Assuring the Reliability of Critical Power Cable Systems

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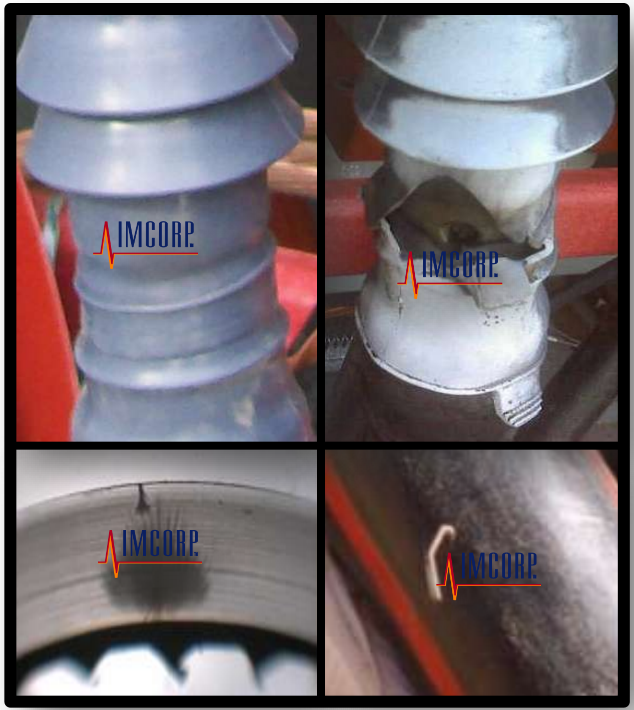


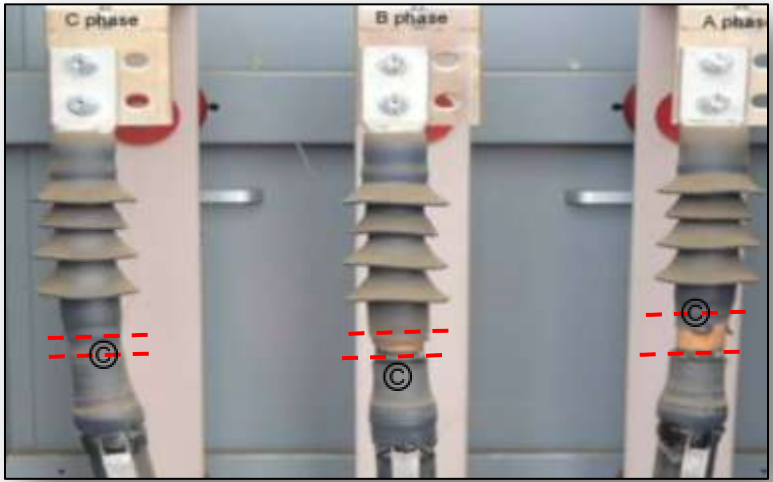
Executive Summary

- Critical industries have lost 100’s of millions of dollars due to defective cable systems (mostly workmanship) & ineffective tests
- New extruded cable systems predominately fail by a process of erosion associated with PD, not conduction (leakage detectable by HIPOT)
- High Potential (HIPOT) (AC & DC) tests are intentionally destructive & do not assure reliability
- Repeating the manufacturers’ off-line 50/60Hz PD QC test in the field is only effective way to assure insulation system meet design life.
- Over the last decade, one diagnostic technology has been demonstrated to effectively reproduce factory test comparable result in the field. (DSD technology)

Question

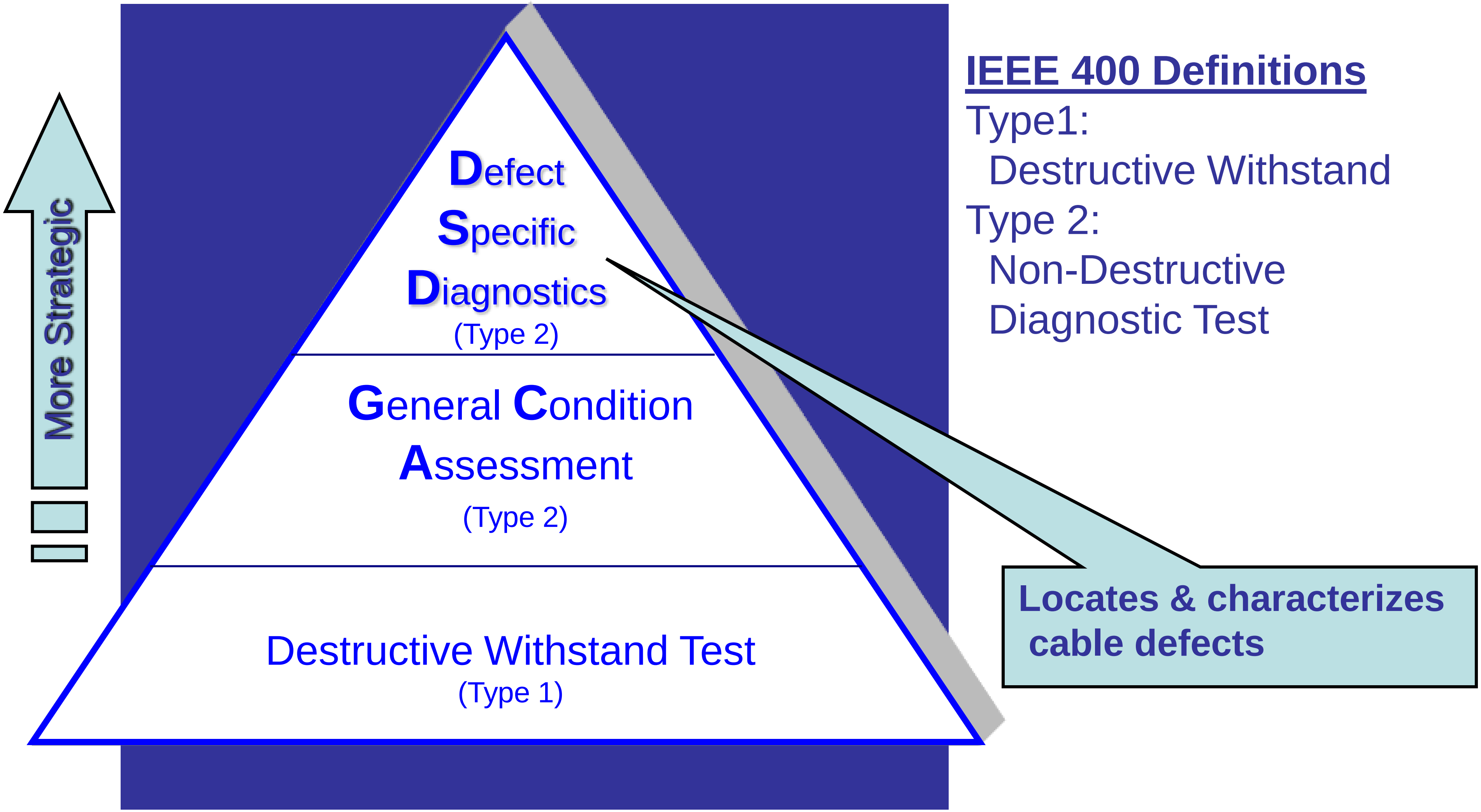
Which cable system test would you consider best practice to assure the reliability of critical cable systems?

- DC withstand
- VLF AC withstand
- Tangent delta
- On-line PD
- Off-line 50/60Hz PD



What test have manufacturers used to assure product design & production reliability for the last 40 years?

The Strategic Value of Cable Tests



IEEE 400 Definitions

Type1:
Destructive Withstand

Type 2:
Non-Destructive
Diagnostic Test

Evolution of Cable Testing In the Field

Change has evolved over past 40+ years

Primarily Paper Insulated Lead Covered Cable (PILC)

Early 1900's

- Failure mechanism associated w/ conduction & PD
- Factory test : DC test
- Field test : DC test
  - Simple
  - Portable

Extruded cable insulation (Rubber, HMWPE, EPR, XLPE)

1960's

- Failure mechanism associated predominantly w/PD
- Factory test:
- 0ff-line 50/60Hz PD
- Field Test: DC test

Issues Arise

1970's

- Water treeing problems
- DC HIPOT
  - Can't fail most defects
  - Aged PE fails at higher rate after passing test
- 0.1Hz VLF AC invented
  - Fails more defects
  - Answer to DC space charge issue
  - Tangent Delta developed for field

1990's

- VLF HIPOT can't fail most defects
- Tangent Delta
  - Can't detect many type of defects
  - Can't locate issues
- PD diagnostic developed for field
  - Can locate most issues
  - Not comparable to factory standards

State-of-the-Art

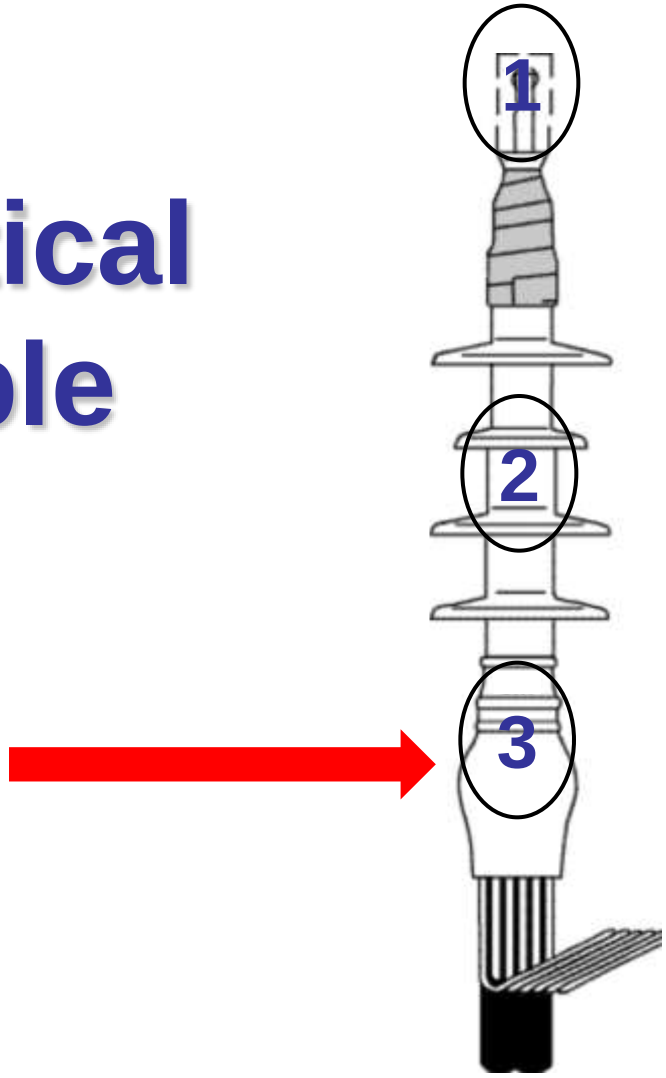
Today

- Most common HIPOT test still DC test – ineffective
- Best practice is off-line power frequency PD
  - Comparable w/ factory PD test
  - Assures IEEE/ IEC/ICEA/ AEIC compliance

"What the industry wants is leading edge technology proven over the past 30 years."

Question:

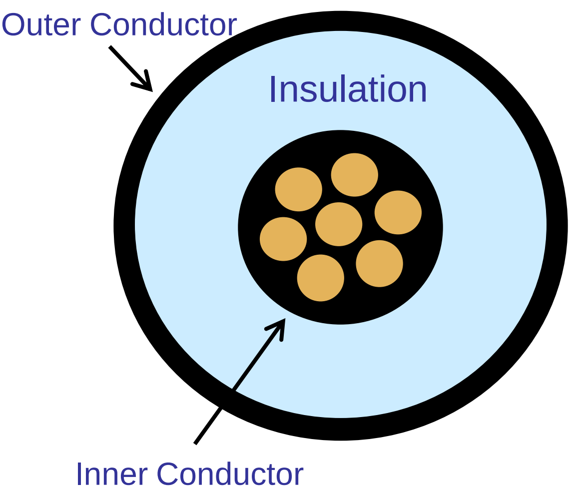
What is the most critical part of an MV/HV cable termination?

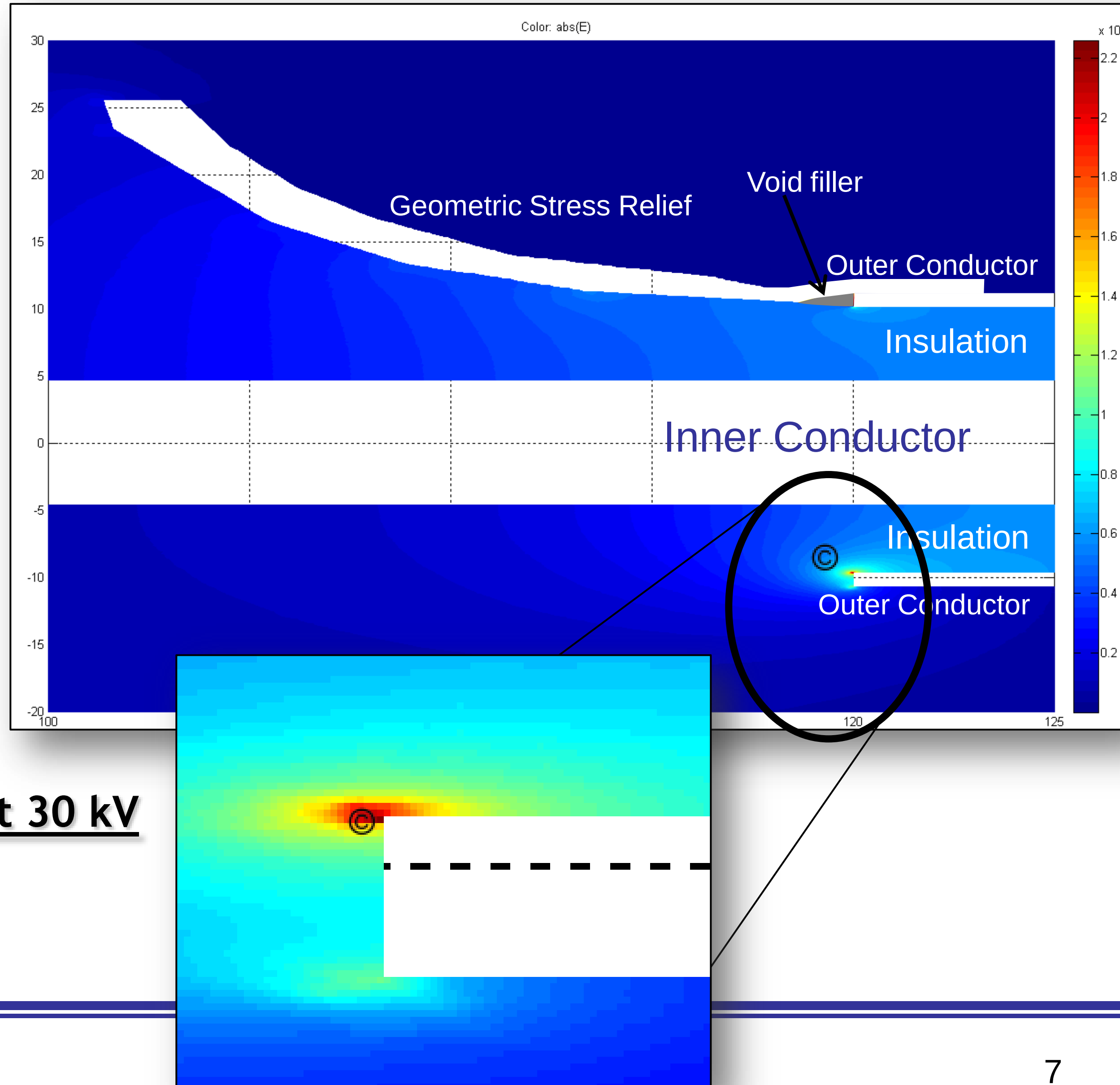


Terminated vs. Unterminated

Stress relief element reduces electric stress significantly at cutback of semiconducting outer conductor (ground)

Basic MV/HV Cable Design





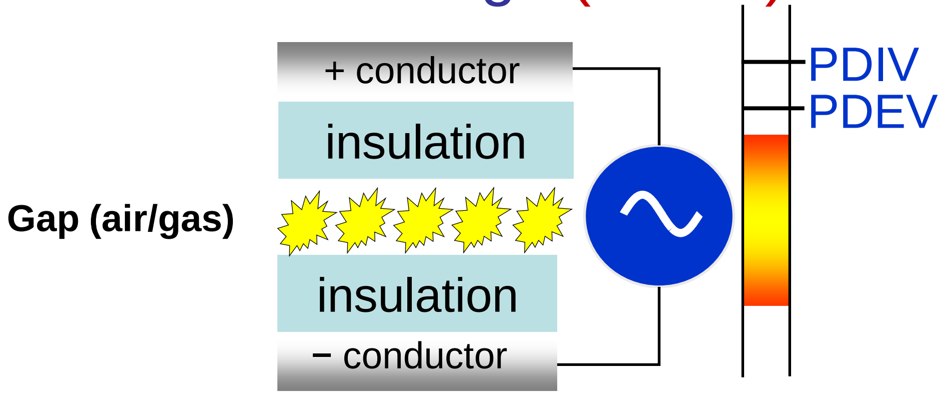
Electric field - conductor at 30 kV

dark blue = low electric stress

dark red = high electric stress

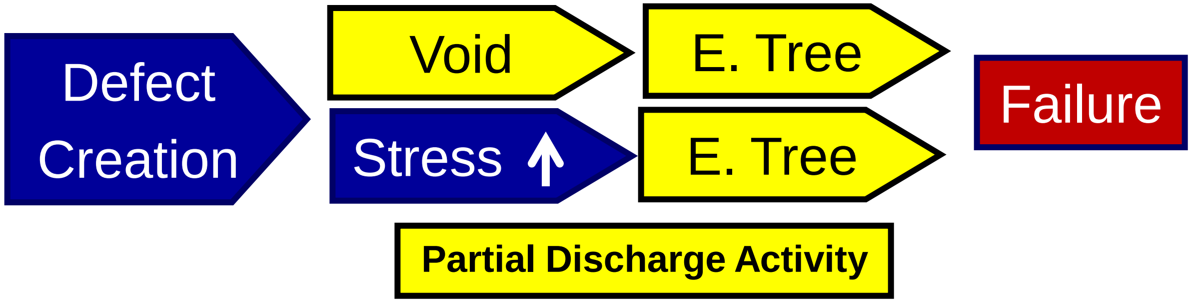
What is PD?

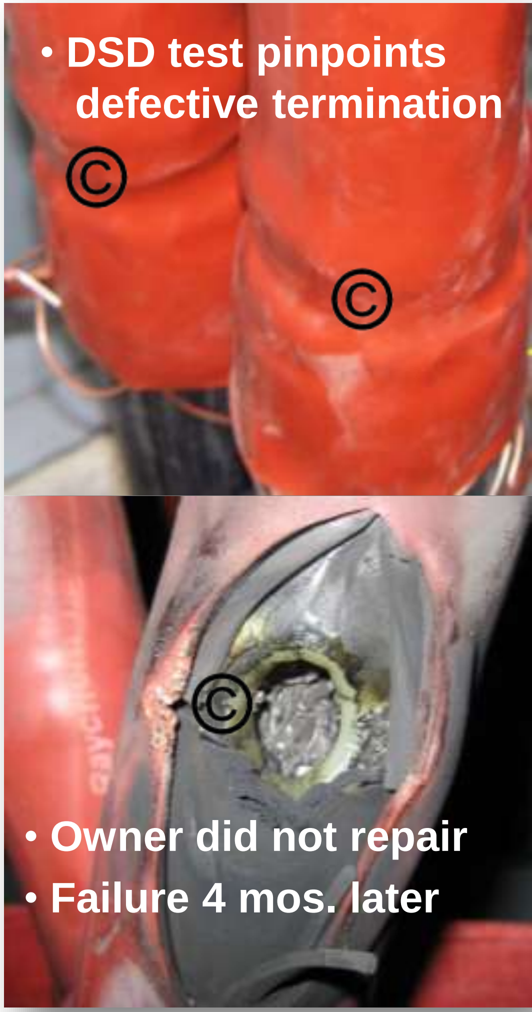
- An electrical discharge that does not completely bridge the space between two electrodes.
- The apparent discharge magnitude of a PD signal is measured in picoCoulombs (pC)
- The voltage at which PD first appears is the **I**nception **V**oltage (PDIV)
- The PD is extinguished when the voltage is reduced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



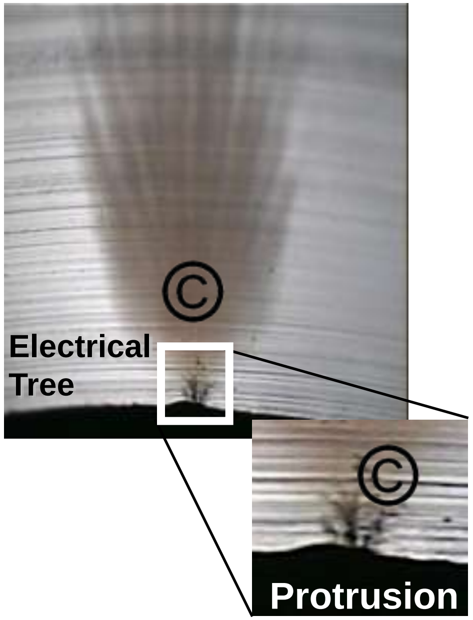
Modes of Failure

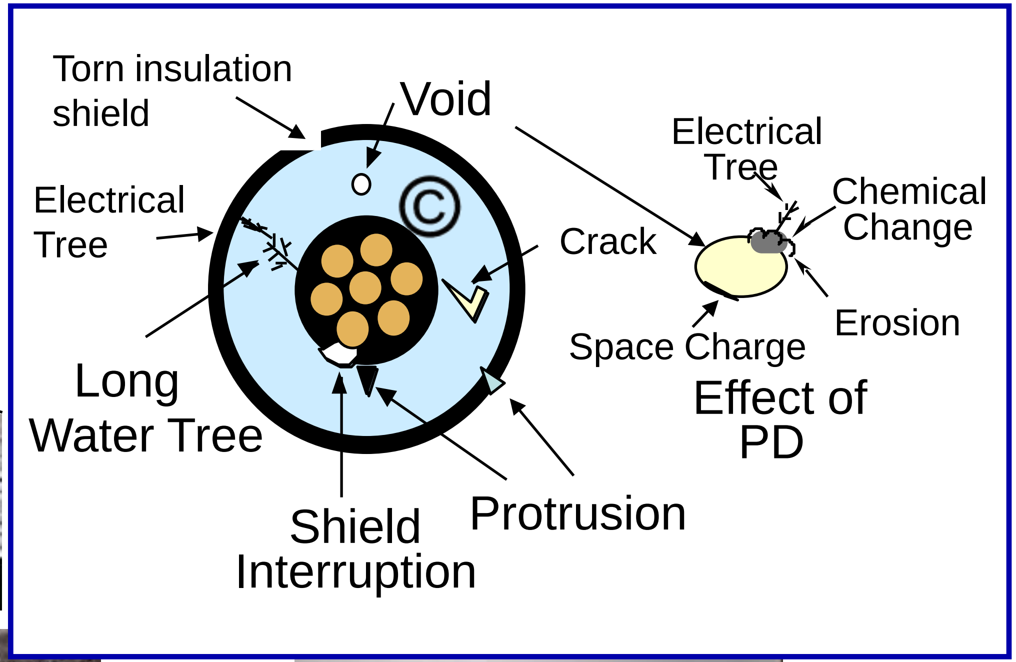
- High impedance defects
  - Workmanship nicks, voids, cuts
  - Aged 20yrs+ old -water/electrical trees
- Low impedance defects –conduction (PILC)
- External Influence
  - Poor mechanical connections
  - Extreme operating temperature
  - Dig-ins, vandalism

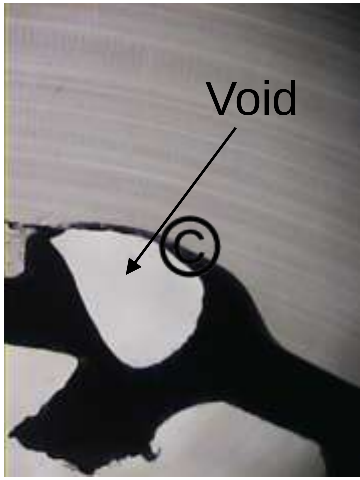


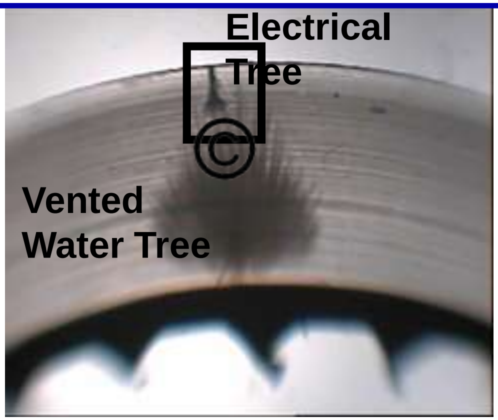


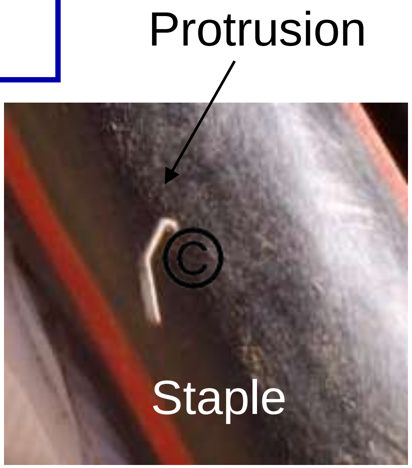
Typical PD Producing Defects in Extruded cables



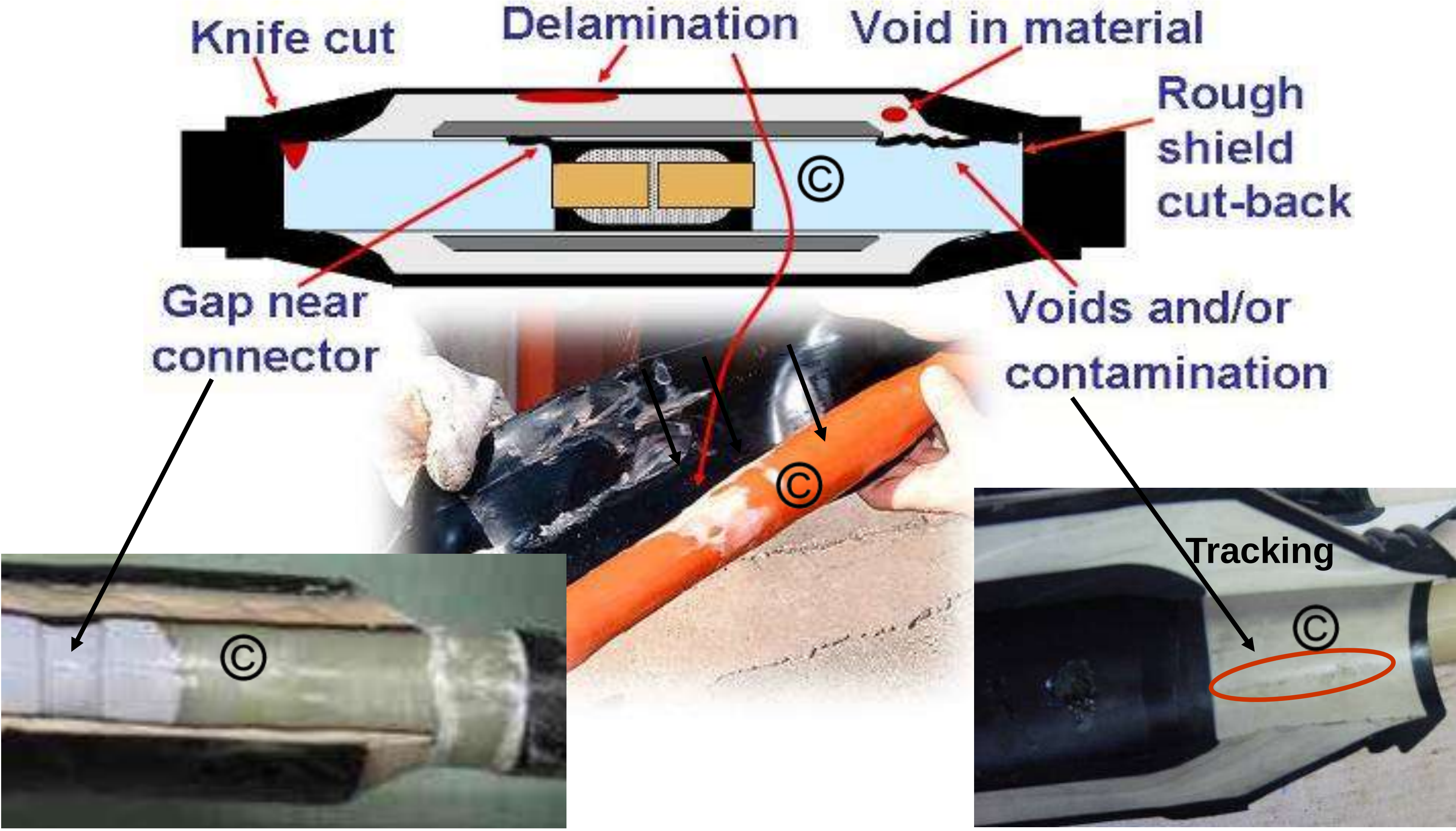




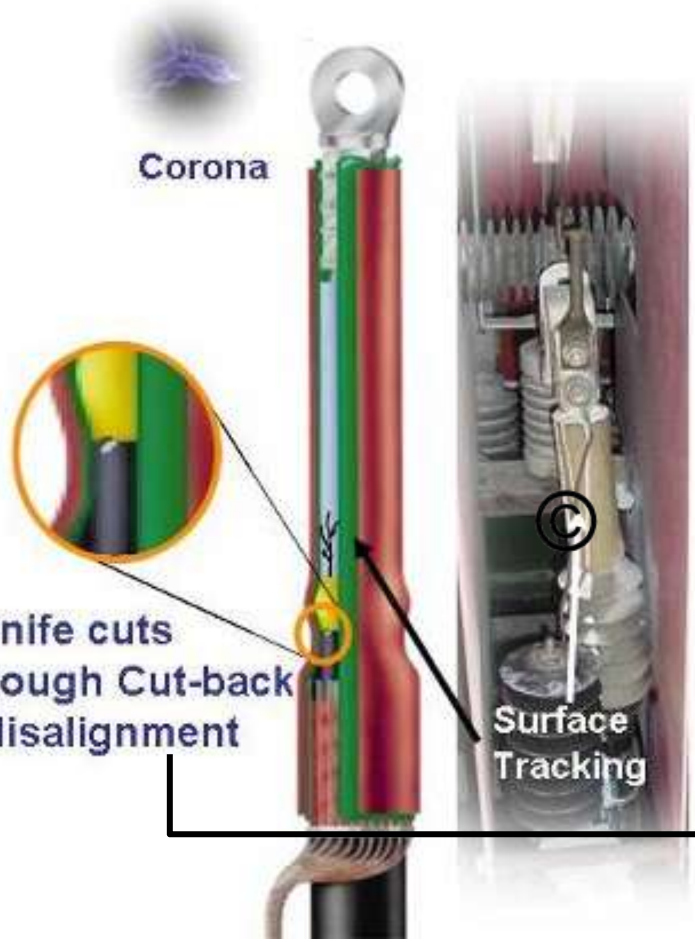




Typical PD Producing Defects in Joints

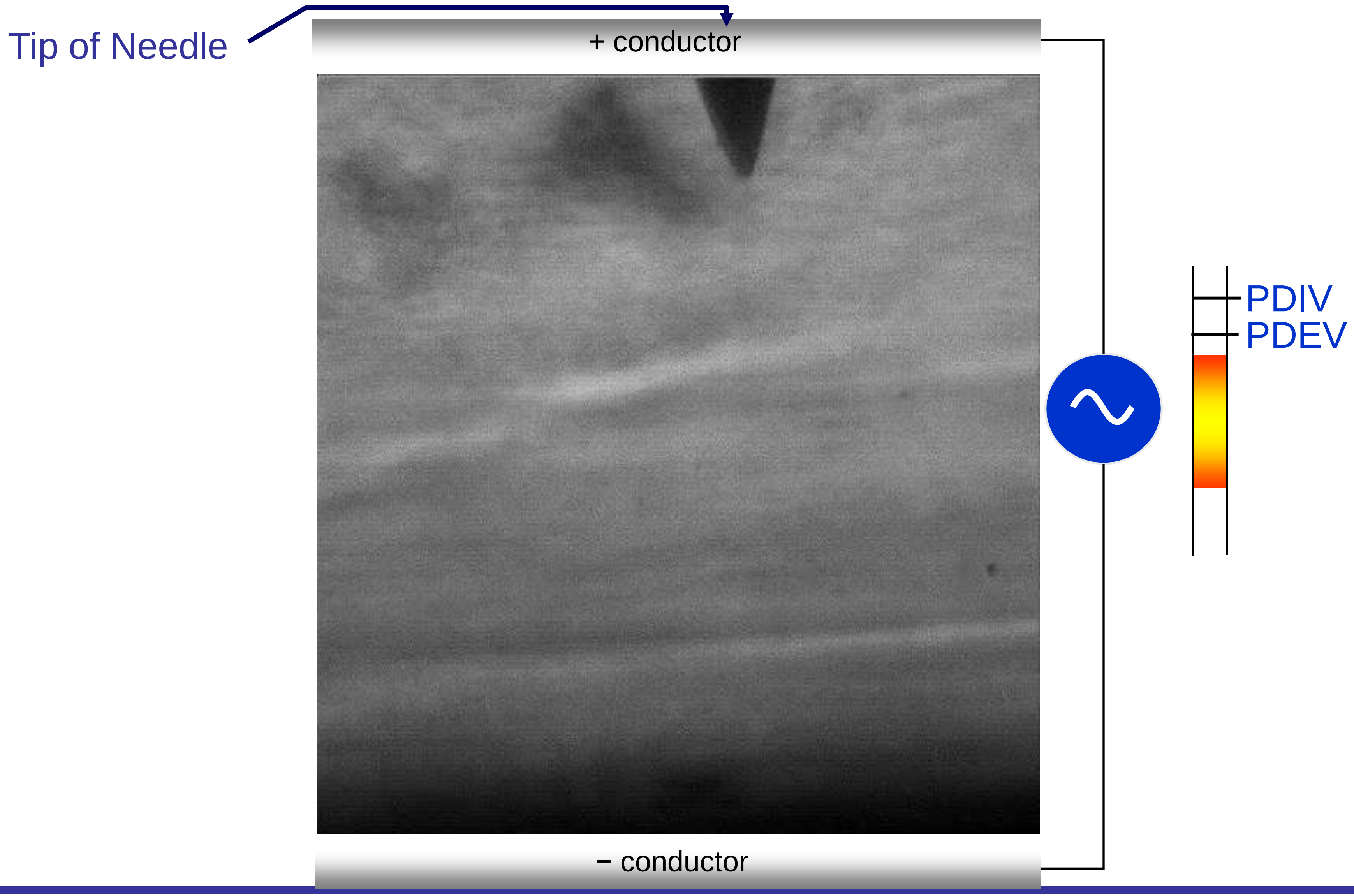


Typical PD Producing Defects in Terminations



Irregular/ non-radial cut-back

Electrical Tree



Time scale greatly <u>accelerated ~100 times</u> (e.g. 175mils, 15kV class cable)
Worst case tree growth @3Uo @60Hz (120V/mil) is ~78mils/hour or 0.1mil/5sec test

What is a critical cable system?

Example Categories

- Life support
- 24x7 facilities
- Power generation
- Government facilities
- Military facilities
- Manufacturing facilities
- Transportation facilities
- Large public venues

Example Facilities

- Hospitals, elder care facilities
- Large IT, bio tech
- Nuclear, fossil, renewable
- Gov. buildings, DOE, DOD
- Army, Air force, Navy
- Injection mold, steel, IC chip
- Air & rail support facilities
- Stadiums, arenas

Question:

What is the typical economic impact of a critical cable system failure?

- $100k+
- $10k to $99k
- $5k to $9k
- <$5k

Critical Power Plant Case Study

Excerpt from client's internal report

- All cable systems pass VLF AC HIPOT acceptance test
- Failure occurs during the first year of operation
- Estimated production lost = $156,212.00
- Emergency fault location labor cost = $44,670.00
- Emergency repair cost = $13,285.00
- **Total Loss = $214,167.00**
- DSD 50/60Hz off-line PD test performed, several additional cable insulation & accessory defects pinpointed

Case Study
Critical Industrial Plant

- 12 new 15kV cables installed
- DC HIPOT –all cable systems pass
- DSD 50/60Hz Off-line PD diagnostic
- Termination defect pinpointed per IEEE 48
- Stress control material accidentally misplaced
- Repair proven after successful retest
- Client says an outage > USD1million

Example of misplaced stress material

Question:

Which test can fail (detect) a higher percentage of cable system defects, a DC HIPOT or an AC HIPOT? (e.g. VLF HIPOT)

How long will massive workmanship defects last under a 2Uo AC HIPOT?

Knife Cut 1/3rd of Insulation Wall

Poor Cleaning -Semicon Residue

Stress Control Misplaced

Question:

What percent of cable defects can an VLF AC HIPOT fail (detect)?

- <5%
- <40%
- >70%
- >95%

What percent can a DC HIPOT fail? <1%

Critical Power Plant Cable System Case Study

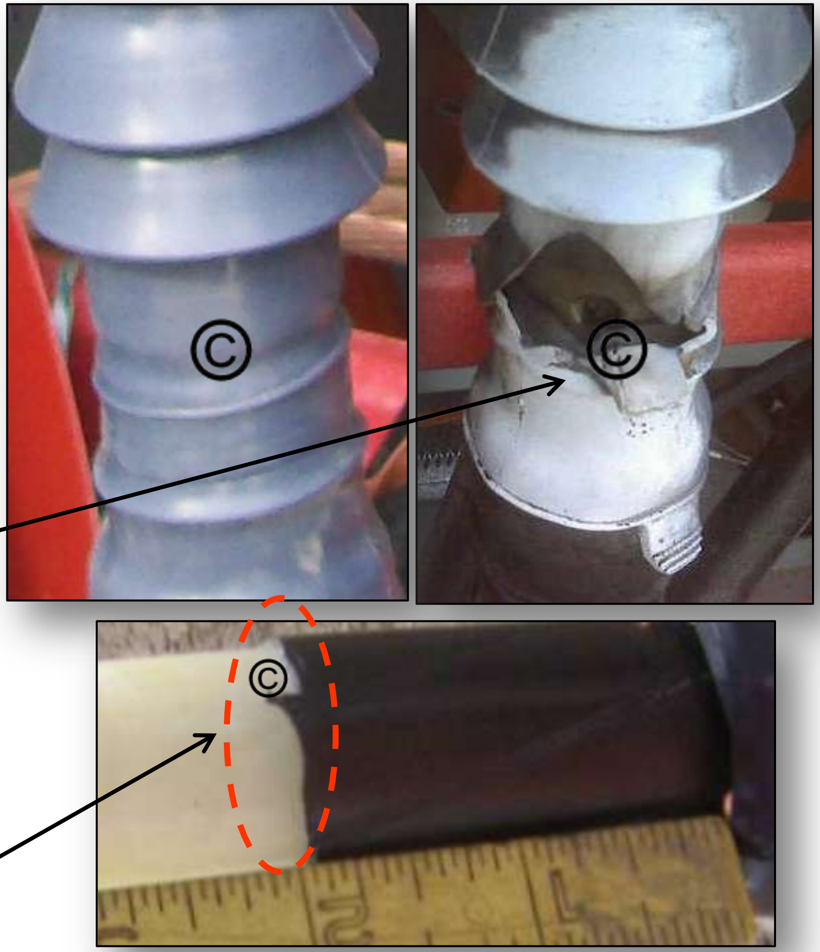
- All systems pass VLF AC HIPOT
- 1st failure on energization
- 2nd failure within one year
- DSD PD Test performed
- Defects pinpointed: 1 cable, 1 splice & 10 terminations

In service failure 1
Termination contamination

In service failure 2
Cable damage

Critical Cable System Case Study

- All 12 terminations at substation determined to be defective by DSD
- E. contractor disagreed
- VLF AC HIPOT performed
- All cable systems passed
- Termination fails in 3 weeks time
- All repaired & retested
- Some terminations still did not pass IEEE standards



Critical Plant Case Study

- Client opted not to perform DSD test.
- All cables pass HIPOT commissioning test
- Experienced fault after five months
- **Production loss & failure cost =$480K**
- DSD 50/60Hz off-line PD tests performed
- Pinpoints additional cable defect & several termination defects
- No failures for 4 years since completion of repairs and successful retests

Question:

What is the likelihood of an on-line PD test detecting a cable defect?

- >95%
- >70%
- < 40%
- < 5%

Cable System 731

- 567 -NO PD in cable
- 164 -with PD in cable

< 5% of cable defects w/PDIV ≤ 1 Uo

Critical Power Plant Cable System Case Study

- All systems pass DC HIPOT
- 9 failures in 3yrs, >$300k
- All systems pass on-line PD test -3 failures next yr.
- Total losses >$400k
- DSD PD Test performed
- Defects pinpointed 6 cable, 4 splice & 5 terminations
- After repairs & retests -no failures in 5 yrs.

Case Study

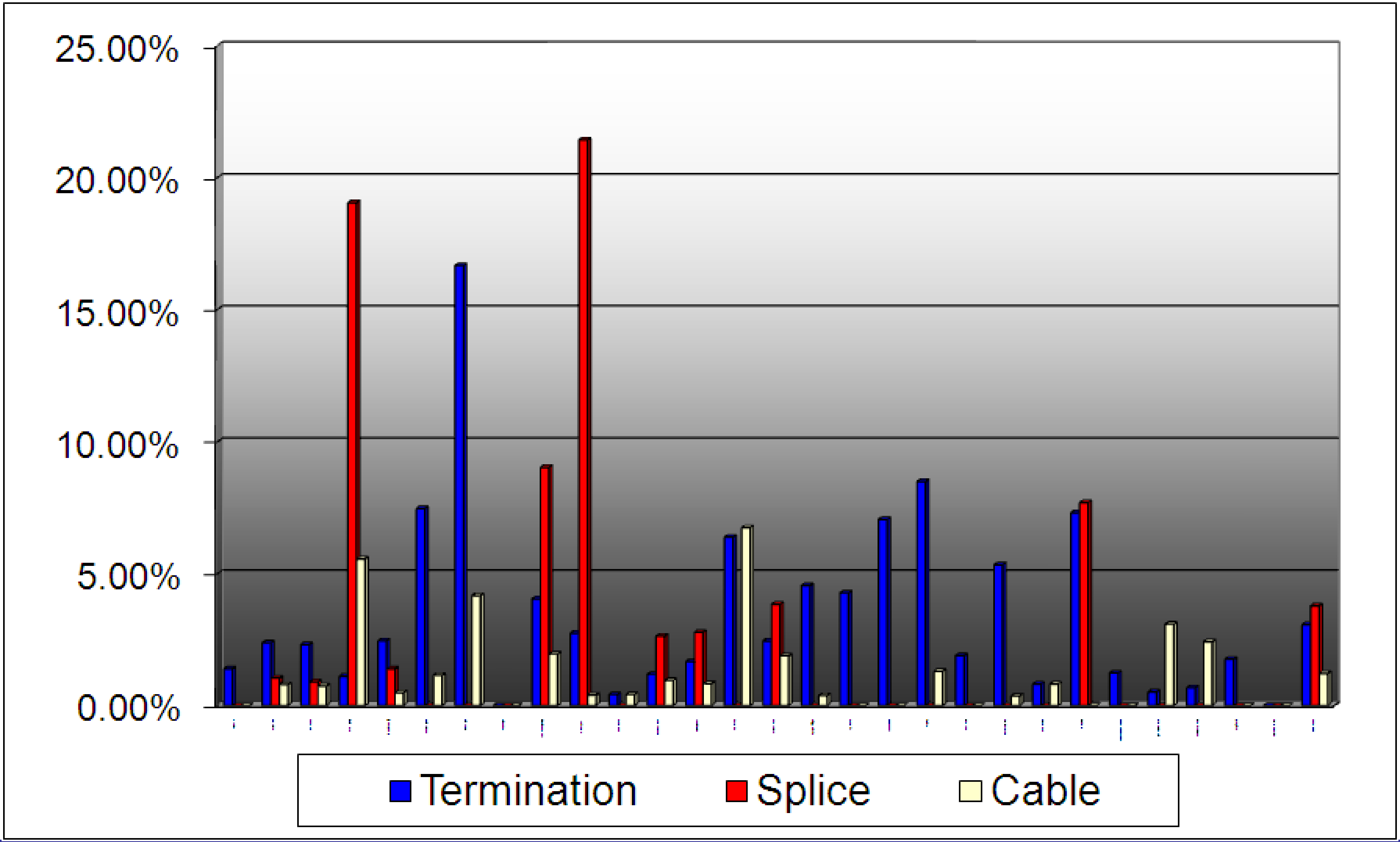
Critical Industrial Plant

- Cable systems routinely pass DC maintenance test
- **Plant historical avg. 1 cable failure/ 3 years**
- Fault records indicates mostly termination issues
- Off-line PD diagnostic test performed in 2000
- 40 repairs recommended
- **No failures since diagnostic & repairs 2000 (8 yrs)**
- Historical failure rate predicted 2 more failures

Plant A: Pareto Analysis

Cables Diagnosed (3 phase)	44
Termination Defects	40
Splice (joint) Defects	9
Cable segments recommended for replacement	3

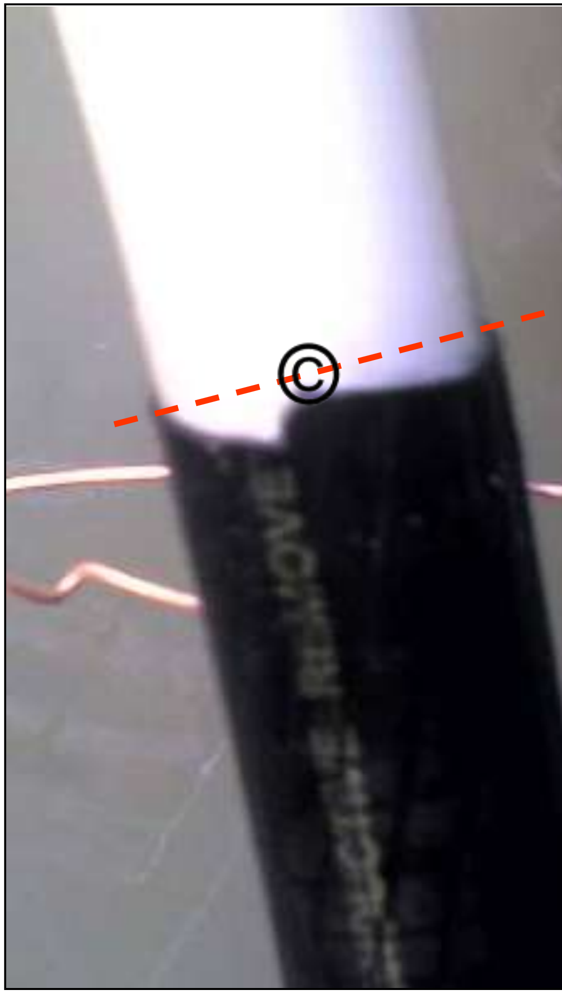
2009 Selected Project Performance



Percentage of components **NOT** passing manufacturers' standards

Critical Client Experience 2003-2009

- Failures after (no DSD) >150
  - DC HIPOT
  - VLF HIPOT
  - VLF Tangent Delta
  - On-line PD
- Defects pinpointed by DSD after other tests ‘pass’ cable >403
- Failures after DSD 1*



*Based on over 20,000 tests; excluding post test damage such as dig-ins, thermal design issues

IEEE 400-2001

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".

Cable defect was location matched within 6 inches on a 1400' Cable

ANSI/ICEA S 97-682 Noncompliant

Insulation Defect Defined by IEEE, ICEA, IEC & VDE Standards

Standards

Standard	Joints	Terminations	Separable Connectors	MV Cable	HV Cable
IEEE/ICEA	404_2006	48_1996	386_2006	S_97_682_2007	S-108-702-2009
VDE DIN	0278_629_1	0278_629_1	0278_629_1	0276_620	-
IEC	60502_4	60502_4	60502_4	60502_2	62067

Thresholds

IEEE/ICEA	<3 pC@ ≥ 1.5Uo	<5 pC@≥ 1.5xUo	<3 pC @≥ 1.3xUo	<5 pC @≥ 4.0xUo*	<5 pC @≥ 2.0xUo
VDE DIN	<10pC@≥ 2.0Uo	<10 pC@≥ 2.0xUo	<10 pC @≥ 2.0xUo	<2 pC @≥ 2.0xUo	-
IEC	<10pC@ ≥1.7Uo	<10 pC@≥ 1.7xUo	<10 pC @≥ 1.7xUo	<10 pC@≥2.0/1.7xUo	<10pC@≥1.5Uo

- Uo is cable system's voltage at 50/60Hz
- All pC values are in apparent charge

* actually 200V/mil (7.87kV/mm)

Design/Specification Best Practices

- Follow manufacturer standards: IEEE, ICEA, IEC
- Adequate neutral/metallic shield size ≥1/6, concentric wire
- Avoid cross-bonding
- Limit cable lengths to 8,500 ft.
- Minimize number of in-line joints (splices)
- Specify quality cable and accessories
- Specify joints with crimped neutral connector
- Off-line 50/60Hz PD Test on complete site & substation
- Specify No HIPOTs > Uo
- Termination preparation: Bag & tape, position & support

Summary

- 100's of millions of dollars have been lost due to inept tests and cable system defects –primarily workmanship
- Modern cable systems fail by a process of erosion associated with PD (not conduction detected by a HIPOT)
- High Potential (HIPOT) (AC & DC) tests are destructive & do not assure reliability
- Repeating the manufacturers' PD diagnostic test in the field is only way to assure insulation system design life
- The off-line 50/60Hz PD diagnostics (Defect Specific Diagnostics -DSD) is the only technology which can repeat the manufacturer's QC test in the field
- Where:
  - financial risk is significant
  - contractor warranties are involved
  - reliability is critical
  - significant assets need to be prioritized for replacement

DSD technology can assure cable system reliability at the lowest cost.