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

March 2020

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KK Anderson

Prepared for the U.S. Nuclear Regulatory Commission
under agreement NRC-HQ-25-14-D-0001,
Task Order No.: 31310018F0028
as requested in the Statement of Work for
Task Order No. NRC-HQ-60-16-T-0002

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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

Research conducted by the Electric Power Research Institute (EPRI) and other research institutions has concluded that water trees are one of the leading degradation mechanisms that contribute to the loss of dielectric insulation strength in medium-voltage cable insulating materials in wet or submerged environments. The electrochemical reactions are caused by the combined effect of water presence and relatively high electrical stress. Records of cable failures provided by the licensees in response to Generic Letter (GL) 2007-01 (NRC 2007) have called into question the reliability of medium-voltage cables in wet or submerged environments. EPRI's dissipation factor or Tan Delta testing guidelines and acceptance criteria have been adopted by most nuclear power plant operators as the primary tool for condition monitoring of medium-voltage cables in wet or submerged environments. EPRI has been collecting member data since late 2009 to analyze and provide feedback to members, validate the EPRI-developed acceptance criteria guidelines, support analysis of test results, recommend appropriate actions for the "action required" category, and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation.

EPRI has collected data from 37 nuclear sites, which represent 44 operating units. The test results have been organized by insulation type, such as cross-linked polyethylene (XLPE); butyl rubber; black, pink, and brown ethylene-propylene rubber (EPR); and compact insulation (black and pink EPR)[1]. The data have been analyzed, and follow-up information was obtained from members for "action required" test results. EPRI has also performed correlations between Tan Delta tests and the information gathered under the EPRI forensic research on medium-voltage cables. In addition, EPRI has developed guidance by cable insulation type on how to systematically analyze Tan Delta test results.

For the NRC to perform the evaluation of the EPRI criteria issued in reports 3002000557 and 3002005321, EPRI has agreed to provide the NRC with the Tan Delta data collected from the licensees. The objective of this project is to perform a statistical analysis to determine whether the Tan Delta test data collected by EPRI support the EPRI criteria issued in EPRI reports 3002000557 and 3002005321 to manage the aging of cables in submerged environments. The specific questions to be addressed are as follows:

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

The analysis described here reviewed the two primary EPRI reports (EPRI 3002000557 and EPRI 3002005321) as well as two precedent EPRI reports (EPRI 1028262 and EPRI 1021070) that were cited in the primary reports.

[1] The term 'compact' refers to the semiconductor and shield design as used by EPRI in reports referenced herein and as discussed in section 3.1. The 'compact' designator is applied to the cable design and compact design cables are referred to as 'EPR compact' or 'EPR compact cable' throughout this document.

The principal results and conclusions from the project analyses are as follows:

- Cable insulation degradation failures are relatively few during the first 10 years of cable service. Thereafter, however, there is no strong correlation between cable age and failure rate. The correlations between the Tan Delta test data and service year are at most 0.1 (low on the scale from −1 to +1, which is perfect negative to perfect positive correlation) when considered at the cable level and at the phase level.
- The threshold guidance set in EPRI report 3002005321 (EPRI 2015) has resulted in very few false positive and false negative calls. False positives are cables erroneously indicating a fault where forensic examination revealed no problematic degradation. Forensic investigations of cables identified as “repair or replace” have always identified cable segments with problems. The false positive rate is estimated to be less than 8.4% with 95% confidence. False negatives are cables testing “good” that were in a failed or degraded state. The false negative rate for cables testing “good” is less than 2.3% with 95% confidence. This implies that the guideline thresholds are appropriate.
- The test intervals recommended in EPRI report 3002000557 (EPRI 2013) and EPRI report 3002005321 (EPRI 2015) may be evaluated by considering the rates that cables testing “good” or “further study” subsequently fail within the suggested 6- or 2-year re-inspection intervals, respectively. The observed rate that cables testing “good” fail within 2 years is less than 1.79% with 95% confidence. The rate that cables testing “further study” fail within 6 years is less than 6.17% with 95% confidence. This implies that the overall testing interval guidelines are appropriate. The confidence intervals for the same analysis by specific insulation category are larger because there are fewer available data points for each individual insulation category in the available data (Table 4-5).
- Cable insulation degradation in the context of test interval guidance may be further understood by the data set consisting of multiple tests of the same cable. Across all cable types at the cable level, the probability of transitioning from “good” to “action required” within a 6-year re-inspection interval is estimated as 3/22 = 13.6%. Because of the uncertainty with the small sample size, the 95% confidence interval on that transition probability is (1.6%, 32.2%). Across all cable types at the cable level, the probability of transitioning from “further study” to “action required” within a 2-year re-inspection interval is estimated as 2/6 = 33.3% with a very wide 95% confidence interval (2.1%,73.9%). The small sample size prohibits any strong statement about the “further study” 2-year re-inspection interval.

Recommendation: Given the zero incidence of age-related Green to failure within 6 years or Yellow to failure within 2 years and the low incidence of false positives and false negatives, the EPRI guideline thresholds and intervals seem to be suitable. Continuing to collect Tan Delta and related cable failure data, particularly on cable insulation types for which there is currently limited data available, would allow statistical confidence intervals to be narrowed and thereby improve the confidence of the EPRI guidance assessment. Continued data collection is therefore recommended.

Acknowledgments

This work was performed with Contracting Officer Representative oversight provided by Darrell Murdock, Liliana Ramadan, and Eric Lysiak of the U.S. Nuclear Regulatory Commission (NRC). The authors would like to thank Susan Tackett, Catherine Himes, and Kay Hass for assistance in formatting and editing this document.

Acronyms and Abbreviations

CI	Confidence Interval
DOE	U.S. Department of Energy
EPR	Ethylene-propylene rubber
EPRI	Electric Power Research Institute
NDA	Non-Disclosure Agreement
NRC	U.S. Nuclear Regulatory Commission
P	Probability
PNNL	Pacific Northwest National Laboratory
Std. Dev.	Standard Deviation
Tan Delta	Cable test also referred to as dissipation factor test
VLF	Very low frequency
XLPE	Cross-linked polyethylene

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1.0 Introduction

Research conducted by the Electric Power Research Institute (EPRI) and other research institutions has concluded that water trees are one of the leading degradation mechanisms that contribute to the loss of dielectric insulation strength in medium-voltage cable insulating materials in wet or submerged environments. Water treeing is a phenomenon in which tree-like micro-voids are formed in electric cable insulation due to electrochemical reactions.

The electrochemical reactions are caused by the combined effect of water presence and relatively high electrical stress. The electrical stress is generally 480 V and above at local imperfections like voids and contaminants within the insulating materials and at areas of high mechanical stress such as bends. The breakdown of the dielectric insulating strength is commonly a result of water treeing. Water treeing is the absorption of water into the cable insulation which follows a tree-like branching pattern and can extend to the conductor. As the insulation degrades, electrical failures become more prevalent and the reliability of circuits can be compromised.

Based on operating experience, water treeing can occur in a variety of cable insulating materials including ethylene-propylene rubber (EPR), cross-linked polyethylene (XLPE), and tree-retardant (TR)-XLPE. Under wet conditions, several environmental and operational parameters can influence the rate at which water tree related degradation affects the cable insulation. These parameters include voltage cycling, field frequency, temperature, liquid ion concentration, and chemistry. Water trees increase in length with time and voltage level, and eventually can result in complete electrical breakdown of the cable insulation.

Records of cable failures provided by the licensees in response to Generic Letter (GL) 2007-01 (NRC 2007) have called into question the reliability of medium-voltage cables in wet or submerged environments. Concerns over the cable degrading to the point where a cable failure may occur when called upon to perform safety functions have reinforced the need for an aging management program to manage the aging of cable in wet or submerged environments.

EPRI’s dissipation factor or Tan Delta testing guidelines and acceptance criteria have been adopted by most nuclear power plant operators as the primary tool for condition monitoring of medium-voltage cables in wet or submerged environments. 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 the “action required” category, and gather candidate cables for EPRI-sponsored forensic research on causes for insulation degradation.

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

For the U.S. Nuclear Regulatory Commission (NRC) to perform the evaluation of the EPRI criteria issued in reports 3002000557 and 3002005321, EPRI has agreed to provide the NRC with the Tan Delta data collected from the licensees. The data that EPRI will provide to the NRC (and NRC contractor) will be comprised of the following parameters: Utility Name, Site Name, Years in Service, Equipment ID, Test Date, Cable Manufacturer, Cable Type, Cable Size, Cables Tested, Length of Cable, Voltage Rating, Maximum Test Voltage, Test Discussion, Tan Delta Value, Delta Tan Delta Value, and Standard Deviation Value.

2.0 Objective

The objective of this project is to perform a statistical analysis to determine whether the Tan Delta test data collected by EPRI supports the criteria issued in EPRI reports 3002000557 and 3002005321 to manage the aging of cables in submerged environments.

Based on the data collected by EPRI, determine if the EPRI recommended testing intervals in report 3002000557 for cables that test Green (good) and Yellow (further study) are suitable to manage the aging of cables in submerged environments. The contractor should identify instances in which there was a cable failure within the EPRI recommended testing interval for good (6 years) and further study (2 years).

Specific tasks are as follows:

Task 1a: Obtain the licensee-acquired Tan Delta test data results from EPRI. The DOE laboratory will be required to sign a Non-Disclosure Agreement (NDA) with EPRI to acquire the Tan Delta test data from EPRI.

Task 1b: Conduct an inspection and perform a statistical analysis of the Tan Delta test data acquired from EPRI to ensure that the Tan Delta test data is statistically significant.

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

Task 1d: Arrange the Tan Delta test data from XLPE, black EPR, butyl rubber, pink EPR, brown EPR, plus black and pink EPR compact cables into service age categories from 0-10 years, 10-20 years, 20-30 years, 30-40 years, 40-50 years, and 50-60 years.

For each of the cable types within the in-service age groups (0-10, 10-20, 20-30, 30-40, 40-50, and 50-60), determine the total number of cables tested.

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

3.0 Reports Reviewed

The initial charter was to consider data and analysis from:

- EPRI report 3002000557, Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Plants, Revision 1. (EPRI 2013)
- EPRI report 1028262, Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis. (EPRI 2012)

These reports were transferred under a September 2018 NDA. Review and discussion of these data prompted consideration of two additional reference documents shown directly below. These documents were covered under a subsequent December 2018 NDA again between EPRI and Pacific Northwest National Laboratory (PNNL). Completing these two NDAs fulfilled the objective 1a.

- EPRI report TR-1021070, Medium-Voltage Cable Aging Management Guide, Revision 1. (EPRI 2010)
- EPRI report 3002005321, Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis - Update. (EPRI 2015)

3.1 Overview of EPRI Report 3002000557; Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1

This report (EPRI 2013) provides guidance for developing and implementing a cable aging management program for medium-voltage cable circuits in nuclear power plants. It incorporates lessons learned from the initial implementation of aging management programs and additional EPRI technical findings. Medium-voltage cables are defined as those rated 5 kV to 46 kV, with operating voltages from 2.3 kV to 34 kV.

The Compact Design Cable Construction is a designation that EPRI uses in the reviewed reports (3002000557, 1028262). Compact design EPR cable differs from standard MV EPR cable in the construction of its semiconducting layers that can lead to an additional layer separation failure mechanism. Further information on cables of this designation may be found in the EPRI 2013 report 3002000554 Plant Engineering: Medium-Voltage Cable Failure Mechanism Research, Update 5, that states:

> “The cable manufactured in 1987 has extruded insulation shield of thickness 33 mil (0.84 mm) consisting of thermoplastic chlorinated polyethylene. In a separate process, 90 mil (2.3 mm) of semiconducting thermoset chlorinated polyethylene was extruded over six corrugated copper wires. That layer served as cable jacket. Together with insulation shield, these two semiconducting layers had thickness of about 120 mil (3.0 mm). The thickness of extruded insulation shields of medium voltage cable is usually about 30 mil (0.76 mm). This means that semiconducting layers covering the insulation in the compact design cable are about four times thicker than the semiconducting layer on cable on non-compact design.” (pg 4-2), and

> “Medium voltage cables used in nuclear plants were expected to have very long lives, at least the 40 years of the initial licensed period. The cable of compact design is of interest because it has had quite extensive operating experience of in-service failures over a wide

> range of service lives. Also, this cable construction seems to not benefit from a switch from black to pink insulation as the failure rate of pink EPR compact design cable remains unacceptably high." (pg 4-3), and
>
> "Compact design EPR cable insulation, as all polymeric insulation, suffers from water tree formations in wet electrical aging. The formation of water trees is a discrete phenomenon.
>
> In addition, in the cable of compact design there is another mechanism of insulation degradation related to propensity of this design's insulation shield to separate from the insulation. Such separation was observed on long length of some of these cables. The research shows that de-lamination at the insulation shield interface to the insulation leads to partial discharges which results in the disintegration of ethylene-propylene part of the insulation at these locations. What remains is the white insulation filler which is not affected by partial discharge. The end result is that only about half of the original insulation wall remains. The combinations of these two phenomena are the key reasons for the relative short lifetime of wet-aged compact design cable that have been evaluated, 22-29 years." (pg 4-8)

Tan Delta criteria are noted to have been validated through EPRI report 1025262. The 3002000557 report notes "The program is intended to identify adverse localized environments and adverse service conditions that could lead to early failure of medium-voltage cable circuits to manage significant aging effects to preclude in-service failure". The text goes on to state:

> "However, cables or accessories that are subject to adverse conditions should be governed by an aging management program [to ensure their operability]. The following are recognized adverse conditions with respect to the longevity of medium-voltage cable circuits:
>
> - Adverse localized high temperature and/or high radiation ambient environments under normal operating conditions
> - High conductor temperature from ohmic heating
> - High-resistance connections at terminations or splices
> - Long-term submergence (partial or full submergence).
>
> …The presence or absence of these conditions can be determined by inspection and analysis, environmental monitoring, or infrared thermography. If one or more adverse conditions are observed, further assessment, testing, and/or corrective action will be necessary to ensure reliability, unless the cable and/or its accessories have been designed for the conditions".

Adverse conditions are specifically described for various cable materials and manufacturers along with information about the oldest cables in plants, information about the earliest expected onset of water degradation, and a discussion of industry experience.

Three practical tests are currently available for shielded extruded polymer medium-voltage cable: partial discharge, Tan Delta, and power frequency or very low frequency (VLF) withstand. Partial discharge testing may be most useful in detecting termination and splice problems, but water-related degradation such as water treeing does not produce partial discharge signals. VLF withstand testing applies an elevated voltage across an insulation for a significant period to purposely identify the presence of a significantly weakened location in the insulation that will break down during the test. This test is a go/no-go test and detects localized, significant degradation or defects but provides no information concerning widespread, low-level water degradation. As the focus of this report is on Tan Delta, further summary comments related to 3002000557 will primarily relate to Tan Delta. The Tan Delta test (also referred to as a dissipation factor test) determines the ratio of resistive leakage current through the insulation to the capacitive current and provides a figure of merit relating to the condition of the insulation. The measurement is independent of the cable length excepting the practical consideration of the Tan Delta instrument that the capacitance is greater than ~ 0.1 nF (which corresponds to ~ 50-ft.). Tan Delta has no units and is generally a small number given in terms of 10^{-3}. Tan Delta is a bulk test and does not provide location information for the degradation. It can be performed at line frequency or VLF frequencies and is generally performed at levels of 0.5, 1.0, 1.5, and 2 times line-to-ground operating voltage (V_0). Tan Delta values that are elevated or unstable at a particular test voltage or values that increase or decrease with increasing voltage are indicative of deteriorated insulation. This test can identify insulation systems with distributed water-related degradation. If, however, a cable insulation system has only a single flaw, Tan Delta may not detect it even if it is significant. In addition, the test does not discriminate between many widespread degradation or defects and a smaller number of more severely degraded regions. Assessment of Tan Delta requires consideration of the absolute Tan Delta reading, the delta Tan Delta, and the % standard deviation in the Tan Delta reading. If any of these are in either “further study required” or “action required”, the more stringent range applies to the circuit assessment. The threshold guidance is provided in separate tables for XLPE, butyl rubber and black EPR, pink EPR, and brown EPR as shown in Tables 3-1 through 3-4.

Table 3-1. Tan Delta Assessment Criteria for Cross-Linked Polyethylene (XLPE) (@; 0.1 Hz test frequency)

Condition	Tan Delta		Absolute Value of the Difference in Tan Delta between 0.5 V_0 and 1.5 V_0 (1,2)		Percent Standard Deviation of Tan Delta Measurements at any Step of Test Voltage
Good	$\leq$ 1.2	and	$\leq$ 0.6	or	$\leq$ 0.02
Further study required	1.2 < × $\leq$ 2.2	or	0.6 < × $\leq$ 1.0	or	0.02 < × $\leq$ 0.04
Action required	> 2.2	or	> 1.0	or	> 0.04

Notes for Table 3-1:

1. Differentials may be taken at 1 V_0 and 2 V_0 at user option. See the text preceding this table.
2. The difference in Tan Delta is normally positive. Negative differences should be treated as very significant and might indicate either a problem with a test or the presence of a significant defect.

Table 3-2. Tan Delta Assessment Criteria for Butyl rubber and Black EPR (@ 0.1 Hz test frequency)

Condition	Tan Delta		Absolute Value of the Difference in Tan Delta between $0.5V_0$ and $1.5\ V_0$ $^{(1,2)}$		Percent Standard Deviation of Tan Delta Measurements at any Step of Test Voltage
Good	≤ 12	and	≤ 3	or	≤ 0.02
Further study required	$12 < \times \leq 50$	or	$3 < \times \leq 10$	or	$0.02 < \times \leq 0.04$
Action required	> 50	or	> 10	or	> 0.04

Notes for Table 3-2:

1. This is based on analysis performed in EPRI report 1025262.
2. Differentials maybe taken at 1 V_0 and 2 V_0 at user option. See the text preceding this table.
3. The difference in Tan Delta is normally positive. Negative differences should be treated as very significant and might indicate either a problem with a test or the presence of a significant defect.

Table 3-3. Tan Delta Assessment Criteria for Pink EPR[1] (@ 0.1 Hz test frequency)[2]

Condition	Tan Delta		Absolute Value of the Difference in Tan Delta between 0. $5V_0$ and $1.5\ V_0$ $^{(3,4)}$		Percent Standard Deviation of Tan Delta Measurements at any Step of Test Voltage
Good	≤ 15	and	≤ 3	or	≤ 0.02
Further study required	$15 < \times \leq 30$	or	$3 < \times \leq 8$	or	$0.02 < \times \leq 0.04$
Action required	>30	or	> 8	or	>0.04

Notes for Table 3-3:

1. This may also be used for “Gray” UniBlend EPR (The approximate dates of manufacture are from the late 1970s on).
2. This is based on analysis performed in EPRI report 1025262.
3. Differentials maybe taken at 1 V_0 and 2 V_0 at user option. See the text preceding this table.
4. The difference in Tan Delta is normally positive. Negative differences should be treated as very significant and might indicate either a problem with a test or the presence of a significant defect.

Table 3-4. Tan Delta Assessment Criteria for Brown EPR (@ 0.1 Hz test frequency)[1]

Condition	Tan Delta		Absolute Value of the Difference in Tan Delta between 0.5 V_0 and 1.5 V_0[(1,2)]		Percent Standard Deviation of Tan Delta Measurements at any Step of Test Voltage
Good	≤ 50	and	≤ 5	or	≤ 0.02
Further study required	$>50 < \times \leq 60$	or	$5 < \times \leq 15$	or	$0.02 < \times \leq 0.04$
Action required	> 60	or	> 15	or	> 0.04

Notes for Table 3-4:

1. This is based on analysis performed in EPRI report 1021070 and consultation with Tan Delta testers.
2. Differentials maybe taken at 1 V_0 and 2 V_0 at user's option. See the text preceding this table.
3. The difference in Tan Delta is normally positive. Negative differences should be treated as very significant and might indicate a problem with a test or presence of a significant defect

Based on currently available operating experience, the onset of degradation for cables that have successfully passed installation testing and initial condition assessment should not occur until cables are 20-30 years old. Based on this expected age for onset of degradation, a prudent approach for cables in the scope of cable aging management program would be to perform testing after they are in service for 10 years, but prior to 20 years of service. Once cables reach that point where they are being monitored under the cable aging management program, they should be retested on a six-year frequency if they continue to test "good".

Cables with results in the "further study required" range should be subjected to more frequent testing (for example, every two years or once per refueling cycle) to determine whether the condition is stable or worsening. Consideration should be given to performing a VLF withstand test should a "further study required" result occur.

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

3.2 Overview of EPRI Report 1028262 Plant Engineering; Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis

This report EPRI (2012) provides an analysis of Tan Delta test data that were provided by EPRI member utilities between 2009 and 2012 for cables mainly in adverse wet environments. The data represents more than 700 individual cable tests. The analysis performed is an evaluation and validation of the assessment criteria provided in the EPRI report 1020805 Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants. The report also describes insights gained and lessons learned from analysis of the test results.

The data are specifically applicable to four rubber insulation types in roughly the same proportion; XLPE, pink EPR, black EPR, and butyl rubber. In addition, a smaller amount of data (7%) was provided on brown EPR. Degradation was categorized as termination, splice, and insulation deterioration. The Tan Delta tests yielded 12.1% overall action required however only 6.6% of the population were insulation deterioration related. Although these percentages are relatively high, this was not unexpected since the test population primarily included cables that were 25-35 years old. Examples of these results are shown versus the evaluation criteria in Figure 3-1 through Figure 3-6.

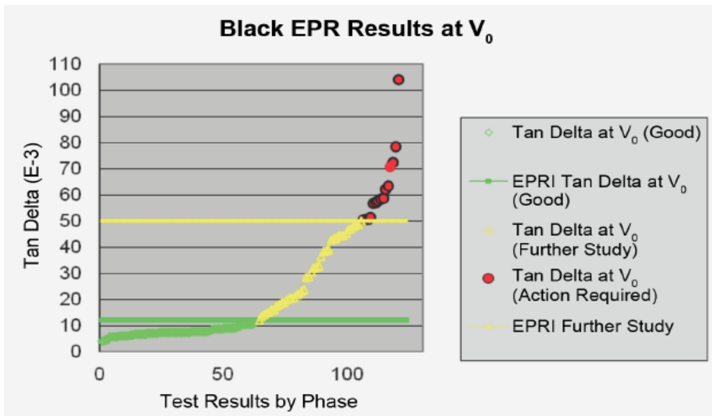

Figure 3-1. Black EPR Tan Delta Results Versus Evaluation Criteria

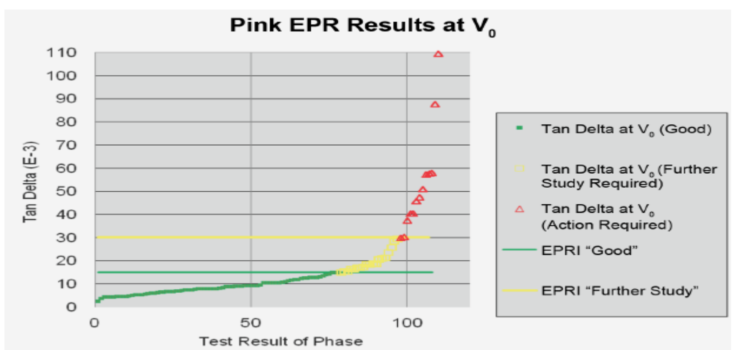

Figure 3-2. Pink EPR Tan Delta Results Versus Evaluation Criteria

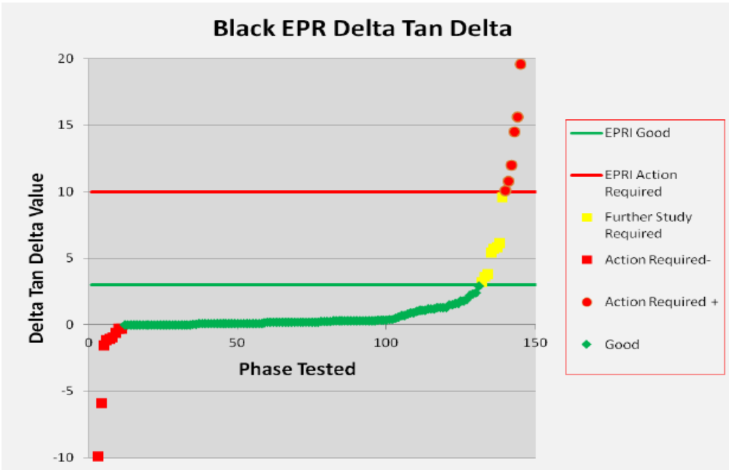

Figure 3-3. Black EPR Delta Tan Delta Results Versus Evaluation Criteria

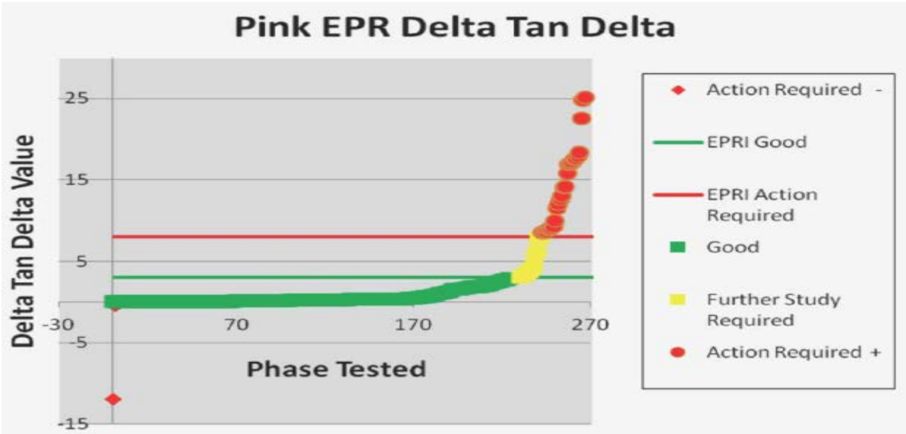

Figure 3-4. Pink EPR Delta Tan Delta Versus Evaluation Criteria

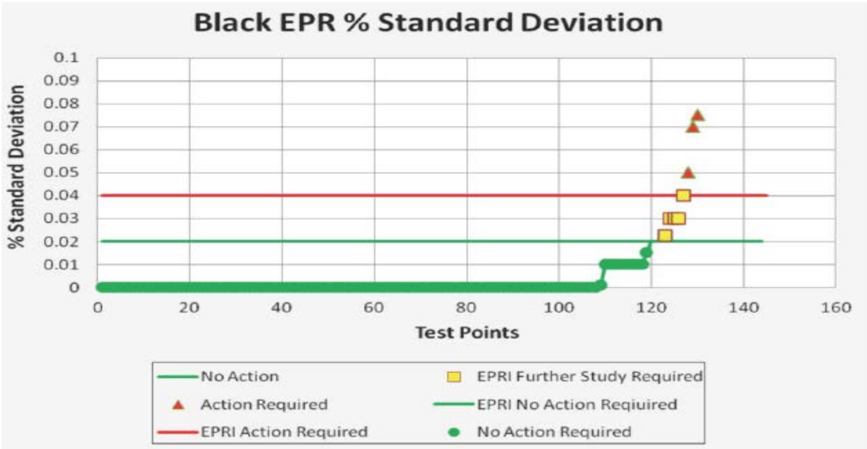

Figure 3-5. Black EPR % Standard Deviation Versus Evaluation Criteria

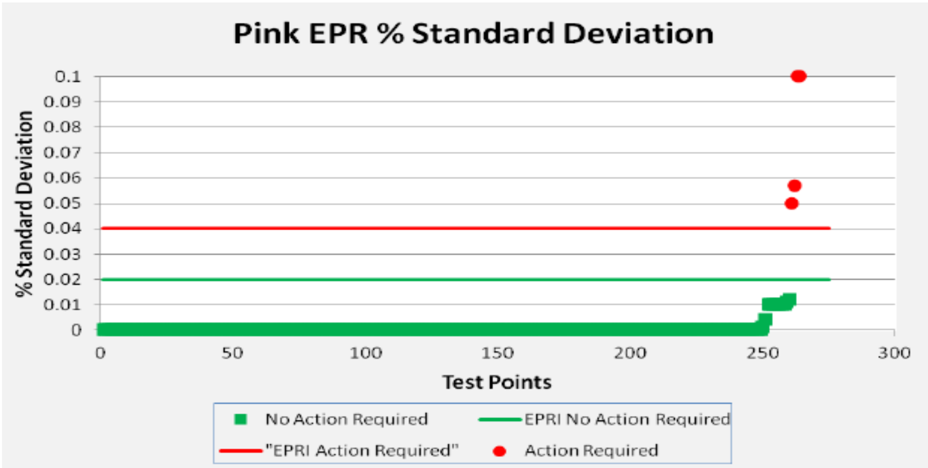

Figure 3-6. Pink EPR % Standard Deviation Versus Evaluation Criteria

3.3 Overview of EPRI Report 3002005321; Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis – Update

This report (EPRI 2015) provided an evaluation and analysis of nearly 580 Tan Delta tests collected from nuclear power plant testing of medium-voltage shielded power cables collected between 2009 and 2012. Tan Delta testing at 0.1 Hz combined with 0.1 Hz withstand testing has been adopted by most nuclear power plant operators as the primary tool for condition monitoring of medium-voltage shielded power cables. The information was used to assess correlations between Tan Delta results and the forensic research to provide insights on how to systematically analyze Tan Delta results. The data used in this report is included within the data provided to PNNL for this report's analysis. Important conclusions and findings were:

- Of the 34 (6% of test population) "action required" findings, approximately half were forensically determined to be related to splices or terminations leaving the other half of these indications to be insulation aging related.
- There were two false negative tests (failures of cables that tested good or slightly degraded) in XLPE insulated cables. There were no false negative tests for brown, black, or pink EPR or butyl rubber insulated cables.
- No false positives (at least one degraded insulation defect) were found in any of the forensically evaluated circuits in the immediate "action required" category.
- The Tan Delta tests identified dry cable issues of thermal degradation, splice defects, and insulation degradation confirming that Tan Delta testing can identify more than water-related degradation.
- All the cables identified with degraded insulation that were provided to EPRI for independent forensic evaluation had at least one degraded insulation site identified.
- There was only one in-service cable failure among all the black, pink, and brown EPR insulated cables that were tested between 2009 and 2012. That non-critical cable was in the "action required" range and was scheduled for replacement. Otherwise, there were no false positive "action required" cables for these cable types (based on those forensically tested).

- The forensic results also indicated that insulation degradation is localized and not distributed. This indicates that EPR insulations do not age uniformly (non-homogeneous aging).
- A correlation was made for black EPR and butyl rubber by using a short section of cable in the lab between high Tan Delta values and low alternating current breakdown strength: this further confirms Tan Delta testing's use for cable condition monitoring.

The balance of these results affirms the reliability of Tan Delta testing in accordance with guidance from (EPRI 2013).

The threshold guidance for black and pink EPR compact cables were added to the test guidelines as shown in Table 3-5. The threshold guidance for XLPE, butyl rubber and black EPR, pink EPR, and brown EPR as shown in Tables 3-1 through 3-4 were repeated in EPRI 3002005321 and were unchanged from EPRI 3002000557.

Table 3-5. Tan Delta Assessment Criteria for Black and Pink EPR Compact Cables (@ 0.1 Hz test frequency)

Condition	Tan Delta		Absolute Value of the Difference in Tan Delta between 0.5 V_0 and 1.5 V_0 (1,2)		Percent Standard Deviation of Tan Delta Measurements at any Step of Test Voltage
Good	≤ 15	and	≤ 3	or	≤ 0.02
Further study required	$15 < \times \leq 30$	or	$3 < \times \leq 8$	or	$0.02 < \times \leq 0.04$
Action required	> 30	or	> 8	or	> 0.04

Notes for Table 3-5:

1. Differentials may be taken at 1 V_0 and 2 V_0 at user option. See the text preceding this table.
2. The difference in Tan Delta is normally positive. Negative differences should be treated as very significant and might indicate either a problem with a test or the presence of a significant defect.

3.4 Overview of EPRI Report 1021070; Medium-Voltage Cable Aging Management Guide, Revision 1

This report EPRI (2010) focuses on nuclear power industry cable and conditions that challenge them. One part of the analysis included a tabulation of cable failures versus years of service. Very few failures were observed during the first 10 years of service. Thereafter, varying frequencies of cable failures are observed. The correlation between age and failure frequency is not obvious.

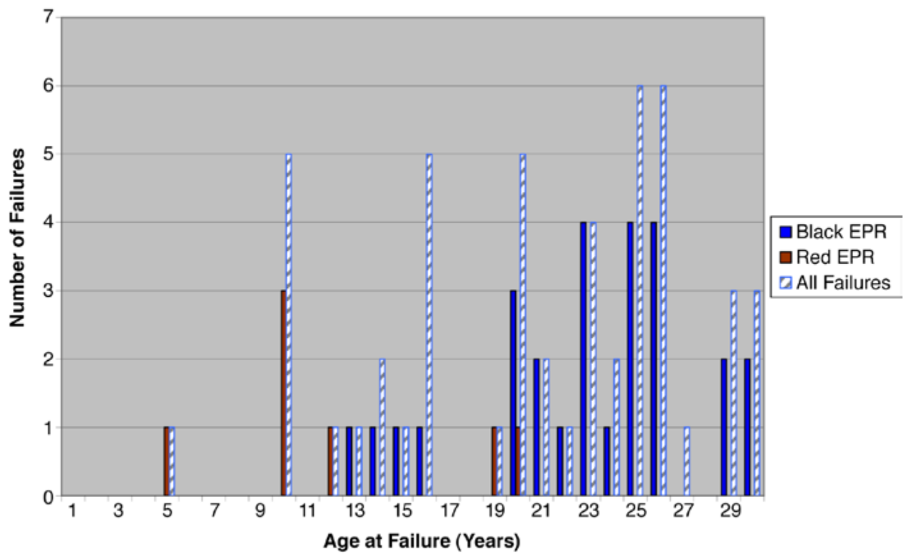

Figure 3-7. Example Plot of EPR Cable Years of Service Versus Number of Failures (from EPRI 2010 report 1021070)

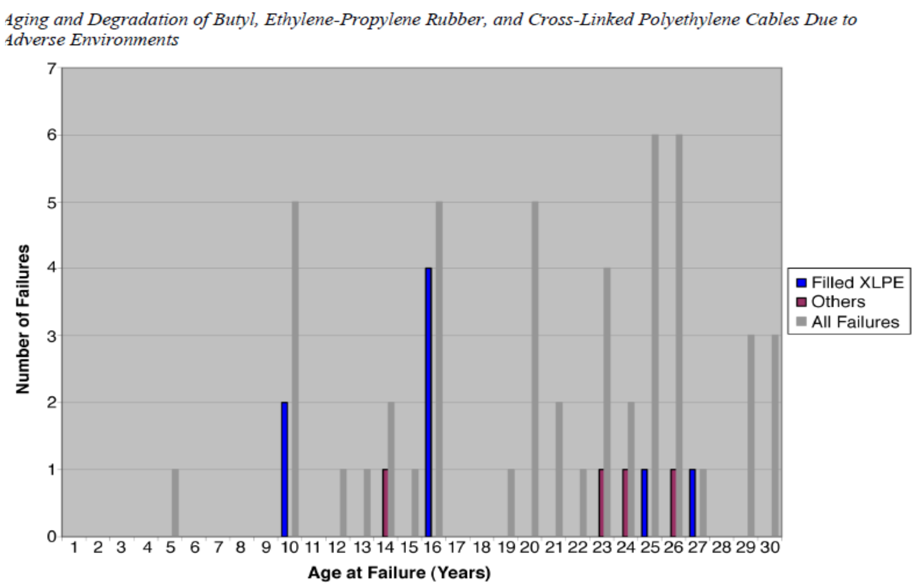

Figure 3-8. Example Plot of XLPE Years of Service Versus Number of Failures (from EPRI 2010 report 1021070)

This report also includes information about cable design, grounding systems, in-plant stresses, assessments of age-related failures versus workmanship or rodent related failures and a number of practical subjects of interest to cable aging management programs. The report discusses historical evolution of fillers resulting in several color classes of EPR and some distinctions between XLPE and EPR. The different fillers, constituent elements, and fabrication practices of the different insulation varieties result in different dielectric characteristics and damage susceptibility. The electrical behavior differences among materials result in differences in characteristic Tan Delta values for each material and material-specific Tan Delta guidelines among the various classes of cable insulation.

4.0 PNNL Statistical Data Review and Analysis

A data table was supplied by EPRI that included 471 cable test entries that were addressed by the test guidelines. An additional 81 entries were provided that did not match the cable test guideline descriptors (i.e. Black Hybrid EPR, Black Non-shielded EPR, Pink/Brown Hybrid EPR, etc.) and therefore were not included in the statistical review. Many of these cables were three-phase bundled cables thereby offering essentially three separate tests even though all phases were within the same cable assembly. Information in this data table included:

- Company Name (by number to preserve anonymity)
- Site (by number to preserve anonymity)
- Years in Service
- Equipment ID
- Test Date
- Cable Manufacturer
- Cable type
- Cable type categories
- Cable size
- Voltage rating
- Max Test voltage
- Tan Delta (for each phase)
- Delta Tan Delta (for each phase)
- Standard Deviation (for each phase)
- Withstand test (if performed)
- Test discussion
- Actions taken

As per Task 1d, the initial analysis was to summarize the EPRI data table by the in-service age categories (0-10, 10-20, 20-30, 30-40, 40-50, and 50-60 years) and the cable types with respect to how many of the test results by cable were within the green, yellow and red categories or were reported to have failed (denoted as the “black” category). See Table 4-1 below. The bulk of the data (160+203)/439 or 83%) fell within the 20-30 and 30-40 years in-service age categories. No data was available within the 50-60 years category. As the interest is primarily in age-related issues, where yellow, red, or failures were observed that were associated with terminations, splices, rodents, or other non-age-related issues, they were removed from the samples. These data are referred to as “filtered” data. The full (unfiltered) data set without removal of these non-age-related issues are included in Appendix A.

Table 4-1. Filtered Data Table Summarization at the Cable Level

Cable Age Range	Cable Type	Total # of Cables	% (Green or Good)	% (Yellow or Further Study)	% (Red or Action Required)	% (Black or Failed)
(0-10)	Black EPR	0	NA	NA	NA	NA
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	9	100%	0%	0%	0%
	Brown EPR	1	0%	0%	100%	0%
	Pink EPR	30	80%	7%	13%	0%
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	0	NA	NA	NA	NA
	Black and pink EPR compact	10	100%	0%	0%	0%
	All	40	83%	5%	13%	0%
(10-20)	Black EPR	1	100%	0%	0%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	5	40%	60%	0%	0%
	Brown EPR	0	NA	NA	NA	NA
	Pink EPR	0	NA	NA	NA	NA
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	1	100%	0%	0%	0%
	Black and pink EPR compact	5	40%	60%	0%	0%
	All	6	50%	50%	0%	0%
(20-30)	Black EPR	19	89%	5%	5%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	2	100%`	0%	0%	0%
	Pink EPR compact	55	60%	9%	27%	4%
	Brown EPR	16	75%	13%	13%	0%
	Pink EPR	67	54%	7%	37%	1%
	XLPE	1	100%	0%	0%	0%
	Butyl rubber and black EPR	19	89%	5%	5%	0%
	Black and pink EPR compact	57	61%	9%	26%	4%
	All	160	63%	8%	27%	2%
(30-40)	Black EPR	96	47%	15%	38%	1%
	Butyl rubber	6	0%	100%	0%	0%
	Black EPR compact	14	64%	7%	21%	7%

Cable Age Range	Cable Type	Total # of Cables	% (Green or Good)	% (Yellow or Further Study)	% (Red or Action Required)	% (Black or Failed)
	Pink EPR compact	5	80%	0%	20%	0%
	Brown EPR	14	21%	21%	57%	0%
	Pink EPR	60	87%	5%	8%	0%
	XLPE	8	38%	13%	50%	0%
	Butyl rubber and black EPR	102	44%	20%	35%	1%
	Black and pink EPR compact	19	68%	5%	21%	5%
	All	203	57%	14%	28%	1%
(40-50)	Black EPR	10	30%	10%	60%	0%
	Butyl rubber	8	50%	50%	0%	0%
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	0	NA	NA	NA	NA
	Brown EPR	8	88%	13%	0%	0%
	Pink EPR	3	67%	0%	33%	0%
	XLPE	1	0%	0%	100%	0%
	Butyl rubber and black EPR	18	39%	28%	33%	0%
	Black and pink EPR compact	0	NA	NA	NA	0%
	All	30	53%	20%	27%	0%

Treating each phase separately, the Task 1d phase results are shown in Table 4-2 below:

Table 4-2. Filtered Data Table Summarization at the Phase Level

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Black or Failed)
(0-10)	Black EPR	0	NA	NA	NA	NA
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	25	100%	0%	0%	0%
	Brown EPR	3	67%	0%	33%	0%
	Pink EPR	88	85%	5%	10%	0%
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	0	NA	NA	NA	NA
	Black and pink EPR compact	25	100%	0%	0%	0%
	All	116	88%	3%	9%	0%
(10-20)	Black EPR	3	100%	0%	0%	0%

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Black or Failed)
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	15	53%	47%	0%	0%
	Brown EPR	0	NA	NA	NA	NA
	Pink EPR	0	NA	NA	NA	NA
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	3	100%	0%	0%	0%
	Black and pink EPR compact	15	53%	47%	0%	0%
	All	18	61%	39%	0%	0%
(20-30)	Black EPR	57	96%	2%	2%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	6	100%`	0%	0%	0%
	Pink EPR compact	164	71%	11%	16%	1%
	Brown EPR	48	88%	4%	8%	2%
	Pink EPR	186	63%	8%	28%	1%
	XLPE	3	100%	0%	0%	0%
	Butyl rubber and black EPR	57	96%	2%	2%	0%
	Black and pink EPR compact	170	72%	11%	16%	1%
	All	464	73%	8%	18%	1%
(30-40)	Black EPR	284	64%	17%	19%	0.4%
	Butyl rubber	18	0%	100%	0%	0%
	Black EPR compact	42	88%	2%	7%	2%
	Pink EPR compact	10	70%	0%	30%	0%
	Brown EPR	36	31%	17%	53%	0%
	Pink EPR	164	92%	4%	4%	0%
	XLPE	24	54%	4%	42%	0%
	Butyl rubber and black EPR	302	60%	22%	18%	0.3%
	Black and pink EPR compact	52	85%	2%	12%	2%
	All	578	69%	14%	16%	0.3%
(40-50)	Black EPR	30	57%	17%	27%	0%
	Butyl rubber	24	67%	33%	0%	0%
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	0	NA	NA	NA	NA
	Brown EPR	22	95%	5%	11%	0%

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Black or Failed)
	Pink EPR	9	78%	11%	11%	0%
	XLPE	3	0%	0%	100%	0%
	Butyl rubber and black EPR	54	61%	24%	15%	0%
	Black and Pink EPR compact	0	NA	NA	NA	0%
	All	88	69%	17%	14%	0%

The above tables were based on treating each set of cable measurements independently. This data is represented more graphically in Figure 4-1 and Figure 4-2.

Plots where a summary tan delta measurement (by cable and by phase) is plotted versus service years is given in Appendix B: Temporal Data Plots and Appendix C: Reduced Temporal Data Plots for each cable type and for all cables. This is simplified and summarized by binning the test disposition by decades in the bar-graphs Figure 4-1 and Figure 4-2 below. One may note that there are very few yellow, red, or black (failure) occurrences within the first and second decade. Thereafter, red and black occurrences increase but not necessarily in proportion to service years. This is addressed more quantitatively in the correlation tables - Table 4-3 and Table 4-4.

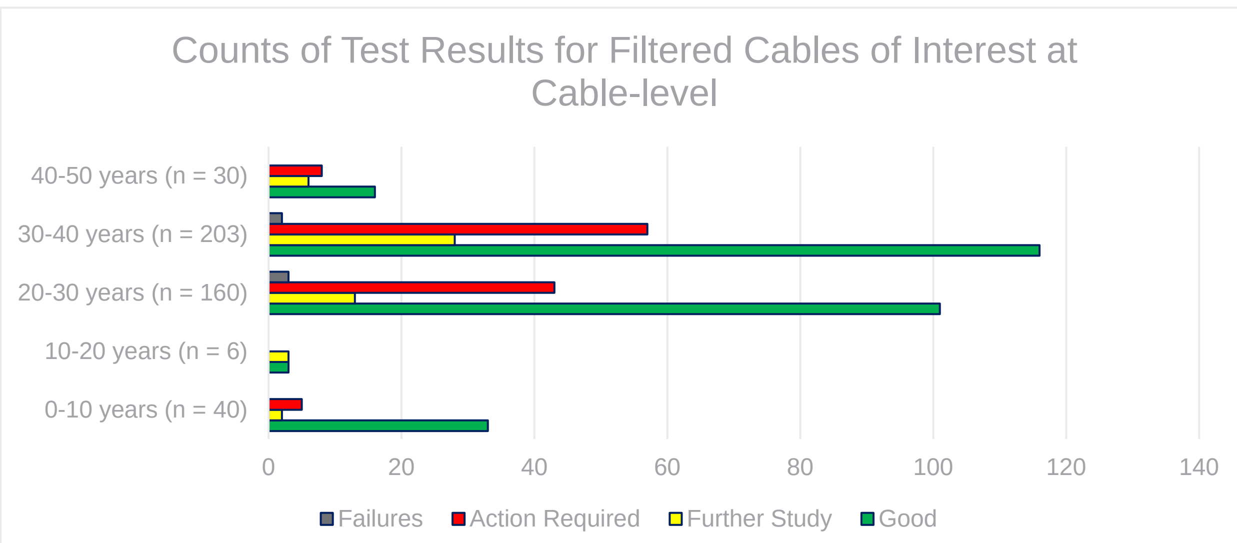

Figure 4-1. Number of Occurrences Where Tan Delta Tests are Binned by Service Decades and By Test Disposition

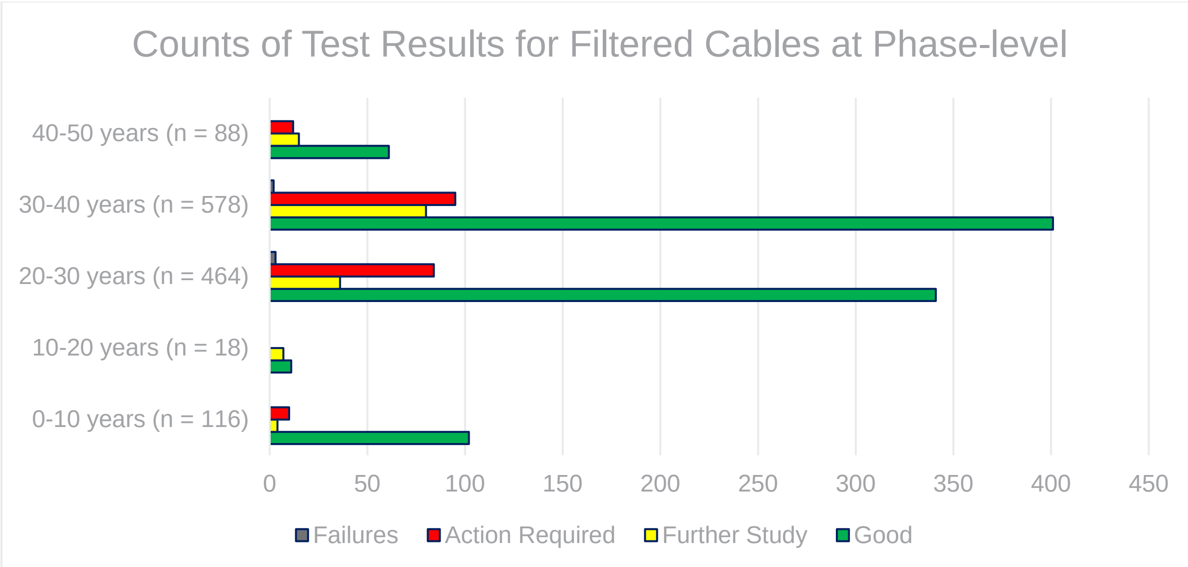

Figure 4-2. Number of Occurrences Where Tan Delta Tests are Binned by Service Decades and By Test Disposition

The Kendall's Tau (Kendall Rank Correlation Coefficient) between the Tan Delta Statistics and Service Years were calculated because Kendall's Tau is nonparametric and less sensitive to outliers than Spearman's Rho and there was no need to transform the Tan Delta statistics (unlike if we used Pearson's correlation) (Hollander 1973). Kendall's Tau is based on the relative ranks of the data rather than the actual values. Table 4-3 gives the correlations by cable type. Table 4-4 gives the correlations by cable type at the phase level. Correlations that are significantly different from zero (based on a statistical hypothesis test) are marked with an asterisk in these tables. Non-asterisked correlation entrees are not significantly different from zero (no correlation).

Table 4-3. Correlations on Filtered Data by Cable Type

		Correlations with Service Years:	
Cable type	n (sample size)	Max. Tan Delta	Tan Delta Std. Dev.
EPR, pink, compact	74	-0.023	-0.050
EPR, black, compact	16	0.243	0.523**
EPR, brown	39	0.215*	0.145
Butyl rubber	14	-0.832**	-0.36
EPR, black	126	0.237**	0.171**
EPR, pink	160	-0.228**	-0.132**
XLPE	10	0.048	0.135
Cable Type Categories			
Black or Pink EPR Compact	90	-0.069	-0.054
Butyl rubber and Black EPR	140	0.207**	0.121*
All	439	0.029	0.072*

** Indicates correlation is significantly different from 0 (p-value < 0.05).
* Indicates correlation maybe different from 0 (0.05 < p-value < 0.10). All non-asterisked entrees are not significant.
Note: It does not make sense to compute a correlation for Delta Tan Delta and Service Years because it is not expected to be a monotonic relationship. If Delta Tan Delta < 0 or Delta Tan Delta is >> 0, the color is red.

Table 4-4. Correlations on Filtered Data by Cable Type at the Phase Level

		Correlations with Service Years:	
Cable type	n (sample size)	Max. Tan Delta	Tan Delta Std. Dev.
EPR, pink, compact	214	0.004	-0.052 (n=206)
EPR, black, compact	48	0.111	0.277 (n=47)**
EPR, brown	109	0.218**	0.295**
Butyl rubber	42	-0.808**	-0.226
EPR, black	374	0.184**	0.147**
EPR, pink	447	-0.208 (n=443)**	-0.123**
XLPE	30	0.034	0.069
Cable Type Categories			
Black or Pink EPR Compact	262	-0.091**	-0.063 (n=253)
Butyl rubber and Black EPR	416	0.194**	0.100**
All	1260	0.064**	0.075(n=1255)**

** Indicates correlation is significantly different from 0 (p-value < 0.05).

* Indicates correlation maybe different from 0 (0.05 < p-value < 0.10). All non-asterisked entrees are not significant.

Note: It does not make sense to compute a correlation for Delta Tan Delta and Service Years because it is not expected to be a monotonic relationship. If Delta Tan Delta < 0 or Delta Tan Delta is >> 0, the color is red.

The correlations with service years overall are weak. If information on stresses other than temporal were available, a stronger correlation to stress, or a stress plus time may be expected. The large negative correlations for Butyl rubber cables are likely due to the small sample size and extremely short range (just two years) of service year data available (see Figure B-2 and Figure B-12).

<u>Task 1b</u>: Conduct an inspection and perform a statistical analysis of the Tan Delta test data acquired from EPRI to ensure that the Tan Delta test data is statistically significant.

As discussed in Section 3.3, the false positive and false negative rates for the assigning of cables into the “action required” and “further study required” conditions are observed to be quite small. The false positive rate (the proportion of cables not having any defects being assigned the “action required” condition) is less than 8.4% with 95% confidence. The false negative rate (the proportion of failed or degraded cables being assigned the “good” condition) is less than 2.3% with 95% confidence. These low rates affirm the reliability of the Tan Delta assessment criteria of Section 3.1.

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

The criteria issued in EPRI reports 3002005321 and 3002000557 involve both cutoff values (for the cable color) and prescribed intervals for testing given the cable Tan Delta results. The prescribed intervals for testing may be assessed with respect to cable failures. No failures were observed within the six-year testing interval for cables in the “good” condition or within the two-year testing interval for cables in the “further study” condition. The by-cable-type and overall 95% confidence intervals for the failure probabilities are given in the table below. Some of the sample sizes in the table were too small to produce informative confidence intervals for some individual cable types (for example XLPE). The overall results are that the probability of transitioning from yellow to failure within two years is less than 6.17% and the probability of transitioning from Green to failure within six years is less than 1.79% with 95% confidence.

Table 4-5. 95% Confidence Intervals of Color Failure Probability on Full Data at the Cable Level

Starting color:	Yellow	Green	95% Confidence Intervals:	
Cable Type	n	n	Yellow to Failed	Green to Failed
Butyl rubber and black EPR	25	36	(0.0%, 11.3%)	(0.0%, 7.98%)
Black or pink EPR compact	6	42	(0.0%, 39.3%)	(0.0%, 6.88%)
Brown EPR	5	19	(0.0%, 45.1%)	(0.0%, 14.6%)
Pink EPR	10	67	(0.0%, 25.9%)	(0.0%, 4.37%)
XLPE	1	2	(0.0%, 95.0%)	(0.0%, 77.6%)
Total	47	166	(0.0%, 6.17%)	(0.0%, 1.79%)

To further test if the EPRI criteria are appropriate, we looked at the distribution of color categories based on the cutoffs alone in Task 1d, but we also needed to look at consecutive measurements on the same cable to judge whether or not the intervals for testing were appropriate. The data set was reduced to only measurements that were made on the same cable multiple times and where initial problems were removed. What is meant by “where initial problems were removed” is that for cases where a problem was identified in initial testing, fixed within a few days, and the cable was retested, only the retest was retained, not the initial testing where the problem (such as a splice issue, a termination issue, etc.) was identified. Failures of cables in the Red category were counted as occurring for the phase with the worst color prior to failure.

Plots where a summary Tan Delta cable (or phase) measurement is plotted versus service years is given in Appendix C: Reduced Temporal Data Plots.

The reduced data was further narrowed by removing suspected (but not confirmed) cases of other issues such as set-up problems, condensation, or a splice or termination issue. Then, for each cable that was measured multiple times, the worst transition (in six years if the initial color was Green, two years otherwise) was counted. Each cable was counted exactly once. No cables in the green or yellow categories failed (i.e., transitioned to failed). The results when suspected cases are not removed are given in Appendix D: Reduced Data Color Transition Analysis. The results at the cable level for the fully reduced data were:

Table 4-6. EPRI Data Table Summarized Counts of Color Transition (starting green) on Fully Reduced Data at the Cable Level

Starting color:	Green	Later Disposition Counts within 6 years:		
Cable Type	n (sample size)	Yellow	Red	No change
Butyl rubber and black EPR	3	0	2	1
Black or pink EPR compact	13	0	1	12
Brown EPR	1	0	0	1
Pink EPR	5	0	0	5

XLPE	0	0	0	0
Total	22	0	3	19

Table 4-7. Data Table Summarized Counts of Color Transition (starting yellow) on Fully Reduced Data at the Cable Level

Starting color:	Yellow	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Red	No change
Butyl rubber and black EPR	1	0	1
Black or pink EPR compact	2	0	2
Brown EPR	1	0	1
Pink EPR	2	2	0
XLPE	0	0	0
Total	6	2	4

Table 4-8. Data Table Summarized Counts of Color Transition (starting red) on Fully Reduced Data at the Cable Level

Starting color:	Red	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and black EPR	3	1	2
Black or pink EPR compact	6	2	4
Brown EPR	2	1	1
Pink EPR	3	1	2
XLPE	0	0	0
Total	14	5	9

The results at the phase level were:

Table 4-9. Data Table Summarized Counts of Color Transition (starting green) on Fully Reduced Data at the Phase Level

Starting color:	Green	Later Disposition Counts within 6 years:		
Cable Type	n (sample size)	Yellow	Red	No change
Butyl rubber and black EPR	15	0	2	13
Black or pink EPR compact	45	2	2	41
Brown EPR	5	0	0	5
Pink EPR	20	1	0	19
XLPE	0	0	0	0
Total	85	3	4	78

Table 4-10. Data Table Summarized Counts of Color Transition (starting yellow) on Fully Reduced Data at the Phase Level

Starting color:	Yellow	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Red	No change
Butyl rubber and black EPR	1	0	1
Black or pink EPR compact	6	0	6
Brown EPR	1	0	1
Pink EPR	3	2	1
XLPE	0	0	0
Total	11	2	9

Table 4-11. Data Table Summarized Counts of Color Transition (starting red) on Fully Reduced Data at the Phase Level

Starting color:	Red	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and black EPR	3	1	2
Black or pink EPR compact	10	2	8
Brown EPR	4	1	3
Pink EPR	5	1	4
XLPE	0	0	0
Total	22	5	17

Then, based on these counts, we constructed 95% Clopper-Pearson "Exact" confidence intervals on the probability of transitioning from one color to another, where if the confidence interval was two-sided, the shortest confidence interval is presented. Additional confidence intervals (90%, 95%, and 99% confidence intervals along with conclusions are given in Appendix E.

Table 4-12. 95% Confidence Intervals of Color Transition Probability (starting green) on Fully Reduced Data at the Cable Level

Starting color:	Green	95% Confidence Intervals:		
Cable Type	n (sample size)	Yellow	Red	No change
Butyl rubber and black EPR	3	(0%, 63.2%)	(13.5%, 100%)	(0.0%, 86.5%)
Black or pink EPR compact	13	(0%, 20.6%)	(0.0%, 31.6%)	(68.4%, 100%)
Brown EPR	1*	0*	0*	1*
Pink EPR	5	(0%, 45.1%)	(0%, 45.1%)	(54.9%, 100%)
XLPE	0*	0*	0*	0*
Total	22	(0%, 12.7%)	(1.6%, 32.2%)	(67.8%, 98.4%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table 4-13. 95% Confidence Intervals of Color Transition Probability (starting yellow) on Fully Reduced Data at the Cable Level

Starting color:	Yellow	95% Confidence Intervals:

Cable Type	n (sample size)	Red	No change
Butyl rubber and black EPR	1*	0*	1*
Black or pink EPR compact	2	(0%, 77.6%)	(22.4%, 100%)
Brown EPR	1*	0*	1*
Pink EPR	2	(22.4%, 100%)	(0%, 77.6%)
XLPE	0*	0*	0*
Total	6	(2.1%, 73.9%)	(26.1%, 97.9%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table 4-14. 95% Confidence Intervals of Color Transition Probability (starting red) on Fully Reduced Data at the Cable Level

Starting color:	Red	95% Confidence Intervals:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and black EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
Black or pink EPR compact	6	(2.1%, 73.9%)	(26.1%, 97.9%)
Brown EPR	2	(1.3%, 98.7%)^	(1.3%, 98.7%)^
Pink EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
XLPE	0*	0*	0*
Total	14	(11.6%, 63.4%)	(36.6%, 88.4%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

^The shortest exact 95% confidence interval is not unique, instead, the equal-tailed 95% confidence interval is presented.

Generally speaking, with such small sample sizes at the cable level, the confidence intervals are quite wide and don't particularly pinpoint the probabilities. It is interesting to note that the probability of transitioning from green to red within 6 years across all the cable types of interest is significantly different from 0%, at least 1.6% (13.5% for Butyl rubber and Black EPR). This may indicate that a testing interval for green cables might be too long at 6 years. The results at the phase level were:

Table 4-15. 95% Confidence Intervals of Color Transition Probability (starting green) on Fully Reduced Data at the Phase Level

Starting color:	Green	95% Confidence Intervals:		
Cable Type	n (sample size)	Yellow	Red	No change
Butyl rubber and black EPR	15	(0%, 18.1%)	(0.4%, 36.5%)	(63.5%, 99.6%)
Black or pink EPR compact	45	(0.1%, 13.4%)	(0.1%, 13.4%)	(80.3%, 98.3%)
Brown EPR	5	(0%, 45.1%)	(0%, 45.1%)	(54.9%, 100%)
Pink EPR	20	(0.0%, 21.6%)	(0%, 13.9%)	(78.4%, 100%)
XLPE	0*	0*	0*	0*
Total	85	(0.4%, 9.0%)	(0.9%, 10.7%)	(84.6%, 97.1%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table 4-16. 95% Confidence Intervals of Color Transition Probability (starting yellow) on Fully Reduced Data at the Phase Level

Starting color:	Yellow	95% Confidence Intervals:	
Cable Type	n (sample size)	Red	No change
Butyl rubber and black EPR	1*	0*	1*
Black or pink EPR compact	6	(0%, 39.3%)	(60.7%, 100%)
Brown EPR	1*	0*	1*
Pink EPR	3	(13.5%, 100%)	(0.0%, 86.5%)
XLPE	0*	0*	0*
Total	11	(0.6%, 47.3%)	(52.7%, 99.4%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table 4-17. 95% Confidence Intervals of Color Transition Probability (starting red) on Fully Reduced Data at the Phase Level

Starting color:	Red	95% Confidence Intervals:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and black EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
Black or pink EPR compact	10	(0.7%, 51.1%)	(48.9%, 99.3%)
Brown EPR	4	(0.0%, 75.1%)	(24.9%, 100%)
Pink EPR	5	(0.0%, 65.7%)	(34.3%, 100%)
XLPE	0*	0*	0*
Total	22	(6.5%, 43.4%)	(56.6%, 93.5%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

At the phase level there is more data, so the confidence intervals are generally thinner than those at the cable level. However, because it was often the case that only one phase was worse than the other two, the probability of transitioning from a color to a worse color generally went down (as compared to the cable-level data). For example, at the phase level, it is interesting to note that the probability of transitioning from green to red within six years for Butyl rubber and Black EPR is significantly different from 0% but is only at least 0.9% (when it was at least 1.6% for the cable-level data). This may indicate that a testing interval for green cables might be too long at six years.

5.0 Conclusions and Recommendation

- Cable insulation degradation failures are relatively few during the first 10 years of cable service. Thereafter, however, there is no strong correlation between cable age and failure rate. The correlations between the Tan Delta test data and service year are at most 0.1 (low on the scale from −1 to +1, which is perfect negative to perfect positive correlation) when considered at the cable level and at the phase level.
- The thresholds set in EPRI report 3002005321 (EPRI 2015) have resulted in very few false positive and false negative calls. False positives are cables erroneously indicating a fault where forensic examination revealed no problematic degradation. Forensic investigations of cables identified as “repair or replace” have always identified cable segments with problems. The false positive rate is estimated to be less than 8.4% with 95% confidence. False negatives are cables testing “good” that were in a failed or degraded state. The false negative rate for cables testing “good” is less than 2.3% with 95% confidence. This implies that the guideline thresholds are appropriate.
- The test intervals recommended in EPRI report 3002000557 (EPRI 2013) and EPRI report 3002005321 (EPRI 2015) may be evaluated by considering the rates that cables testing “good” or “further study” subsequently fail within the suggested 6- or 2-year re-inspection intervals, respectively. The observed rate that cables testing “good” fail within 2 years is less than 1.79% with 95% confidence. The rate that cables testing “further study” fail within 6 years is less than 6.17% with 95% confidence. This implies that the overall testing interval guidelines are appropriate. The confidence intervals for the same analysis by specific insulation category are larger because there are fewer available data points for each individual insulation category in the available data (Table 4-5).
- Cable insulation degradation in the context of test interval guidance may be further understood by the data set consisting of multiple tests of the same cable. Across all cable types at the cable level, the probability of transitioning from “good” to “action required” within a 6-year re-inspection interval is estimated as 3/22 = 13.6%. Because of the uncertainty with the small sample size, the 95% confidence interval on that transition probability is (1.6%, 32.2%). Across all cable types at the cable level, the probability of transitioning from “further study” to “action required” within a 2-year re-inspection interval is estimated as 2/6 = 33.3% with a very wide 95% confidence interval (2.1%,73.9%). The small sample size prohibits any strong statement about the “further study” 2-year re-inspection interval.

Recommendation: Given the zero incidence of age-related GREEN to failure within 6 years or YELLOW to failure within 2 years and the low incidence of false positives and false negatives, the EPRI guideline thresholds and intervals seem to be suitable. Continuing to collect Tan Delta and related cable failure data, particularly on cable insulation types for which there is currently limited data available, would allow statistical confidence intervals to be narrowed and thereby improve the confidence of the EPRI guidance assessment. Continued data collection is therefore recommended.

6.0 References

EPRI (2010). TR-1021070 Medium-Voltage Cable Aging Management Guide, Revision 1. Palo Alto, California, Electric Power Research Institute.

EPRI (2012). TR 1025262 Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis. Palo Alto, California, Electric Power Research Institute (EPRI).

EPRI (2013). TR-30020000557 Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Revision 1. Palo Alto, California, Electric Power Research Institute.

EPRI (2015). TR-3002005321 Plant Engineering: Evaluation and Insights from Nuclear Power Plant Tan Delta Testing and Data Analysis - Update. Palo Alto, California, Electric Power Research Institute.

Hollander, M. D. W. (1973). Nonparamatric Statistical Methods. New York, NY, John Wiley & Sons**:** 185-194.

NRC (2007). NRC Generic Letter 2007-01: Inaccessible or Underground Power Cable Failures That Disable Accident Mitigation Systems or Cause Plant Transients. Washington, D.C., U.S. Nuclear Regulatory Commission.

Appendix A – Unfiltered Binned Population Summary

This appendix tables and bar graphs of the full test population without removing failure or weak test results associated with terminations, splices, rodent attack, or other non-age-related modes.

Table A-1. Data Table Summarization at the Cable Level

Cable Age Range	Cable Type	Total # of Cables	% (Green or Good)	% (Yellow or Further Study)	% (Red or Action Required)	% (Failed
(0-10)	Black EPR	0	NA	NA	NA	NA
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	10	90%	0%	10%	0%
	Brown EPR	1	0%	0%	100%	0%
	Pink EPR	30	80%	7%	13%	0%
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	0	NA	NA	NA	NA
	Black and pink EPR compact	10	90%	0%	10%	0%
	All	41	80%	5%	15%	0%
(10-20)	Black EPR	1	100%	0%	0%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	5	40%	60%	0%	0%
	Brown EPR	0	NA	NA	NA	NA
	Pink EPR	0	NA	NA	NA	NA
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	1	100%	0%	0%	0%
	Black and pink EPR compact	5	40%	60%	0%	0%
	All	6	50%	50%	0%	0%
(20-30)	Black EPR	22	91%	5%	5%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	2	100%`	0%	0%	0%
	Pink EPR compact	56	59%	9%	29%	4%
	Brown EPR	18	72%	11%	11%	6%
	Pink EPR	75	49%	8%	41%	1%
	XLPE	1	100%	0%	0%	0%
	Butyl rubber and black EPR	22	91%	5%	5%	0%
	Black and pink EPR compact	58	60%	9%	28%	3%

Cable Age Range	Cable Type	Total # of Cables	% (Green or Good)	% (Yellow or Further Study)	% (Red or Action Required)	% (Failed
	All	174	61%	8%	29%	2%
(30-40)	Black EPR	102	44%	15%	40%	1%
	Butyl rubber	6	0%	100%	0%	0%
	Black EPR compact	14	64%	7%	21%	7%
	Pink EPR compact	5	80%	0%	20%	0%
	Brown EPR	18	17%	22%	61%	0%
	Pink EPR	63	86%	5%	10%	0%
	XLPE	8	38%	13%	50%	0%
	Butyl rubber and black EPR	108	42%	19%	38%	1%
	Black and pink EPR compact	19	68%	5%	21%	5%
	All	216	55%	14%	31%	1%
(40-50)	Black EPR	12	25%	8%	67%	0%
	Butyl rubber	8	50%	50%	0%	0%
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	0	NA	NA	NA	NA
	Brown EPR	10	70%	20%	10%	0%
	Pink EPR	3	67%	0%	33%	0%
	XLPE	1	0%	0%	100%	0%
	Butyl rubber and black EPR	20	35%	25%	40%	0%
	Black and pink EPR compact	0	NA	NA	NA	0%
	All	34	47%	21%	32%	0%

Treating each phase separately, the Task 1d phase results were:

Table A-2. Data Table Summarization at the Phase Level

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Failed)
(0-10)	Black EPR	0	NA	NA	NA	NA
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	28	96%	0%	4%	0%
	Brown EPR	3	67%	0%	33%	0%
	Pink EPR	88	85%	5%	10%	0%
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	0	NA	NA	NA	NA

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Failed)
	Black and pink EPR compact	28	96%	0%	4%	0%
	All	119	87%	3%	9%	0%
(10-20)	Black EPR	3	100%	0%	0%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	15	53%	47%	0%	0%
	Brown EPR	0	NA	NA	NA	NA
	Pink EPR	0	NA	NA	NA	NA
	XLPE	0	NA	NA	NA	NA
	Butyl rubber and black EPR	3	100%	0%	0%	0%
	Black and pink EPR compact	15	53%	47%	0%	0%
	All	18	61%	39%	0%	0%
(20-30)	Black EPR	66	97%	2%	2%	0%
	Butyl rubber	0	NA	NA	NA	NA
	Black EPR compact	6	100%`	0%	0%	0%
	Pink EPR compact	165	70%	10%	18%	1%
	Brown EPR	54	83%	4%	11%	2%
	Pink EPR	208	60%	8%	32%	0.5%
	XLPE	3	100%	0%	0%	0%
	Butyl rubber and black EPR	66	97%	2%	2%	0%
	Black and pink EPR compact	171	71%	10%	18%	1%
	All	502	71%	10%	18%	1%
(30-40)	Black EPR	302	61%	18%	21%	0.3%
	Butyl rubber	18	0%	100%	0%	0%
	Black EPR compact	42	88%	2%	7%	2%
	Pink EPR compact	10	70%	0%	30%	0%
	Brown EPR	48	29%	21%	50%	0%
	Pink EPR	173	91%	3%	5%	0%
	XLPE	24	54%	4%	42%	0%
	Butyl rubber and black EPR	320	57%	23%	20%	0.3%
	Black and pink EPR compact	52	85%	2%	12%	2%
	All	617	67%	15%	18%	0.3%
(40-50)	Black EPR	36	47%	19%	33%	0%
	Butyl rubber	24	67%	33%	0%	0%

Cable Age Range	Cable Type	Total # of Cables	% (Good or Green)	% (Yellow or FS)	% (Red or AR)	% (Failed)
	Black EPR compact	0	NA	NA	NA	NA
	Pink EPR compact	0	NA	NA	NA	NA
	Brown EPR	28	82%	7%	11%	0%
	Pink EPR	9	78%	11%	11%	0%
	XLPE	3	0%	0%	100%	0%
	Butyl rubber and black EPR	60	55%	25%	20%	0%
	Black and pink EPR compact	0	NA	NA	NA	0%
	All	100	63%	18%	19%	0%

The above tables were based on treating each set of cable measurements independently. This data is represented more graphically in Figure A-1 and Figure A-2.

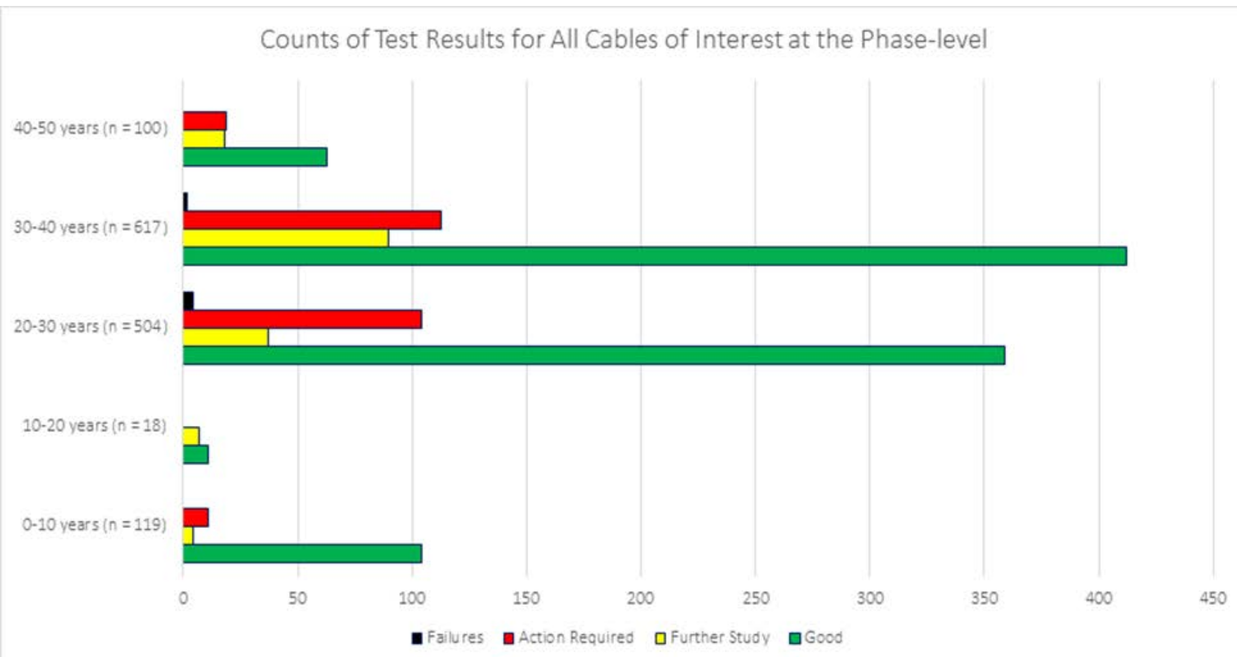

Figure A-1. Number of Occurrences Where Tan Delta Tests are Binned by Service Decades and By Test Disposition

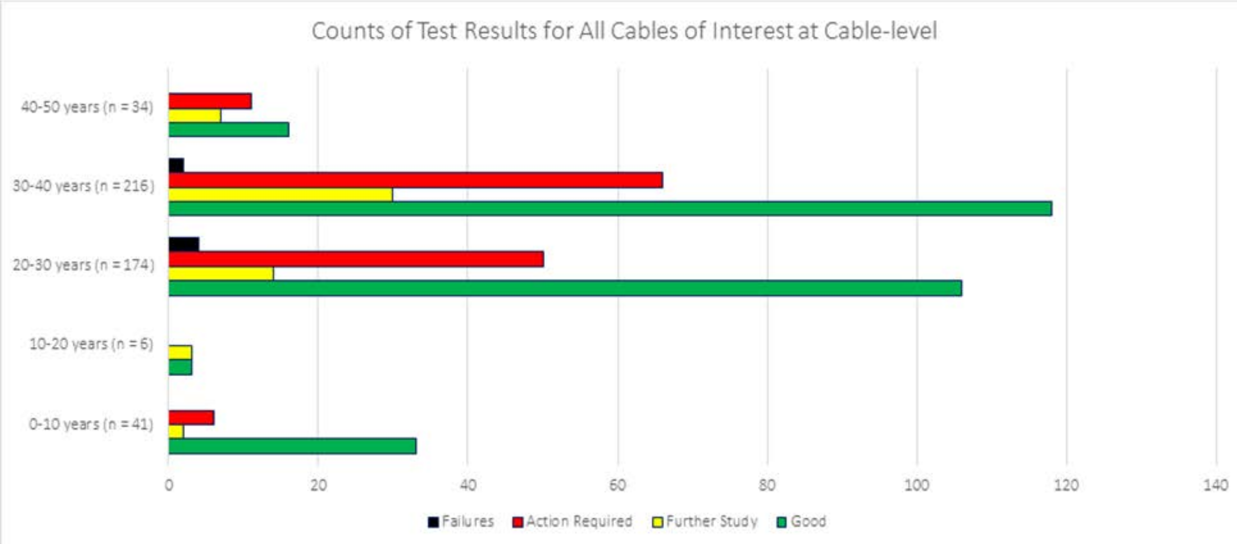

Figure A-2. Number of Occurrences Where Tan Delta Tests are Binned by Service Decades and By Test Disposition

Table A-3. Correlations by Cable Type

		Correlations with Service Years:	
Cable type	n (sample size)	Max. Tan Delta	Tan Delta Std. Dev.
EPR, pink, compact	75	-0.022	-0.065
EPR, black, compact	15	0.139	0.42
EPR, brown	47	0.183	0.142
Butyl rubber	14	-0.832	-0.36
EPR, black	136	0.27	0.219
EPR, pink	171	-0.217	-0.131
XLPE	10	0.048	0.135
Cable Type Categories			
Black or Pink EPR compact	90	-0.089	-0.092
Butyl rubber and Black EPR	150	0.235	0.163
All	468	0.048	0.09

Indicates correlation is significantly different from 0 (p-value < 0.05).

Indicates correlation maybe different from 0 (0.05 < p-value < 0.10).

Note: It does not make sense to compute a correlation for Delta Tan Delta and Service Years because it is not expected to be a monotonic relationship. If Delta Tan Delta < 0 or Delta Tan Delta is >> 0, the color is red.

Table A-4. Correlations by Cable Type at the Phase Level

		Correlations with Service Years:	
Cable type	n (sample size)	Max. Tan Delta	Tan Delta Std. Dev.
EPR, pink, compact	217	0.029	-0.035 (n=209)
EPR, black, compact	45	0.056	0.229 (n=44)
EPR, brown	130	0.178	0.265
Butyl rubber	42	-0.808	-0.226
EPR, black	404	0.22	0.193
EPR, pink	476	-0.198 (n=474)	-0.123
XLPE	30	0.034	0.069
Cable Type Categories			
Black or Pink EPR compact	262	-0.075	-0.07 (n=253)
Butyl rubber and Black EPR	446	0.22	0.139
All	1345	0.025	0.101 (n=1338)

Indicates correlation is significantly different from 0 (p-value < 0.05).

Indicates correlation maybe different from 0 (0.05 < p-value < 0.10).

Note: It does not make sense to compute a correlation for Delta Tan Delta and Service Years because it is not expected to be a monotonic relationship. If Delta Tan Delta < 0 or Delta Tan Delta is >> 0, the color is red.

Appendix B – Temporal Data Plots

This appendix contains plots of summary tan Delta statistics by cable type plotted on the log scale. The cable-level results are shown in the first 10 figures, while phase-level results are show in the second 10 figures. The cable green, yellow, red and failed category determination is used for the color of the points in the plots. Note: the Delta Tan Delta statistic was not plotted at the cable-level as it was unclear what an appropriate summary measure (across the 3 phases) would be. Multiple temporal measurements of the same cable are connected by line segments in these plots.

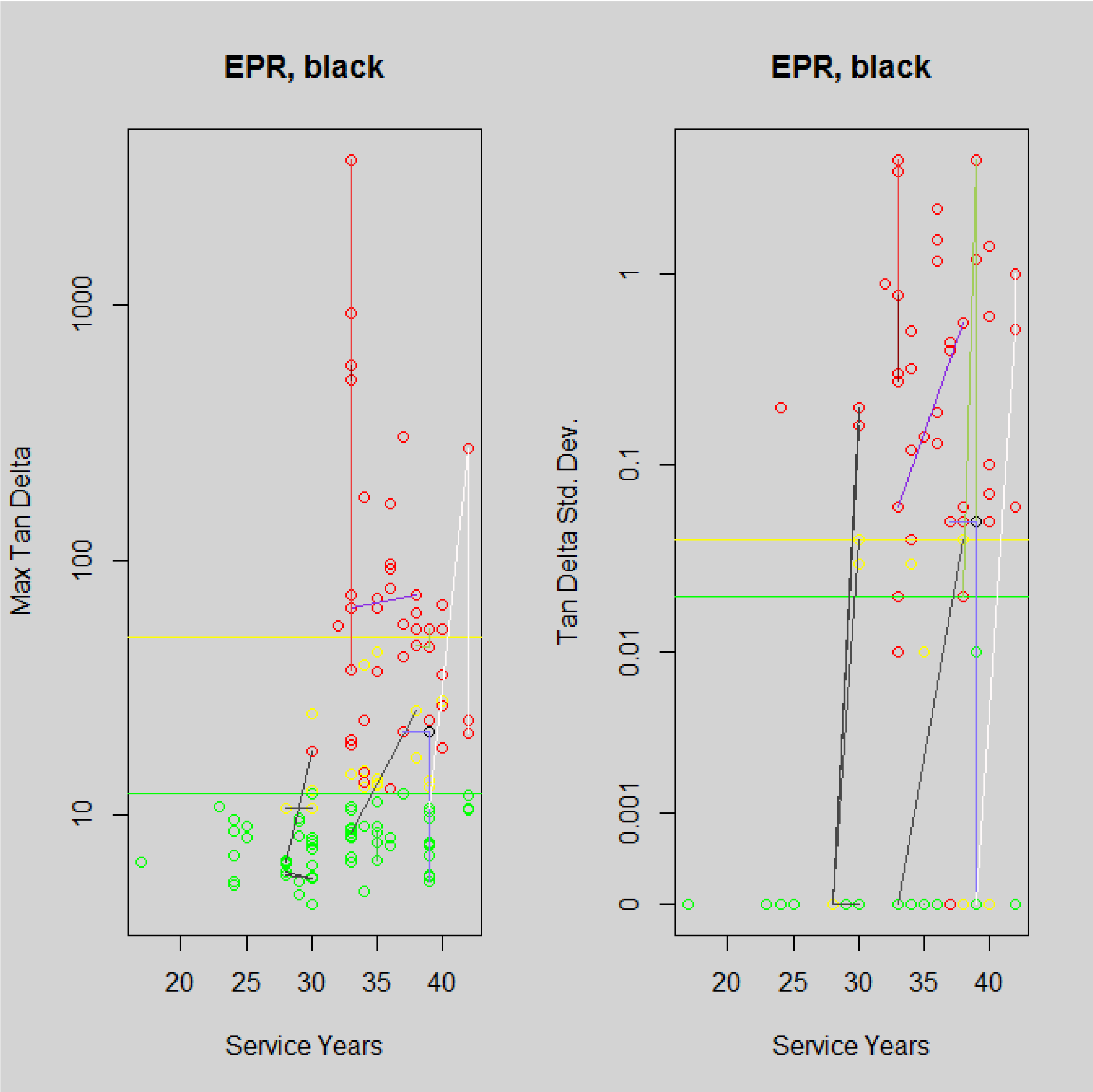

Figure B-1. Max Tan Delta and Tan Delta Standard Deviation for EPR Black Cables

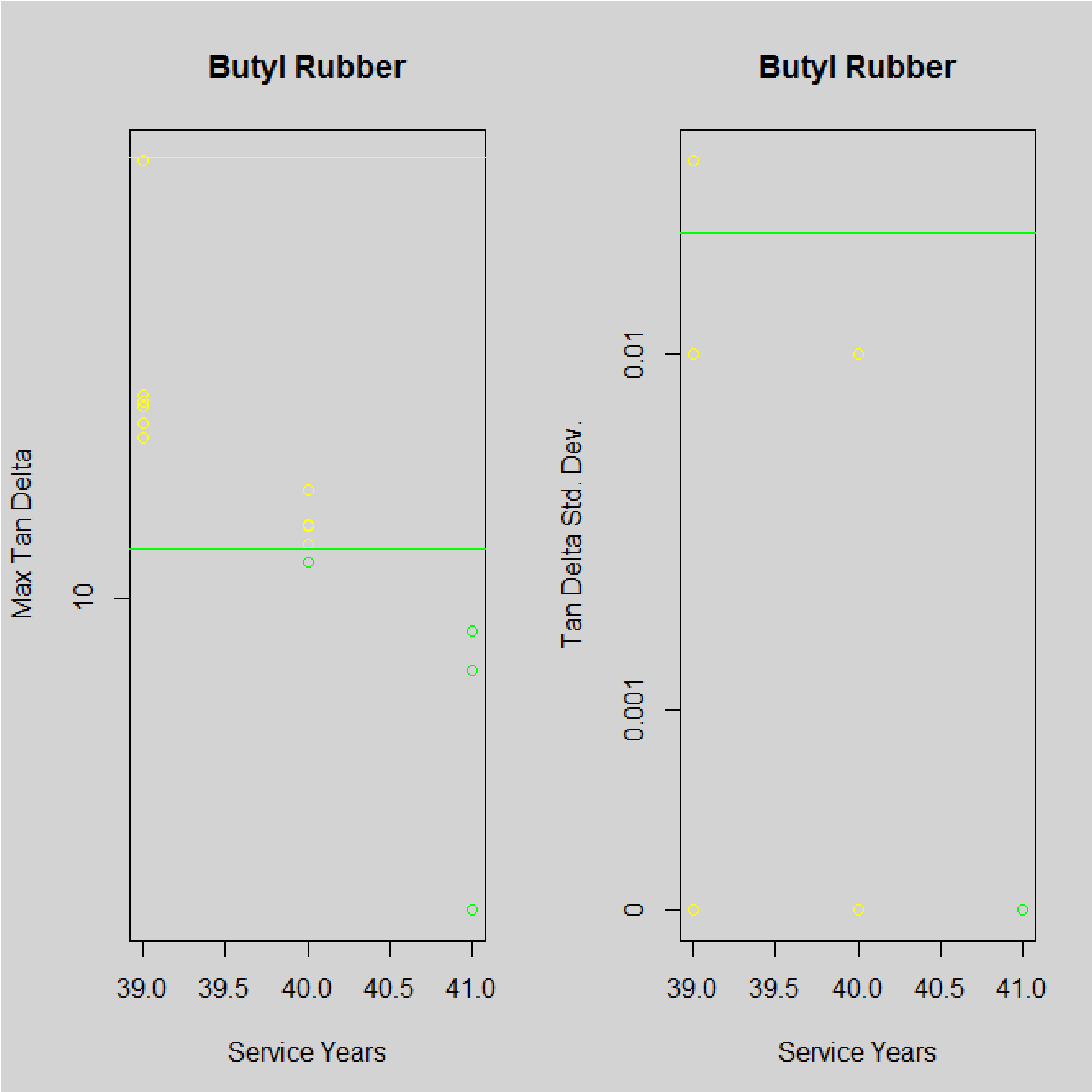

Figure B-2. Max Tan Delta and Tan Delta Standard Deviation for Butyl rubber cables

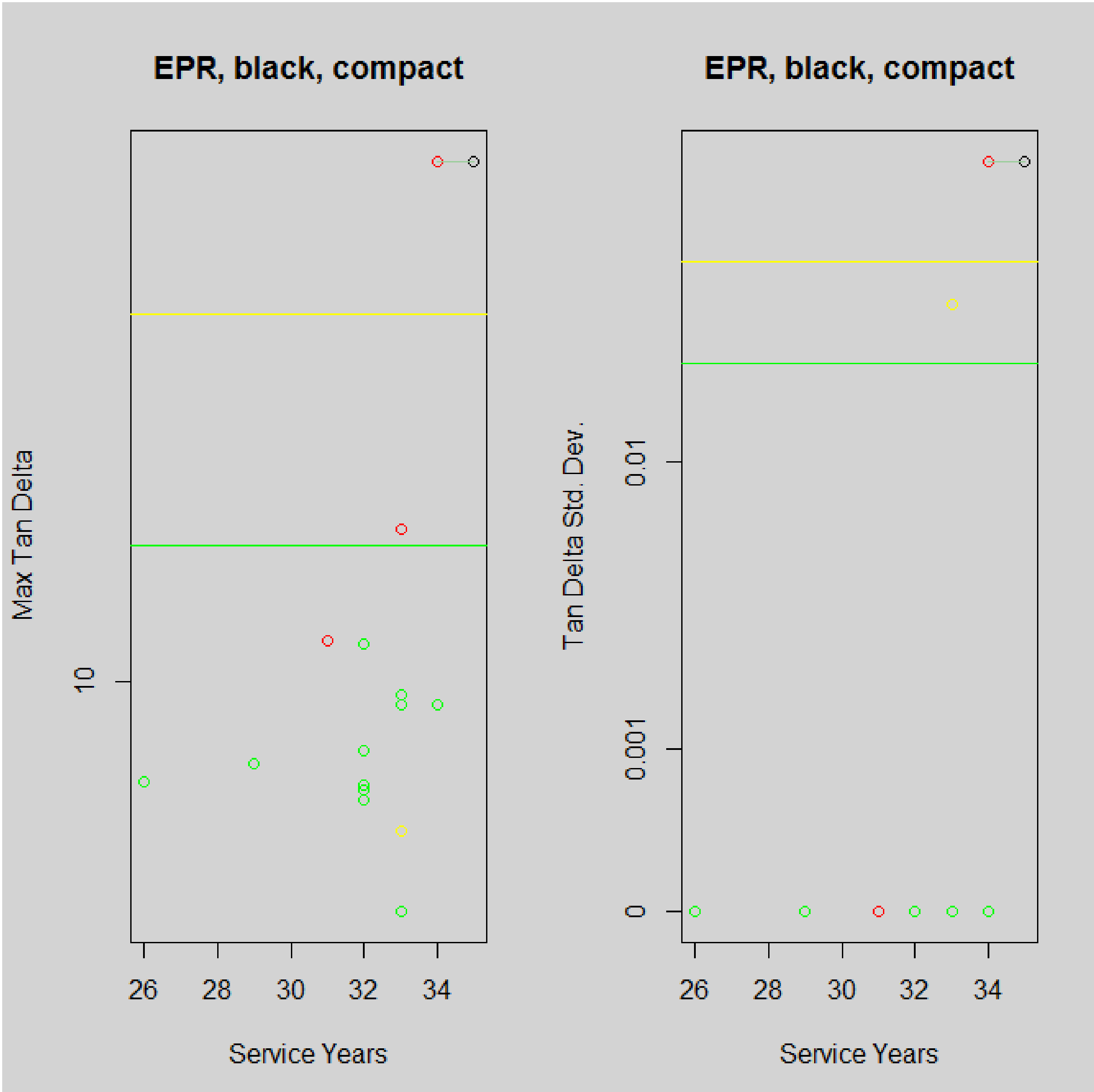

Figure B-3. Max Tan Delta and Tan Delta Standard Deviation for EPR Black Compact Cables

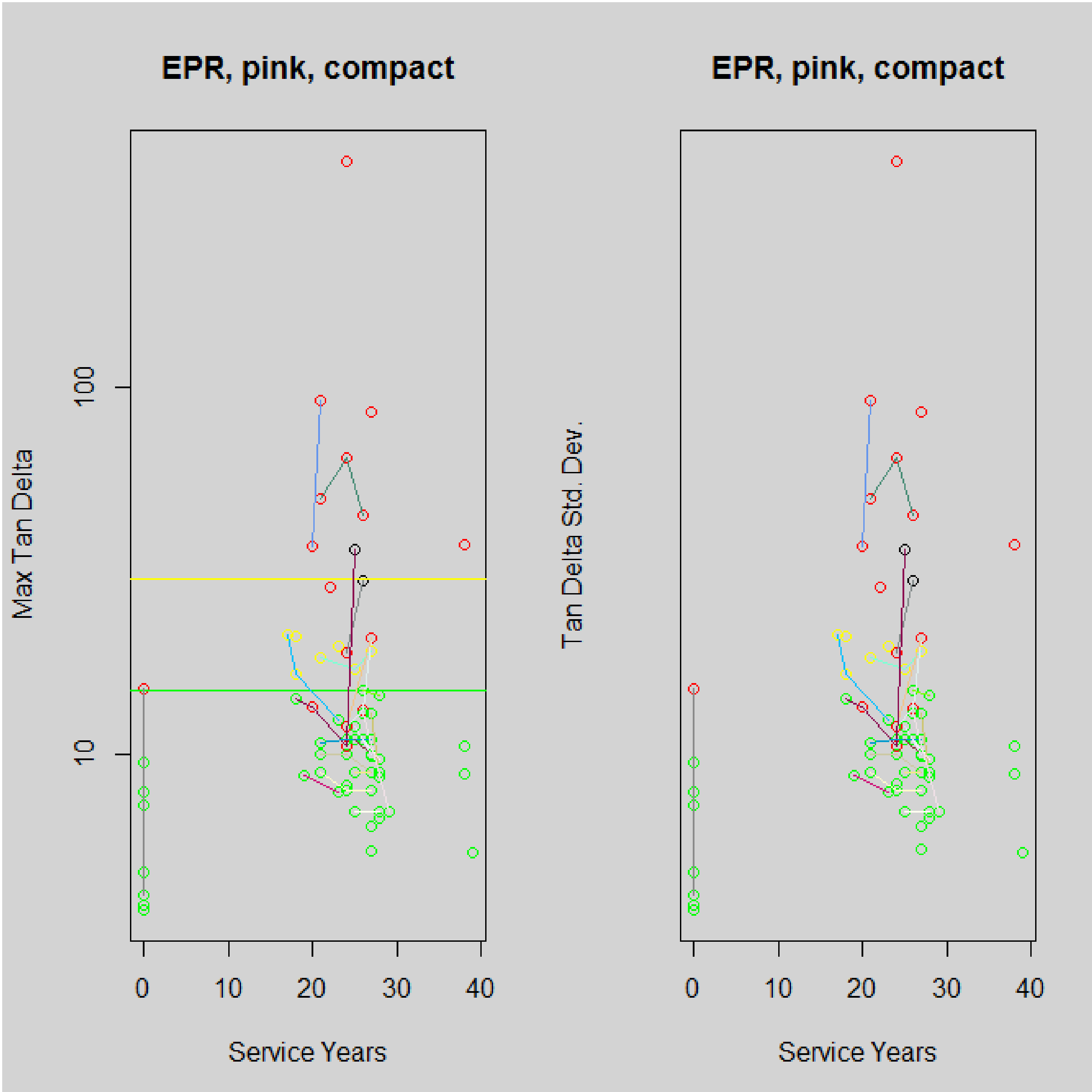

Figure B-4. Max Tan Delta and Tan Delta Standard Deviation for EPR Pink Compact Cables

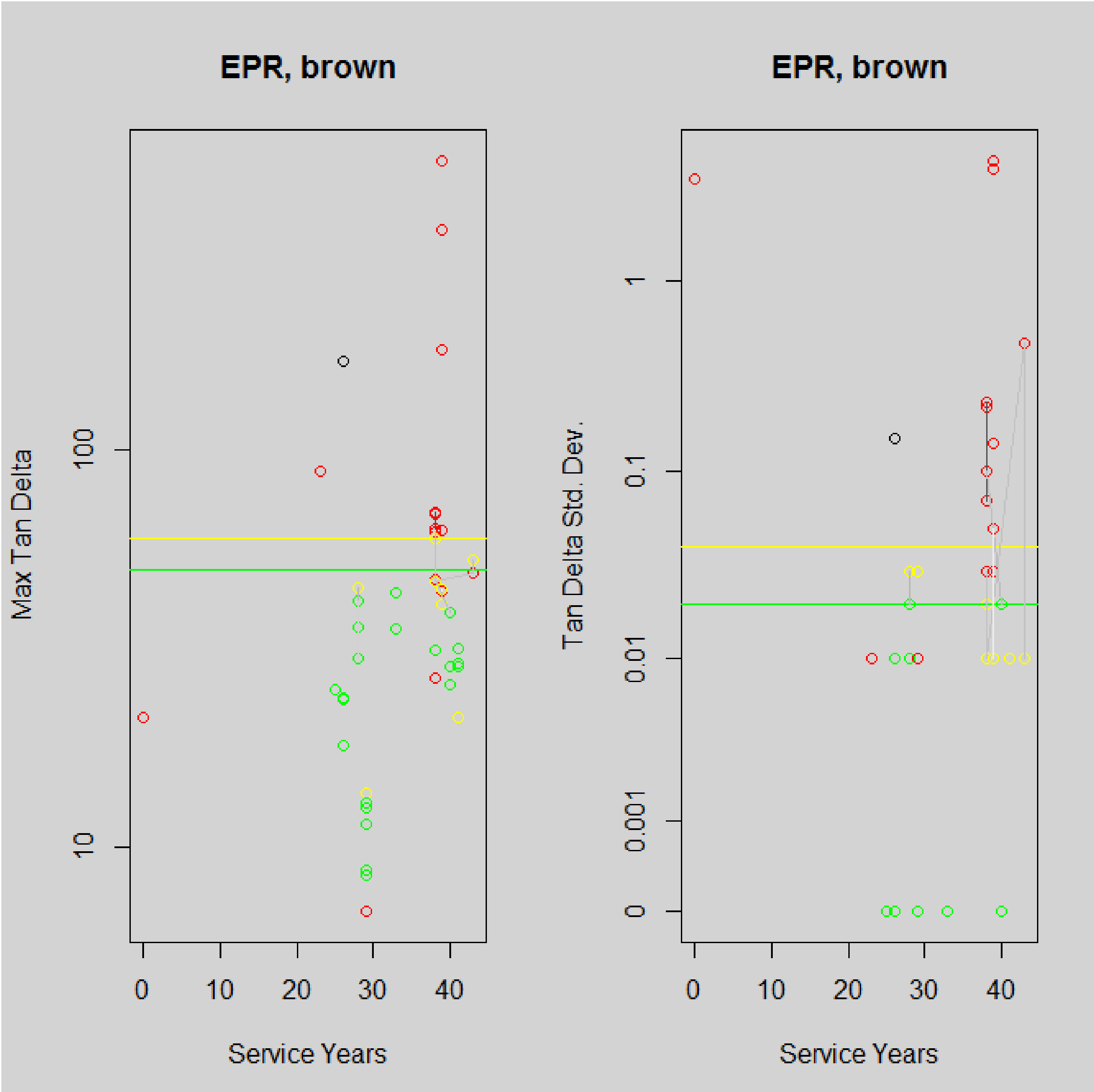

Figure B-5. Max Tan Delta and Tan Delta Standard Deviation for EPR Brown Cables

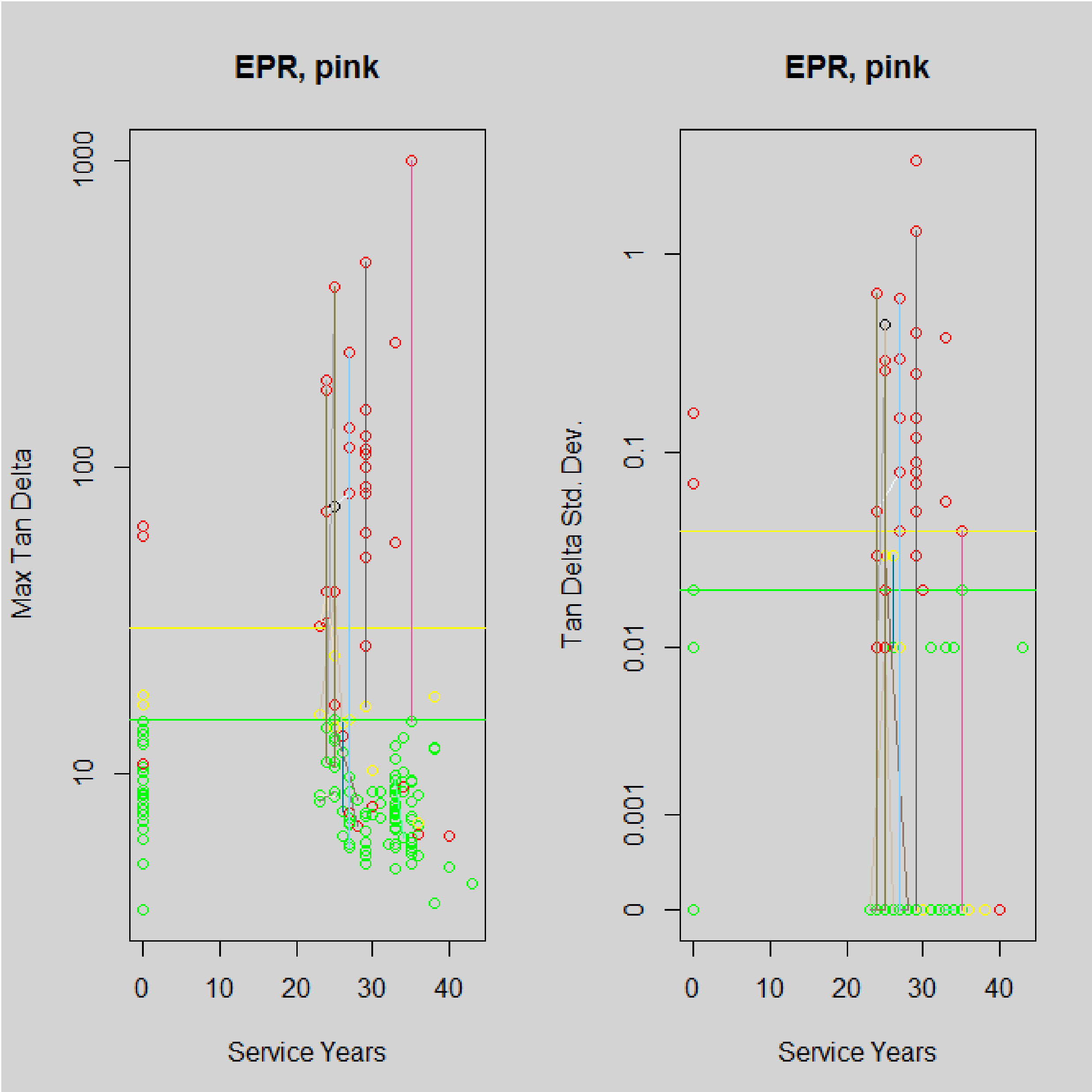

Figure B-6. Max Tan Delta and Tan Delta Standard Deviation for EPR Pink Cables

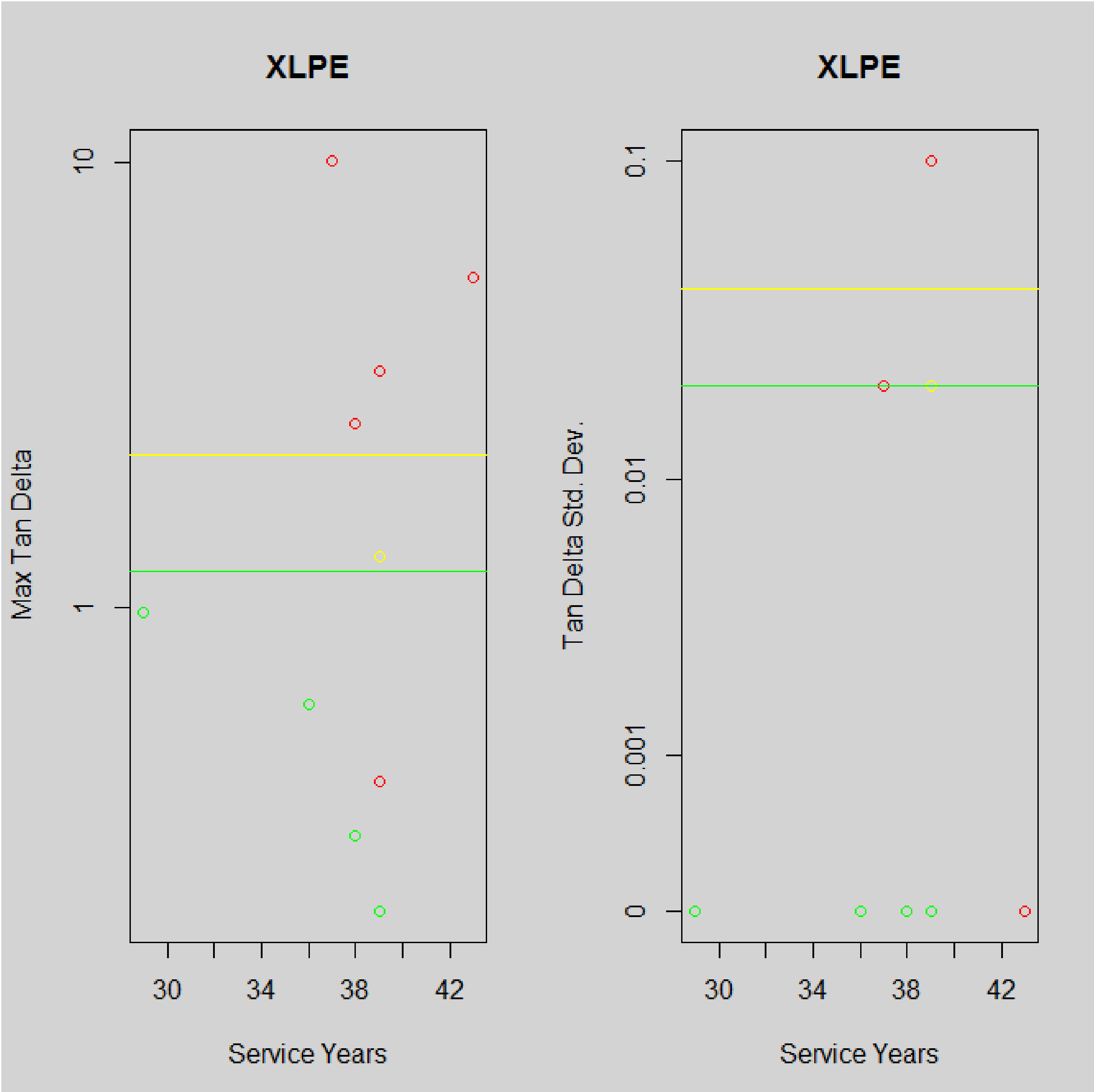

Figure B-7. Max Tan Delta and Tan Delta Standard Deviation for XLPE Cables

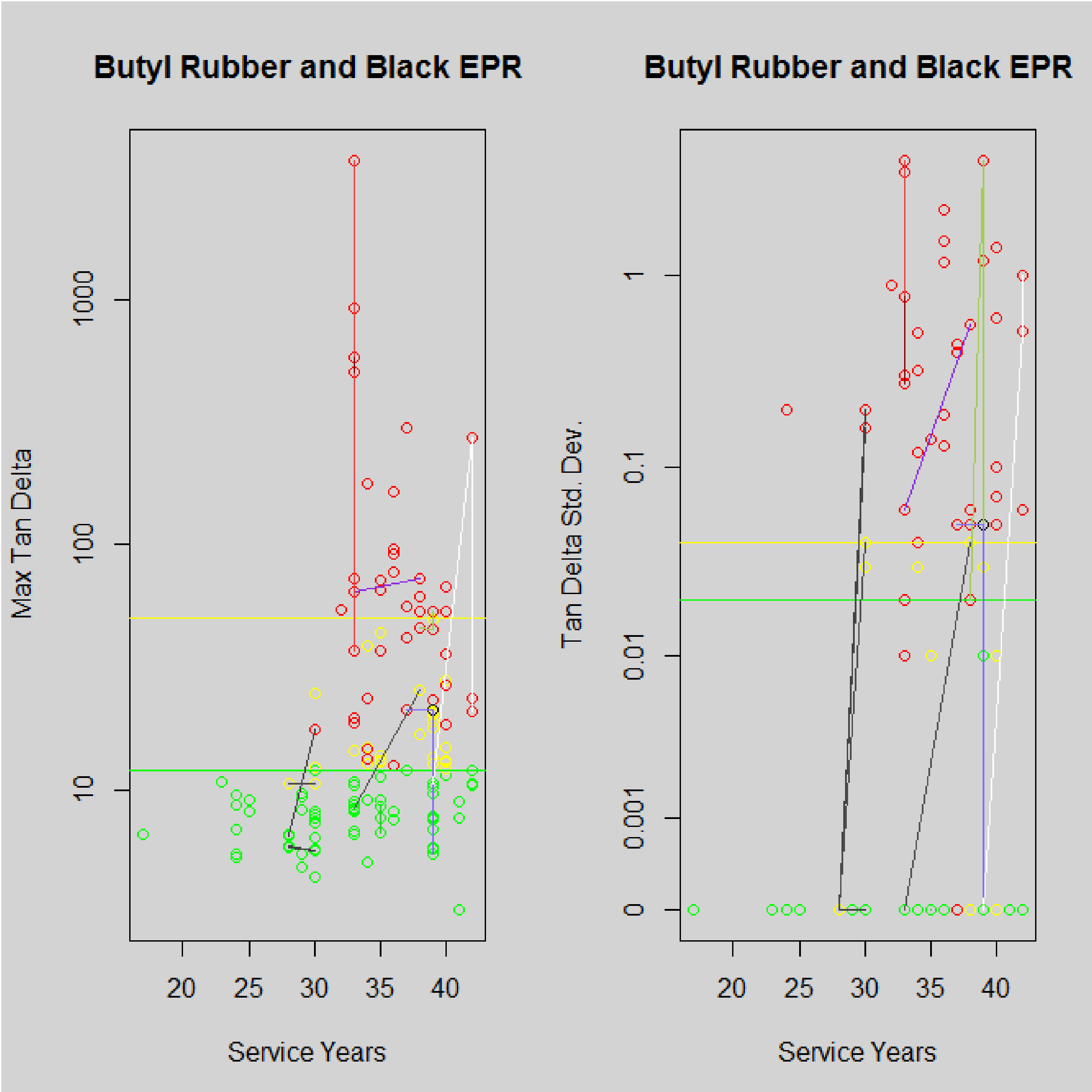

Figure B-8. Max Tan Delta and Tan Delta Standard Deviation for Butyl rubber and EPR Black Cables

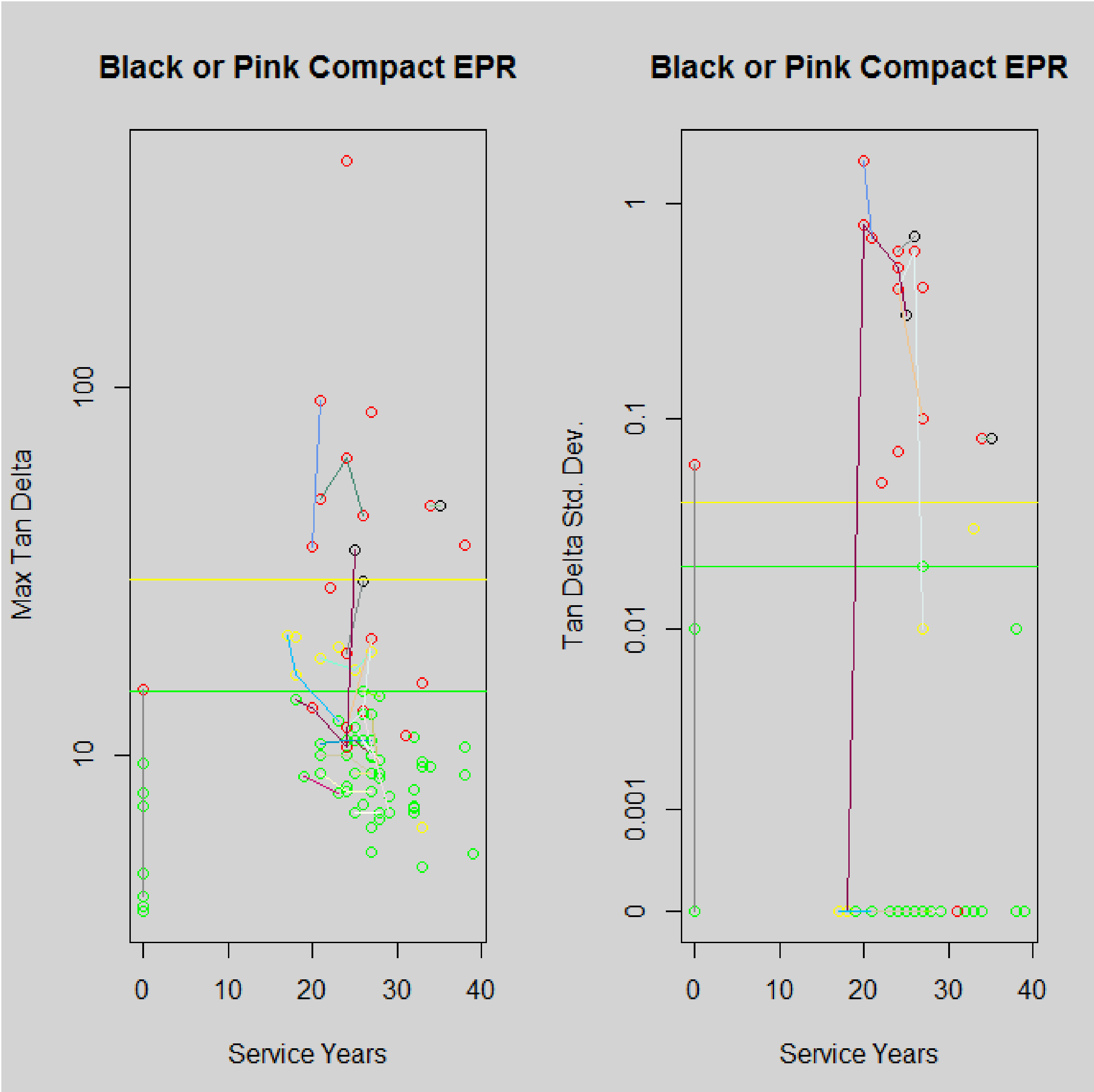

Figure B-9. Max Tan Delta and Tan Delta Standard Deviation for EPR Black and Pink Compact Cables

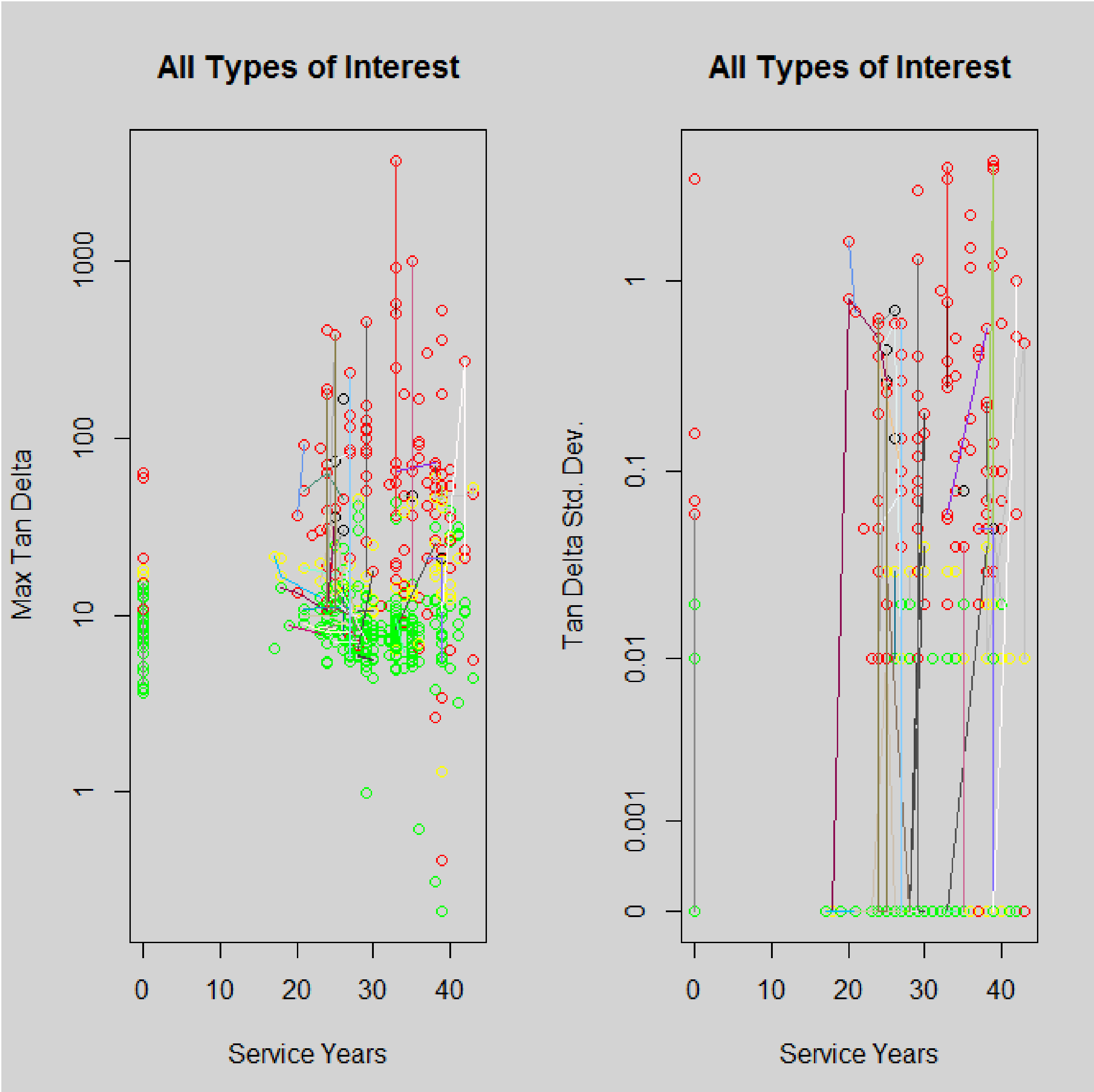

Figure B-10. Max Tan Delta and Tan Delta Standard Deviation for All Cable Types of Interest

Phase level results by cable type:

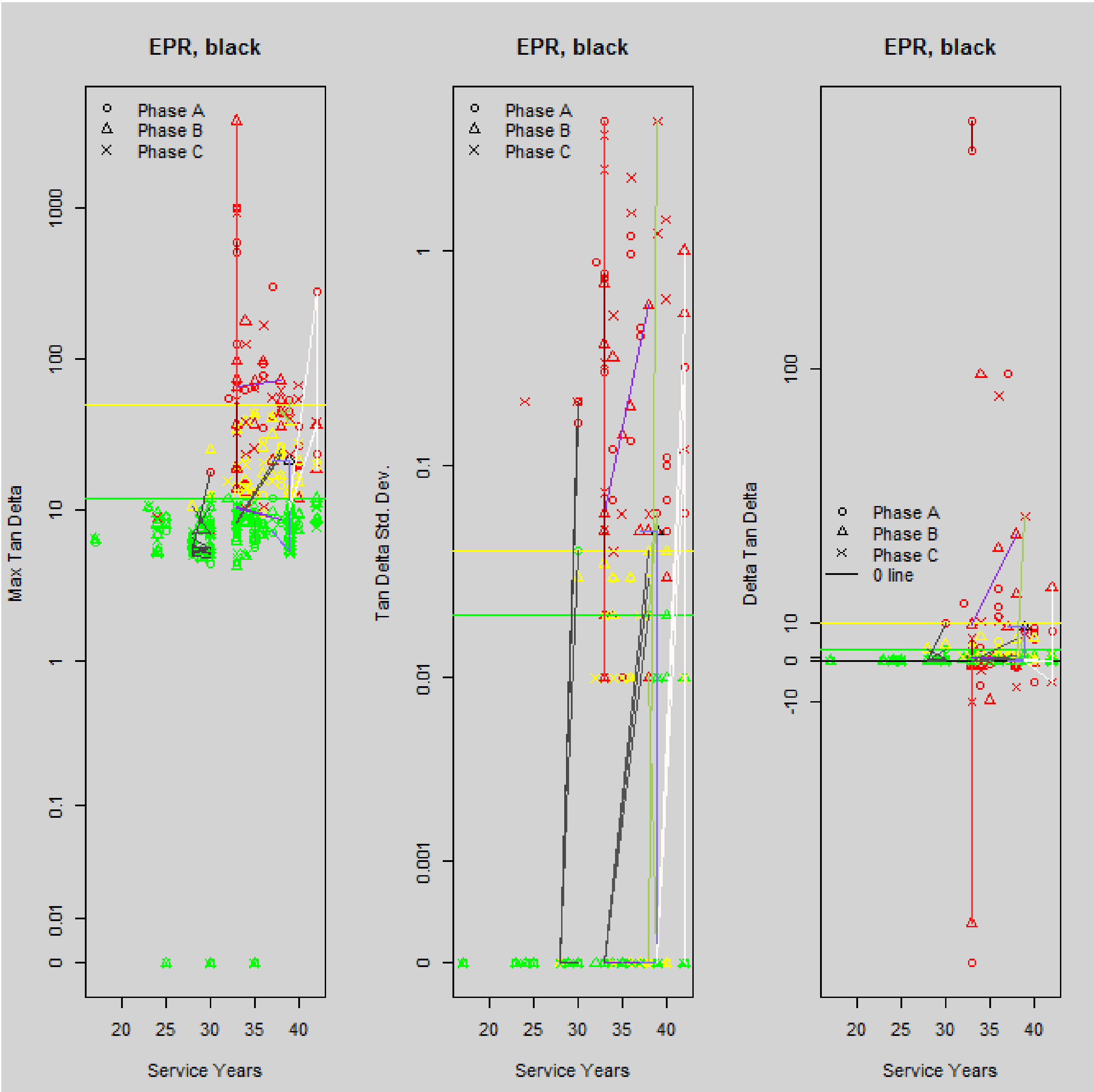

Figure B-11. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Black Cables for Each Phase

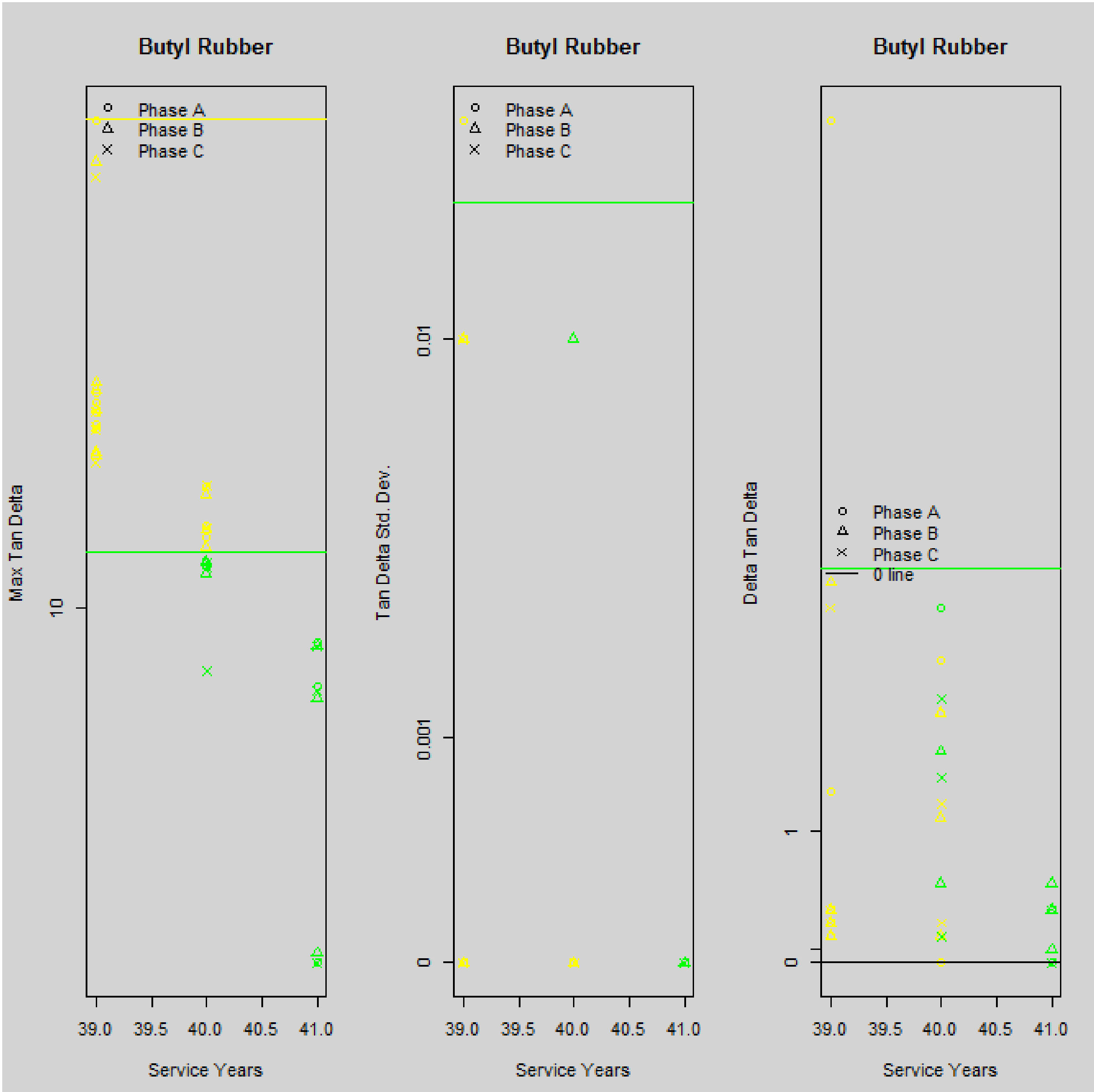

Figure B-12. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Butyl rubber Cables for Each Phase

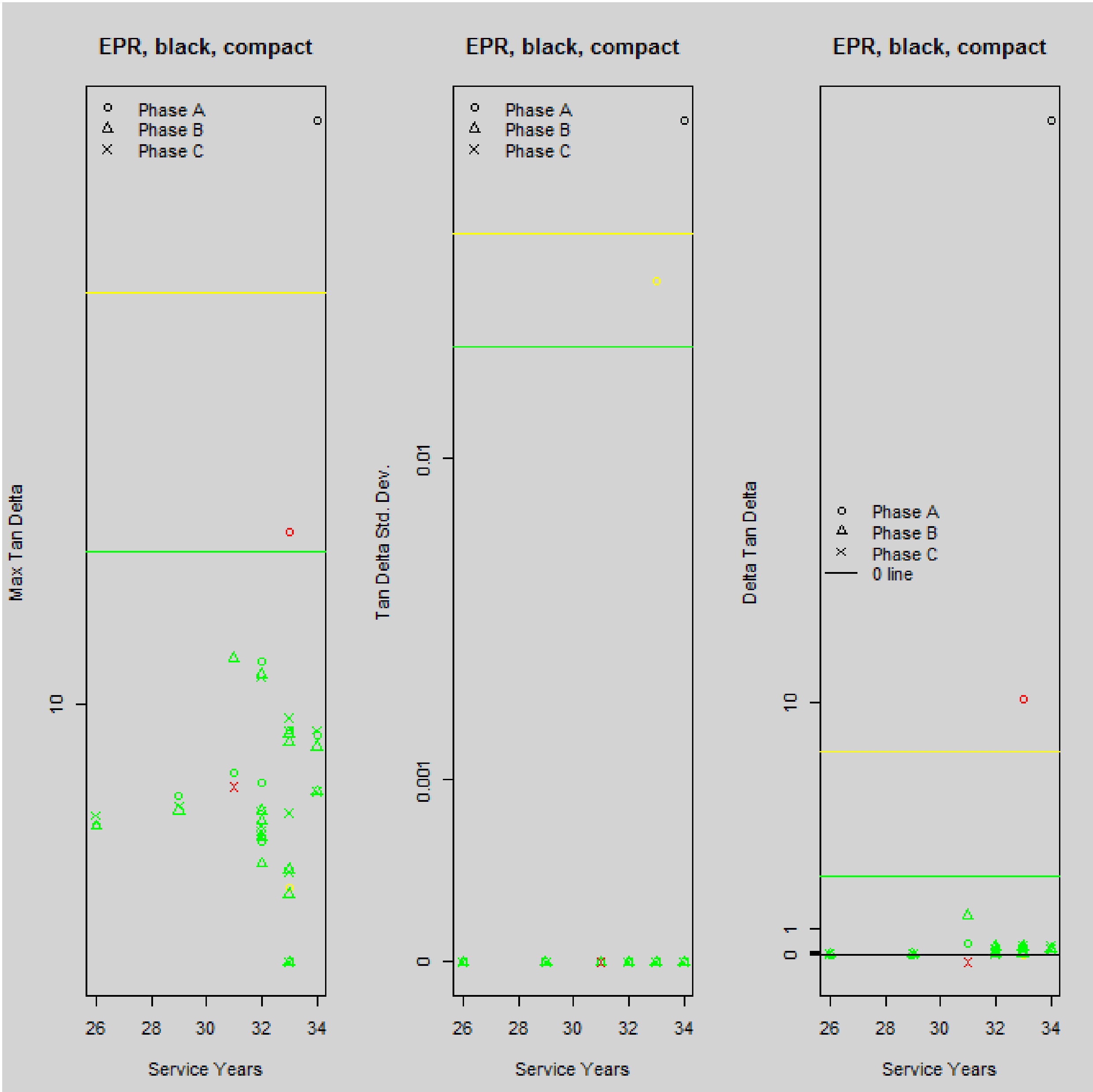

Figure B-13. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Black Compact Cables for Each Phase

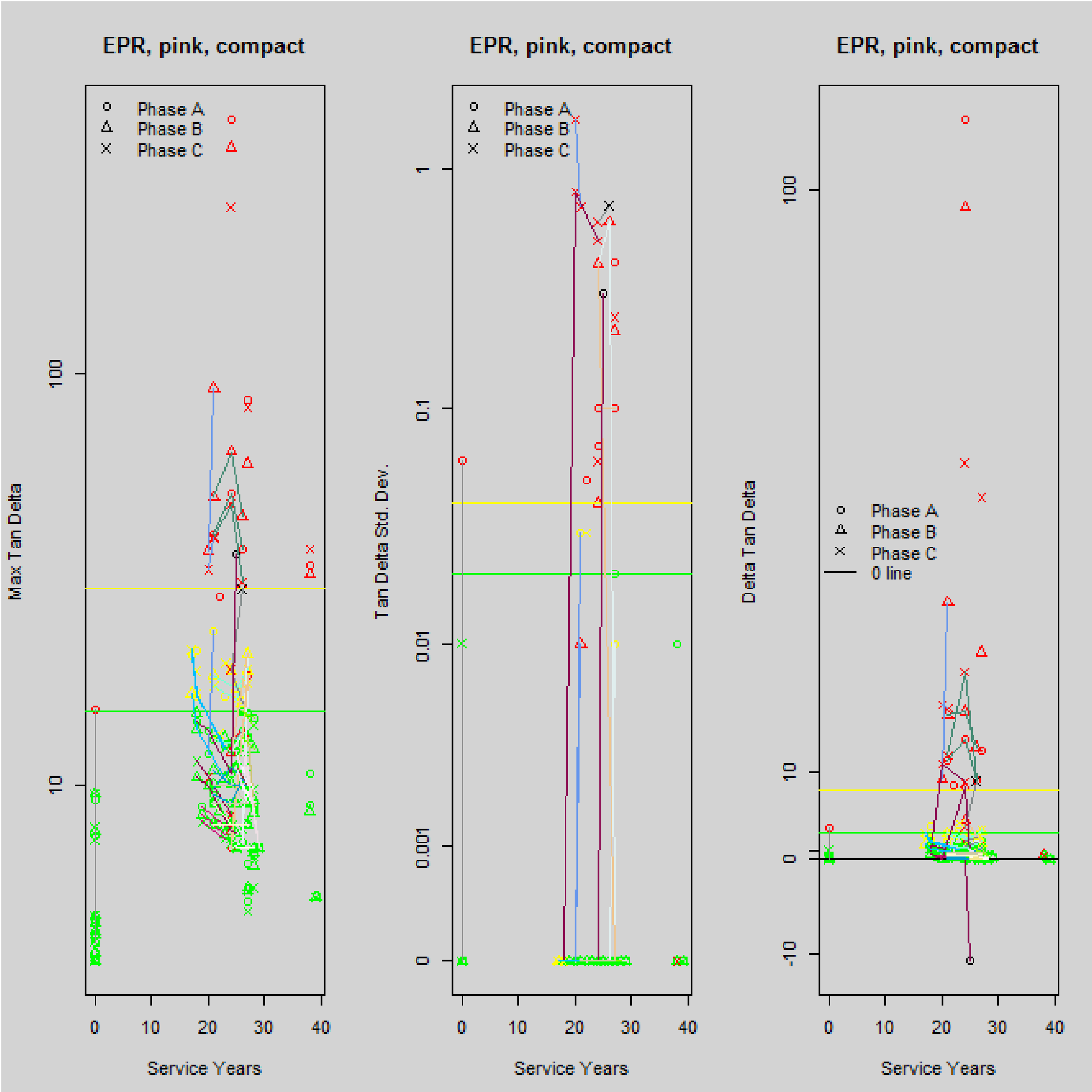

Figure B-14. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Pink Compact Cables for Each Phase

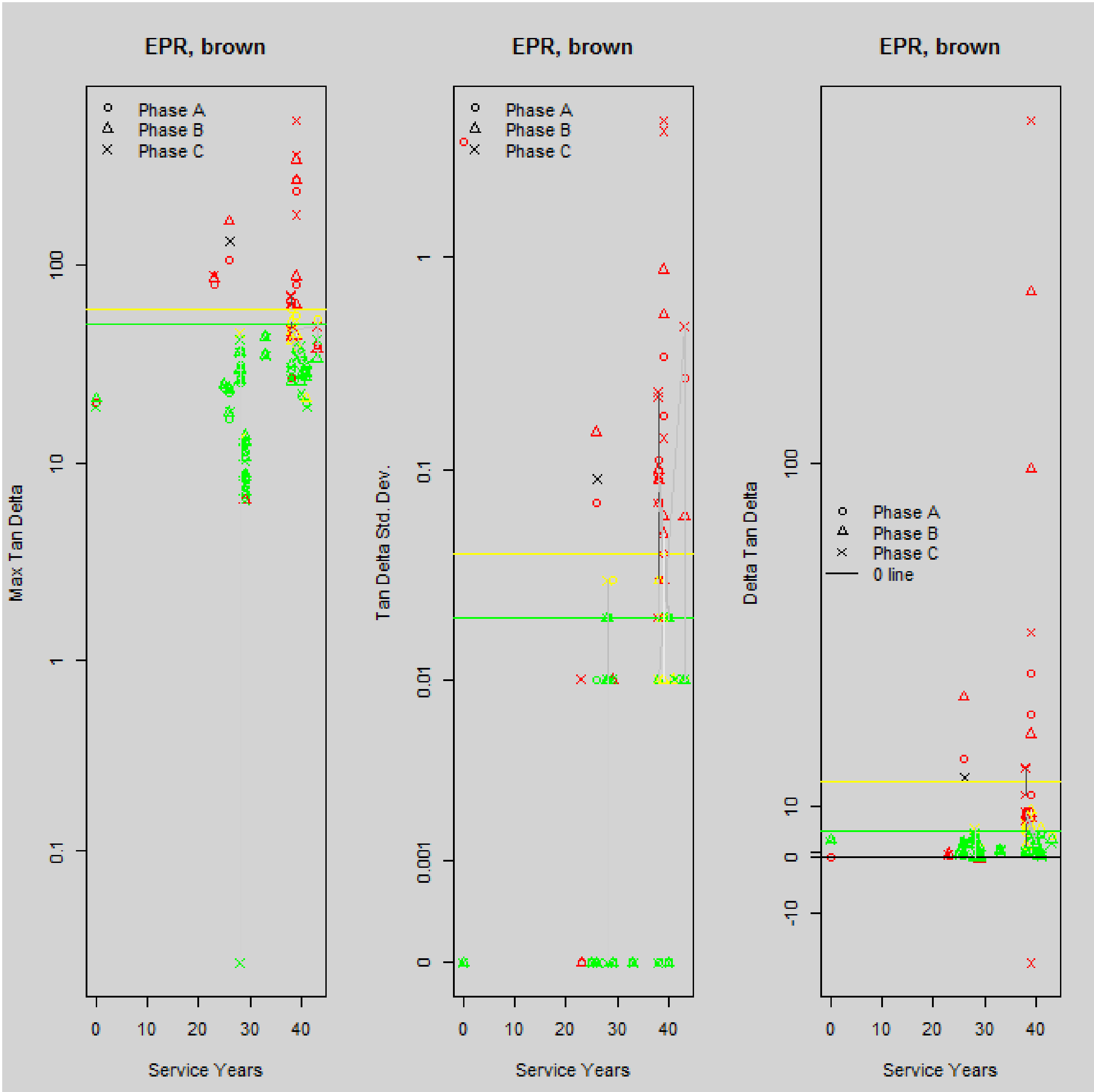

Figure B-15. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Brown Cables for Each Phase

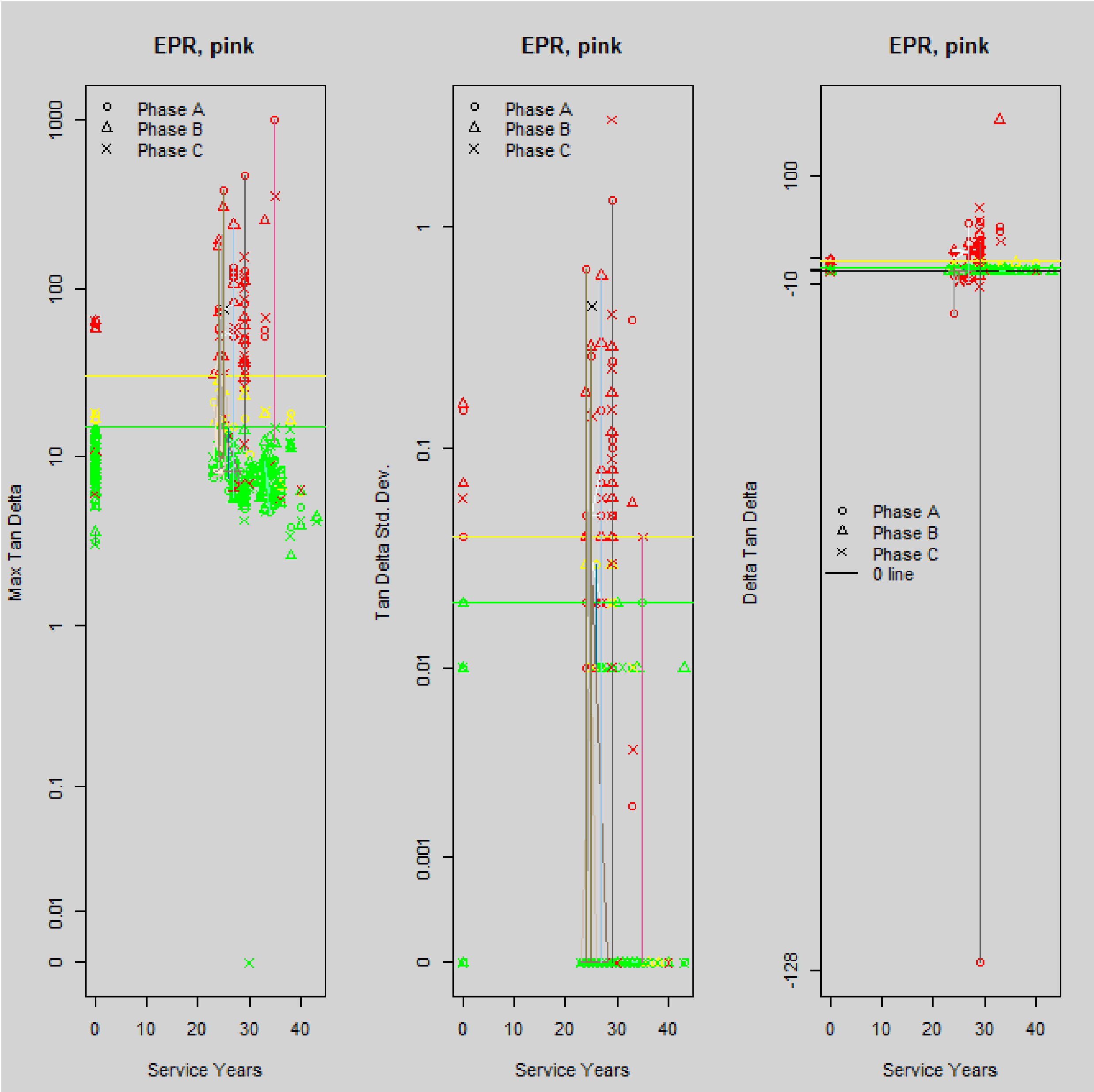

Figure B-16. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Pink Cables for Each Phase

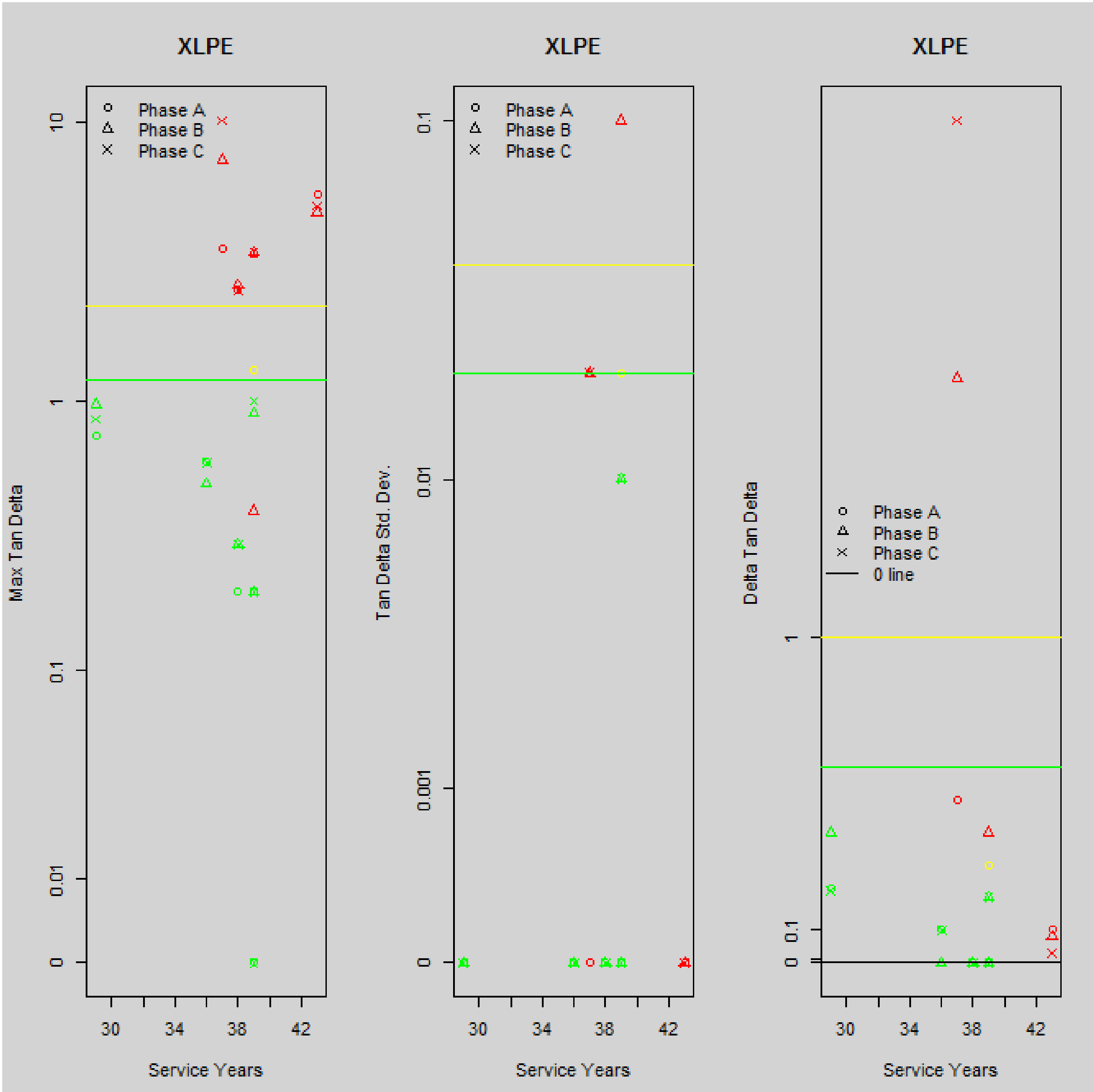

Figure B-17. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for XLPE Cables for Each Phase

Higher-level categories:

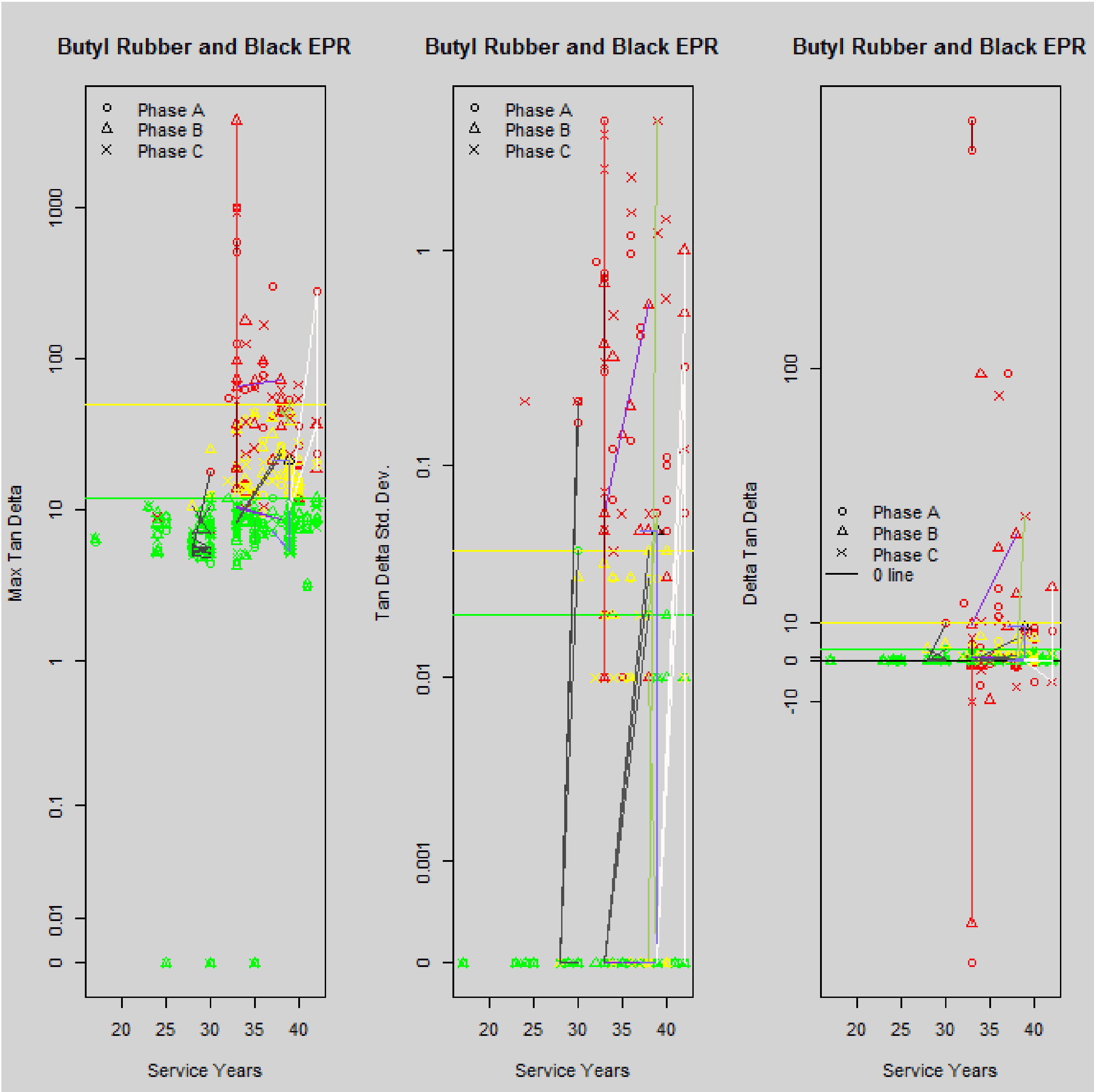

Figure B-18. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Butyl rubber and Black EPR Cables for Each Phase

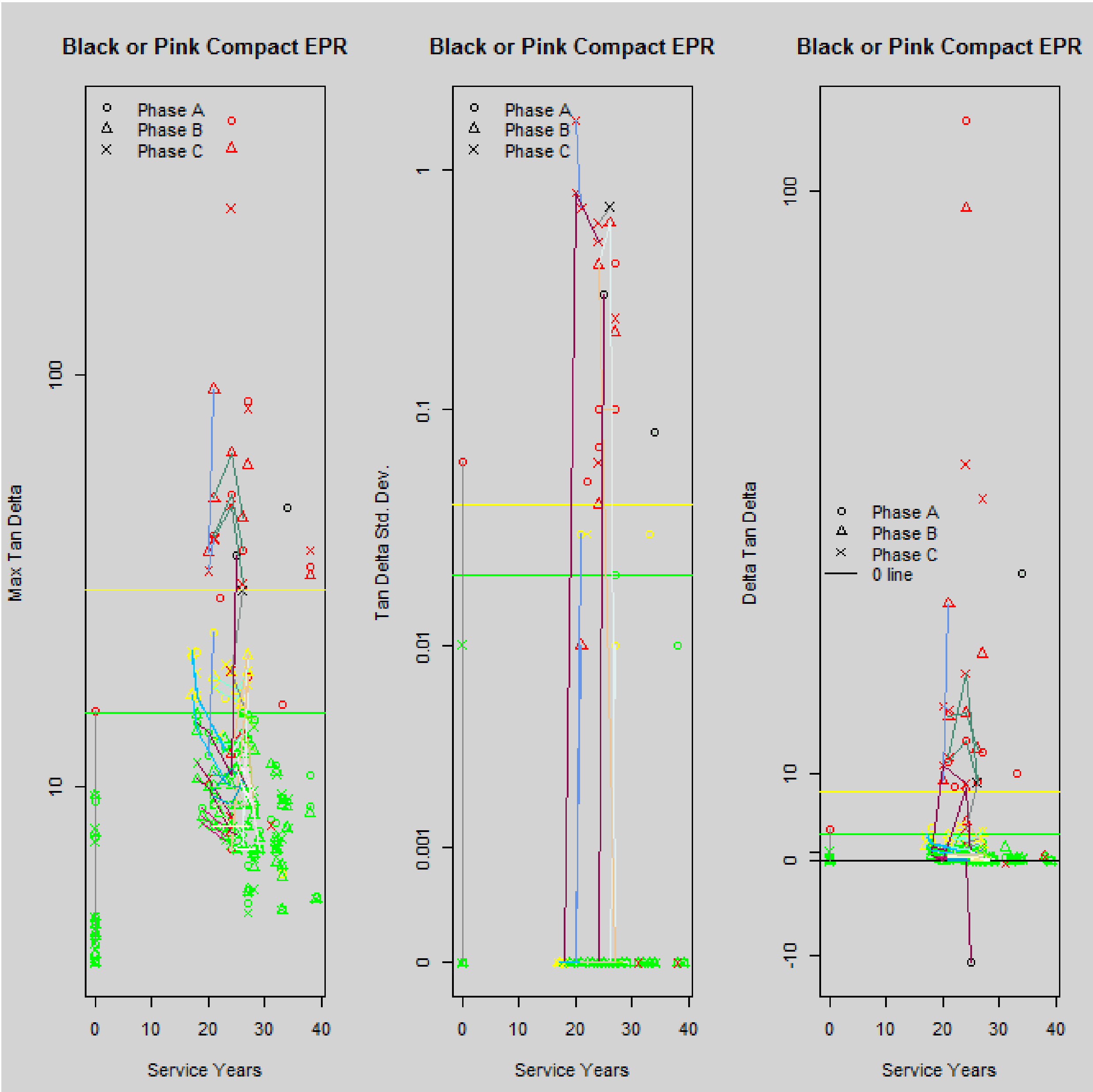

Figure B-19. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Black or Pink EPR compact Cables for Each Phase

All cable types:

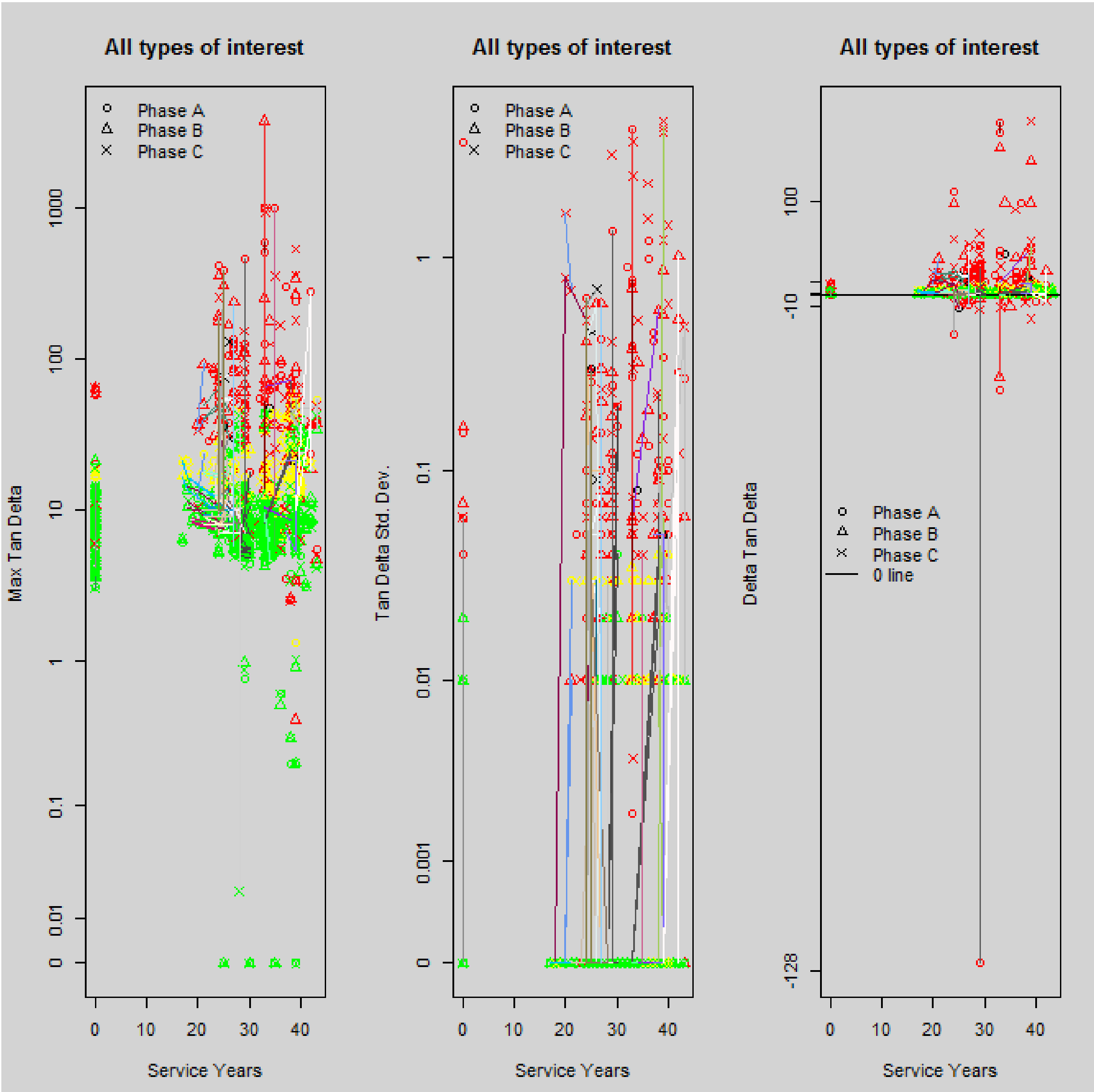

Figure B-20. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for All Cable Types of Interest for Each Phase

Appendix C – Reduced Temporal Data Plots

This appendix contains plots of summary Tan Delta statistics by cable type plotted on the log scale based on the reduced data set where only measurements taken on the same cable multiple times are retained (where data based on initial problems that were fixed within a few days were removed). The cable-level results are shown in the first eight figures, while phase-level results are shown in the second eight figures. The cable Green, Yellow, Red and failed category determination is used for the color of the points in the plots. Note: the Delta Tan Delta statistic was not plotted at the cable level as it was unclear what an appropriate summary measure (across the three phases) would be. Multiple temporal measurements of the same cable are connected by line segments in these plots. No butyl rubber or XLPE cables were measured multiple times, so no plots are presented for this cable type.

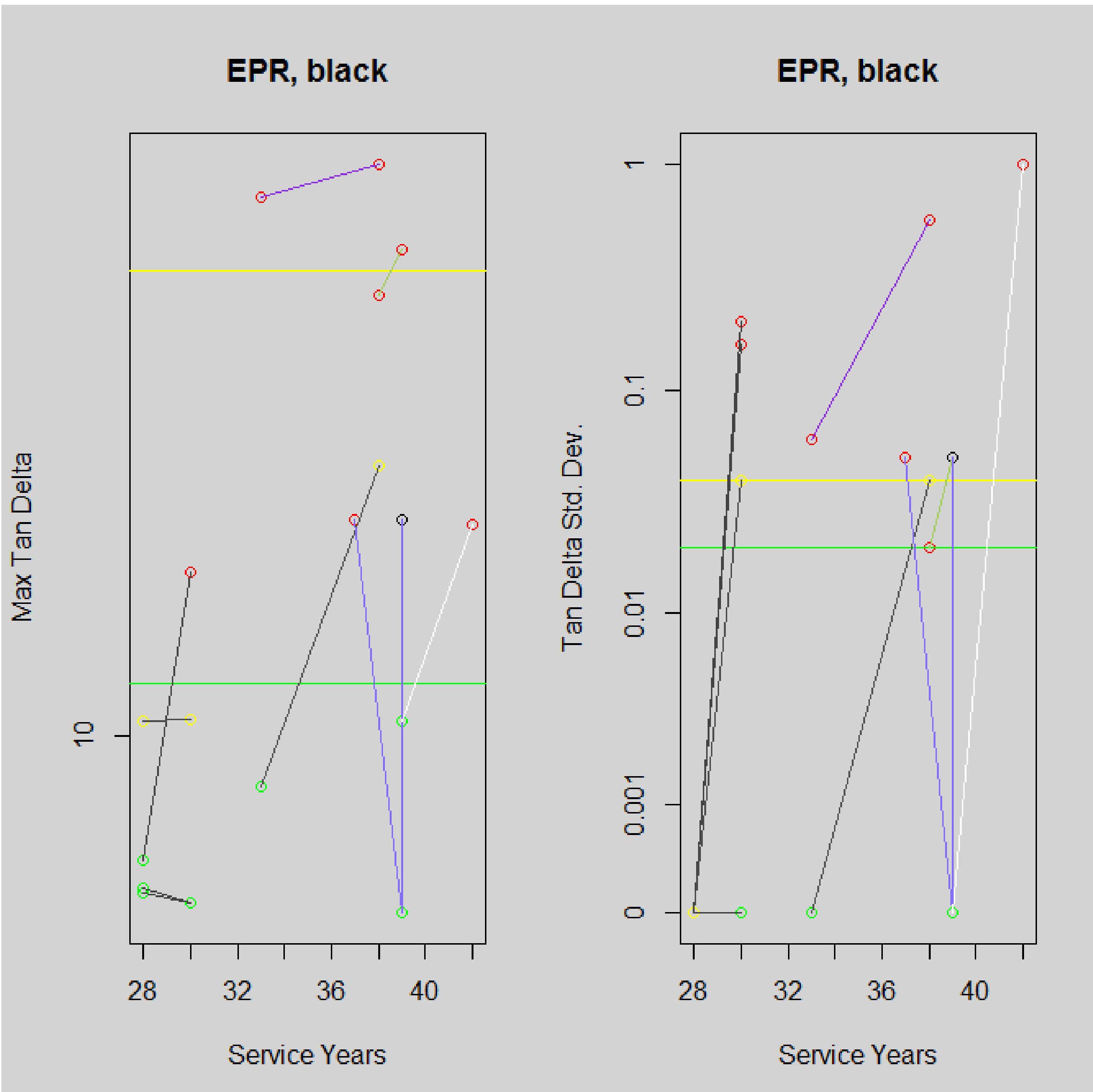

Figure C-1. Max Tan Delta and Tan Delta Standard Deviation for EPR Black Cables on Reduced Data

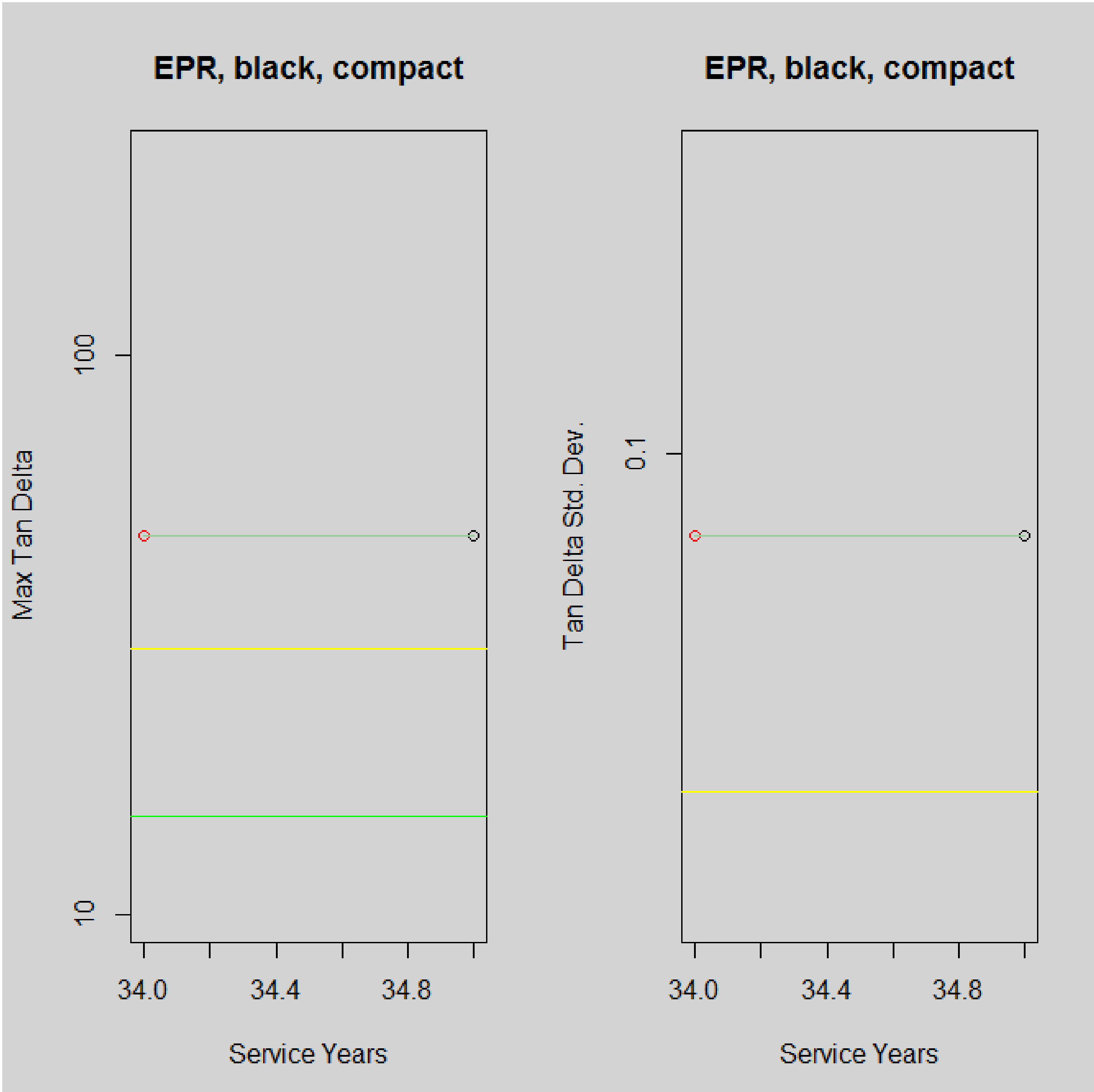

Figure C-2. Max Tan Delta and Tan Delta Standard Deviation for EPR Black Compact Cables on Reduced Data

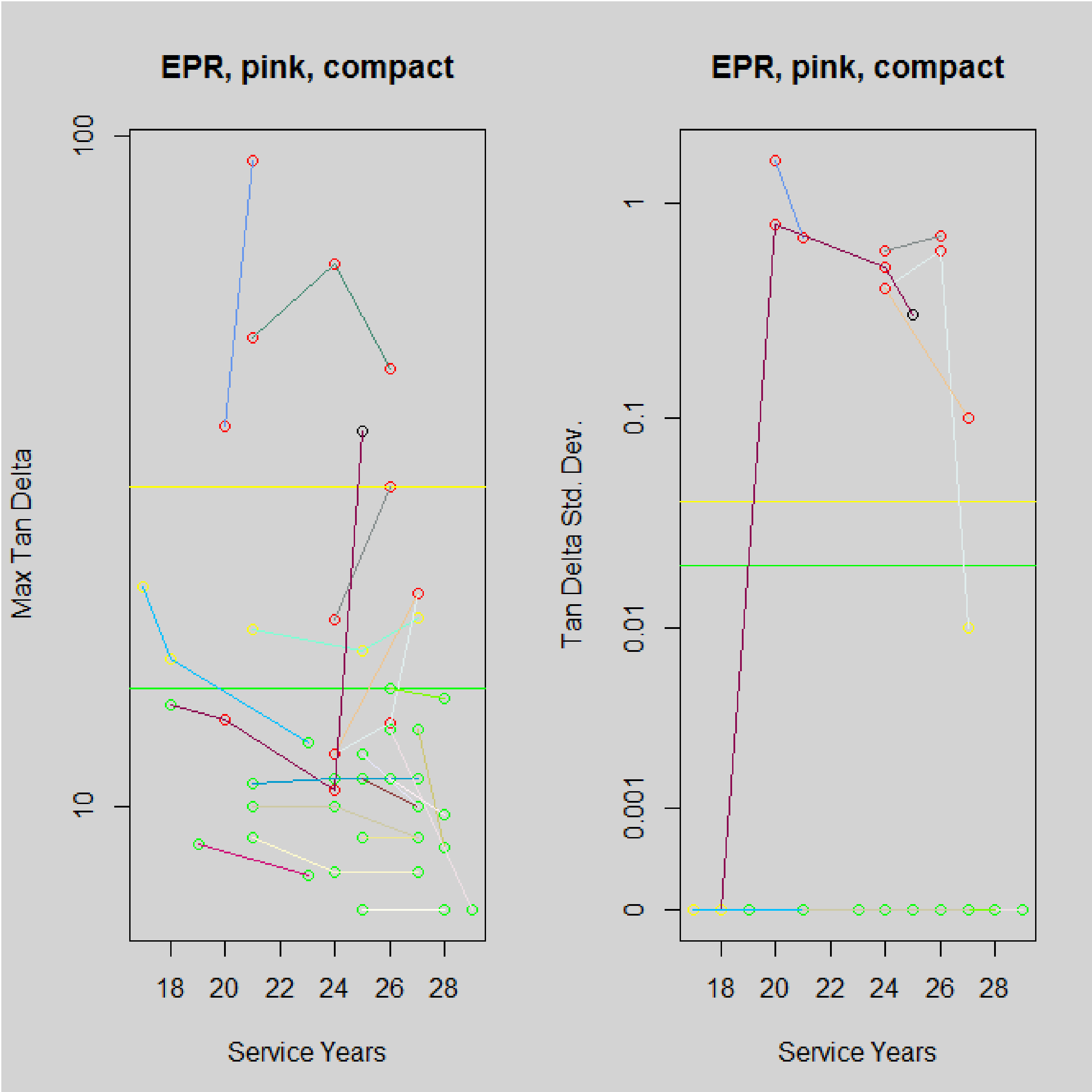

Figure C-3. Max Tan Delta and Tan Delta Standard Deviation for EPR Pink Compact Cables on Reduced Data

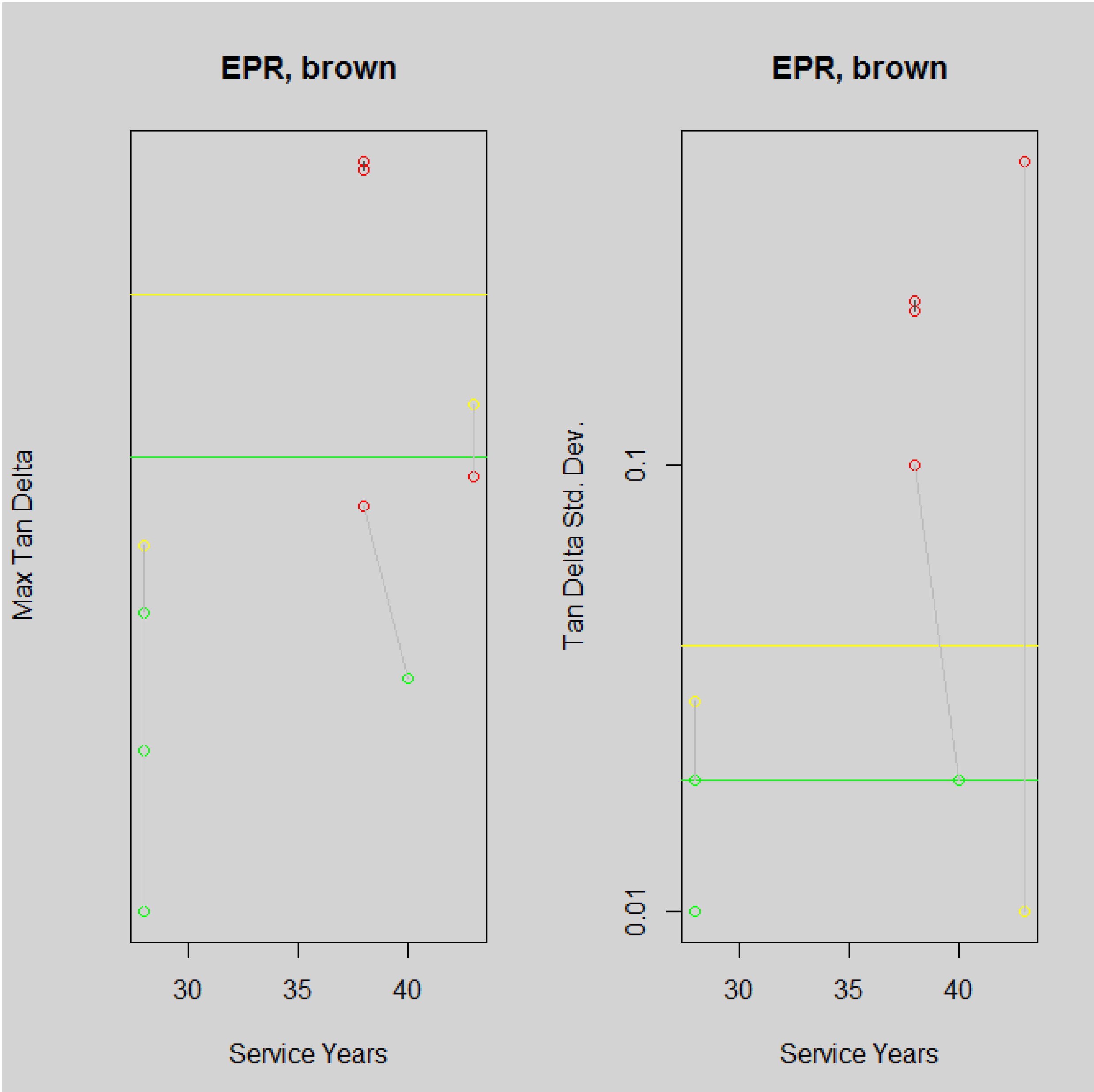

Figure C-4. Max Tan Delta and Tan Delta Standard Deviation for EPR Brown Cables on Reduced Data

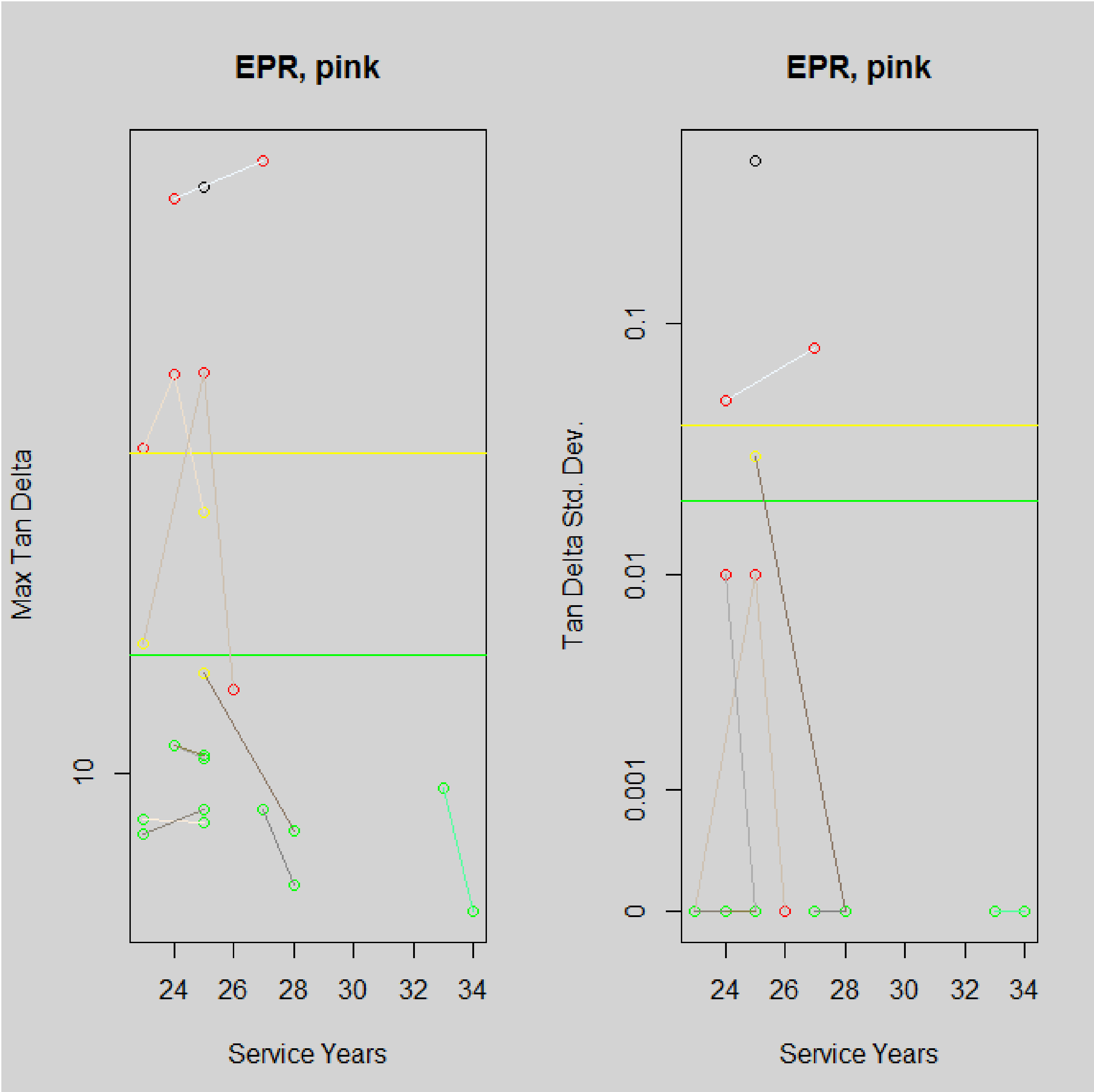

Figure C-5. Max Tan Delta and Tan Delta Standard Deviation for EPR Pink Cables on Reduced Data

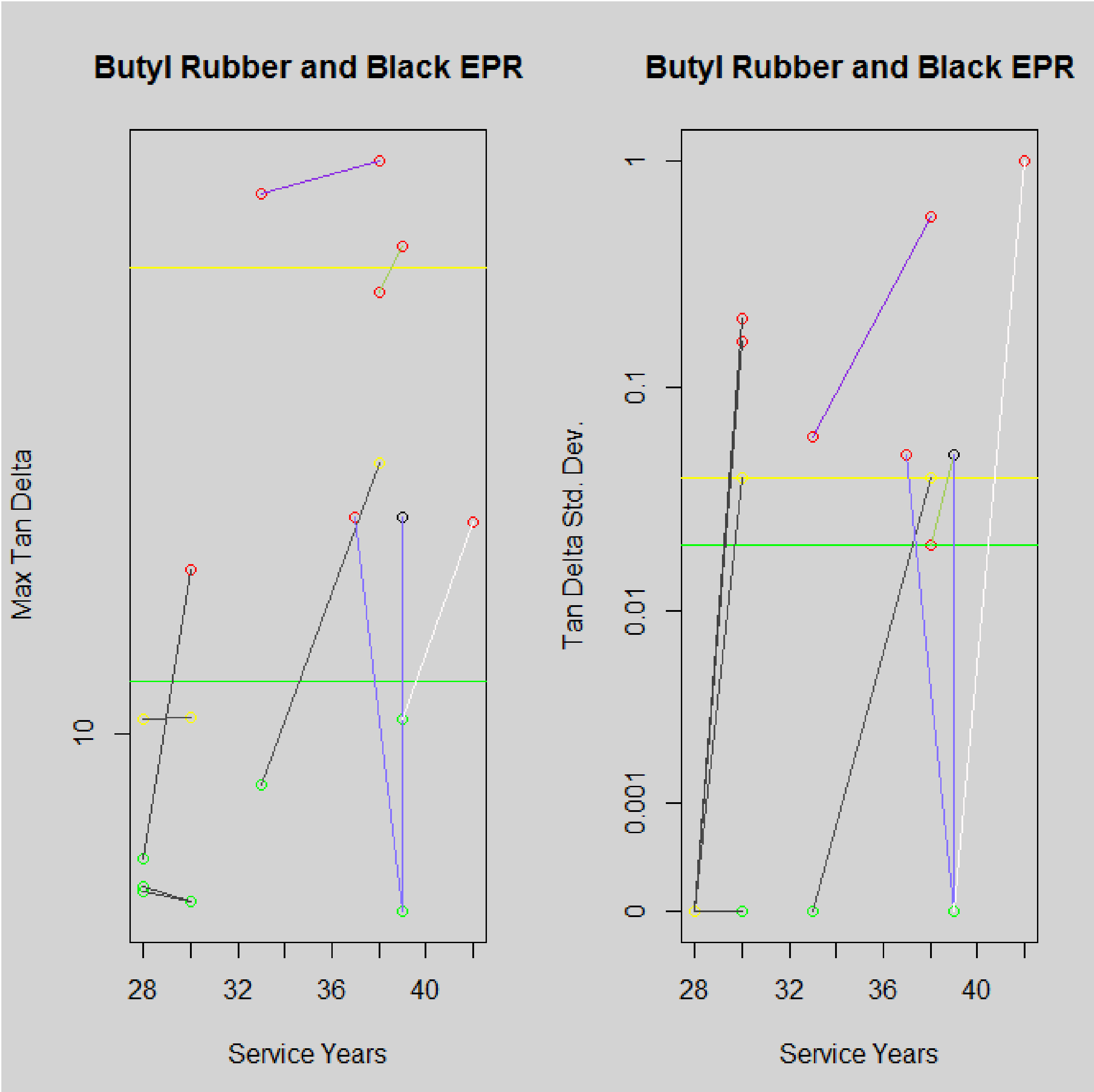

Figure C-6. Max Tan Delta and Tan Delta Standard Deviation for Butyl rubber and Black EPR Cables on Reduced Data

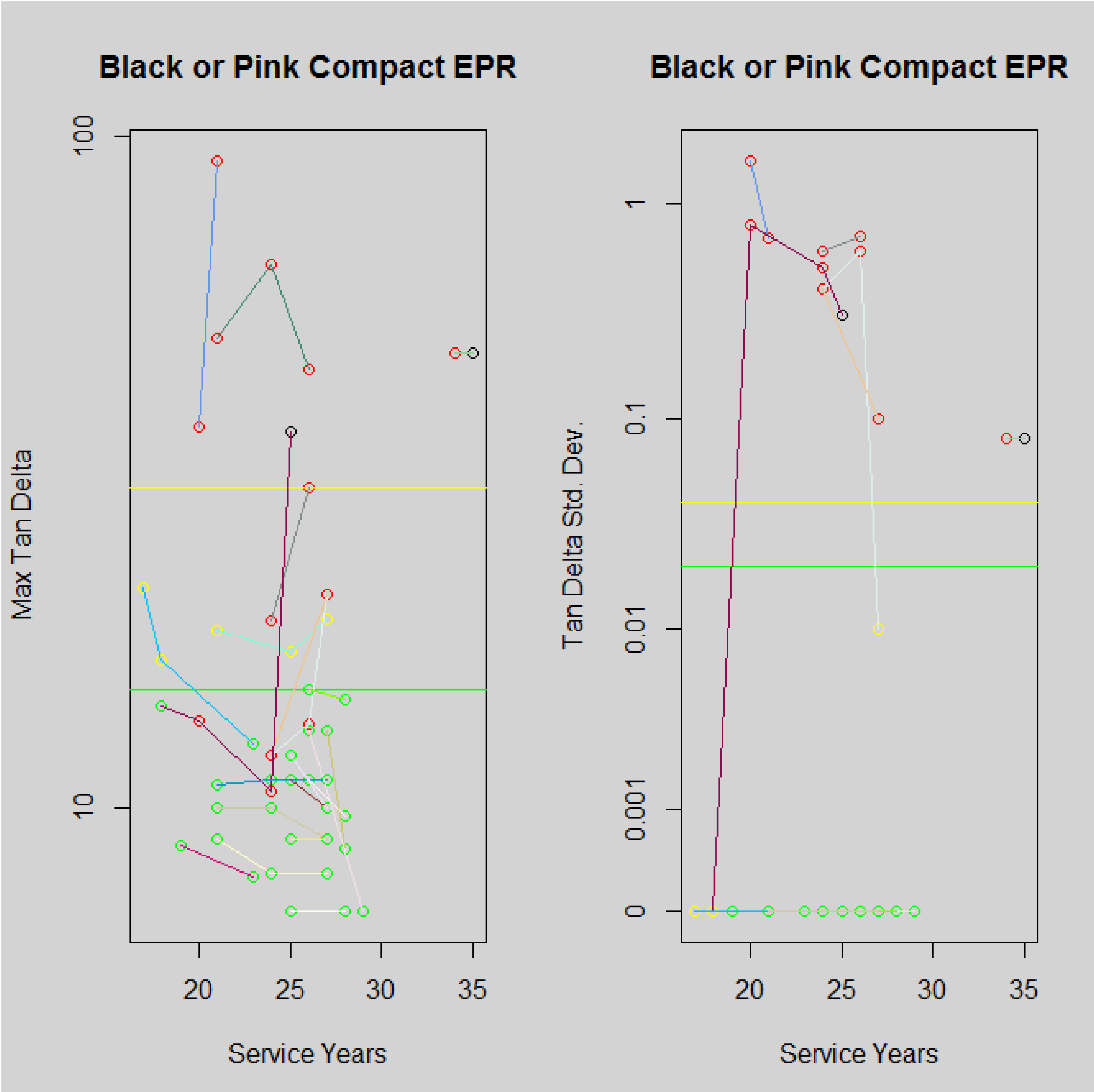

Figure C-7. Max Tan Delta and Tan Delta Standard Deviation for Black or Pink EPR compact Cables on Reduced Data

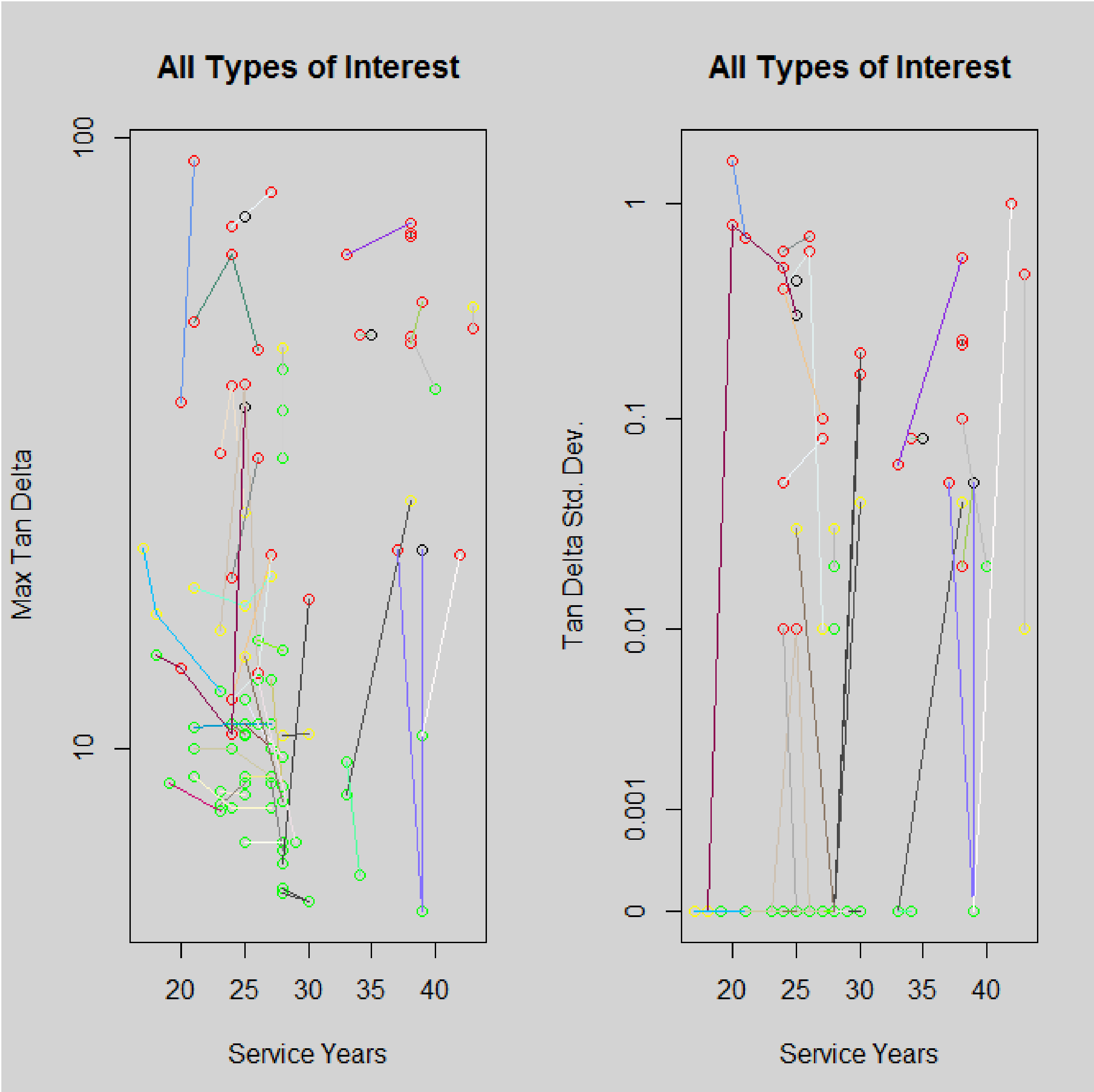

Figure C-8. Max Tan Delta and Tan Delta Standard Deviation for All Cable Types of Interest on Reduced Data

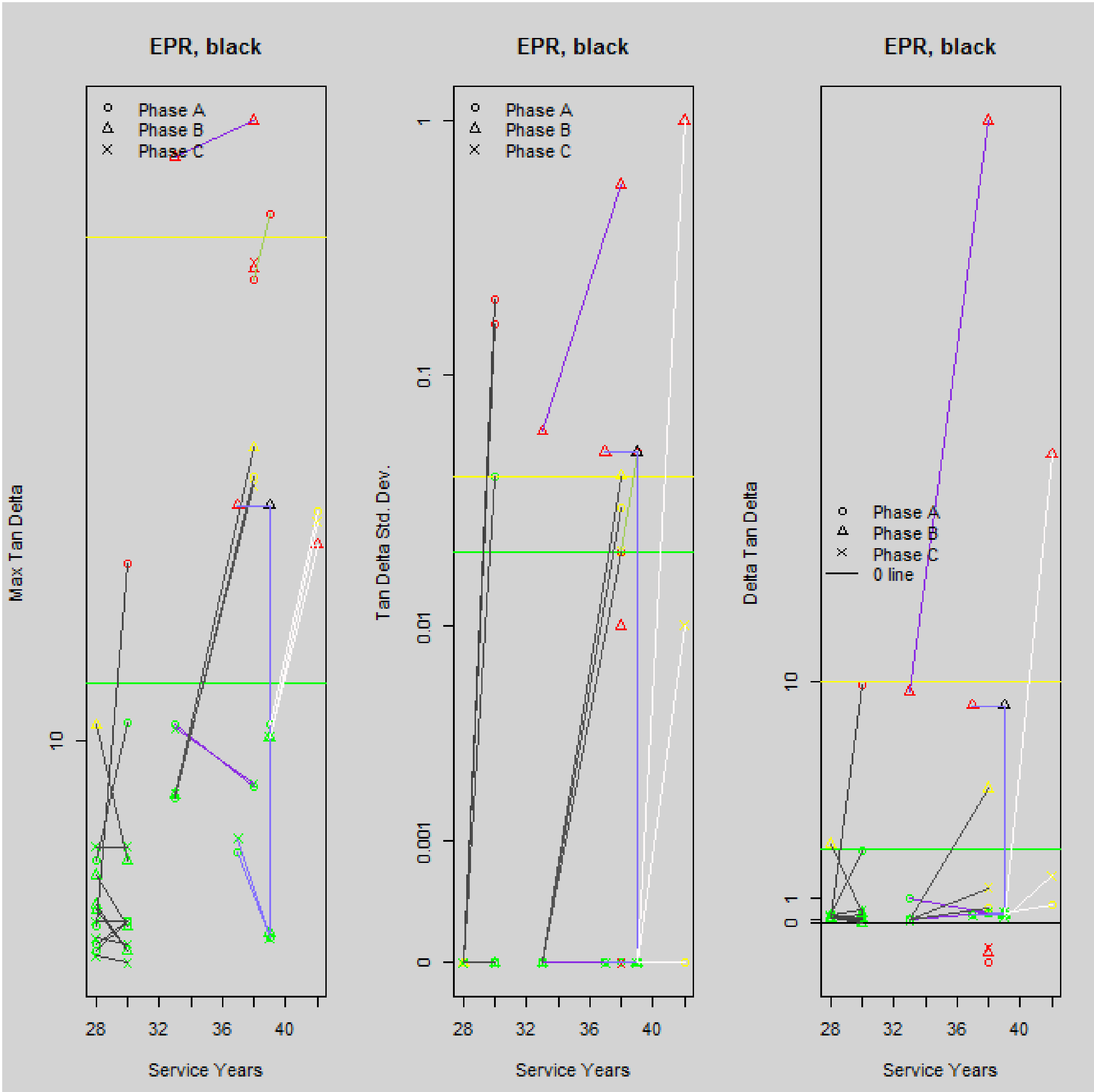

Figure C-9. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Black for Each Phase on Reduced Data

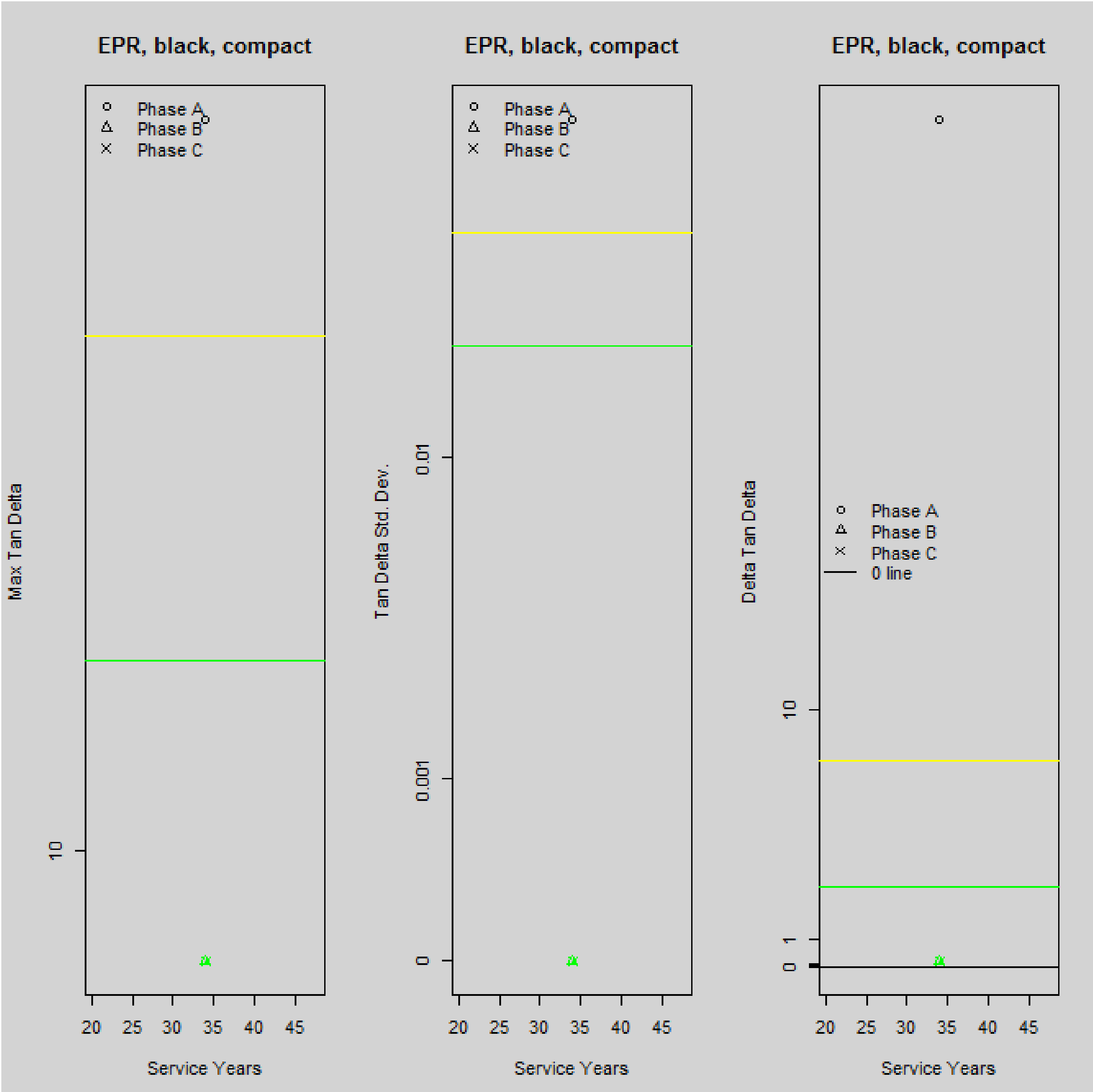

Figure C-10. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Black Compact for Each Phase on Reduced Data

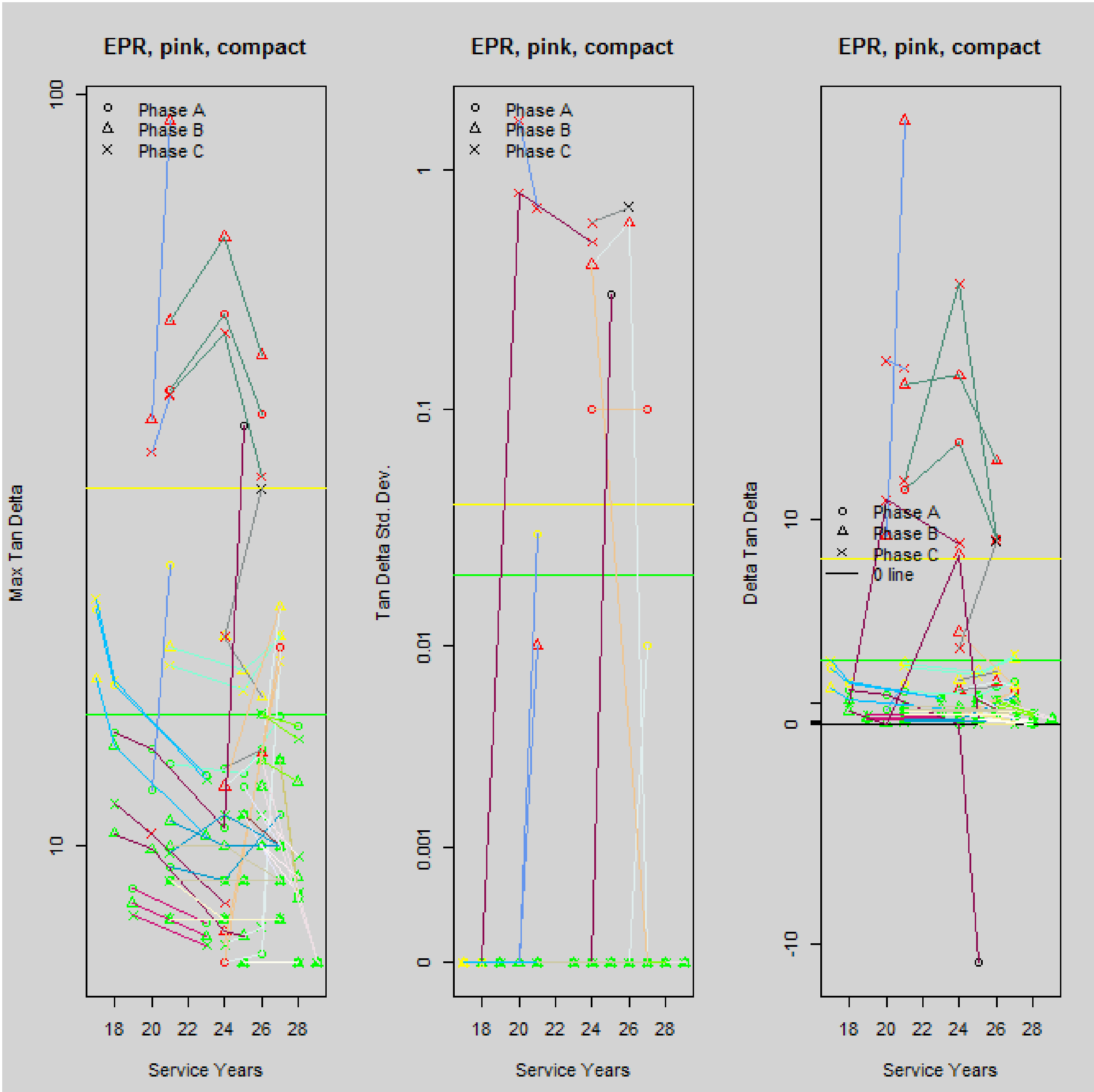

Figure C-11. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Pink Compact for Each Phase on Reduced Data

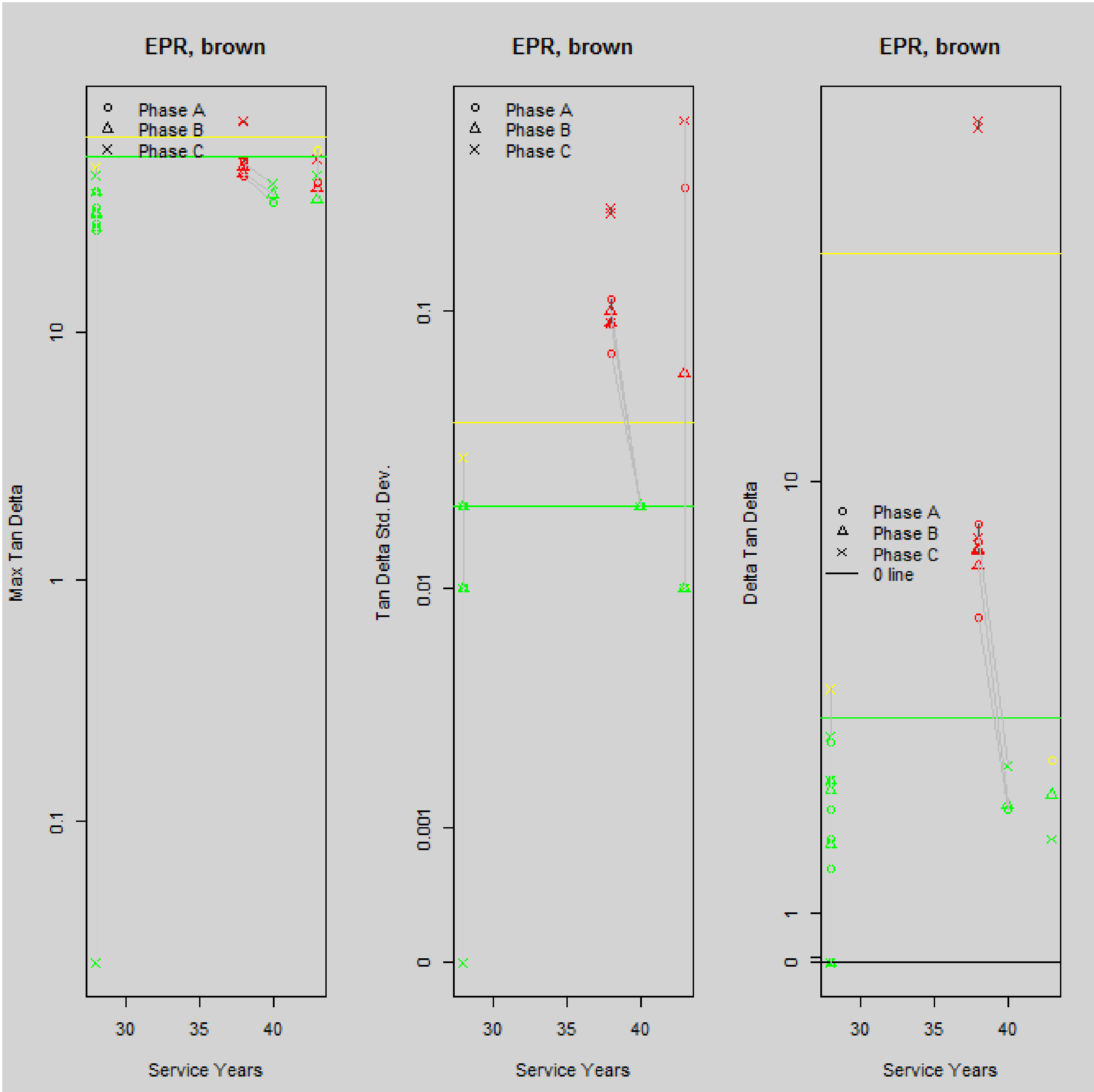

Figure C-12. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Brown for Each Phase on Reduced Data

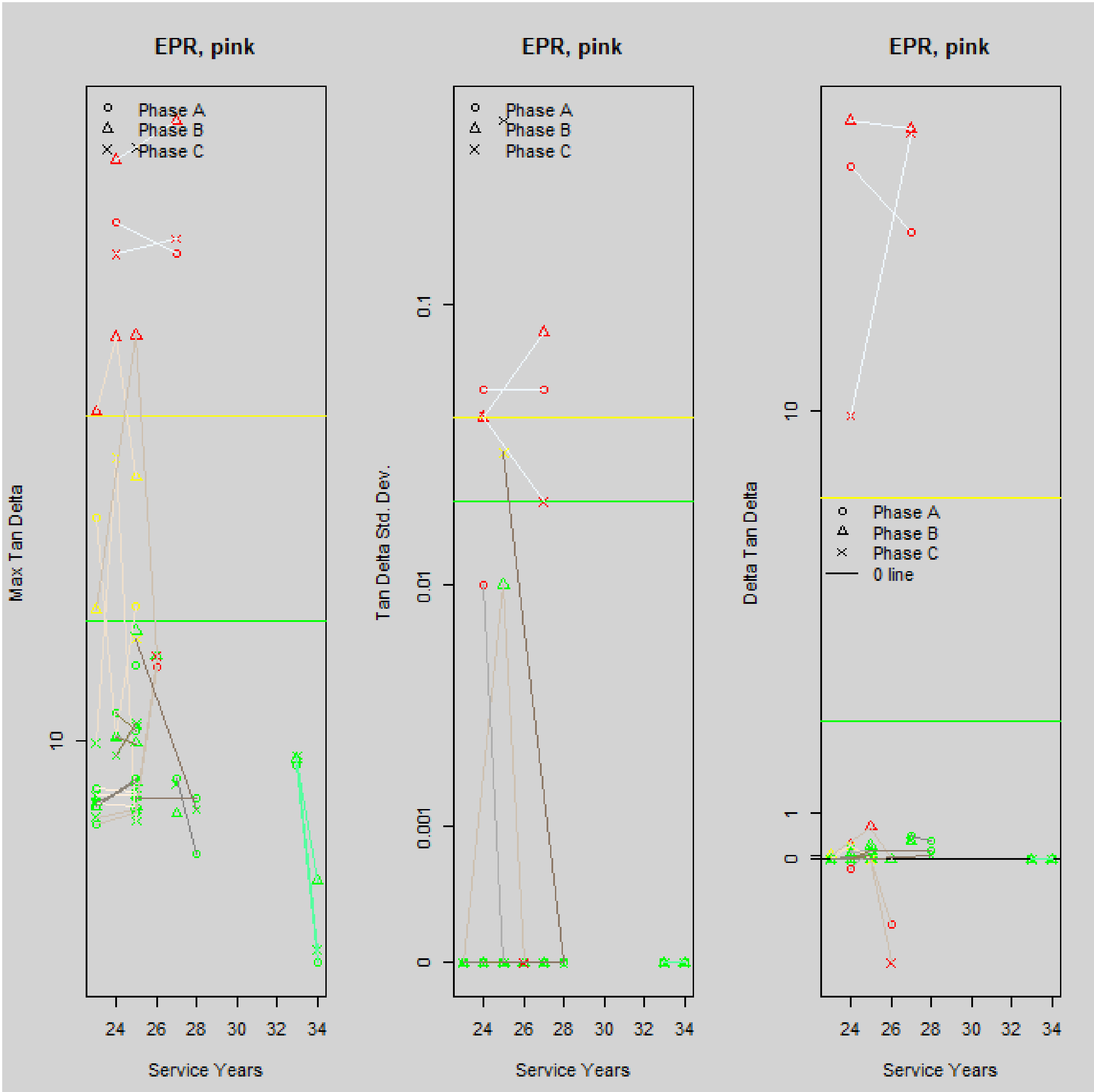

Figure C-13. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for EPR Pink for Each Phase on Reduced Data

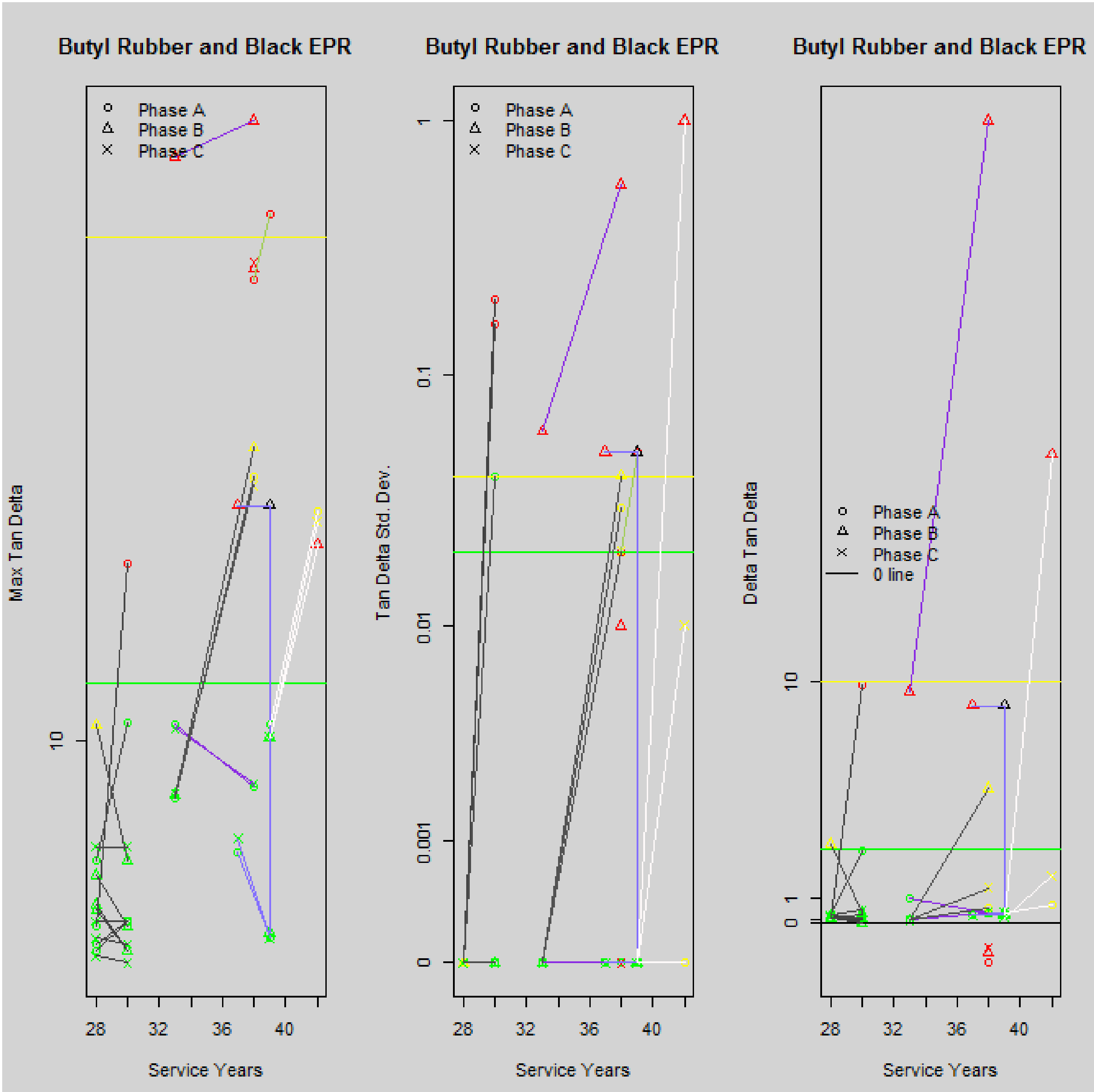

Figure C-14. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Butyl rubber and Black EPR for Each Phase on Reduced Data

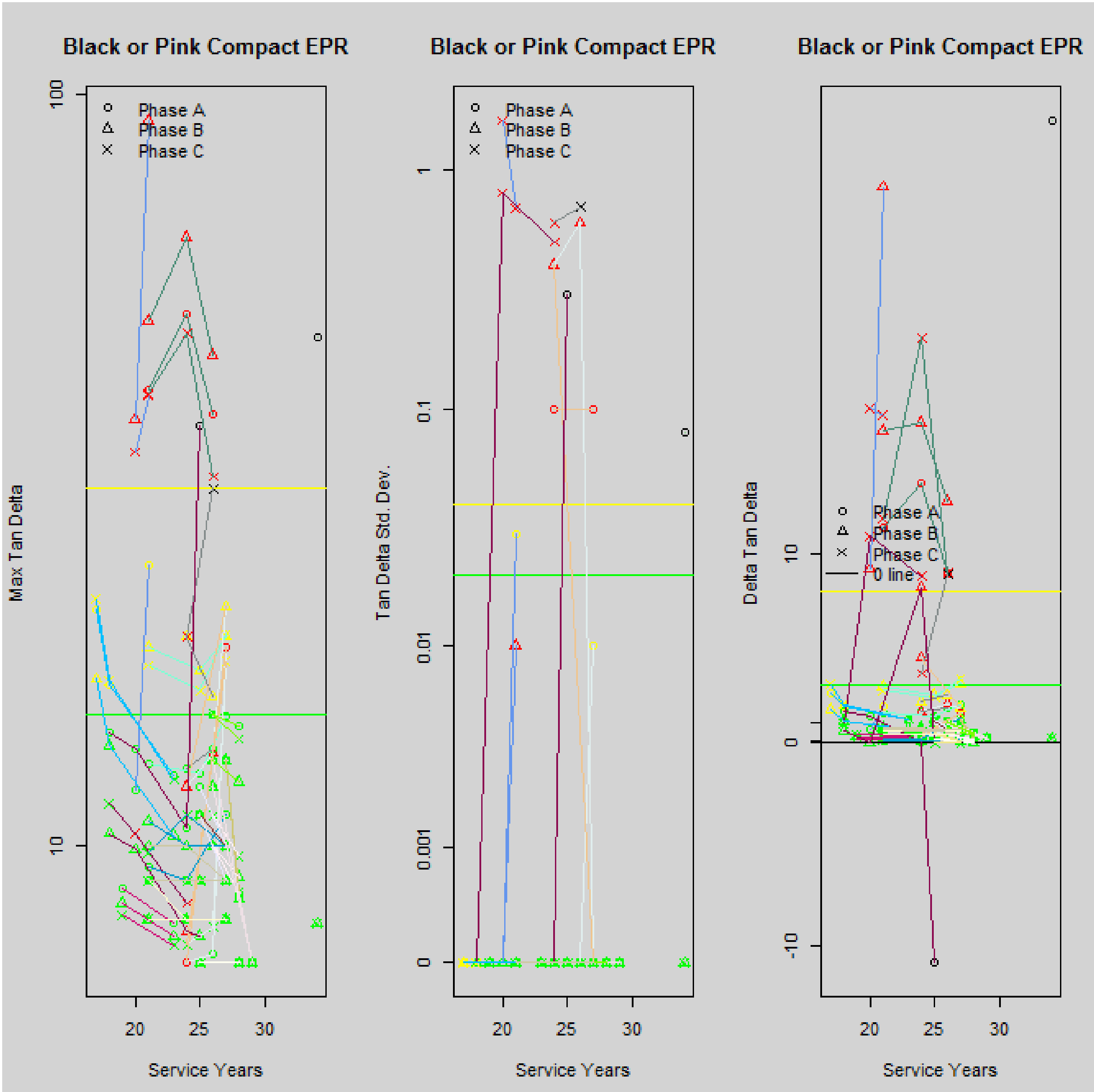

Figure C-15. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for Black or Pink EPR compact for Each Phase on Reduced Data

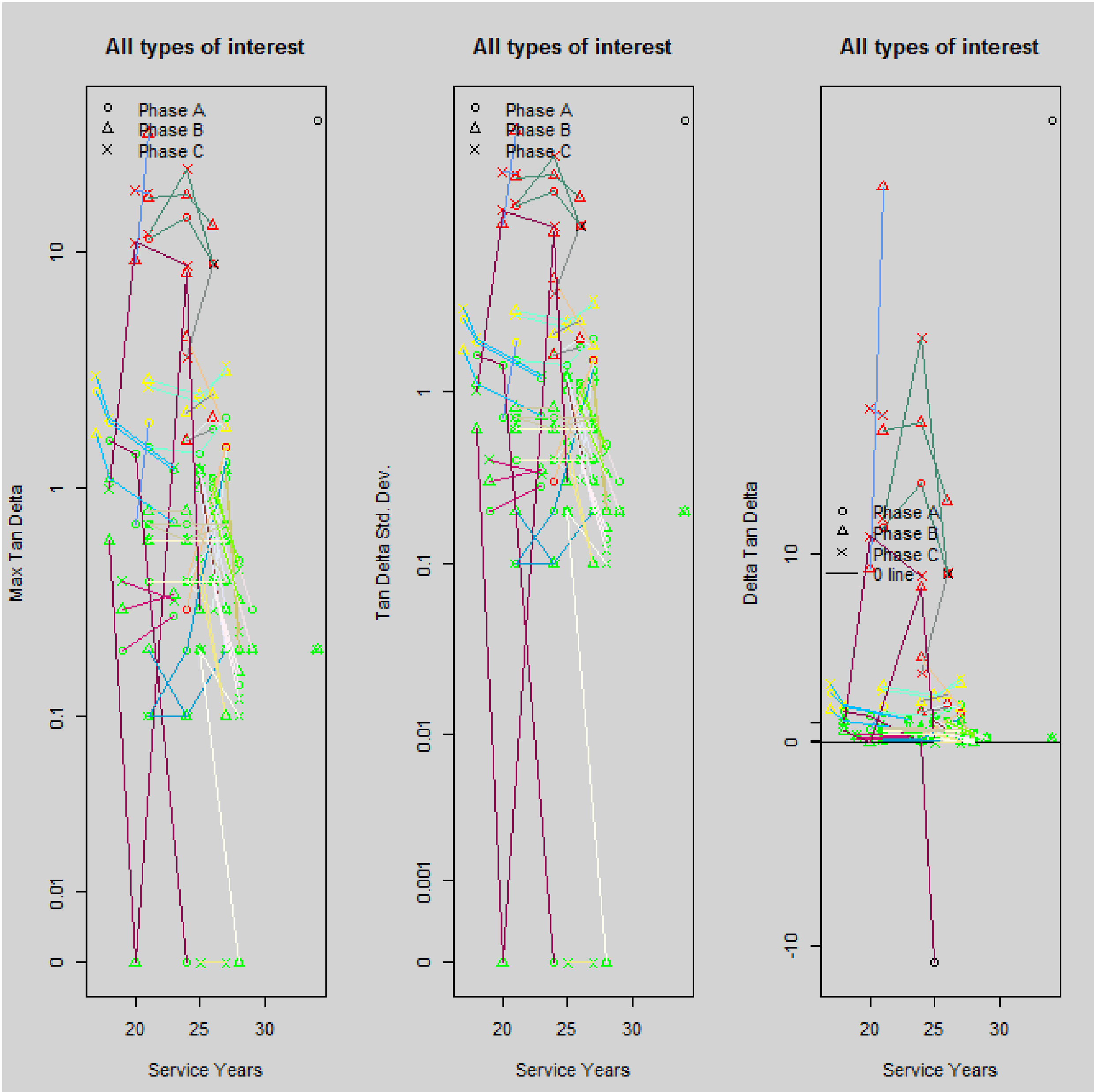

Figure C-16. Max Tan Delta, Tan Delta Standard Deviation, and Delta Tan Delta for All Cable Types of Interest for Each Phase on Reduced Data

Appendix D – Reduced Data Color Transition Analysis

Table D-1. Summarized Counts of Color Transition (starting green) on Reduced Data at the Cable Level

Starting color:	Green	Later Disposition Counts within 6 years:			
Cable Type	n (sample size)	Yellow	Red	Failed	No change
Butyl rubber and Black EPR	5	1	3	0	1
Black or pink EPR compact	13	0	1	0	12
Brown EPR	1	0	0	0	1
Pink EPR	5	0	0	0	5
XLPE	0	0	0	0	0
Total	24	1	4	0	19

Table D-2. Summarized Counts of Color Transition (starting yellow) on Reduced Data at the Cable Level

Starting color:	Yellow	Later Disposition Counts within 2 years:		
Cable Type	n (sample size)	Red	Failed	No change
Butyl rubber and Black EPR	1	0	0	1
Black or pink EPR compact	2	0	0	2
Brown EPR	1	0	0	1
Pink EPR	3	2	0	1
XLPE	0	0	0	0
Total	7	2	0	5

Table D-3. Summarized Counts of Color Transition (starting red) on Reduced Data at the Cable Level

Starting color:	Red	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and Black EPR	3	1	2
Black or pink EPR compact	6	2	4
Brown EPR	4	1	3
Pink EPR	3	1	2
XLPE	0	0	0
Total	16	5	11

The results at the phase level were:

Table D-4. Summarized Counts of Color Transition (starting green) on Reduced Data at the Phase Level

Starting Color:	Green	Later Disposition Counts within 6 years:			
Cable Type	n (sample size)	Yellow	Red	Failed	No change
Butyl rubber and black EPR	21	5	3	0	13
Black or pink EPR compact	45	2	2	0	41
Brown EPR	5	0	0	0	5
Pink EPR	21	1	0	0	20
XLPE	0	0	0	0	0
Total	92	8	5	0	79

Table D-5. Summarized Counts of Color Transition (starting yellow) on Reduced Data at the Phase Level

Starting color:	Yellow	Later Disposition Counts within 2 years:		
Cable Type	n (sample size)	Red	Failed	No change
Butyl rubber and Black EPR	1	0	0	1
Black or pink EPR compact	6	0	0	6
Brown EPR	1	0	0	1
Pink EPR	4	2	0	2
XLPE	0	0	0	0
Total	12	2	0	10

Table D-6. Summarized Counts of Color Transition (starting red) on Reduced Data at the Phase Level

Starting Color:	Red	Later Disposition Counts within 2 years:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and Black EPR	3	1	2
Black or pink EPR compact	10	2	8
Brown EPR	10	1	9
Pink EPR	5	1	4
XLPE	0	0	0
Total	28	5	23

Table D-7. 95% Confidence Intervals of Color Transition Probability (starting green) on Reduced Data at the Cable Level

Starting color:	Green	95% Confidence Intervals:			
Cable Type	n (sample size)	Yellow	Red	Failed	No change
Butyl rubber and Black EPR	5	(0.0%, 65.7%)	(17.3%, 96.6%)	(0%, 45.1%)	(0.0%, 65.7%)
Black or Pink EPR compact	13	(0%, 20.6%)	(0.0%, 31.6%)	(0%, 20.6%)	(68.4%, 100%)
Brown EPR	1*	0*	0*	0*	1*
Pink EPR	5	(0%, 45.1%)	(0%, 45.1%)	(0%, 45.1%)	(54.9%, 100%)
XLPE	0*	0*	0*	0*	0*
Total	24	(0.0%, 18.3%)	(3.5%, 35.1%)	(0%, 11.7%)	(59.8%, 94.1%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table D-8. 95% Confidence Intervals of Color Transition Probability (starting yellow) on Reduced Data at the Cable Level

Starting color:	Yellow	95% Confidence Intervals:		
Cable Type	n (sample size)	Red	Failed	No change
Butyl rubber and Black EPR	1*	0*	0*	1*
Black or Pink EPR compact	2	(0%, 77.6%)	(0%, 77.6%)	(22.4%, 100%)
Brown EPR	1*	0*	0*	1*
Pink EPR	3	(13.5%, 100%)	(0%, 63.2%)	(0.0%, 86.5%)
XLPE	0*	0*	0*	0*
Total	7	(1.5%, 66.6%)	(0%, 34.8%)	(33.4%, 98.5%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table D-9. 95% Confidence Intervals of Color Transition Probability (starting Red) on Reduced Data at the Cable Level

Starting color:	Red	95% Confidence Intervals:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and Black EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
Black or Pink EPR compact	6	(2.1%, 73.9%)	(26.1%, 97.9%)
Brown EPR	4	(0.0%, 75.1%)	(24.9%, 100%)
Pink EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
XLPE	0*	0*	0*
Total	16	(9.7%, 56.9%)	(43.1%, 90.3%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table D-10. 95% Confidence Intervals of Color Transition Probability (starting green) on Reduced Data at the Phase Level

Starting Color:	Green	95% Confidence Intervals:			
Cable Type	n (sample size)	Yellow	Red	Failed	No change
Butyl rubber and Black EPR	21	(6.9%, 45.2%)	(1.7%, 33.5%)	(0%, 13.3%)	(39.3%, 82.6%)
Black or Pink EPR compact	45	(0.0%, 13.4%)	(0.0%, 13.4%)	(0%, 6.4%)	(80.3%, 98.3%)
Brown EPR	5	(0%, 45.1%)	(0%, 45.1%)	(0%, 45.1%)	(54.9%, 100%)
Pink EPR	21	(0.0%, 20.7%)	(0%, 13.3%)	(0%, 13.3%)	(79.3%, 100%)
XLPE	0*	0*	0*	0*	0*
Total	92	(3.4%, 15.7%)	(1.3%, 11.4%)	(0%, 3.2%)	(77.7%, 92.7%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table D-11. 95% Confidence Intervals of Color Transition Probability (starting yellow) on Reduced Data at the Phase Level

Starting color:	Yellow	95% Confidence Intervals:		
Cable Type	n (sample size)	Red	Failed	No change
Butyl rubber and Black EPR	1*	0*	0*	1*
Black or Pink EPR compact	6	(0%, 39.3%)	(0%, 39.3%)	(60.7%, 100%)
Brown EPR	1*	0*	0*	1*
Pink EPR	4	(6.8%, 93.2%)	(0%, 52.7%)	(6.8%, 93.2%)
XLPE	0*	0*	0*	0*
Total	12	(0.5%, 44.1%)	(0%, 22.1%)	(55.9%, 99.5%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Table D-12. 95% Confidence Intervals of Color Transition Probability (starting yellow) on Reduced Data at the Phase Level

Starting color:	Red	95% Confidence Intervals:	
Cable Type	n (sample size)	Failed	No change
Butyl rubber and Black EPR	3	(0.0%, 86.5%)	(13.5%, 100%)
Black or Pink EPR compact	10	(0.7%, 51.1%)	(48.9%, 99.3%)
Brown EPR	10	(0.0%, 39.4%)	(60.6%, 100%)
Pink EPR	5	(0.0%, 65.7%)	(34.3%, 100%)
XLPE	0*	0*	0*
Total	28	(4.9%, 35.0%)	(65.0%, 95.1%)

*Too few samples to construct a confidence interval. Count given instead of confidence interval.

Appendix E – 90%, 95%, and 99% Confidence Intervals for Transition Probabilities on the Reduced and Fully Reduced Data

Table E-1. Terminology Definitions

Term:	Definition:
n	Number of observations
X	Count, the number of observations that went from the starting color to the color of interest
p	The probability of transitioning from the starting color to the color of interest
$\hat{p}$	The point estimate for the probability p
CIs	Confidence Intervals

Cable–level multiple confidence intervals for reduced data:

Butyl rubber and Black EPR:

Table E-2. CIs for Probability of Transitioning from Green to Failure in Six Years for Butyl rubber and Black EPR on the Reduced Data at Cable Level

	Shortest Confidence Interval:		
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-3. CIs for Probability of Transitioning from Green to Red in Six years for Butyl rubber and Black EPR on the Reduced Data at Cable Level

	Shortest Confidence Interval:		
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 3, n = 5, $\hat{p}$ = 0.6		
Confidence Interval	(22.1%, 94.8%)	(17.3%, 96.6%)	(10.0%, 98.7%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 10%. With so few observations (5), the confidence intervals are quite wide.		

Table E-4. CIs for Probability of Transitioning from Green to Yellow in Six Years for Butyl Rubber and Black EPR on the Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 5, $\hat{p}$ = 0.2		
Confidence Interval	(0%, 58.4%)	(0%, 65.7%)	(0%, 77.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0% and are quite wide because the number of observations is small (5).		

There was only one butyl rubber or black EPR cable that was measured multiple times and started out yellow, so a confidence interval on the probability of transitioning from yellow to red or failure cannot be constructed.

Table E-5. CIs for Probability of Transitioning from Red to Failure in Two Years for Butyl Rubber and Black EPR on the Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and are quite wide because the number of observations is small (3).		

Black or pink EPR compact:

Table E-6. CIs for Probability of Transitioning from Green to Failure in Six Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 13, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 16.2%)	(0%, 20.6%)	(0%, 29.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are wide because the number of observations is fairly small (13).		

Table E-7. CIs for Probability of Transitioning from Green to Red in Six Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 13, $\hat{p}$ = 0.0769		
Confidence Interval for p	(0%, 26.8%)	(0%, 31.6%)	(0%, 41.3%)
Conclusion:	The confidence intervals for the probability of transitioning from green to red in 6 years contain 0% and are wide because the number of observations is fairly small (13).		

Table E-8. CIs for Probability of Transitioning from Green to Yellow in Six Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 13, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 16.2%)	(0%, 20.6%)	(0%, 29.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in six years contain 0% and are wide because the number of observations is fairly small (13).		

Table E-9. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 2, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 68.4%)	(0%, 77.6%)	(0%, 90%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in two years contain 0% and are quite wide because the number of observations is small (2).		

Table E-10. CIs for Probability of Transitioning from Yellow to Red in Two Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 2, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 68.4%)	(0%, 77.6%)	(0%, 90%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to Red in 2 years contain 0% and are quite wide because the number of observations is small (2).		

Table E-11. CIs for Probability of Transitioning from Red to Failure in Two Years for Black or Pink EPR compact on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 6, $\hat{p}$ = 0.333		
Confidence Interval for p	(3.4%, 68.4%)	(2.1%, 73.9%)	(0.7%, 83%)
Conclusion:	Based on the confidence intervals, the probability of transitioning from Red to failure in 2 years is at least 0.7%, but the interval is quite wide because the number of observations is small (6).		

Brown EPR:

There were too few brown EPR cables (one that started Green, one that started Yellow) to construct a confidence interval on the parameters: probability of transitioning from Green to failure, Red, or Yellow, in six years and the probability of transitioning from Yellow to failure or Red in two years.

Table E-12. CIs for Probability of Transitioning from Red to Failure in Two Years for Brown EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 4, $\hat{p}$ = 0.25		
Confidence Interval for p	(0%, 68%)	(0%, 75.1%)	(0%, 85.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (4).		

Pink EPR:

Table E-13. CIs for Probability of Transitioning from Green to Failure in Six Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%, but the intervals are quite wide because the number of observations is small (5).		

Table E-14. CIs for Probability of Transitioning from Green to Red in Six Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from green to Red in 6 years contain 0%, but the interval is quite wide because the number of observations is small (5).		

Table E-15. CIs for Probability of Transitioning from Green to Yellow in Six Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%, but the interval is quite wide because the number of observations is small (5).		

Table E-16. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 3, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 53.6%)	(0%, 63.2%)	(0%, 78.5%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (3).		

Table E-17. CIs for Probability of Transitioning from Yellow to Red in Two Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 3, $\hat{p}$ = 0.667		
Confidence Interval for p	(19.6%, 100%)	(13.5%, 100%)	(5.9%, 100%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 5.9%, the interval is quite wide because the number of observations is small (3).		

Table E-18. CIs for Probability of Transitioning from Red to Failure in Two Years for Pink EPR on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval for p	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (3).		

XLPE: There are no XLPE cables that were tested multiple times in the data set, so confidence intervals cannot be constructed.

Results across cable type:

Table E-19. CIs for Probability of Transitioning from Green to Failure in Six Years for All Cable Types on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 24, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 9.1%)	(0%, 11.7%)	(0%, 17.5%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%.		

Table E-20. CIs for Probability of Transitioning from Green to Red in Six Years for All Cable Types on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 4, n = 24, $\hat{p}$ = 0.167		
Confidence Interval for p	(4.45%, 31.8%)	(3.46%, 35.1%)	(2%, 41.7%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 2%.		

Table E-21. CIs for Probability of Transitioning from Green to Yellow in Six Years for All Cable Types on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 24, $\hat{p}$ = 0.0417		
Confidence Interval for p	(0%, 15.3%)	(0%, 18.3%)	(0%, 24.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%.		

Table E-22. CIs for Probability of Transitioning from Yellow to Failure in Two Years for All Cable Types on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 7, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 28.0%)	(0%, 34.8%)	(0%, 48.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0%, but the confidence intervals are quite wide because of the small number of observations (7).		

Table E-23. CIs for Probability of Transitioning from Yellow to Red in Two Years for All Cable Types on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 7, $\hat{p}$ = 0.286		
Confidence Interval for p	(2.5%, 60.8%)	(1.49%, 66.6%)	(0.5%, 76.6%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 0.45%, but the confidence intervals are quite wide because of the small number of observations (7).		

Table E-24. CIs for Probability of Transitioning from Red to Failure in Two Years for All Cables on Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 16, $\hat{p}$ = 0.313		
Confidence Interval for p	(11.8%, 53.0%)	(9.72%, 56.9%)	(6.42%, 64.3%)
Conclusion:	The probability of transitioning from Red to failure in 2 years is at least 6.42%, but the confidence intervals are wide because of the fairly small number of observations (16).		

Cable-level hypothesis tests for Reduced Data at Cable level, removing other suspected cases (termination, splices, etc.):

Butyl rubber and Black EPR:

Table E-25. CIs for Probability of Transitioning from Green to Failure in Six Years for Butyl rubber and Black EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-26. CIs for Probability of Transitioning from Green to Red in Six Years for Butyl rubber and Black EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 3, $\hat{p}$ = 0.667		
Confidence Interval for p	(19.6%, 100%)	(13.5%, 100%)	(5.9%, 100%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 5.9%, but the confidence intervals are quite wide because the number of observations is small (3).		

Table E-27. CIs for Probability of Transitioning from Green to Yellow in Six Years for Butyl rubber and Black EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 3, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 53.6%)	(0%, 63.2%)	(0%, 78.5%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%, but the intervals are quite wide because the number of observations is small (3).		

There was only one butyl rubber or black EPR cable that was measured multiple times and started out Yellow, so a confidence interval on the probability of transitioning from Yellow to Red or failure cannot be constructed.

Table E-28. CIs for Probability of Transitioning from Red to Failure in Two Years for Butyl rubber and Black EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval for p	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (3).		

Black or pink EPR compact:

Table E-29. CIs for Probability of Transitioning from Green to Failure in Six Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence Level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 13, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 16.2%)	(0%, 20.6%)	(0%, 29.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%, but the intervals are wide because the number of observations is fairly small (13).		

Table E-30. CIs for Probability of Transitioning from Green to Red in Six Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 13, $\hat{p}$ = 0.0769		
Confidence Interval for p	(0%, 26.8%)	(0%, 31.6%)	(0%, 41.3%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0%, but intervals are wide because the number of observations is fairly small (13).		

Table E-31. CIs for Probability of Transitioning from Green to Yellow in Six Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 13, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 16.2%)	(0%, 20.6%)	(0%, 29.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%, but the intervals are wide because the number of observations is fairly small (13).		

Table E-32. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 2, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 68.4%)	(0%, 77.6%)	(0%, 90%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (2).		

Table E-33. CIs for Probability of Transitioning from Yellow to Red in Two Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 2, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 68.4%)	(0%, 77.6%)	(0%, 90%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to Red in 2 years contain 0%, but the intervals are quite wide because the number of observations is small (2).		

Table E-34. CIs for Probability of Transitioning from Red to Failure in Two Years for Black or Pink EPR compact on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 6, $\hat{p}$ = 0.333		
Confidence Interval for p	(3.4%, 68.4%)	(2.1%, 73.9%)	(0.7%, 83%)
Conclusion:	The probability of transitioning from Red to failure in 2 years is at least 0.7%, but the intervals are quite wide because the number of observations is small (6).		

Brown EPR:

There were too few brown EPR cables (1 that started Green, 1 that started Yellow) to construct confidence intervals on the parameters: probability of transitioning from green to failure, Red, or Yellow, and the probability of transitioning from Yellow to failure or Red.

Table E-35. CIs for Probability of Transitioning from Red to Failure in Two Years for Brown EPR on Fully Reduced Data at Cable Level

Equal-Tail Confidence Intervals:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 2, $\hat{p}$ = 0.5		
Confidence Interval for p comment:	The shortest confidence interval is not unique, so instead equal-tailed confidence intervals are presented.		
Confidence Interval for p (equal-tail):	(2.5%, 97.5%)	(1.3%, 98.7%)	(0.3%, 99.7%)
Conclusion:	The probability of transitioning from Red to failure is not zero but could be quite small (0.3%). With so few observations (2), the confidence intervals are very large.		

Pink EPR:

Table E-36. CIs for Probability of Transitioning from Green to Failure in Six Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-37. CIs for Probability of Transitioning from Green to Red in Six Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-38. CIs for Probability of Transitioning from Green to Yellow in Six Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-39. CIs for Probability of transitioning from Yellow to Failure in Two Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 2, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 68.4%)	(0%, 77.6%)	(0%, 90%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0% and are quite wide because the number of observations is small (2).		

Table E-40. CIs for Probability of Transitioning from Yellow to Red in Two Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 2, $\hat{p}$ = 1		
Confidence Interval for p	(31.5%, 100%)	(22.4%, 100%)	(10%, 100%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to Red in 2 years contain 0% and are quite wide because the number of observations is small (2).		

Table E-41. CIs for Probability of Transitioning from Red to Failure in Two Years for Pink EPR on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval for p	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and are quite wide because the number of observations is small (3).		

XLPE: There are no XLPE cables that were tested multiple times in the data set, so confidence intervals on the probability of transitioning from one color to another cannot be constructed.

Results across cable type removing suspected termination, splice, etc. cases:

Table E-42. CIs for Probability of Transitioning from Green to Failure in Six Years for All Cable Types on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 22, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 9.94%)	(0%, 12.7%)	(0%, 18.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%.		

Table E-43. CIs for Probability of Transitioning from Green to Red in Six Years for All Cable Types on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 3, n = 22, $\hat{p}$ = 0.136		
Confidence Interval for p	(2.30%, 28.7%)	(1.63%, 32.2%)	(0.760%, 39.1%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 0.76%.		

Table E-44. CIs for Probability of Transitioning from Green to Yellow in Six Years for All Cable Types on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 22, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 9.94%)	(0%, 12.7%)	(0%, 18.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%.		

Table E-45. CIs for Probability of Transitioning from Yellow to Failure in Two Years for All Cable Types on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 6, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 31.9%)	(0%, 39.3%)	(0%, 53.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0% and are quite wide due to a small number of observations (6).		

Table E-46. CIs for Probability of Transitioning from Yellow to Red in Two Years for All Cable Types on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 6, $\hat{p}$ = 0.333		
Confidence Interval for p	(3.4%, 68.4%)	(2.1%, 73.9%)	(0.7%, 83%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 0.7%, and the confidence intervals are quite wide because the number of observations is small (6).		

Table E-47. CIs for Probability of Transitioning from Red to Failure in Two Years for All Cables on Fully Reduced Data at Cable Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 14, $\hat{p}$ = 0.357		
Confidence Interval for p	(14.0%, 59.4%)	(11.6%, 63.4%)	(7.72%, 70.7%)
Conclusion:	The probability of transitioning from red to failure in 2 years is at least 7.72%, the interval is wide because the number of observations is small (14).		

Phase-level hypothesis tests for reduced data:

Butyl rubber and black EPR:

Table E-48. CIs for Probability of Transitioning from Green to Failure in Six Years for Butyl rubber and Black EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 21, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 10.4%)	(0%, 13.3%)	(0%, 19.7%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%.		

Table E-49. CIs for Probability of Transitioning from Green to Red in Six Years for Butyl rubber and Black EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 3, n = 21, $\hat{p}$ = 0.143		
Confidence Interval for p	(2.43%, 30.0%)	(1.73%, 33.5%)	(0.807%, 40.7%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 0.8%.		

Table E-50. CIs for Probability of Transitioning from Green to Yellow in Six Years for Butyl rubber and Black EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 21, $\hat{p}$ = 0.238		
Confidence Interval for p	(8.44%, 41.7%)	(6.91%, 45.2%)	(4.50%, 52.1%)
Conclusion:	The probability of transitioning from Green to Yellow in 6 years is at least 4.5%.		

There was only one butyl rubber or black EPR cable that was measured multiple times and started out with one yellow phase, so a confidence interval cannot be constructed on the probability of transitioning from Yellow to Red or failure.

Table E-51. CIs for Probability of Transitioning from Red to Failure in Two Years for Butyl rubber and Black EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval for p	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and are quite wide because the number of observations is small (3).		

Black and pink EPR compact:

Table E-52. CIs for Probability of Transitioning from Green to Failure in Six Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 45, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 4.99%)	(0%, 6.44%)	(0%, 9.73%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are narrow because the number of observations is large (45).		

Table E-53. CIs for Probability of Transitioning from Green to Red in Six Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 45, $\hat{p}$ = 0.0444		
Confidence Interval for p	(0.2%, 11.5%)	(0.1%, 13.4%)	(0%, 17.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0%.		

Table E-54. CIs for Probability of Transitioning from Green to Yellow in Six Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 45, $\hat{p}$ = 0.0444		
Confidence Interval for p	(0.2%, 11.5%)	(0.1%, 13.4%)	(0%, 17.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%.		

Table E-55. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 6, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 31.9%)	(0%, 39.3%)	(0%, 53.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0% and are quite wide because the number of observations is small (6).		

Table E-56. CIs for Probability of Transitioning from Yellow to Red in Two Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 6, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 31.9%)	(0%, 39.3%)	(0%, 53.6%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is quite small, but the intervals are large due to a small number of observations (6).		

Table E-57. CIs for Probability of Transitioning from Red to Failure in Two Years for Black and Pink EPR compact on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 10, $\hat{p}$ = 0.2		
Confidence Interval for p	(1.3%, 45.6%)	(0.7%, 51.1%)	(0.2%, 61.3%)
Conclusion:	The probability of transitioning from Red to failure in 2 years is non-zero (minimum 0.2%), but the intervals are wide because of a small number of observations (10).		

Brown EPR:

Table E-58. CIs for Probability of Transitioning from Green to Failure in Six Years for Brown EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-59. CIs for Probability of Transitioning from Green to Red in Six Years for Brown EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0% and are quite wide because the number of observations is small (5).		

Table E-60. CIs for Probability of Transitioning from Green to Yellow in Six Years for Brown EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0% and are quite wide because the number of observations is small (5).		

There was only one brown EPR cable that was measured multiple times and started out with one Yellow phase, so a confidence interval cannot be constructed on the probability of transitioning from Yellow to Red or failure.

Table E-61. CIs for Probability of Transitioning from Red to Failure in Two Years for Brown EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 10, $\hat{p}$ = 0.1		
Confidence Interval for p	(0%, 33.7%)	(0%, 39.4%)	(0%, 50.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and the intervals are wide because of a small number of observations (10).		

Pink EPR:

Table E-62. CIs for Probability of Transitioning from Green to Failure in Six Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 21, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 10.4%)	(0%, 13.3%)	(0%, 19.7%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%.		

Table E-63. CIs for Probability of Transitioning from Green to Red in Six Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 21, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 10.4%)	(0%, 13.3%)	(0%, 19.7%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0%.		

Table E-64. CIs for Probability of Transitioning from Green to Yellow in Six Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 21, $\hat{p}$ = 0.0476		
Confidence Interval for p	(0%, 17.3%)	(0%, 20.7%)	(0%, 27.7%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%.		

Table E-65. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 4, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 43.8%)	(0%, 52.7%)	(0%, 68.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contain 0% and are quite wide due to a small number of observations (4).		

Table E-66. CIs for Probability of Transitioning from Yellow to Red in Two Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 4, $\hat{p}$ = 0.5		
Confidence Interval for p	(9.76%, 90.2%)	(6.76%, 93.2%)	(2.94%, 97.1%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 2.94%, but the confidence intervals are wide due to a small number of observations (4).		

Table E-67. CIs for Probability of Transitioning from Red to Failure in Two Years for Pink EPR on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 5, $\hat{p}$ = 0.20		
Confidence Interval	(0%, 58.4%)	(0%, 65.7%)	(0%, 77.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and are quite wide because of the small number of observations (5).		

XLPE: There are no XLPE cables that were tested multiple times in the data set, so hypothesis tests cannot be conducted.

Cable phase results for reduced data across all categorized cable types:

Table E-68. CIs for Probability of Transitioning from Green to Failure in Six Years for All Cable Types on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 92, $\hat{p}$ = 0		
Confidence Interval	(0%, 2.47%)	(0%, 3.20%)	(0%, 4.88%)
Conclusion:	The probability of transitioning from Green to failure in 6 years is quite small (less than 5%) and the confidence intervals contain 0%.		

Table E-69. CIs for Probability of Transitioning from Green to Red in Six Years for All Cable Types on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 92, $\hat{p}$ = 0.0543		
Confidence Interval	(1.67%, 10.2%)	(1.35%, 11.4%)	(0.8%, 13.8%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is small but non-zero (greater than 0.8%).		

Table E-70. CIs for Probability of Transitioning from Green to Yellow in 6 years for All Cable Types on Reduced Data at Phase level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 8, n = 92, $\hat{p}$ = 0.0870		
Confidence Interval	(3.9%, 14.4%)	(3.4%, 15.7%)	(2.5%, 18.3%)
Conclusion:	The probability of transitioning from Green to Yellow in 6 years is small but non-zero (greater than 2.5%).		

Table E-71. CIs for Probability of Transitioning from Yellow to Failure in Two years for All Cable Types on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 12, $\hat{p}$ = 0		
Confidence Interval	(0%, 17.5%)	(0%, 22.1%)	(0%, 31.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contains 0%, but the intervals are wide due to a small number of observations (12).		

Table E-72. CIs for Probability of Transitioning from Yellow to Red in Two Years for All Cable Types on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 12, $\hat{p}$ = 0.167		
Confidence Interval	(1.0%, 39.0%)	(0.5%, 44.1%)	(0.1%, 53.8%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 0.1%, but the intervals are wide due to a small number of observations (12).		

Table E-73. CIs for Probability of Transitioning from Red to Failure in Two Years for All Cables on Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 28, $\hat{p}$ = 0.179		
Confidence Interval	(6.0%, 32.0%)	(4.9%, 35.0%)	(3.2%, 41.1%)
Conclusion:	The probability of transitioning from Red to failure in 2 years is at least 3.2%.		

Phase-level hypothesis tests for reduced data removing suspected termination, splice, etc. cases:

Butyl rubber and black EPR:

Table E-74. CIs for Probability of Transitioning from Green to Failure in Six Years for Butyl rubber and Black EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 15, $\hat{p}$ = 0		
Confidence Interval	(0%, 14.2%)	(0%, 18.1%)	(0%, 26.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in six contains 0% and the intervals are wide due to a fairly small number of observations (15).		

Table E-75. CIs for Probability of Transitioning from Green to Red in Six Years for Butyl Rubber and Black EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 15, $\hat{p}$ = 0.133		
Confidence Interval	(0.7%, 32.1%)	(0.4%, 36.5%)	(0.1%, 45.4%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is at least 0.1%, and the intervals are wide due to a fairly small number of observations (15).		

Table E-76. CIs for Probability of Transitioning from Green to Yellow in Six Years for Butyl rubber and Black EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 15, $\hat{p}$ = 0		
Confidence Interval	(0%, 14.2%)	(0%, 18.1%)	(0%, 26.4%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in six contains 0% and the intervals are wide due to a fairly small number of observations (15).		

There was only one Butyl rubber or black EPR cable that was measured multiple times and started out with one yellow phase, so a confidence interval cannot be constructed on the probability of transitioning from yellow to red or failure.

Table E-77. CIs for Probability of Transitioning from Red to Failure in Two Years for Butyl rubber and Black EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence Level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 3, $\hat{p}$ = 0.333		
Confidence Interval for p	(0%, 80.4%)	(0%, 86.5%)	(0%, 94.1%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0% and are quite wide because of the small number of observations (3).		

Black and pink EPR compact:

Table E-78. CIs for Probability of Transitioning from Green to Failure in Six Years for Black and Pink EPR compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 45, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 4.99%)	(0%, 6.44%)	(0%, 9.73%)
Conclusion:	The probability of transitioning from Green to failure in 6 years is small (at most 9.73%).		

Table E-79. CIs for Probability of Transitioning from Green to Red in Six Years for Black and Pink EPR compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 45, $\hat{p}$ = 0.0444		
Confidence Interval for p	(0.2%, 11.5%)	(0.1%, 13.4%)	(0%, 17.4%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is small.		

Table E-80. CIs for Probability of Transitioning from Green to Yellow in Six Years for Black and Pink EPR Compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 45, $\hat{p}$ = 0.0444		
Confidence Interval for p	(0.2%, 11.5%)	(0.1%, 13.4%)	(0%, 17.4%)
Conclusion:	The probability of transitioning from Green to Yellow in 6 years is small.		

Table E-81. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Black and Pink EPR Compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 6, $\hat{p}$ = 0		
Confidence Interval	(0%, 31.9%)	(0%, 39.3%)	(0%, 53.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contains 0%, but the intervals are wide due to a small number of observations (6).		

Table E-82. CIs for Probability of Transitioning from Yellow to Red in Two Years for Black and Pink EPR Compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 6, $\hat{p}$ = 0		
Confidence Interval	(0%, 31.9%)	(0%, 39.3%)	(0%, 53.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to Red in 2 years contains 0%, but the intervals are wide due to a small number of observations (6).		

Table E-83. CIs for Probability of Transitioning from Red to Failure in Two Years for Black and Pink EPR Compact on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 10, $\hat{p}$ = 0.2		
Confidence Interval for p	(1.3%, 45.6%)	(0.7%, 51.1%)	(0.2%, 61.3%)
Conclusion:	The probability of transitioning from Red to failure in 2 years is at least 0.2%, and the intervals are wide due to a fairly small number of observations (10).		

Brown EPR:

Table E-84. CIs for Probability of Transitioning from Green to Failure in Six Years for Brown EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contain 0%, but the intervals are wide due to a small number of observations (5).		

Table E-85. CIs for Probability of Transitioning from Green to Red in Six Years for Brown EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contain 0%, but the intervals are wide due to a small number of observations (5).		

Table E-86. CIs for Probability of Transitioning from Green to Yellow in Six Years for Brown EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 5, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 36.9%)	(0%, 45.1%)	(0%, 60.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contain 0%, but the intervals are wide due to a small number of observations (5).		

Probability transitioning from yellow to failure in two years for brown EPR on Fully Reduced Data at Phase level:

There was only one brown EPR cable that was measured multiple times and started out with one Yellow phase, so a confidence interval cannot be constructed on the probability of transitioning from Yellow to Red or failure.

Table E-87. CIs for Probability of Transitioning from Red to Failure in Two Years for Brown EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 4, $\hat{p}$ = 0.25		
Confidence Interval for p	(0%, 68%)	(0%, 75.1%)	(0%, 85.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contain 0%, but the intervals are very wide because the number of observations is small (4).		

Pink EPR:

Table E-88. CIs for Probability of Transitioning from Green to Failure in Six Years for Pink EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 20, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 10.9%)	(0%, 13.9%)	(0%, 20.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to failure in 6 years contains 0%.		

Table E-89. CIs for Probability of Transitioning from Green to Red in Six Years for Pink EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 20, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 10.9%)	(0%, 13.9%)	(0%, 20.6%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Red in 6 years contains 0%.		

Table E-90. CIs for Probability of Transitioning from Green to Yellow in Six Years for Pink EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 20, $\hat{p}$ = 0.05		
Confidence Interval for p	(0%, 18.1%)	(0%, 21.6%)	(0%, 28.9%)
Conclusion:	The confidence intervals for the probability of transitioning from Green to Yellow in 6 years contains 0%.		

Table E-91. CIs for Probability of Transitioning from Yellow to Failure in Two Years for Pink EPR on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 3, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 53.6%)	(0%, 63.2%)	(0%, 78.5%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contains 0%, but the intervals are very wide because the number of observations is small (3).		

Table E-92. Probability of Transitioning from Yellow to Red in Two Years for Pink EPR

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 3, $\hat{p}$ = 0.667		
Confidence Interval for p	(19.6%, 100%)	(13.5%, 100%)	(5.9%, 100%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is at least 5.9%, but the confidence interval is very wide because the number of observations is small (3).		

Table E-93. Probability of Transitioning from Red to Failure in Two Years for Pink EPR

Shortest Confidence Interval:			
Confidence:	90%	95%	99%
X, n, $\hat{p}$	X = 1, n = 5, $\hat{p}$ = 0.20		
Confidence Interval	(0%, 58.4%)	(0%, 65.7%)	(0%, 77.8%)
Conclusion:	The confidence intervals for the probability of transitioning from Red to failure in 2 years contains 0%, but the intervals are very wide because the number of observations is small (5).		

XLPE: There are no XLPE cables that were tested multiple times in the data set, so confidence intervals cannot be constructed.

Cable phase results for reduced data removing suspected termination, splice, etc. cases across all categorized cable types:

Table E-94. CIs for Probability of Transitioning from Green to Failure in Six Years for All Cable Types on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 85, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 2.7%)	(0%, 3.5%)	(0%, 5.3%)
Conclusion:	The probability of transitioning from Green to failure in 6 years is quite small (maximum 5.3%).		

Table E-95. CIs for Probability of Transitioning from Green to Red in Six Years for All Cable Types on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 4, n = 85, $\hat{p}$ = 0.047		
Confidence Interval for p	(1.1%, 9.5%)	(0.9%, 10.7%)	(0.5%, 13.2%)
Conclusion:	The probability of transitioning from Green to Red in 6 years is small but non-zero (minimum 0.5%).		

Table E-96. CIs for Probability of Transitioning from Green to Yellow in Six years for All Cable Types on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 3, n = 85, $\hat{p}$ = 0.035		
Confidence Interval for p	(0.5%, 7.9%)	(0.4%, 9.0%)	(0.2%, 11.4%)
Conclusion:	The probability of transitioning from Green to Yellow in 6 years is small but non-zero (minimum 0.2%).		

Table E-97. CIs for Probability of Transitioning from Yellow to Failure in Two Years for All Cable Types on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 0, n = 11, $\hat{p}$ = 0		
Confidence Interval for p	(0%, 18.9%)	(0%, 23.8%)	(0%, 34.2%)
Conclusion:	The confidence intervals for the probability of transitioning from Yellow to failure in 2 years contains 0%, but the confidence interval is wide because the number of observations is small (11).		

Table E-98. CIs for Probability of Transitioning from Yellow to Red in Two Years for all Cable Types on Fully Reduced Data at Phase Level

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 2, n = 11, $\hat{p}$ = 0.182		
Confidence Interval for p	(1.1%, 42.1%)	(0.6%, 47.3%)	(0.2%, 57.3%)
Conclusion:	The probability of transitioning from Yellow to Red in 2 years is non-zero (minimum 0.2%), but the confidence interval is wide because the number of observations is small (11).		

Table E-99. Probability of Transitioning from Red to Failure in 2 Years for All Cables

Shortest Confidence Interval:			
Confidence level:	90%	95%	99%
X, n, $\hat{p}$	X = 5, n = 22, $\hat{p}$ = 0.227		
Confidence Interval for p	(8.0%, 40.0%)	(6.5%, 43.4%)	(4.2%, 50.2%)
Conclusion:	The probability of transitioning from Red to failure in 2 years at least 4.2%, but the confidence interval is wide because the number of observations is small (22).		

Generally speaking, definitive conclusions about the probability of transitioning from one color to another in the interval can only be made when the number of observations is large enough (usually $n \geq 10$). When the count (X) is 0 or 1, the probability of transitioning from one color to another in the interval is not significantly different from 0%.

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