Estimating Reliability of Critical Distribution System Components

1001704

Final Report, February 2003

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Estimating Reliability of Critical Distribution System Components, EPRI, Palo Alto, CA: 2003. 1001704.

PRODUCT DESCRIPTION

EPRI has been developing methods for distribution planning since 1992. At that time, research directed at the concept of distributed resources begun by EPRI, Pacific Gas & Electric, and the National Renewable Energy Laboratory led to further consideration of distribution planning in general. More recently this analysis has raised the issue of aging of the distribution infrastructure and how to optimize maintenance and replacement of aging systems. This report discusses: 1) research into the prediction of failure rates for distribution assets and 2) spreadsheets that have been developed to assist in the prediction of failure rates. Four such spreadsheets have been developed: a basic template that is applicable to any type of distribution asset and three failure rate prediction spreadsheet templates specific to underground cable, distribution transformers, and power transformers. Descriptions of the spreadsheets include the methodology used in the spreadsheets, the inputs to the spreadsheets, and the calculations performed by the spreadsheets.

Results & Findings

The spreadsheets are useful tools for estimating failure rates. They are unique in both their detail and their approach to determining failure rates. No other failure rate source links detailed descriptions of equipment, environment, use, and test results with failure rates or provides the detail necessary to estimate relevant failure rates. No other tool formally considers uncertainty in failure-rate estimates, allows integration of such a wide variety of knowledge relevant to failure rates, or uses a consistent Bayesian approach to knowledge integration.

Due to lack of historical failure data, lack of data on test accuracy, lack of operating data, uncertainty with respect to future equipment use, and lack of field testing the spreadsheets predict wide confidence bands about failure rates. Additional research including expanding expert input, testing with utilities, expanding the equipment covered and standardizing failure data collection would be highly valuable.

Challenges & Objectives

The overall project objective is to develop methodology, data, and software tools to help companies determine repair/replace strategies for existing distribution assets that provide maximum value to the utility. The objective of the research described in this report was to develop a methodology and practical tools for estimating failure rates and hazard or failure functions.

Applications, Values & Use

As distribution systems age, planners increasingly face repair, upgrade, and replacement decisions. The problem of aging assets has become more important because of the increasing emphasis on reliability, customer service, and cost reduction. The EPRI Distribution Aging Asset project is developing methodology, data, and software tools to help companies determine maximum value repair/replace strategies for existing distribution assets; generate business cases for investment and O&M decisions; evaluate risks; and, focus manpower on high-value solutions.

EPRI Perspective

The aging asset project began in 2000. The status report for the project (EPRI report 1000422) describes research done to identify and develop analytical methods for making decisions about aging assets in electric distribution systems. In 2001, the EPRI project team designed and implemented repair/replace software specifically tailored for electric distribution equipment and initiated extensive equipment failure research. These activities are documented in "A Review of the Reliability of Electric Distribution System Components: EPRI White Paper," (EPRI report 1001873). The 2001 work also produced databases of failure rates and of failure literature. These databases are available on the website www.vmngroup.com. The 2001 research highlighted the need for equipment-specific and detailed tools for estimating failure rates. Consequently, a program of more specific Equipment Failure research was initiated in 2002. This status report summarizes the 2002 Equipment Failure research.

Approach

The project team selected key distribution system components for analysis (underground cable, distribution transformers, and power transformers) and gathered information from experts and literature on the design, use, and failure rates of these components. The team developed a failure estimation template spreadsheet that integrated design, use, and testing information using Bayesian updating and developed three equipment specific spreadsheets that estimate hazard functions.

Keywords

Reliability
Reliability of distribution systems
Failure rates
Hazard functions

ABSTRACT

This report discusses 1) research into the prediction of failure rates for distribution assets and 2) spreadsheets that have been developed to assist the prediction of failure rates. The report describes: gathering information from experts and literature, the approach taken to failure estimation in the spreadsheets, some details of the spreadsheet design, and needed future work. The spreadsheets are useful tools for estimating failure rates. They are unique in both their detail and their approach to determining failure rates. These spreadsheets predict wide bands about failure rates, due to factors such as lack of historical data and uncertainty with respect to equipment use. Additional research including expanding expert input, testing with utilities, expanding the equipment covered, and standardizing failure data collection would be highly valuable.

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1
INTRODUCTION

Utilities must make frequent decisions about operation, maintenance, and replacement of equipment. These decisions are becoming more critical as much of our distribution system equipment reaches 30, 40, or more years of operation. To make these decisions in an optimal or near optimal way, utilities need to estimate the likelihood of failure if they continue to operate the equipment. This report discusses research on failure estimation and describes spreadsheets developed to assist in estimating the likelihood of failure.

The research described in this report is part of the EPRI Distribution Aging Asset project. The overall project objective is to develop methodology, data, and software tools to help companies determine "maximum value," repair/replace strategies for existing distribution assets; generate business cases for investment and O&M decisions; evaluate risks; and, focus manpower on high-value solutions. The objective of the research described in this report was to develop a methodology for estimating hazard or failure functions. Estimates of these functions would include both most likely values and measures of the variance about those values.

More detailed objectives of this study include:

- Select appropriate hazard functions describing the change in failure rate with time for individual pieces of equipment;
- Estimate the parameters of these functions and the current point on the hazard function; that is, the current failure rate;
- Develop a general process for this estimation that uses all relevant information likely to be available to the utility, including relevant industry statistics, utility specific statistics and test results;
- Capture the logic of this process in a spreadsheet template; and
- Build spreadsheets for specific equipment.

To reach these objectives we took the following steps in the project:

- Selected the equipment to be studied (underground cable, distribution transformers, and power transformers);
- Gathered information from experts and literature;
- Developed a failure estimation template spreadsheet; and
- Developed three equipment specific spreadsheets that estimate hazard functions (for underground cable, distribution transformer, power transformer)

Our selection of underground cable and transformers as the focus of the 2002 analysis was based on reports from utility advisors concerning the high and growing costs of maintaining or replacing these assets and the difficulty of estimating their failure rates. After some study of the transformer literature, transformers were divided into distribution and power transformers. Distribution transformers are those found on feeders, usually either pad or pole mounted. Power transformers are larger transformers located in sub-stations.

Information gathering was extensive. In 2001, EPRI conducted an broad literature survey in the area of failure rate estimation and failure rate data. Over 150 books, proceedings, and articles were reviewed and summarized. This work is described in "A Review of the Reliability of Electric Distribution System Components: EPRI White Paper," 1001873, December 2001. Building on last year's work, we expanded the failure literature database to 201 articles. (The revised literature database, an Excel workbook, is posted at www.vmngroup.com and available to EPRI members from Steve Chapel, EPRI Project Manager.) The references from this database that were chosen to support estimates in the spreadsheet are listed in Appendix A, References.

Three principles guided the design of the spreadsheets:

1. They should consider all the data that a utility is likely to have that is relevant to estimating the failure rate. This includes three classes of information: information about the equipment and its use, information about recent failure patterns, and the results of testing.

2. The spreadsheets should formally recognize uncertainty in the estimates of failure rates or the parameters of failure functions.

3. As far as possible the integration of the information should be based on Bayesian statistical concepts.

The study has produced the following deliverables:

- An expanded literature database;
- A template for estimation of the hazard function associated with distribution equipment;
- Initial hazard function estimation spreadsheets for underground cable, distribution transformers, and power transformers; and
- This report on the project.

The next section of this report, Section 2, describes our approach in more detail. The following section describes some of the details of the spreadsheets. Section 4 discusses how this research fits into the larger EPRI project on managing aging distribution assets. The last Section presents conclusions and suggestions for further research. An Appendix provides the references used in the development of the spreadsheets

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APPROACH

This section describes the information gathering and the methodology embodied by the spreadsheets. The next section describes the spreadsheet structure and some details of the individual spreadsheets for underground cable, distribution transformers, and power transformers.

Data Collection

We performed an extensive literature review and conducted in-depth interviews with EPRI experts to develop our methodology and provide data for the spreadsheets.

A particularly useful source for data on underground cable is the IEEE-Insulated Cable Committee. We reviewed this committee's online meeting minutes back to 1996. Included in the review were minutes from the following subcommittees: Cable Construction and Design, Cable Systems, Cable Characteristics, Insulation, Sheaths and Coverings.

Unfortunately, the literature we identified did not provide sufficient statistical data or findings to establish hazard functions for equipment that could be readily applied by utilities to their diverse equipment inventories. Hazard functions depend on specific equipment and operating environment attributes. Data reported in the literature commonly have the following problems:

- Only point estimates of failure rates are made, not complete hazard functions;
- Details of equipment design and history including vintage and age are omitted;
- Estimates are based on small samples or aggregates of diverse types of equipment; and
- Analysis procedures are inappropriate.

Because of these limitations in the available data, we made extensive use of EPRI experts in completing the underground cable, distribution transformer and power transformer spreadsheets. We held five workshops with EPRI cable and transformer experts. At the initial workshops, we explained the project and data needs and had a general discussion of the nature of the equipment, how the equipment fails, and attributes that contribute to earlier or later failure.

At later meetings, we would present our findings from the literature, ask the experts to comment on these findings, and – most importantly—ask the experts to provide their own estimates of failure rates, test accuracy and other quantitative inputs to the spreadsheets. The experts, while supplying these opinions, emphasized that because of the diversity of equipment and its pattern of use and the lack of good statistical data, their estimates are highly, highly uncertain. This uncertainty is captured with the variances, or error bands, placed on the estimates of failure rates.

Calculation Methodology

The common model of the failure rate with aging is a bathtub curve. Curves of this type are illustrated in Figure 2-1 Typical Bathtub Curve of Failure Rates. The curve is typified by an early period of high but rapidly falling failure rates, a long period of stable or very slowly growing failure rates, and a period of more rapidly increasing failure rates. The three lines in the figure illustrate that generally we are uncertain about the failure rate.

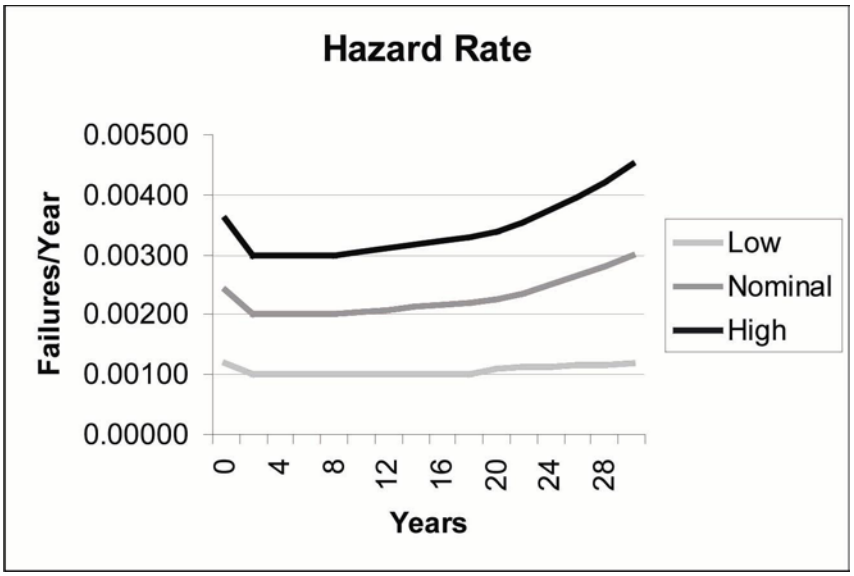


Figure 2-1
Typical Bathtub Curve of Failure Rates

Our first objective was to choose a failure rate form for the equipment. A small set of functions are used in the vast majority of failure studies. These functions are popular because they are easily manipulated mathematically and have the flexibility to fit empirical data well. Two of the most popular are the exponential and the Weibull functions. The Weibull also has a theoretical basis for modeling failures. If a piece of equipment is composed of many components each independently "competing" to be the first to fail, the Weibull function will describe the failure of the equipment as a whole.

We define the failure rate at time t as the probability of failure in the next small increment of time (given that the equipment has lived to time t). We will designate the failure rate as h(t) (it is also known as the hazard rate or function). For the exponential distribution of failures the failure rate is a constant.

$$h(t)=\lambda$$

A component with an exponential failure rate essentially does not grow old. It may fail but the failure rate is the same for a brand new or an aged component.

For the Weibull distribution of failures the failure rate is given by:

$$h(t)=(\gamma/\alpha^{\gamma})t^{\gamma-1}$$

With a Weibull function and γ greater than 1, equipment ages; and the failure rate increases with time. A difficulty with the Weibull is that for increasing failures the function must have zero failures at time zero.

Another alternative is to combine functions. The following function combines the exponential and Weibull models. This function can be interpreted as describing a piece of equipment with two failure modes: a mode that has a constant rate of failure through out its life and another that increases with age.

$$h(t)=\lambda + (\gamma/\alpha^{\gamma})t^{\gamma-1}$$

This function is more flexible than the simpler functions. It captures both non-zero initial failures and increasing failures with age. However, the additional complexity may not be needed or may not be justified by the quality of available data.

For the template, the cable failure rate, and power transformer failure rate, we use the Weibull distribution. The Weibull distribution was chosen for the following reasons:

- It has some theoretical support for equipment with multiple failure modes or components;
- It is widely used;
- It is relatively easy to fit to empirical data;
- It has the increasing failure rate with time that we expect with most aging distribution assets; and
- It has only two parameters -- given the limited available data, a more complex function is not justified.

We were uncomfortable with the Weibull to represent failures in distribution transformers and repairable outages in power transformers. The literature suggests that distribution transformers have significant early failures and power transformers have significant early repairable outages. For these, we used the more complex combined function.

The spreadsheets are unique tools for estimating hazard functions based on a variety of relevant data. The more data available, the more accurate we expect the estimate of the failure rate to be. The spreadsheets require only that the vintage of the equipment be identified, but the user can identify additional design characteristics, recent performance, and test results.

Hazard function estimates are uncertain for several reasons:

- Often important information on the equipment is missing,
- Information on its past use and stresses is incomplete,
- Future stresses are uncertain,
- Historic data useful for statistical analysis is rare, and
- Spreadsheet methodologies and rules of thumb are untested.

The estimate of the failure rate can be divided into four parts:

- Initial selection of failure rates/parameters based on key characteristics,
- Adjustments based on additional design characteristics and environmental conditions,
- Bayesian updating based on recent equipment performance, and
- Bayesian updating based on test results.

Based on the literature review and interviews with experts we determined a list of design characteristics and environmental conditions that significantly affect failures. Based on these same sources, we established relationships between failure rates and these design characteristics and environmental conditions. These relationships are stored as tables and equations in the spreadsheets.

The user must identify the equipment vintage. If the key design parameters are not known, they are assumed to be typical of the vintage. Tables are setup in the spreadsheets that identify failure rate - age pairs, based on the vintage and the key design parameters. A failure rate-age pair is established for a middle-aged and an older piece of equipment.

The user is also asked to identify as many additional significant design characteristics and environmental conditions as possible. If these characteristics and conditions are not known, they are assumed based on the vintage of the equipment and typical environmental conditions. Adjustments are then made based on these characteristics and conditions. If the characteristics or conditions are discrete, age adjustments are looked up in tables. If the characteristics or conditions are continuous, equations for age adjustment are provided.

Based on the two adjusted failure-rate pairs, the parameters of the hazard function are calculated. The failure rate and the increase in failure rate at the current age are then calculated from the failure rate function. Based on the amount of information provided by the user, judgments are made about the variance in the estimates of the failure rate and the rate of increase in the failure rate.

If the spreadsheet user has provided information on recent failures, the estimates of failure rate and failure rate increase are updated using this data. To do this updating, the probability distributions, not just point estimates of the failure rate and the increase in failure rate, must be specified. Currently the distributions are based upon the author's judgment. A goal for future research is to derive these distributions directly from the underlying failure rate functions that we are using. The failure rate function must be positive and we expect it to have a long tail on the upside. The failure rate increase can be positive or negative. We have chosen the Gamma and the Normal distributions respectively to describe the failure rate and the failure rate increase distributions. These functions have the right general characteristics and their updating rules are simple.

Having set variances on the estimates and chosen the functions describing the estimates, we are prepared to update the estimates with respect to recent failures. First, we must weight the new information. We experimented with different weightings and used our judgment to select an initial default weighting scheme. These weights are built into the spreadsheet. Second, the spreadsheet carries out the Bayesian updating calculations.

If the user has supplied results of tests on the equipment, the next step is to incorporate these results into the estimates of failure rate and failure-rate increase. While there are many tests, particularly for transformers, that can provide information on the equipment's condition, we have found severe limitations in their usefulness. The impact of test data is limited because:

- Test interpretation is often an art,
- Tests have been used to pinpoint problems not to predict failure probability,
- Statistics on accuracy of tests in predicting failures or outages simply have not been collected.

The calculations for updating failure rate and failure rate increase based on test results are assumed to be independent. Further research is necessary to validate and refine this assumption. The failure rate and failure rate increase calculations are handled similarly. We will describe the failure rate calculations here. A set of tables in the spreadsheet describe test accuracy. These tables are based on discrete equipment states and test results. For example, cable equipment states are: less than 1, 1 to 3, 3 to 5, 5 to 9, and greater than 9 failures per 100 miles per year; and cable insulation resistance test results are: greater than 90% of original resistance, between 50% and 90% of original resistance, and less than 50% of original resistance. Test results are entered into the spreadsheet as being in one of the discrete categories. The distributions specified above for the failure rate and failure-rate increase are used to determine the prior probability of each equipment state. With the prior distributions on test states, the discrete test results, and the test accuracy data, the Bayesian updating of the state probabilities is straightforward and will not be detailed here.

At this point, the design and environmental data, the recent performance data and the test data have all been incorporated. The spreadsheet has developed estimates of the probability that the failure rate and failure rate increase are in one of several discrete states or ranges of failure rates and failure rate increases. This information is available for planning purposes.

3
DESCRIPTION OF THE SPREADSHEETS

Typically an estimation spreadsheet has four individual spreadsheets:

1. Data input sheet,
2. Hazard function calculations,
3. Notes, and
4. Test accuracy data.

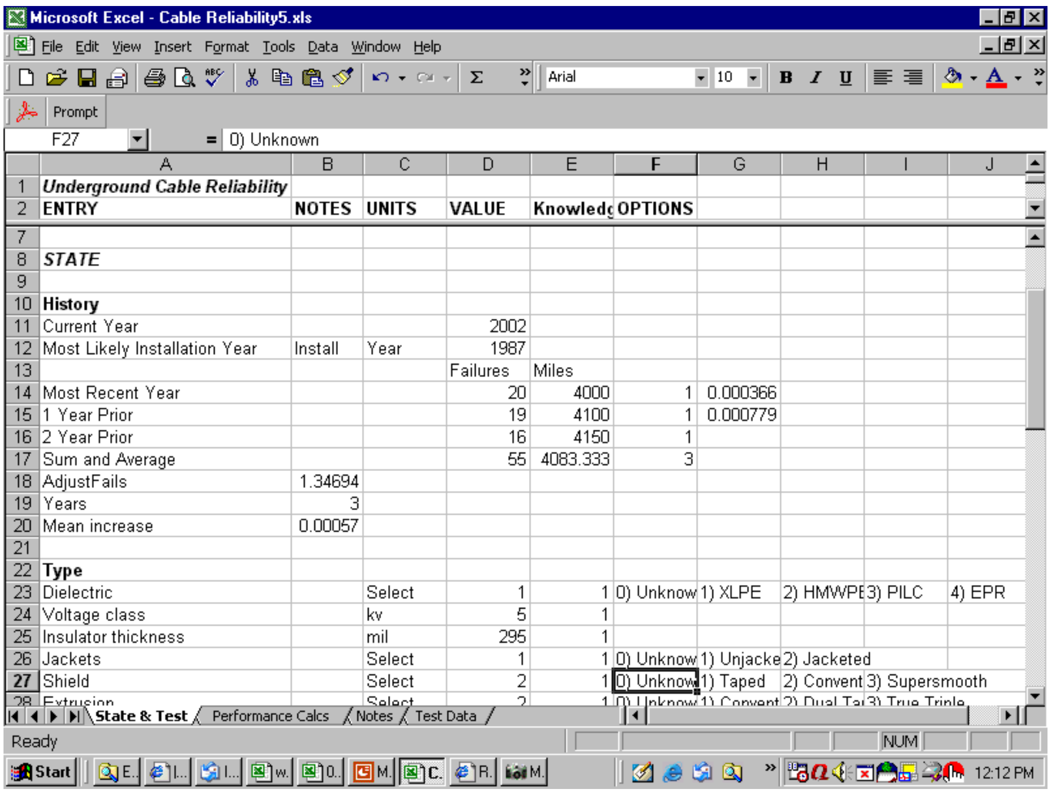


Figure 3-1
Portion of the Underground Cable Input Sheet

The input sheet collects a wide range of data, as can be seen in Figure 3-1. First, data about the vintage of the equipment and recent performance is entered. Next, a more detailed description of the equipment is entered.

For underground cable the following design information is requested:

- Dielectric,
- Voltage class,
- Insulator thickness,
- Jackets,
- Shield,
- Extrusion,
- Curing method,
- Strand filling,
- Moisture barrier,
- Purer semi-con material,
- Extra clean XLPE, and
- Installation.

The only installation or use characteristic requested for underground cable is burial depth.

For distribution transformers the following design information is requested:

- Mounting type,
- Location type,
- High side voltage,
- Design hottest spot temp, and
- Phase.

For power transformers the following design information is requested:

- Size classification,
- Design hottest spot temp,
- Pumps and fans,
- LTC,
- Shell or core,
- Oil preservation, and
- GE Type U bushings.

For both distribution and power transformers the spreadsheet requests the median hottest spot temperature and the hottest spot temperature that is not exceeded 90% of the time.

Lastly the input sheet allows the user to specify test results for the different types of tests.

For underground cable the following tests are considered:

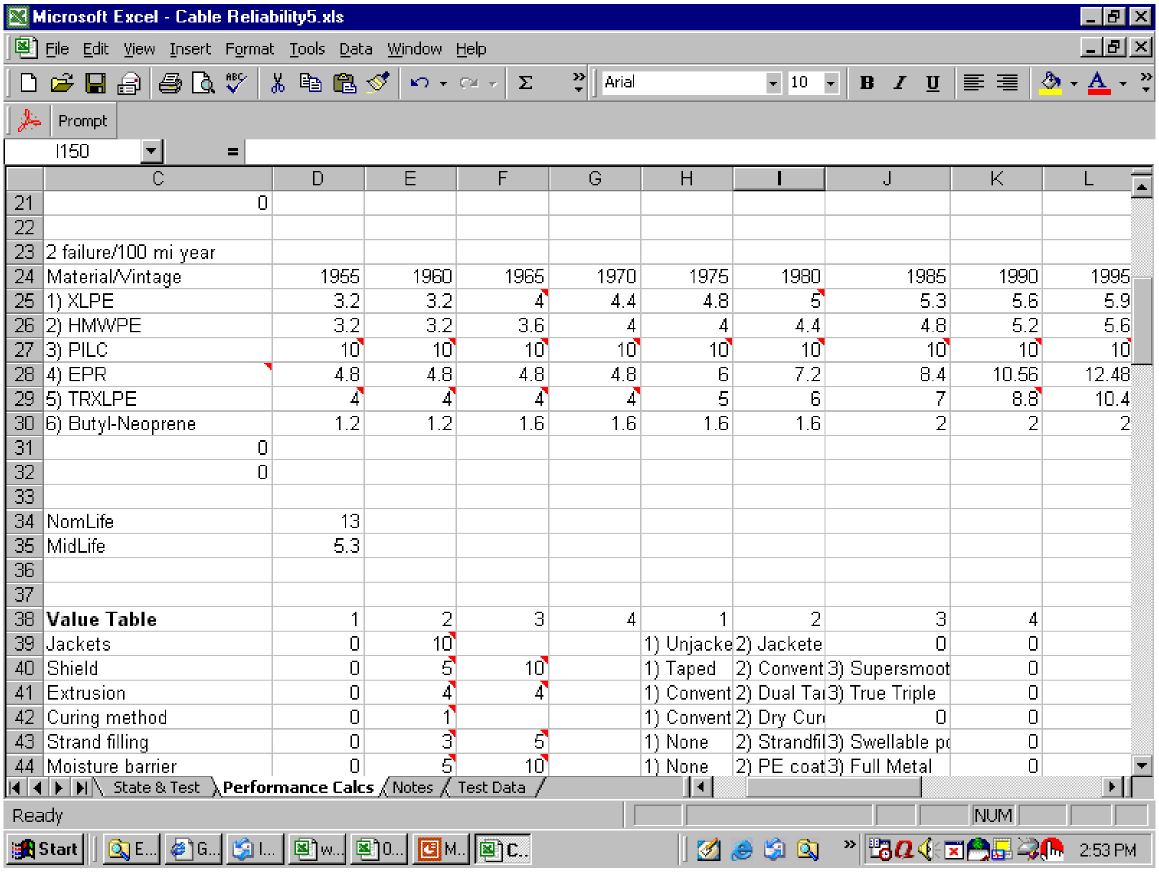
- Visual inspection,
- Insulation resistance,
- Partial discharge test, and
- Dissipation factor.

For distribution transformers no test data is used.

For power transformers the following tests are considered:

- DGA (gas chromatography),
- Insulating oil dielectric strength,
- Insulating oil moisture,
- Insulating oil power factor,
- Transformer power factor,
- Bushings power factor, and
- LTC (Non Arcing) oil power Factor

Figure 3-2 shows a portion of the calculation sheet.



	C	D	E	F	G	H	I	J	K	L
21	0									
22										
23	2 failure/100 mi year									
24	Material/Vintage	1955	1960	1965	1970	1975	1980	1985	1990	1995
25	1) XLPE	3.2	3.2	4	4.4	4.8	5	5.3	5.6	5.9
26	2) HMWPE	3.2	3.2	3.6	4	4	4.4	4.8	5.2	5.6
27	3) PILC	10	10	10	10	10	10	10	10	10
28	4) EPR	4.8	4.8	4.8	4.8	6	7.2	8.4	10.56	12.48
29	5) TRXLPE	4	4	4	4	5	6	7	8.8	10.4
30	6) Butyl-Neoprene	1.2	1.2	1.6	1.6	1.6	1.6	2	2	2
31	0									
32	0									
33										
34	NomLife	13								
35	MidLife	5.3								
36										
37										
38	**Value Table**	1	2	3	4	1	2	3	4	
39	Jackets	0	10			1) Unjacke	2) Jackete	0	0	
40	Shield	0	5	10		1) Taped	2) Convent	3) Supersmoot	0	
41	Extrusion	0	4	4		1) Convent	2) Dual Tai	3) True Triple	0	
42	Curing method	0	1			1) Convent	2) Dry Curi	0	0	
43	Strand filling	0	3	5		1) None	2) Strandfil	3) Swellable pi	0	
44	Moisture barrier	0	5	10		1) None	2) PE coat	3) Full Metal	0	

Figure 3-2
Portion of Calculation Sheet for Underground Cable

Calculation of the hazard function parameters is carried out in four stages.

- Based on age and key attributes, parameters are chosen from data tables. (Values in tables based on literature and EPRI experts.) A portion of such a table is shown in Figure 3-2 Portion of Calculation Sheet for Underground Cable lines 23 to 30.
- Based on additional attributes (for example, cable insulation thickness or transformer core type) adjustments are made. A partial list of adjustments is shown in Figure 3-2 Portion of Calculation Sheet for Underground Cable lines 38 to 44.
- Probability distributions on the parameters are updated based on recent failures.
- Probability distributions on the parameters are updated based on test results.

In the power transformer spreadsheet, these stages are carried out separately for repairable outages and un-repairable failures.

After the first two stages, we have two adjusted age-failure-rate pairs. Based on these, the parameters of the hazard function are calculated; and the failure rate and the increase in failure rate at the current age are calculated from the failure rate function. The remaining spreadsheet calculations focus on the failure rate and the rate of change in the failure rate.

Based on the amount of information provided by the user, judgments are made about the variance in the estimates of the failure rate and the rate of increase in the failure rate. The measure of variance used is the ratio of the 95% failure rate over the median failure rate. The 95% failure rate is defined as a failure rate that we believe is 95% probable to be greater than or equal to the true failure rate. For example, if more than five important underground cable design characteristics are unknown, the 95% failure rate over median failure rate is set at 10. If four or less important underground cable design characteristics are unknown and the dielectric is paper-insulated-lead-covered or tree-retardant-cross-linked-polyethylene, the 95% failure rate over median failure rate is set at 2.

Assuming the failure rate has a Gamma distribution and the failure rate increase has a Normal distribution, the spreadsheet carries out the Bayesian updating calculations.

The last calculation updates the probability distributions based on the test results. Table 3-1 Partial Discharge Test Data, illustrates typical test accuracy data. This data is for tests on underground cable. Columns refer to equipment failure rates and rows refer to test outcomes. Entries indicate the probability of the test outcome given that the equipment is in the state indicated by the failure rate at the top of the column. Given a prior distribution on failure rates and a test result an updated distribution on failure rate can be easily calculated using the test accuracy data and Bayesian updating.

Table 3-1
Partial Discharge Test Data

Partial discharge test					
Failure/Results	<1	1-3	3-5	7-9	>9
Very Good	0.93	0.65	0.15	0.01	0.01
Good	0.05	0.25	0.20	0.04	0.09
Nominal	0.01	0.09	0.35	0.25	0.10
Poor	0.005	0.005	0.25	0.50	0.30
Very Poor	0.005	0.005	0.05	0.20	0.50

4 CONTRIBUTION TO DISTRIBUTION BUSINESS PLANNING METHODOLOGY

EPRI is working on three decision tools whose use and usefulness would benefit greatly from the results of this research:

- Project Prioritization Model – this model prioritizes disparate distribution projects, many of which involve replacing or refurbishing physical assets with non-zero failure rates. Currently, the P^2 model relies on user judgment to specify the failure rates. There is no guarantee of consistency, either within each project set for a given distribution area or across areas or other utilities who share similar equipment. A predictive failure rate model would greatly reduce the assessment burden and improve the accuracy and credibility of each P^2 model application.
- Aging Assets Model – this model determines the appropriate repair / replace / maintain / refurbish policy for an asset as a function of age, test results, external conditions, performance and other uncertain variables. Two fundamental inputs to the A^2 model are failure rates and conditional probability distributions on failure rates given test results. These inputs are difficult for most individual users to provide, both because of their technical nature and also because the appropriate statistics require an industry rather than an single-utility perspective. A predictive failure rate model that automatically updates failure rates based on observed test results would make the A^2 model much easier to use and its results would be much more credible.
- Test Evaluation Model – this model is currently a module in the Aging Assets Model. The notion of a stand-alone test evaluation model was received with enthusiasm at the 2002 Advisors meeting. For exactly the same reasons as with the A^2 model, a predictive failure rate model that automatically updates failure rates based on observed test results would integrate perfectly with the Test Evaluation Model and make it more useful and easy to use.

5
CONCLUSIONS

The spreadsheets described in this document are unique in both their detail and their approach to determining failure rates. We have found no failure rate sources that allow the detail of description with links to failure rates allowed by these spreadsheets. This detail regarding vintage, design, and use is necessary to estimate relevant failure rates. Also, we do not know of any other tool that formally considers the uncertainty of failure-rate estimates, allows integration of such a wide variety of knowledge relevant to failure rates, and uses a consistent Bayesian approach to the knowledge integration.

However, this work is far from complete. These spreadsheets predict wide bands about failure rates, due to the following factors:

- Often important information on the equipment design is missing,
- Information on its past use and stresses is incomplete,
- Future stresses are uncertain,
- Historic data useful for statistical analysis is rare, and
- Spreadsheet methodologies and rules of thumb are untested.

Table 5-1 Variation in Failure Estimates, illustrates the level of uncertainty in failure estimates. Median Failure is a value that we estimate the true failure rate has a 50% chance of falling below; 95% Failure is a value that we estimate the true failure rate has a 95% chance of falling below. All estimates are for common equipment designs installed in 1975 for which we have complete information and all important design features. Transformers are assumed to need no significant adjustment for past or future operating temperatures. For power transformers both a repairable outage rate and a non-repairable failure rate are given. These events are mutually exclusive.

Table 5-1
Variation in Failure Estimates

Equipment	Units	Median Failure	95% Failure
Cable	Failures/100 mi/year	8	40
Distribution Transformers	% Failures/year	0.3	1.8
Power Transformers	% Outages/year	3.5	14.0
Power Transformers	% Failures/year	3.7	14.8

As noted above good historic data on which to base failure estimates is surprisingly rare. We recommend that utilities collect their individual failure data to improve internal prediction and industry capabilities. The most basic data for outage/failures are: type of equipment, age/installation date, repairable or non-repairable failure, time to repair, number of similar units in operation during period for which failures are recorded. More detailed statistics would include: details of equipment design and manufacture, history of loads, mode of failure, and cause of failure

In addition to equipment failure data, data linking tests to failures would also be extremely useful. Utilities should track test results and the condition of tested equipment at regular intervals into the future. The goal is to establish a clear relationship between a test result and a failure rate.

The following additional research is needed to improve our capability to predict failure rates and ultimately to improve maintenance, repair, and retirement decisions.

- Much of the current data is based on the judgments of a handful of EPRI experts. Expert judgments about failure rates should be gathered from a broader expert panel that has field experience with the equipment. We envision a panel drawn from interested utilities.
- Spreadsheets should be developed for additional equipment. Circuit breakers and poles were mentioned by utility advisors as high priority items.
- The spreadsheets need to be tested and improved through applications. We would like to work with utility personnel to make estimates of failure rates for their equipment. The accuracy of these estimates could then be checked over time.
- We have located no industry guidelines for failure and test data collection. The lack of guidelines leaves utilities without guidance on good information collection practices and prevents any standardization of data collection and sharing of data within the industry. Preparing appropriate guidelines would provide a significant long-term benefit to the industry.

While the importance of understanding failure rates to good decision making regarding maintenance, repair, and retirement is well understood, the data and methods available to the electric power industry are surprisingly weak. Because of equipment diversity and the very low failure rates that are acceptable in the power industry, it is extremely difficult for even the largest utility to gather sufficient data to make reliable estimates of failure rates. An industry-wide research organization such as EPRI has an indispensable role in working with groups of interested utilities to share data and ideas and to create useful decision support tools based on these data and ideas. The work represented in this and prior project reports is both unique and useful, but it has only delivered a small increment of the total value that can be obtained by improved management of aging assets.

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