NEETRAC — A Research Center in the School of Electrical and Computer Engineering at the Georgia Institute of Technology

Georgia Institute of Technology

ICC Education Session

Cable Diagnostic Focused Initiative

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Spring 2009 Meeting

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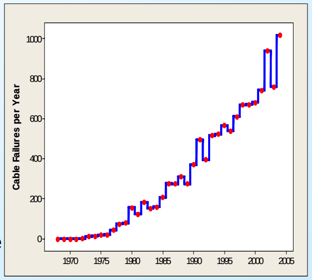
Outline

CDFI Background

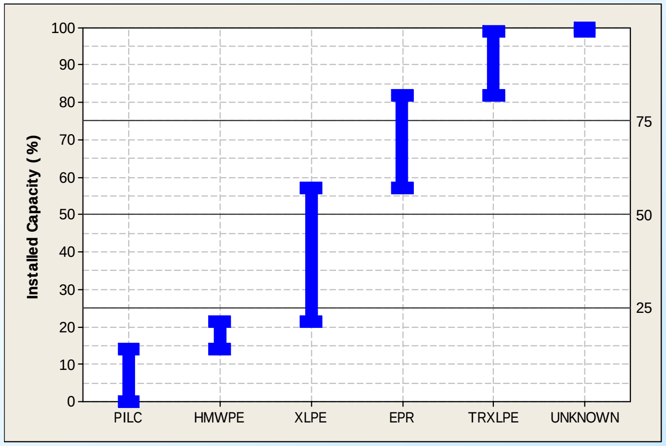
Rick Hartlein

Why do we need diagnostics?

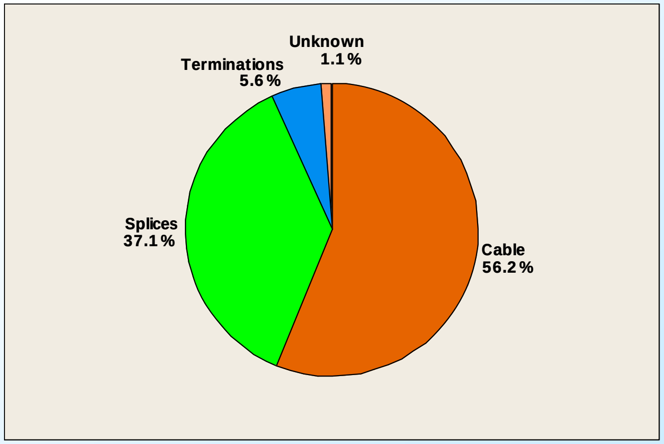
- Underground cable system infrastructure is aging (and failing). Much of the system is older than its design life.
- Not enough money / manufacturing capacity to simply replace cable systems because they are old.
- Need diagnostic tools that can help us decide which cables/accessories to replace & which can be left in service.
- Always remember that we are talking about the cable SYSTEM, not just cable.



Composition of US MV system

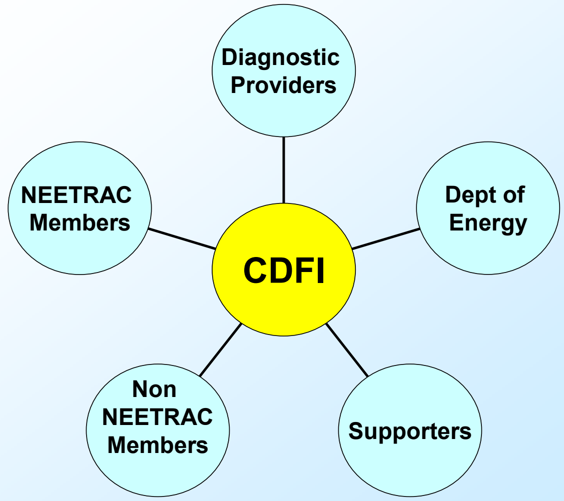


Failure Split



Overview

- **In the CDFI, NEETRAC worked with *17 utilities*, *5 manufacturers and 5 diagnostic providers* to achieve the objective of clarifying the concerns and defining the benefits of diagnostic testing.**
- **Phase 1 has almost exclusively focused on aged medium voltage systems.**
- **This is the largest coherent study of cable system diagnostics anywhere.**



Participants

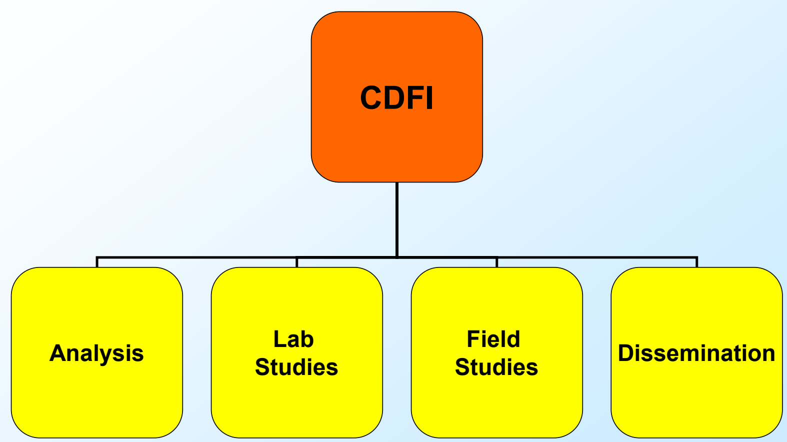
American Electric Power	HV Technologies
Ameren	Hydro Quebec
Cablewise / Utilx	IMCORP
CenterPoint Energy	NRECA
Con Edison	PacifiCorp (added mid 2005)
Cooper Power Systems	Pacific Gas & Electric (added Jan 06)
Duke Power Company	PEPCO
Exelon (Commonwealth Edison & PECO)	Oncor (TXU)
First Energy	Prysmian
Florida Power & Light	Public Service Electric & Gas
Georgia Tech	Tyco / Raychem
GRESCO	Southern California Edison
HDW Electronics	Southern Company
HV Diagnostics	Southwire

CDFI - Primary Activities

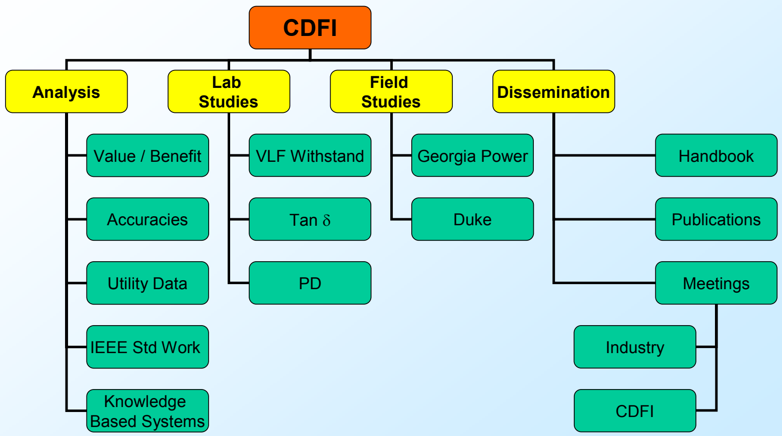
1) Technology Review
2) Analysis of Existing (Historical) Data
3) Collection and Analysis of Field (New) Data
4) Verification of VLF Test Levels
5) Defect Characterization
6) Develop Knowledge Based System
7) Quantify Economic Benefits
8) Reports, Update Meetings and Tech Transfer Seminars

Analyses are data / results driven

CDFI Activities



CDFI Activities



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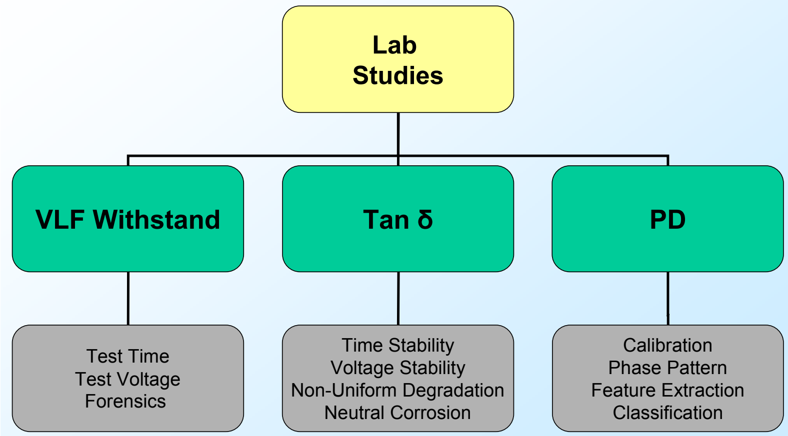
CDFI Activities



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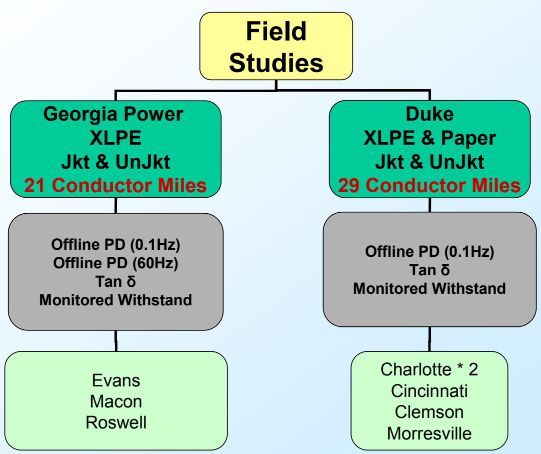
CDFI Activities



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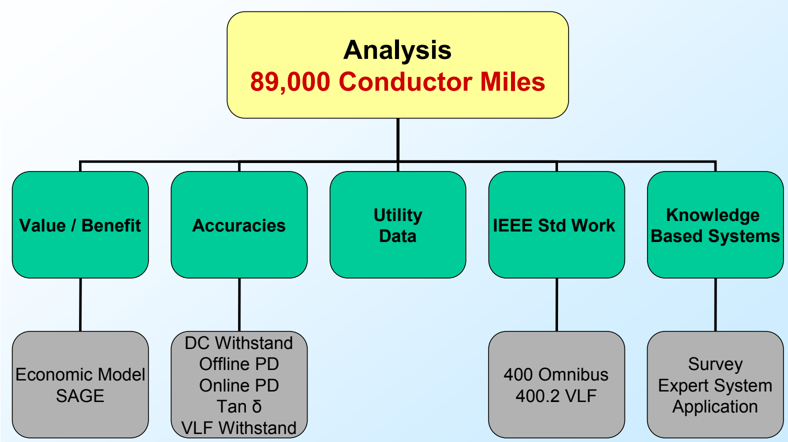
CDFI Activities



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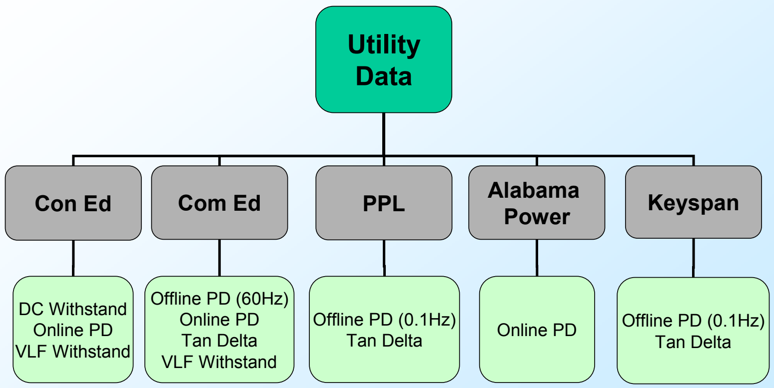
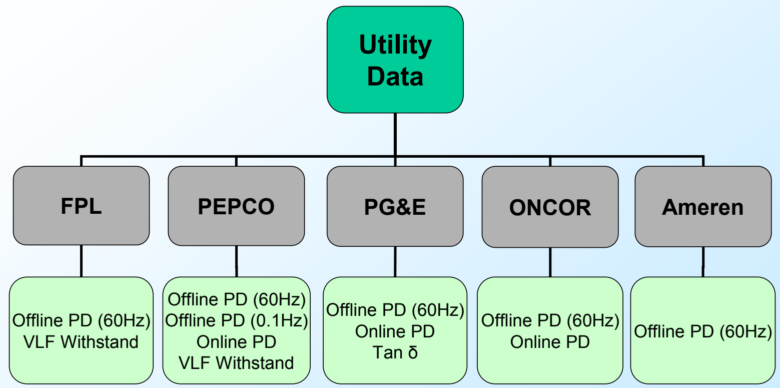
CDFI Activities



CDFI Activities

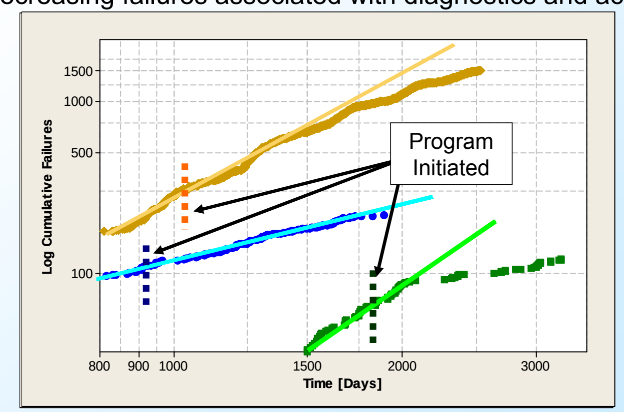


Dataset Sizes

Data Type	Technique	Laboratory [Conductor miles]	Field [Conductor miles]
Diagnostic	DC Withstand	-	78,105
	Monitored Withstand	-	149
	PD Offline	2	490
	PD Online	-	262
	Tan δ	1.5	550
	VLF Withstand	1.5	9,810
	IRC	0.3	-
Service Performance	ALL	89,000	

Benefits from Diagnostic Programs

Decreasing failures associated with diagnostics and actions



At the Start

- For many utilities, the usefulness of diagnostic testing was unclear.
- The focus was on the technique, not the approach.
- The economic benefits were not well defined.
- There was almost no independently collated and analyzed data.
- There were no independent tools for evaluating diagnostic effectiveness.

Where we are today (1)

1. Diagnostics work – they tell you many useful things, but not everything.
2. Diagnostics do not work in all situations.
3. Diagnostics have great difficulty definitively determining the longevity of individual devices.
4. Utilities HAVE to act on ALL replacement/repair recommendations to get improved reliability.
5. The performance of a diagnostic program depends on
   - Where you use the diagnostic
   - When you use the diagnostic
   - What diagnostic you use
   - What you do afterwards

Where we are today (2)

6. Quantitative analysis is complex BUT is needed to clearly see benefits.
7. Diagnostic data require skilled interpretation to establish how to act.
8. No one diagnostic is likely to provide the detailed data required for accurate diagnoses.
9. Large quantities of field data are needed to establish the accuracy/limitations of different diagnostic technologies.
10. *Important to have correct expectations – diagnostics are useful but not perfect!*

Overview

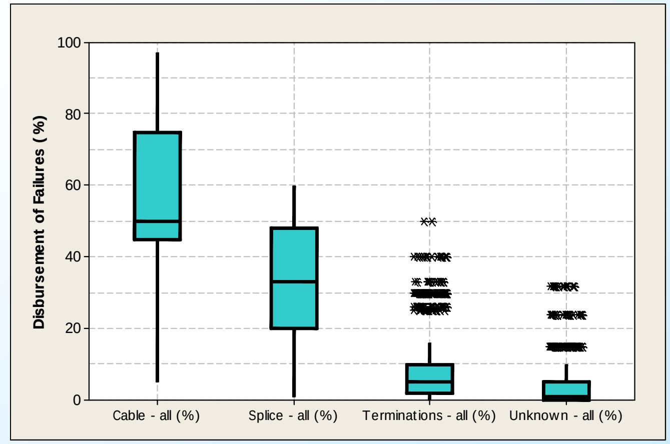
- **In the CDFI, NEETRAC worked with *17 utilities*, *5 manufacturers and 5 diagnostic providers* to achieve the objective of clarifying the concerns and defining the benefits of diagnostic testing.**
- **We have come a long way wrt the project objective.**
  - **Analysis driven by data / results**
  - **Developed a good understanding that diagnostic testing can be useful, but the technologies are not perfect.**
  - **Developed ways to define diagnostic technology accuracy and found ways to handle inaccuracies.**
  - **Developed diagnostic *technology selection* and *economic analysis* tools.**
  - **Understand that there is yet more to learn.**

How things fail and what fails have a big impact on the selection of diagnostics

Cable System Failure Process

Rick Hartlein

Failures by Equipment



Major Cable Components

Conductor

Conductor or Strand Shield

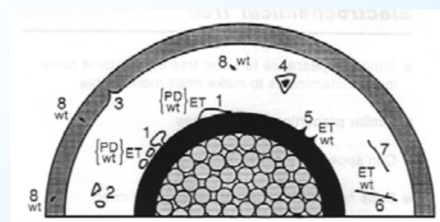
Insulation

Insulation Shield

Metallic Shield/Neutral

Jacket (Recommended)

Defect Types in Extruded Cables

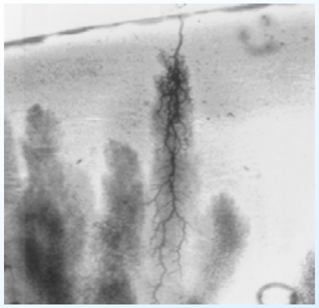


1. Cavity at shield(s)
2. Cavities due to shrinkage
3. Insulation shield defect
4. Contaminant (poor adhesion)
5. Protrusions at shield(s)

6,7 Splinter/Fiber

8. Contaminants in insulation or shields

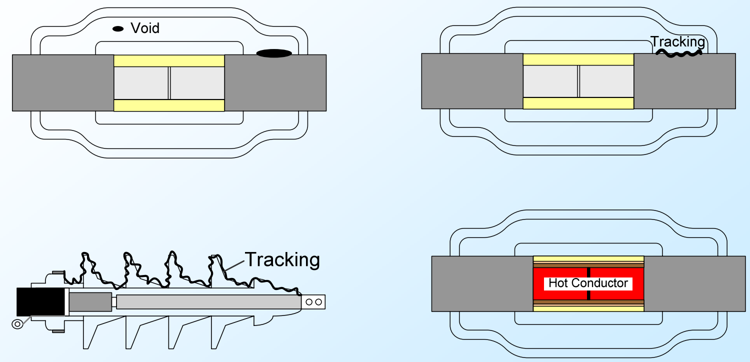
Conversion of Water to Electrical Trees



Electrical tree growing from water tree

- Acts as a stress enhancement or protrusion (non-conducting)
- Water tree increases local electric field
- Water tree also creates local mechanical stresses
- **If** electrical and mechanical stresses high enough ⇒ electrical tree initiates
- Electrical tree completes the failure path – rapid growth

Defect Types in Extruded Cable Accessories



Diagnostics used in Challenging Areas

Summary

- Cable system aging is a complex phenomenon.
- Multiple factors cause systems to age.
- Increases in dielectric loss and partial discharge are key phenomenon.
- The aging process is nonlinear.
- Diagnostics must take these factors into consideration.

SAGE Approach to Diagnostic Programs

Nigel Hampton

Diagnostic Program Phases - SAGE

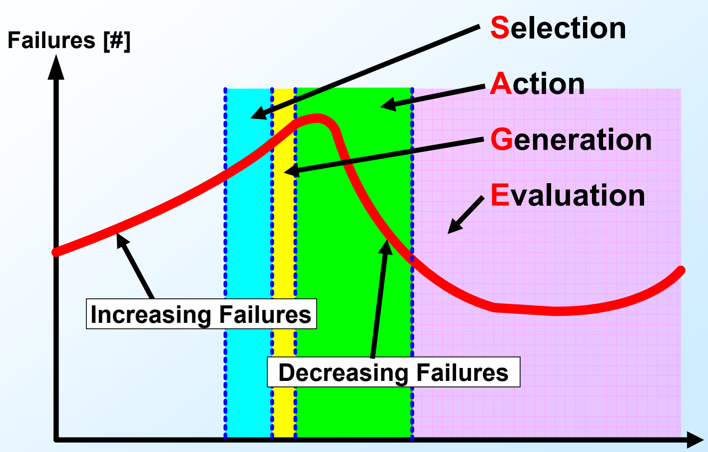
Selection
Data compilation and analysis needed to identify circuits that are at-risk for failure (at-risk population).

Action
Determine what actions can be taken on circuits based on the results of diagnostic testing.

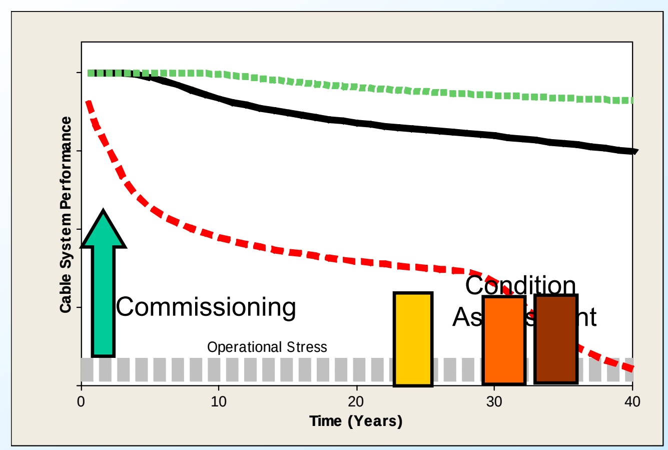
Generation
Conduct diagnostic testing of the at-risk population.

Evaluation
Monitor at-risk population after testing to observe/improve performance of diagnostic program.

SAGE at Work



When to deploy diagnostics



Context – is important

Data Generation from Diagnostic Measurement

Local Context
Comparisons within one area

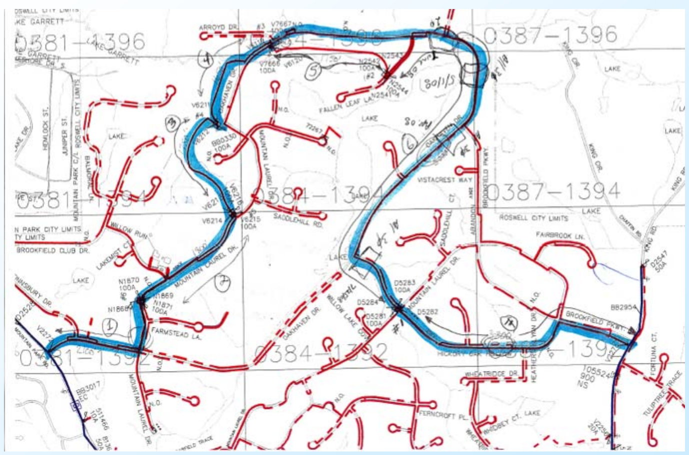
Global Context
Comparison with many tests
Databases
Standards

Case Study
Roswell, GA
November 2008 & January 2009

Nigel Hampton

TDR
Tan Delta
Monitored Withstand
Offline PD

Roswell Map

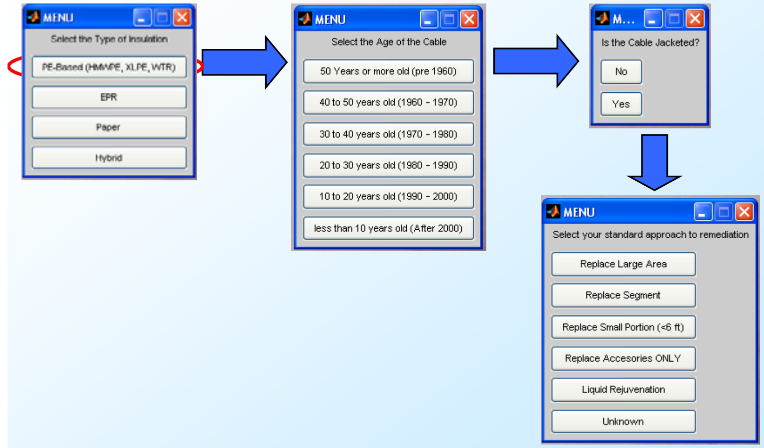


SELECTION

Roswell Background Info.

- 1980 vintage XLPE feeder cable, 1000 kcmil, 260 mils wall, jacketed.
- Failures have occurred over the years – no data on source
- Recently experienced very high failure rates of splices on this section: 80 failures / 100 miles / yr.
- Overall there have been 10 -15 failures of these splices in last two years on a variety of GPC feeders.
- Splice replacement **may** be acceptable if there is a technical basis.

Knowledge Based Selection System



Summary for Diagnostic Selection

Action Scenario	Diagnostic Technique: DC Withstand	VLF 15 Mins	VLF 30 Mins	VLF 60 Mins	HV DC Leakage	Monitored Withstand	Tan Delta	PD Online	PD Offline	TDR & Historical Records ONLY
Replace Small Portion	red	green	green	green	red	green	yellow	yellow	green	yellow
Replace Segment	red	yellow	green	yellow	red	green	green	yellow	green	yellow
Replace Accessories	red	yellow	green	green	red	green	yellow	green	green	yellow

Have a shortlist of three techniques

Economic Details – prior to testing

- Complete System Replacement $1,000,000 approx
- Complete Splice Replacement $60,000
- Test time (determined by switching) 3 - 4 Days
- Selection Costs $5,000
- Splice Replacement 7 Days
- Retest after remediation 1 Day

Monitored Withstand, Offline PD and VLF (30 mins) offer economic benefit over doing nothing.

Scenario Assessment <u>before</u> Testing

Offline PD

- If 51,000ft is tested
- 0.5% fails on test, no customer interrupted
- 1 site / 1,000ft (median)
- 40% discharges in cable
- Estimate
  - 0 fails on test
  - 51 discharge sites
    - 20 cable,
    - 31 accessories
  - 15 splices
  - <2 failure in 12 months from test

Monitored Withstand

- If 51,000ft is tested
- <4% fails on test, no customer interrupted
- 70% of loss tests indicate no further action
- Estimate
  - <2 fails on test
  - 3 assessed for further consideration by loss
  - 0.5 failure in 12 months from test

ACTION

Initial Corrective Action Options

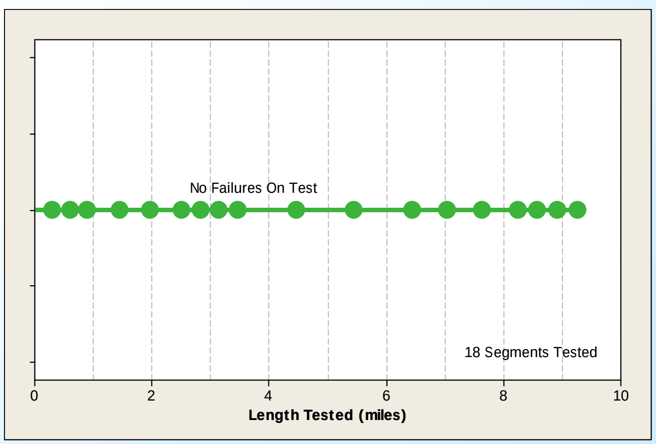
- Replace splices only – no detailed records assume 12 splices.
- Complete system replacement.

GENERATION

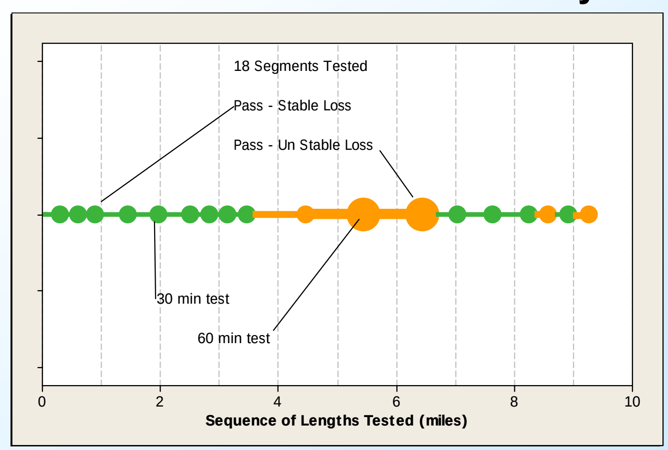
Overhead and Cabinet Terminations

Monitored Withstand

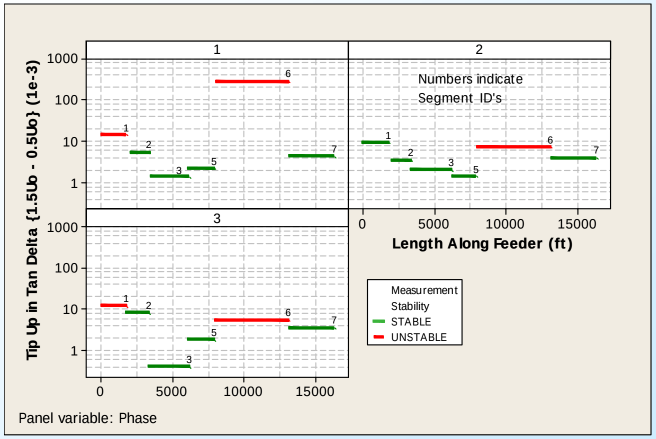
If this had been a Simple Withstand



Monitored Withstand - Stability



Test Results - Local Perspective



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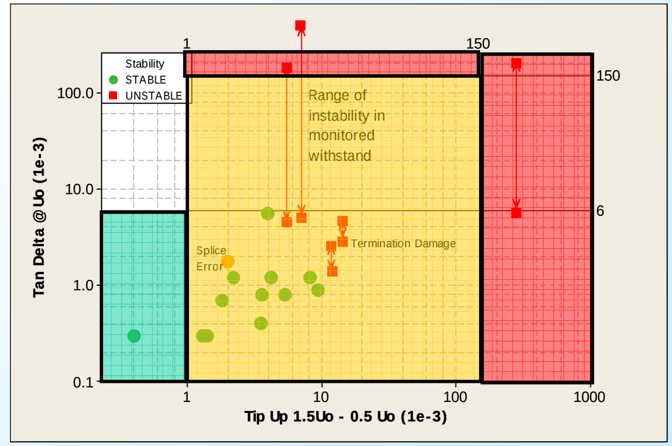
Case Study: Roswell 53

Test Results – Global Perspective



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Case Study: Roswell 54

Targeted Offline PD

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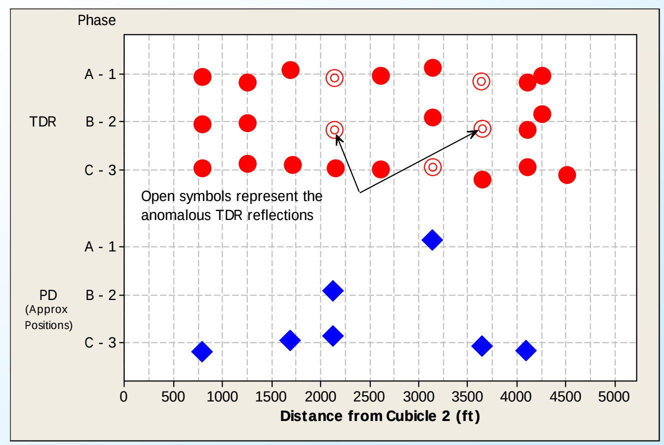
Case Study: Roswell 55

Targeted Offline PD Test – Segment 6



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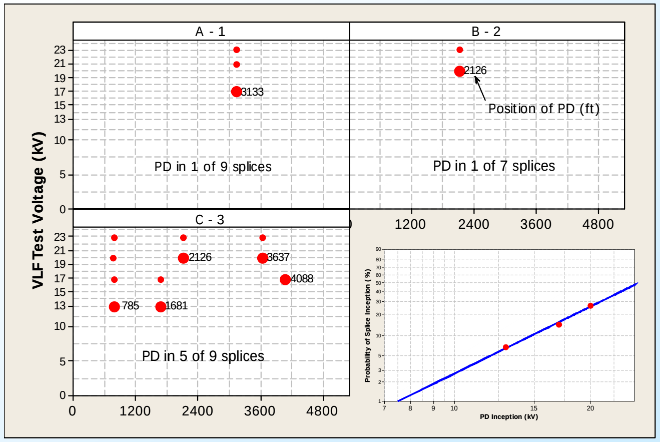
Case Study: Roswell 56

PD Inception – local perspective



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Case Study: Roswell 57

EVALUATION

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Case Study: Roswell 58

Evaluation <u>after</u> Testing

Offline PD
- 15,000ft <u>actually</u> tested
- <u>Estimate</u>
  - 15 discharge sites
    - 6 cable,
    - 9 accessories
  - 6 splices
  - <1 failure in 12 months from test
- **<u>Actual</u>**
  - **7 discharge sites**
    - **0 cable,**
    - **7 accessories**
  - **25 splices**
  - **0 failure 4 months from test**

Monitored Withstand
- 51,000ft <u>actually</u> tested
- <u>Estimate</u>
  - 2 fails on test
  - 3 assessed for further consideration by loss
  - 0.5 failure in 12 months from test
- **<u>Actual</u>**
  - **0 fails on test**
  - **6 assessed for further consideration by stability, tip up & loss**
  - **1 failure (cable) 5 months from test**

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After Testing…

- Actions have been performed by GPC.
  - Suspect splice investigated, actually broken neutral.
  - Damaged termination replaced.
  - Test excavations & Ground Penetrating Radar tests conducted, concluded that it was not practical to replace splices as planned
- System Re enforcements Planned.
- All tested circuits have been left in service and are being monitored by GPC.

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Case Study: Roswell 60

Diagnostic Accuracies

Nigel Hampton

Performance of Diagnostics

- Performance evaluation primarily focuses on diagnostic accuracy.
- Diagnostic accuracies quantify the diagnostic's ability to correctly assess a circuit's condition.
- Accuracy must be assessed based on "pilot" type field test programs in which no actions are performed.
- Circuits must be tracked for a sufficient period of time.

Objective of Diagnostic Tests

The target population contains both "Good" and "Bad" components

- "Good" – Will not fail within diagnostic time horizon
- "Bad" – Will fail within diagnostic time horizon

Diagnostic Operation

Applying the diagnostic will separate the population into:

- No Action Required group
- Action Required group

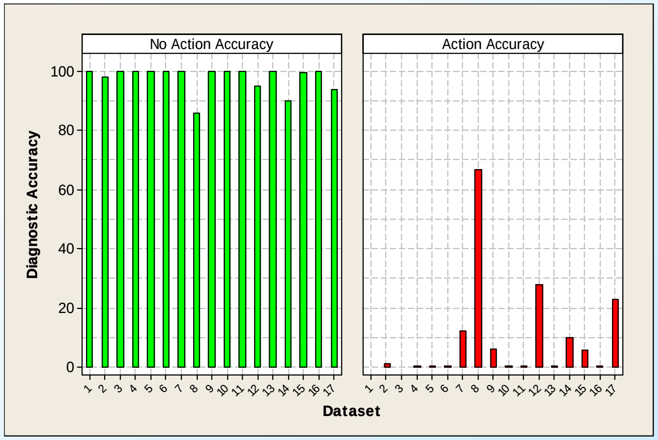
But the diagnostic is imperfect...

Perspective

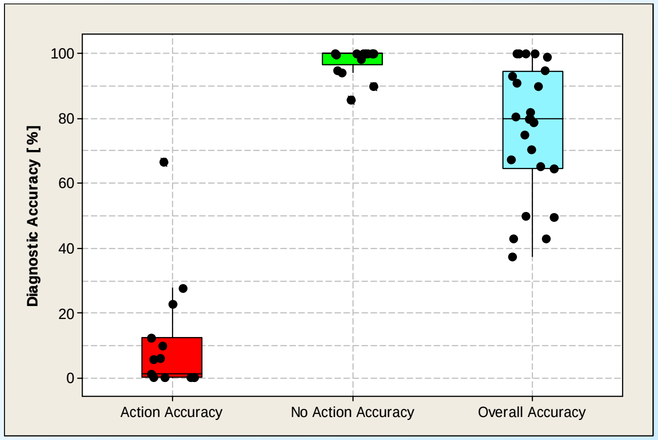
- Diagnostics make measurements in the field and find Anomalies.
- Detecting the presence of an Anomaly is, in our view, not sufficient.
- The goal, in our view, is to detect an Anomaly which leads to reduced reliability (failure in service) or compromised performance (severed neutrals – stray voltage).

In accuracy estimates we have used failures in service and interpreted the diagnostics as "Bad Means Failure."

"Bad Means Failure" Accuracies



All Accuracies



Diagnostic Testing Technologies

Nigel Hampton

Introduction

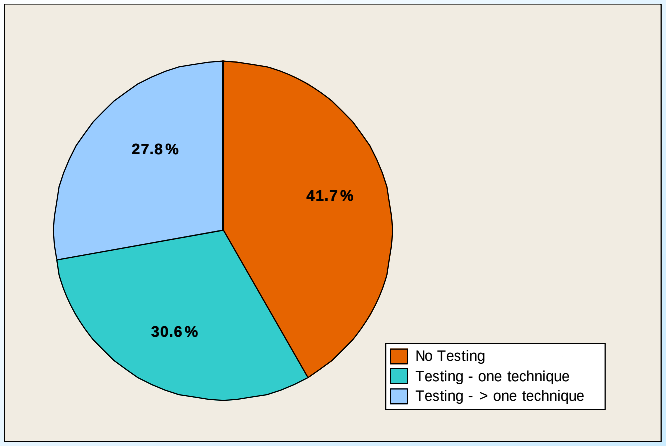
- A wide range of diagnostic techniques are commercially available.
- Tests are performed either offline (circuit de-energized)) or online (energized) and by service providers or utility crews.
- Different voltage sources may be used to perform the same measurement.
  - DC
  - 60 Hz. AC
  - Very Low Frequency (VLF) AC
  - Damped AC (DAC)

Utility Use of Diagnostics

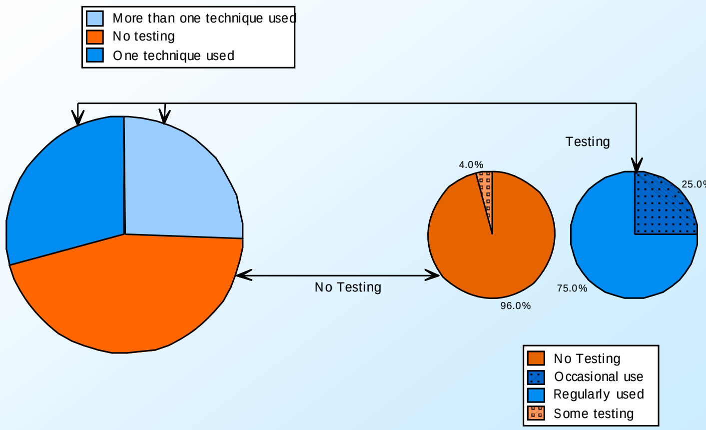
Diagnostic Survey

- A survey of CDFI participants in 2006 was conducted to determine how diagnostics were employed.
- Survey was updated at the end of 2008.
- Survey results focused CDFI work on technologies currently used in the USA.

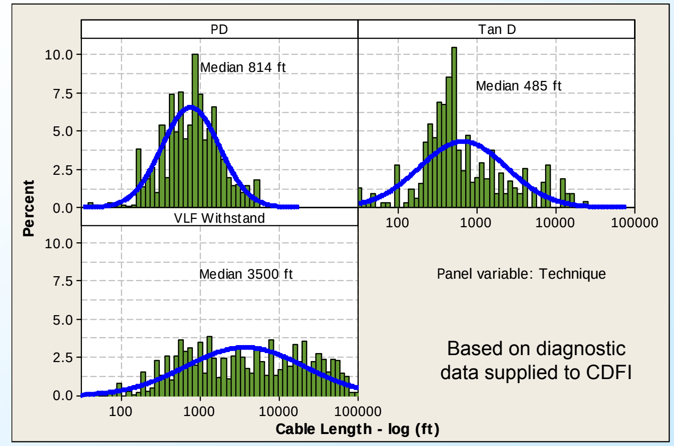
Survey of Use of Diagnostics



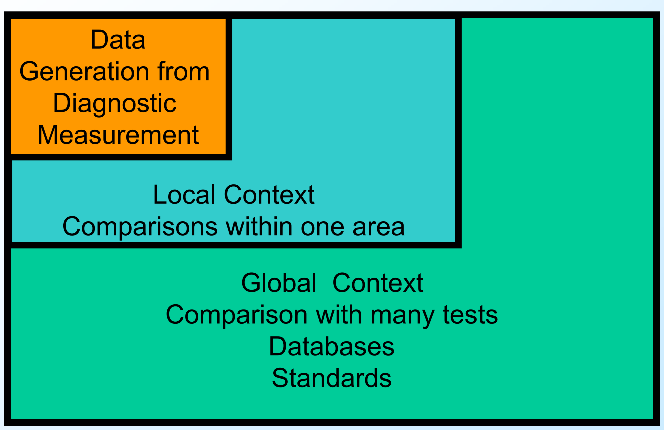
Survey of Use of Diagnostics



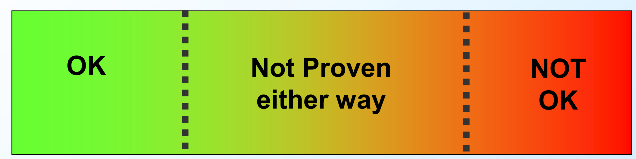
Lengths Tested



Context



Diagnostic Context



- Extreme conditions are easy to decide what to do about.
- What to do about the ones in the middle?
- How to define the boundaries?

Simple Dielectric Withstand

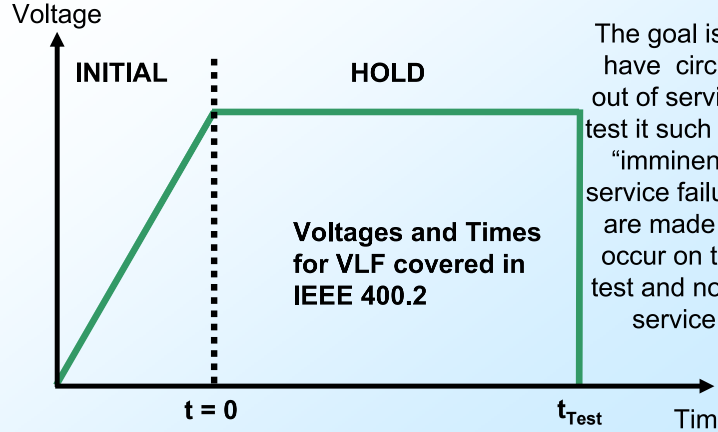
Test Description

- Application of voltage above normal operating voltage for a prescribed duration.
- Attempts to drive weakest location(s) within cable segment to failure while segment is not in service.

Field Application

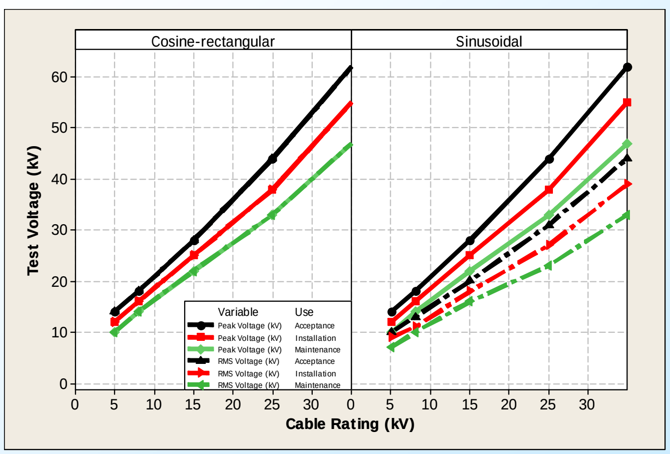
- Offline test that may use:
  - DC
  - 60 Hz. AC
  - VLF AC
  - Damped AC
- Testing may be performed by a service provider or utility crew.

Withstand Test Process



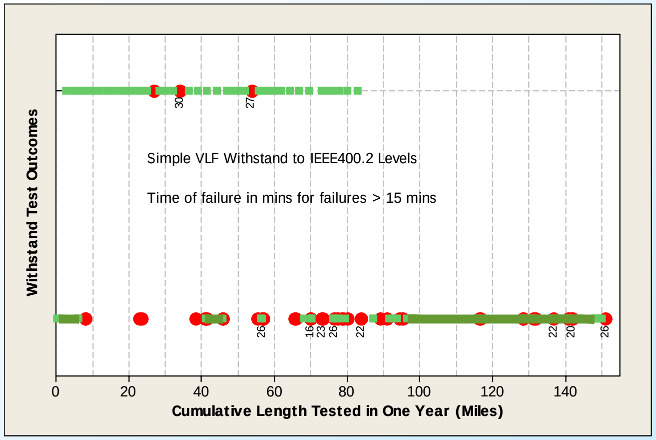
The goal is to have circuit out of service, test it such that "imminent" service failures are made to occur on the test and not in service

VLF Test Voltages



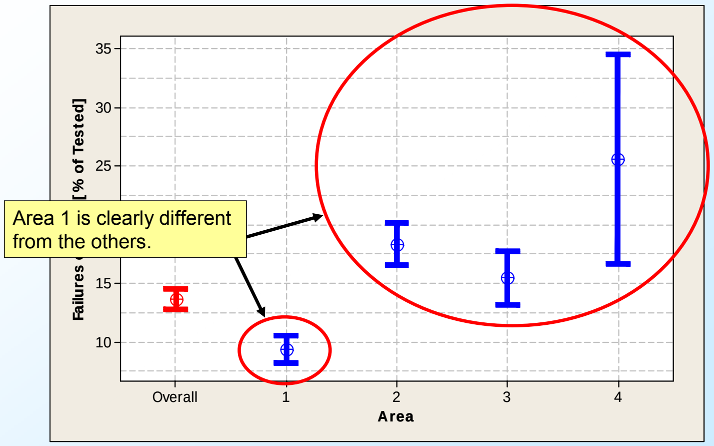
Data Generation from Diagnostic Measurement

Test Sequences



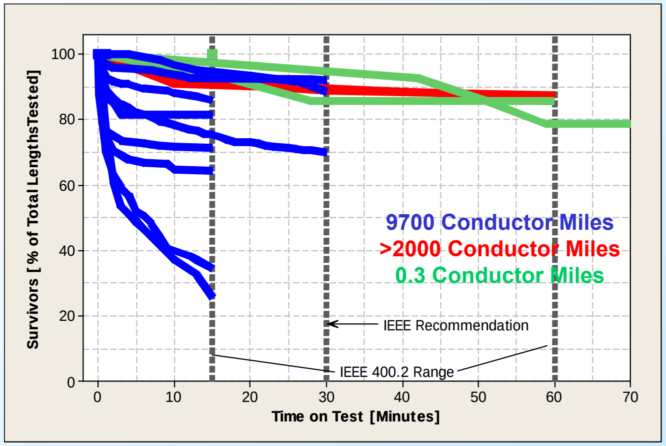
Local Context
Comparisons within one area

Separation with Simple VLF Outcomes

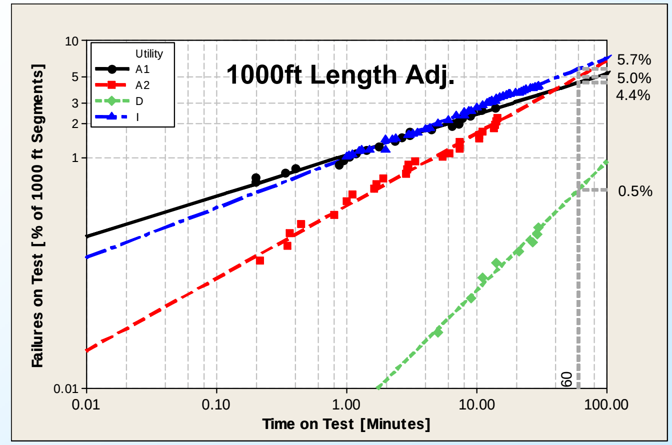


Global Context
Comparison with many tests
Databases
Standards

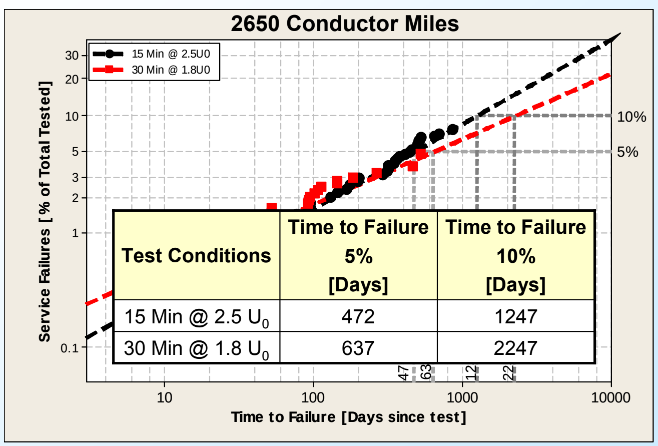
Withstand Testing Experience



Test Performance for Different Utilities



Service Experience



Test Conditions	Time to Failure 5% [Days]	Time to Failure 10% [Days]
15 Min @ 2.5 U_0	472	1247
30 Min @ 1.8 U_0	637	2247

Dielectric Loss (Tan δ)

Test Description

- Measures total cable system loss (cable, elbows, splices & terminations).
- May be performed at one or more frequencies (dielectric spectroscopy).
- May be performed at multiple voltage levels.
- Monitoring may be conducted for long durations.

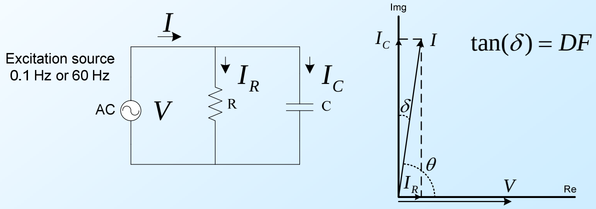
Field Application

- Offline test that may use:
  - 60 Hz. AC
  - VLF AC
  - Damped AC
- Testing may be performed by a service provider or utility crew.

Dielectric Loss (Tan δ)

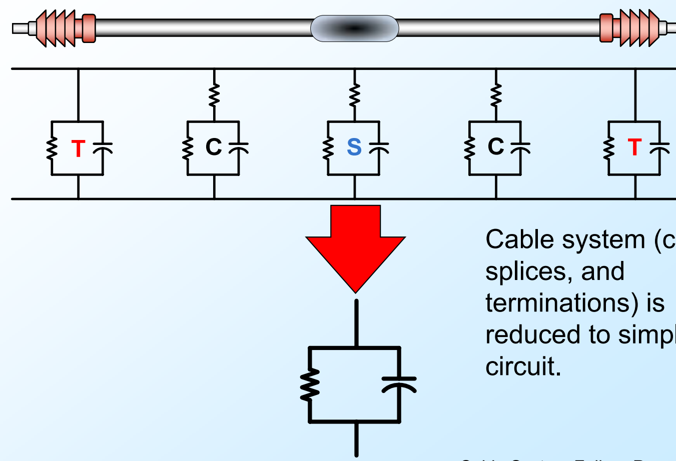
Dielectric losses - Tan δ:

- The cable insulation system is represented by an equivalent circuit
- In its simplest form it consists of two parameters; a resistor and a capacitor [IEEE Std. 400]
- When voltage is applied to the cable, the total current will be the contributions of the capacitor current and the resistor current



$$\tan(\delta) = DF = \frac{I_R}{I_C} = \frac{1}{\omega RC}$$

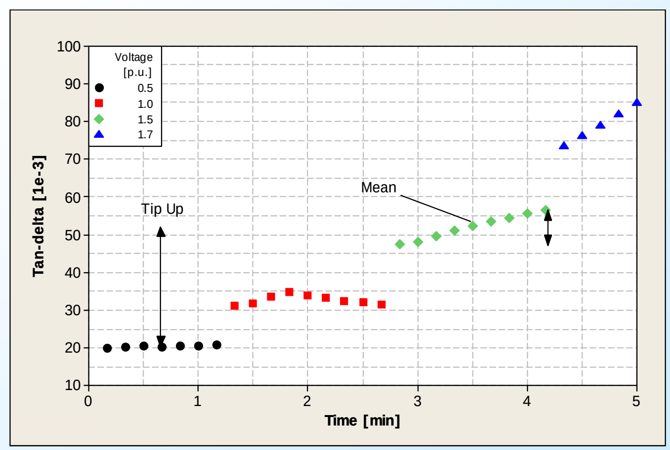
Cable System Equivalent



Cable system (cable, splices, and terminations) is reduced to simple circuit.

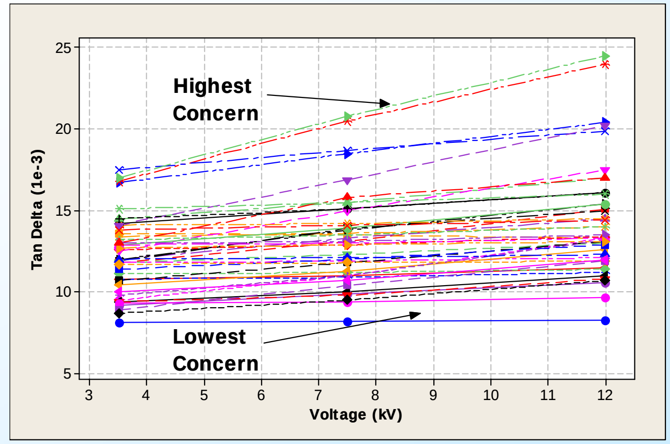
Data Generation from Diagnostic Measurement

Tan δ Test Data

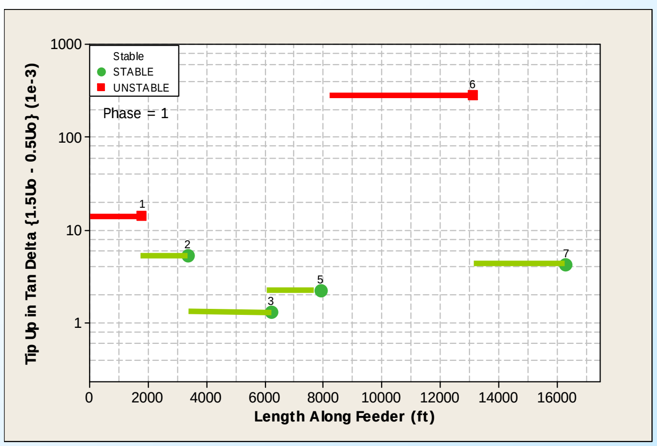


Local Context
Comparisons within one area

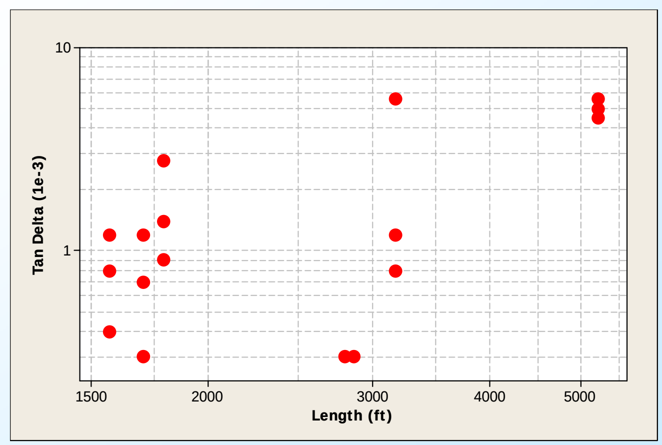
Tan δ Data for EPR Cable Systems



Segments within a Feeder

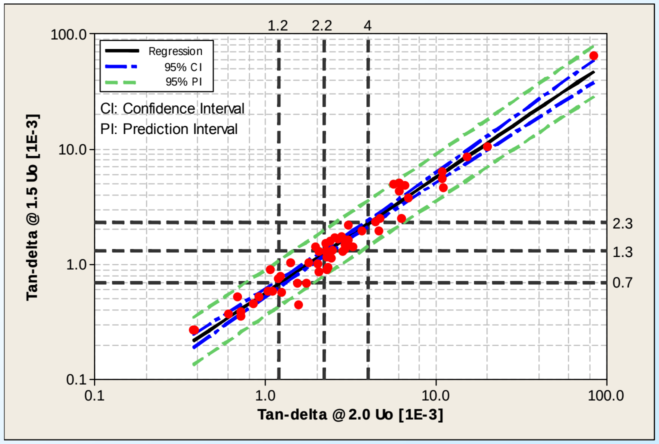


Lengths within a Locality



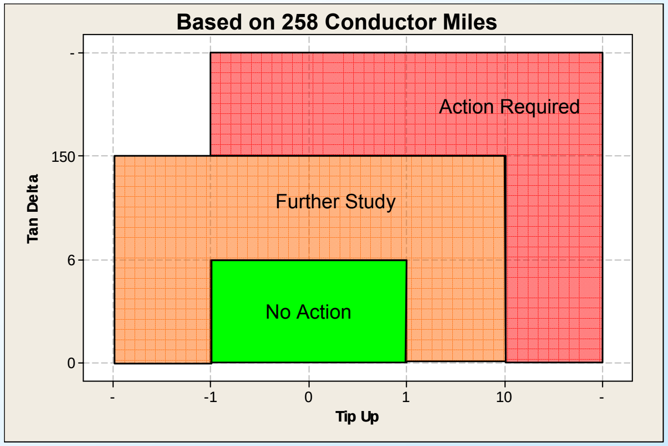
Global Context
Comparison with many tests
Databases
Standards

Testing at Reduced Voltages



"Cool Wall"

Tan δ Interpretation



Time Domain Reflectometry (TDR)

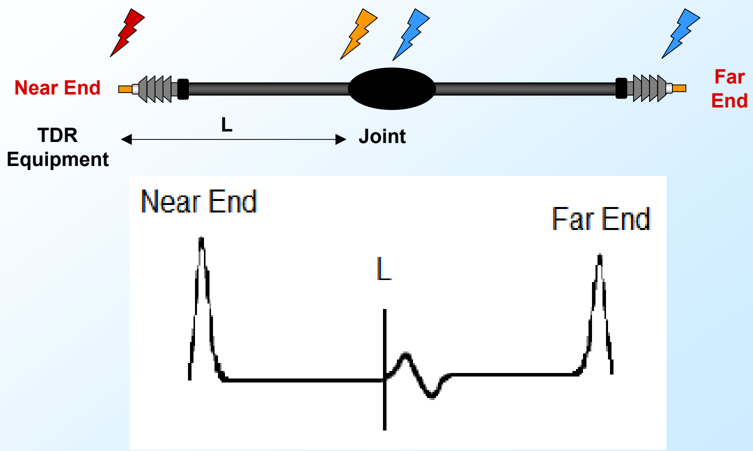
Test Description

- Measures changes in the cable impedance as a function of circuit length by observing the pattern of wave reflections.
- Used to identify locations of accessories, faults, etc.

Field Application

- Offline test that uses a low voltage, high frequency pulse generator.
- Testing may be performed by a service provider or utility crew.

TDR Principles



Online Partial Discharge

Test Description

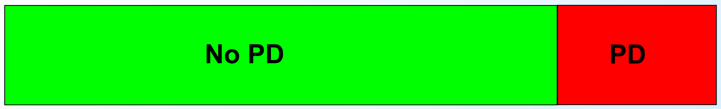
- Measurement and interpretation of discharge and signals on cable segments and/or accessories.
- Signals captured over minutes / hours.
- Monitoring may be conducted for long durations.

Field Application

- Online test that does not require external voltage supply.
- Testing typically only be performed by a service provider.
- Assessment criteria are unique to each embodiment of the technology

Data Generation from Diagnostic Measurement

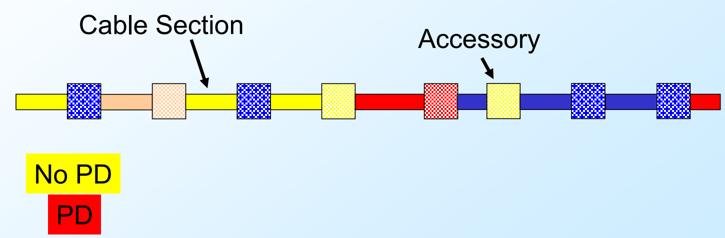
Discharge Occurrence



Local Context
Comparisons within one area

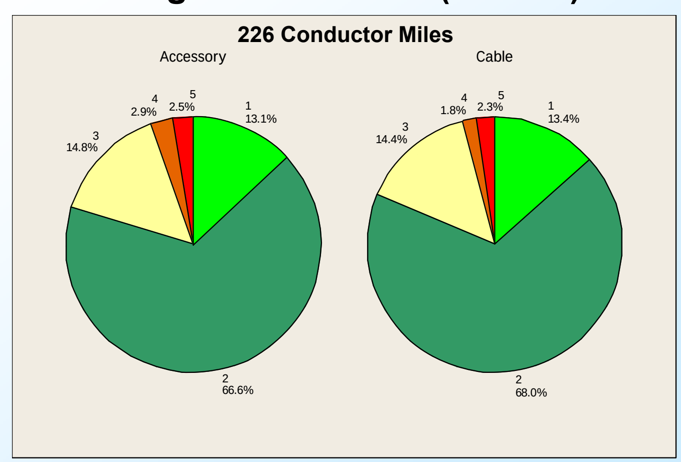
Distribution of PD along Lengths

- 5000 ft. portion of sample feeder
- Mixture of different PD levels for different sections and accessories.



Global Context
Comparison with many tests
Databases
Standards

Diagnostic Results (Overall)



Offline Partial Discharge

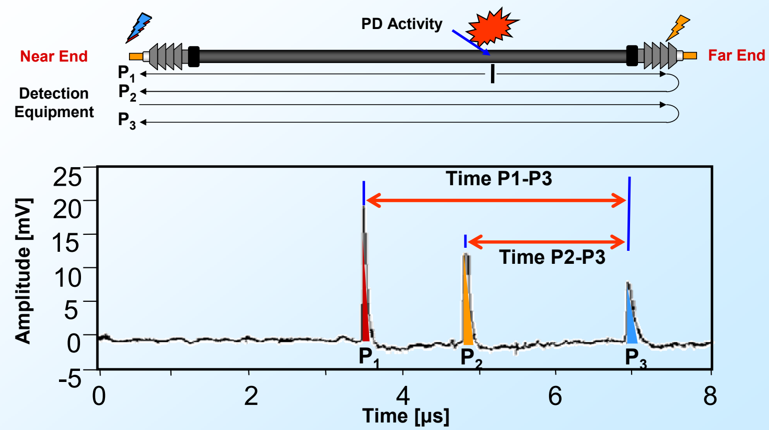
Test Description

- Measurement and interpretation of partial discharge signals above normal operating voltages.
- Signal reflections (combined with TDR information) allows location to be identified within cable segment.

Field Application

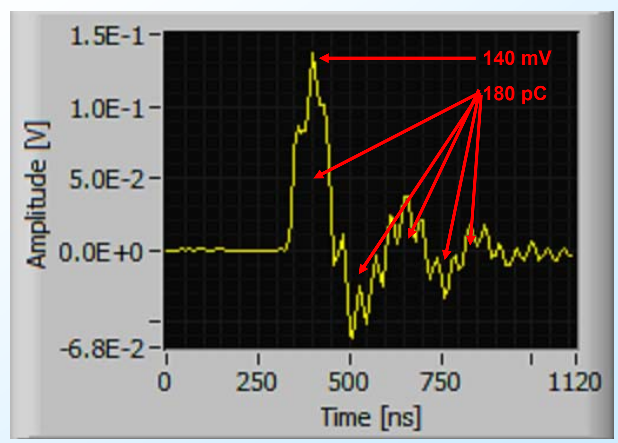
- Offline test that may use:
  - 60 Hz. AC — service provider
  - VLF AC — utility crew
  - Damped AC — utility crew

PD

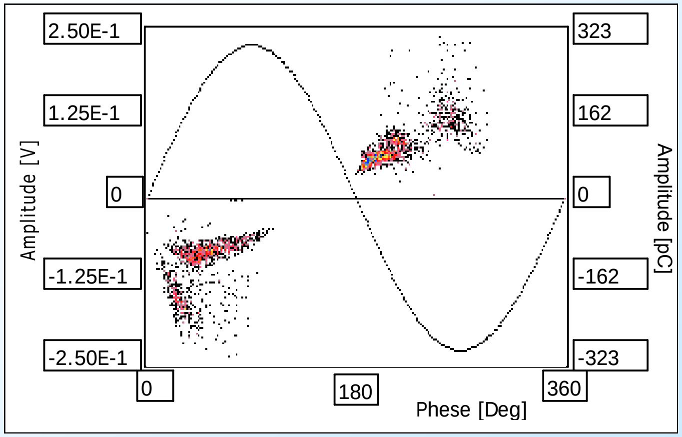


Data Generation from Diagnostic Measurement

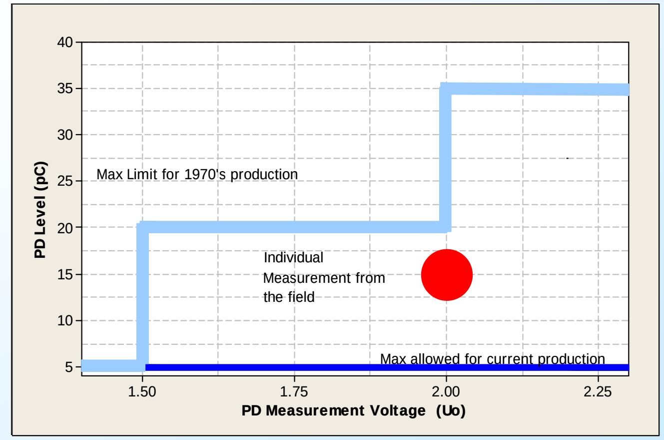
PD Pulse



PD Phase Resolved Pattern



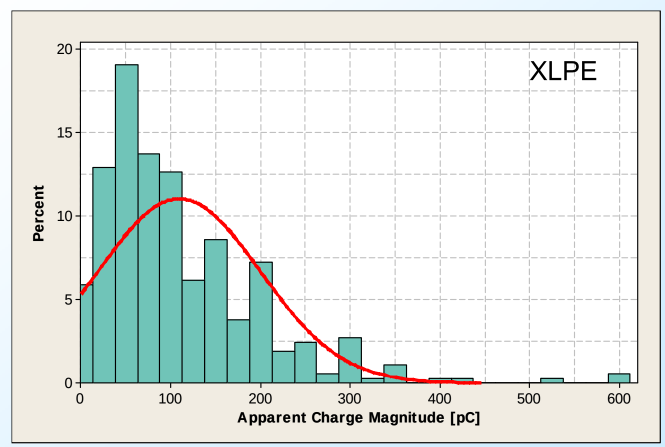
PD Magnitude



Local Context
Comparisons within one area

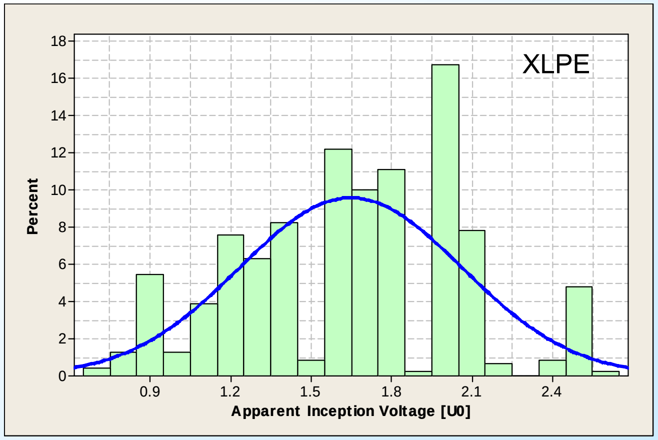
 Diagnostic Testing Technologies

PD Charge Magnitude Distributions



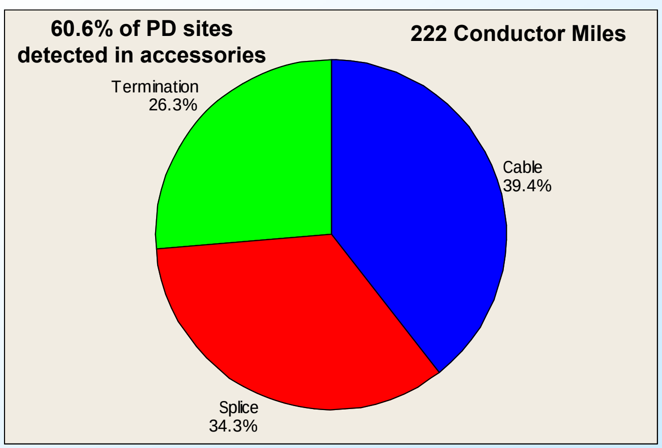
 Diagnostic Testing Technologies

PD Inception Voltage



Global Context
Comparison with many tests
Databases
Standards

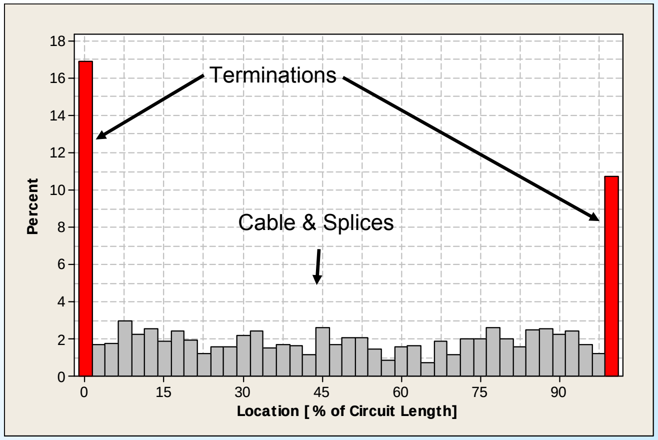
Location of PD



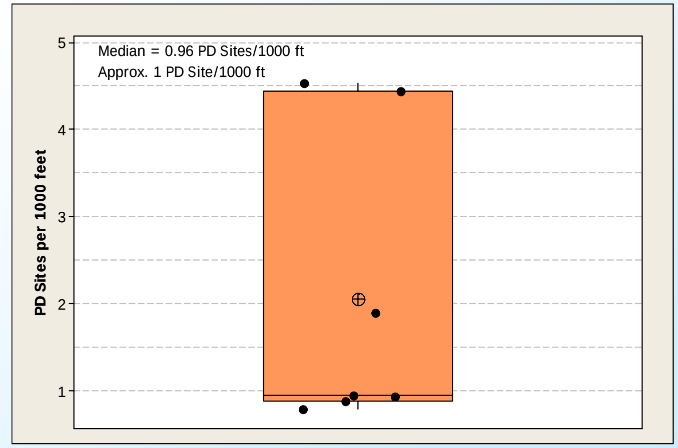
Offline PD Test Sequence

- Testing sequence for 16,000 ft.

PD Location



PD Sites per Length



Isothermal Relaxation Current

Test Description

- Measures the time constant of trapped charges within the insulation material as they are discharged.
- Discharge current is observed for 15-30 minutes.

Field Application

- Offline test that uses DC to charge the cable segment up to 1kV.
- Testing is performed by a service provider.

Recovery Voltage

Test Description

- Similar to IRC only voltage is monitored instead of current

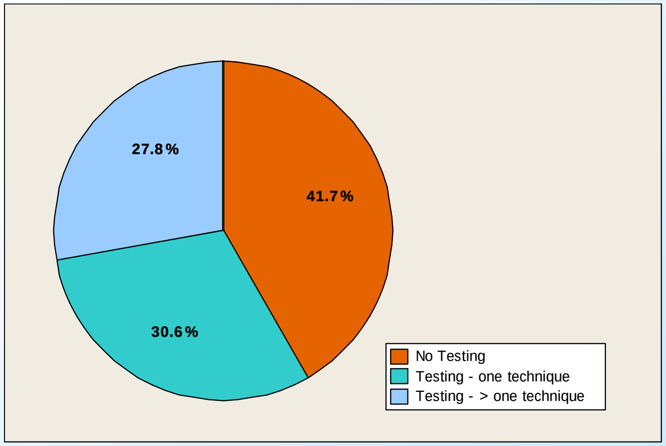
Field Application

- Offline test that requires initial charging by DC source up to 2kV.
- Testing is performed by a service provider.

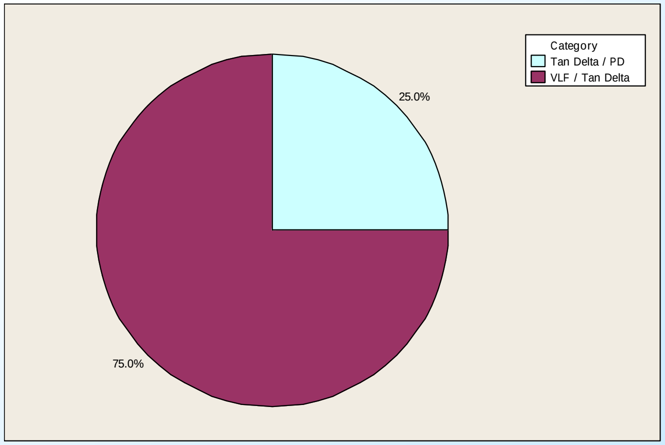
Combined Diagnostics

Multiple degradation mechanisms mean that two diagnostics are often better than one

Survey of Use of Diagnostics

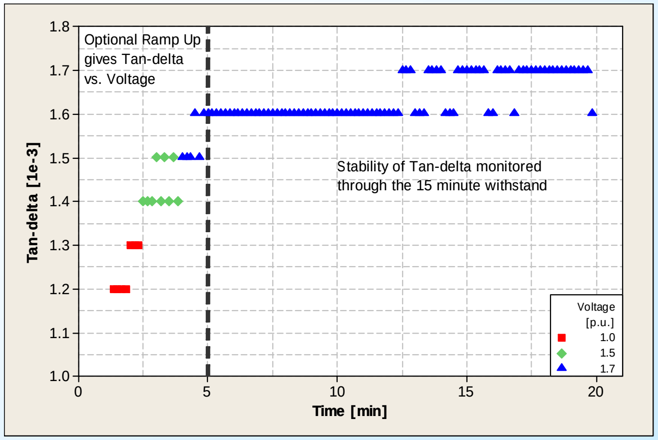


Multiple Diagnostics



Data Generation from Diagnostic Measurement

Monitored Withstand - Data



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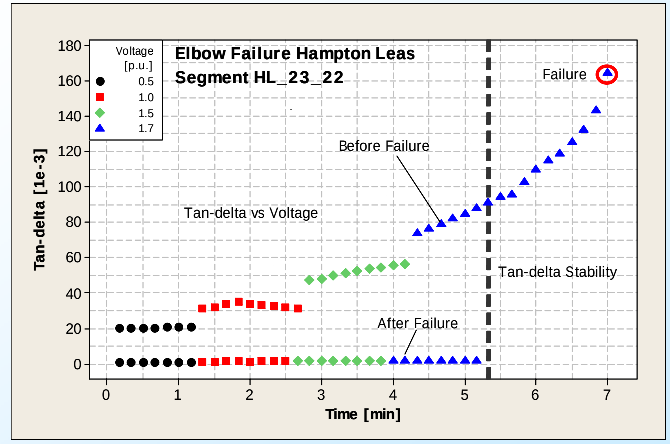
Monitored Withstand Data - Elbow



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Global Context
Comparison with many tests
Databases
Standards

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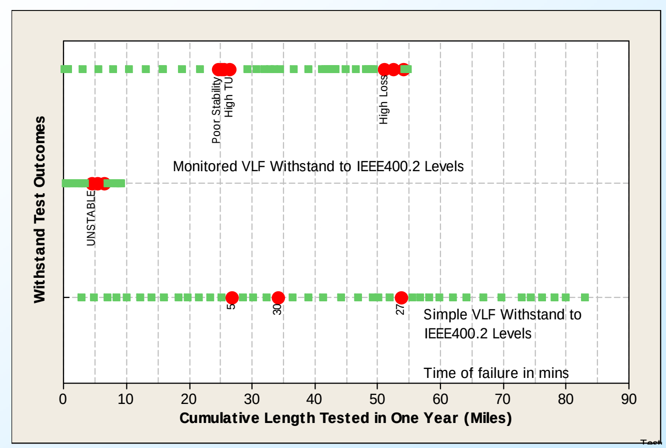
Monitored Withstand



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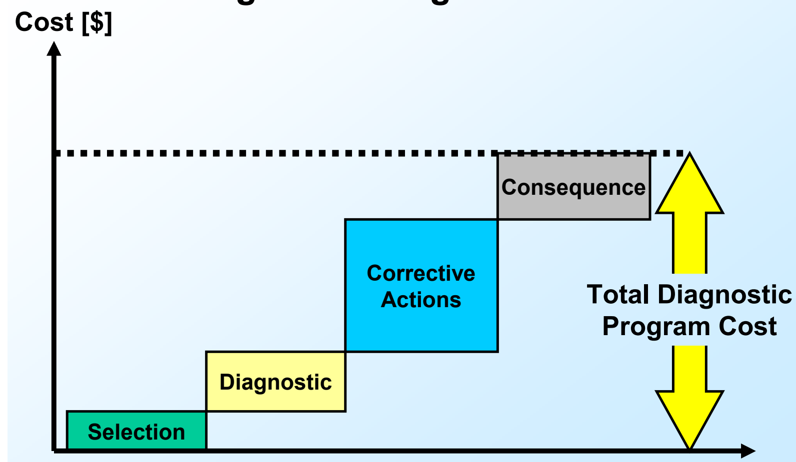
Accuracies Revisited

Why do they matter?

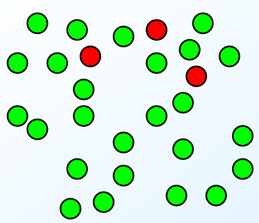
Josh Perkel

Diagnostic Program Costs



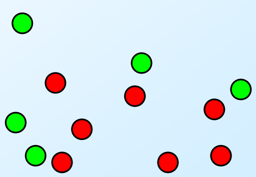
Recall the Example...

No Action Required



Avoided Corrective Actions

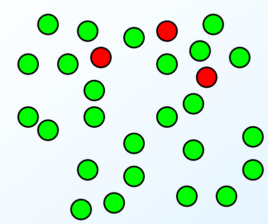
Action Required



Avoided service failures

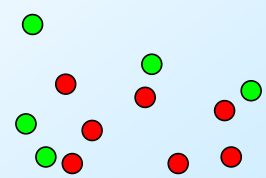
Incorrect Diagnosis

No Action Required



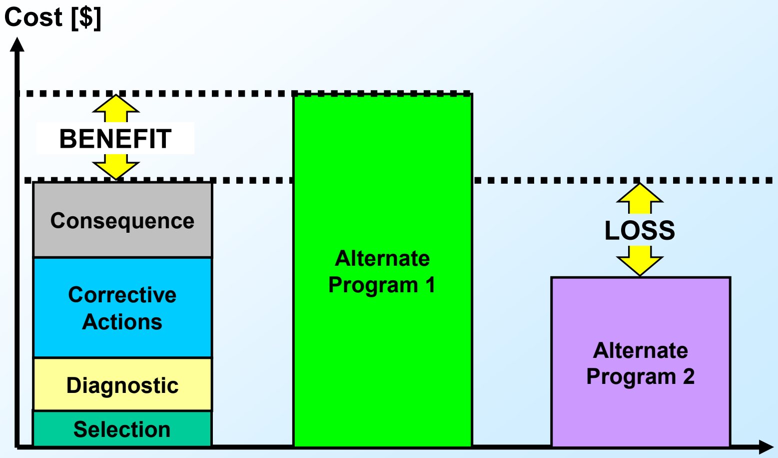
Future service failures

Action Required



Unneeded Corrective Actions

Benefit and Loss



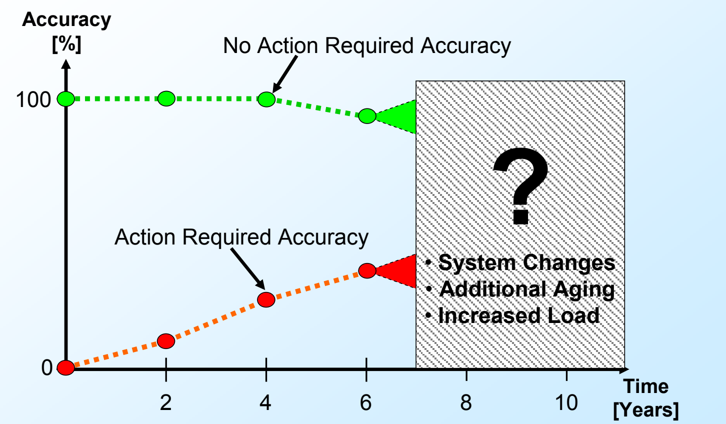
Considerations

- Diagnostic program economic calculations are based on ability to **predict** future failures.
- Total diagnostic program cost is more sensitive to certain elements than others.
  - Failure Rate
  - Diagnostic Accuracy
  - Failure Consequence

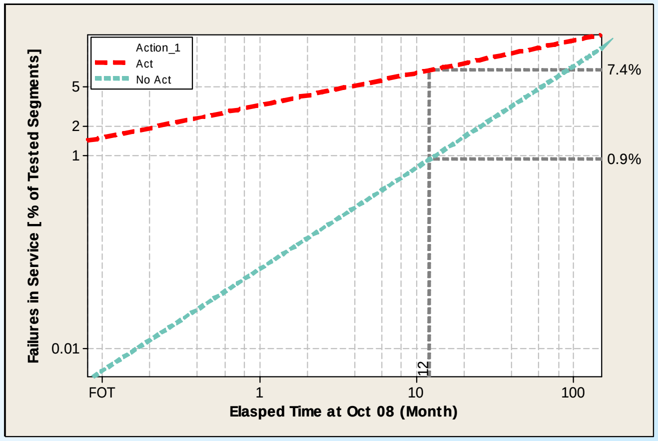
Diagnostic Accuracy Complications

- Time is a critical factor in the assessment of accuracy.
  - Failures do not happen immediately after testing.
- Two approaches to computing diagnostic accuracy.
  - "Bad Means Failure" Approach
  - "Probabilistic" Approach

Accuracy Over Time – "Bad Means Failure"



Probabilistic Approach – Tan δ



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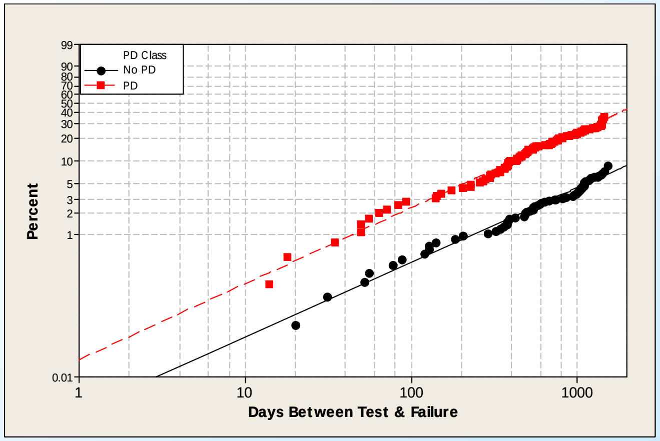
Probabilistic Approach - PD



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The Things We Know Now
That We Did Not Know Before

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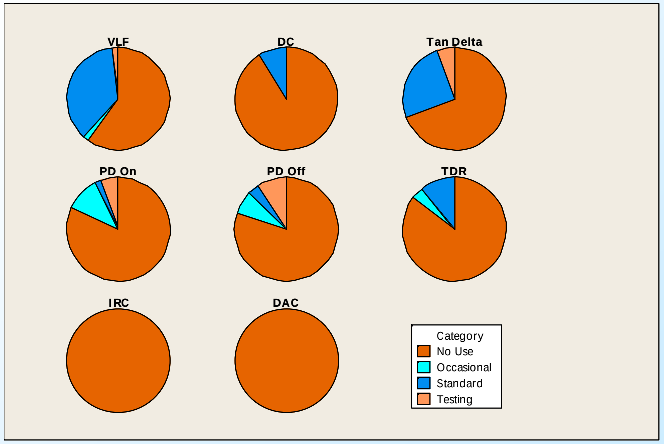
By Diagnostic Technique



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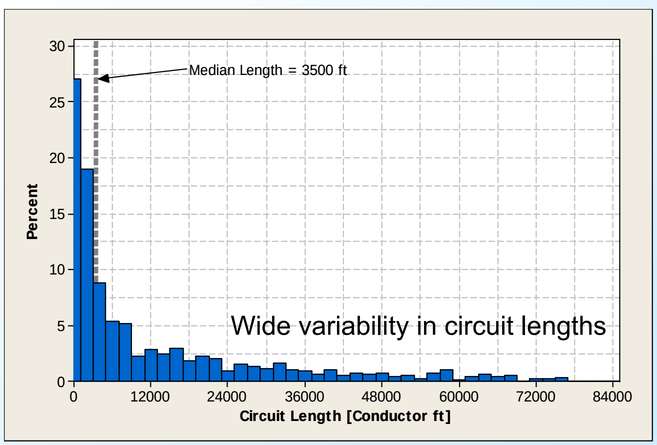
CDFI
Dielectric Withstand

Josh Perkel

Dielectric Withstand

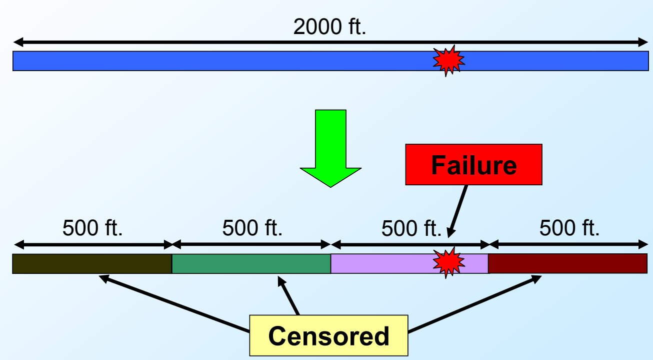
- Withstand techniques are most widely used diagnostic in the USA.
- Most utilities use VLF (either sine or cosine-rectangular) in their withstand programs.
- Test duration and voltage are critical to performance on test and in service.
- Explored the concept of "Monitored" Withstand tests.

Length Distribution (Overall)

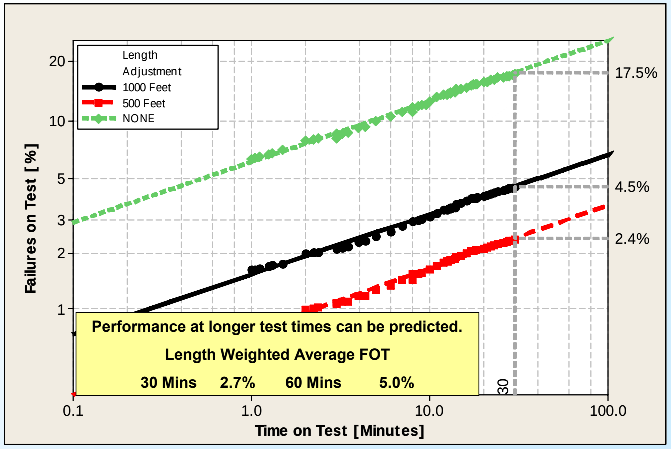


Length Effects

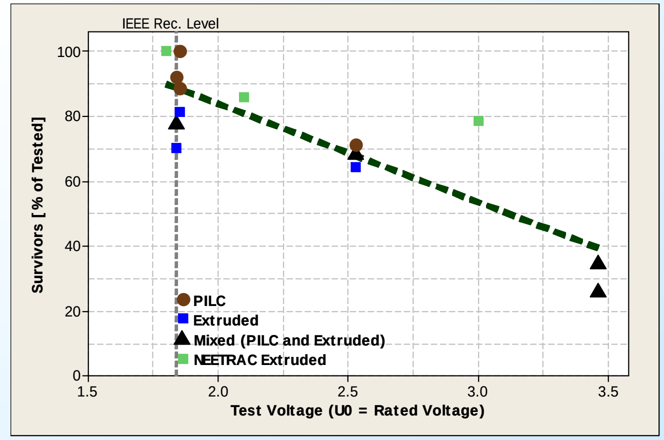
- Comparison of withstand failure on test rates must include length adjustments.



Utility I – Hybrid System



Effect of Test Voltage



VLF Lab Program

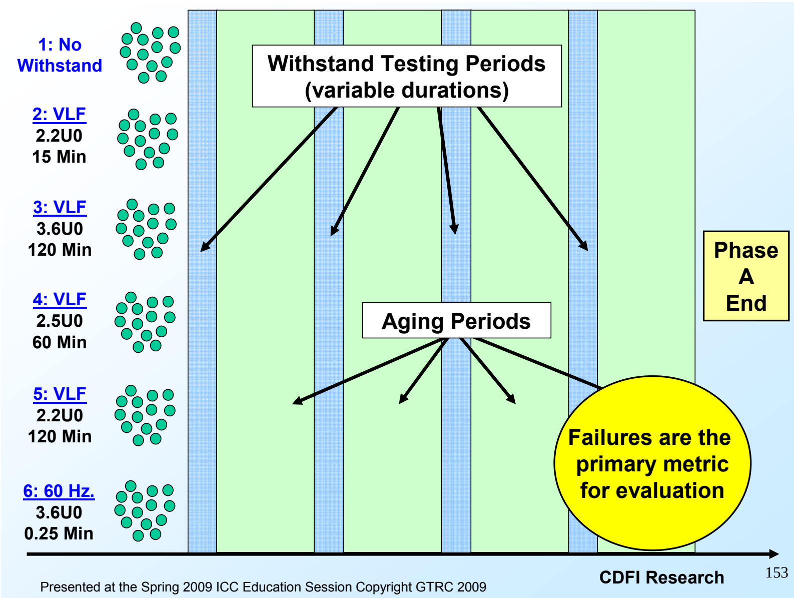
Josh Perkel

Overview

- Test program combining aging at U_0 with multiple applications of high voltage VLF.
- Uses field aged cable samples - one area within one utility.
- Evaluate the effects of
  - Voltage and time on the performance on test and
  - Subsequent reliability during service voltages.

Primary Metric
Survival during aging and testing

Secondary Metrics
- Before and after each VLF application, PD at U_0
- Between Phase A & B IRC, PD (AC $2.2U_0$, DAC), Tan δ


1: No Withstand
2: VLF 2.2U0 15 Min
3: VLF 3.6U0 120 Min
4: VLF 2.5U0 60 Min
5: VLF 2.2U0 120 Min
6: 60 Hz. 3.6U0 0.25 Min
Withstand Testing Periods (variable durations)
Aging Periods
Phase A End
Failures are the primary metric for evaluation
CDFI Research
153
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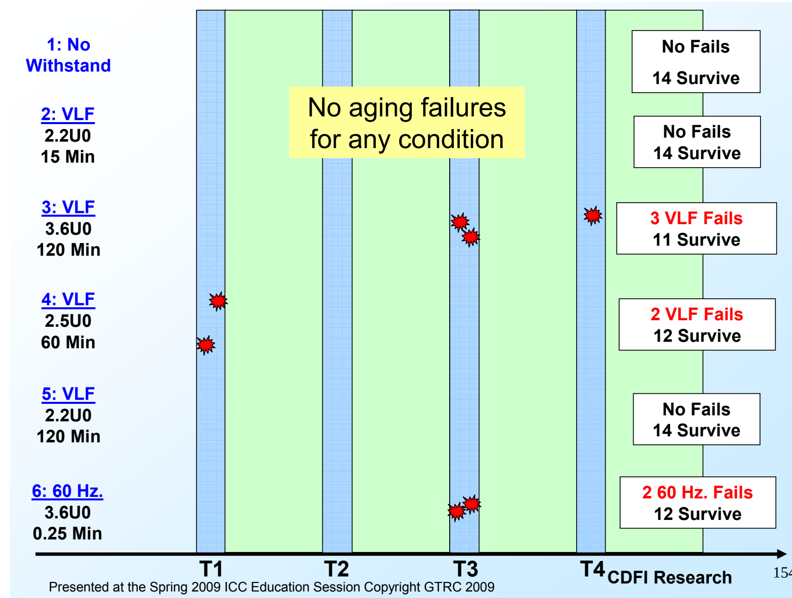
1: No Withstand
2: VLF 2.2U0 15 Min
3: VLF 3.6U0 120 Min
4: VLF 2.5U0 60 Min
5: VLF 2.2U0 120 Min
6: 60 Hz. 3.6U0 0.25 Min
No aging failures for any condition
No Fails 14 Survive
No Fails 14 Survive
3 VLF Fails 11 Survive
2 VLF Fails 12 Survive
No Fails 14 Survive
2 60 Hz. Fails 12 Survive
T1
T2
T3
T4
CDFI Research
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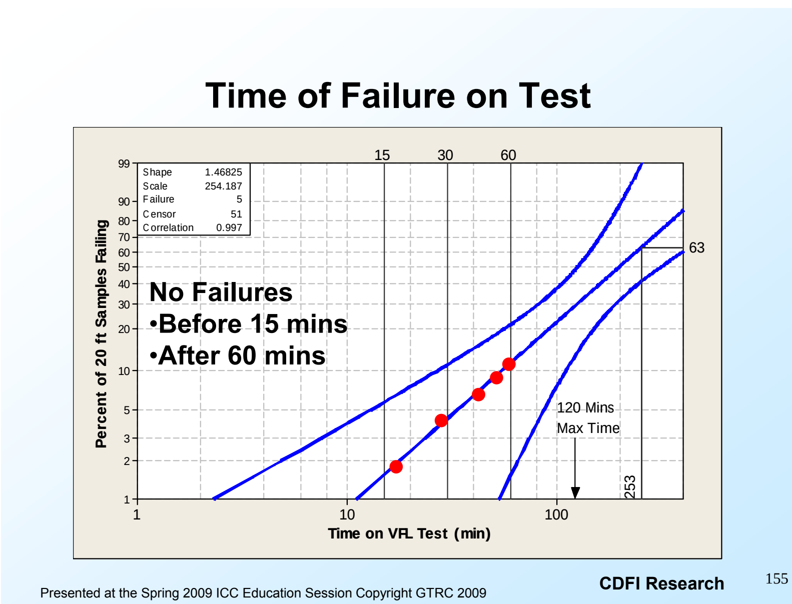
Time of Failure on Test
No Failures
•Before 15 mins
•After 60 mins
120 Mins Max Time
Percent of 20 ft Samples Failing
Time on VFL Test (min)
15
30
60
63
253
CDFI Research
155
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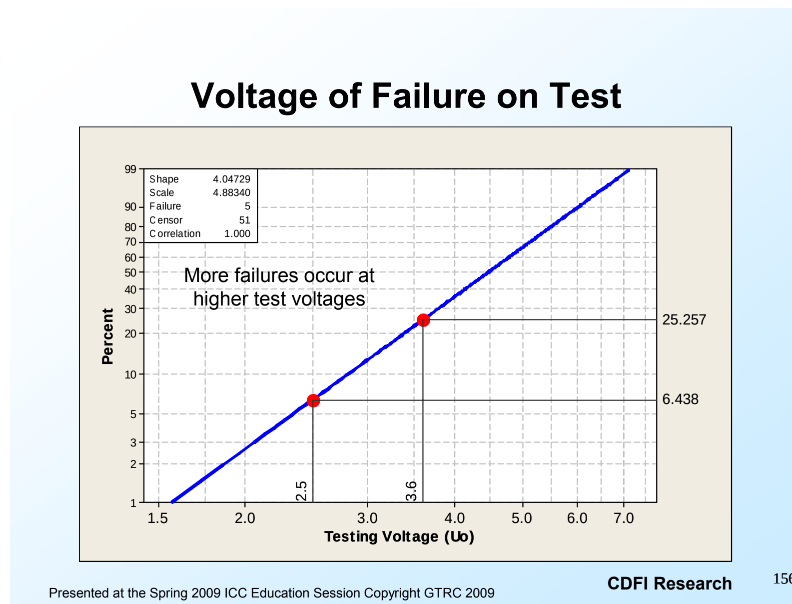
Voltage of Failure on Test
More failures occur at higher test voltages
Percent
Testing Voltage (Uo)
25.257
6.438
2.5
3.6
CDFI Research
156
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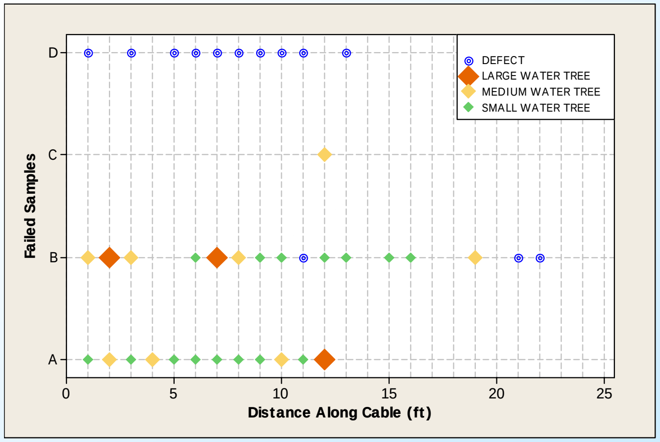
Failure Analyses - Trees & Defects in Cables



VLF Test Program Summary

- Analysis of Phase A is complete.
- Phase B ($2U_0$ aging, 45°C Cosine Rectangular) underway.
- Phases A & B show that **no VLF exposed samples have failed under 60 Hz aging @ Uo & 2Uo**.
- Phase B tests showed **two samples without VLF exposure failed during 60 Hz aging @ 2Uo.**
- All failures occurred at the appropriate time. i.e. within the VLF testing periods.
- 80% (4 out of 5) of VLF failures between 15 and 60 mins

Selecting a Diagnostic Technology Knowledge-Based System

Nigel Hampton

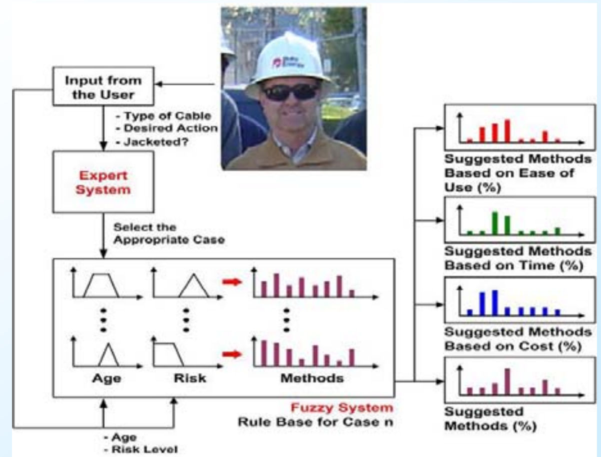
KBS

- Selecting the right diagnostic is not easy.
- No one diagnostic covers everything.
- How you measure is influenced by what you do with the results.
- The KBS captures the experience and knowledge of people who have been operating in the field

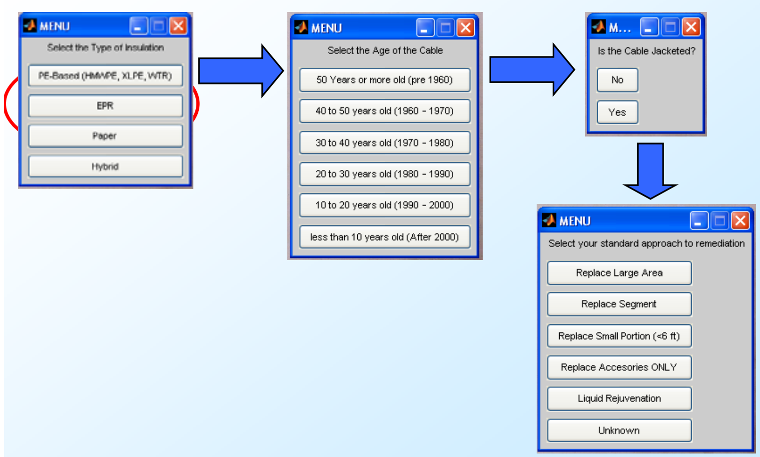
Knowledge Based Systems

- Knowledge-Based Systems are computer systems that are programmed to imitate human problem-solving.
- Uses a combination of artificial intelligence and reference to a database of knowledge on a particular subject.
- KBS are generally classified into:
  - Expert Systems
  - Case Based Reasoning
  - Fuzzy Logic Based Systems
  - Neural Networks

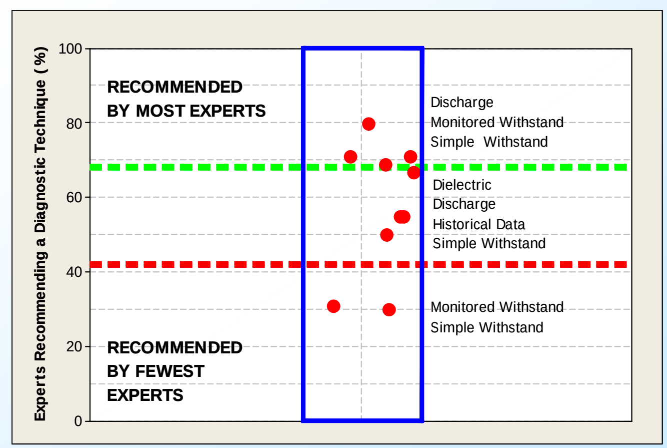
Extruded Cable Diagnostics



KBS Example



Short Listing of Diagnostic Approaches

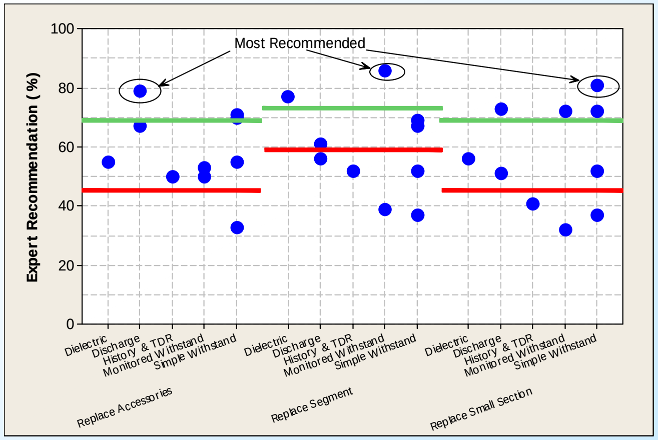


Impact of Remedial Action

- Hybrid Cable System
- Most service failures occur in Accessories
- Usual remediation is by replacement of cable sections

System Component	Portion [%]	Service Failure Rate	Age [yrs]
PE	33	Medium	20 - 30
EPR	42	Low	0 - 10
Paper	25	High	40 - 50

Hybrid Cable System



Summary

Rick Hartlein

What we have learned about diagnostics (1)

1. A developing database of field failure diagnostic data shows that different diagnostic techniques can provide some indication about cable system condition.
2. Even if the diagnostics themselves are imprecise, diagnostic programs can be beneficial.
3. Benefits can be quantified, however this is not simple and requires effort.
4. Many different data analysis techniques, including some non conventional approaches, are needed to assess diagnostic effectiveness.
5. Utilities HAVE to act on ALL replacement/repair recommendations to get improved reliability.

What we have learned about diagnostics (2)

6. PD, VLF, DC and Tan δ & VLF withstand tests detect problems in the field and can be used to improve system reliability.

7. It is very difficult to predict whether or not the problems/defects detected by PD and Tan δ will lead to failure in the short/medium term.

8. PD assessments are good at establishing groups of cable system segments that are not likely to fail.

9. Tan δ measurements provide a number of interesting features for assessing the condition of cable systems.

10. Tan δ & PD measurements require interpretation to establish how to act.

What we have learned about diagnostics (3)

11. Interpretation of PD measurements is more complex than interpretation of Tan δ measurements.

12. IRC & RV are particularly difficult to deploy in the field.

Reflections

- Approach to data analysis established in CDFI
- Many questions answered, there still remain gaps in our understanding of:
  - Benefits
  - Distinguishing anomalies from weaknesses
- Answers will come with continued analysis of field test data (diagnostic tests followed by circuit performance monitoring) as well as controlled laboratory tests.
- The potential value of continued analysis is high.