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Assessment of EPRI's Tan Delta Approach to Manage Cables in Submerged Environments: Statistical Review of EPRI Data

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ABSTRACT

In a submerged environment, power cables may experience accelerated insulation degradation due to water-related aging mechanisms. Progressive reduction of the cable dielectric strength is commonly a result of water treeing. Water treeing is a phenomenon in which dendritic micro-voids (branched tree-like structures) are formed in electrical cable insulation because of electrochemical reactions and diffusion of contaminants over time. The combined effects of water presence and high electrical stresses in the material cause these reactions. Based on established research, water treeing or water-induced damage can occur in a variety of electrical cables, including cross-linked polyethylene; butyl rubber; black, pink, and brown ethylene-propylene rubber (EPR); and compact insulation (black and pink EPR). Under wet conditions or in submerged environments, several environmental and operational parameters can influence water tree initiation and affect water tree growth. These parameters include voltage cycling, field frequency, temperature, ion concentration and chemistry, dielectric stress, type of insulation material, and the characteristics of the cable's defects.

Records of cable failures provided by licensees in response to Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients," dated February 7, 2007, have called into question the reliability of medium-voltage cables in wet or submerged environments. The primary tool for condition monitoring of medium-voltage cables in wet or submerged environments is universally believed to be measurement and tracking of dissipation factor, also known as Tan Delta testing.

The Electric Power Research Institute (EPRI) documented its dissipation factor (Tan Delta) testing guidelines and acceptance criteria in two reports: TR-3002000557, "Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants," Revision 1, issued June 2013; and TR-3002005321, "Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis—Update," issued September 2015.

Most nuclear power plant operators have adopted the test criteria provided in these reports for interpreting the results obtained from Tan Delta testing. EPRI collected member data since late 2009 to analyze and provide feedback to members, validate the EPRI-developed acceptance criteria guidelines, support the analysis of test results, recommend appropriate actions for the "action required," (defined as "Red" category), and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation. EPRI has also performed correlations between Tan Delta test results and the information gathered under the EPRI forensic research on medium-voltage cables. In addition, EPRI has developed guidance on how to systematically analyze Tan Delta test results by cable insulation type.

The U.S. Nuclear Regulatory Commission contracted with the Pacific Northwest National Laboratory (PNNL) to perform a statistical analysis to determine whether the Tan Delta test data collected by EPRI supported the EPRI criteria in TR-3002000557 and TR-3002005321 for managing the aging of cables in submerged environments. The contract also called for PNNL to determine whether the EPRI-recommended testing intervals in TR-3002000557 for cables that test Green (good) and Yellow (further study) are suitable for managing the aging of cables in submerged environments.

The project statement of work for Task 1 and Task 2 cited both of these requirements:

TASK 1: STATISTICAL ANALYSIS OF THE EPRI DATA

Perform a statistical analysis to determine if the data provided to EPRI by the licensees is statistically significant to support conclusion that cables can be operated until the next test interval. In addition, determine if the data provided to EPRI by the licensees aligns with the criteria issued in EPRI Reports 3002005321 and 3002000557 to manage the aging of cables in submerged environments. Based on the data collected by EPRI, determine if the EPRI recommended testing intervals in report 3002000557 for cables that test Green (good) and Yellow (further study) are suitable to manage the aging of cables in submerged environments. The contractor should identify instances in which there was a cable failure within the EPRI recommended testing interval for good (6 years) and further study (2 years).

Task 1c: Determine if the data provided by the licensees to EPRI aligns with the criteria issued in EPRI reports 3002005321 and 3002000557.

Once a determination has been made regarding the number of test results per cable type within the in-service age group, the DOE laboratory should determine how many of the tests results per cable type fall within the Green, Yellow, and Red categories.

TASK 2: ASSESSMENT OF EPRI'S RECOMMENDED TESTING INTERVALS:

Task 2a: Based on the EPRI provided data, determine if the recommended testing intervals for "good or green" (6 years), "further study or yellow" (2 years) are suitable to manage the aging of cable s in submerged environments.

In March 2020, PNNL provided the findings of the statistical assessment analysis in PNNL-28542-1, "Assessment of EPRI's Tan Delta Approach to Manage Cables in Submerged Environments: Statistical Review of EPRI Data." The purpose of this research information letter is to provide an overview of PNNL-28542-1 and evaluate whether any regulatory guidance changes can be proposed based on the results of this study.

Based on an analysis of these available data, new regulatory guidance or endorsement of the proposed EPRI guidelines is not recommended at this time. This is due to the limited test results for some categories of cable types and material, as well as a few reported cases of multiple test results for the same cables. These results do not support consistent and reliable trending due to the limited dataset.

FOREWORD

Assessment of the Electric Power Research Institute's (EPRI's) Tan Delta testing as a tool to assist in managing cables in submerged environments (a statistical review of EPRI data) was performed in partial response to User Need Request (UNR) NRR 2011-014, "Response to User Need Request for Research for Assessment of Cable Condition Monitoring" issued February 24, 2012, and NRR 2016-012, "Response to Amendment to User Need Request for Assessment of Condition Monitoring Methods for Electrical Cables" issued November 3, 2017. The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation (NRR) initiated these UNRs to (1) evaluate condition monitoring techniques on naturally aged and new electrical cable samples, (2) assess cable condition monitoring, and (3) verify whether suitable methods are available to track cable degradation as a function of time and to establish a range of acceptance criteria for the methods to ensure operability for medium-voltage power. This request was coordinated among the staff and management of the Office of Nuclear Regulatory Research (RES), Division of Engineering, Instrumentation, Controls, and Electrical Engineering Branch; and the NRR Division of Engineering and External Hazards, Long Term Operation and Modernization Branch.

In response to Generic Letter 2007-01, "Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients," dated February 7, 2007, licensees submitted records of submerged cable failures to the NRC. These records have called into question the reliability of medium-voltage cables in wet or submerged environments.

Most nuclear power plant operators have adopted dissipation factor (Tan Delta) testing guidelines and acceptance criteria, developed by EPRI, as the primary tool for condition monitoring of medium-voltage cables in wet or submerged environments. EPRI also has been collecting member data since late 2009 to analyze and provide feedback to members, validate the EPRI-developed acceptance criteria guidelines, support the analysis of test results, recommend appropriate actions for the "action required," defined as "Red" category, and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation. EPRI has also performed correlations between Tan Delta tests and the information gathered under the EPRI forensic research on medium-voltage cables. In addition, EPRI has developed guidance on how to systematically analyze Tan Delta test results by cable insulation type.

In response to the NRR UNRs, RES contracted with the Pacific Northwest National Laboratory (PNNL) to conduct a statistical assessment of EPRI's Tan Delta test data collected from nuclear power plant operators to determine whether the reported Tan Delta test evaluation criteria are suitable for monitoring cable condition in wet areas. PNNL provided the assessment final report in PNNL-28542-1, "Assessment of EPRI's Tan Delta Approach to Manage Cables in Submerged Environments: Statistical Review of EPRI Data," in March 2020. This report identifies the confidence level of Tan Delta testing data for each category of cables in EPRI guideline thresholds and test intervals for monitoring cable conditions in submerged environments. PNNL concluded that the test result threshold guidelines are appropriately derived based on the available test data from participating member utilities. PNNL report mentions that the guidelines could be deemed suitable. PNNL's conclusion was based on zero incidence of age-related transitions from Green (good) to Black (failure) within 6 years or Yellow (further study) to Black (failure) within 2 years and the low incidence of false positives and false negatives. PNNL also noted that if EPRI continues to collect data, the statistical confidence intervals could be narrowed.

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ABBREVIATIONS AND ACRONYMS

ADAMS	Agencywide Documents Access and Management System
CFR	*Code of Federal Regulations*
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
GDC	general design criterion
GL	generic letter
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
PNNL	Pacific Northwest National Laboratory
RES	Office of Nuclear Regulatory Research
RIL	research information letter
Tan Delta	cable test also referred to as a dissipation factor test
UNR	user need request
XLPE	cross-linked polyethylene

1 INTRODUCTION

Water treeing is a phenomenon in which tree-like micro-voids are formed in electrical cable insulation because of electrochemical reactions, which may degrade the cable. Electrochemical reactions are caused by the combined effect of water presence and relatively high electrical stress. The electrical stress is generally 480 volts and above acting on local imperfections like voids and contaminants within the insulating materials and at areas of high mechanical stress such as bends. This phenomenon is known to be one of the leading degradation mechanisms that contribute to the loss of dielectric insulation strength in medium-voltage cable insulating materials in wet or submerged environments. It can occur in a variety of cable insulating materials, including ethylene-propylene rubber (EPR), cross-linked polyethylene (XLPE), and tree-retardant XLPE.

Under wet conditions, several environmental and operational parameters can influence the rate at which degradation related to water treeing affects the cable insulation. These parameters include voltage cycling, field frequency, temperature, liquid ion concentration, and chemistry. Water trees increase in length with time and voltage level and eventually can result in complete electrical breakdown of the cable insulation. As the insulation degrades, electrical failures become more prevalent, and the reliability of circuits can be compromised.

Records of cable failures provided by the licensees in response to Generic Letter (GL) 2007-01, “Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients,” dated February 7, 2007 (Ref. 1), have called into question the reliability of medium-voltage cables in wet or submerged environments. Concerns over the cable degrading such that it may fail when called on to perform safety functions have reinforced the need for a program to manage the aging of cables in wet or submerged environments.

Most nuclear power plant operators have adopted the Electric Power Research Institute’s (EPRI’s) dissipation factor or Tan Delta testing guidelines and acceptance criteria (explained in the sections below) as the primary tool for condition monitoring of medium-voltage cables in wet or submerged environments. EPRI has been collecting Tan Delta test data from member utilities since late 2009 to analyze and provide feedback to members, validate the EPRI-developed acceptance criteria, support the analysis of test results, recommend appropriate actions category, and gather candidate cables for EPRI-sponsored forensic research on causes of insulation degradation.

EPRI has collected data from 37 nuclear sites, which represent 44 units. The test results have been organized by insulation type such as XLPE; butyl rubber; black, pink, and brown EPR; and compact insulation (black and pink EPR). These data have been analyzed, and follow-up information was obtained from members for “action required” test results. EPRI has also performed correlations between Tan Delta tests and the information gathered under the EPRI forensic research on medium-voltage cables. In addition, EPRI has developed guidance on how to analyze Tan Delta test results systematically.

The U.S. Nuclear Regulatory Commission (NRC) awarded a contract to the Pacific Northwest National Laboratory (PNNL) to perform a statistical analysis to determine whether EPRI’s Tan Delta test data support the criteria in EPRI reports (Refs. 2 and 3) for managing the aging of cables in submerged environments. The contract also called for PNNL to determine whether the EPRI-recommended testing intervals (Ref. 2) for cables that test Green (good) and Yellow (further study) are suitable for managing the aging of cables in submerged environments.

2 METHOD OF INVESTIGATION (EPRI REPORTS REVIEWED)

2.1 Overview of EPRI TR-3002000557, "Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants," Revision 1

EPRI TR-3002000557, "Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants," Revision 1, issued June 2013 (Ref. 2), provides guidance for developing and implementing a cable aging management program for medium-voltage cables in nuclear power plants. It incorporates lessons learned from the initial implementation of aging management programs and additional EPRI technical findings. Medium-voltage cables (those rated 5 to 46 kilovolts, with operating voltages from 2.3 to 34 kilovolts) used in nuclear plants were expected to have very long lives (generally at least 40 years to cover the initial plant license term).

There are four practical tests for insulation degradation in shielded extruded medium-voltage cables: partial discharge, Tan Delta, and power frequency or very-low frequency withstand. Tan Delta testing determines the ratio of resistive leakage current through the insulation to the capacitive current. As noted in EPRI TR-1025262, "Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis," issued July 2012 (Ref. 4), Tan Delta offers some merits relating to the condition of the insulation.

In March 2020, PNNL provided the findings of a statistical assessment analysis of EPRI's Tan Delta test data in PNNL-28542-1, "Assessment of EPRI's Tan Delta Approach to Manage Cables in Submerged Environments: Statistical Review of EPRI Data" (Ref. 5). As PNNL-28542-1 focuses on Tan Delta, further summary comments on EPRI TR-3002000557, Revision 1, are primarily related to Tan Delta. The Tan Delta test (also referred to as a dissipation factor test) determines the ratio of resistive leakage current through the insulation to the capacitive current and provides a figure of merit relating to the condition of the insulation.

Tan Delta has no units and is generally a small number given in terms of a multiplier of $1x10^{-3}$. Tan Delta is a bulk test and does not provide location information for the degraded portion of the cable. It can be performed at line frequency or very low frequencies and is generally conducted at levels of 0.5, 1.0, 1.5, and 2 times the line-to-ground operating voltage. Tan Delta values that are elevated or unstable at a test voltage or values that increase or decrease with increasing voltage indicate deteriorated insulation

The Tan Delta technique does have disadvantages; for example, if a cable insulation system has only a single flaw (e.g., cut or construction defect), Tan Delta may not detect it even if significant. Also, the test does not discriminate between many widespread degradations or defects and a smaller number of more severely degraded regions. Assessment of Tan Delta requires consideration of (1) the absolute Tan Delta reading, (2) the delta Tan Delta, and (3) the percent standard deviation by the test instruments. These are typically built-in programmed features of these instruments, and the results are displayed or printed. As such, such an assessment can be rather lengthy and could be considered a minor disadvantage if any of these factors are classified as either "further study" or "action required." In such cases, the more stringent range (action required) applies to the circuit assessment.

Consistent with GL 2007-01, the onset of degradation for cables that have successfully passed installation testing and initial condition assessment should not occur until the cables are 20–30 years old. Given this expected age for the onset of degradation, a prudent approach for cables in the scope of a cable aging management program would be to test them after they are in service for 10 years but before they reach 20 years of service. Once the cables reach the point of being monitored under the cable aging management program, they should be retested on a 6-year frequency if they continue to test as “good.”

Per industry and EPRI guidelines, cables with results in the “further study” range should be subjected to more frequent testing (for example, every 2 years or once per refueling cycle) to determine whether the condition is stable or worsening. Licensees should consider performing a very low frequency withstand test if a “further study” result occurs.

According to EPRI guidelines, while immediate repair or replacement is desirable for a cable with an “action required” result, additional testing could be performed to verify serviceability for a limited period to allow the cable to return to service. Placing cables back in service after they pass a withstand test would not preclude an inservice failure, but it would provide some assurance that the defect is not significant enough to fail in the near term. Such decisions should consider the operational effects of failure during plant operation.

Tables 3.1 through 3.4 in PNNL-28542-1 (Ref. 5) show the EPRI-recommended Tan Delta assessment criteria for the different types of cables.

2.2 Overview of EPRI TR-1025262, “Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis”

In EPRI TR-1025262,[1] EPRI analyzes the Tan Delta test data that were provided to it by member utilities between 2009 and 2012 for cables mainly in adverse wet environments. The data represent more than 700 individual cable tests. The analysis performed is an evaluation and validation of the assessment criteria in EPRI TR-1020805, “Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants,” issued June 2010 (Ref. 6). The report also describes insights gained and lessons learned from analysis of the test results.

The data are specifically applicable to four types of rubber insulation in roughly the same proportion: XLPE, pink EPR, black EPR, and butyl rubber. Fewer data (7 percent of the total) were provided on brown EPR. Degradation was categorized as termination, splice, and insulation deterioration. Of the reported Tan Delta tests, 12.1 percent resulted in “action required”; however, only 6.6 percent of that population was related to insulation deterioration. Although these percentages are relatively high, this was not unexpected since the test population primarily included cables that were 25–35 years old.

Figures 3-1 through 3-6 in PNNL-28542-1 (Ref. 5) give examples of these results versus the evaluation criteria. Figures 3-1 through 3-4 show Tan Delta results versus the evaluation criteria for different types of cables, while Figures 3-5, “Black EPR % Standard Deviation Versus Evaluation Criteria” and 3-6, “Pink EPR % Standard Deviation Versus Evaluation Criteria” are the percent standard deviation versus the evaluation criteria for black EPR and pink EPR cables, respectively.

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[1] This EPRI report is incorrectly referenced on multiple pages in PNNL-28542-1 as TR-1028262.

2.3 Overview of EPRI TR-3002005321, “Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis—Update”

EPRI TR-3002005321, “Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis—Update,” issued September 2015 (Ref. 3), provides an evaluation and analysis of nearly 580 Tan Delta tests collected from nuclear power plant testing of medium-voltage shielded power cables collected between 2009 and 2015. Most nuclear power plant operators have adopted Tan Delta testing at 0.1 hertz, combined with 0.1 hertz withstand testing, as the primary tool for condition monitoring of medium-voltage shielded power cables. EPRI evaluated and analyzed the collected data and used them to assess correlations between Tan Delta results and the forensic research to provide insights on how to analyze Tan Delta results systematically.

Conclusions and findings from the EPRI report include the following:

- Of the 34 (6 percent of the test population) “action required” findings, approximately half were forensically determined to be related to splices or terminations, leaving the other half as related to insulation aging.
- There were two false negative tests (failures of cables that tested good or slightly degraded) in XLPE insulated cables. There were no false negative tests for brown, black, or pink EPR or butyl rubber insulated cables.
- No false positives (at least one degraded insulation defect) were found in any of the forensically evaluated circuits in the “action required” category.
- Tan Delta tests identified dry cable issues of thermal degradation, splice defects, and insulation degradation, confirming that Tan Delta testing can identify more than water-related degradation.
- All the cables identified with degraded insulation that were provided to EPRI for independent forensic evaluation had at least one degraded insulation site identified.
- There was only one inservice cable failure among all the black, pink, and brown EPR insulated cables tested between 2009 and 2015. That noncritical cable was in the “action required” range and was scheduled for replacement. Otherwise, there were no false positive “action required” cables for these cable types (based on those forensically tested).
- The forensic results also showed that insulation degradation is localized and not distributed. This indicates that EPR insulations do not age uniformly (i.e., they exhibit nonhomogeneous aging).
- A correlation was made between high Tan Delta values and low alternating current breakdown strength for black EPR and butyl rubber by using a short section of cable in the laboratory. This further confirms Tan Delta testing’s use for cable condition monitoring.

According to PNNL-28542-1, (Ref. 5) the findings discussed above affirm the reliability of Tan Delta testing in accordance with guidance from EPRI TR-3002000557.

Tables 3-1 to 3-4 in PNNL-28542-1 illustrate the threshold guidance for XLPE, butyl rubber, and black EPR, pink EPR, and brown EPR. These values were repeated in EPRI TR-3002005321 (Ref. 3) and were unchanged from EPRI TR-3002000557 (Ref. 2). Table 3-5, “Tan Delta Assessment Criteria for Black and Pink EPR Compact Cables (@ 0.1 Hz test frequency)” of the PNNL-28542-1 (Ref. 5), shows the threshold guidance for black and pink EPR compact cables.

2.4 Overview of EPRI TR-1021070, “Medium-Voltage Cable Aging Management Guide,” Revision 1

EPRI TR-1021070, “Medium-Voltage Cable Aging Management Guide,” Revision 1, issued November 2010 (Ref. 7), focuses on nuclear power industry cables and the degradation conditions that challenge them. Figures 3-7, “Example Plot of EPR Cable Years of Service Versus Number of Failures (from EPRI 2010 report 1021070)” and Figure 3-8, “Example Plot of XLPE Years of Service Versus Number of Failures (from EPRI 2010 report 1021070)” in PNNL-28542-1 depict the analysis of cable failures versus years of cable service. The figures include the performance of EPR and XLPE cables’ age (years in service) as a function of their failure numbers. The plots show few failures observed during the first 10 years of service. Thereafter, varying frequencies of cable failures are observed. The correlation between age and failure frequency in that case is not obvious.

The above EPRI report also includes information about cable design, grounding systems, in-plant stresses, assessments of age-related failures versus workmanship or rodent-related failures, and several practical subjects of interest to cable aging management programs. The report discusses the historical evolution of insulation material fillers resulting in several color classes of EPR and some distinctions between XLPE and EPR. The different fillers, constituent elements, and fabrication practices of the different insulation varieties result in different dielectric characteristics and damage susceptibility. The electrical behavior differences among cable materials result in differences in characteristic Tan Delta values for each material (see PNNL-28542-1, Figures 3-7 and 3-8).

3 STATISTICAL DATA REVIEW AND ANALYSIS BY PACIFIC NORTHWEST NATIONAL LABORATORY

EPRI supplied a data table that included 471 cable test entries that were addressed by the test guidelines. An additional 81 entries were provided that did not match the cable test guideline descriptors (e.g., black hybrid EPR, black non-shielded EPR, pink/brown hybrid EPR); the statistical review did not include these entries. Many of these cables were three-phase bundled cables, thus offering essentially three separate tests even though all phases were within the same cable assembly. Page 4.1 of PNNL-28542-1 lists information on the cables.

The initial analysis summarized the EPRI data table by the inservice age categories (0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 years) and the cable types with respect to how many of the test results by cable were within the Green, Yellow, and Red categories or were reported to have failed (denoted as the Black category). As age-related issues are of primary interest, Yellow, Red, or Black (failure) occurrences associated with terminations, splices, rodents, or other nonage-related issues were removed from the samples. The remaining data are referred to as “filtered” data. Table 4-1, “Filtered Data Table Summarization at the Cable Level,” and Table 4-2, “Filtered Data Table Summarization at the Phase Level,” in Appendix A, “Unfiltered Binned Population Summary,” to PNNL-28542-1 includes the full (unfiltered) dataset without removal of these nonage-related issues. The bulk of the data (83 percent) fell within the age categories of 20–30 and 30–40 years in service. No data were available for the category of 50–60 years.

Tables 4-1 and 4-2 of PNNL-28542-1 are based on treating each set of cable measurements independently. Figures 4-1, and 4-2, of that report represent number of occurrences where Tan Delta tests are binned by service decades and by test disposition more graphically.

Appendix B, “Temporal Data Plots,” and Appendix C, “Reduced Temporal Data Plots,” to PNNL-28542-1 plot a summary Tan Delta measurement (by cable and by phase) versus service years for each cable type and for all cables. This is simplified and summarized by binning the test disposition by decades in the bar graphs in Figures 4-1 and 4-2 of that report. There are very few Yellow, Red, or Black (failure) occurrences within the first and second decades. Thereafter, Red and Black occurrences increase but not necessarily in proportion to service years. The correlation tables (Tables 4-3 and 4-4 of the PNNL report) address this more quantitatively.

The Kendall’s Tau (Kendall Rank Correlation Coefficient) between the Tan Delta statistics and service years was calculated because Kendall’s Tau is nonparametric and less sensitive to outliers than Spearman’s Rho, and there was no need to transform the Tan Delta statistics (as there would have been if the Pearson’s correlation were used) (Ref. 8). Kendall’s Tau is based on the relative ranks of the data rather than the actual values. In PNNL-28542-1, Table 4-3, gives the correlations by cable type, and Table 4-4, gives the correlations by cable type at the phase level. These tables use asterisks to mark correlations that are significantly different from zero (based on a statistical hypothesis test). Correlation entries without asterisks are not significantly different from zero (no correlation).

The Kendall Rank correlations with service years overall are weak. If information on stresses other than temporal were available, a stronger correlation to stress, or a stress plus time, may be expected. The large negative correlations for butyl rubber cables are likely due to the small sample size and extremely short range (just 2 years) of service year data available (see

Figure B-2, “Max Tan Delta and Tan Delta Standard Deviation for Butyl Rubber Cables,” and Figure B-12, “Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Butyl Rubber Cables for Each Phase,” in Appendix B to PNNL-28542-1).

As discussed in Section 3.3, “Overview of EPRI Report 3002005321; Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis—Update,” of PNNL-285421, the false positive and false negative rates for assigning cables to the “action required” and “further study” conditions are observed to be quite small. The false positive rate (the proportion of cables not having any defects being assigned the “action required” condition) is less than 8.4 percent with 95-percent confidence. The false negative rate (the proportion of failed or degraded cables being assigned the “good” condition) is less than 2.3 percent with 95-percent confidence. These low rates, according to PNNL, affirm the reliability of the Tan Delta assessment criteria of Section 3.1 “Overview of EPRI Report 3002000557; Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1,” of PNNL-28542-1.

The criteria in the EPRI reports (Refs. 2 and 3) involve both cutoff values (for the cable color) and prescribed intervals for testing given the cable Tan Delta results. The prescribed intervals for testing may be assessed with respect to cable failures. No failures were observed within the 6-year testing interval for cables in the “good” condition or within the 2-year testing interval for cables in the “further study” condition. Table 4-5, “95% Confidence Intervals of Color Failure Probability on Full Data at the Cable Level,” of PNNL-28542-1 gives the by-cable-type and overall 95-percent confidence intervals for the failure probabilities. Some of the sample sizes in the table were too small to produce informative confidence intervals for some individual cable types (e.g., XLPE). The overall results are that the probability of transitioning from Yellow to Black (failure) within 2 years is less than 6.17 percent, and the probability of transitioning from Green to Black (failure) within 6 years is less than 1.79 percent, both with 95-percent confidence.

To further test whether the EPRI criteria are appropriate, PNNL reviewed the distribution of color categories based on the cutoff values alone, but the PNNL study also needed to examine consecutive measurements on the same cable to judge whether the intervals for testing were appropriate. The dataset was reduced to only measurements that were (1) made on the same cable multiple times and (2) where initial problems were removed. With respect to the latter, if a problem was identified in initial testing and fixed within a few days, and the cable was retested, only the retest was retained, not the initial testing where the problem (such as a splice issue or a termination issue) was identified. Failures of cables in the Red category were counted as occurring for the phase with the worst color before failure.

Appendix C, “Reduced Temporal Data,” to PNNL-28542-1 includes a reduced temporal data plot showing a summary Tan Delta cable (or phase) measurement plotted versus service years. Reduced data are those that were further narrowed by removing suspected (but not confirmed) cases of other issues, such as setup problems, condensation, or splice or termination issues. Then, for each cable that was measured multiple times, the worst transition (in 6 years if the initial color was Green, 2 years otherwise) was counted. Each cable was counted exactly once. No cables in the Green or Yellow categories failed (i.e., transitioned to Black (failure)). Tables 4-6 through 4-11 in PNNL-28542-1 are EPRI data tables summarizing counts of color transition (starting with Green) on fully reduced data at the cable level and phase level.

Appendix D, “Reduced Data Color Transition Analysis,” to PNNL-28542-1 presents the results when suspected cases are not removed. Based on these counts, PNNL constructed 95-percent

Clopper-Pearson “Exact” confidence intervals on the probability of transitioning from one color to another, where if the confidence interval was two sided, the shortest confidence interval is presented at cable levels (Tables 4-12 through 4-14).

Appendix E, “90%, 95%, and 99% Confidence Intervals for Transition Probabilities on the Reduced and Fully Reduced Data,“ to PNNL-28542-1 presents the additional confidence intervals (90, 95, and 99 percent), along with conclusions. With such small sample sizes at the cable level, the confidence intervals are wide and do not particularly pinpoint the probabilities. It is interesting to note that the probability of transitioning from Green to Red within 6 years across all cable types of interest is significantly different from 0 percent—at least 1.6 percent (13.5 percent for butyl rubber and black EPR). This may indicate that a 6-year testing interval for Green cables might be too long.

More data are available at the phase level (Tables 4-15 through 4-17 of PNNL-28542-1), so the confidence intervals are generally thinner than those at the cable level. However, because in many cases only one phase was worse than the other two, the probability of transitioning from a color to a worse color generally went down (as compared to the cable-level data). For example, at the phase level, the probability of transitioning from Green to Red within 6 years for butyl rubber and black EPR is at least 0.9 percent, while it was at least 1.6 percent for the cable-level data. Therefore, PNNL report noted that this may indicate that a 6-year testing interval for Green cables might be too long.

4 DISCUSSION OF RESULTS

This analysis sought to address the following specific questions:

- Are the EPRI-recommended testing intervals and thresholds for cables that test Green (good) and Yellow (further study) able to manage the aging of cables in submerged environments?
- Based on the data, are the EPRI thresholds and interval guidelines statistically supported?
- Are the data provided to EPRI by licensees aligned with the test guidelines?
- After binning the data in ranges from 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 years, is there a correlation between failure rates and test data?

The analysis documented in PNNL-28542-1 (Ref. 5) reviewed the two primary EPRI reports (Refs. 2 and 3), as well as two precedent EPRI reports (Refs. 5 and 6) that were cited in the primary reports.

PNNL-28542-1 states the following results:

- Relatively few cable insulation degradation failures occurred during the first 10 years of cable service. However, there is no strong correlation between cable age and failure rate thereafter. The correlations between Tan Delta test data and service year are at most 0.1 (low on the scale from −1 to +1, which is perfect negative to perfect positive correlation), when considered at the cable level and at the phase level.
- The threshold guidance set in EPRI TR-3002005321 has resulted in very few false positive and false negative calls. False positives are cables erroneously indicating a fault where forensic examination revealed no problematic degradation. Forensic investigations of cables identified as “action required” have always identified cable segments with problems. The false positive rate is estimated to be less than 8.4 percent with 95-percent confidence. False negatives are cables testing “good” that were in a failed or degraded state. The false negative rate for cables testing “good” is less than 2.3 percent with 95-percent confidence. This implies that the guideline thresholds are appropriate.
- The test intervals recommended in the two primary EPRI reports (Refs. 2 and 3) may be evaluated by considering the rates at which cables testing as Green (good) or Yellow (further study) subsequently fail within the suggested 6-year or 2-year reinspection intervals, respectively. The observed rate that cables testing “good” fail within 6 years is less than 1.79 percent with 95-percent confidence. The rate that cables testing “further study” fail within 2 years is less than 6.17 percent with 95-percent confidence. This implies that the overall testing interval guidelines are appropriate. The confidence intervals for the same analysis by specific insulation category are larger because there are fewer data points for each individual insulation category in the available data (Table 4-5 in PNNL-28542-1).

- Cable insulation degradation in the context of test interval guidance may be further understood by examining a dataset consisting of multiple tests of the same cable. Across all cable types at the cable level, the probability of transitioning from “good” to “action required” within a 6-year reinspection interval is estimated as 3/22 = 13.6 percent. Because of the uncertainty associated with the small sample size, the 95-percent confidence interval on that transition probability is 1.6 percent, 32.2 percent. Across all cable types at the cable level, the probability of transitioning from “further study” to “action required” within a 2-year reinspection interval is estimated as 2/6 = 33.3 percent with a very wide 95-percent confidence interval (2.1 percent, 73.9 percent). The small sample size prohibits any strong statement about the “further study” 2-year reinspection interval.

Based on the conclusions above and given the zero incidence of age-related transitions from Green to Black (failure) within 6 years or from Yellow to Black (failure) within 2 years and the low incidence of false positives and false negatives, PNNL concluded that EPRI guideline thresholds and intervals seem to be suitable. PNNL also noted that continuing to collect Tan Delta and related cable failure data, particularly on cable insulation types for which limited data are currently available, would allow statistical confidence intervals to be narrowed and thereby improve the confidence and reduce the uncertainty of the EPRI guidance assessment.

5 REGULATORY IMPLICATIONS

NRC's design criteria require that electrical cables be capable of performing their intended function when subjected to anticipated environmental conditions. For example:

Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criterion (GDC) 4, "Environmental and dynamic effects design bases," states that "Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation…."

10 CFR Part 50, Appendix A, GDC 17, "Electric power systems," states that "Provisions shall be included to minimize the probability of losing electric power from any of the remaining [power] supplies as a result of, or coincident with...the loss of power from the transmission network, or the loss of power from the onsite electric power supplies."

10 CFR Part 50, Appendix A, GDC 18, "Inspection and testing of electric power systems," states that "Electric power systems important to safety shall be designed to permit appropriate periodic inspection and testing of important areas and features, such as wiring [and] insulation…, to assess the continuity of the systems and the condition of their components. The systems shall be designed with a capability to test periodically…(2) the operability of the systems as a whole and…the transfer of power among the nuclear power unit, the offsite power system, and the onsite power system."

10 CFR 50.65(a)(1) states that "[e]ach holder of an operating license for a nuclear power plant...shall monitor the performance or condition of structures, systems, or components...in a manner sufficient to provide reasonable assurance that these structures, systems, and components...are capable of fulfilling their intended functions."

10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," Criterion XI, "Test Control," states that "[a] test program shall be established to assure that all testing required to demonstrate that structures, systems, and components will perform satisfactorily in service is identified and performed…."

10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," discusses requirements for license renewal. 10 CFR 54.33, "Continuation of CLB and conditions of renewed license," states the following:

> …systems, structures, and components subject to review in accordance with § 54.21 will continue to perform their intended functions for the period of extended operation. In addition, the renewed license will be issued in such form and contain such conditions and limitations as the Commission deems appropriate and necessary to help ensure that systems, structures, and components associated with any time-limited aging analyses will continue to perform their intended functions for the period of extended operation.

A variety of environmental stressors in nuclear power plants influence the aging of electrical cables; such stressors include temperature, radiation, moisture/humidity, vibration, chemical spray, and mechanical stress. Exposure to these stressors over time can lead to degradation that may go undetected unless the aging mechanisms are identified and electrical, mechanical, or physical properties of the cable are monitored. Since some electrical cables never receive inspection, maintenance, condition monitoring tests, or periodic replacement, degraded conditions in electrical cables can go undetected over time, which could lead to failure and prevent various components from performing their safety function. Cable failures have resulted in-plant transients and shutdowns, loss of safety redundancy, entries into limiting conditions for operation, and challenges for plant operators.

In its review of responses to GL 2007-01, the NRC staff confirmed that aging analyses and condition monitoring evaluations often overlook or ignore electrical cables, since the cables are passive components that are considered to require no inspection and maintenance. However, electrical cables are important-to-safety components if they provide power to safety-related equipment. Responses to GL 2007-01 showed that a number of failures occurred under normal service conditions within the service interval of 20–30 years, which is before the renewed license period and before the end of the expected life span of the cables. The staff's evaluation of the licensee responses to GL 2007-01 concluded that licensees should have a program for using available diagnostic cable testing methods to assess cable condition. The staff finds that condition monitoring is essential for assessing the health and aging degradation of electrical cables to ensure reliable operation of safety-related equipment, instruments, and controls during normal operations and design-basis events.

The staff notes that electrical cables can fail for several reasons. The most common causes of electrical cable failures are external interference or damage, overheating, water treeing, high-voltage stress, moisture ingress, poor installation, manufacturing defects, and aging. These electrical cable failures can result in safety-related, important-to-safety, and nonsafety-related equipment failures.

In response to GL 2007-01, NRC staff issued a summary report (Ref. 9) on November 12, 2008, which provided the following recommendations and conclusions:

- Based on the review of licensees' responses, the NRC staff has identified 269 cable failures for 104 reactor units. Licensees for plants undergoing license renewal have agreed to a cable testing program for the extended period of plant operation for a limited number of cables that are within the scope of licensee renewal, but only a few plants have established a cable testing program for the current operating period. The data obtained from the GL responses show an increasing trend of cable failures. These cables are failing within the plants' 40-year licensing periods. As shown by the January 2008 event at Point Beach Nuclear Plant, cable failures have resulted in plant transients and shutdowns, loss of safety redundancy, entries into limiting conditions for operation, and challenges to plant operators.

- Licensees have identified failed cables and declining insulation resistance properties through current testing practices; however, licensees have also reported that some failures may have occurred before the failed condition was discovered. Although the majority of inservice and testing failures have occurred on cables that are normally energized, the staff is concerned that additional cable failures have not been identified for cables that are not normally energized or tested. The NRC staff recommends that the licensees should also include normally deenergized cables in a cable testing program. It appears that no manufacturer or insulation type is immune from failure. In addition, licensees have identified failures and declining performance capability in both shielded and unshielded cables.

- The NRC staff has noted that the predominant factor contributing to cable failures at nuclear power plants appears to be the presence of water/moisture or exposure to submerged conditions. If cables have been exposed to conditions for which they are not designed or qualified, licensees should demonstrate, through adequate testing, reasonable assurance that the cables can perform their intended design function and are operable. Licensees should also make reasonable provisions to keep cables dry.

- The regulations in 10 CFR Part 50 require licensees to assess the condition of their components; to monitor the performance or condition of structures, systems, and components in a manner sufficient to provide reasonable assurance that they are capable of fulfilling their intended functions; and to establish a test program to ensure that all testing required to demonstrate that components will perform satisfactorily in service is identified and performed. The Office of Nuclear Reactor Regulation (NRR) staff believes that licensees should have a program for using available diagnostic cable testing methods to assess cable condition.

- Based on the review of the licensees' responses, the staff plans to take the following actions:

  – By December 2009, issue a regulatory guide that identifies the essential elements of an electrical cable monitoring program.

  – Issue revisions to applicable Reactor Oversight Process inspection procedures to ensure that the cable qualifications are maintained consistent with regulatory requirements.

  – Continue to take regulatory actions for licensees that have not demonstrated cable qualification for the current license period.

Following the issuance of GL 2007-01, NRR requested assistance from the Office of Nuclear Regulatory Research (RES) in User Need Request 2008-08 (Ref. 10) to identify the essential elements of a condition monitoring program for electrical cables. As a result, RES published NUREG/CR-7000 (Ref. 11) in January 2010. NUREG/CR-7000 provided recommendations for a comprehensive cable condition monitoring program, including periodic cable condition monitoring inspections and tests, cable operating environment monitoring and management activities, and the incorporation of cable-related operating experience. NUREG/CR-7000 also discussed commonly used condition monitoring techniques but did not specify which techniques would be applicable to particular materials. In addition, RES developed regulatory guide RG 1.218 (Ref. 12) in June 2012, outlining the essential elements of a cable condition monitoring program.

PNNL-28542-1 (Ref. 5) focused on cable degradation primarily as detected by Tan Delta testing. The objective was to statistically assess EPRI data collected from multiple nuclear power plant members and apply EPRI Tan Delta testing criteria (Refs. 2 and 3) to determine whether the Tan Delta testing approach is suitable for monitoring cable conditions in wet areas. EPRI collected data from 2009 to 2012, analyzed these data, and provided feedback to nuclear power plant members. EPRI used these data to validate EPRI-developed acceptance criteria, support the analysis of test results, recommend appropriate actions for the "action required" category, and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation.

Based on the results of the statistical analysis of Tan Delta test data from nuclear power plants detailed in PNNL-28542-1, NRC staff note the following:

- Relatively few cable insulation degradation failures occurred during the first 10 years of cable service. However, there is no strong correlation between cable age and failure rate thereafter.
- The threshold guidance set in EPRI TR-3002005321 resulted in very few false positives and false negatives This indicated that the guideline thresholds proposed by EPRI are appropriate. However, additional data and analysis are needed to validate the guidelines with a high degree of confidence.
- The test intervals recommended by EPRI (Refs. 2 and 3) are appropriate, although the confidence intervals for the same analysis by specific insulation category are larger because fewer data points are available for each individual insulation category (Table 4-5 of PNNL-28542-1).
- The small sample size prohibits a definitive conclusion regarding a 2-year reinspection interval for the Yellow “further study” category.

Based on an analysis of the available data, new NRC guidance or endorsement of the proposed EPRI guidelines is not recommended at this time. This is due to the limited data/test results for some categories of cable types and material, as well as reported cases of multiple test results for the same cables. These data do not support consistent and reliable interpretation of trend results.

6 REFERENCES

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