Shielded Power Cable Testing

Choosing the Right Test

Presented by

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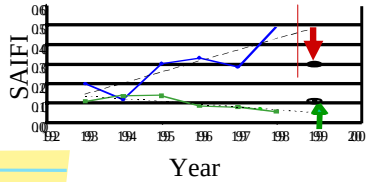
October 11, 2005

Introduction

- **Latest Standards**
- **Shielded Power Cable Tests**
  - **Toolbox**
  - **Pros and Cons of each tool**
- **The most effective tests**
  - **Very Low Frequency HIPOT**
  - **Offline Partial Discharge (PD) Location**
- **Comparison Case Studies –emulated PD factory test baseline**
  - **What is PD?**
  - **How does one perform an off-line PD test?**

Questions to be answered con't

- **What are the objectives of a MV or HV cable reliability program?**
  - Highest Reliability
  - Longest Life
  - Lowest Cost



- **Why should a cable reliability strategy involve a test?**
  - Cradle to grave condition monitoring
  - Direction, Direction, Direction
- **Can a test predict end of life? I**f you define 'end of life' and select the appropriate test , yes. Useful life is a better term.

Questions to be answered

- **Which test do I use for my application?**
  - **-Depends on the application and the expected result.**
- **How do I know if the test is effective?**
  - **-Only a few tests have a way to measure effectiveness and are backed by industry standards.**
- **Which are the most effective tests?**
  - **Destructive Withstand, VLF HIPOT**
  - **Nondestructive Diagnostic, 60Hz Offline PD**
- **Is there any one test that works in all conditions and finds everything?**
  - **–No, every test has limitations**

How Does Cable Insulation Fail?

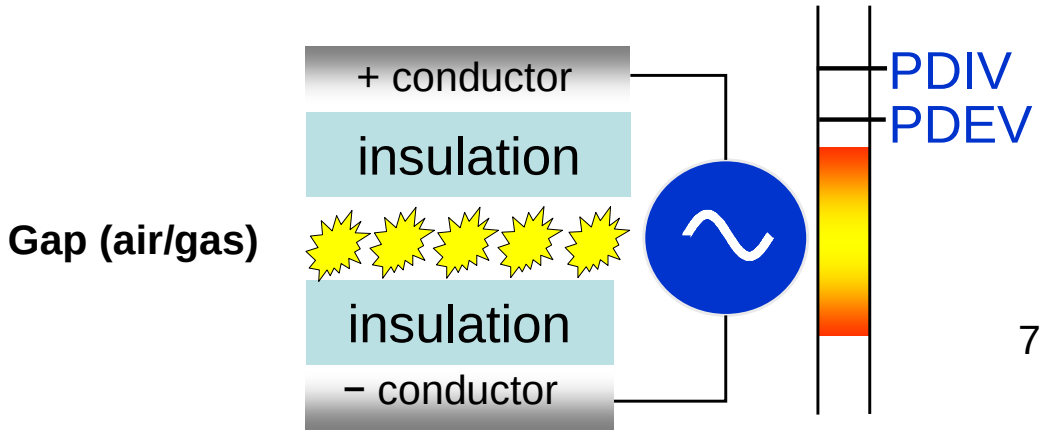
Failure Modes

- High impedance defects
  - Workmanship nicks, voids, cuts
  - Ageing mechanisms, electrical trees
- Low impedance defects –conduction (PILC)
- Thermal
  - Poor mechanical connections
  - Extreme operating temperature
- External influence –dig-ins, vandalism

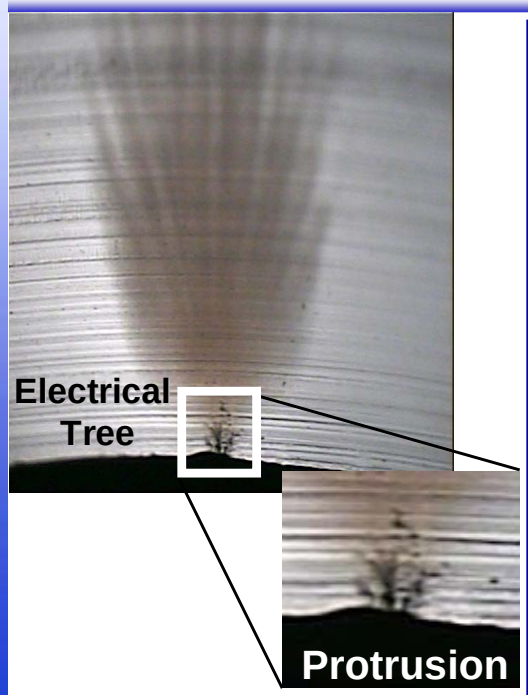
What is PD?

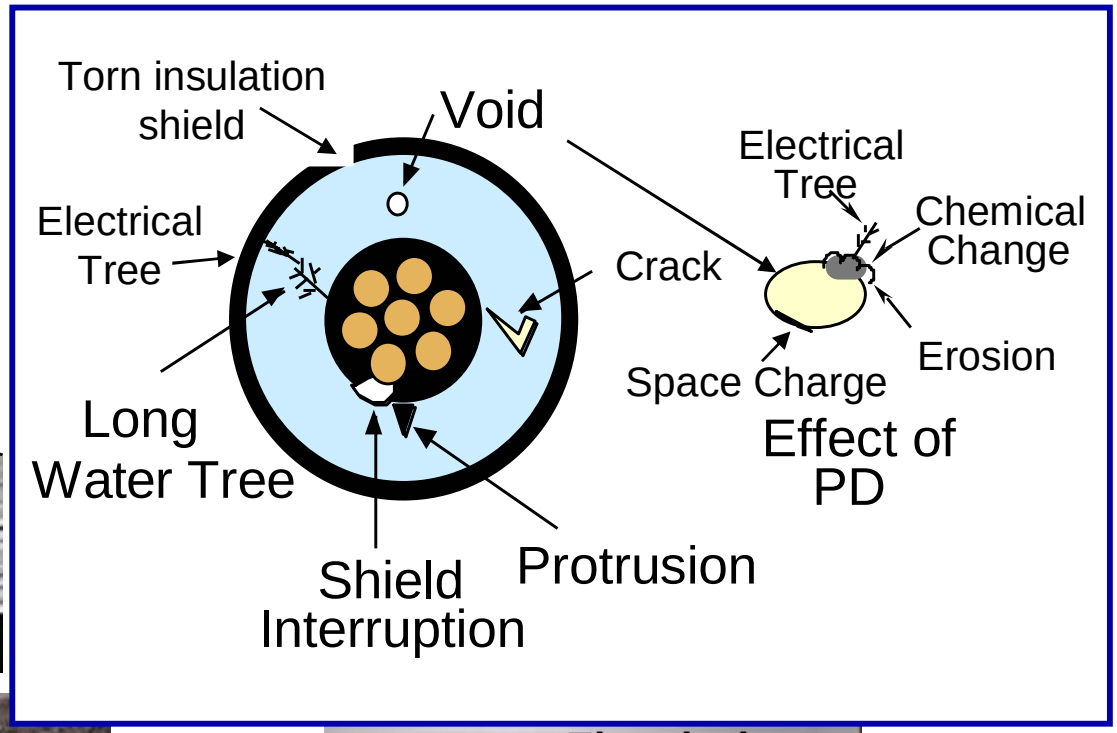
Definitions

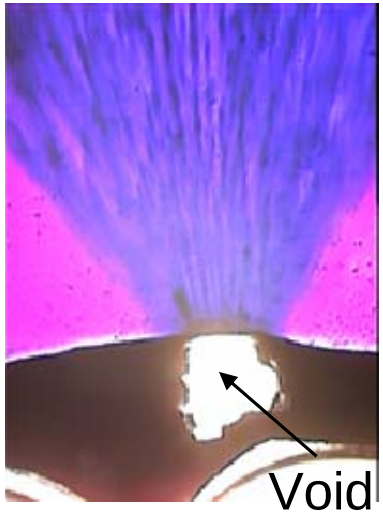
- An electrical discharge that does not completely bridge the space between two electrodes.
- PicoCoulomb (pC) – unit of charge magnitude
- The voltage at which PD first appears is the **I**nception **V**oltage (PDIV)
- The PD is extinguished when the voltage is reduced below the level called the **E**xtinction **V**oltage (PDEV)

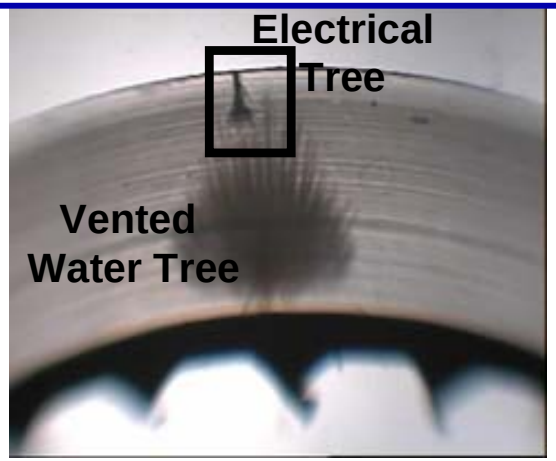


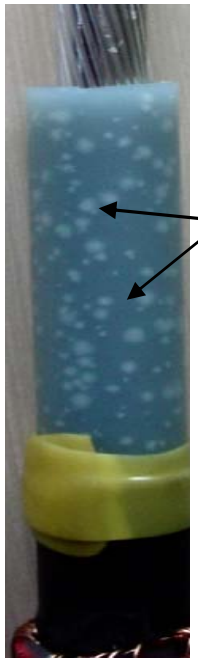
Typical PD producing defects in Extruded cables



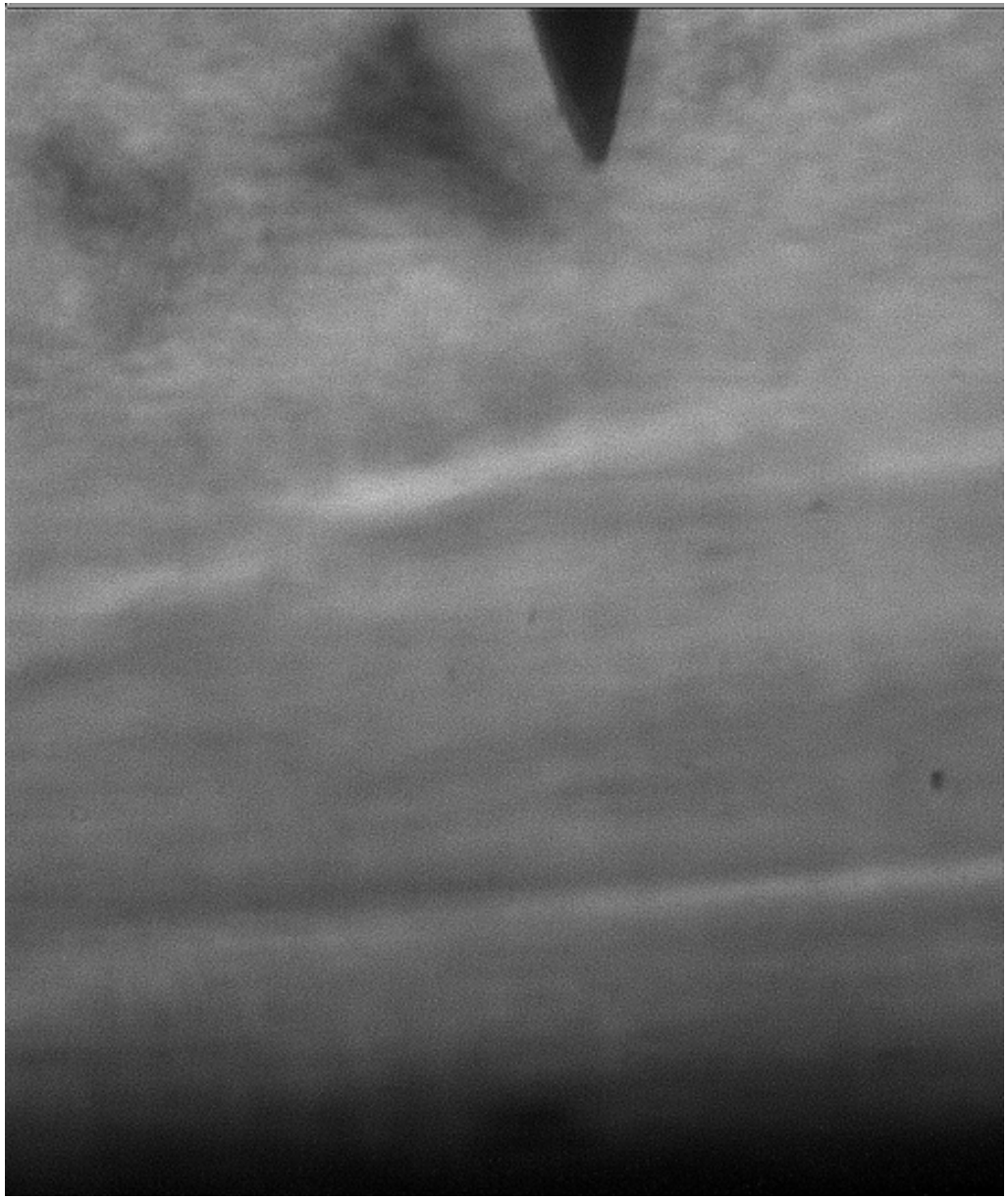




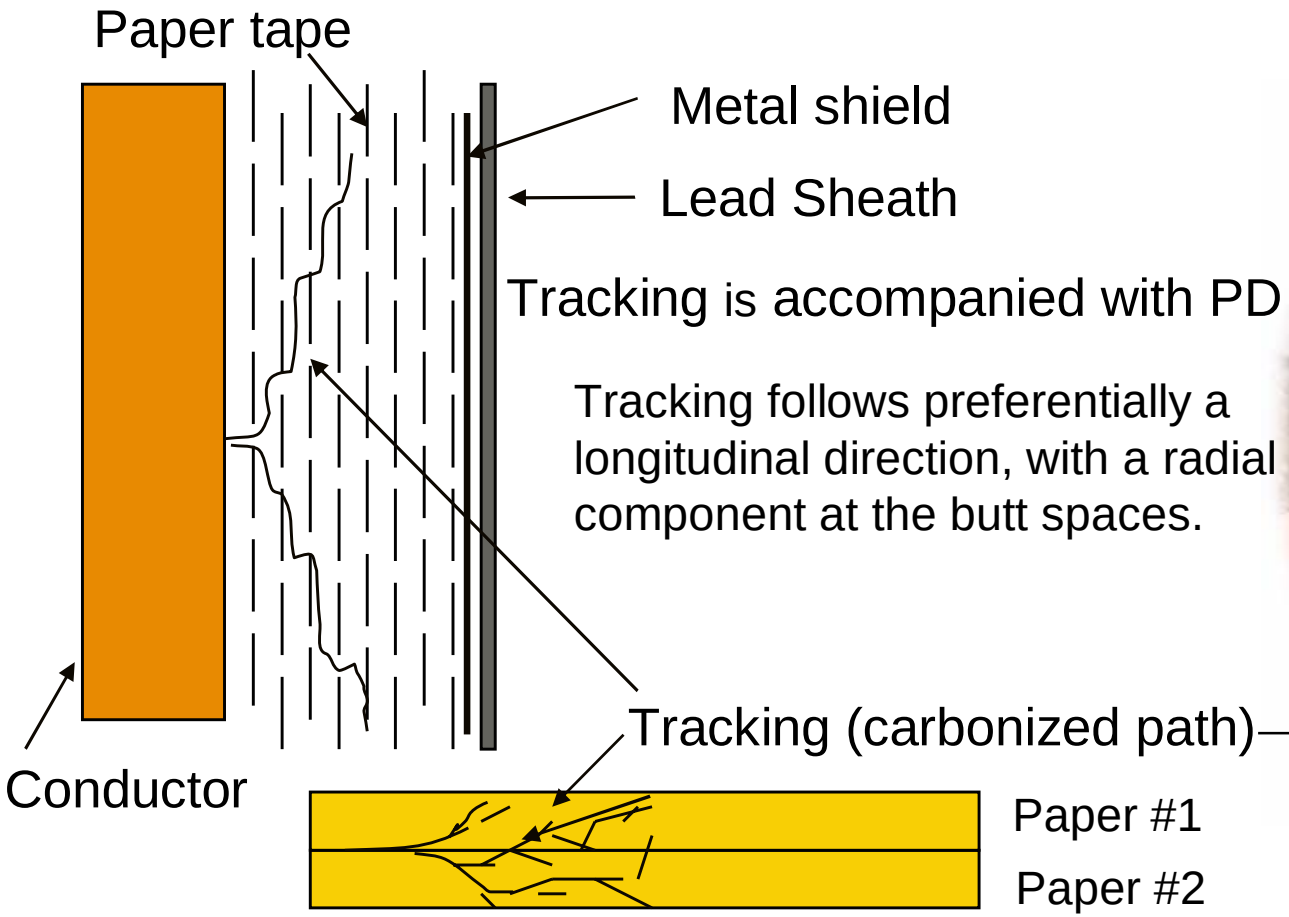


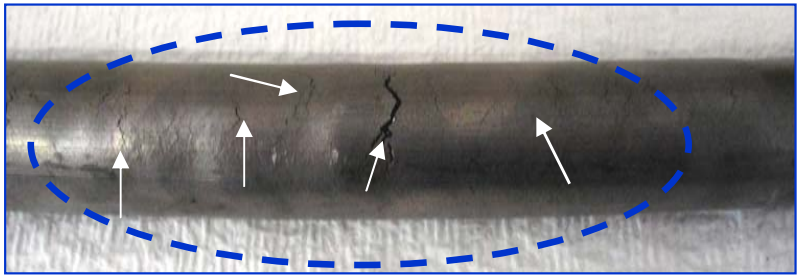


Electrical Tree

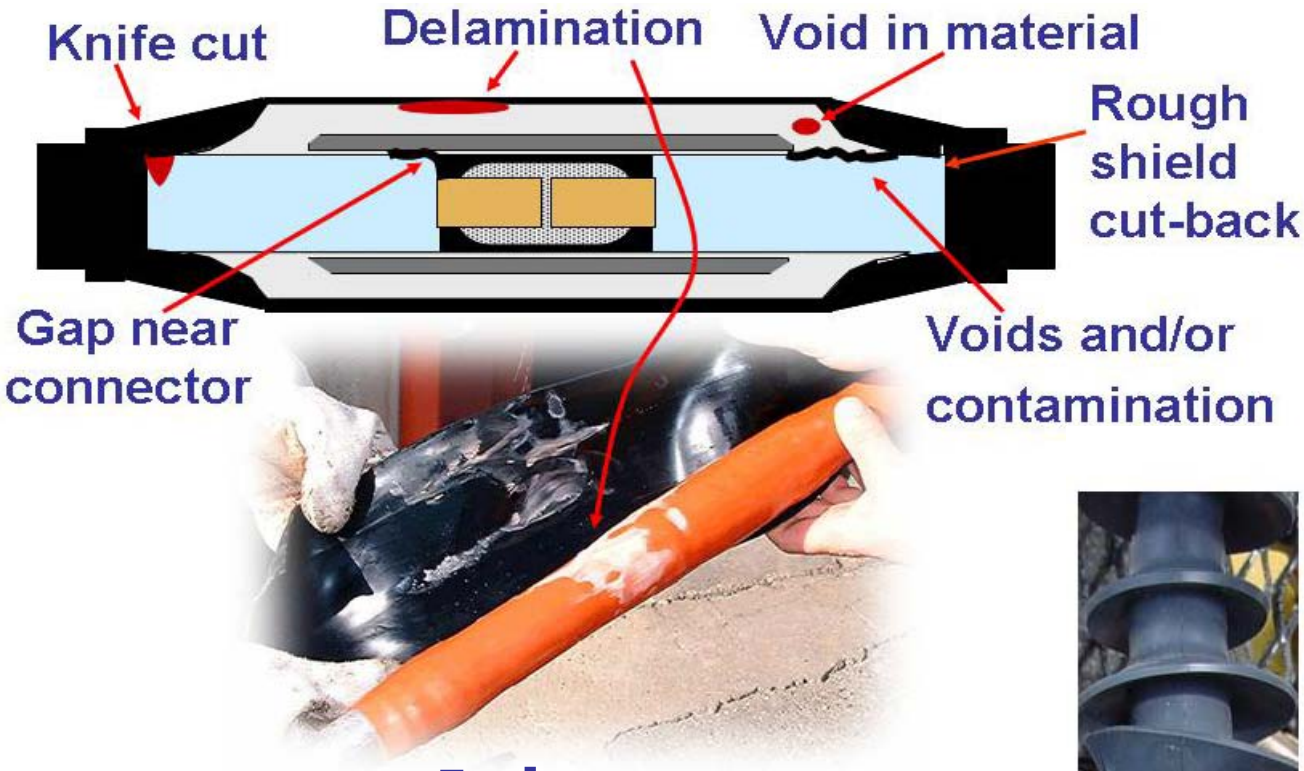


PD in Paper Insulated Cable



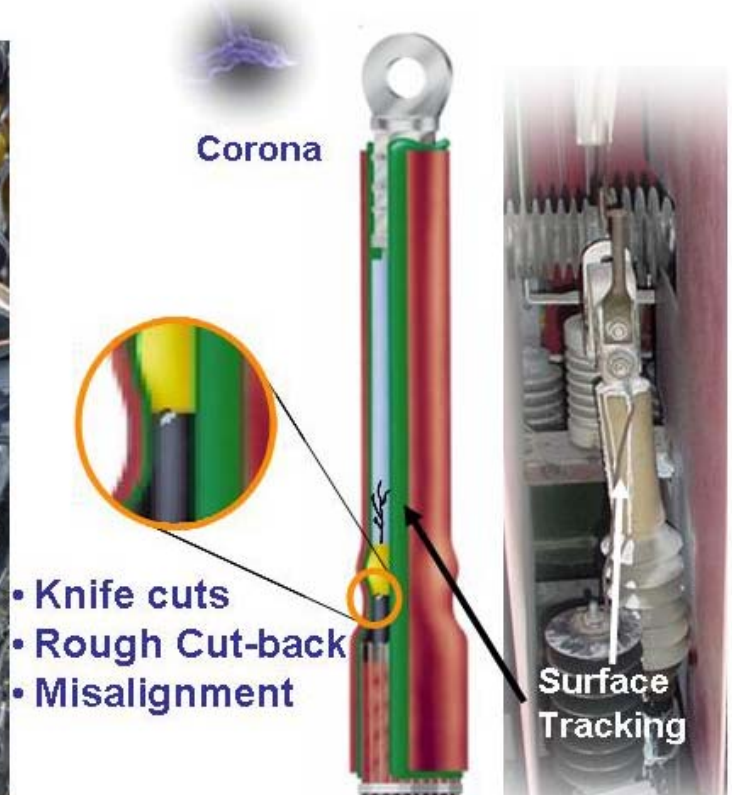


PD in Accessories



Joints

Terminations



Latest Cable Test Standards

IEEE 400

Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems

- IEEE 400.1 DC –Direct Voltage
- IEEE 400.2 VLF –Low frequency AC
- IEEE 400.3 PD –Partial discharge

- International consensus documents
- Guide to select appropriate test for application
- List advantages and disadvantages

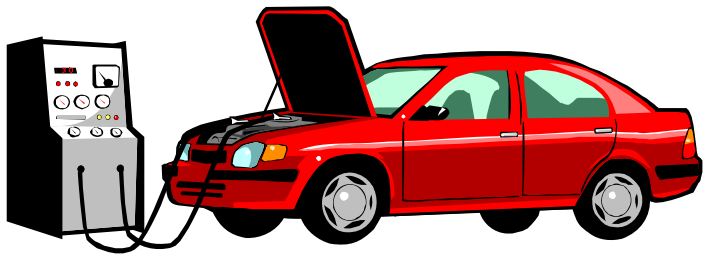
What Cable Test Methods are Available?

Cable Testing Options
IEEE 400 -2 Categories

- **Withstand (Pass/Fail)**
  - Direct Voltage (DC) –driveway
  - AC –teenage son
    - Very Low Frequency (VLF)
    - Power Frequency
- **Diagnostic (Predictive)**
  - General Condition Assessment (GCA) – mechanic fluid check
  - Partial Discharge (PD) –computer diagnostic –on-line = driveway, –off-line = expert test drive

Has anyone heard of a 'soak' test?

History of Cable Testing



Car diagnostic before a long road trip comparison

HIPOT Tests
Common Denominators

- Pros **SIMPLE**
  - Prescribed voltage for specified time
  - Simple and relatively inexpensive equipment
  - Simple pass or fail procedure–low skill requirement
- Cons **NOT PREDICTIVE, DESTRUCTIVE**
  - Does not monitor the effect of test
  - Destructive to cable insulation
  - Serial process with multiple defects
  - Blind to certain types of defects
  - Sledge hammer approach which weakens all defects equally

DC HIPOT

- Pros
  - Long history of use
  - Most portable source, w/ lowest pwr. req.
  - Good HIPOT for conductive defects (water in PILC)
- Cons
  - space charge aggravates defects in aged extruded cable long after test
  - Blind to high impedance defects e.g. cuts and voids
  - Leakage current highly dependent on atmospheric conditions
  - Does not replicate service conditions or factory tests
  - Not supported by IEEE as a acceptance or maintenance test

The DC HIPOT

What does IEEE 400 say about the DC HIPOT test?

Maintenance Test:

"Testing of cables that have been service aged in a wet environment (specifically XLPE) with dc at the currently recommended dc voltage levels (see IEEE P400.1) may cause the cables to fail after they are returned to service." (section 4.2)

Acceptance Test

"A field test made after cable system installation, including terminations (see IEEE 48) and joints (see IEEE 404), but before the cable system is placed in normal service. The test is intended to further detect installation damage and to show any gross defects or errors in installation of other system components"

"Furthermore, from the work of Bach [B5], we know that even massive insulation defects in extruded dielectric insulation cannot be detected with dc at the recommended voltage levels."

(section 4.2)

A DC HIPOT will catch gross defects, right?

All of these defects pass a DC HIPOT

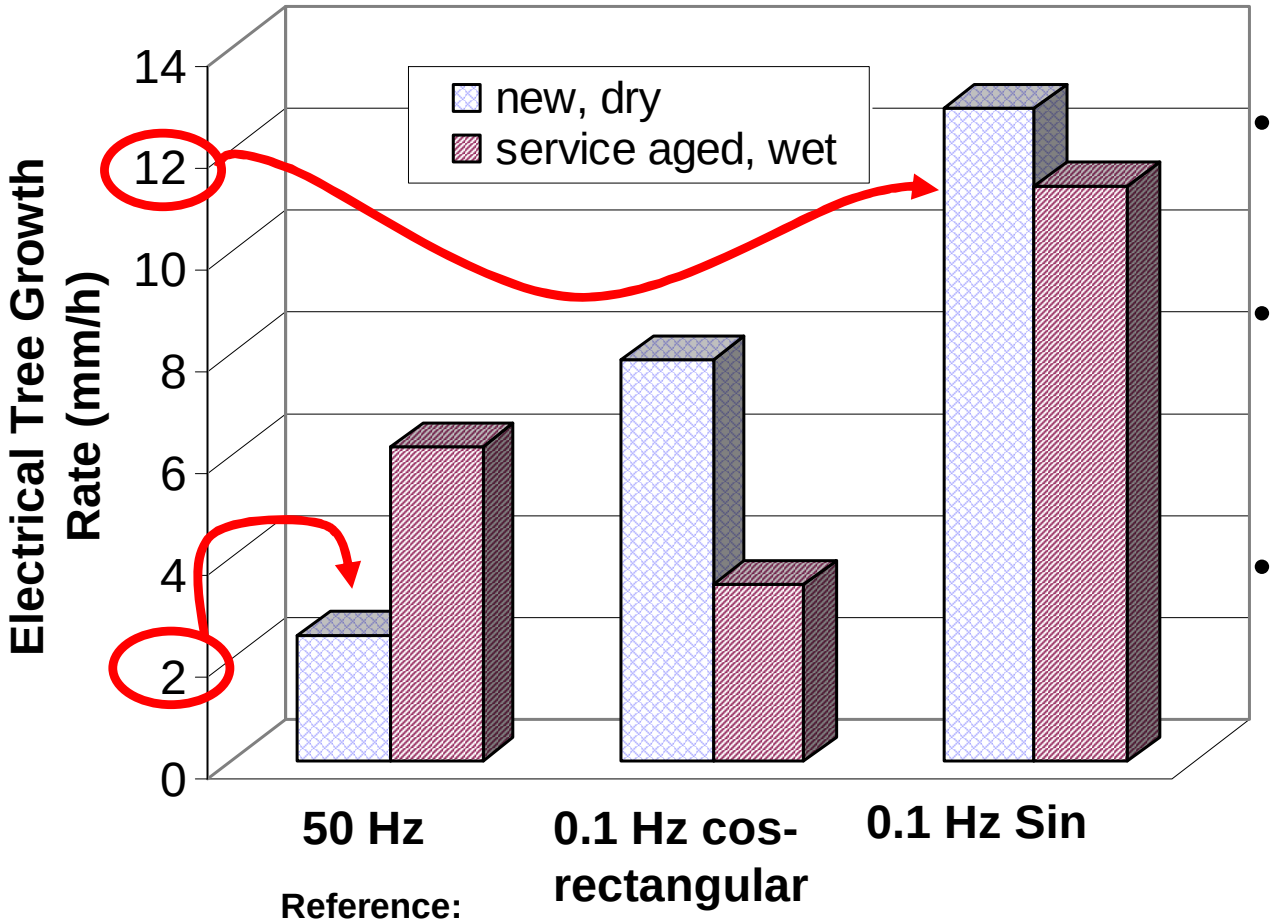
Please define gross!

VLF HIPOT

- Pros
  - Very portable source, w/ relatively low pwr. req.
  - Good HIPOT for conductive and high impedance defects
  - Does not induce as much space charge –no continued aging affects after test (.1Hz, AC)
  - Some defects grow rapidly –short test time
- Cons
  - Relatively short history of usage
  - Aggravates aged cable defects w/o failing
  - Standards recommend against use for aged cable w/multiple defects
  - Does not replicate service conditions or factory tests

VLF (0.1Hz) -A very good HIPOT

Electrical Tree Growth Rate vs. Voltage Waveforms
PD -Needle Point Fault at 3Uo



- VLF HIPOT can fail defects that DC cannot!
- VLF HIPOT is much more destructive than Pwr Frequency = better HIPOT
- Insulation/ Tree growth rate = test time? NO!

Reference:
Research and Development, Annual Report 1992, TU Berlin
High Voltage Institute
Prof. Dr.- Ing. Kalkner, Dipl. Ing. R. Bach

AC HIPOT

- Pros
  - Good HIPOT for conductive and high impedance defects
  - Does not induce space charge –no continued aging affects after test
  - Replicates steady state service conditions and factory HIPOT test
- Cons
  - Largest source, most costly, highest power requirements
  - Grows some defects slower than VLF HIPOT

General Condition Assessment
Numerous Types

Measurement of the overall insulation losses

- Dissipation Factor/Tangent Delta/Power Factor
  - 50/60 Hz
  - 0.1Hz (VLF)
- Dielectric Spectroscopy (Time and Freq. domain)
- Depolarization –Return Voltage (recovery voltage)
- Depolarization –Isothermal Relaxation Current
- Leakage Current –pA range
- Total Harmonic Distortion

General Condition Assessment

Pros

- Nondestructive
- Monitors overall condition during voltage application
- Effective at detecting & assessing conduction type defects
- Recommendations provide 3 categories

  Critically Aged, Moderately Aged (‘gray’ area), Like-new

General Condition Assessment

Cons

- Prior signature files of various cable types required
- Poor economic trade-off, All or nothing
- Large scale correlation studies 50-69% accuracy
- Highly temperature dependent in extruded cables
- Blind to high impedance defects (cuts and voids)
- Cannot find singular defect. (req. hundreds of w-trees in XPLE,EPR)
- Not effective with mixed dielectric cables
- Not effective as a commissioning test (no defect location)
- Not comparable with factory test standard (accessories)
- Req. analyst to interpret results
- Req. costly equipment compared to HIPOT equipment

Partial Discharge
3 Categories

- Off line various voltage supplies
- On line testing
  - Acoustic
  - Electromagnetic
- On line monitoring

Partial Discharge
In General

- Pros
  - Nondestructive
  - Only test to locate high-impedance defects
    (cuts, voids, e-trees, & tracking)
  - Can be performed on-line in limited applications
  - Effective at locating defects in mixed dielectric cables

- Cons
  - Limited cables with continuous metallic shield
    (time & frequency domain tests) –Tape shields
  - Trained analyst required
  - Cannot detect or locate conduction type defects
  - Branched networks are challenging

On-line Partial Discharge

Pros:

- Test w/o switching circuit out of service
- Detects & locates some accessory & few cable defects
- No external voltage source

On-line Partial Discharge

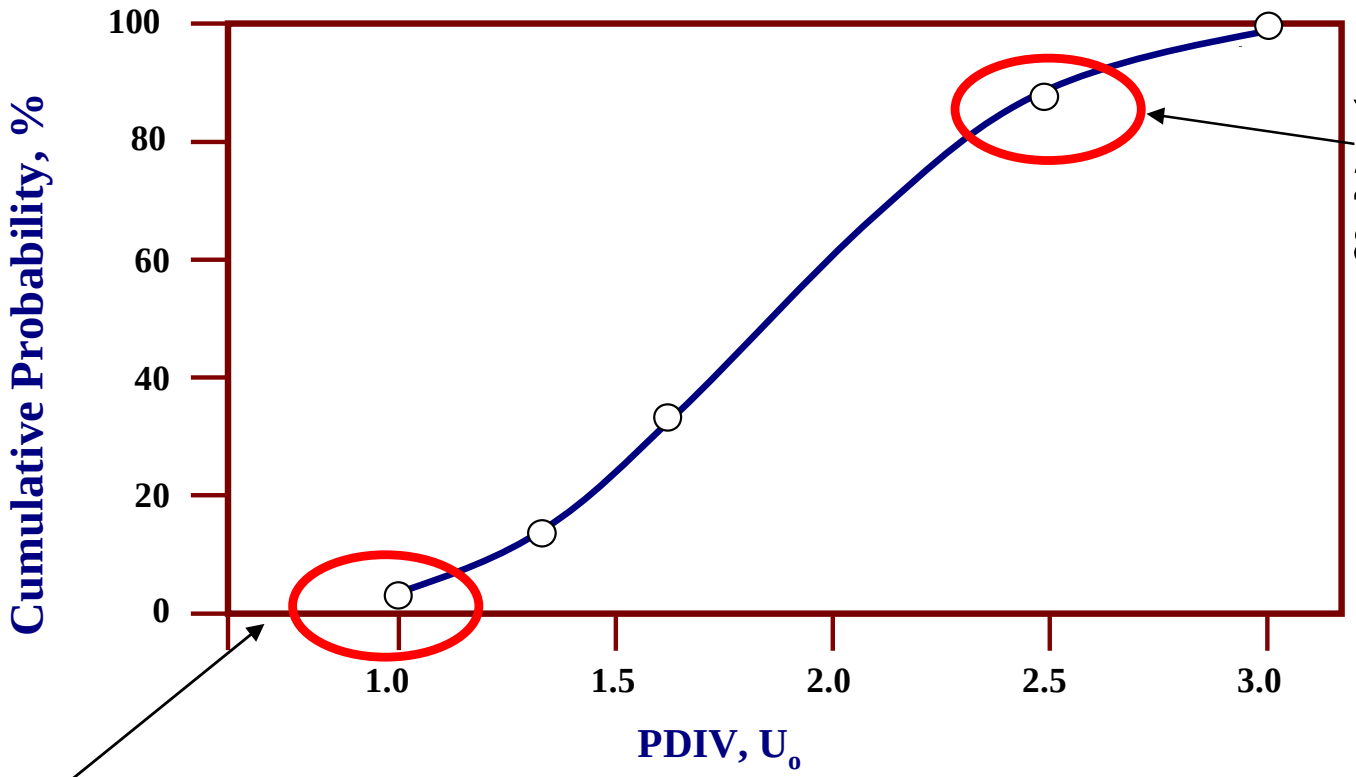
Cons:

- Detects ≤3% cable insul. defects -extruded cable*
- Test not calibrated; test results are not objective*
- Not comparable to factory tests/IEEE standards
- No large scale correlation field studies
- Cable length < few hundred ft (depends on cable construction)
- Manholes must be pumped
- Service only -equipment cannot be purchased
- No onsite report of the test results

***Refer to the following slides**

Cumulative Probability of PD vs. Voltage

1,555 miles of Extruded Cable



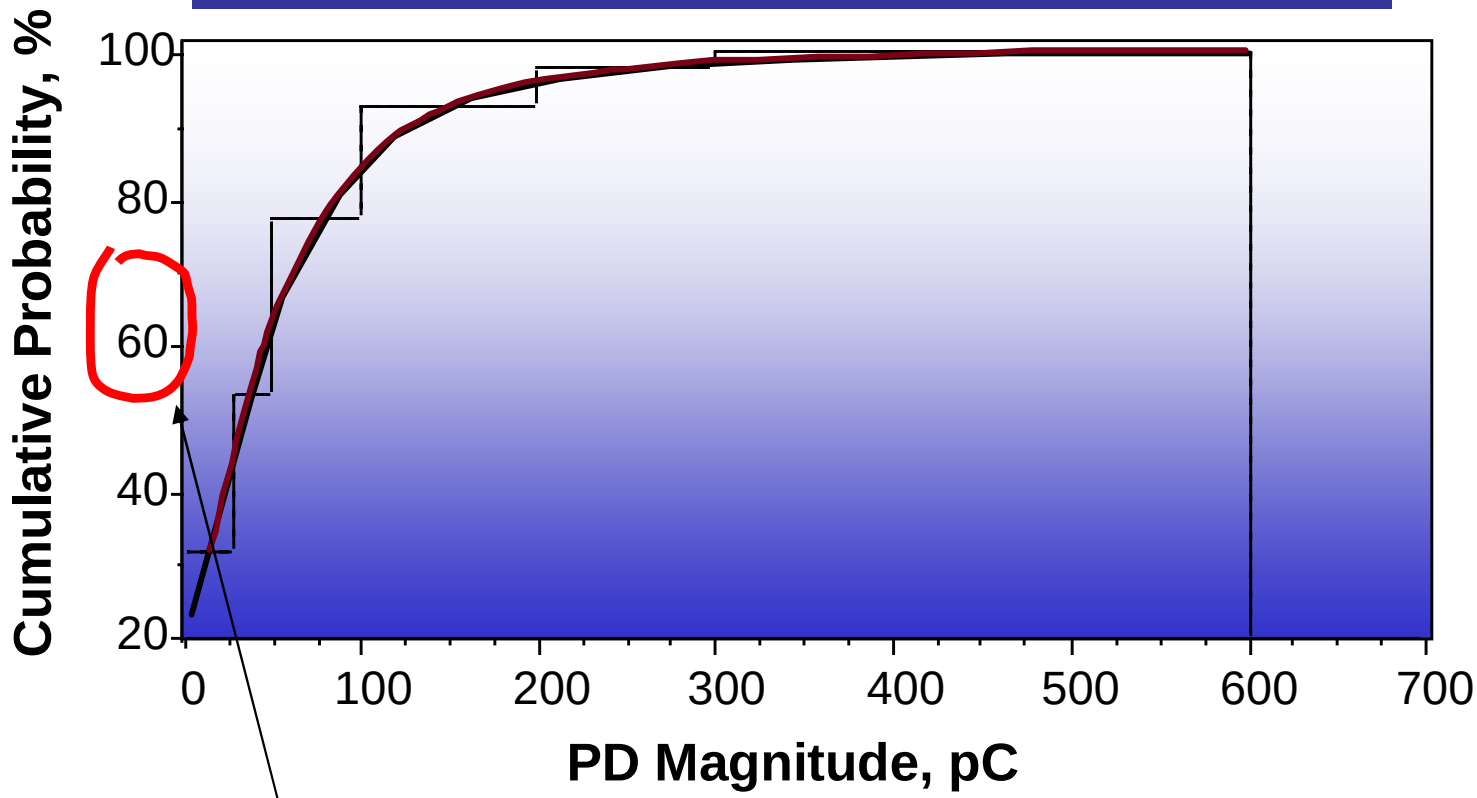
You must go to $2.5U_0$ to see 85% of the defects in cable!

DATA BASED ON 960 PD EVENTS IN CABLES

At 1.0 U_0, less than 3% of PD events can be identified.

Why should we calibrate?
Effect of Detection Sensitivity

Statistics based on 61 PD events in extruded cables



60% of all PDs in extruded material (XPLE and EPR) are below 50 pC!

Off-line Partial Discharge

Pros

- Proven nondestructive (4yr large scale field study)
- Replicates calibrated factory baseline tests
- Replicates steady state and transient operating conditions
- Locates all defects in one test from one cable end (parallel process)
- Indirectly locates large w-trees associated w/ e-trees
- Is proven to be highly accurate (Large scale correlation studies 85-95%)
- Test up to 1 to 3 miles (depends on cable construction)
- Monitors cable insulation response during voltage app.
- Effective with mixed dielectric cable
- Backed by IEEE 400 as most effective test (60Hz Off-line PD)
- Equipt. can be purchased & operated by utility personnel
- Provides onsite test results

Off-line Partial Discharge

- Cons
  - Cable must be taken off-line
  - Equipment costly compared to HIPOT equipment

Test Comparison Chart

		Defect											
			Cable		Accessories								
	Predictive	Location	Moisture/ Conduction	Cut/ Void/ Tracking	Moisture/ Conduction	Cut/ Void/ Tracking	Factory Test Comparable	Fast Test	Onsite Report	Non- Destruct	No Outage	Low Skill Req.	Inexpensive Equipment
DC HIPOT			X		X							X	X
VLF HIPOT			X	X	X	X		X				X	X
PWRFRQ HIPOT			X	X	X	X	X					X	
On-line PD	X	X				X				X	X		
GCA	X		X		X			X	X	X			
Off-line PD	X	X		X		X	X	X	X	X			
GCA & Off-line PD	X	X	X	X	X	X	X	X	X	X			

Key
GCA =General Condition Assessment
PD = Partial Discharge
HIPOT= High Potential Withstand
VLF = Very Low Frequency voltage source (0.1Hz)
PWRFRQ = Power Frequency (20-80Hz)

Application of Standards

IEEE 400

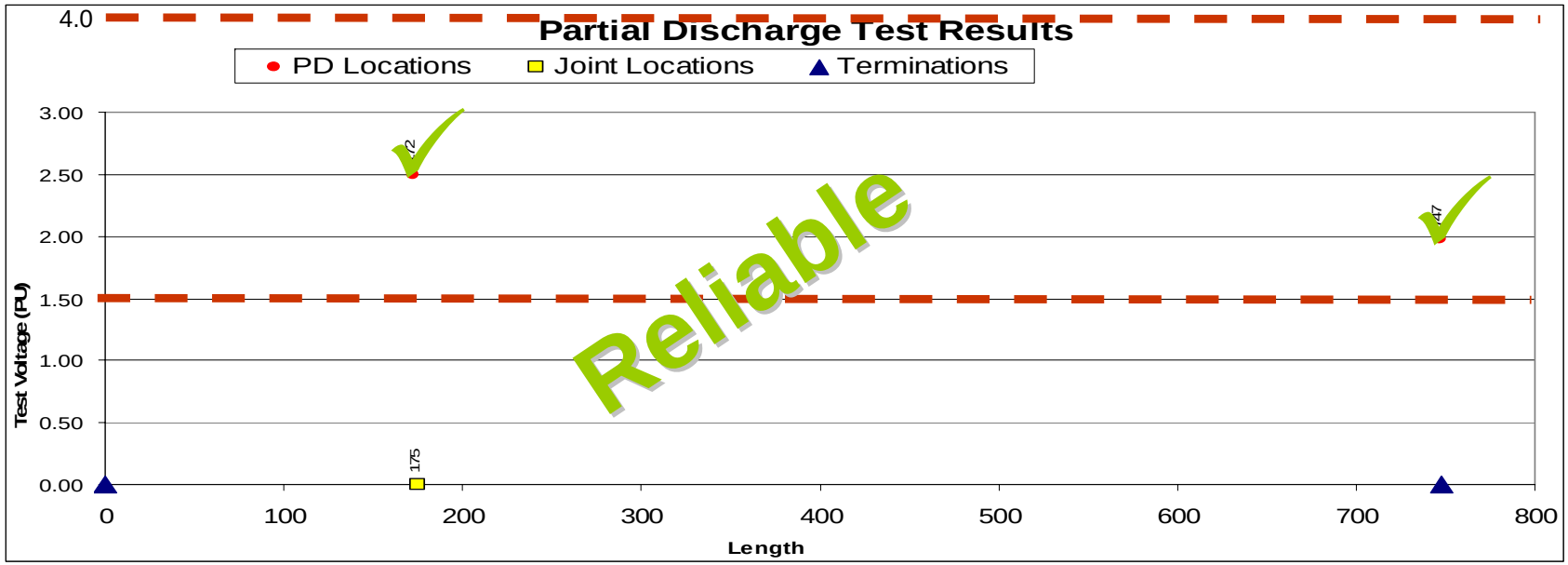
Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems

"if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition".

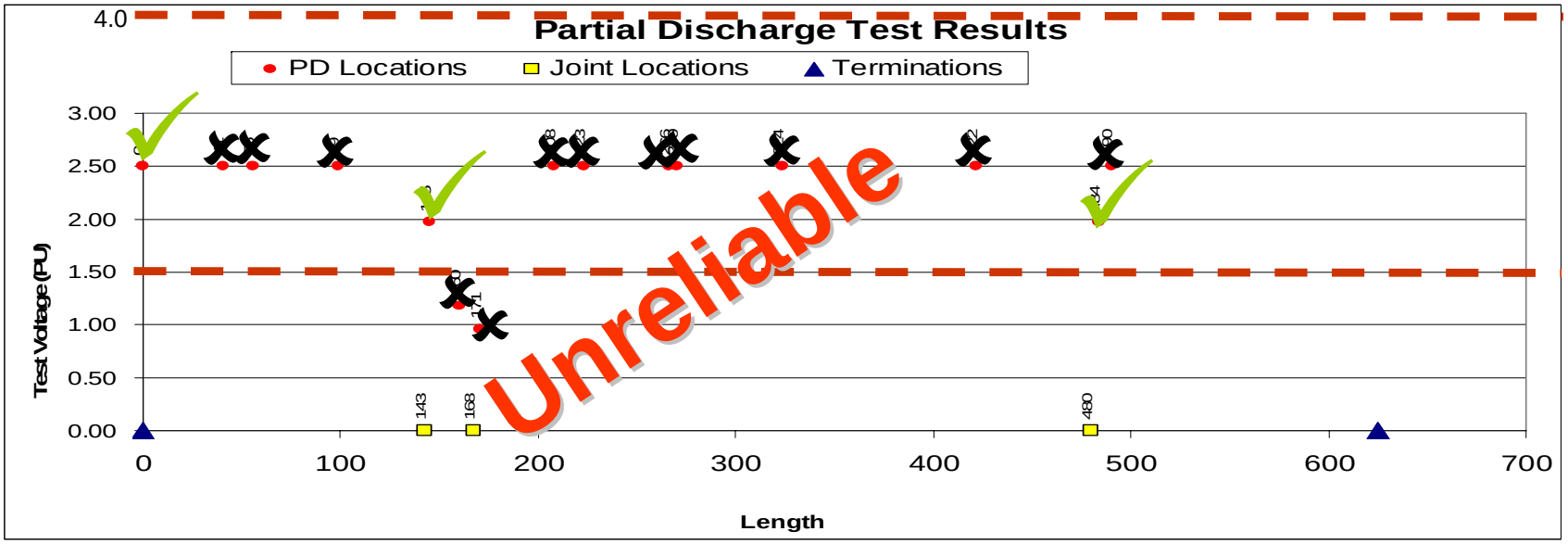
IEEE 48 Terminations	No PD ≥ 5pC up to 1.5Uo
IEEE 404 Joints	No PD ≥ 3pC up to 1.5Uo
IEEE 386 Separable Connectors	No PD ≥ 3pC up to 1.3Uo
ICEA S-94-649 MV Extruded Cable	No PD ≥ 5pC < 4Uo

Example Test Report –Unreliable vs. Reliable

Case 1



Case 2



60Hz Offline PD Diagnostic Test

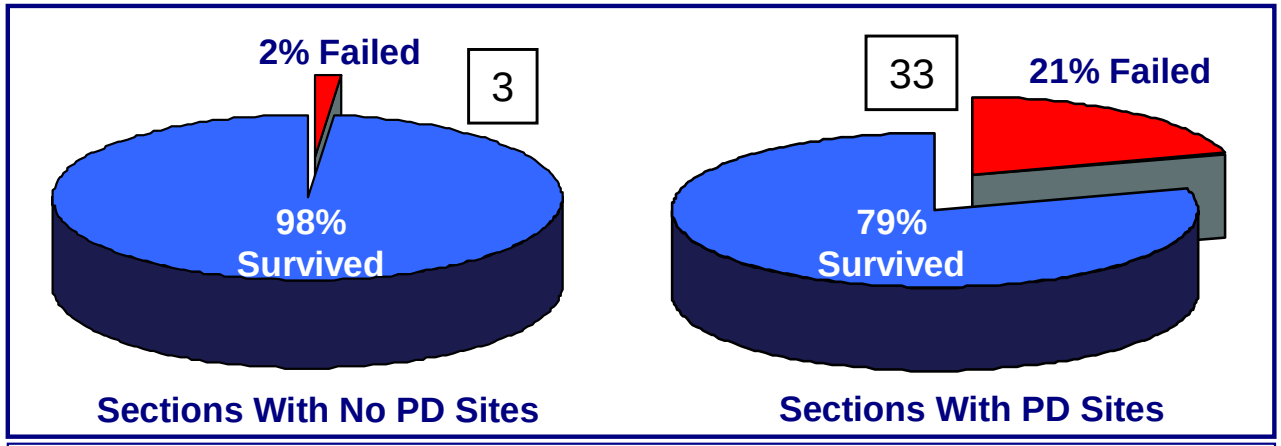
Case Studies

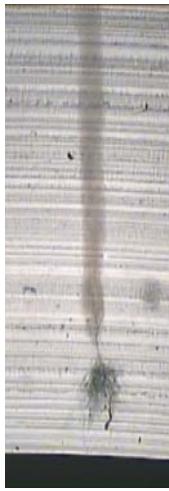
60Hz Off-line PD Diagnostics

Effective, Nondestructive, Asset Prioritization Tool

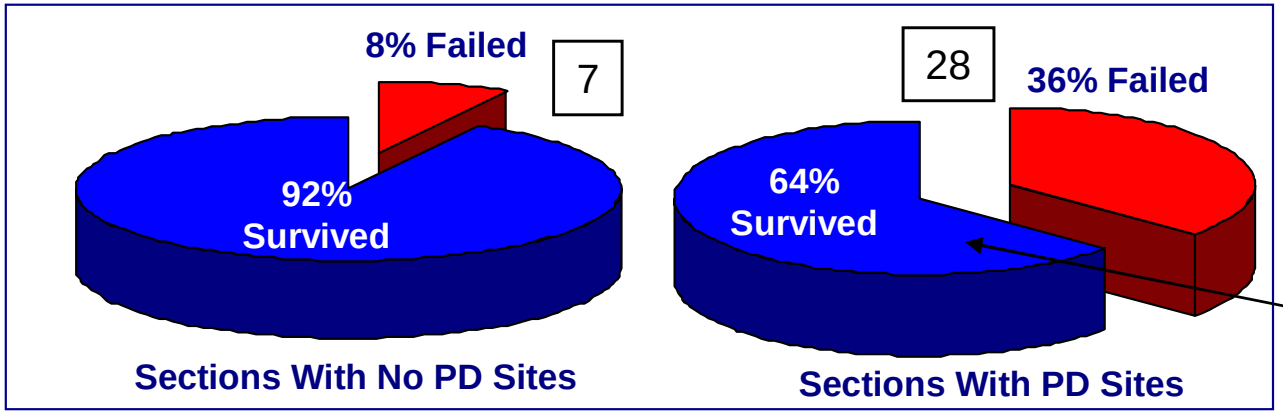
151, 30 yrs old,15&25kV (twice failed) feeder cables observed for 3 yrs
51% w/o PD, 49% w/o PD, All returned to service
Each cable tested 2.0 or 2.5Uo every year

After 1.5-Year Service





After 3-Year Service



12/12 samples have significant e-tree activity

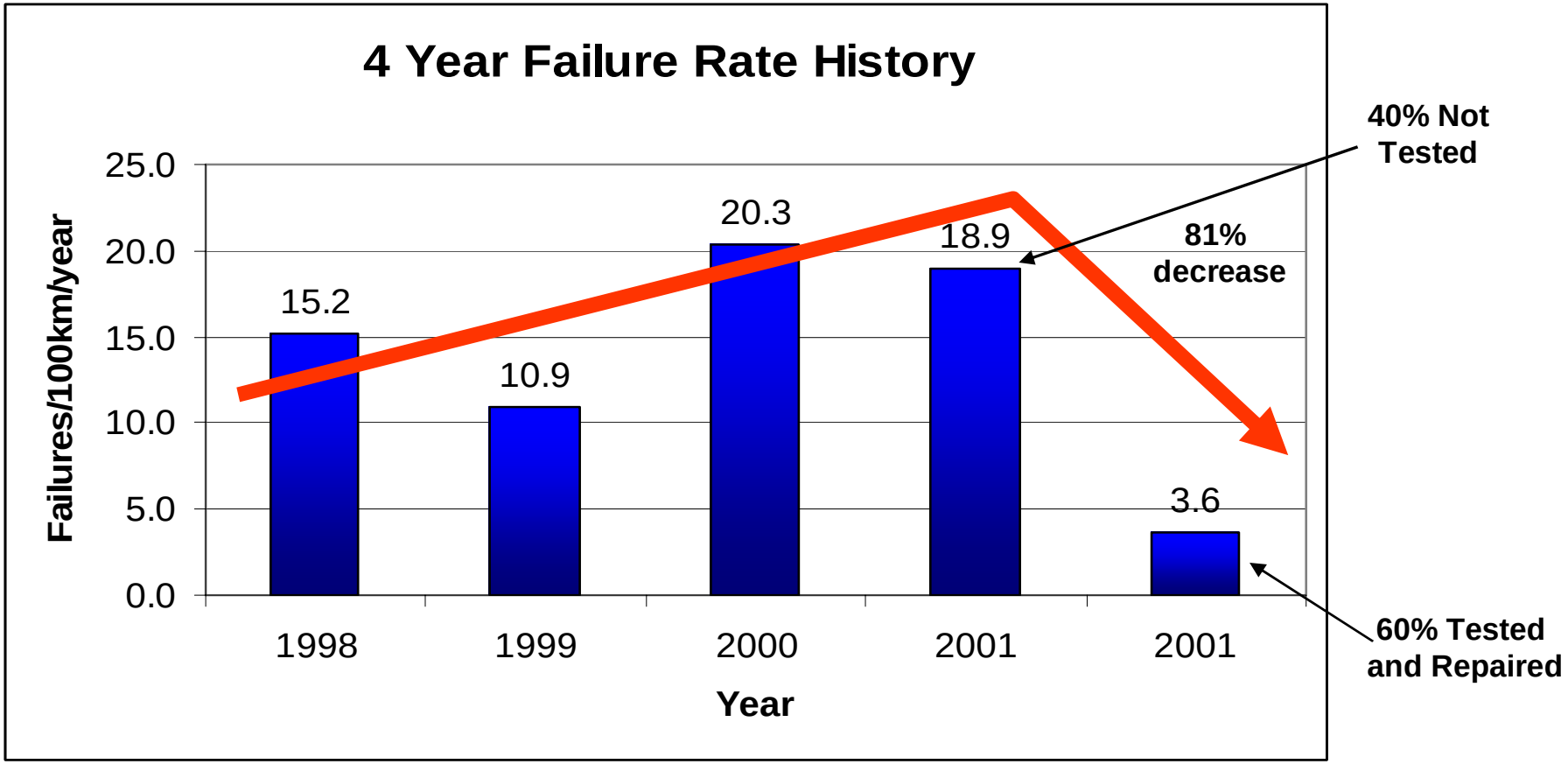
Assuming avg. length of 1100ft ~33miles - Failures/100miles/yr

Data supplied by utility

60Hz Off-line PD Diagnostics

Improve Reliability at the Lowest Cost

- 276km PILC Cable Tracked (control)
- 170km PILC Cable Tested and Repaired (experimental)



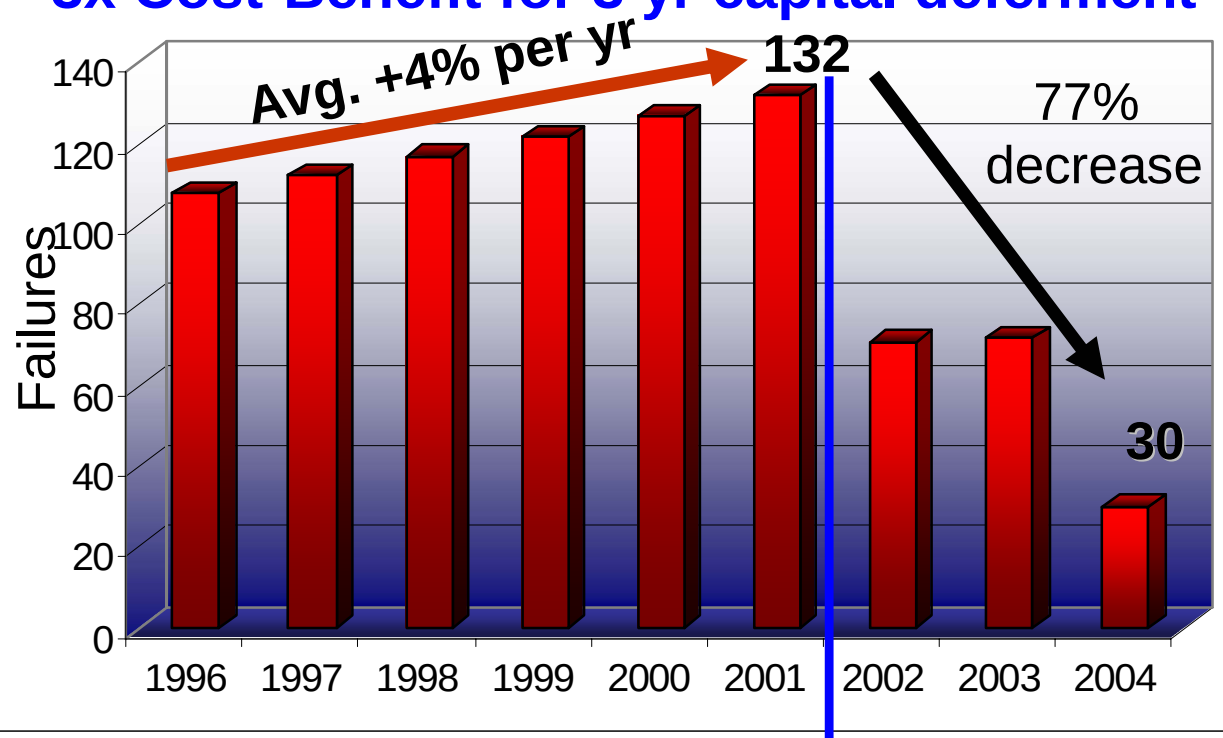
Data supplied by utility

60Hz Off-line PD Diagnostics

Improve Reliability at the Lowest Costs

On the basis of 430 miles of 30 yr old extruded feeder cable

Same budget, 14% of Cables Replaced
77% less failures,
3x Cost-Benefit for 3 yr capital deferment*



Replace based on failure history and age

Repair/Replace based testing

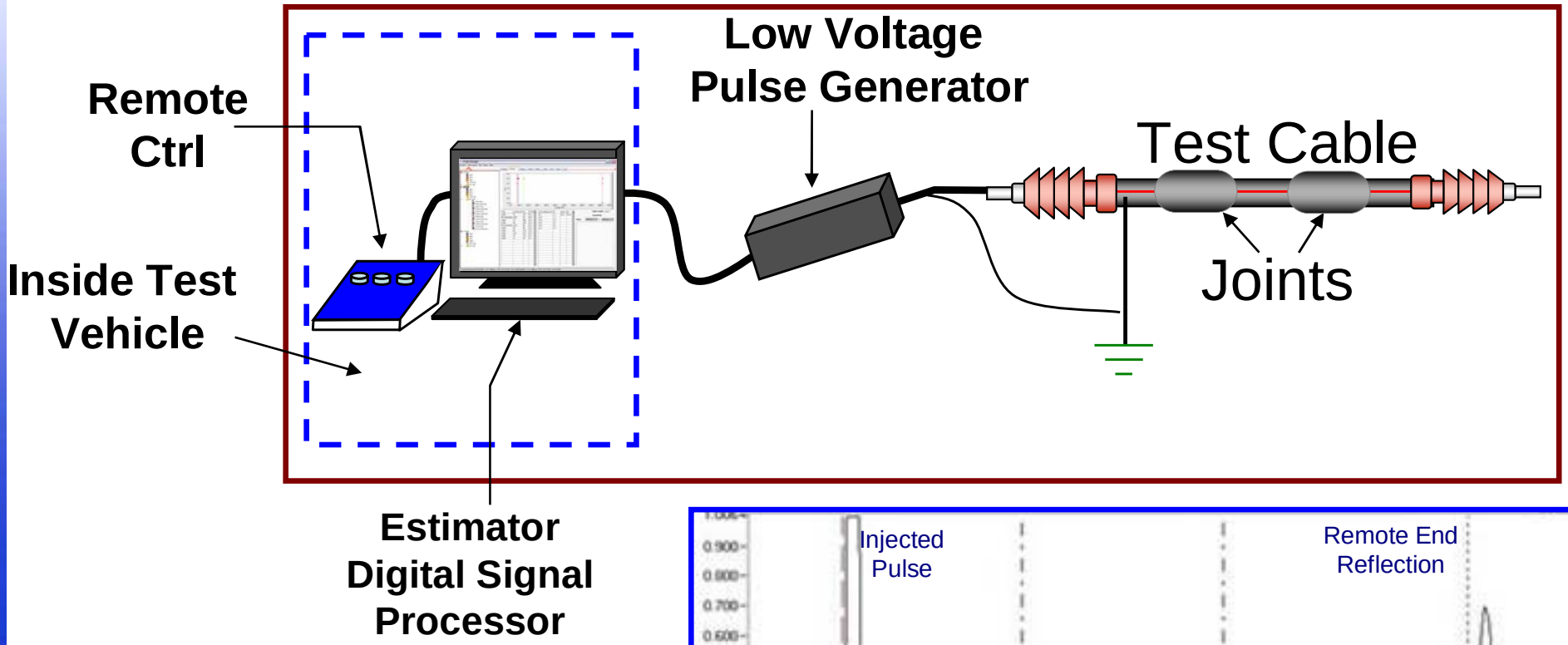
Data supplied by utility

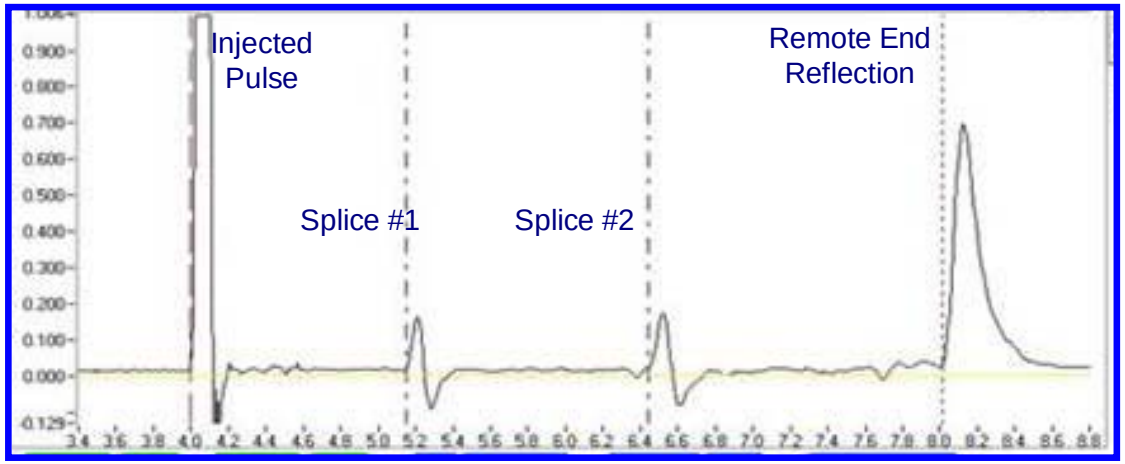
*Not including 38% tax rate!

PD Test Procedure (~ 90 minutes)

1. Cable Mapping (TDR)
2. Sensitivity Calibration
3. Diagnostic Stress Test
4. Signal Data Analysis
   - Location of PD sources
   - Determination of severity
5. Report appropriate recommendations **ON SITE!**
   - Cable clean to highest test voltage
   - Repair at specific location/section
   - Replace cable
   - Retest in 3-5 years

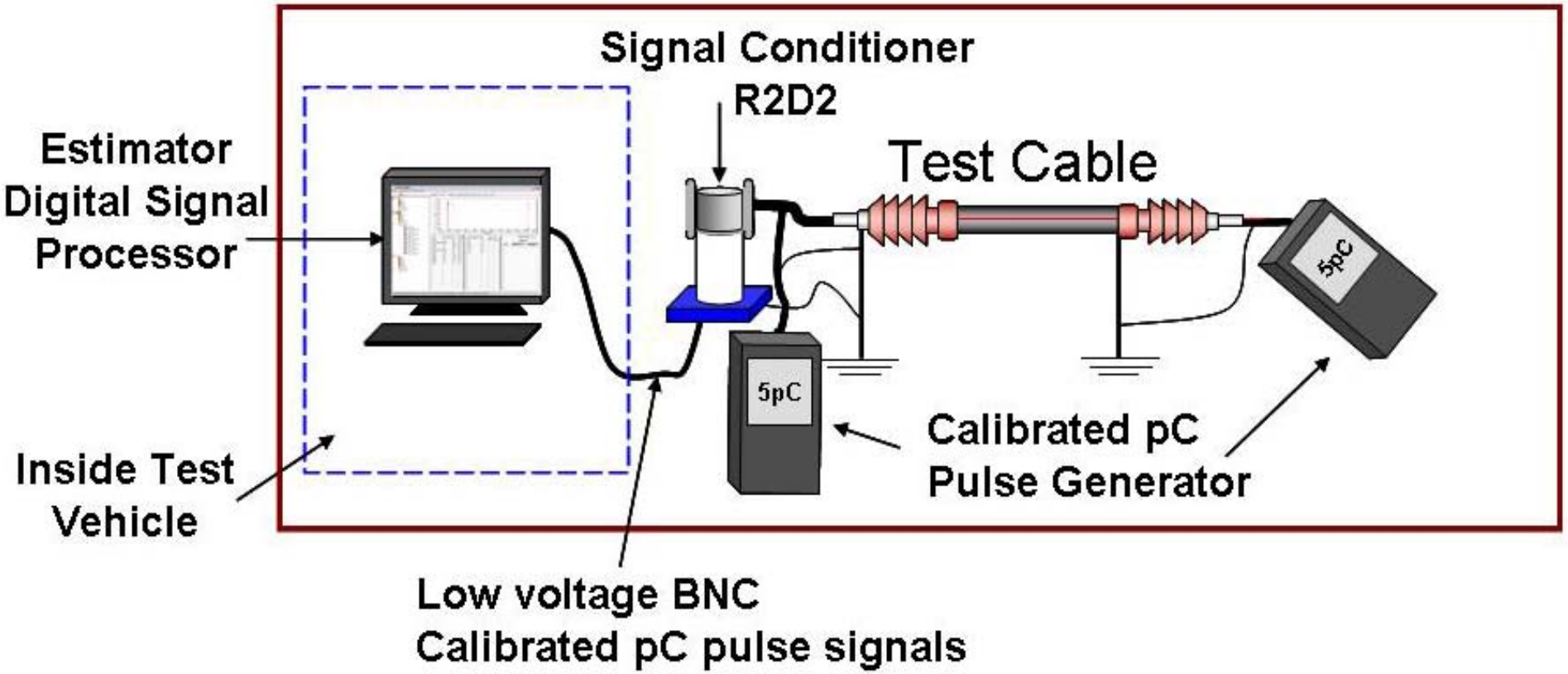
Step 1:
Low Voltage Cable Mapping (2-8V)





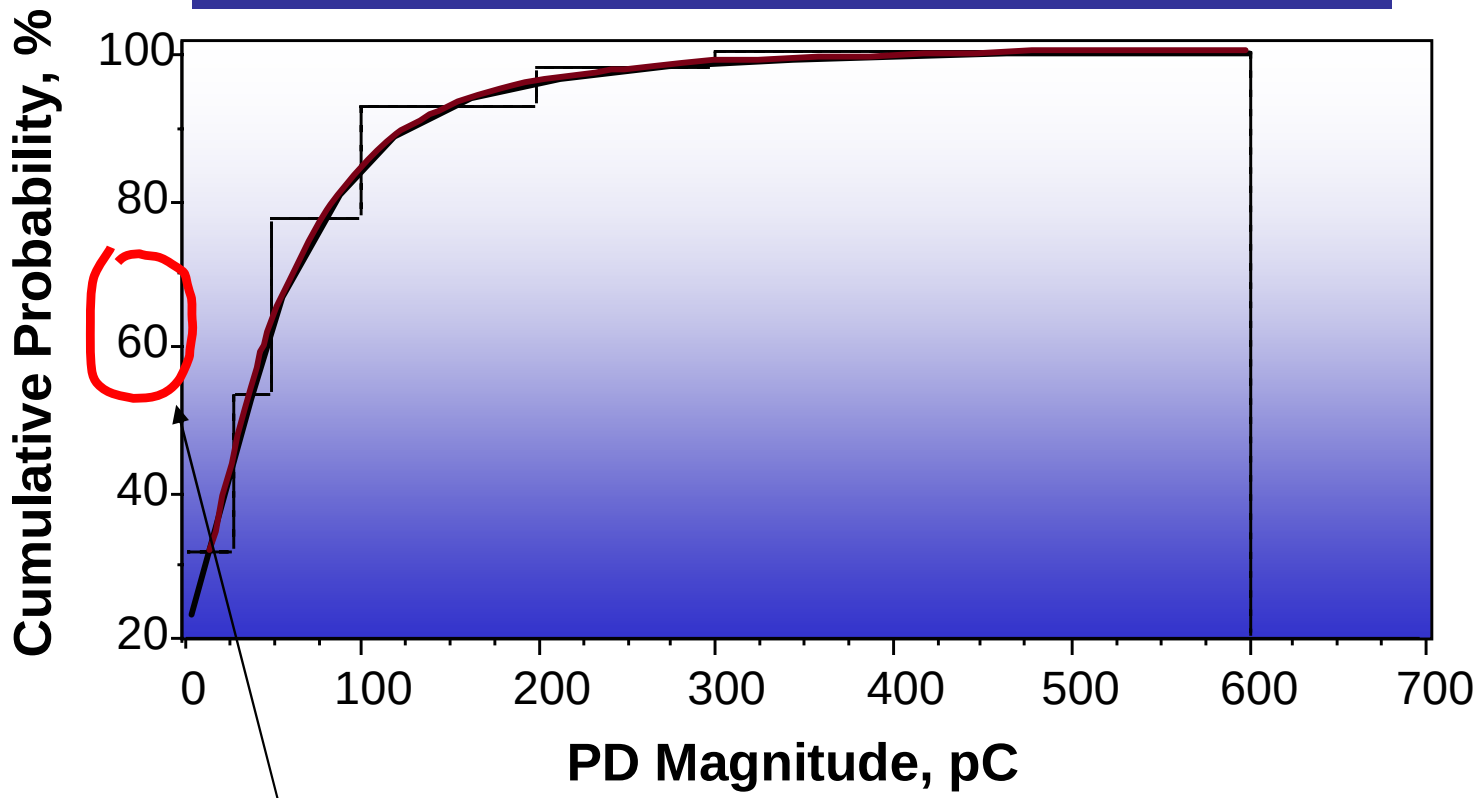
- Cable Length
- Splice location
- Neutral corrosion location

Step 2: Sensitivity Calibration



Why should we calibrate?
Effect of Detection Sensitivity

Statistics based on 61 PD events in extruded cables



60% of all PDs in extruded material (XPLE and EPR) are below 50 pC!

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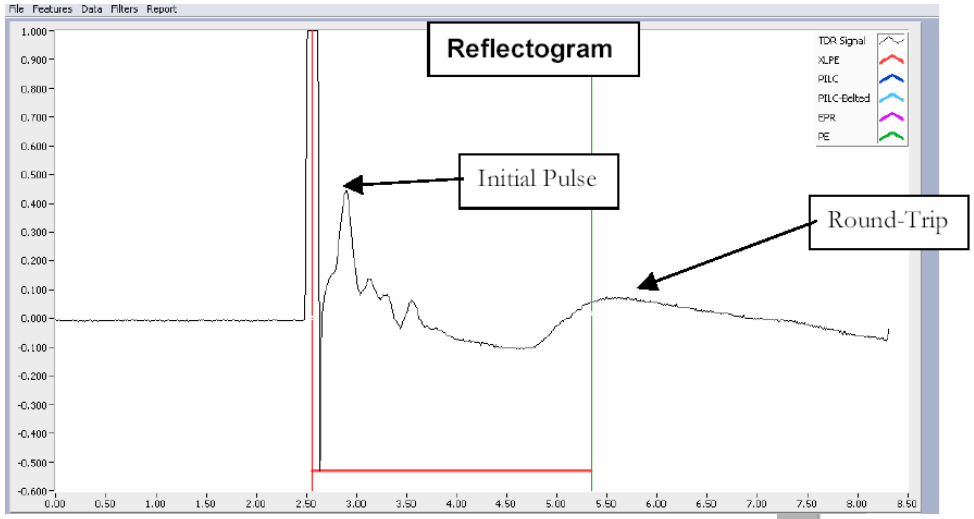
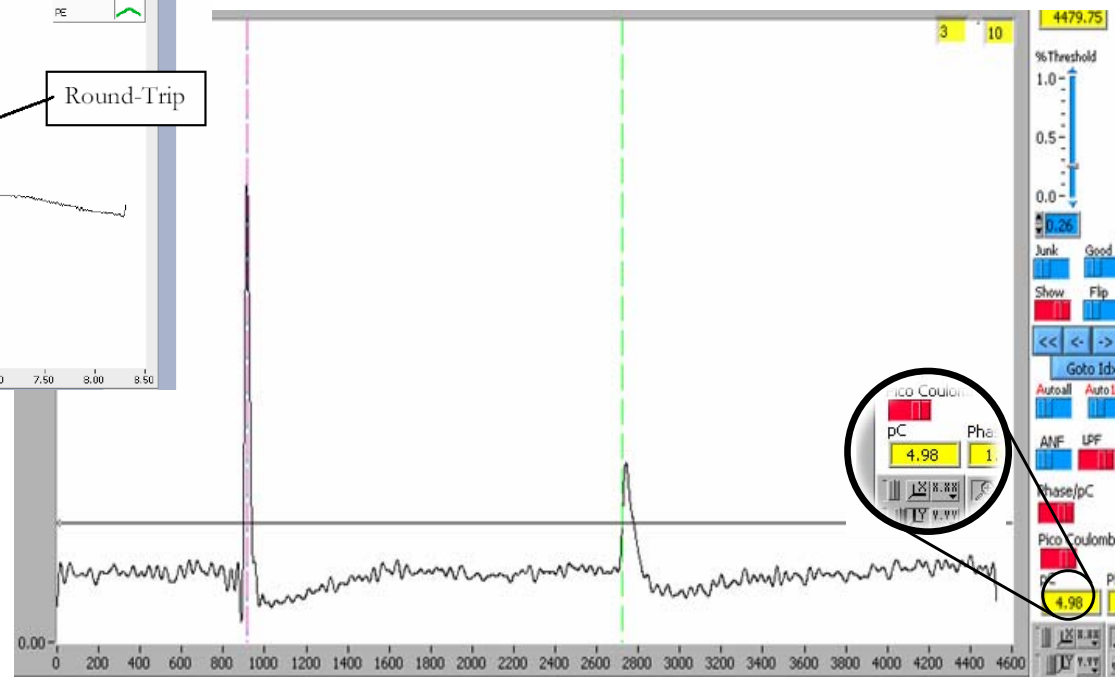
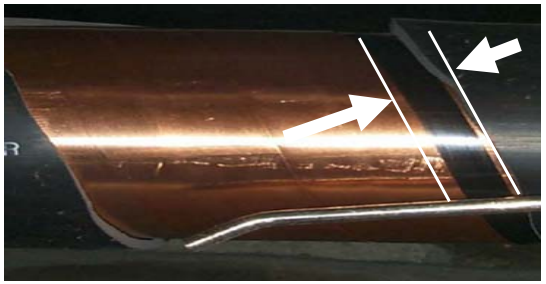
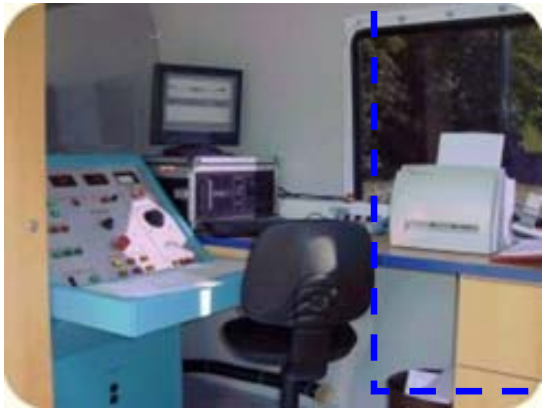
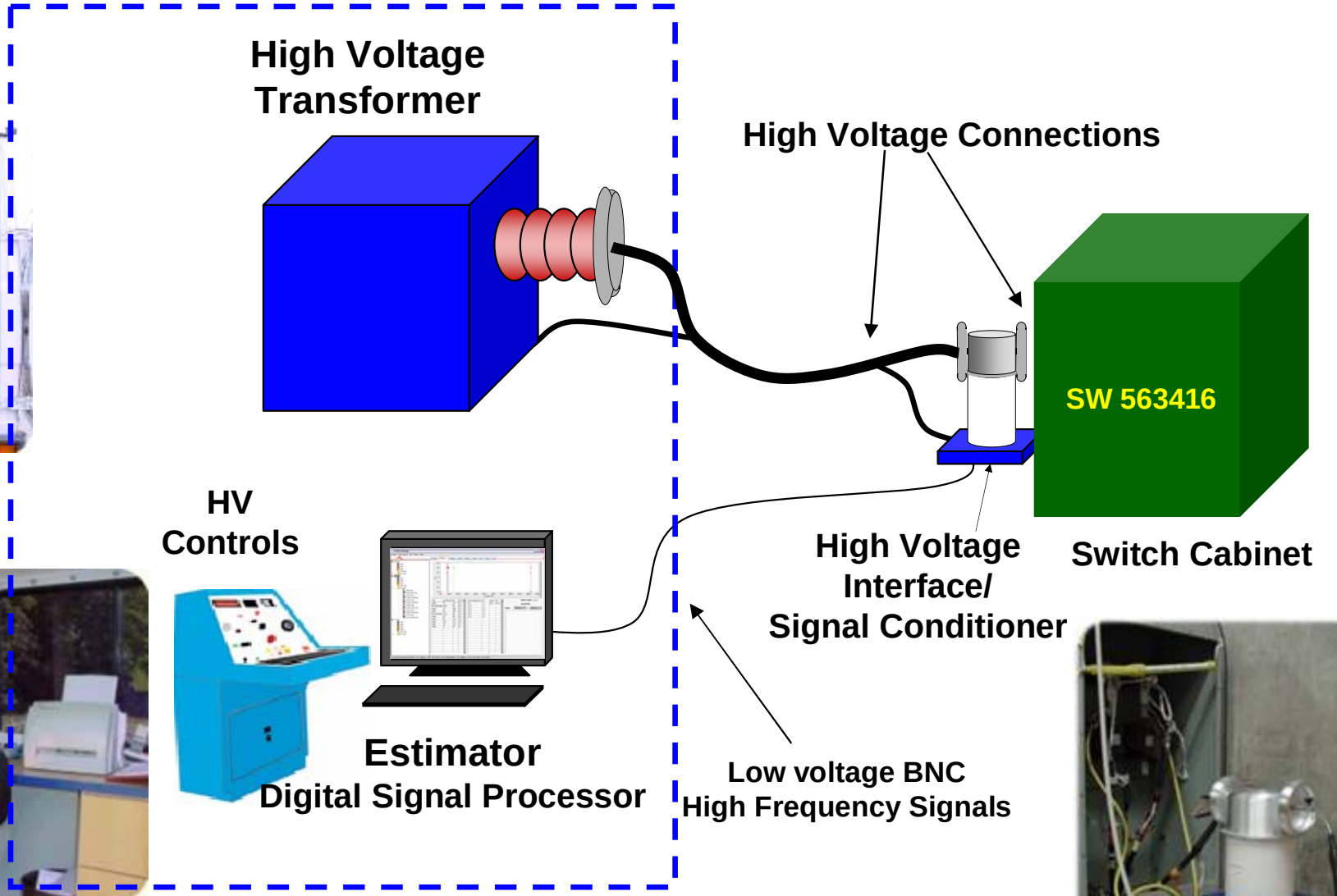






Step 3: Diagnostic Stress Test

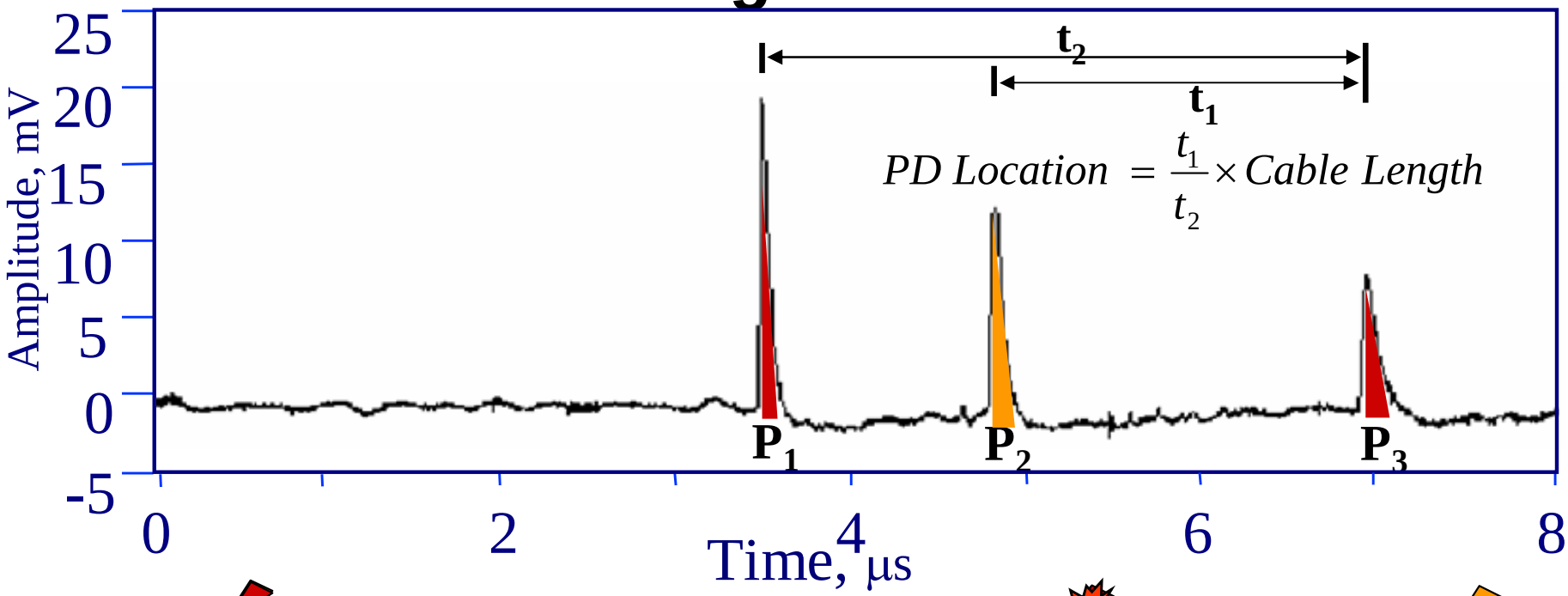


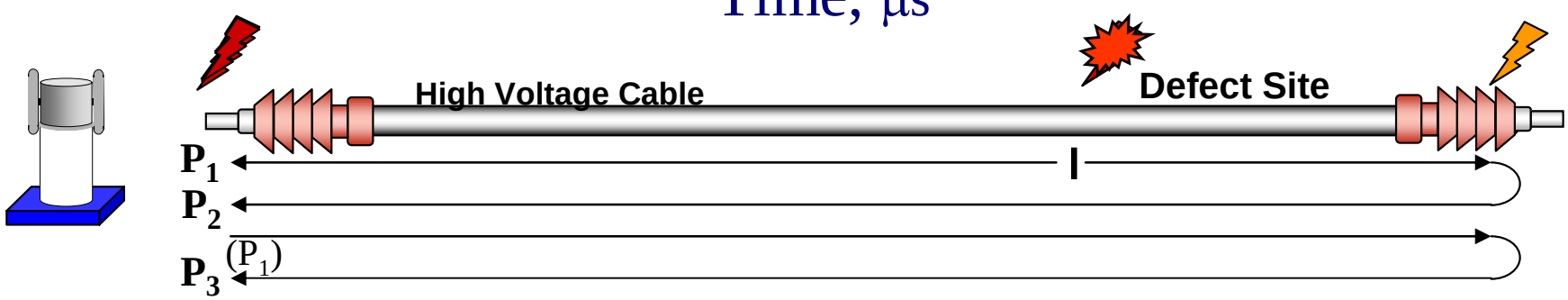


Defect Location

Time Domain Reflectometry

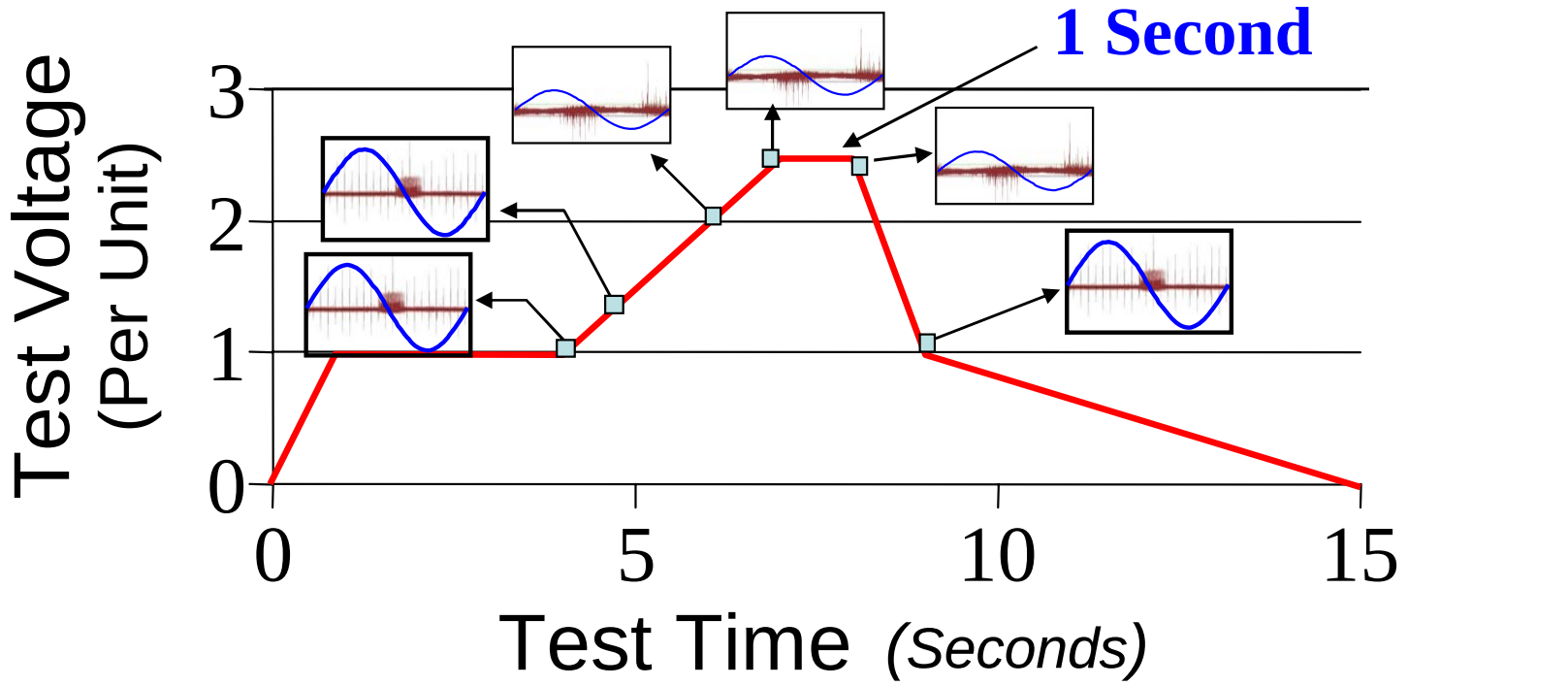
Partial Discharge Waveform Pattern





Step 4:
One-step Diagnostic Data Capture

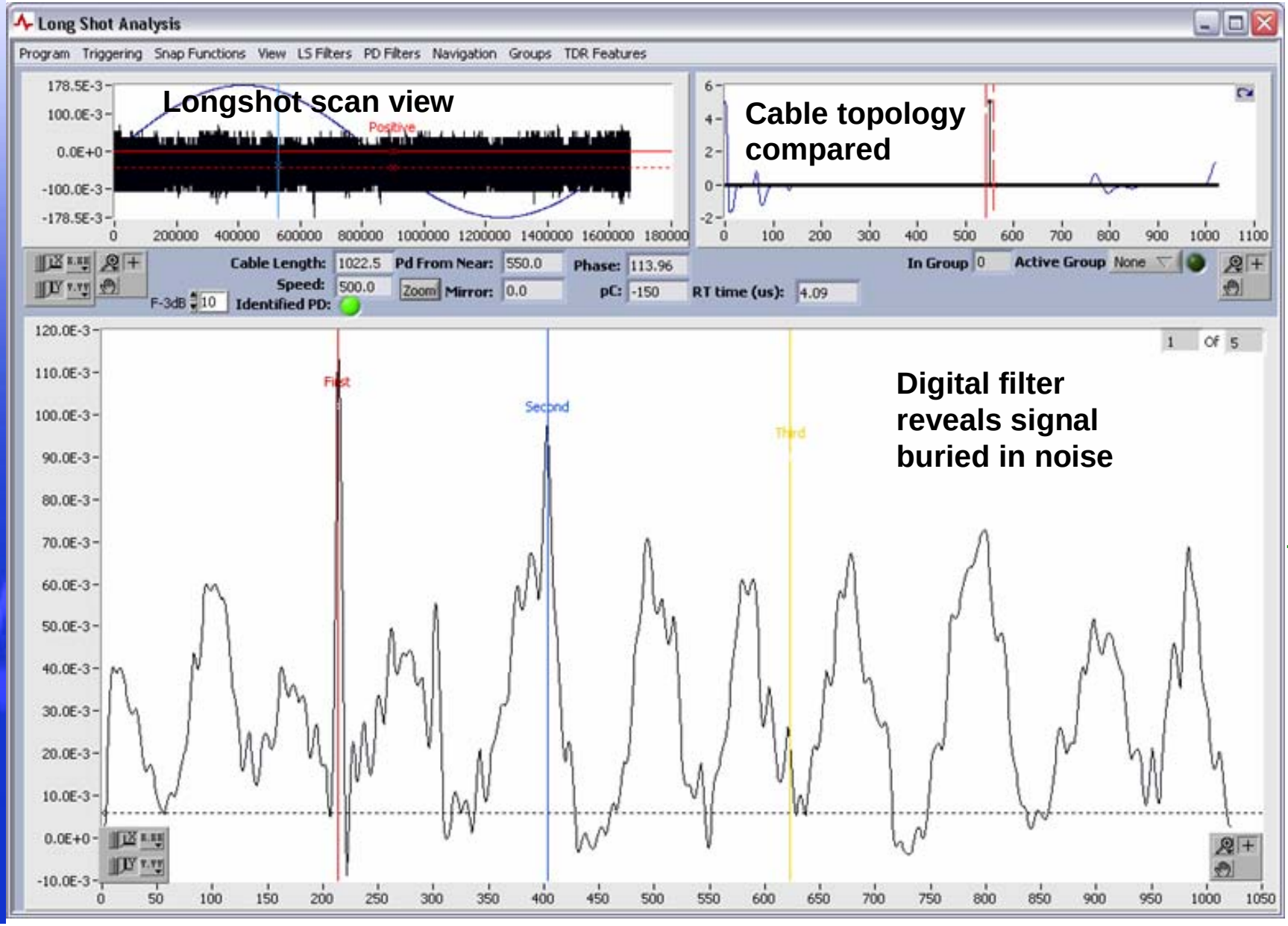
Voltage-time profile using “Longshot” technology



Diagnostic data captured via continuous recording 1-16 cycles

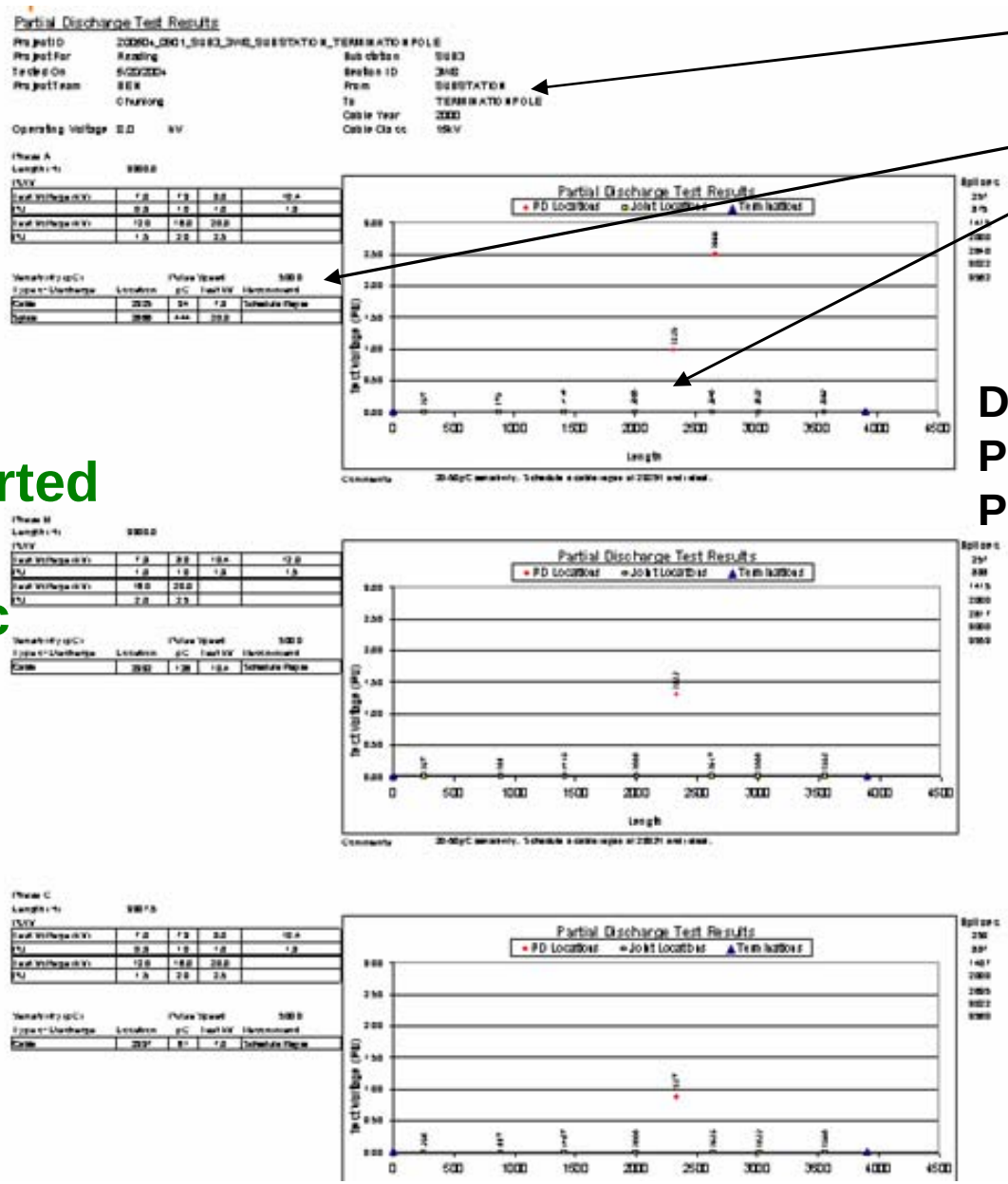
Less dwell time means
- **fewer in test failure**
- **more non-distructive**

Signal Analysis
Continuous Recording Method (Longshot)



Result exported to Microsoft Excel® and Database

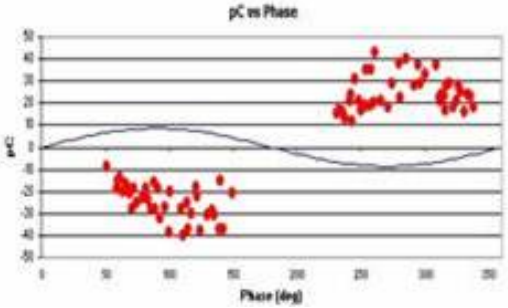
Step 5: Typical Test Report
(presented on site)



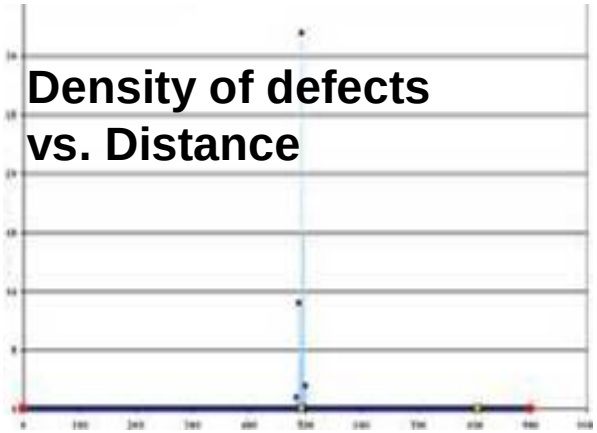
Test Summary
- Cable Information
- Recommendations
- Simplified defect & topology information map

Data imported from Diagnostic Software

Defect Phase Pattern



Density of defects vs. Distance

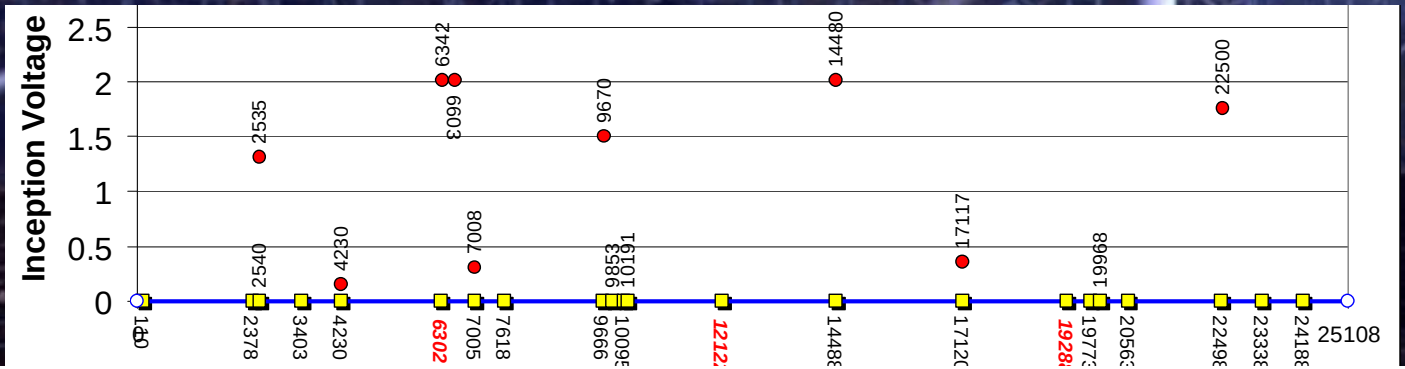


Comparison Case Studies

DC HIPOT vs. Offline 60Hz Offline PD

New Extruded Cable System

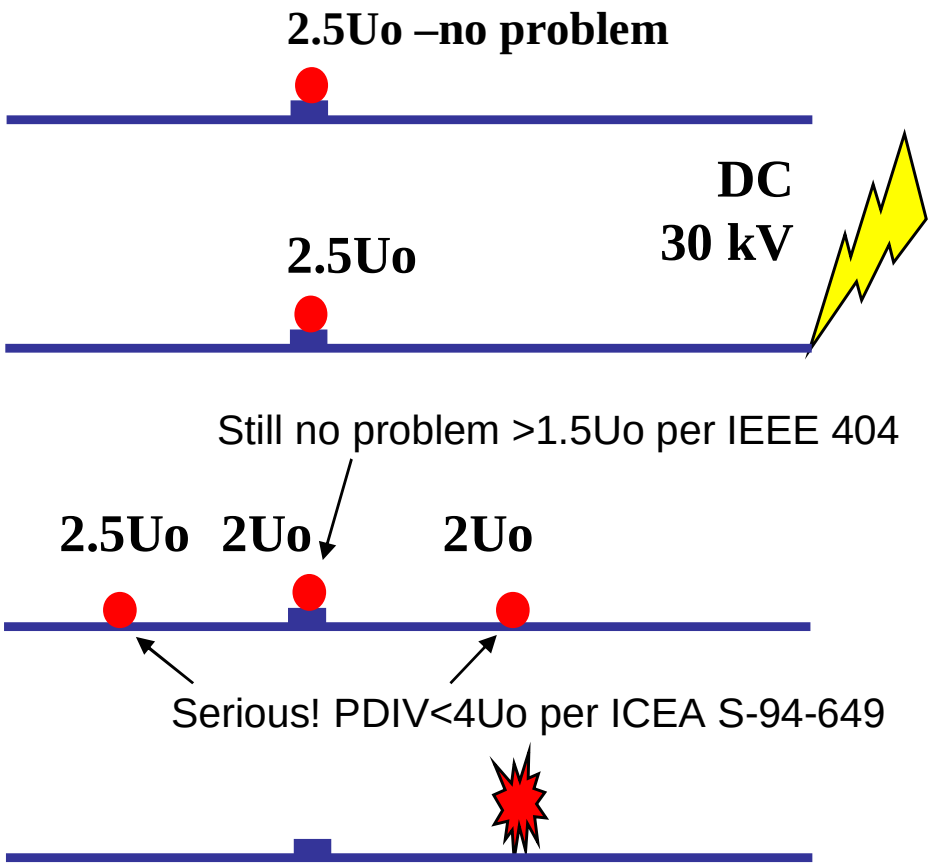
- 300MW Wind Plant commissioned with 150 miles of cable installed
- DC HIPOT performed on all cables -passed
- Failures start occurring 3/month for one year
- Failures in excess of $3million in repairs
- After PD testing and repairs one failure in two years.



DC HIPOT vs. 60Hz Off-line PD

Aged XPLE Cable Case

- PD Test -2.5Uo Splice
- DC Test -30kV, 5 min.
- Re-tested
  - Splice PDIV Dropped to 2Uo
  - New Cable PD at 2 and 2.5Uo
- Re-energized
- In one month, cable failed at 2Uo location



VLF HIPOT vs. Off-line PD

EPR Insulated

- Cables Tested with VLF HIPOT
- All cables passed HIPOT Test
- Cable Tested with PD Diagnostic System
- One phase failed to pass /ICEA S-94-649 PD at 0.25Uo<<4Uo!
- Cable defect located -nearly faulted defect
- New cable test on the reel and after installation
- Retest showed that new cable was defect free

Example: jacket and outer semicon layer stripped during installation

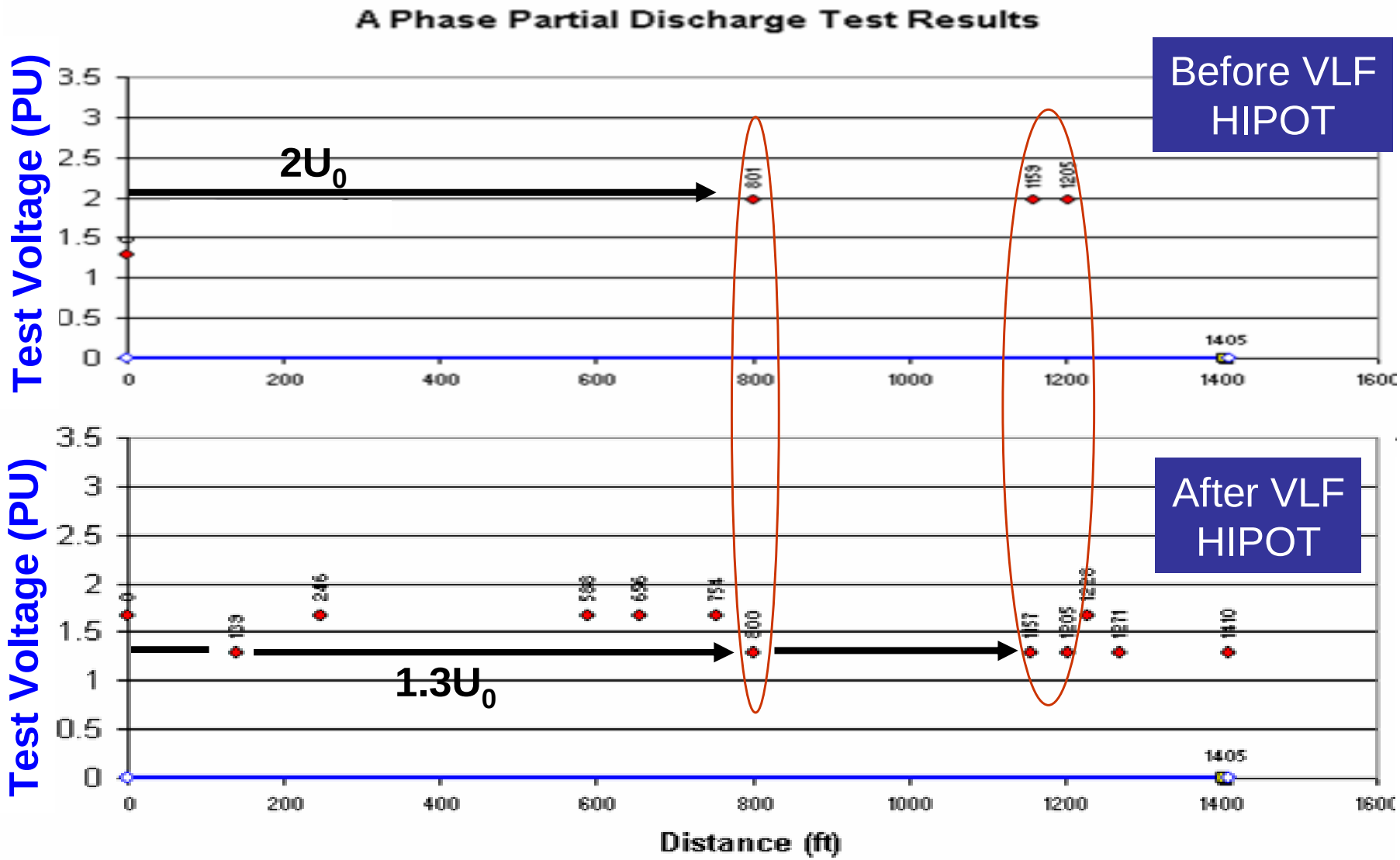
VLF HIPOT vs. 60Hz Off-line PD–XLPE

- PD test performed on cable
- VLF 40kV$_{pk}$ 30min* HIPOT performed
- A phase survived 31mins
  - B phase failed after 20mins
  - C phase failed after 37mins (no faliure in 30mins)
- PD test repeated

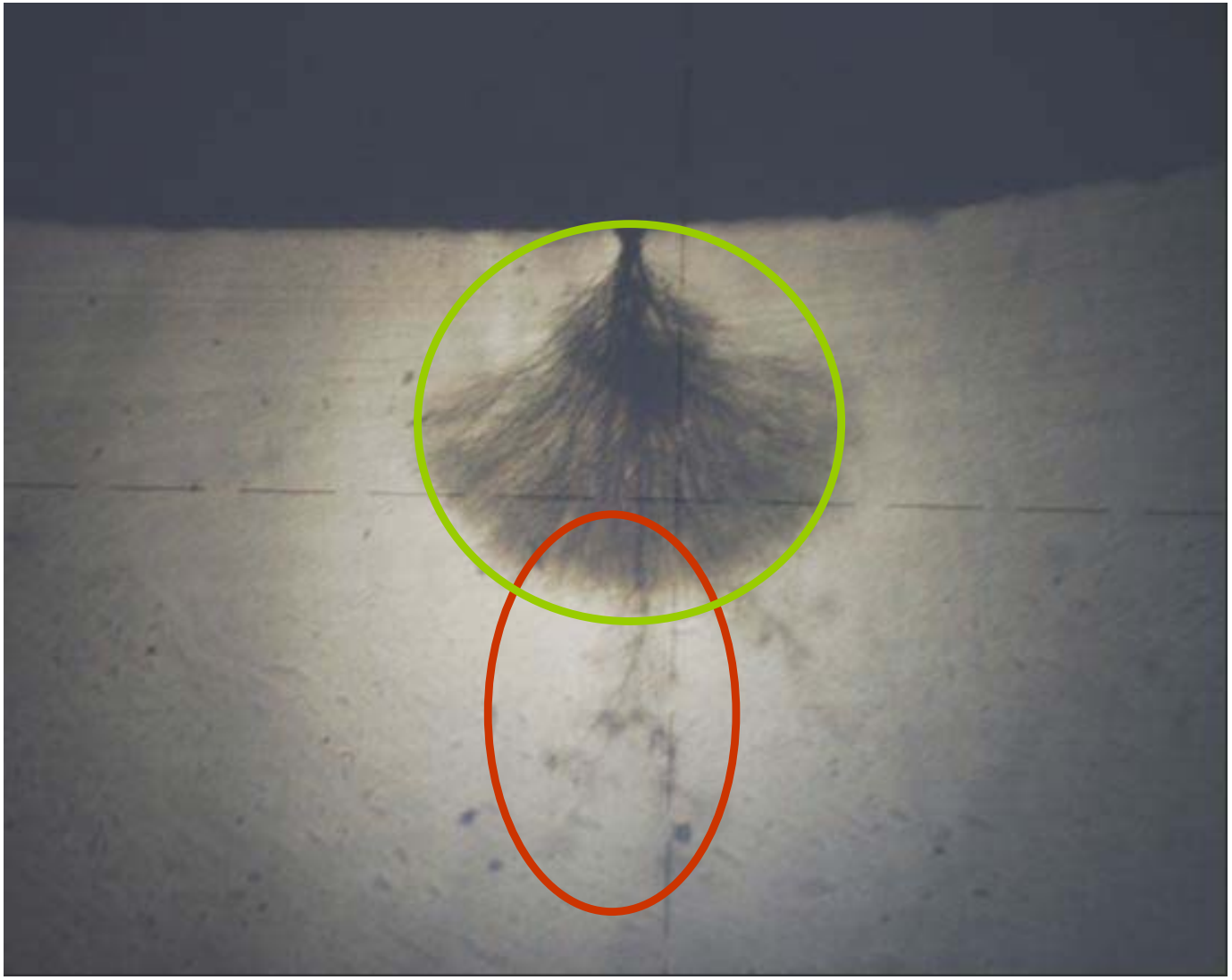
*Manufacturer's recommendation on the basis of IEEE 400.2

VLF HIPOT vs. 60Hz Off-line PD

The Results



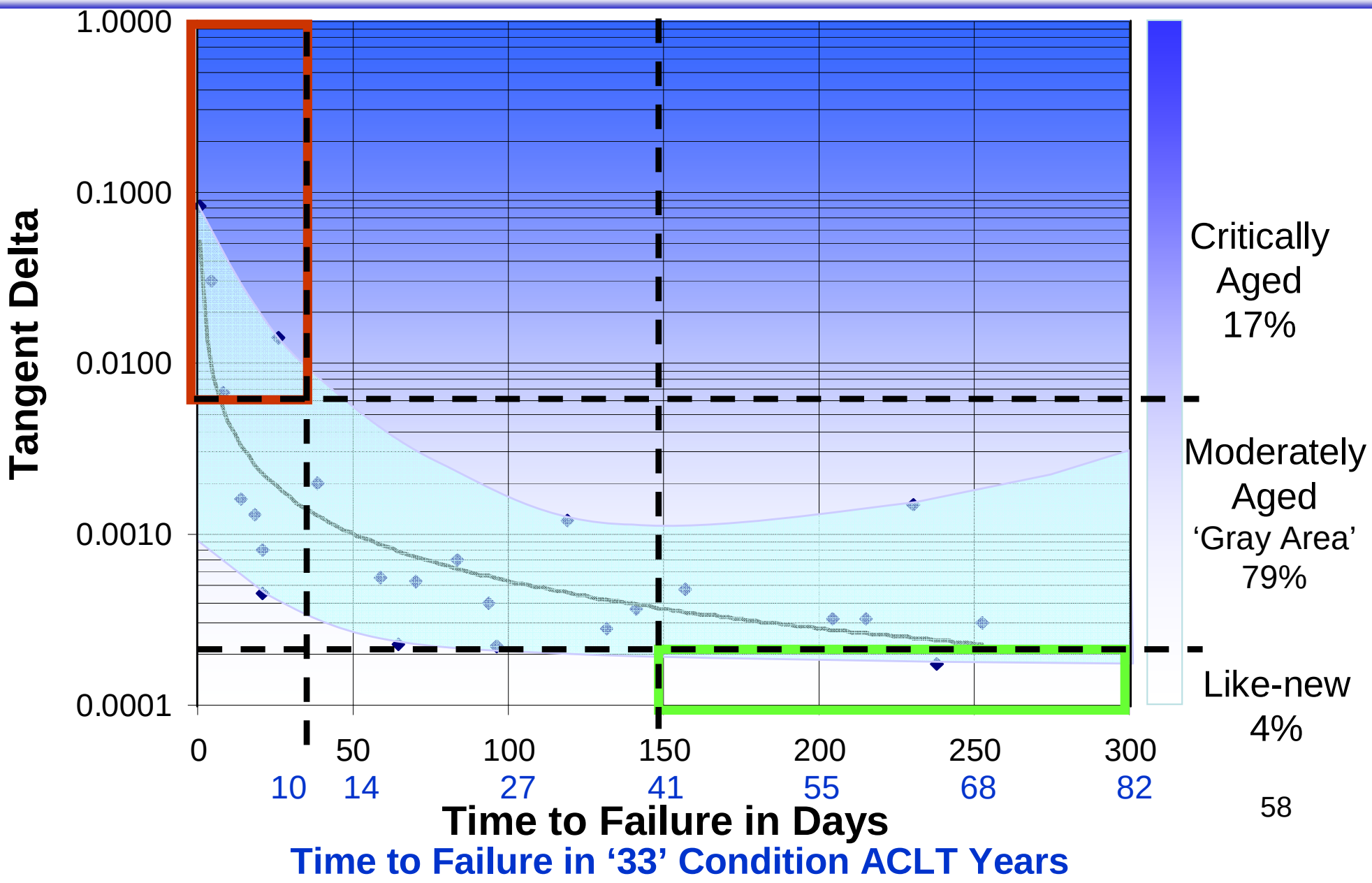
Natural and VLF Grown E-tree



How effective is GCA?

VLF TD ($1U_0$) vs. Characteristic Life*

*At '33' ACLT (60Hz) Conditions (1 Day ≈ 100 Days) -basis of 109 failure samples

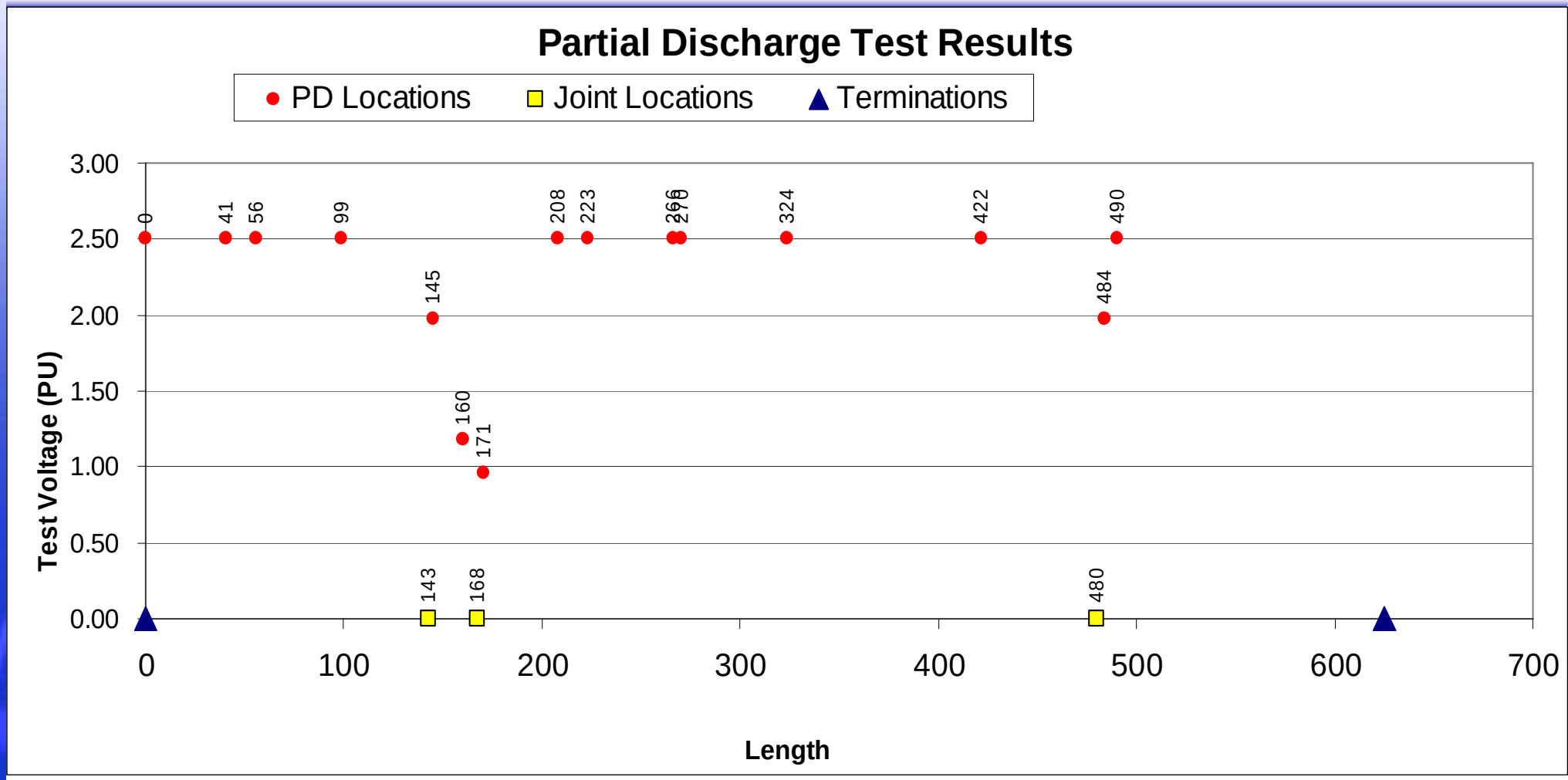


On-line PD vs. 60Hz Off-line PD

Cable tested with Off-line PD

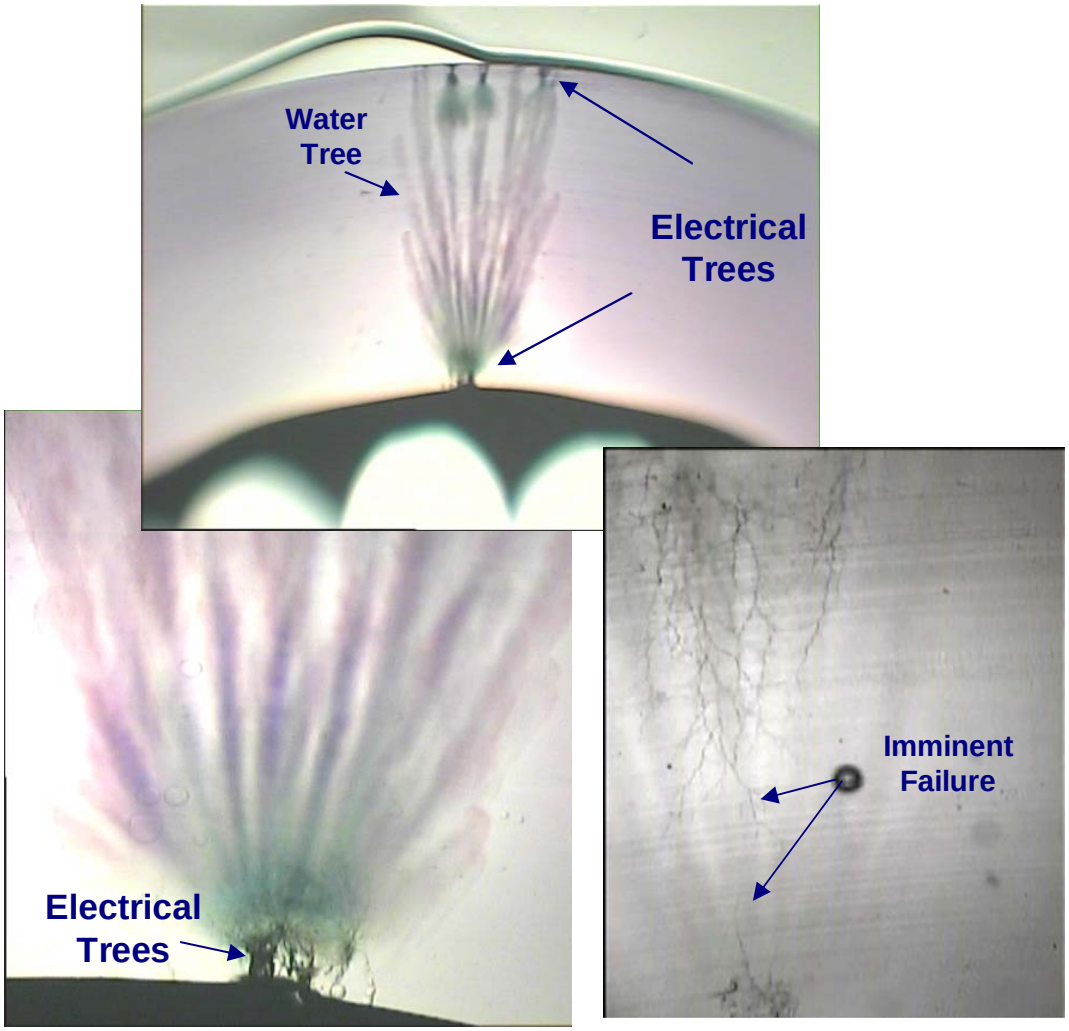
- 14 cable insulation defects (one at 1.3Uo)
- 1 Joint defect at $.8U_0$
- Cable tested w/ On-line PD
- Cable declared defect free by on-line test

On-line PD vs. 60Hz Off-line PD



- **Splice discharging at 0.8pu**
- **14 defects in the cable insulation.**

On-line PD vs. 60Hz Off-line PD



Typical Defect from Utility's Cable System

On-line PD vs. Off-line PD

- Third party online testing results show no trouble with cable
- Offline test reveals severe termination degradation
- Cable owner takes immediate action and applies repair kit
- Original test PDIV@ $1U_0$, 1000pC
- Retest PDIV@$1.2U_0$, 50pC

Conclusion

- **Shielded Power Cable Tests**
  - **Withstand Tests**
  - **Diagnostics Tests**
- **Test selection depends on**
  - **Application**
  - **Expected results**
- **DC is no longer supported by IEEE 400 for extruded cables**
- **A HIPOT test can not predict future performance**
- **The best bench mark is IEEE and manufacturer's test standards**
- **The most effect destructive withstand test is the VLF HIPOT**
- **The most effective nondestructive diagnostic test can repeat the calibrated factory test in the field. The 60Hz off-line PD diagnostic test meets this requirement.**
- **A comprehensive cable reliability strategy will lead to cable operation with the highest reliability, for the longest duration, at the lowest cost.**

Detailed Slides