATION MANAGEMENT PRACTICES

Table B-1
Questions used to define the current vegetation management program

Tab 1, Management Question
Which best describes your current distribution system vegetation management plan?
Which best describes your current approach to VM work measurement?
Which best describes your approach to conducting post-incident assessments of tree caused interruptions? Pick all that apply.
Do you have data on tree failure & interruption rates by species?
Do you have information on re-growth rates by species?
Which best describes your basic approach to planning, scheduling, and completing VM?
Do you maintain a list and manage a discrete group of "critical circuits" differently? All that apply:
Which best describes your approach to tree removal? Pick all that apply
What is your current ratio of trees removed vs. trees pruned, expressed as % trees removed?
Which best describes how decisions for tree removal based on workload reduction (rather than hazard trees) are made?
What level of incidental tree contact with primary conductors is acceptable and/or triggers the need for VM?
What is your current ratio of spending on scheduled preventive maintenance and correct maintenance (a.k.a. "hot-spotting") expressed as % of budget spent on CM
Which best describes your approach to D-VM work quality? Pick all that apply.
Is the overcurrent protection system considered when planning and scheduling D-VM work? Pick all that apply.
Which best describes the extent to which the overcurrent protection coordination system is considered when planning and scheduling D-VM work? Pick all that apply.
Are alterations to existing lines considered when planning and scheduling D-VM work? Pick all that apply.
Which infrastructure options are considered when planning scheduled D-VM work? Pick all that apply.
Which best describes the interruption cause codes used to record tree caused events?

Tab 1, Management Question
Is there a regulatory mandate affecting D-VM program management?
What best describes your management expectation for RCM driven D-VM program recommendations?
Are formal condition assessment inspection processes used in your D-VM program? Pick all that apply.
To what extent do VM personnel consider condition of the in-service energy delivery system while in the field performing work?

Table B-2
Questions used to define the current vegetation maintenance work specifications

Tab 2, Specification Question
When VM work is completed on a scheduled preventive maintenance basis which trees are worked on?
Which best describes the dominant manner in which your VM specifications establish clearances?
Do D-VM specification requirements for VM on the distribution primary system vary by voltage class? Pick all that apply.
Do D-VM specification requirements for VM on the distribution primary system vary by line type? Pick all that apply.
Do D-VM specification requirements for VM on the distribution primary system vary by conductor type? Pick all that apply
Do D-VM specification requirements for VM on the distribution secondary system vary by line type? Pick all that apply.
Do D-VM specification requirements for VM on the distribution secondary system vary for underbuild vs. stand-alone secondary?
Do D-VM specification requirements vary by site type?
Do D-VM specification requirements vary by species? Check all that apply.
Do D-VM specification requirements vary by areas of local severe weather?
Do D-VM specification requirements vary by access to the site?
What is included in your D -VM specification requirements for line clearance pruning? Pick all that apply.
Which of the following are included in your D-VM specifications? Pick all that apply.
Do D-VM specification requirements vary by region or geography? Pick all that apply
Which D-VM zones are addressed in your management plans and specifications? Pick all that apply

Table B-3
Questions used to define the current vegetation maintenance tasks

Tab 3, Maintenance Task Question
Do you conduct dedicated Hazard Tree inspection and removal as a standalone program? Pick all that apply:
Do you conduct any form of mid-cycle inspection and follow-up VM work? Pick all that apply:
Which best describes the manner in which Hazard Tree risk is mitigated?
What is the intended PM Interval for each of the following line types:
➢ Sub-sub dedicated feeders (a.k.a. sub-T or "express") & express are managed as a separate work type. URBAN SITES
➢ Sub-sub dedicated feeders (a.k.a. sub-T or "express") & express are managed as a separate work type. RURAL SITES
➢ 3Ø lines protected by a substation breaker are managed as a separate work type. URBAN SITES.
➢ 3Ø lines protected by a substation breaker are managed as a separate work type. RURAL SITES
➢ 3Ø lines protected by a line recloser are managed as a separate work type. URBAN SITES.
➢ 3Ø lines protected by a line recloser are managed as a separate work type. RURAL SITES.
➢ 1Ø laterals typically protected by a fuse are managed as a separate work type. URBAN SITES.
➢ 1Ø laterals typically protected by a fuse are managed as a separate work type. RURAL SITES
➢ Distribution secondary. URBAN SITES
➢ Distribution secondary. RURAL SITES
➢ Services URBAN SITES
➢ Services RURAL SITES
Which best describes your approach to maintaining vines encroaching on high voltage equipment? Check all that apply.
Which best describes your approach to maintaining "brush" (small trees)? Pick all that apply

C

APPLICATION OF RCM-BASED FAILURE MODE AND EFFECT ANALYSIS TO VEGETATION MAINTENANCE

Table C-1
Vegetation Related Failure Modes, Effects and Causes for the Function: ***Conduct current up to rated design capacity***

Failure Mode	Cause	Detailed cause, VM Related Risk	Most likely VM cause
No conduction-open circuit	Conductor open-mechanical failure	Physical breakage due to tree & large branch failures	Broken limb detached Broken trunk Uprooted tree
	Conductor open-electrical failure	Vegetation provided a pathway to initiate and sustain an arc, conductor burn open.	Broken limb attached Broken limb detached

Table C-2
Vegetation Related Failure Modes, Effects and Causes for the Function: *Provide rated phase to phase electrical insulation*

Failure Mode	Cause	Detailed cause, VM Related Risk	Most likely VM cause
Fails to provide steady state phase to phase insulation	Phase-phase faults	Branch provides fault pathway and/or entanglement with vines	Broken limb attached Broken limb detached Vines Top growth Side growth Bending limb wind
	Phases displacement/deflection	Tree or branch contact	Broken limb attached Broken limb detached Broken trunk Uprooted tree
	Mechanical failure of Insulator or tie wire	Physical breakage due to branch failures	Broken limb attached Broken limb detached Broken trunk Uprooted tree
	Mechanical failure of support (cross arm)	Physical breakage due to tree & large branch failures	Broken limb detached Broken trunk Uprooted tree
	Mechanical failure of pole	Physical breakage due to tree & major crown failures	Broken limb detached Broken trunk Uprooted tree

Table C-3
Vegetation Related Failure Modes, Effects and Causes for the Function: *Provide rated phase to ground or neural electrical insulation*

Failure Mode	Cause	Detailed cause, VM Related Risk	Most likely VM cause
Fails to provide steady state phase to ground insulation	Phase–neutral faults	Branch contacts provide fault pathway and/or entanglement with vines	Broken limb attached Broken limb detached Vines Top growth Side growth Bending limb wind
	Phase-earth faults	Branch and stem provide fault pathway to earth	Not possible
	Phases displacement/deflection	Tree or branch contact	Broken limb attached Broken limb detached Broken trunk Uprooted tree
	Mechanical failure of Insulator or tie wire	Physical breakage due to branch failures	Broken limb attached Broken limb detached Broken trunk Uprooted tree
	Mechanical failure of support (cross arm)	Physical breakage due to tree & large branch failures	Broken trunk Uprooted tree Broken limb attached Broken limb detached
	Mechanical failure of pole	Physical breakage due to tree & major crown failures	Broken trunk Uprooted tree Broken limb attached Broken limb detached

Table C-4
Vegetation Related Failure Modes, Effects and Causes for the Function: *Maintain design clearance or regulatory mandate*

Failure Mode	Cause	Detailed cause, VM Related Risk	Most likely VM cause
Failure to maintain design clearance	Encroachment from above into clearance space	Vegetation overhanging conductors	Side growth Bending limb wind
	Encroachment from side into clearance space	Side growth	Side growth Bending limb wind
	Encroachment from below into clearance space	Height growth	Top growth
	Entanglements	Growth of vines	Vines

D
VEGETATION MAINTENANCE COST MODULE

The following table is an abridged version of the module used to establish the cost of a wide range of approaches to vegetation maintenance. The full module also includes a table of costs for stocking densities ranging from <50 to >200 trees per line mile. It also includes adjusted costs for site type (rural, urban) and access (accessible and inaccessible to equipment). Finally the actual module also provides a means of adjusting maintenance cost for a range of crew costs.

Table D-1
Standard vegetation maintenance cost reference

Preventive Maintenance Vegetation Management Tasks	Standard Cost ($/mi), all Sites,
Conduct dedicated Hazard Tree initiative	$320
➢ Conduct Hazard Tree assessment as a separate dedicated initiative	$80
➢ Complete risk mitigation, assumes a 2.5% hazard tree rate	$240
Conduct a mid-cycle risk assessment and mitigation work	$251
➢ Conduct a mid-cycle risk assessment	$80
➢ Complete mitigation of risks Identified in mid-cycle risk assessment	$171
Pre-inspection cost/mile for all subsystems	$325
Routine PM VM, Sub-Transmission	$4,052
➢ Routine PM Pruning, Sub-T	$3,175
➢ Routine PM Tree Removal, Sub-T	$877
Routine PM VM, 3Ø Feeder protected by substation breaker	$2,437
➢ pre-inspection cost/mile	$325
➢ Routine PM Pruning, 3Ø protected by breaker	$2,015
➢ Routine PM Tree Removal, 3Ø protected by breaker	$422
Routine PM VM, 3Ø Feeder protected by line recloser	$2,437
➢ Routine PM Pruning, 3Ø protected by line recloser	$2,015
➢ Routine PM Tree Removal, 3Ø protected by line recloser	$422
Routine PM VM, other multi-phase protected by line fuse	$2,437

Preventive Maintenance Vegetation Management Tasks	Standard Cost ($/mi), all Sites,
➢ Routine PM Pruning, other multi-phase protected by line fuse	$2,015
➢ Routine PM Tree Removal, other multi-phase protected by line fuse	$422
Routine PM VM 1Ø protected by line fuse	$2,100
➢ Routine PM Pruning, 1Ø laterals	$1,700
➢ Routine PM Tree Removal, 1Ø laterals	$400
Routine PM VM, stand alone Uninsulated Secondary	$1,575
➢ Routine PM Pruning, stand alone secondary	$1,275
➢ Routine PM Tree Removal, stand alone secondary	$300
Routine PM VM, stand alone Insulated Secondary	$1,260
➢ Routine PM Pruning, stand alone secondary	$1,020
➢ Routine PM Tree Removal, stand alone secondary	$240
Routine PM VM, services, all types	$330

E

STANDARD COST REFERENCE, COST OF REPAIRING TREE CAUSED DAMAGE TO DISTRIBUTION INFRASTRUCTURE

The following table is an abridged tab from the standard corrective repair cost module. A table like this has been created for each system and subsystem. The unabridged module also includes estimated repair times, and a means for adjusting standard cost for site type (rural, urban) and equipment access. Finally the module provides a method for adjusting repair costs for variations in labor, equipment, and material costs.

Table E-1
Example of standard cost reference for repairs to damaged infrastructure

Restore & repair field force resources & materials	Cost to repair broken 1Ø lateral pole	Cost to repair broken 1Ø cross arm	Cost to repair broken 1Ø Conductor	Cost to repair floating primary conductor	Cost to restore electrical fault (refuse of close breaker)
Trouble man	$130	$65	$65	$65	$130
Service truck	$30	$15	$15	$15	$30
Crew foreman	$75	$75	$75	$75	$0
Lineman	$130	$130	$130	$65	$0
Groundman or apprentice	$0	$0	$0	$0	$0
Line truck	$20	$20	$20	$20	$0
Bucket truck	$20	$20	$20	$20	$0
PU ton truck	$6	$6	$6	$6	$0
Pole	$750	$0	$0	$0	$0
X-arm assembly	$0	$150	$0	$0	$0
Insulators, pins	$50	$150	$0	$0	$0
Conductors	$100	$0	$100	$0	$0
Splices	$50	$75	$50	$0	$0
Total	**$2,365**	**$1,459**	**$1,234**	**$638**	**$160**

F

VEGETATION MAINTENANCE TASK SELECTION MODULE

Table F-1
Example of vegetation maintenance task selection module for one failure cause on one system

Tree Failure Causes	PM Task Option	Cost Reference	Efficacy (% of Historical)
Uprooting, whole tree failure in the root/soil plate	Conduct dedicated Hazard Tree risk assessment and risk mitigation work as a separate initiative. Focus on sites and exposures that increase risk of whole tree wind throw failure.	See VM PM cost module	0.80
	Conduct a mid-cycle risk assessment inspection and complete risk mitigation tree removal or height reduction work reducing the risk of wind throw uprooting tree failures.	See VM PM cost module	0.80
	Increase efforts during routine VM PM placing greater emphasis on identification and mitigation of risk of wind throw uprooting failures in the soil/root plate This may increase the VM workload on a project.	Increase tree removal VM PM $	0.95
	Shorten PM Interval; perform VM focusing on managing the risk of uprooting whole tree failures more frequently (assume -1 yr).	Use Interval Adjustment Module cost curves	Use Interval Adjustment Module reliability curves
	Revise specification; refocus work efforts during routine VM PM on reducing risk of wind throw uprooting failures in the soil/root plate. This will result in a reallocation of effort, but should not increase workload on a project.	No increase in overall cost from "as is" program	0.95
	Continue current D-VM practices regarding managing the risk of uprooting whole tree failures. Make no change.	No increase in overall cost from "as is" program	1.00
	Lengthen PM Interval, perform VM focusing on managing the risk of uprooting whole tree failures less frequently (assume +1 yr).	Use VM PM cost and adjust with cost curve.	Use VM PM cost and adjust with reliability curve.
	Reduce the current level of VM tasks related to managing the risk of wind throw uprooting tree failures. Reduced cost.	0.90	1.05
	Eliminate current VM tasks related to managing the risk of wind throw uprooting tree failures. Run to failure, no cost.	0.01	1.20

Export Control Restrictions

Program:

ROW: Siting, Vegetation Management, and Avian Issues

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com