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Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis – Update

2015 TECHNICAL REPORT

Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis – Update

3002005321

Final Report, September 2015

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ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report.

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis – Update. EPRI, Palo Alto, CA: 2015. 3002005321.

ABSTRACT

This report is an update to the Electric Power Research Institute (EPRI) report 1025262, *Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis, 2012*. This report includes the findings and results from evaluating nearly 580 tan δ test collected from nuclear power plant testing of medium-voltage, shielded power cables.

Tan delta (δ) testing at 0.1 hertz combined with 0.1 hertz withstand testing has been adopted by most U.S. nuclear power plant operators as the primary tool for condition monitoring of medium-voltage, shielded power cables. EPRI has been collecting member data since late 2009 to analyze and provide feedback to members, validate the EPRI-developed acceptance criteria, support analysis of test results, recommend appropriate actions for “action required,” and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation.

This report will be useful for maintenance and engineering personnel involved with testing, analyzing, and managing cable aging management programs. The objective of this research is to provide those persons involved with tan δ testing, analyzing tan δ data, and making recommendations based on those results with a broader range of knowledge based on industry-wide data rather than the limited knowledge that their site-specific test results provide.

Data have been received from 37 nuclear sites and represent data from 44 units. The test results have been organized by types of insulation, which are butyl rubber; black, pink, and brown ethylene propylene rubber cable insulations; and mixed insulation circuits (hybrid circuits). The data have been analyzed, and follow-up information was obtained from members for “action required” test results. This information was used to determine what actions were taken and what forensic information was obtained. This report summarizes the data and is organized by insulation type and severity level (based on criteria found in EPRI report 3002000557); a breakdown of issues identified in the “action required” range is provided. Correlations between tan δ results for insulation degradation with the information gathered under EPRI forensic research of medium-voltage cables are also presented. In addition, insights into how to systematically analyze tan δ test results are offered.

Keywords
Cable
Dissipation factor
Ethylene propylene rubber (EPR)
Medium-voltage cable
Tan delta

EXECUTIVE SUMMARY

Medium-voltage cables operating in wet environments have been an ongoing concern in the nuclear power industry. In-service failures have resulted in extended forced outages and, in some cases, millions of dollars in repair and lost generating costs. The majority of these cables are 25–40+ years old and have never been adequately evaluated (historical testing of cables has been with dc insulation resistance or dc withstand tests). These two facts are the incentive to have a condition monitoring tool that can identify at-risk cables so that actions can be taken to repair or replace degraded cables in order to maintain cable circuit reliability.

Tan delta (δ), also called *dissipation factor*, testing was chosen by the Electric Power Research Institute (EPRI) for monitoring the condition of medium-voltage, shielded power cables. As of June 2015, EPRI had collected data from 18 of 24 U.S. nuclear plant operators; this accounts for 37 U.S. nuclear power plant sites covering 44 operating units. Test results provided to EPRI since late 2009 consist of 579 tests that have been evaluated using the EPRI-developed condition action levels for classifying cable health.

The following items summarize the important results found in this report:

- Thirty-four test results were in the “action required” range, and the problem was determined to be a splice, termination, or cable insulation issue. Approximately half of these cable circuits was identified as insulation degradation, and the other half was split evenly between degraded splice and degraded termination issues. Black EPR has the most insulation issues. Pink and brown EPR insulation had mostly splice and termination issues. The lack of degraded insulation issues identified for the pink and brown EPR insulation indicates that they are less susceptible to long-term wet insulation degradation.
- In-service failures were limited for cables tested using tan δ condition monitoring. Two specific design types (compact design or cross-linked polyethylene) have had in-service failures. One of the in-service failures was on a non-critical, “action required” EPR insulated cable that failed prior to a scheduled replacement. Black EPR, which is the oldest EPR insulation, had the most insulation issues, but no in-service failures had occurred on this insulation type for those evaluated using tan δ testing.
- Roughly 580 cable tests were evaluated, and there were two false negatives (failure of cables that tested good or slightly degraded). The two false negatives were both at one site on the same equipment feed; the failed cable had cross-linked polyethylene insulation, which is susceptible to degradation in wet service conditions. This insulation type is rarely used in the power industry.
- No false positives (at least one degraded insulation defect) were found in any of the forensically evaluated circuits in the immediate “action required” category.

- Tan δ identified dry cable issues of thermal degradation, splice defects, and insulation degradation, confirming that tan δ can identify more than water-related degradation.
- Tan δ is a global or bulk evaluation of cable insulation. The circuit characteristics (multiple conductors, long circuit length, and so on) could mask a single, large defect. Performing a monitored withstand test (combined tan δ and withstand test) at IEEE-recommended levels will preclude this from affecting circuit reliability.
- All the cables identified (by tan δ testing) with degraded insulation that were provided to EPRI for independent forensic evaluation had at least one degraded insulation site identified.
- The forensic results also indicate that insulation degradation is localized, not distributed. This indicates that EPR insulations do not age uniformly (non-homogeneous aging). The remaining insulation tests in the "good" range by tan δ testing. This means that only the bad section of insulation needs to be removed if it can be easily isolated (this is not always the case) and if the remaining cable insulation can continue to be condition monitored.
- Finally, a correlation has been made—by using a short section of cable in the lab—between high tan δ test values and low alternating current breakdown strength; this further confirms tan δ testing's use for cable condition monitoring.

These research results support tan δ testing using 0.1 hertz combined with 0.1 hertz withstand testing (monitored tan δ withstand test) as an effective way to manage the reliability of aged, medium-voltage, shielded power cable circuits in wet or dry locations.

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BACKGROUND

The research results that are provided in this report are part of an ongoing evaluation of Electric Power Research Institute– (EPRI-) member-supplied 0.1-hertz tan delta (δ) test results, also known as *dissipation factor testing*. EPRI has been collecting, evaluating, and analyzing tan δ test results since late 2009. An initial evaluation of the data was performed in 2012 in report 1025262 [1]. At that time, data had been received from 11 out of 24 U.S. nuclear utilities, covering 25 sites and 28 units. As of June 2015, data that have been received increased to 18 of the 24 U.S. nuclear utilities, covering 37 sites and 44 units. The number of tan δ test reports has increased from 240 to 570 over the last three years, and the total number of cables tested has increased from 700 to approximately 1800 cables.

The information provided in this report can be used to transfer the knowledge gained from this data analysis and evaluation combined with insights gained from EPRI-sponsored forensic evaluations [2, 3, 4, 5, 6, 7, 8, 9] of cables identified as "action required" by this test protocol. These cables were replaced and provided to EPRI for forensic analysis. The information here can be used by maintenance personnel, system engineers, and cable program owners to evaluate their tan δ test data and inform their decisions regarding a course of actions based on that data evaluation.

The first test report [1] used the data collected before June 2012 to validate the EPRI acceptance criteria for evaluating test results and described a few case studies and lessons learned at that time. That report evaluated the member-collected data results, and they were used to affirm the EPRI acceptance criteria levels in Section 5 of EPRI report 3002000557 [10]. Those criteria were initially developed by an expert panel of EPRI staff, several members, test service providers, and researchers. That methodology is documented in Appendix C of EPRI report 1021070 [11].

The test data collected are organized to identify the utility, site, unit number, equipment identification, test date, cable manufacturer, cable insulation type, cable length (if available), cable voltage rating, cable operating voltage, maximum test voltage, and the average values of tan δ, delta tan δ, and percent standard deviation for each of the four voltage test steps for each phase. The database also contains whether a withstand test was performed and the test duration. A "test discussion" field was added to note specific points of interest for a test, a yes/no "problem identified" field, and a "problem description" field to note the type of problem—a splice, a termination, or an insulation issue.

The research results from the data evaluated in this report include the original data and all additional data received and evaluated prior to June 2015. This report summarizes the data results received to date, provides a methodology for evaluation of test results, and provides an evaluation of the effectiveness of 0.1-hertz tan δ testing.

2
TEST METHODOLOGY AND ACCEPTANCE CRITERIA

A cable in good condition acts as a capacitor. The charging current of the capacitor (I_C) is 90° out of phase with the applied voltage. Degraded insulation has a resistive current component (I_R) that is in phase with the applied voltage. Tan δ is the angle created by the vector equivalent current (I_C+ I_R) and the y-axis depicted in Figure 2-1. An increasing I_R is an indication of cable insulation degradation, which is manifested by an increased magnitude of tan δ. Delta tan δ is used as an indicator of the presence of an ionization potential. The stability of tan δ during each applied voltage step is equivalent to percent standard deviation, which is used to evaluate the degree of degradation of the ionization potential.

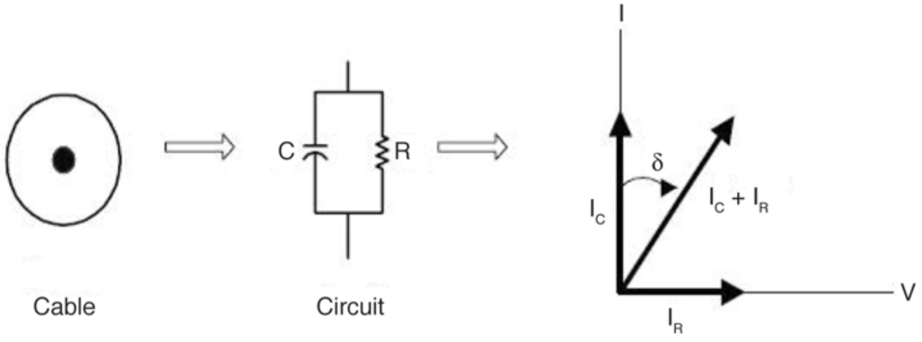


Figure 2-1
Tan δ depiction of loss angle

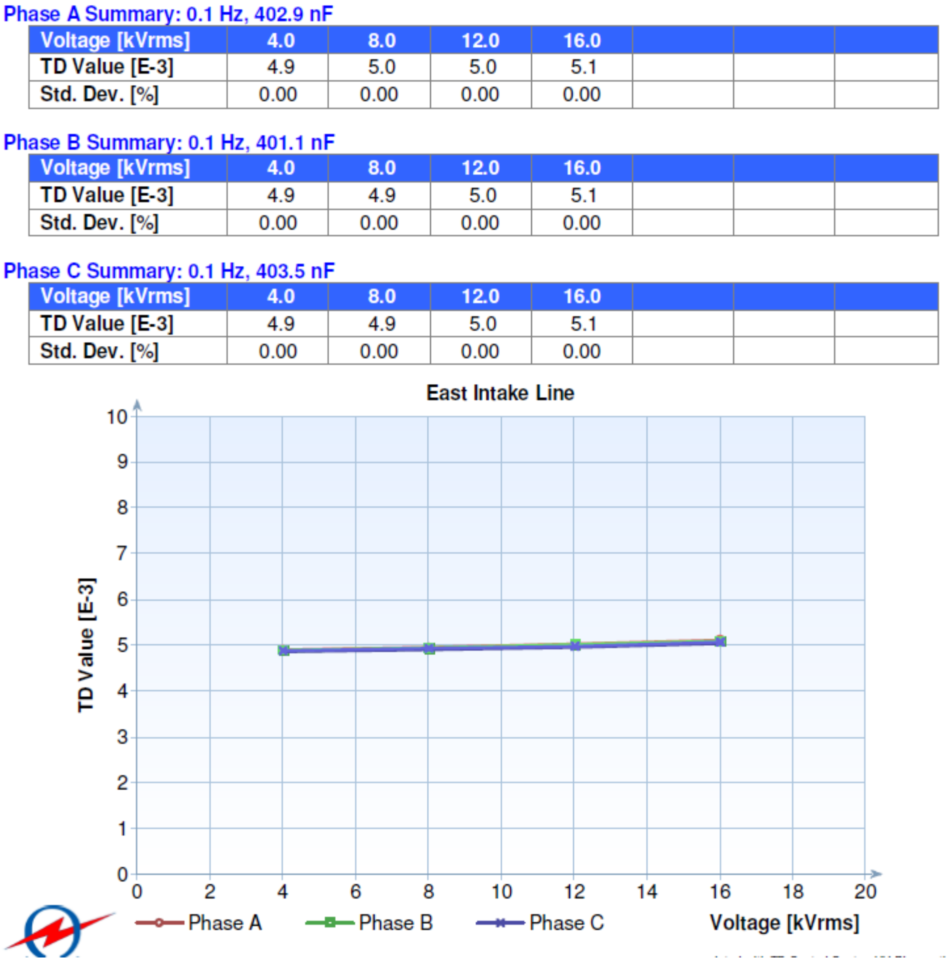
The tan δ test method applies a test voltages in three or four increasing voltage steps. *Test voltages* are defined as a fraction of cable line-to-ground operating voltage (U_0). The steps are done in 3–4 minute increments at voltages of 0.5 U_0, 1.0 U_0, and 1.5 U_0. Historically, the fourth step was 2.0 U_0, but recently it has often been replaced with the IEEE 400.2 [12] recommended withstand voltage and duration.

This withstand test combined with the tan δ is known as a *monitored tan δ withstand test*, or just *monitored withstand test*. The final test voltage is held for 15–60 minutes with 30 minutes the most commonly used time. The monitored withstand test combines the diagnostic capability of tan δ and the withstand test's purpose, which is to prevent the masking of a single large insulation defect that may be caused by the circuit configuration, that is, a bad splice, termination, or the longer length of the cable. (The same defect on a short cable will be smaller in magnitude on a long cable.) A monitored withstand test is considered to be the best test practice because it takes advantage of the programmability of most test sets (which are limited to four steps) and combines the bulk insulation condition evaluation of tan δ with the withstand test's ability to prevent in-service failure caused by a large single defect.

Data evaluation is performed using the acceptance criteria for the insulation type under the test provided in EPRI report 3002000557 [10]. Evaluation criteria are provided for the mean tan δ magnitude at U_0, percent standard deviation at each step except during a withstand test (stability of readings during the step), and delta tan δ (the difference between the 0.5 U_0 and 1.5 U_0 step mean values). Percent standard deviation and tan δ are monitored during the withstand test portion to see how it changes over time, but not against the EPRI evaluation criteria.

An example of good test results is shown in Figure 2-2. They are considered good for the following reasons:

- Mean tan δ value at U_0 is low.
- Percent standard deviation is zero at each step.
- Delta tan δ is nearly zero.



Phase A Summary: 0.1 Hz, 402.9 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	4.9	5.0	5.0	5.1			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase B Summary: 0.1 Hz, 401.1 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	4.9	4.9	5.0	5.1			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase C Summary: 0.1 Hz, 403.5 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	4.9	4.9	5.0	5.1			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Figure 2-2
Good tan δ results showing low magnitude, zero percent standard deviation, and delta tan δ is nearly zero (minimal slope to the line)

3
DATA OVERVIEW

The population being tested, with two exceptions, is shielded, medium-voltage cables (those rated between 5–43 kV). Shielded cables are best suited for tan δ testing because the shield provides a uniform ground plane to apply the test voltage evenly between the metallic shield and the conductor to the cable insulation. This allows for uniform stress and consistency of test results. Non-shielded cables are generally excluded from this test because there is no metallic shield to evenly distribute the stress of the applied test voltage along the cable length. This design difference increases the chances of overstressing the insulation under test. However, there are two non-shielded cables that were tested to see if repeatable, useful data could be obtained. These cables were non-shielded, three-conductor, armored cable, results of which were similar and repeatable over one operating cycle.

The breakdown of the cables that test data have provided is displayed in Figure 3-1.

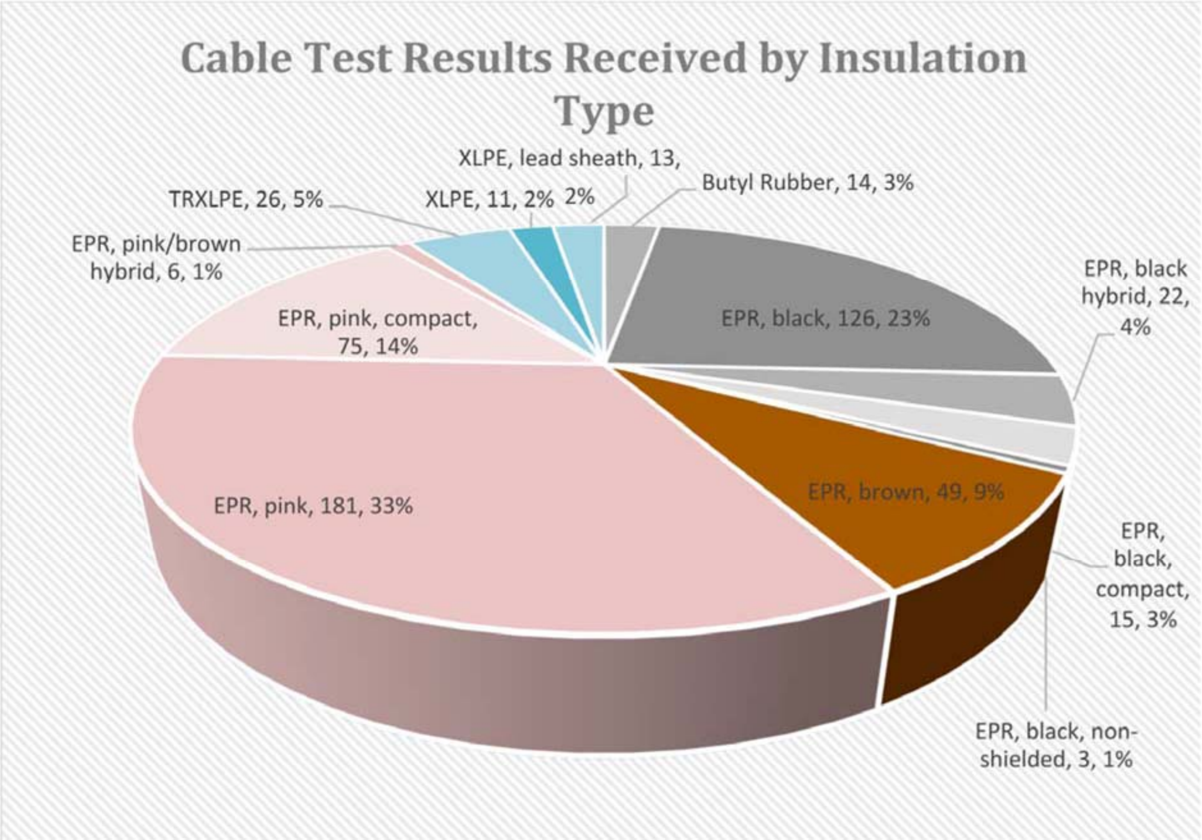


Figure 3-1
Tan δ test data shown by the number of tests and the percentage of the total for each insulation type

Figure 3-1 depicts, by cable insulation type, the population of cables tested. EPR cables make up 91% of the cable test results supplied by U.S. nuclear power plants, and XLPE[1] accounts for 9%. XLPE cables are a relatively small percentage of the installed cables in the power generation industry, and insufficient data exist for the XLPE cables to be able to draw any real conclusions; consequently, those results will not be discussed in any detail in this report.

The distribution of cable insulations for EPR based on the available test data can be seen in Table 3-1. The percentage of cables tested by type provides a reasonable approximation of the population distribution of cables that are installed in the U.S. nuclear plants. Pink EPR at 34% and black EPR/butyl rubber cable insulation at 26% are the predominant cable insulation types. Lesser used cables such as the compact design pink and black EPR make up 17%, brown EPR insulation is at 9%, and the hybrid[2] EPR circuits account for only 4% of installed cables.

Table 3-1
Percentage of EPR cables tested by insulation type

Insulation Type	Percentage of Test Data Received
Black EPR and butyl rubber	26%
Pink EPR	34%
Compact design (black and pink)	17%
Brown EPR	9%
Hybrid black and pink EPR	4%

3.1 Tan δ Test Results Summary of Issue Identified

Test data are evaluated against the criteria supplied in EPRI report 3002000557 [10]. It is recommended for cables in the “action required” range of data for any of the three test acceptance criteria to be repaired or replaced. The cables that have been reported to be repaired or replaced and the part of the cable system (insulation, termination, or splice) that was found to be degraded are summarized in Table 3-2. Some members have chosen to assess the risk of failure, and some have performed a 30-minute withstand test and then returned the cable to service for some period of time so that they could plan to replace the cable. This assumes the risk of an in-service failure, but it has resulted in only one in-service failure to date, which will be discussed later in this report.

Black EPR and pink EPR have the most issues. This is partly due to the fact that they make up the greatest percentage of cables by type. However, for black EPR the numbers exceed pink EPR, which has the most data points by a significant margin (55 more tests, which equates to at least 165 more cables tested). This issue is discussed later in this section where forensic results have shown that design differences in black EPR make it more susceptible to insulation degradation in wet environments.

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[1] XLPE here represents the combined test results received for all cross-linked polyethylene cables tested including TR-XLPE, XLPE, and lead sheath XLPE

[2] Hybrid refers to cables that have a combination of shielded and non-shielded cable designs with the same insulation type, or cables with a combination of insulation types, such as EPR and XLPE, but with a shielded design.

Table 3-2
Tan δ test-identified cable issues summary table by insulation type

Insulation Type	Circuits Tested (Percent of Total Circuits)	Number of Circuit Issues	Deteriorated Component Identified		
			Termination	Splice	Insulation
Butyl rubber	14 (3%)	0	0	0	0
EPR, black	126 (23%)	13 (38%)	2	4*	7**
EPR black, hybrid	22 (4%)	1			
EPR, black, compact	15(3%)	1 (3%)	0	0	1
EPR, black, non-shielded	3(<1%)	0	0	0	0
EPR, brown	50 (9%)	2 (4%)	1	1	0
EPR, pink	181 (34%)	12 (35%)	5	3	4
EPR, pink, compact	74 (14%)	5 (17%)	1	1	3
EPR, pink/brown hybrid	6(1%)	0	0	0	0
TRXLPE	26(5%)	0	0	0	0
XLPE	11(2%)	0	0	0	0
XLPE, lead sheath	13(2%)	0	0	0	0
Totals	**541*** **	**34 (6.3%)**	**9 (26.5%)**	**9 (26.5%)**	**15 (47%)**

* One circuit had deteriorated insulation and a deteriorated splice.
** Three cables were replaced due to historical issues, not high tan δ results.
*** The 541 circuits comprise approximately 1800 individual cables.

Note: One in-service failure occurred for a black compact cable that was tested and met the “action required” acceptance criteria, but was returned to service. Plans were in place to replace the cable, but the cable failed in service before it could be replaced.

Compact pink and black EPR insulation account for four insulation issues identified, but only one of them was confirmed to be water treeing. The other three issues were caused by partial-discharge-related degradation associated with a design weakness, which will be discussed in Section 6.

The sections that follow discuss the results evaluation for black and butyl rubber, pink, compact design, brown, and hybrid insulation listed in Table 3-2 above to provide details on the results and key lessons learned from the evaluation of those cables. A correlation with the EPRI medium-voltage cable forensic research is made where applicable.

4

BLACK EPR AND BUTYL RUBBER TAN DELTA TEST RESULTS DISCUSSION

Butyl rubber and black EPR insulations shown in Figures 4-1 and 4-2 are the older style of rubber insulation in U.S. nuclear power plants that are still in use but were primarily used between 1969 to around 1975. They are grouped together because they have similar design features and their insulations degrade in a similar manner in wet conditions. As such, the same acceptance criteria are used to evaluate both insulation tan δ test results.

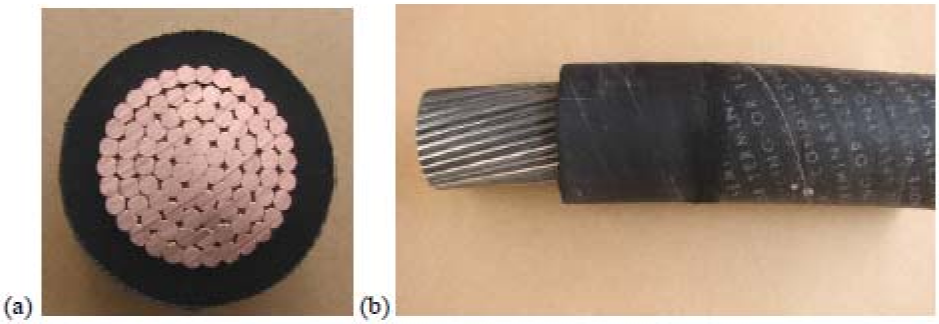

Figure 4-1
Butyl rubber cable with the metallic shield and jacket removed. The insulation shield is a semi-conducting tape in early EPR cable designs. (a) Transverse view and (b) lengthwise view

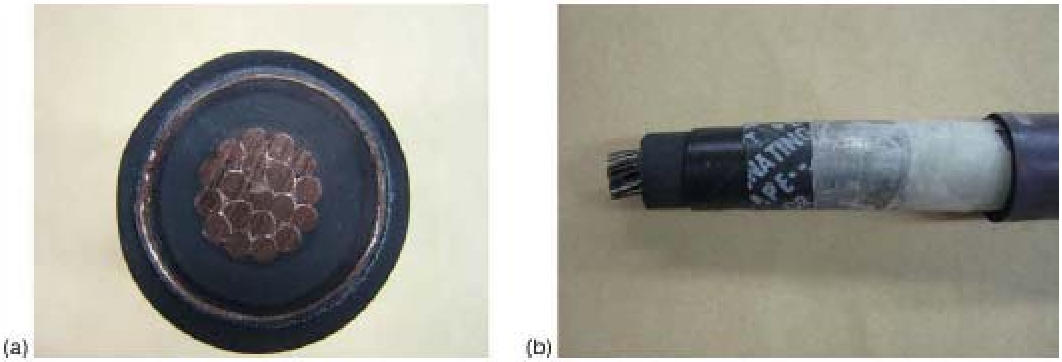

Figure 4-2
Black EPR cable design also employed a tape semi-conducting Insulation shield. (a) Transverse view and (b) lengthwise view

4.1 Tan δ Test Result Data by Test Type for Butyl Rubber and Black EPR

The breakdown of test data for tan δ at U_0, percent standard deviation results at U_0, and delta tan δ results are provided in Tables 4-1, 4-2, and 4-3.[3]

Table 4-1
Black EPR and Butyl rubber mean tan δ at U_0 results

	Green – Good (-≤ 12 E-3)	Yellow – Further Study (>12 E-3≤ 50 E-3)	Red – Action Required (>50 E-3)
Circuit classification	80	30	29
% of total tests performed	57%	22%	21%

Table 4-2
Black EPR and butyl rubber percent standard deviation results at U_0

	Green – Good (≤ 0.02)	Yellow – Further Study (>0.02 ≤ .04)	Red – Action Required (>.04)
Circuit classification	109	11	19
% of total tests performed	78%	8%	13%

Table 4-3
Black EPR and butyl rubber delta tan δ results

	Green – Good (≤ 3)	Yellow – Further Study (>3≤ 10)	Red – Action Required (>10)
Circuit classification	114	8	17
% of total tests performed	82%	6%	12%

Based on the analysis of data in the tables above, there is very good correlation between percent standard deviation and delta tan δ for black EPR. This is not the case when either of those two classifications are compared with mean tan δ at U_0. In the 10 cases where tan δ magnitude was not confirmed by either of the other two test acceptance criteria, no "action required" issues were identified in the issue results based on tan δ magnitude alone. All identified issues either correlated to all three criteria, or the issues were identified on standard deviation and delta tan δ. This supports the ranking of acceptance criteria based on standard deviation as the most important, followed by delta tan δ and then magnitude as confirmation of the other two criteria.

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[3] The test result "action required" issue totals are derived from test results received and are not necessarily equal numbers for each category. An example is that some tests may consist of three phases tied together, but counted as only one result because the individual phase values are not known. Typically, all three cables are tested individually.

4.1.1 Analysis of Butyl Rubber and Black EPR Tan δ Test Results

Several facts are associated with the data results in the tables above:

- No severely degraded test report cases for butyl rubber cables results were analyzed.
- To date, no tested cables in the "green" or "yellow" ranges have had in-service failures (no false negatives).
- One "action required" cable was returned to service and failed prior to replacement.
- Three of 13 cable replacements were due to historic issues, not as the result of "action required" test results.
- All of the 10 "action required" cables with issues identified were confirmed by more than one acceptance criterion.
- Insulation defects all have increasing tan δ magnitudes, high standard deviation, and usually high delta tan δ.
- Splice and termination "action required" issues usually have high, but decreasing, values of tan δ magnitude and high percent standard deviation, and they are more likely to have negative delta tan δ.
- For black EPR, the main focus of cables tested is in wet/submerged/high humidity environments, but there is a small population of dry cables tested that tan δ has identified degrades terminations, splices, or insulation. In one case discussed below, elevated percent standard deviation tan δ test result was found to be caused by a thermally degraded termination of a reactor coolant pump (RCP) motor cable penetration.
- Forensic evaluation did not find uniform overall degradation of the insulation (homogeneous aging), but rather the insulation defects found were in one or more discreet locations of severe degradation (heterogeneous aging).

No butyl rubber cables were higher than "further study required" acceptance criterion. This is more likely due to the relatively small population of these cables. There were only 16 test reports that were available for analysis.

It is important to note that there have been no false positive or false negative results for this insulation type. That is, no cable that tested below "action required" levels has failed in service. Likewise, no "action required" cables that have been repaired have subsequently failed in service.

4.2 Use of Withstand Testing in Conjunction with Tan δ Results

The one cable noted above in the "action required" range that failed prior to being replaced was not connected to critical plant equipment. A withstand test at the IEEE 400.2 [12] recommended level for 30 minutes was not performed prior to returning the cable to service. The withstand test may or may not have identified the defect that resulted in the in-service failure, but withstand testing is recommended to preclude in-service failures prior to repairs being performed. Due to the low risk and the time required to make repairs, the operator returned the cable to service, but the cable failed prior to the scheduled replacement. This case highlights the risk that is assumed when returning a degraded cable to service. The proper risk factors were considered (criticality, impact of failure, chance of failure, and so on) with the exception of performing a withstand test, which is designed to identify a single large defect.

Note: Combining tan δ and withstand testing ensures that no large single defect exists that may cause failure or that no defect is masked by cable length.

4.3 Black EPR "Action Required" Issues Summary, Use of Percent Standard Deviation, and Observations on Negative Delta Tan δ

The 13 black EPR issues identified in Table 3-2 include three cables that were tested prior to their scheduled replacement. Those three cable tests did not identify severely degraded insulation, but the cables were replaced anyway. This was because they were part of a systematic replacement of that cable type based on past failures at that site.

The remaining 10 incidents consisted of four cases with bad insulation, three cases with bad splices, and three cases with bad terminations—all identified as a result of follow-up investigation after exceeding "action required" tan δ testing criteria. In all but two of these 10 cases, the cables were in the "action required" levels for all three acceptance criteria. The two outliers were "further study required" for tan δ at U_0, but were "action required" for delta tan δ and percent standard deviation**.** Each criterion was able to show that the cable was degraded, but percent standard deviation and delta tan δ are the most sensitive to the degree of degradation of cable insulation based on the cases analyzed.

Note: Percent standard deviation and delta tan δ are the most important indicators of cable degradation for "action required" test results.

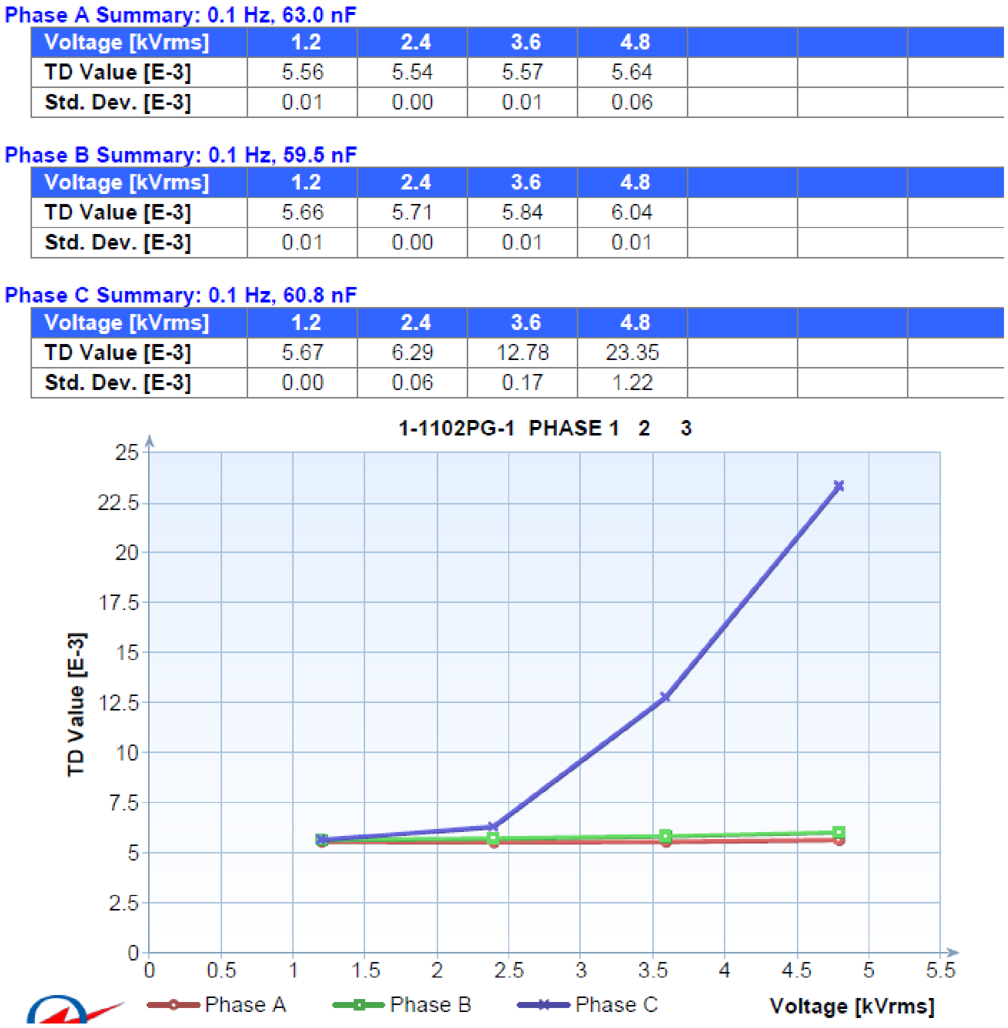
Another observation is that insulation defects in all "action required" cases for black EPR had increasing and high magnitude of tan δ with corresponding high standard deviation and delta tan δ. On the other hand, splices and terminations are more likely (not in all cases analyzed) to have high, but decreasing, tan δ magnitude, resulting in a negative delta tan δ. This provides insight as to whether a repair of a terminations or splice could be the cause of the issue.

Note: Any repair that affects insulation integrity should be tan δ tested and withstand tested when repairs are complete.

Inspection, repair, or replacement of an accessory could be all that is needed to return a cable to service. In the case of a splice; the cable should be tan δ tested in both directions prior to installing a new splice to ensure that no degraded insulation is present that might have been masked by a bad splice. Cables whose terminations are replaced should also be retested before being returned to service. Any repair or replacement of a splice or cable section should be tan δ tested and withstand tested when repairs are completed.

4.4 Tan δ Test Result Leads to Identifying Thermally Degraded Penetration

Although the majority of cables tested are due to wet aging concerns, tan δ testing can be used on dry cables for condition monitoring. The specific case noted in the list of facts mentioned earlier is a test of RCP cables from the motor breaker through a reactor building penetration to the motor. The test results are shown in Figure 4-3, where C phase has high magnitude, percent standard deviation, and delta tan δ all in the "action required" range.



Phase A Summary: 0.1 Hz, 63.0 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	5.56	5.54	5.57	5.64			
Std. Dev. [E-3]	0.01	0.00	0.01	0.06			

Phase B Summary: 0.1 Hz, 59.5 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	5.66	5.71	5.84	6.04			
Std. Dev. [E-3]	0.01	0.00	0.01	0.01			

Phase C Summary: 0.1 Hz, 60.8 nF

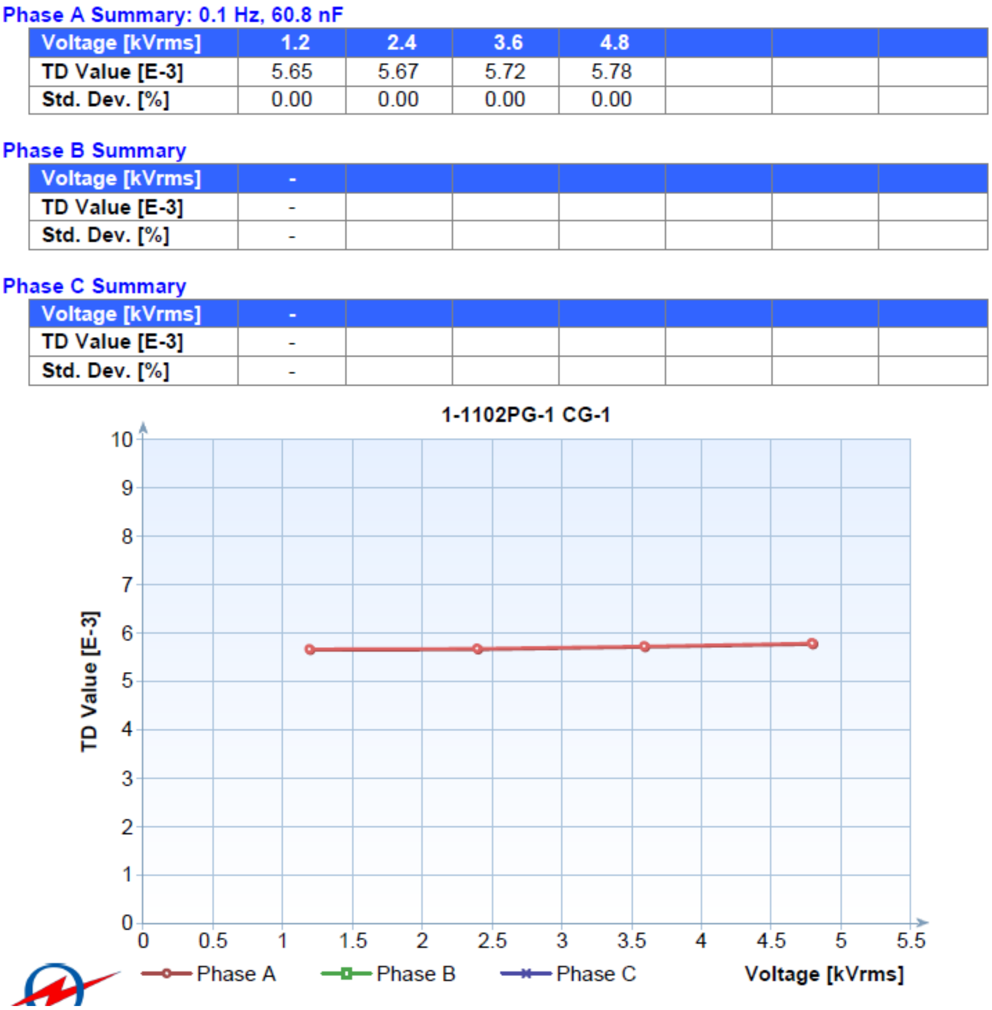
Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	5.67	6.29	12.78	23.35			
Std. Dev. [E-3]	0.00	0.06	0.17	1.22			

Figure 4-3
Tan δ results for an RCP motor showing a degraded C phase

This circuit had no splices, but it did contain terminations at the cable ends and on either side of a containment electrical penetration. In a case like this, the first step would be to visually inspect the penetrations for signs of overheating, partial discharge, or water intrusion. It can be seen in Figure 4-4 that the C phase was visually found to be overheating.

Figure 4-4
Noticeable overheating of the C phase penetration. Note the tan color of the parallel cables in the background.

Removal of the tape over the connection revealed a high resistance connection that was cleaned, remade, and reinsulated. The post-repair testing seen in Figure 4-5 confirms that the thermally degraded termination was the cause of the “action required” test results. It also demonstrates that it is possible to determine more than just wet cable degradation with tan δ testing.



Phase A Summary: 0.1 Hz, 60.8 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	5.65	5.67	5.72	5.78			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase B Summary

Voltage [kVrms]	-						
TD Value [E-3]	-						
Std. Dev. [%]	-						

Phase C Summary

Voltage [kVrms]	-						
TD Value [E-3]	-						
Std. Dev. [%]	-						

Figure 4-5
Post-repair testing for a reactor coolant pump motor showing the C phase. Only the C phase was retested so the data appear under the A phase.

4.5 Black and Butyl Rubber Tan δ "Action Required" Results Confirmation via Forensic Analysis

Several of the cables whose insulation was degraded were provided to EPRI for forensic evaluation [3, 4, 6]. In addition, one butyl rubber insulated cable [3] and one black EPR cable [6] that failed in service (before tan δ testing was being performed) were provided to EPRI for forensic research. In all these cases, the cables had water trees identified in their insulation. Sometimes, there were several water tree locations, and one had a single defect (as identified by localized low-insulation resistance, high tan δ, and low alternating current (ac) breakdown strength). However, the forensic results showed that the degraded locations were localized in wetted areas of the cable and that these localized weak spots were discreet areas surrounded by otherwise good insulation. This is important because this fact, along with the fact that most often only a single phase is found degraded, negates a "common cause" failure mode and indicates that if the degraded area can be isolated and removed, there is good insulation remaining.

Note: There is no indication that water treeing is a common cause failure mode. Testing and forensic evaluations show discreet, localized defects with surrounding good insulation.

Over the course of forensic evaluation of butyl rubber and black EPR [3, 4, 6] cable insulation, a process for isolating the degraded insulation areas was employed. Cables were divided into two sections, and tan δ testing was used to identify which section had degraded insulation. This process of "dividing and conquering" was continued until the degraded section was too short to test with tan δ. At that point, various probes in ever-decreasing sizes were used to scan the surface of the insulation with 1000 V dc applied, and resistance was measured between the conductor and insulation surface. Once the defects were marked, an ac breakdown test was performed in 5-minute steps until breakdown. Both degraded and good insulation were ac breakdown tested to provide a spread of data for the insulation condition with and without defects.

Figure 4-6 shows the data that resulted from the forensic testing. V/V_0 is the ratio of applied voltage to line-to-ground voltage. Insulation breakdown strength ranges were from 12 times to 30 times V/V_0 in the tan δ range of "good" (4 E-3 to 12 E-3 range). Cable insulation was 8–16 times V/V_0 for cables in the "further study required" tan δ range (12>, ≤ .50 E-3). In the "action required" tan δ range (>.50 E-3), the ac breakdown values were as low as 4.5–8.0 times V/V_0.

Cables with less remaining breakdown strength than those in the "action required" range above have some remaining margin to failure, but they should be replaced. At this level of reduced dielectric strength, the insulation could fail during breaker operation voltage surges. Cables in this weakened condition should be subjected to and pass a 30-minute, IEEE-recommended withstand test if they need to be returned service for any period of time until repairs or replacement can be made. Also, because withstand test voltages are only never more than two times the line-to-ground voltage, it is reasonable to see that only the most degraded cable would fail this test.

Note: Laboratory testing of short sections of good and degraded cables indicate that high tan δ test results correlate well with reduced ac breakdown strength.

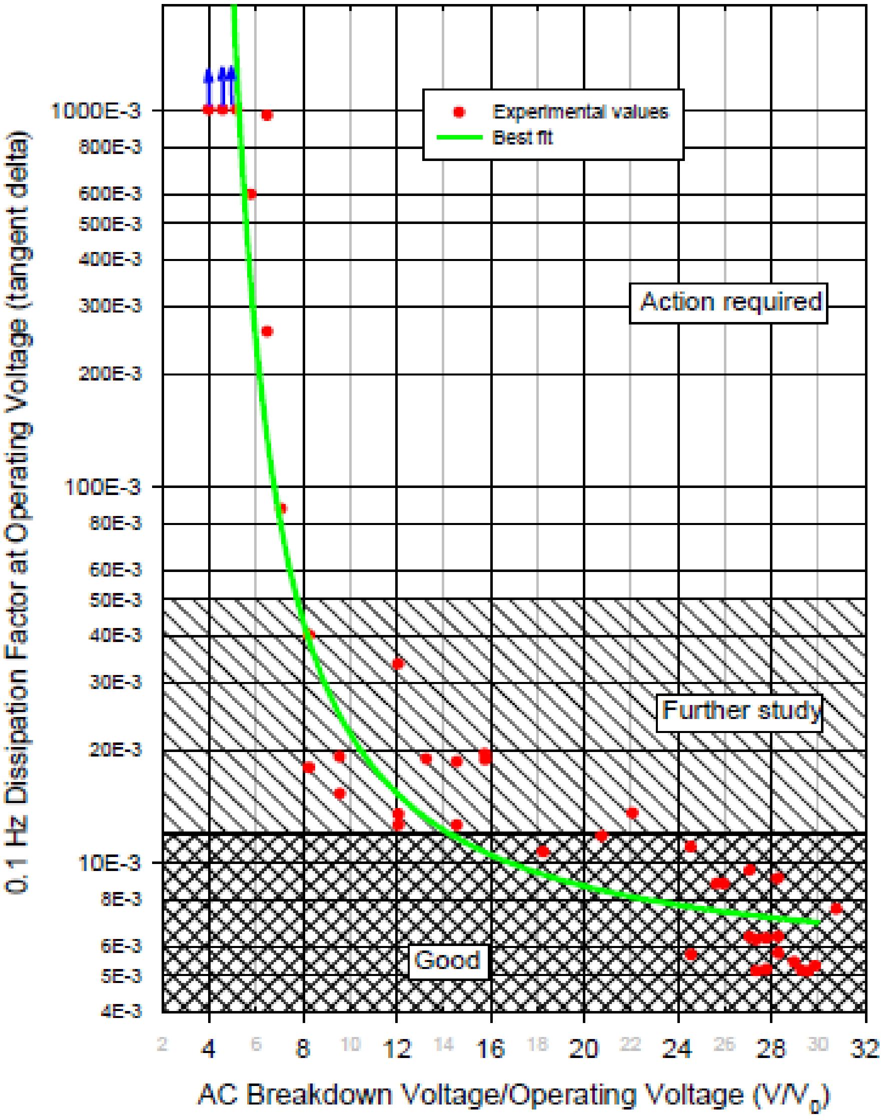


Figure 4-6
Plot of ac breakdown voltage versus tan δ at operating-line-to-ground voltage

4.6 Butyl Rubber and Black EPR Test Evaluation Section Summary

Butyl rubber and black EPR are the oldest type of rubber cables used in nuclear power plants. The design of these cable types is more prone to insulation degradation than other types of rubber cables (pink and brown EPRs mentioned later specifically) because of the materials used in compounding (carbon black, untreated clay fillers) and processes used in manufacturing (taped semi-conducting insulation shield, cleanliness standards, and so on). This is supported by the fact that this insulation type is the only EPR type for which the “action required” insulation issue outnumbers splice and termination issues.

Evaluation using the acceptance criteria in EPRI report 3002000557 [1010] has not resulted in any false negative results for EPR insulations (two cases have occurred for cross-link polyethylene insulated cables), and there have been no false positives identified of the issues that have been identified and forensically analyzed.

Forensic results have not identified any homogeneous aging of the cable insulations, just localized/heterogeneous defects. This does not support allegations that wet/submerged cables could fail simultaneously during a plant transient, especially if they are being condition monitored using 0.1-hertz tan δ and withstand testing.

A combined tan δ and withstand test (monitored withstand) is recommended as the standard test. This ensures that no large single defect is masked by circuit configuration or length. Additionally, cable whose insulation integrity is disturbed (by a splice or cable section replacement) should be withstand tested prior to its return to service.

The case history presented for the RCP motor confirms that tan δ can identify thermal degradation in dry cable, not just wet insulation degradation.

Finally, ac breakdown testing, using the factory acceptance test methodology, of forensically analyzed, short cable sections shows a very strong, inverse correlation between the degradation level of black EPR insulation measured by 0.1-hertz tan δ with ac breakdown strength.

5

PINK EPR TAN DELTA TEST RESULTS DISCUSSION

Pink EPR, shown in Figure 5-1, is a newer generation insulation type that was developed in the mid-1970s as a replacement for black EPR and butyl rubber insulated cables. The major design improvements include the use of extruded insulation shields versus semi-conducting tapes, replacement of carbon black[4] with lead oxide in the insulation, and the use of silane-treated clay to improve bonding of the clay and EPR. These improvements made for a less hydrophilic insulation, making it less susceptible to water treeing than black EPR.

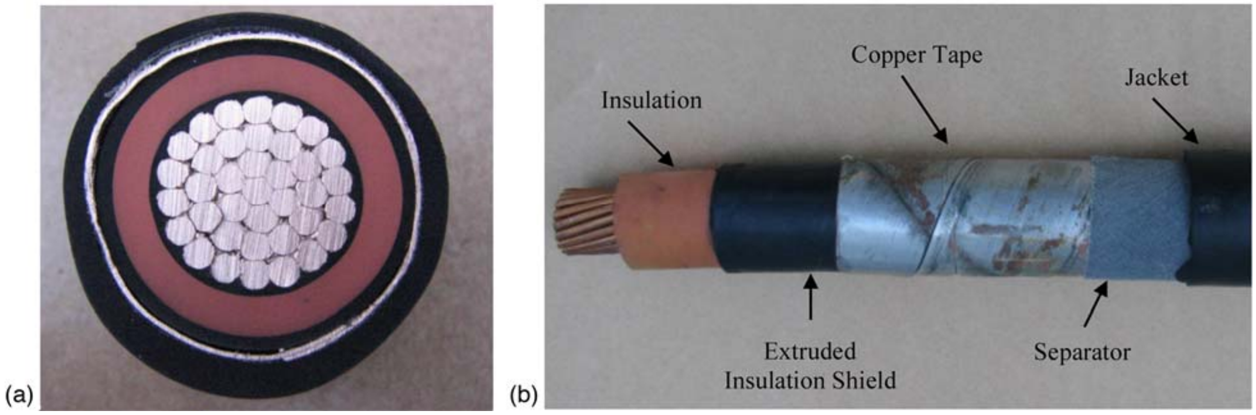


Figure 5-1
Construction of the 8-kV cable: [a] transverse view, [b] lengthwise view

A pink EPR cable is shown in Figure 5-1. Cables discussed in this section are those that have a copper tape metallic insulation shield. This discussion refers only to this copper tape design and not the compact design, which comes in both pink and black EPR versions. The compact design is discussed separately because there are specific design-related issues that influence its failure history that are wholly separate from the tape shield design.

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[4] Carbon black was used in black EPR insulation and jacket materials. It is much more hydrophilic than the lead oxide used in pink EPR. This made the black EPR insulation capable of absorbing much more water than the pink EPR does.

5.1 Tan δ Test Result Data by Test Type for Pink EPR

The breakdown of test data for tan δ at U_0, percent standard deviation results at U_0, and delta tan δ results is provided in Tables 5-1, 5-2 and 5-3. Pink EPR[5] makes up 33% of the cable tests received, and 35% of cables with issues identified in Table 3-2 following unsatisfactory tan δ testing results. The 12 issues for pink EPR are second only to black EPR in the number of issues identified. Although numerically close, it is somewhat misleading because black EPR has fewer test cases. Pink EPR has 10% more test results received and analyzed than black EPR. Also, consider that insulation issues shown in Table 3-2 for pink EPR accounted for only 4 of the 12 issues identified, compared to more than half the black EPR issues. Both of these facts indicate that this insulation is much less susceptible to water treeing.

Two of the four insulation failures were forensically analyzed [3, 7]; one was attributed to water treeing, and one was indeterminate (but suspected of being a water tree) because the defect site was too badly damaged during ac breakdown testing in the defect location.

Table 5-1
Pink EPR mean tan δ at U_0 results

	Green – Good (-≤ 15 E-3)	Yellow – Further Study (>15 E-3≤ 30 E-3)	Red – Action Required (>30 E-3)
Circuit Classification	145	8	25
% of total tests performed	81%	5%	14%

Table 5-2
Pink EPR percent standard deviation results at U_0

	Green – Good (≤ 0.02)	Yellow – Further Study (>0.02 ≤ .04)	Red – Action Required (>.04)
Circuit Classification	154	7	17
% of total tests performed	87%	4%	9%

Table 5-3
Pink EPR delta tan δ results

	Green – Good (≤ 3)	Yellow – Further Study (>3≤ 8)	Red – Action Required (>8)
Circuit Classification	150	3	25
% of total tests performed	84%	2%	14%

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[5] Test result totals are derived from test results received and are not necessarily equal numbers; for example, some tests may consist of three phases tied together, but counted as only one result because individual phase values are not known.

There is much better correlation between all three "action required" acceptance criteria for pink EPR compared to black EPR. There are also lower percentages of "further study" and "action required." The difference is even less if you consider more pink EPR cables were tested (178 tests evaluated) than black EPR cables (130 tests evaluated).

5.1.1 Analysis of Pink EPR Tan δ Test Results

Tan δ magnitude at U_0 for black EPR test results are 57% "good" compared to 81% in the "good" range for pink EPR. The "further study required" range is 22% of the test results for black EPR versus 5% for pink EPR. The "action required" range is 21% of the test results for black EPR versus 14% for pink EPR. The differences in these percentages show that black EPR has more cases of degradation and that there are somewhat different degradation paths from "good" to "action required" for black EPR versus pink EPR. This is not surprising considering that black EPR is more hydrophilic because its design uses carbon black in its jacket and semi-conducting layers, which allows more water retention compared to improved insulation compounding constituents and extrusion methods in formulating pink EPR, which make it more hydrophobic (the improved methods impede and lessen water permeation into the insulation).

Accessories (splices and terminations) accounted for 8 of the 12 issues for pink EPR. Five were termination related and three were splice related. The fact that insulation does not have the greatest percentage of issues identified as black EPR combined with the analysis of the results above supports pink EPR as being less susceptible to wet/submerged insulation degradation than black EPR.

5.2 EPR Tan δ Results

Several facts that should be noted are associated with the test results for pink EPR:

- To date, no cables tested in the "green," "yellow," or "red" acceptance ranges have had in-service failures (no false negatives).
- All of the 12 "action required" cable test results were confirmed by more than one tan δ acceptance criterion.
- Insulation defects all have increasing tan δ magnitudes, high standard deviations, and usually high delta tan δ, whereas splices and terminations usually have high, but decreasing, values of magnitude and high standard deviations, and are more likely to have negative delta tan δ.
- As with black EPR, the main focus of cables tested is wet/submerged/high humidity environments, but there is a small population of dry cables tested that tan δ has identified as degraded terminations, splices, or insulation.
- Forensic evaluation was performed on two of the four insulation failures; reduced dielectric strength insulation locations were identified, and indications of water treeing were found. No cases were found to indicate uniform overall degradation of the insulation (homogeneous aging), but rather one or a few discreet locations of severe degradation (heterogeneous aging).
- Forensic evaluation of degraded insulation in the "action required" range appears to correlate well with reduced ac breakdown strength similar to black EPR, but sufficient test points are not yet available to create a correlation curve.

As was the case with black EPR, pink EPR has not had any reported cases of false positive or false negative results. That is, no cable that tested below "action required" levels has failed in service. Likewise, no "action required" cables that have been repaired have subsequently failed in service.

5.3 Pink EPR "Action Required" Issues Summary, Use of Percent Standard Deviation, and Observations on Negative Delta Tan δ

Test data were provided for analysis on only 6 of the 12 "action required" issues identified in Table 3-2 for pink EPR. In several cases, only the post-replacement tests were provided and not the as-found tests. In two cases, the cables were replaced as extent of condition actions because of the previous cable failures of that manufacturer. Those cables were tested only for information prior to replacement (they tested well). The eight cables with issues for which data were provided were shown to be degraded by two or all three of the tan δ evaluation criteria. As was the case with black EPR, standard deviation and delta tan δ are better indicators of cable degradation than tan δ magnitude alone. Another similarity with black EPR was that negative delta tan δ was present in all four cases where the test data were available for bad splices and terminations.

Note: Negative delta tan δ, in all cases where data have been provided, was found to be an indication of degraded splices or terminations.

5.4 Pink EPR Tan δ "Action Required" Results Confirmation via Forensic Analysis

Forensic research [5, 8] was performed on two of the four pink EPR insulation issues identified in Table 3-2. In both cases, the degraded insulation was isolated forensically in the lab. The isolated sections' level of degradation was determined by the results of reduced ac breakdown strength of the degraded area compared with the surrounding insulation. In the first case [5], the resultant breakdown destroyed any evidence to be able to confirm the presence of water treeing. In the second case [7], the breakdown area was minimal, and the image [b] in Figure 5-2 shows the bow-tie water tree. The tree spans nearly all of the insulation from conductor shield to insulation shield.

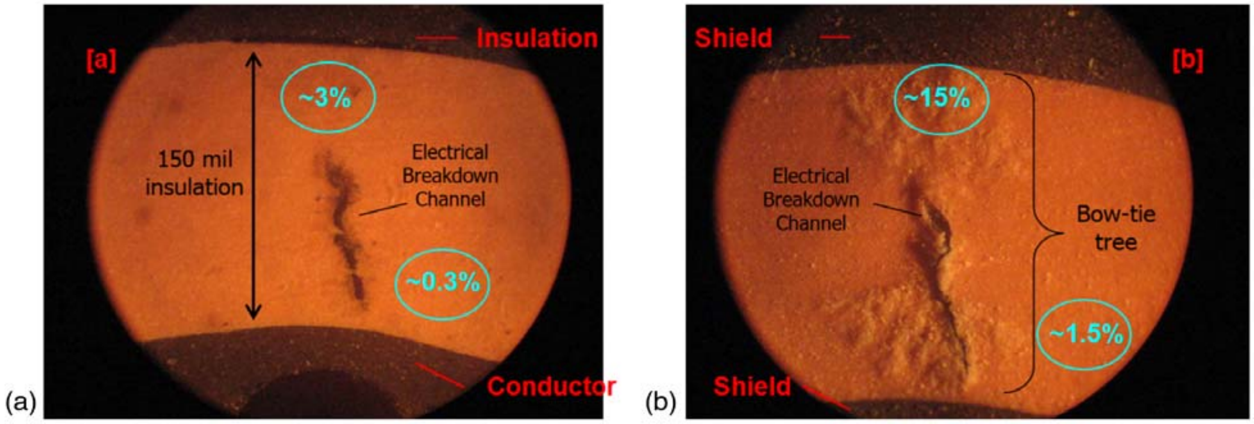

Figure 5-2
[a] A wafer containing the breakdown channel of the degraded insulation, [b] the degraded area and large bow-tie water tree that has been “developed” by soaking the wafer in water

The issues of these two cables resulted in the cables being removed from the plant, based on tan δ results for all three criteria. The laboratory cable ac breakdown test showed that the insulation strength was much less for the degraded areas (4.6 V/V_0 and 2.5 V/V_0) than the surrounding “good” insulation (12 V/V_0 to 17 V/V_0). It is surmised that tan δ will equate to degraded ac breakdown strength similar to black EPR, but insufficient data points have been obtained from the two forensic reports to provide a correlation graph like the one shown for black EPR in Figure 4-6.

Forensic evaluation for pink EPR, like black EPR, showed that tan δ exceeding the acceptance criteria correlates with degraded insulation as determined by the ac breakdown strength and that the degradation is limited to a few discreet locations. If those discreet degradation locations can be isolated and repaired, then the entire cable length need not be replaced. Isolating degraded sections can be difficult, and the time and effort to do so must be considered in evaluating whether to repair or replace a cable.

5.4.1 Pink EPR Test Evaluation Section Summary

Pink EPR insulation is a newer generation insulation that was developed in the mid-1970s as a replacement for black EPR and butyl rubber insulated cables. Design improvements in compounding and extruding make this insulation less hydrophilic, which makes it less susceptible to water treeing than black EPR and butyl rubber insulations.

The fact that pink EPR is less susceptible to water treeing is further supported by the analysis of data received, which has fewer “action required” insulation issues than the older EPR insulation types. Additionally, there were twice as many splice and termination “action required” issues compared to insulation issues for pink EPR insulation; whereas, for black EPR and butyl rubber, the ratio was 2:1 insulation to splice and termination issues.

There have been no false negative failures of issues in the “good” or “further study required” ranges of EPRI acceptance criteria [10], nor have there been any false positive issues determined by the forensic analysis of insulation, splices or terminations of “action required” level from the test results analyzed.

Several cases of "action required" issues were found for dry cables and newly installed replacement cables by using tan δ test results and then sequentially eliminating the terminations, splices, and then finally the cable insulation until the degraded section was isolated.

Negative delta tan δ has been found to be an effective indication of a splice or termination issue, confirming that any negative slope[6] should be treated as "action required" when confirmed by at least one other criterion.

Finally, it is expected that issues identified as "action required" by tan δ testing will correlate to low ac breakdown strength. Initial testing of the two forensically analyzed cables show this relationship, but an insufficient number of test points exist to create a correlation graph of pink EPR tan δ versus ac breakdown strength like the one that exists for black EPR.

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[6] There have been instances of minimal negative delta tan δ (< 1) that had low tan δ magnitude and standard deviation.

6
COMPACT DESIGN TAN DELTA TEST RESULTS DISCUSSION

Compact design EPR cables were manufactured using black and pink EPR. The black EPR compact design has the same characteristics and is manufactured from the same materials as other black EPRs. They are presented here together based on the fact that their design dominates how they degrade more than the insulation type does as determined by forensic evaluations of these types of cable that have been evaluated by EPRI. Additionally, this cable design has a long history of in-service failures in industry operating experience.

Figure 6-1 shows the construction of the compact design cable.

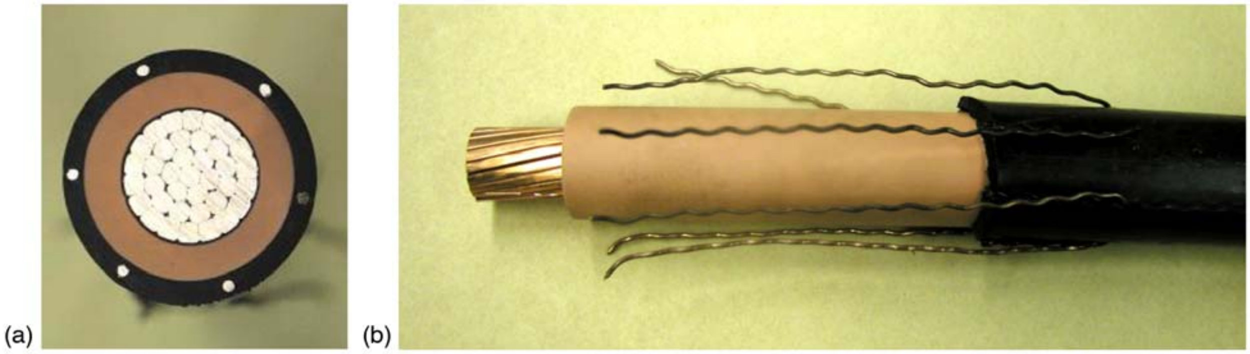


Figure 6-1
Construction of pink EPR compact design cable [a] transverse view, [b] lengthwise view

The major differences in this design from other EPR types is the use of six, corrugated, bare copper drain wires embedded in a semi-conducting, extruded, thermoplastic shield. This layer acts as both a shield and jacket for this design. The combined insulation shield/jacket with embedded metallic shield drain wires requires a compromise between the bonding strength of this layer and the insulation. Ease of prepping the cable for terminating and splicing requires a trade-off between a minimum adhesive strength that can be stripped it away easily enough not to destroy the insulation surface for a splice or termination versus better electrical stress properties if the semi-conducting surface was more strongly bonded to the insulation surface.

Additionally, carbon black is used to provide the semi-conducting property and good ultraviolet light protection, but because it is both the jacket and insulation shield, it contains more carbon black, making it more hydrophobic. This hydrophobicity makes it able to absorb more water. These properties will be shown to be the dominant factor in degradation.

6.1 Tan δ Test Result Data by Test Type for Black and Pink Compact Design EPR

Black and pink compact design EPR comprise 17% of the cable tests received and 20% of cables with issues identified following poor tan δ testing results.[7] Four of the six issues identified have been insulation issues, but only one of those four was due to water treeing. The remaining three of the four insulation failures were forensically analyzed [2, 7, 8] and determined to be the result of partial discharges at the insulation surface. The forensic analysis will be discussed later.

Table 6-1
Compact design EPR mean tan δ at U_0 results

	Green – Good (-≤ 15 E-3)	Yellow – Further Study (>15 E-3≤ 30 E-3)	Red – Action Required (>30 E-3)
Circuit Classification	81	11	6
% of total tests performed	85%	12%	3%

Table 6-2
Compact design EPR percent standard deviation results at U_0

	Green – Good (≤ 0.02)	Yellow – Further Study (>0.02 ≤ .04)	Red – Action Required (>.04)
Circuit Classification	77	1	5
% of total tests performed	93%	1%	6%

Table 6-3
Compact design EPR delta tan δ results

	Green – Good (≤ 3)	Yellow – Further Study (>3≤ 8)	Red – Action Required (>8)
Circuit Classification	70	8	12
% of total tests performed	78%	9%	13%

---

[7] Test result totals are derived from test results received and are not necessarily equal numbers. An example is that some tests may consist of three phases tied together, but counted as only one result because individual phase values are not known.

The test data results in Tables 6-1, 6-2, and 6-3 appear to indicate that the compact design has a low percentage of degraded insulation. However, the compact design has had the poorest operating experience of all EPR types based on 2005 Nuclear Energy Institute (NEI) survey results [13] and the GL 2007-01 Nuclear Regulatory Commission (NRC) survey results [14] for medium-voltage cable failures in U.S. nuclear power plants. Although this failure history has been attributed to wet conditions, forensic evaluations performed as part of EPRI research into wet medium-voltage cable failures [2, 7, 8] indicate that two distinct degradation mechanisms exist for this design, which will be discussed later in this section.

6.1.1 Analysis of Compact Design EPR Tan δ Test Results

The accessories (splices and terminations) accounted for two of the six issues for compact design EPR. There was one splice and one termination issue. The termination issue was a cleanliness issue of the terminations and was resolved by thorough cleaning and retesting. The splice issue was the workmanship on a new splice, which will be discussed in more detail in this section. It is interesting because it was a new splice and it was flagged as "action required" at $2U_0$ for percent standard deviation. Magnitude and delta tan δ were only in the "further study required" range. In this case, percent standard deviation provided the best indication that there was an issue. It was critical to identify this issue because the circuit voltage was 13.8 kilovolts and would likely have failed shortly after being put in service due to the high-voltage stress.

Three of the four insulation issues were in-service failures—two at the same site. Issue one involved a degraded phase cable that tested in the "action required" range for all three criteria, but was returned to service (without a withstand test). The cable circuit was classified as low significance and scheduled for replacement in a year. The cable failed in service eight months later prior to the scheduled replacement. The second and third in-service failures were at the same site and involved cables that were not considered to have an insulation issue. Cable two failed, but it was not evaluated as "action required" because only the percent standard deviation was elevated above the acceptable limit, and the other two criteria were "good." Cable three had no known issues at the time when a single phase failed, but after the failure, another phase in the circuit showed "action required" readings for negative delta tan δ and 5 standard deviations. The fourth cable insulation issue was identified from tan δ testing by a high standard deviation and was rejuvenated.

6.1.2 EPR Tan δ Results

Several facts that should be noted are associated with the data results:

- A poorly made new splice was identified by percent standard deviation in the "action required" range during post-installation testing (new, dry cable) is an example that shows that tan δ can detect splice defects
- Forensic evaluation [2, 7, 8] shows that water treeing is not the only failure mechanism of compact design cable insulations. A partial-discharge mechanism between the insulation and insulation shield weakens the dielectric strength of the insulation from the outside in.

6.2 Forensic Evaluation of Compact Design Tan δ

It was mentioned in the introduction to this section that the compact design EPR cables employ a combined jacket and insulation shield that has metallic shield drain wires embedded into it, as can be seen in Figure 6-2.

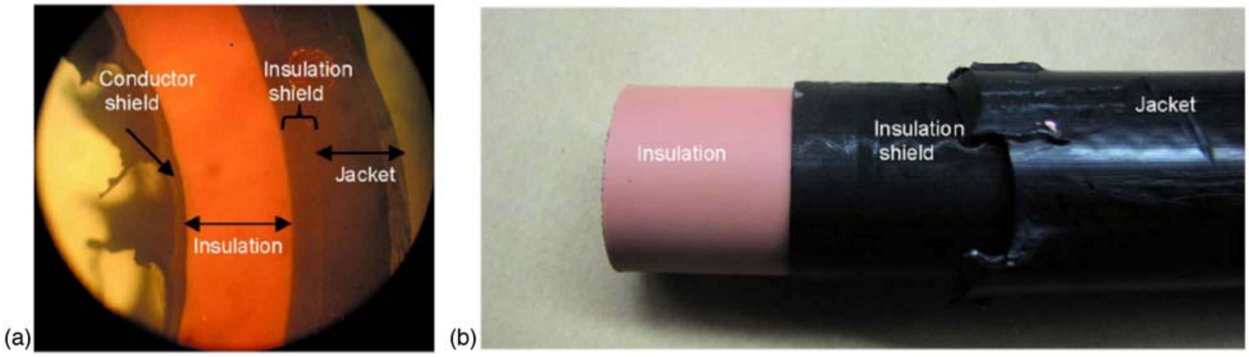


Figure 6-2
Compact design construction showing [a] the cross-section and [b] the lengthwise cut back view

This EPRI research [8] identified that this jacket/shield-to-insulation adhesion has been compromised by water trapped at the interface that has created a water-filled pocket shown in Figure 6-3.

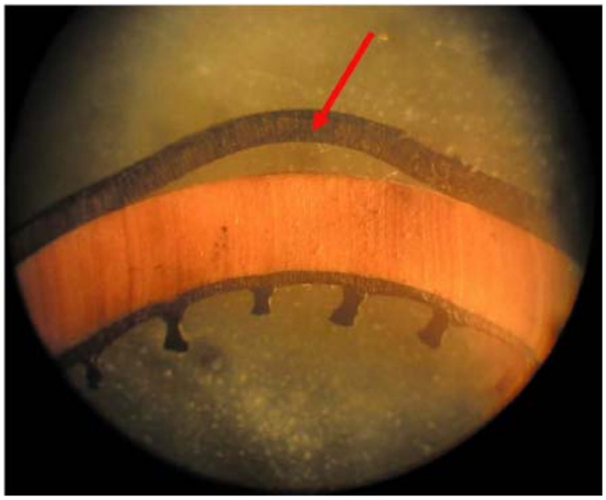


Figure 6-3
Arrow shows the insulation shield lifted off the insulation surface by trapped water

This delamination pocket creates stress between the insulation and insulation shield, and subsequently partial discharging occurs. The energy released by this partial discharge disintegrates the EPR at the surface as seen as the white areas in Figure 6-4, reducing the overall dielectric strength of the remaining insulation by as much as 50%.

Figure 6-4
The white substance in the figure is the partial-discharge-affected surface of the EPR insulation.

6.2.1 Compact Design EPR Test Evaluation Section Summary

Compact design EPR cables were manufactured using black and pink EPR. The black EPR compact design shares similar compounds with other black EPRs as does the compact design pink EPRs. This design incorporates a jacket/insulation shield with six corrugated, bare copper drain wires embedded in a semi-conducting, extruded, thermoplastic shield. A design trade-off between a minimum adhesive strength that can be stripped it away easily enough not to destroy the insulation surface for a splice or termination versus better electrical stress properties if the semi-conducting surface was more strongly bonded to the insulation surface.

Loss of surface contact at this electrical stress point has resulted in partial-discharge sites. Forensic evaluations [2, 7, 8] have identified such sites at insulation degradation in cables provided to EPRI. The discharge energy at these sites results in weakened insulation dielectric breakdown strength and can lead to failure. The operating history of insulation failures for this type of insulation is the worst of all the cables installed in nuclear power plants.

7

BROWN EPR TAN DELTA TEST RESULTS DISCUSSION

Brown EPR insulation, shown in Figure 7-1, is different from black, pink, and compact design EPRs because it is a partial-discharge-resistant insulation, whereas the other EPRs are partial-discharge-free designs. Brown EPR is not partial-discharge tested as a factory acceptance criterion as the other EPR types are. The end effect of this design is that the insulation system has higher acceptable tan δ magnitude values than the other EPRs (50 E03 compared to 12 or 15 E-3 for "good").

Like the pink EPR insulation, brown EPR insulation is considered to be less affected by water treeing than black EPR or the compact design EPRs. These facts are somewhat confirmed by the tan δ test results analyzed to date, EPRI-sponsored forensic analysis research, and industry operating experience.

Even though only 48 tests were available for review, they are included here for the insights available from the data, even though the data are not a statistically significant sample set of the test data available for analysis.

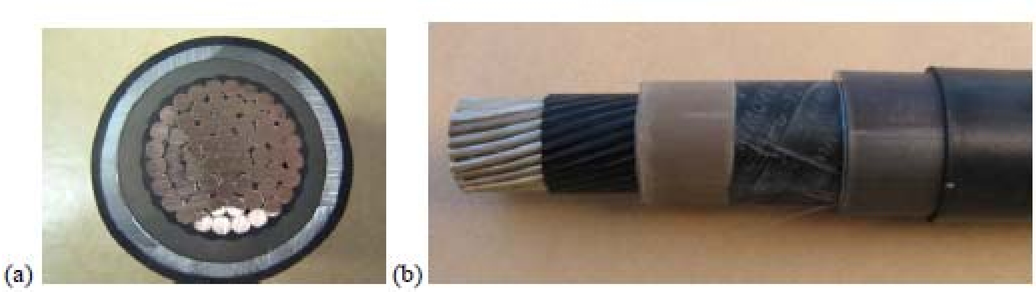


Figure 7-1
Construction of brown EPR 5-kV cable, (a) transverse view, (b) lengthwise view

The cable in Figure 7-1 is a lead sheathed cable that is water impervious by design. The majority of shielded cables in the U.S. nuclear power plant fleet are not lead sheathed, but they have a zinc tape metallic shield. There are also several plants that use non-shielded 5-kV rated brown EPR cables. The data reviewed apply to the zinc tape metallic shield cable types.

7.1 Tan δ Test Result Data by Test Type for Brown EPR

Brown EPR[8] makes up 9% of the cable tests received and only 4% of cables with issues identified following poor tan δ testing results. The only issues identified were for a degraded termination and a degraded splice.

Table 7-1
Brown EPR mean tan δ at U_0 results

	Green – Good (50≤ E-3)	**Yellow – Further Study (>50 E-3≤ 60 E-3)**	**Red – Action Required (>60 E-3)**
Circuit classification	37	5	7
% of total tests performed	75%	10%	15%

Table 7-2
Brown EPR percent standard deviation results at U_0

	Green – Good (≤ 0.02)	**Yellow – Further Study (>0.02 ≤ .04)**	**Red – Action Required (>.04)**
Circuit classification	37	3	9
% of total tests performed	76%	6%	18%

Table 7-3
Brown EPR delta tan δ results

	Green – Good (≤ 5)	**Yellow – Further Study (>5≤ 15)**	**Red – Action Required (>15)**
Circuit classification	33	9	6
% of total tests performed	69%	19%	12%

---

[8] Test result totals are derived from test results received and are not necessarily equal numbers; for example, some tests may be have three phases tied together, but the test counted only as one result because individual phase values are not known.

7.1.1 Analysis of Brown EPR Tan δ Test Results

The number of tests in each acceptance criteria category for brown EPR is consistent for each category. Standard deviation has more instances of "action required," but if you look at the "further study required" ranges of the other two categories, the same number of degraded cables are identified. As can be seen by reviewing the information obtained for the cause of the degraded cables, the causes are all either splice or termination related. Standard deviation and delta tan δ are good indicators and more indicative of such degradation, so they (terminations and splices) would be expected to have the highest number of occurrences.

Several facts that are associated with the data results for brown EPR should be noted:

- To date, no cables tested in the "green," "yellow," or "red" acceptance ranges have had in-service failures (no false negatives).
- The two identified issues of the "action required" results were a splice (water intrusion) and a termination (stress cone degraded).
- Several "action required" range cables with suspected splice issues have been returned to service following a withstand test and have not failed in service.
- Percent standard deviation exceeding "action required" was the most frequent indicator of degradation.

7.2 Examples of "Good" Tan δ Test Results

Brown EPR insulated cable acceptance criteria are higher than other EPR types for magnitude and delta tan δ, but the same for percent standard deviation. One might think that standard deviation would be higher on a partial-discharge-resistant insulation, but this is not the case. A typical example of a test with "good" results is shown in Figure 7-2. The delta tan δ values are often higher than shown here, but even this test has only a value of 1 or less for any phase (4.0–1.2 voltage levels) that is 1.5 U_0 – 05 U_0.

Phase A Summary: 0.1 Hz, 113.9 nF

Voltage [kVrms]	1.2	2.4	4.0	7.0			
TD Value [E-3]	27.7	28.1	28.6	30.2			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase B Summary: 0.1 Hz, 112.0 nF

Voltage [kVrms]	1.2	2.4	4.0	7.0			
TD Value [E-3]	28.3	28.9	29.6	31.5			
Std. Dev. [%]	0.00	0.00	0.00	0.01			

Phase C Summary: 0.1 Hz, 112.1 nF

Voltage [kVrms]	1.2	2.4	4.0	7.0			
TD Value [E-3]	26.9	27.3	27.9	29.6			
Std. Dev. [%]	0.00	0.00	0.00	0.01			

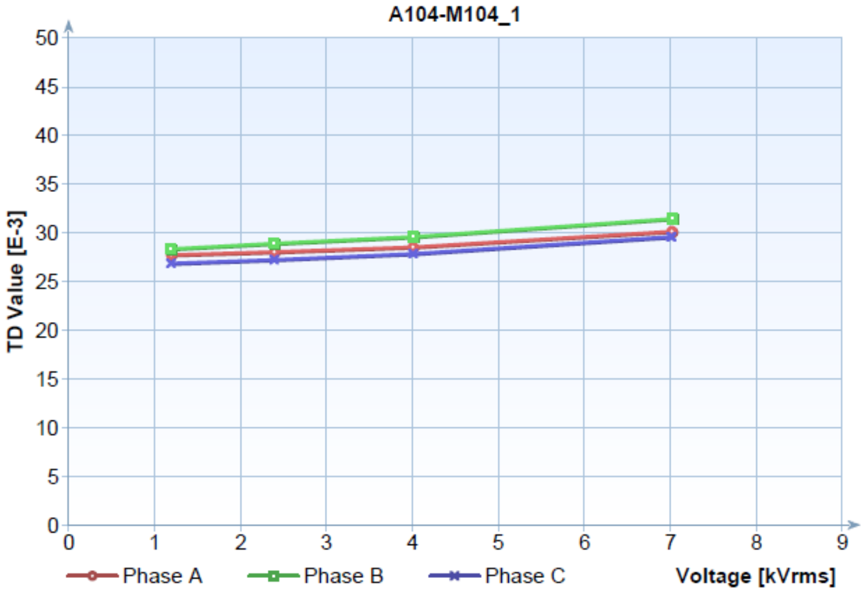
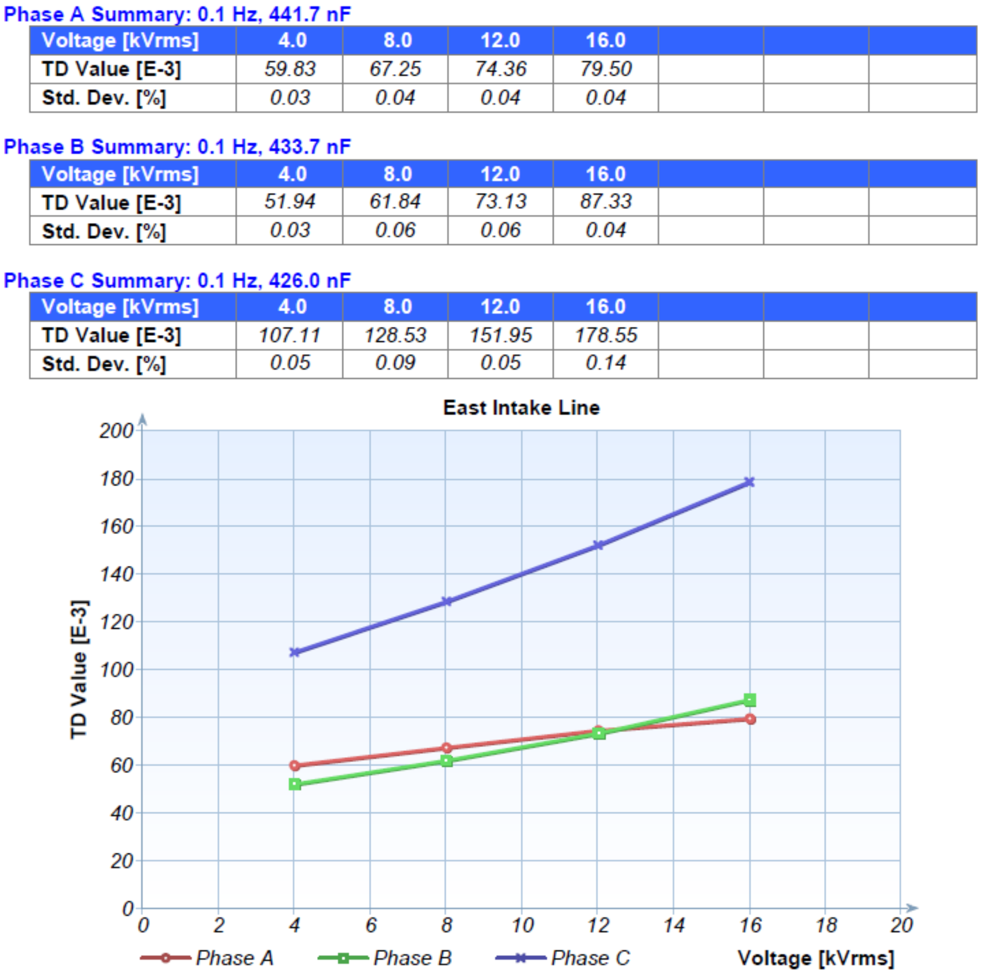


Figure 7-2
Typical “good” brown EPR insulation tan δ test results

7.3 Example of "Action Required" Tan δ Test Results

An example of "action required" test data is shown in Figure 7-3. All three criteria are above the "action required" level on all three phases. There are several splices in this cable, and they are suspected of being the cause for these results. This cable was withstand tested for 60 minutes at 16 kV and returned to service for a year. It will be repaired in November 2015.



Phase A Summary: 0.1 Hz, 441.7 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	59.83	67.25	74.36	79.50			
Std. Dev. [%]	0.03	0.04	0.04	0.04			

Phase B Summary: 0.1 Hz, 433.7 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	51.94	61.84	73.13	87.33			
Std. Dev. [%]	0.03	0.06	0.06	0.04			

Phase C Summary: 0.1 Hz, 426.0 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	107.11	128.53	151.95	178.55			
Std. Dev. [%]	0.05	0.09	0.05	0.14			

Figure 7-3
Example of "action required" brown EPR with suspected bad splices

7.3.1 Additional Information Obtained from Tan δ Testing

In addition to the test data analysis, the following information that should be noted was identified during tan δ issue investigation:

- Zinc shield deterioration was identified on an "action required" cable that had a bad splice due to water intrusion from a poor heat shrink of the splice jacket.
- Acceptance testing (tan δ and withstand) identified an issue ("action required" percent standard deviation) that was determined to be poor splice workmanship (human performance error).
- Forensic evaluation has identified only a few water trees, and the ones identified have been isolated, small bow-tie water trees that affected the ac breakdown strength of the insulation.

7.4 Zinc Metallic Insulation Shield Deterioration When Exposed to Water

The test data shown in Figure 7-4 identified a degraded splice. The cable failed during a monitored withstand test. It is presumed that this cable would have failed in service due to the degraded splice. When the splice was opened, it was found that the zinc tape used for the metallic insulation shield had turned to zinc oxide powder. This created a non-continuous shield. The heat shrink splice could be seen visibly to have a poor shrink on one end that would have allowed water ingress into the splice. It is surmised that the electrical stress combined with water resulted in the deterioration of the zinc into the zinc oxide that is visible in Figure 7-5.

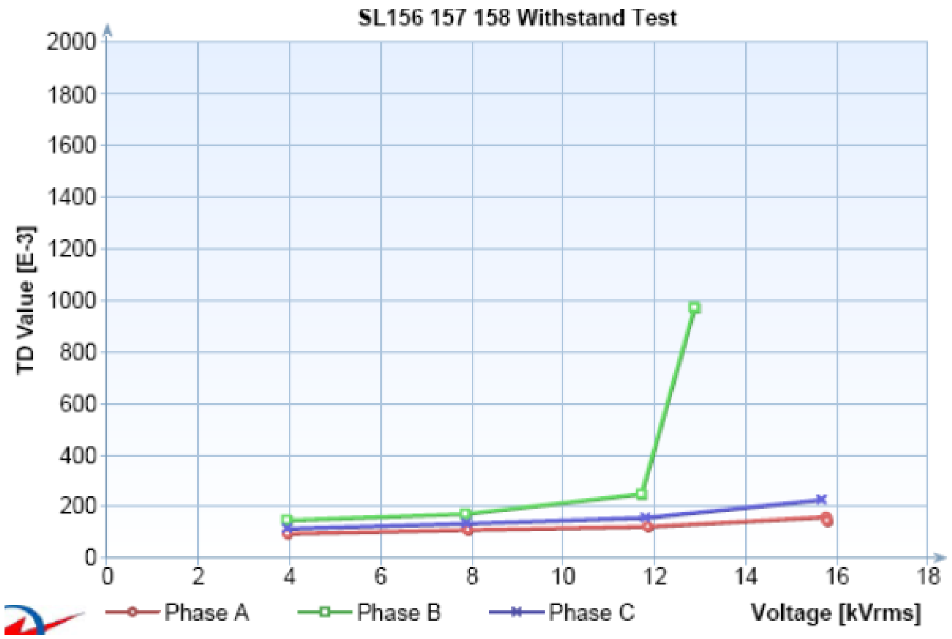


Figure 7-4
One documented case where a cable failed during a monitored withstand test

Figure 7-5
Splice with a poor heat shrink being opened and exposing the degraded zinc metallic insulation shield

While not specifically identified by testing, it is important to note that Kerite cables with a zinc metallic tape shield can deteriorate if exposed to water.

7.5 Withstand Test of Repaired Cable

It is often questioned whether repaired or replaced cables should be tan δ tested and/or withstand tested. The recommended practice is to do both. Tan δ values are taken to provide a new baseline for comparison with future tests. Withstand testing is done to confirm workmanship for installation, terminations, and splices if applicable. An example of why this is important is shown in Figure 7-6.

Figure 7-6
New splice of a 15-kV cable operated at 13.8-kV that failed at the 12-kV tan δ step prior to the 16-kV withstand test

The black mark on the insulation in the left photo is the residue of the test set arc flash. The photo on the right shows that the brown EPR insulation was cut clean through to the conductor shield (black layer around the copper conductor). At a 13.8-kV operating voltage (8-kV line-to-ground), the voltage stress is high enough that this cable would have failed in a matter of hours or days in service. This points out the importance of verifying circuit integrity via a withstand test for all repaired or newly installed cables (a similar defect at a termination would result in the same condition).

Note: For all new or repaired cables, establish a new tan δ baseline, and perform a withstand test to ensure workmanship integrity.

7.6 Forensic Study of Brown EPR Insulation

The two forensic studies [4] performed on this insulation type that operated in wet service conditions did not reveal anything unexpected in regard to insulation and water treeing. The ac breakdown testing performed indicated that breakdown values are about 50% of that of new cable or about 18 V/V_0 (breakdown voltage/in-service line-to-ground voltage). This is expected of a wet aged cable with no significant, if any, water treeing.

7.6.1 Brown EPR Test Evaluation Section Summary

Brown EPR insulation is different from black, pink, and compact design EPRs because it is a partial-discharge-resistant insulation where the other EPRs are partial-discharge-free designs. The end effect of this design in regard to tan δ test results is the higher acceptable tan δ magnitude values than the other EPRs (50 E03 compared to 12 or 15 E-3 for “good”).

Like the pink EPR insulation, brown EPR insulation is considered to be less affected by water treeing than black EPR or the compact design EPRs. These facts are somewhat confirmed by the limited tan δ test results analyzed to date that have identified “action required” issues for splice and termination defects but not for insulation defects. Additionally, EPRI-sponsored forensic analysis research [4, 6] and industry operating experience have not identified any water-related insulation failures.

In brown EPR with zinc metallic insulation shields, the zinc degrades and turns into zinc oxide when the zinc is exposed to water. This does not prevent the cable from functioning, but it does create a safety issue/shock hazard and may limit the testing that can be done that requires shield continuity (such as reflectometry and partial-discharge testing).

A monitored withstand test performed on a repaired cable and new splice resulted in the failure of the splice during the tan δ 1.5 U_0 step. This failure was in the newly made splice and a dry cable section. The cable, if not withstand tested, would have failed in service due to the dielectric stress at operating voltage for this 13.8-kV circuit.

8

HYBRID CABLE TAN DELTA TEST RESULTS DISCUSSION

Test results evaluated for hybrid cables account for only 4% of the total number of circuits tested, so an in-depth evaluation of the results like those that were performed for other insulations is not presented here. There are some key learnings from evaluating the test data received that is discussed that may be useful in the evaluation of test results for that type of circuit.

A *hybrid cable* is defined here as any as any combination of cable types spliced together that has one of the following attributes:

- Shielded cable spliced to non-shielded cable of the same type
- Shielded cable spliced to non-shielded cable of a different type
- Two different shielded cable insulation types spliced together
- Non-shielded triplexed or three conductor cables

Tan δ is a bulk or global insulation test that looks at the cable as a combination of capacitances. If the cable insulation is one type and the insulation is in good shape, then those capacitances are of equal value. Degraded cable insulation will present as a higher capacitance and associated higher tan δ value than the surrounding insulation. If, instead, the cable is a combination of types of insulation or design (shielded to non-shielded), the combination of different insulation capacitances will change the tan δ results.

Now, consider that the combinations above are of different lengths. The length change combined with the differences in insulation capacitance becomes even more complicated. How the length, capacitance, and presence of a defect interact will determine whether a defect will be masked in either section of cable.

Combinations of shielded cables with non-shielded cables in the circuit add another layer of complexity to the evaluation of test results. The issue with this combination is that non-shielded cables have a non-uniform ground plane. Not only does a non-uniform ground plane affect the tan δ results, performance of a withstand test on hybrid circuits does have some possibility to potentially overstress the non-shielded cable insulation. For these reasons, it is best, if possible, to isolate the different cable types and test the shielded sections only so as not to mask any degraded conditions or damage the non-shielded cables. It should be mentioned that some members feel the benefits outweigh the risk and perform the complete circuit test.

Note: Consider the difficulty of analysis and possible overstressing of insulation when hybrid shielded/non-shielded cable circuits are being tan δ tested. If possible, isolate and tan δ test only the shielded sections of hybrid cable circuits.

8.1 Evaluating Tan δ Mean Value at U_0 and Percent Standard Deviation for Hybrid Circuits

The issues discussed above typically result in higher value results of the tan δ mean value at U_0 than are allowed for "good" cables, based on any insulation type acceptance criteria [1]. The only potentially valid evaluation would be versus baseline results and future test results, or possibly against circuits of similar hybrid configuration and similar lengths.

Evaluation of defects could be masked by cable circuit configuration in the results for percent standard deviation. A hypothetical example would be if an XLPE insulation is spliced to an EPR insulation. Variations of test results due to a defect in XLPE (which, typically, has "action required" values greater than 2 E-3) may be insignificant if connected to a "good" EPR insulation (which range from 4-50 for EPRs). This same case could happen with black EPR connected to non-shielded cables or to brown EPR because the normal "good" magnitude of one is much less than the other. However, should the percent standard deviation be in the "further study" or "action required" ranges, that would still be considered a valid indication of a possible cable issue and should be evaluated the same as any other non-hybrid case.

Note: Hybrid cables with "further study required" or "action required" levels of percent standard deviation are valid indications of cable condition.

An example of a one type of hybrid circuit is shown in Figure 8-1.

Phase A Summary: 0.1 Hz, 70.2 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	85.2	85.8	86.3	86.9			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase B Summary: 0.1 Hz, 69.8 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	89.6	90.4	91.2	92.3			
Std. Dev. [%]	0.00	0.00	0.01	0.00			

Phase C Summary: 0.1 Hz, 68.7 nF

Voltage [kVrms]	1.2	2.4	3.6	4.8			
TD Value [E-3]	85.5	86.3	87.2	88.3			
Std. Dev. [%]	0.00	0.00	0.01	0.00			

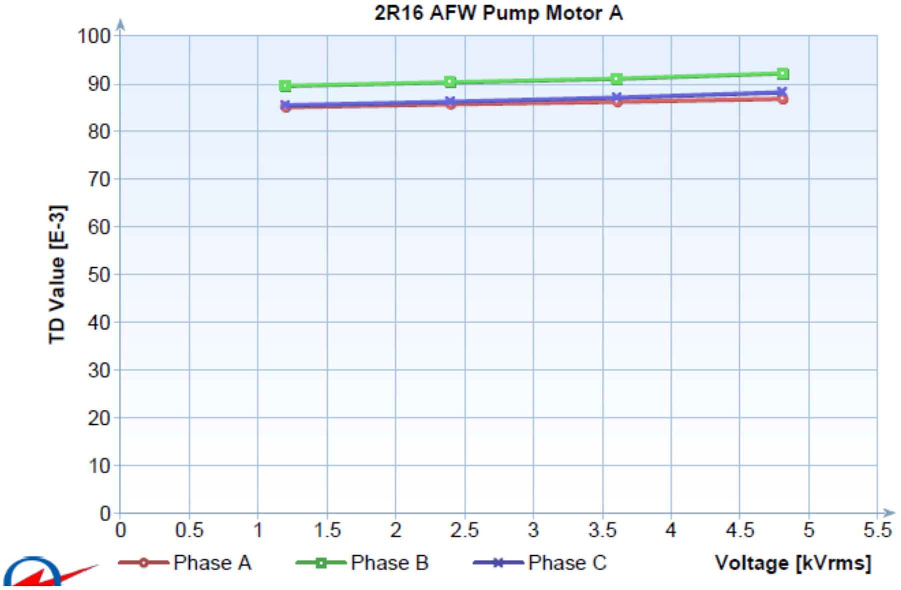


Figure 8-1
Hybrid circuit combining shielded pink EPR and non-shielded brown EPR

This circuit contains 200 feet (61 meters) of shielded pink EPR connected to 500 feet (152 meters) of non-shielded brown EPR. The cable is “good” for both percent standard deviation and delta tan δ, but “action required” is based on tan δ magnitude at U_0. This is likely a cable in “good” condition because degraded cables based on high tan δ in all cases evaluated were confirmed by at least one, or both, of the other two criteria. Therein lies the difficulty in evaluating hybrid circuits—they generally exceed a criterion for “good” when no action may be required.

8.1.1 Evaluating Delta Tan δ for Hybrid Circuits

Delta tan δ is the one criterion that should not mask degraded cables because it is the slope of the line determined by the magnitude at two voltage steps. However, acceptance criteria are picked by insulation type so the values in EPRI report 3002000557 [10] do not apply. Regardless, any increase in the slope of the tan δ results is an indication of some level of degradation. The cable program owner can use a comparison with similar circuits to establish what maximum level is acceptable for an “action required” designation.

8.1.2 Hybrid Cable Test Evaluation Section Summary

Hybrid cables are combinations of insulation type, circuit design (shielded spliced to non-shielded), non-shielded cables, or any combination of the above. These cable circuits are difficult to analyze, and results can potentially mask defects, but some consider the benefits to outweigh the risk.

If possible, it is recommended to isolate the different cable types (insulation, shielded, non-shielded) to allow proper evaluation of the shielded sections. If tested as a complete circuit, there is a possibility of overstressing the non-shielded cables because they do not have a uniform, continuous ground plane.

If testing hybrid circuits in their entirety, do not use the EPRI acceptance criteria [10] for tan δ magnitude, but rather use comparison of like circuits or previous testing to determine if a cable has degraded. Also, do not rely on magnitude alone as an indication of degradation unless it is confirmed by at least one other test criterion (percent standard deviation or delta tan δ).

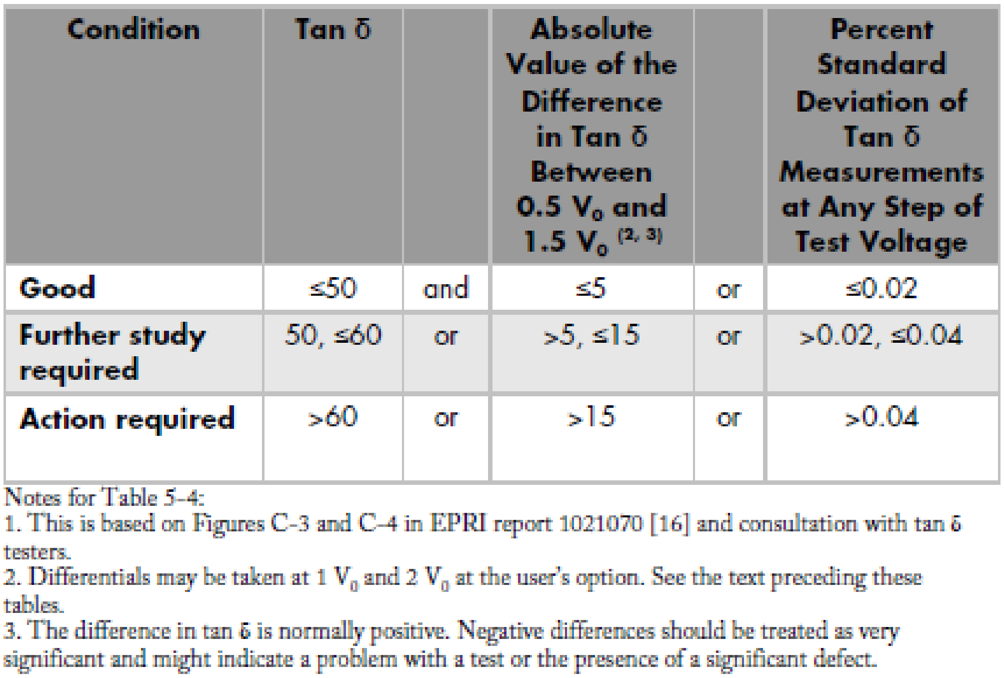
9

EVALUATING TAN DELTA TEST DATA

Tan δ is a bulk or global insulation test, but although it does not provide any information about the location of a defect, when combined with a logical sequence of actions, it can be used to isolate the issue of an "action required" test result. The approach of using percent standard deviation and then delta tan δ as the primary indications of degradation has resulted from evaluation of member test results. Why this is so is explained in this section.

Acceptance criteria for evaluating tan δ test data are provided in EPRI report 3002000557 [10]. There are three criteria levels established for each cable type; the types are XLPE, butyl rubber and black EPR, pink EPR, and brown EPR. The values for brown EPR are shown in Figure 9-1. While each criterion appears to be equally weighted, experience in evaluating test results indicates that the hierarchy of the acceptance criteria is to:

1. Assess the percent standard deviation at each voltage step (except the monitored withstand).
2. Evaluate the delta tan δ.
3. Consider the actual tan δ magnitude.



Condition	Tan δ		Absolute Value of the Difference in Tan δ Between 0.5 V_0 and 1.5 V_0 (2, 3)		Percent Standard Deviation of Tan δ Measurements at Any Step of Test Voltage
Good	≤50	and	≤5	or	≤0.02
Further study required	50, ≤60	or	>5, ≤15	or	>0.02, ≤0.04
Action required	>60	or	>15	or	>0.04

Notes for Table 5-4:

1. This is based on Figures C-3 and C-4 in EPRI report 1021070 [16] and consultation with tan δ testers.
2. Differentials may be taken at 1 V_0 and 2 V_0 at the user's option. See the text preceding these tables.
3. The difference in tan δ is normally positive. Negative differences should be treated as very significant and might indicate a problem with a test or the presence of a significant defect.

Figure 9-1
Tan δ acceptance criteria for brown EPR

The hierarchy of test result analysis is symbolized by the pyramid in Figure 9-2. The analysis of issues identified by testing shows that percent standard deviation and delta tan δ have always been the main indicators of more severe degradation than tan δ magnitude alone.

As discussed in Section 2, cables in "good" condition should not have any variation in test values recorded during any given voltage step. The fact that insulation tan δ magnitude is changing while the applied test voltage is being maintained constant is not expected and should be cause for concern. Note that the range of percent standard deviation between "good" and "action required" is minimal, which is indicative of its sensitivity.

Tan δ should neither increase nor decrease from one voltage step to the next in "good" insulation. While there is some tolerance for an increase in tan δ, this is not the case for decreasing tan δ during the test voltage sequence. Note three in Figure 9-1 warns that negative differences are an indication of the presence of a significant defect.

All cables evaluated with issues identified as unacceptable have never been flagged for high values of tan δ magnitude alone, but only in conjunction with one or both of the other criteria. In fact, high values of tan δ without the presence of instability or increasing values have been very limited.

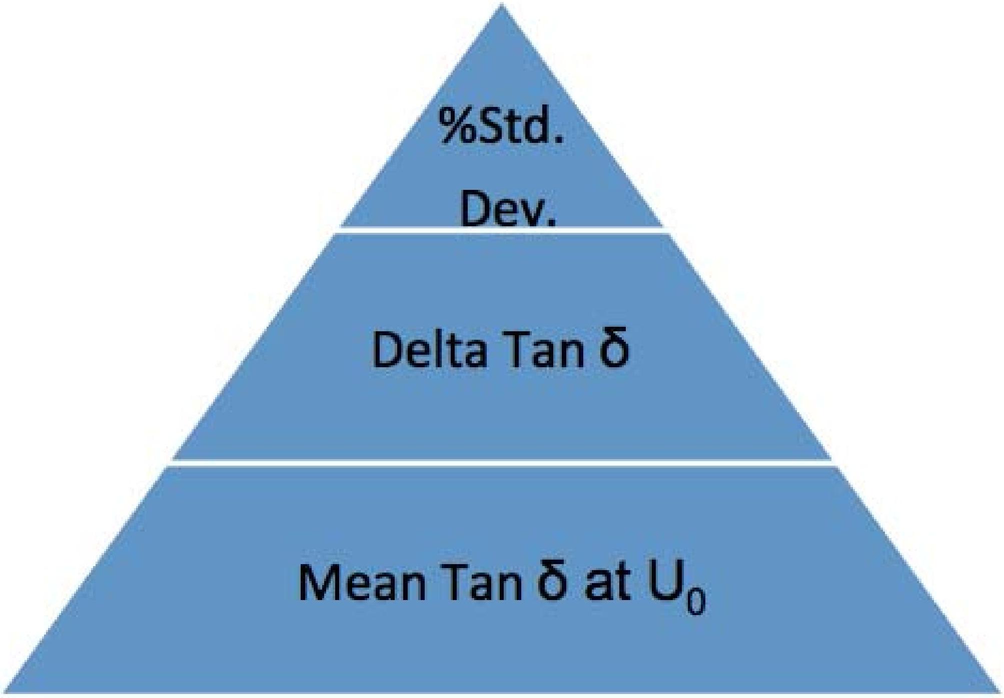


Figure 9-2
Tan δ acceptance test for "action required" cables by order of importance (from the top down)

9.1 Evaluating Causes for “Action Required” Percent Standard Deviation

The presence of percent standard deviation variations not due to cable degradation are either because of poor test setup or poor testing conditions.

Some causes of poor test setup are:

- Dirty terminations
- High humidity, rain, or other weather conditions causing condensation or moisture on terminations
- Test lead crossing or touching ground, causing variations in test data
- Lack of clearance between the cable under test and ground or other cables, causing tracking

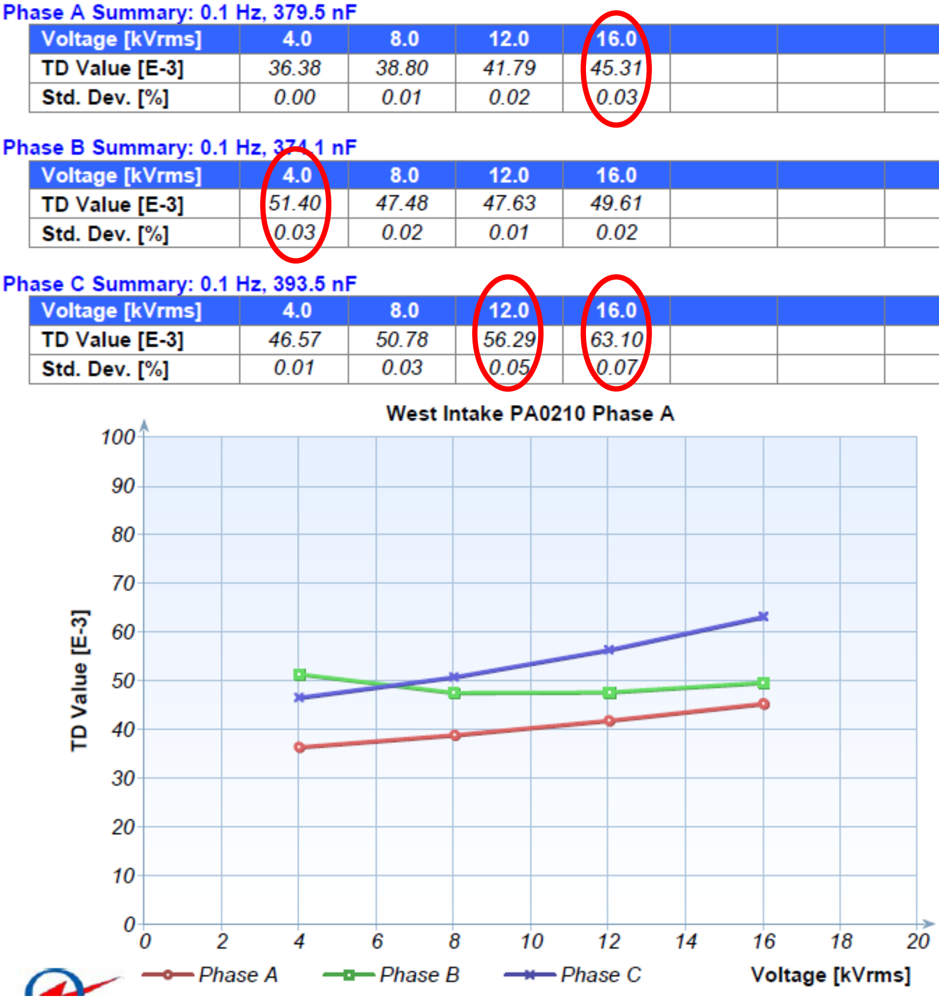
The issues above should be identified and eliminated while the cables are still being tested, so that later test results can be properly evaluated and the causes above will not be misinterpreted as cable issues.

If the percent standard deviation is due to the cable, terminations, or splices; the cause of cable degradation identified by percent standard deviation could be one of the following:

- Moisture intrusion of a splice or termination
- Tracking or arcing of a splice or termination
- Human performance error by the splicer

9.1.1 Evaluation of Percent Standard Deviation Test Results

Figure 9-3 shows a typical example of percent standard deviation’s importance. In this example, both tan δ at U_0 and delta tan δ are in the “good” range. However, the red-circled percent standard deviation values are in either the “further study required” or “action required” range for brown EPR (see Figure 9-1 for criteria). There are several splices on this circuit and a pothead termination (outdoor potted, porcelain insulator) that could be the cause of these values.



Phase A Summary: 0.1 Hz, 379.5 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	36.38	38.80	41.79	45.31			
Std. Dev. [%]	0.00	0.01	0.02	0.03			

Phase B Summary: 0.1 Hz, 374.1 nF

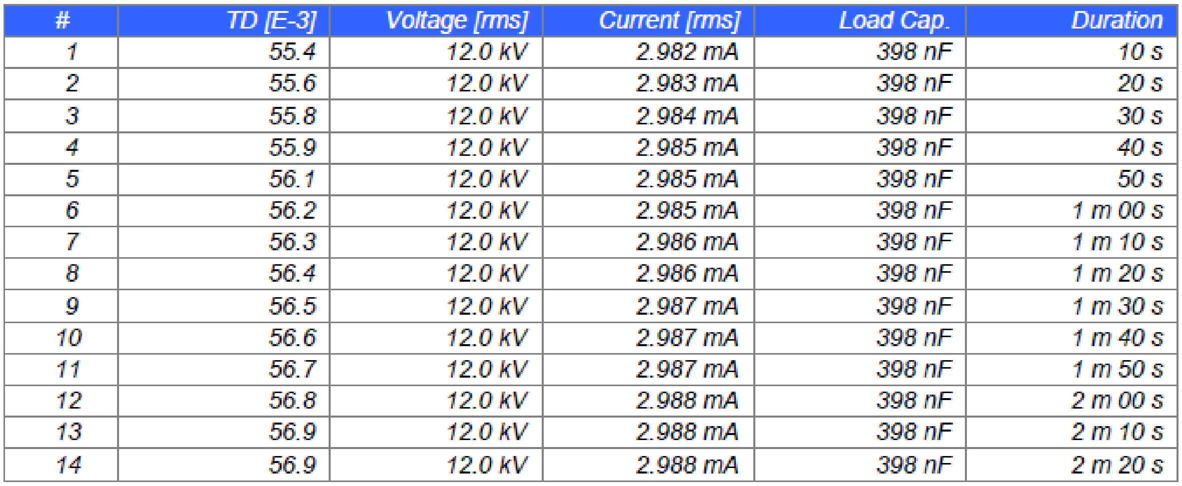
Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	51.40	47.48	47.63	49.61			
Std. Dev. [%]	0.03	0.02	0.01	0.02			

Phase C Summary: 0.1 Hz, 393.5 nF

Voltage [kVrms]	4.0	8.0	12.0	16.0			
TD Value [E-3]	46.57	50.78	56.29	63.10			
Std. Dev. [%]	0.01	0.03	0.05	0.07			

Figure 9-3
Standard deviation shows termination degradation

The C phase, 16-kV voltage step results are shown in Figure 9-4. Note that percent standard deviation is increasing continuously during the step. This has been seen only in cases that have had splice or termination issues. The fact that it is continually increasing has been only in identified issues in terminations or splices where tracking or arcing was found or suspected.



#	TD [E-3]	Voltage [rms]	Current [rms]	Load Cap.	Duration
1	55.4	12.0 kV	2.982 mA	398 nF	10 s
2	55.6	12.0 kV	2.983 mA	398 nF	20 s
3	55.8	12.0 kV	2.984 mA	398 nF	30 s
4	55.9	12.0 kV	2.985 mA	398 nF	40 s
5	56.1	12.0 kV	2.985 mA	398 nF	50 s
6	56.2	12.0 kV	2.985 mA	398 nF	1 m 00 s
7	56.3	12.0 kV	2.986 mA	398 nF	1 m 10 s
8	56.4	12.0 kV	2.986 mA	398 nF	1 m 20 s
9	56.5	12.0 kV	2.987 mA	398 nF	1 m 30 s
10	56.6	12.0 kV	2.987 mA	398 nF	1 m 40 s
11	56.7	12.0 kV	2.987 mA	398 nF	1 m 50 s
12	56.8	12.0 kV	2.988 mA	398 nF	2 m 00 s
13	56.9	12.0 kV	2.988 mA	398 nF	2 m 10 s
14	56.9	12.0 kV	2.988 mA	398 nF	2 m 20 s

Figure 9-4
C phase tan δ results at the 16-kV voltage step shown in Figure 9-3, showing continuously increased percent standard deviation

Another common pattern for percent standard deviation is continuously decreasing tan δ values during a voltage step. Issues identified or suspected for this type of results were:

- Water intrusion into a splice
- Termination
- Large insulation defect
- Water tree

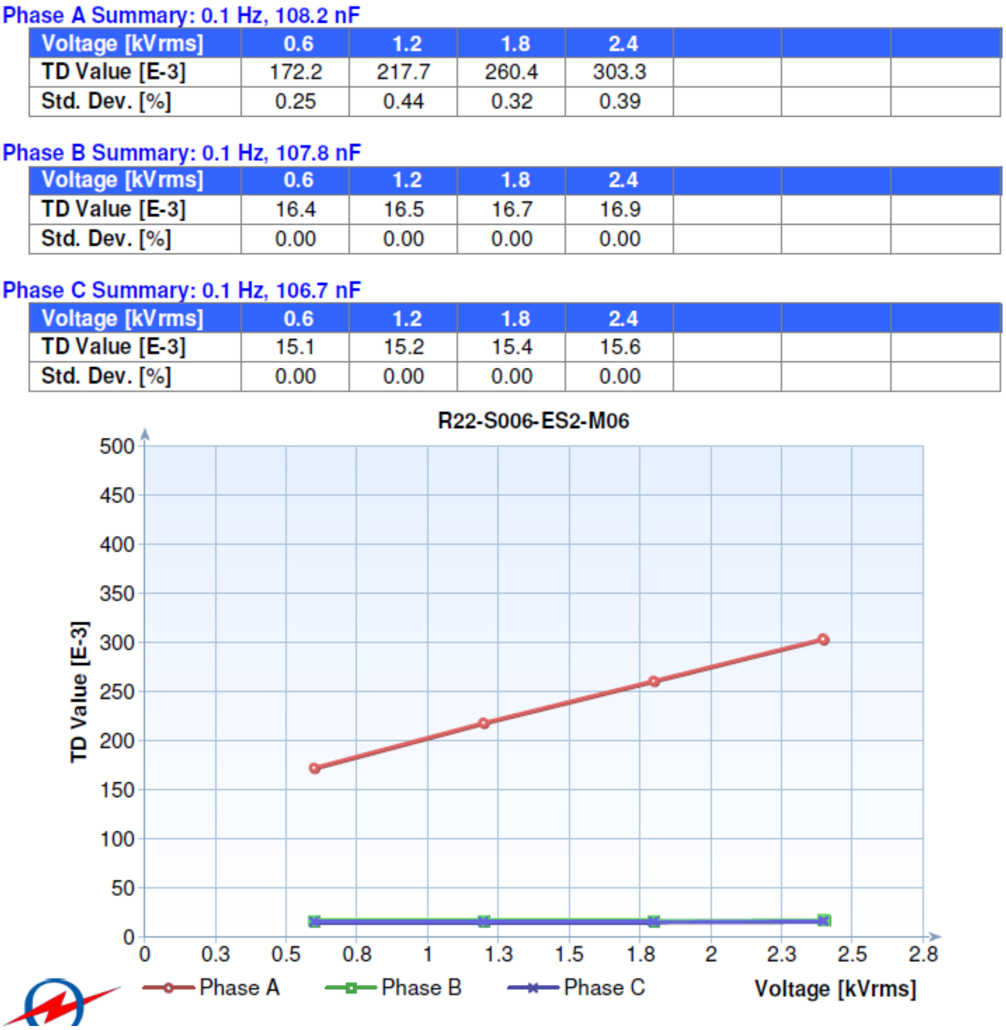
There have also been instances where the tan δ values fluctuate up and down during an applied voltage step. This has been seen in cases where test setup concerns were identified as the cause such as high humidity causing tracking on terminations, tracking to ground or adjacent conductors, or test leads in contact with ground potential.

9.2 Evaluating Causes for "Action Required" Delta Tan δ

Issues identified due to "action required" delta tan δ fall are either because of high magnitude or negative values. Both cases are proven indicators of severe degradation. High magnitude results have been spread across the range of issues identified (poor test setup; bad termination, splice, or insulation), but negative delta tan δ, in all cases, has been caused by a bad termination or splice.

9.2.1 Evaluation Delta Tan δ Test Results

Evaluation of issues identified for high, positive delta tan δ, falls into two classes. An example of even, continually increasing values at each voltage step is shown in Figure 9-5. The A phase values fall out on all three "action required" criteria, while the other two phases are "good." This test was of black EPR insulation. A phase was retested using the divide and conquer methodology[9] until a section with 50 feet (15.2 m) of degraded insulation was replaced. High positive delta tan δ has also been found in cases of degraded splice and terminations.



Phase A Summary: 0.1 Hz, 108.2 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	172.2	217.7	260.4	303.3			
Std. Dev. [%]	0.25	0.44	0.32	0.39			

Phase B Summary: 0.1 Hz, 107.8 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	16.4	16.5	16.7	16.9			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase C Summary: 0.1 Hz, 106.7 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	15.1	15.2	15.4	15.6			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Figure 9-5
"Action required" delta tan δ test results

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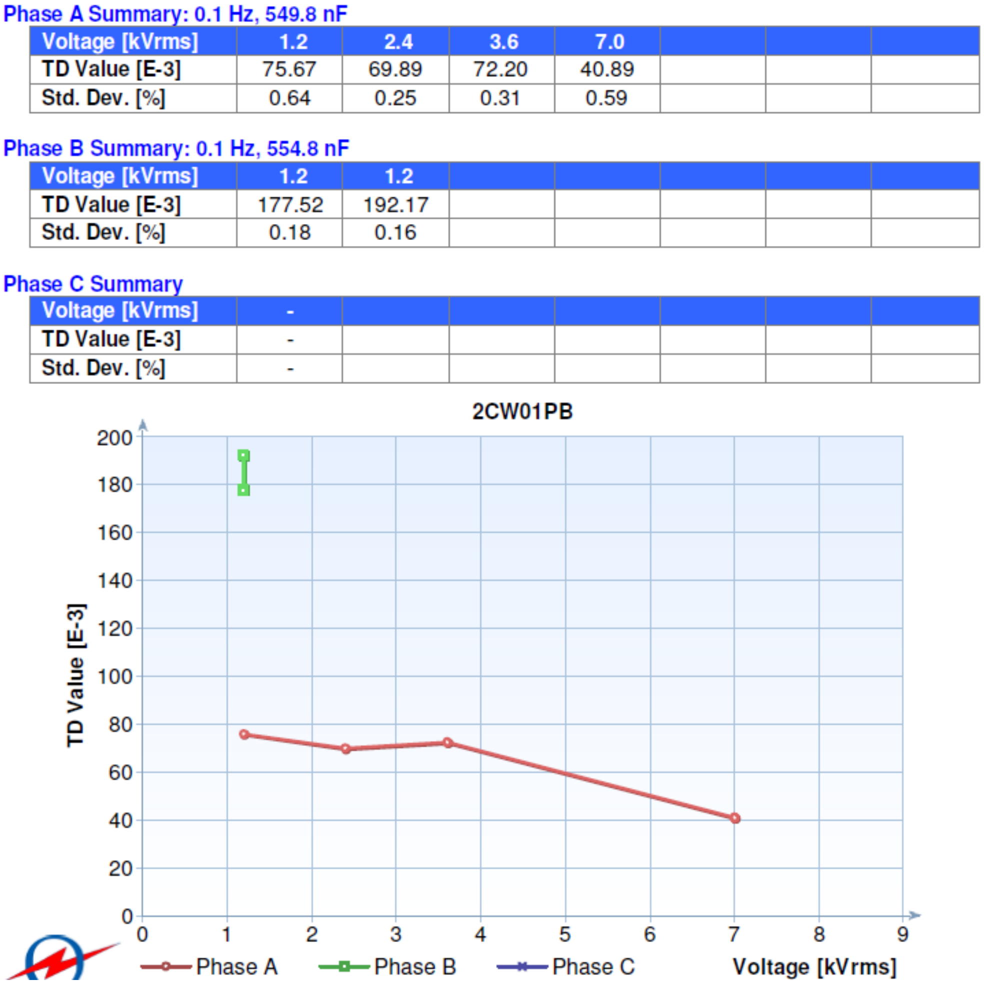
[9] The testing methodology is called *divide and conquer* when there are one or more splices in a circuit that can be opened and sections tested until the degraded section is isolated and removed.

The second example of delta tan δ issues identified had negative values. In every one of these cases evaluated, a bad splice or termination was involved as shown in Figure 9-6.



Phase A Summary: 0.1 Hz, 549.8 nF

Voltage [kVrms]	1.2	2.4	3.6	7.0			
TD Value [E-3]	75.67	69.89	72.20	40.89			
Std. Dev. [%]	0.64	0.25	0.31	0.59			

Phase B Summary: 0.1 Hz, 554.8 nF

Voltage [kVrms]	1.2	1.2					
TD Value [E-3]	177.52	192.17					
Std. Dev. [%]	0.18	0.16					

Phase C Summary

Voltage [kVrms]	-						
TD Value [E-3]	-						
Std. Dev. [%]	-						

Figure 9-6
Tan δ test with negative delta tan δ identified bad splice

Investigation targeted the terminations first, but the retest results were unchanged. The splices on all three phases were replaced, and the circuit was retested (Figure 9-7). The splices were forensically evaluated. The splice was not degraded, but the metallic shield was found to be discontinuous across the splice. The cable splice was reconfigured, and the cable subsequently tested almost like a new cable of this type.

Phase A Summary: 0.1 Hz, 548.4 nF

Voltage [kVrms]	1.2	2.4	3.6	7.0			
TD Value [E-3]	10.97	11.00	10.99	10.81			
Std. Dev. [%]	0.00	0.00	0.00	0.01			

Phase B Summary: 0.1 Hz, 554.1 nF

Voltage [kVrms]	1.2	2.4	3.6	7.0			
TD Value [E-3]	10.01	9.99	10.02	10.13			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

Phase C Summary: 0.1 Hz, 553.6 nF

Voltage [kVrms]	1.2	2.4	3.6	7.0			
TD Value [E-3]	9.30	9.31	9.33	9.46			
Std. Dev. [%]	0.00	0.00	0.00	0.00			

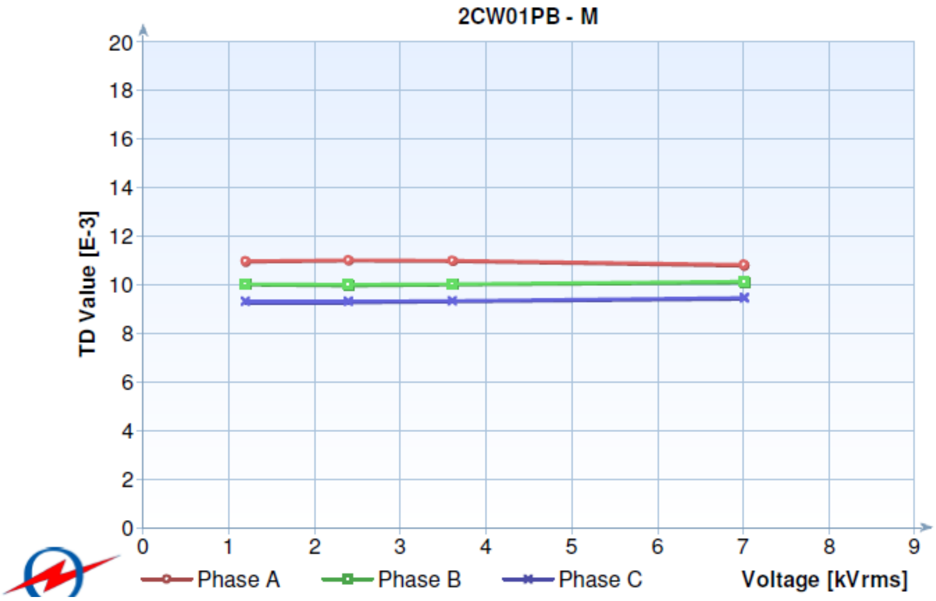


Figure 9-7
Cable with initial negative delta tan δ post-splice replacement results

Investigation into any test results with negative delta tan δ is recommended. Regardless of whether the cable contains splices, it is almost always easiest to confirm the termination condition first and then investigate the splice.

9.2.2 Summary

Tan δ testing evaluation of “action required” test results should follow the hierarchy shown in Figure 9-2, first evaluating for percent standard deviation followed by delta tan δ and then tan δ. This is because severely degraded cables always have high magnitude, but high magnitude cables are not always degraded if they do not have either or both “action required” percent standard deviation and “action required” delta tan δ .

Cables circuits with “action required” delta tan δ due to high values of delta tan δ are indicative of either degraded terminations, splices, insulation, or some combination of them. Cable circuits with negative delta tan δ values usually indicate a degraded termination or splice. It is important, however, to test the cable with the degraded accessory removed to verify that it is not masking degraded insulation.

9.2.3 Conclusions

Tan δ testing at 0.1 hertz when combined with withstand testing of medium-voltage cables has been successful in identifying degraded cables in new installations, wetted cable installations, and dry cable installations. Isolating the degraded sections can be done if one considers the most likely cause of degradation first (terminations and then splices). Sometimes, combining the visual inspection of splice and terminations with the “divide and conquer” technique, frequency domain reflectometry, or partial-discharge testing should be used to isolate the degraded part of the circuit.

There has been only one in-service cable failure among all the black, pink, and brown EPR insulated cables that were tan δ tested since 2009.[10] That non-critical cable was in the “action required” range and was scheduled for replacement. Otherwise, there have been no false positive “action required” cables for these cable types (based on those forensically tested). There have not been any false negatives or failures of cables in the “good” or “further study required” acceptance ranges either. Based on these facts, the reliability of medium-voltage cables is being adequately managed using tan δ testing for condition monitoring of cables using the EPRI-recommended acceptance criteria in EPRI report 3002000557 [10].

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[10] This does not include XLPE or compact design cables that have had false negative failures.

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