Medium Voltage Aging Mechanism Update - 4

Presented by
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Deterioration of Shielded, 5 kV Black EPR Cable*

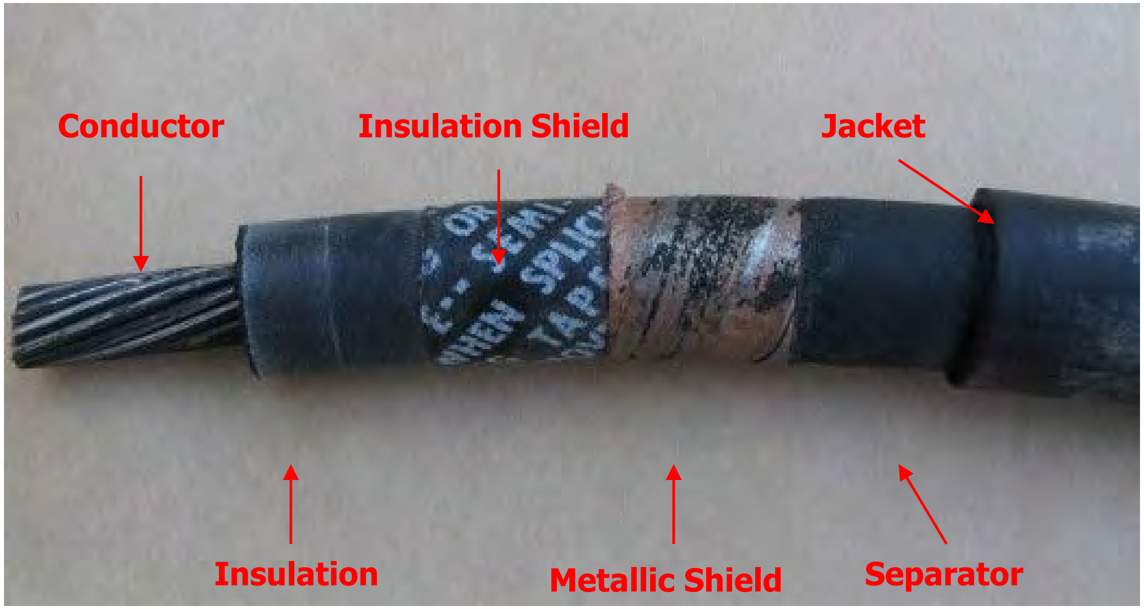
- 3/C cable, 870 ft long run, between pump motor and switchgear
- Operating voltage 2.4 kV to ground
- Installed in 1973, plant commissioned in 1975
- Energized for 35 years (90% of the time)
- Cable did not fail in service

*CTL Code M10-104

Deterioration of Shielded, 5 kV Black EPR Cable (cont'd)

- Removed in 2010 because of high and unstable TD readings at V_0 of phase B
- TD of phases A and C were elevated but tolerable
- Purpose of removal:
  - To replace the deteriorated cable
  - To assess in laboratory degree of insulation degradation
  - To compare laboratory assessed insulation degradation with field measured TDs

Cable Construction



Cable Description:
~1972, 5 kV, 3C, Black EPR Cable

Cable Construction Detail

Conductor:	2/0 AWG (67.4 mm^2) concentric stranded, coated copper
Conductor shield:	15 mil (0.38 mm) of extruded, semi-conducting compound
Insulation:	160 mil (4.1 mm) extruded, black EPR
Insulation shield:	semi-conducting, impregnated, fabric tape
Metallic shield:	single, coated copper tape
Separator:	woven fabric tape
Jacket:	107 mil (2.7 mm) (Hypalon or Neoprene)
Operating stress:	2400 V:170 mil = 14 V/mil (0.56 kV/mm)

Field Measurement Data

HVA TD Report Summary
R22-S006-ES2-M01

Report Information

Cable / Line ID: R22-S006-ES2-M01

System Used: GH0300.09B003
Test Start: 10/26/2010 2:48:26 AM

Station / Location:
From: 1F SWGR
To: 1R34S005D
End Device: 1P41C001D
Comment: *1D PSW PUMP*

Device Under Test: Cable
DUT Voltage Rating: 5.0 kV
Length: 800
Size: 2/0

Insulation Type: EPR
Measurement Type: Maintenance
Manufacturer: Okonite

Company:
Operator:

Region:
Work Order: 1100597601

Phase A Summary: 0.1 Hz, 106.7 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	20.4	23.0	25.8	28.5			
Std. Dev. [%]	0.01	0.03	0.02	0.03			

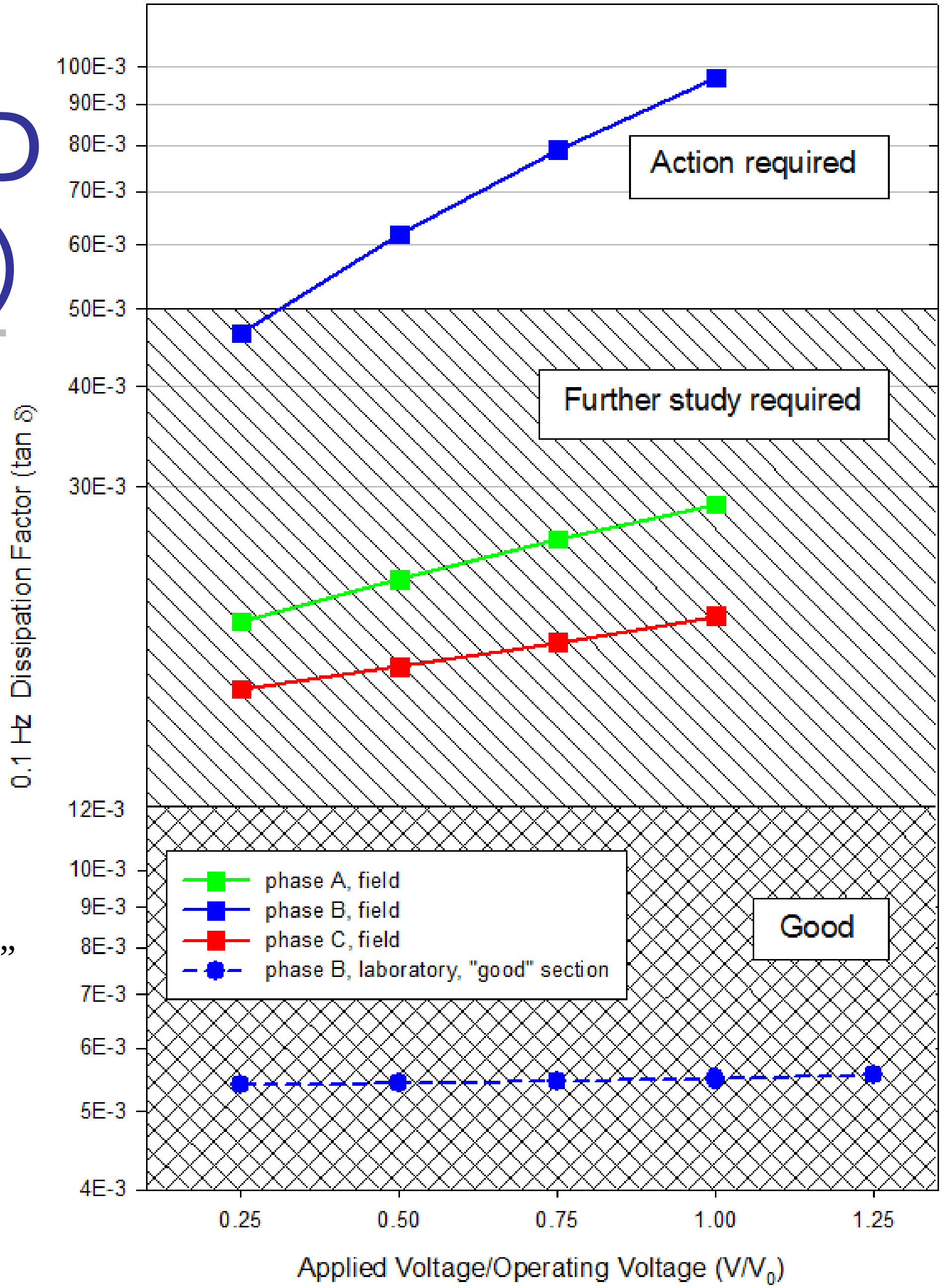
Phase B Summary: 0.1 Hz, 110.6 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	46.6	61.9	78.8	96.9			
Std. Dev. [%]	0.09	0.18	0.15	0.19			

Phase C Summary: 0.1 Hz, 106.1 nF

Voltage [kVrms]	0.6	1.2	1.8	2.4			
TD Value [E-3]	16.8	17.9	19.2	20.7			
Std. Dev. [%]	0.00	0.01	0.01	0.01			

Field Results - TD (Average Values)



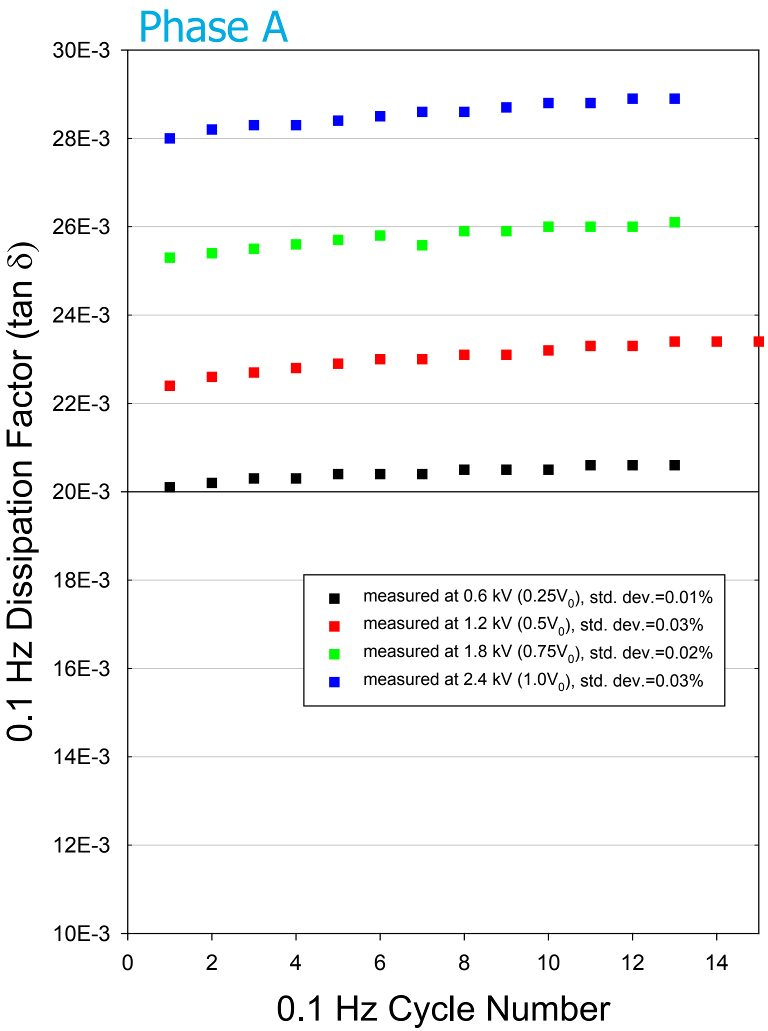
Limits "Good, Further Study Required, Action Required" taken from 2010 EPRI Report 102085, titled "Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants."

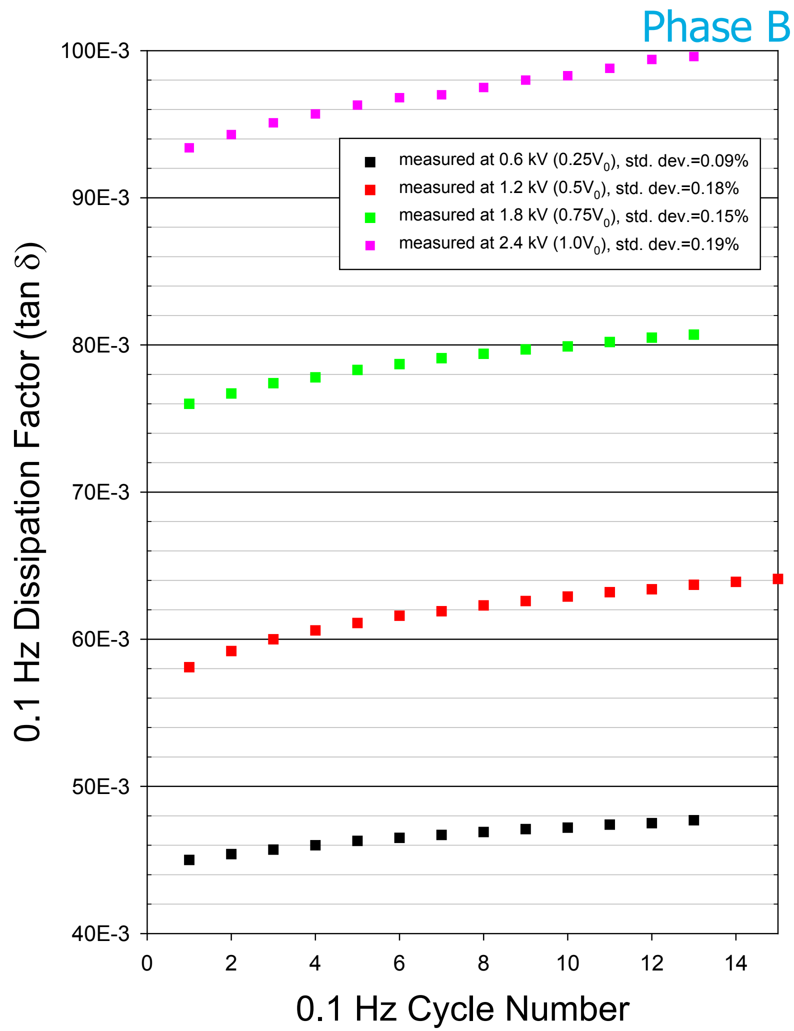
Field Results
Absolute Value of TD Difference

Phase	Difference in Tan δ Between 0.25 V_0 and 1.0 V_0	EPRI Guide*	
		Tan δ Difference (0.5 V_0 - 1.5 V_0)	Cable Condition
A	8.1×10^{-3}	3+ to 10	Further Study Required
B	50×10^{-3}	>10+	Action Required
C	3.9×10^{-3}	3+ to 10	Further Study Required

*EPRI Report 102085, "Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants."

Field Results - Data Stability





Field Results - Data Stability Evaluation

Phase	Percent Standard Deviation of Tan δ		
	Measured at 1.0 V_0	EPRI Report	
		Values	Cable Condition
A	0.03	0.02+ < Std. Dev. < 0.04	Further Study Required
B	0.19	>0.04	Action Required
C	0.01	≤ 0.02	Good

Summary of Field 0.1 Hz TD* Diagnoses

Phase	Average TD Value	Difference in $TD_{1.0V_0}$ - $TD_{0.25V_0}$	TD Stability
A	Further Study	Further Study	Further Study
B	Action Required	Action Required	Action Required
C	Further Study	Further Study	Good

* Measured up to 1.0 V_0 *(Recommended measurement up to 1.5 V_0 or 2.0 V_0)*

Laboratory Evaluations

CTL received phase B only. Whole length in five unmarked sections, arbitrarily designated H1, H2, H3, H4 and H5.

Designation	Condition	Measured Length (ft)	0.1 Hz @ 2.4 kV		Insulation Resistance	
			Dissipation Factor	Standard Deviation, %	Measured MΩ	MΩ per 1000 ft
H1	¾ Mud Covered	167	24×10^{-3}	0.00	5.0×10^{4}	8 400
H2	¾ Mud Covered	106	14×10^{-3}	0.01	1.2×10^{5}	13 000
H3	Completely Mud Covered	194	117×10^{-3}	0.18	4.0×10^{2}	78
H4	Clean	207	5.5×10^{-3}	0.00	3.0×10^{5}	62 000
H5	¼ Mud Covered	195	53×10^{-3}	0.06	4.2×10^{3}	820
H1 - H5 Combined		869	97×10^{-3}	0.19		70
Current Specification Requirement						>4 800

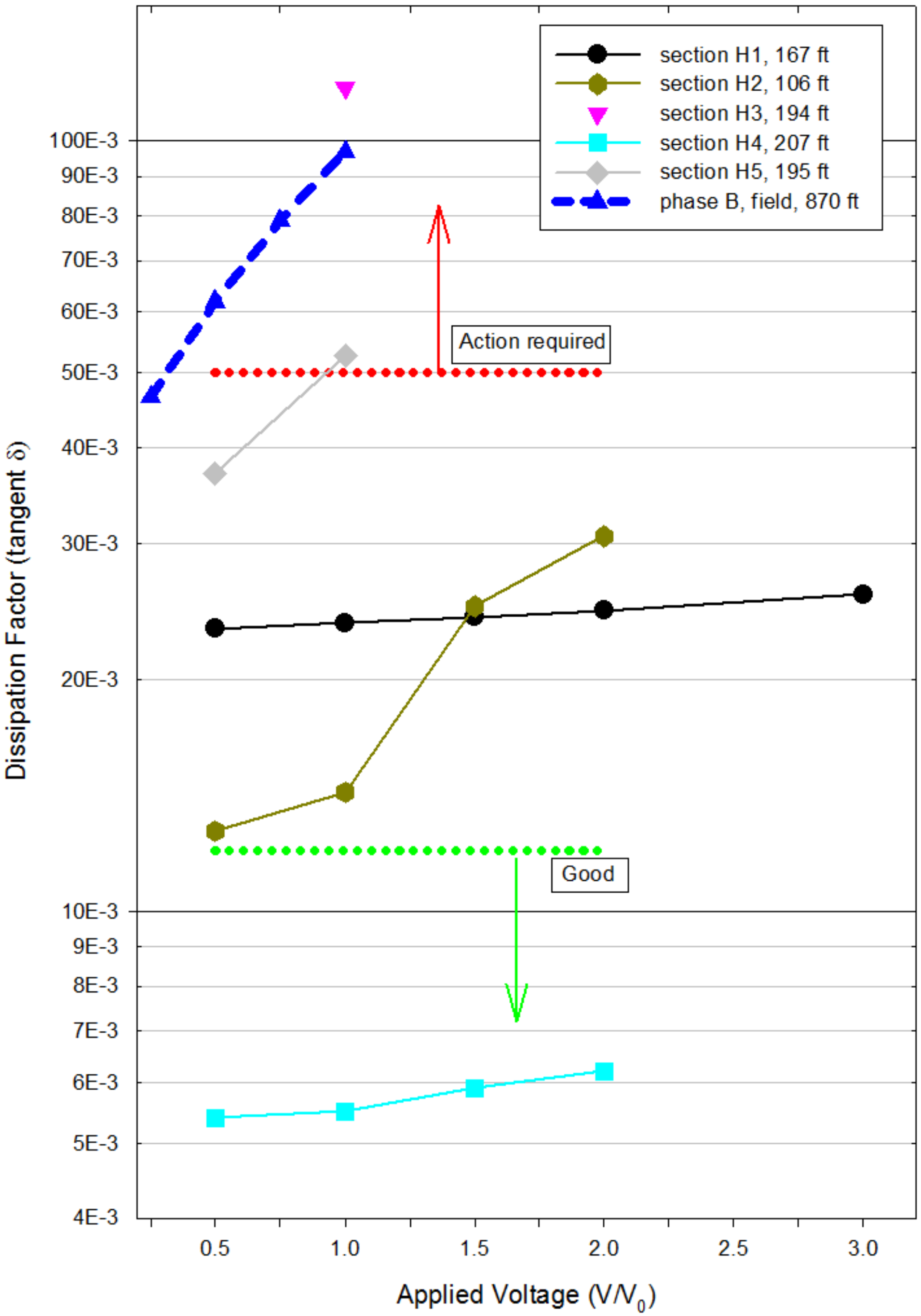
Further Study – Yellow color

Action Required – Red color

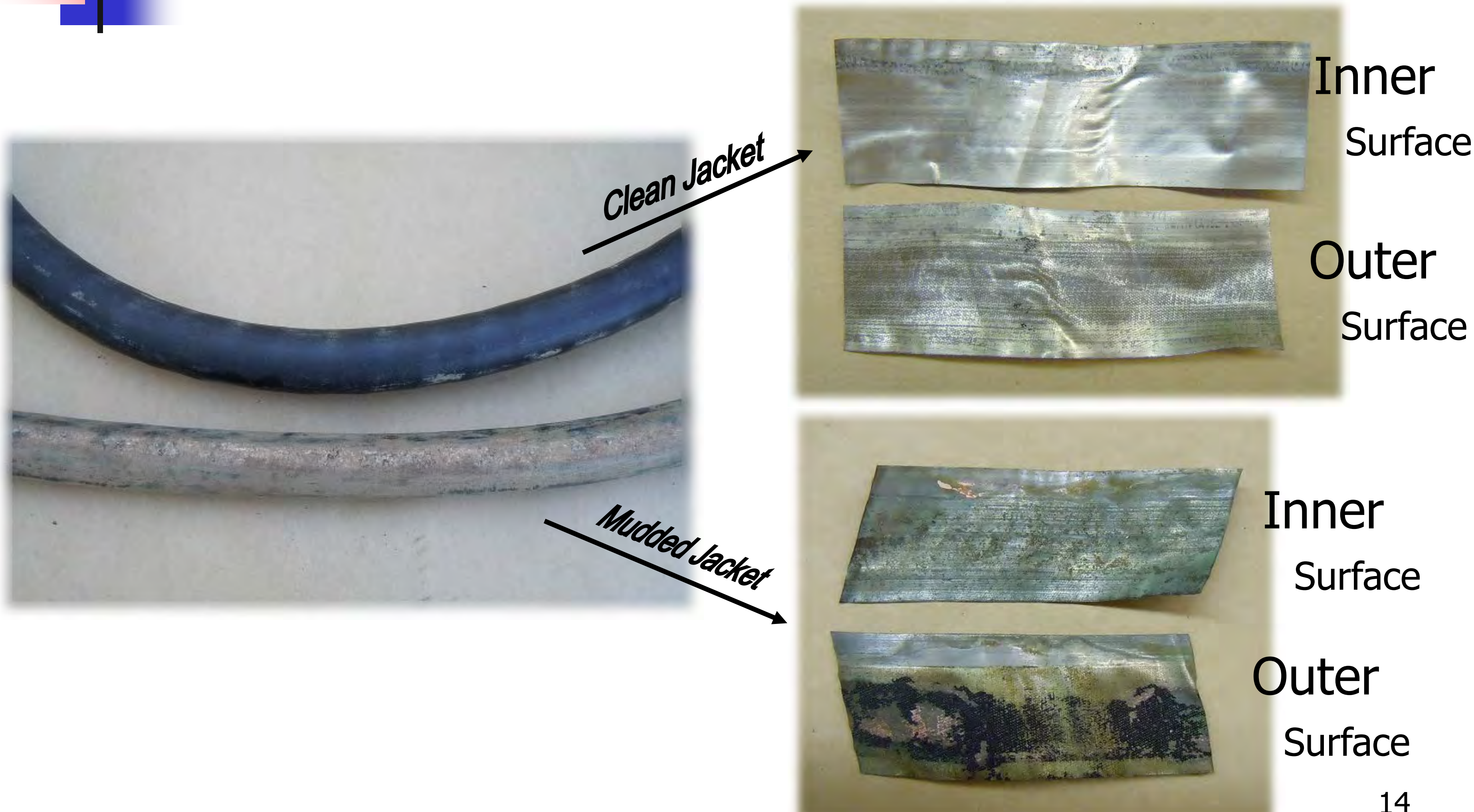
Low insulation resistance alert – Green color

According to EPRI Report 1020805 "Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants"

Laboratory and Field TD Measurement Comparison



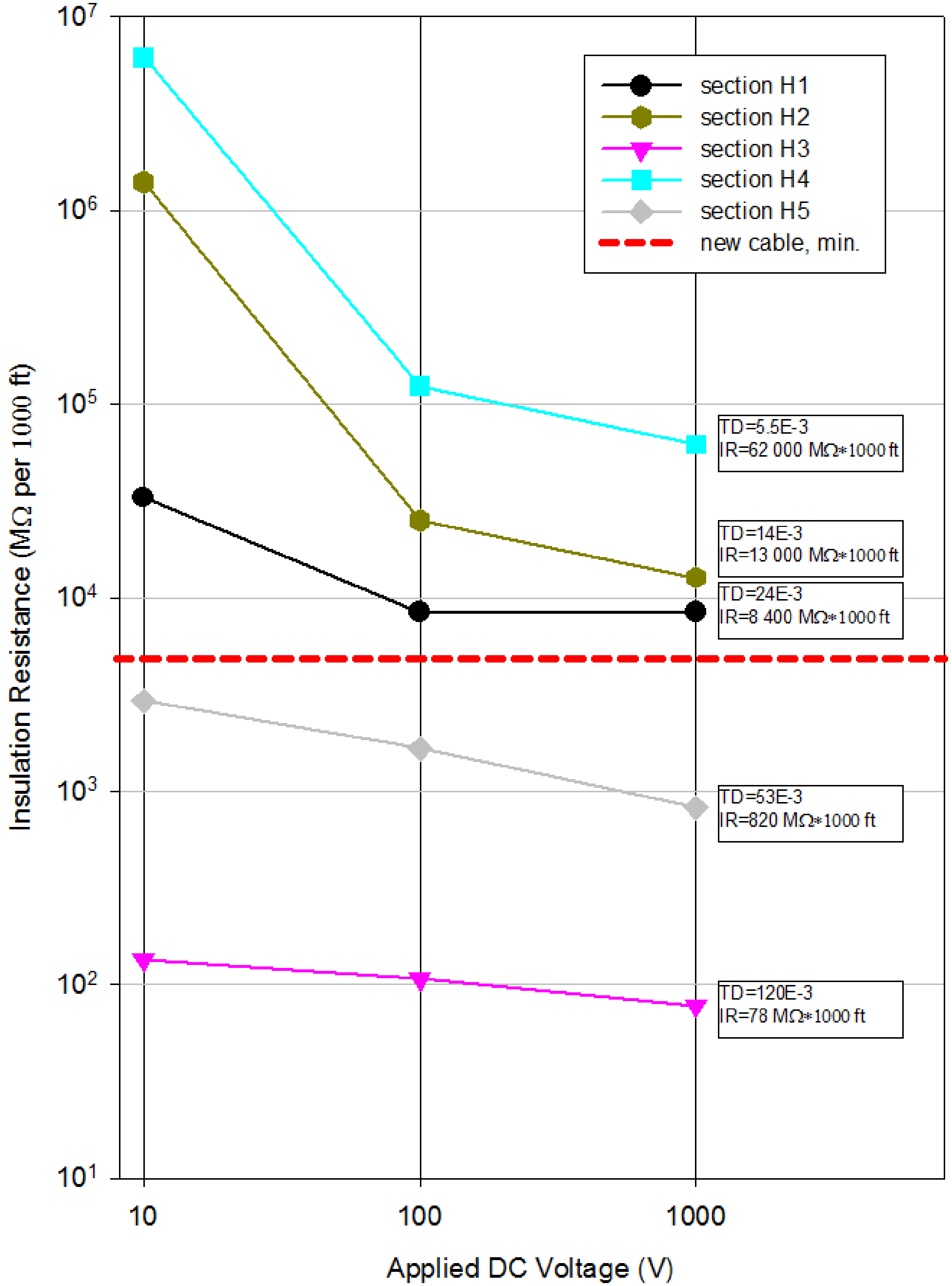
Metallic Shield Under Clean and Mud-covered Jacket



Water Content of Cable Components

Sample		Water Content (weight fraction, %)			Insulation Relative Humidity (%)
Cable Section	Information	Jacket	Insulation	Conductor Shield	
H2	TD = 14 x 10^{-3}	0.84	0.25	- -	83
H3	TD = 120 x 10^{-3}	15.6	0.29	- -	97
H4	TD = 5.5 x 10^{-3}	0.76	0.18	- -	60
- -	Black Okonite EPR after 15 years in wet, underground service	- -	0.3	~1.0	100
H5	After drying 11 days at 120°C in air circulating oven no jacket, no insulation shield TD = 5.5 x 10^{-3}	- -	0.09	0.19	30

Looking Back: Insulation Resistance vs. DC Voltage



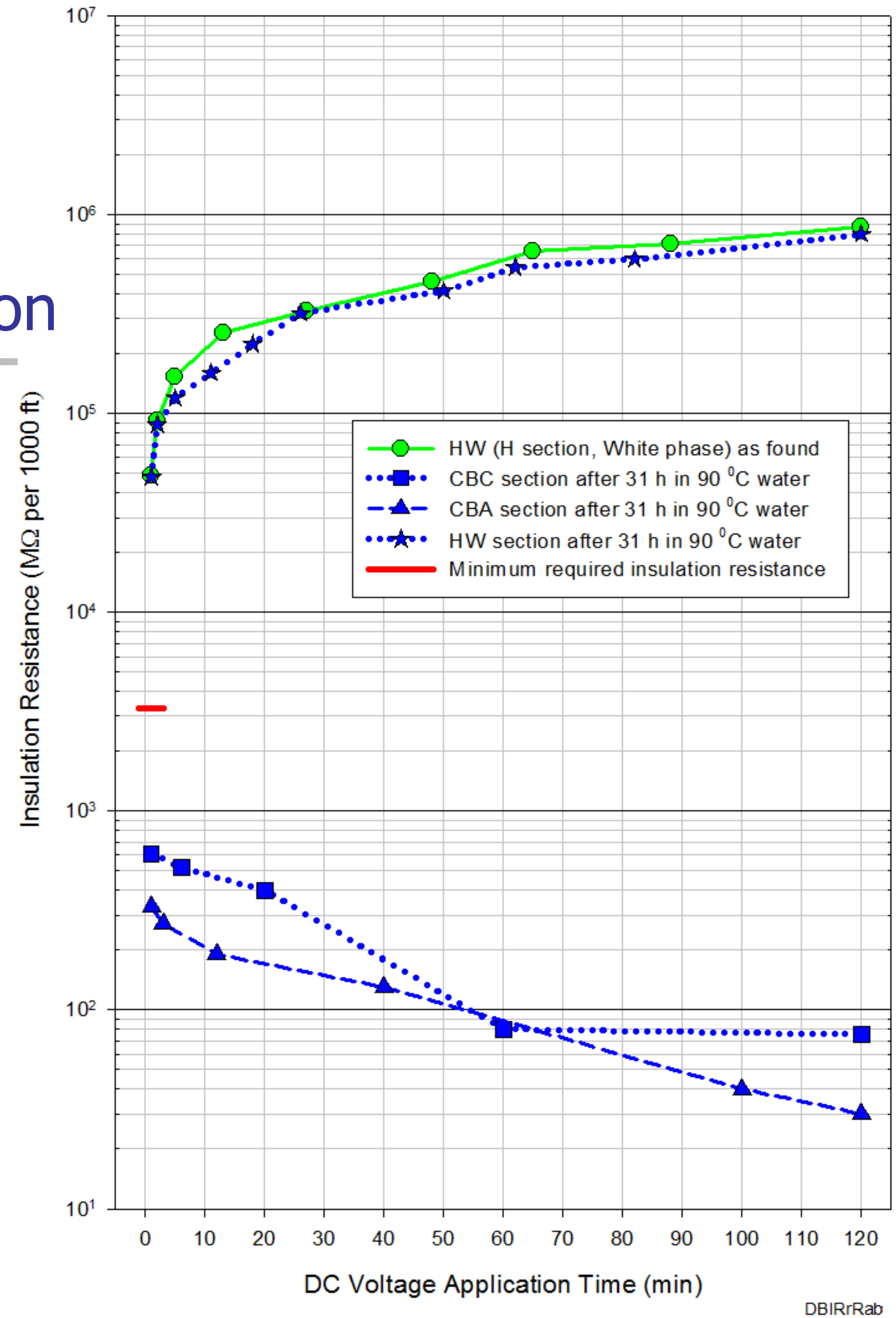
Looking Back (cont'd): Insulation Resistance vs. Time of Voltage Application

(another Black EPR cable)

Polarization Index:

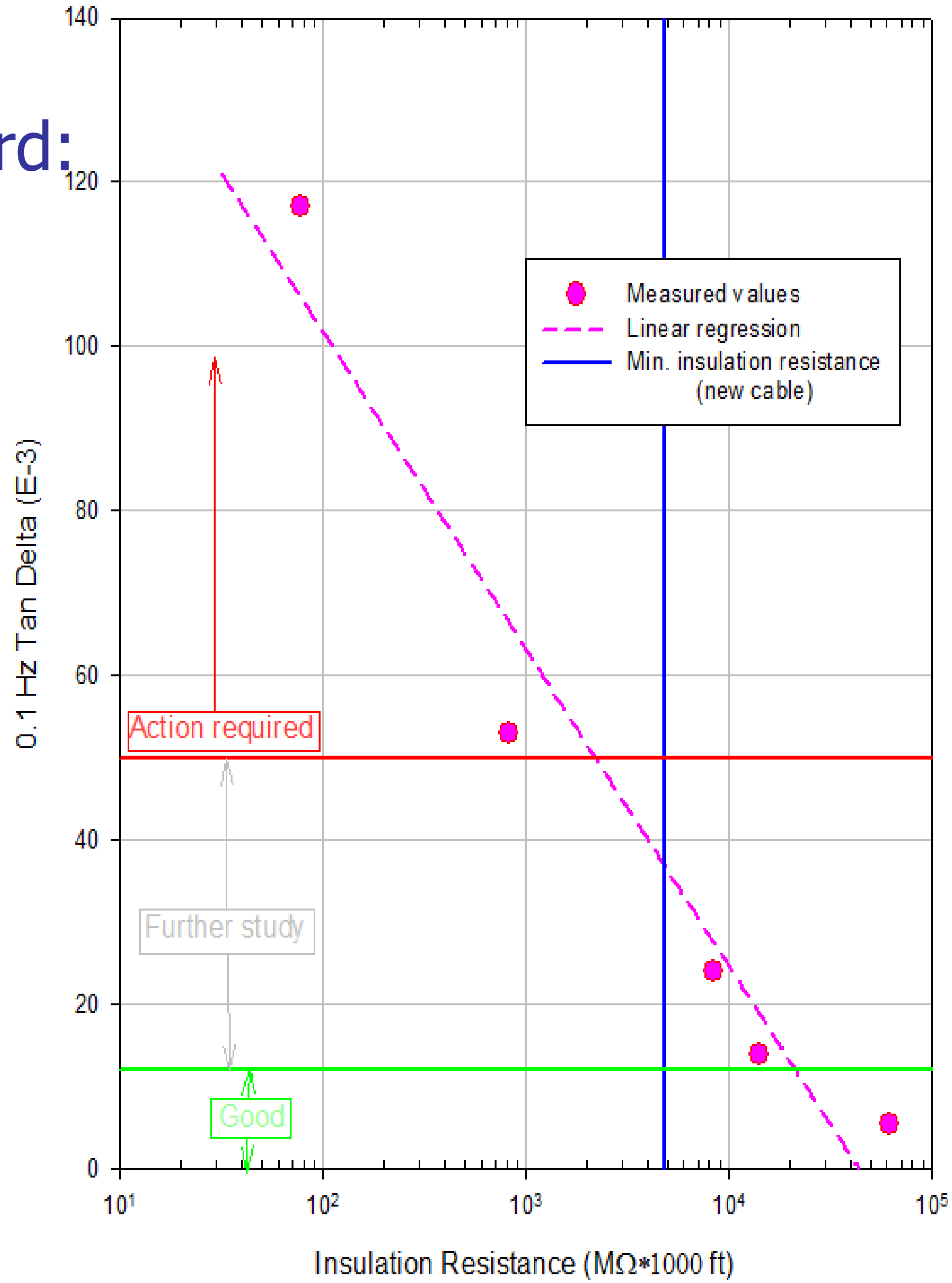
Insulation Resistance after 10 min / Insulation Resistance After 1 minute

Polarization index previously used as indicator of insulation status made sense.



Looking Back & Forward: 0.1 Hz Tan Delta vs. Insulation Resistance

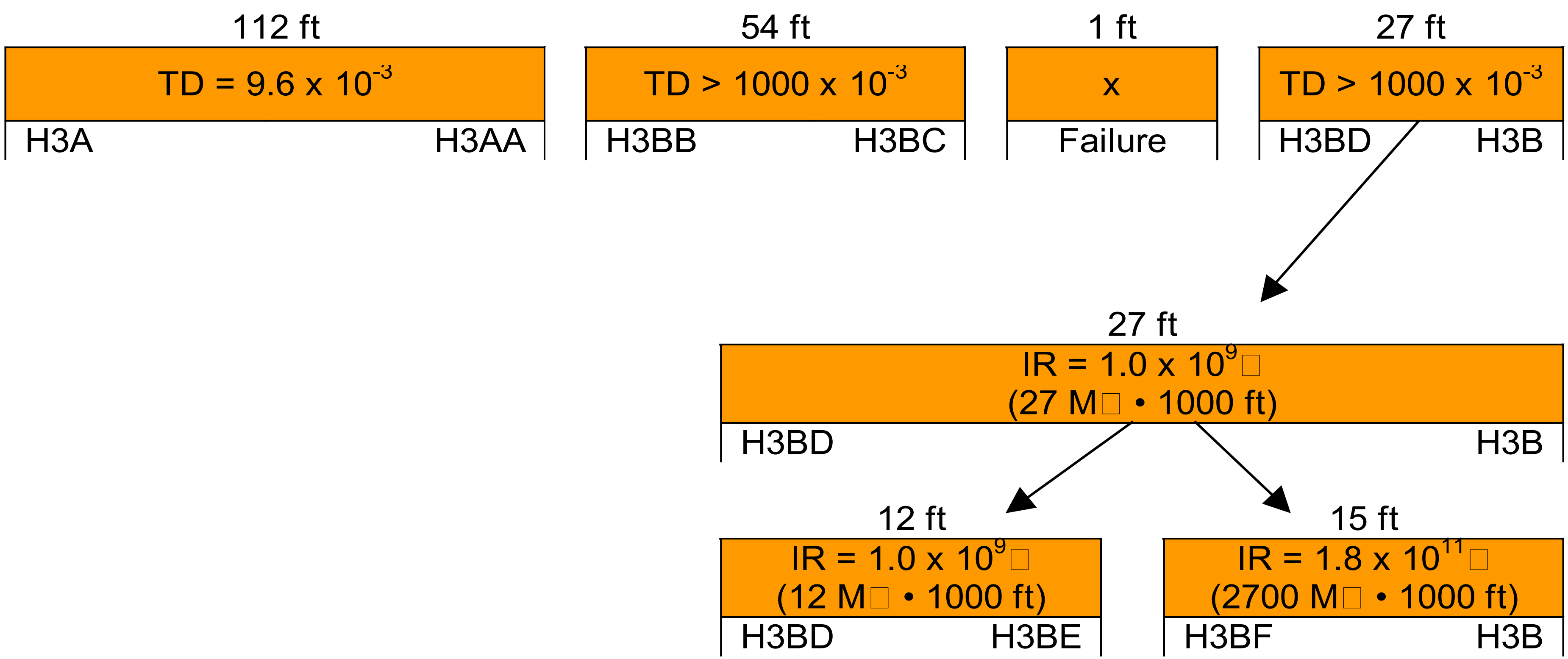
In wet aging, insulation resistance correlates well with 0.1 Hz Tan Delta



Partial Discharge (PD) and Laboratory Breakdown

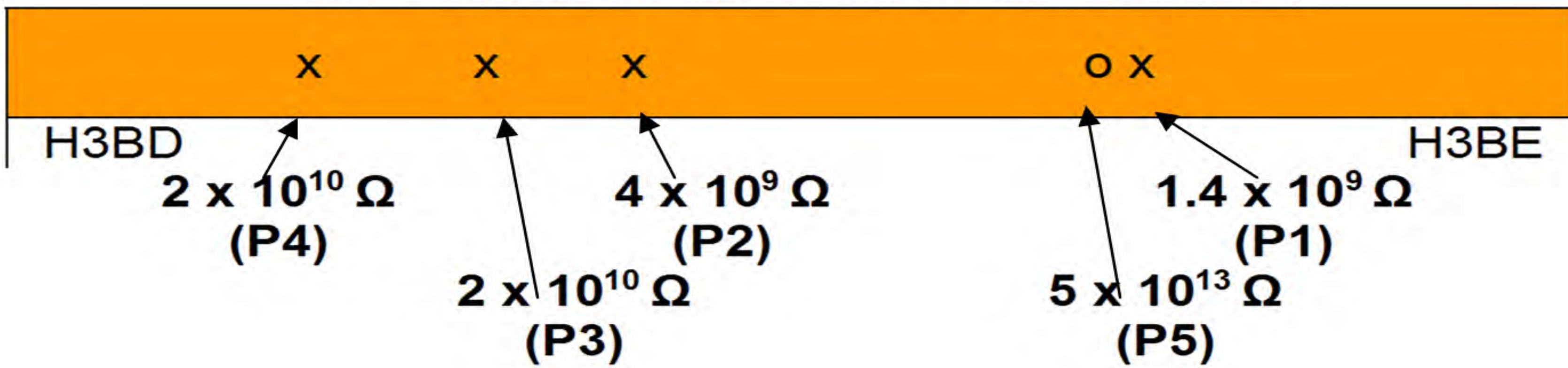
- Attempt made to measure PD of H3 section at 60 Hz
- Section failed at 6.5 kV (2.4 V_0) -> 38 V/mil (1.5 kV/mm) (in less than 2 minutes)
- No PD observed prior to failure
- Phase B would have failed during IEEE P400.2 0.1 Hz recommended withstand test at 7 kV for 0.5 hour
- Other sections of phase B failed as high as 69 kV (29 V_0) -> 410 V/mil
- Probable dielectric strength of new cable was ~ 104 kV/mm (43 V_0) -> 650 V/mil

H3 Sub-sections
After Unexpected AC Voltage Breakdown

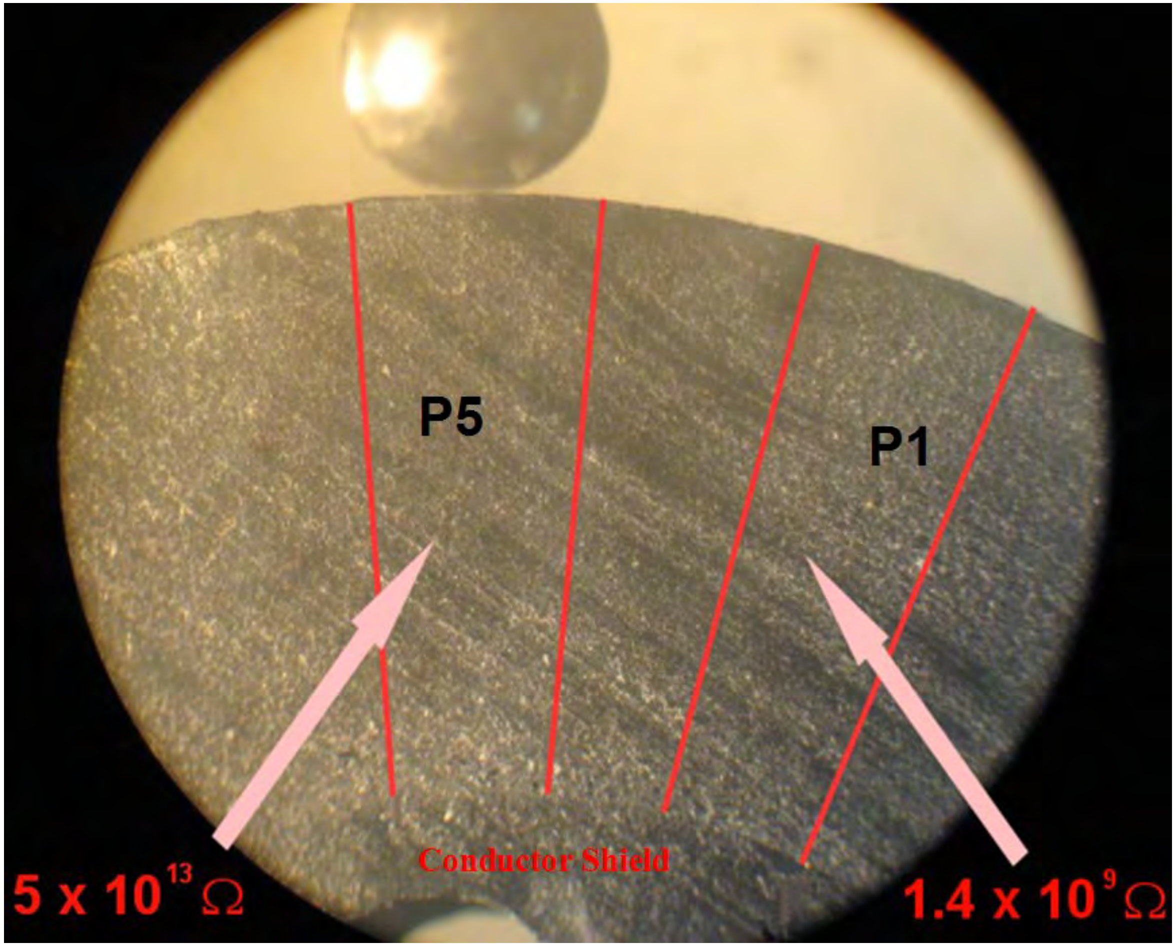


Search For Low Resistance Points

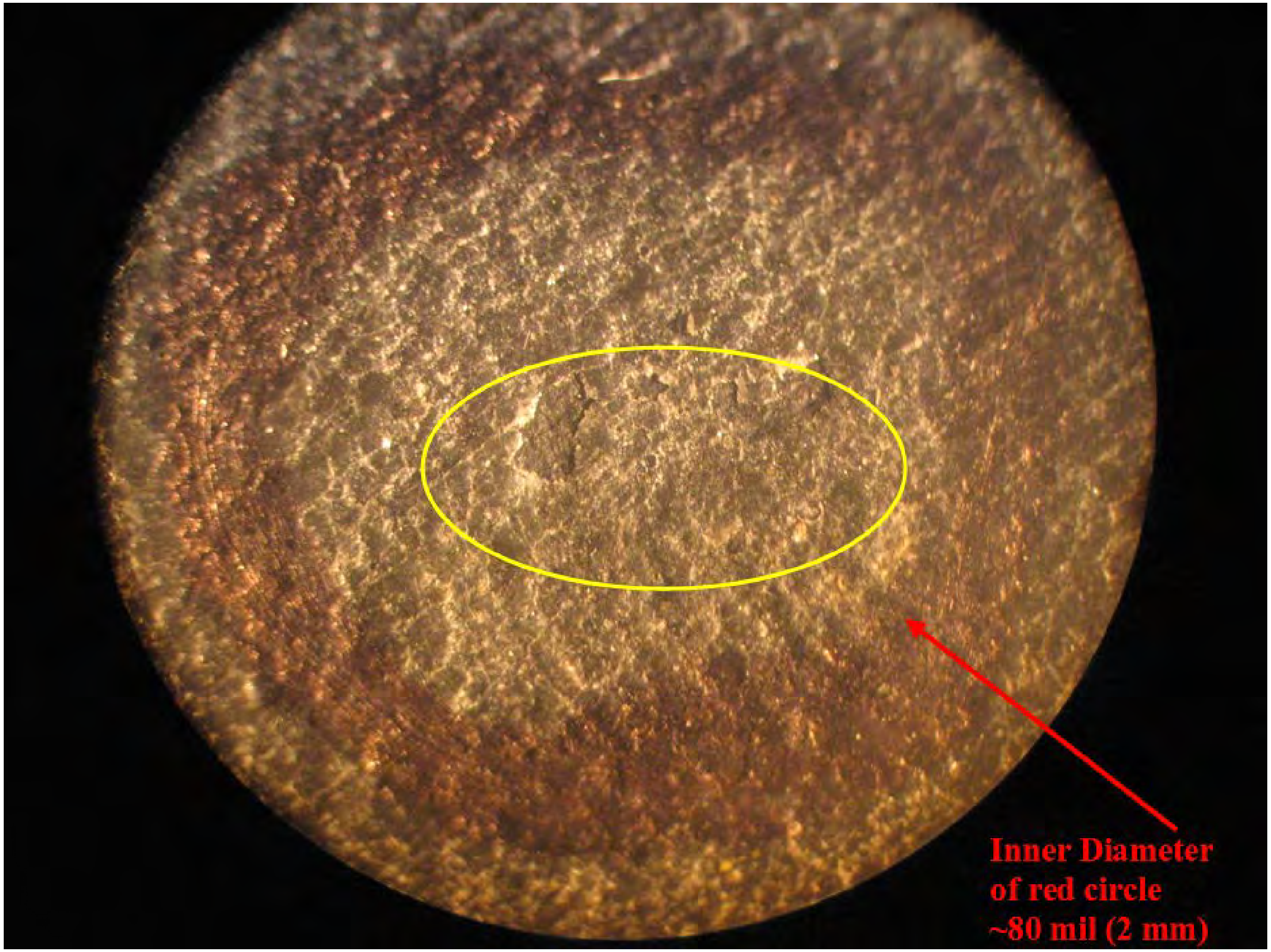
$IR = 1.0 \times 10^{9}\ \Omega = 12\ M\ \Omega \cdot 1000\ ft$



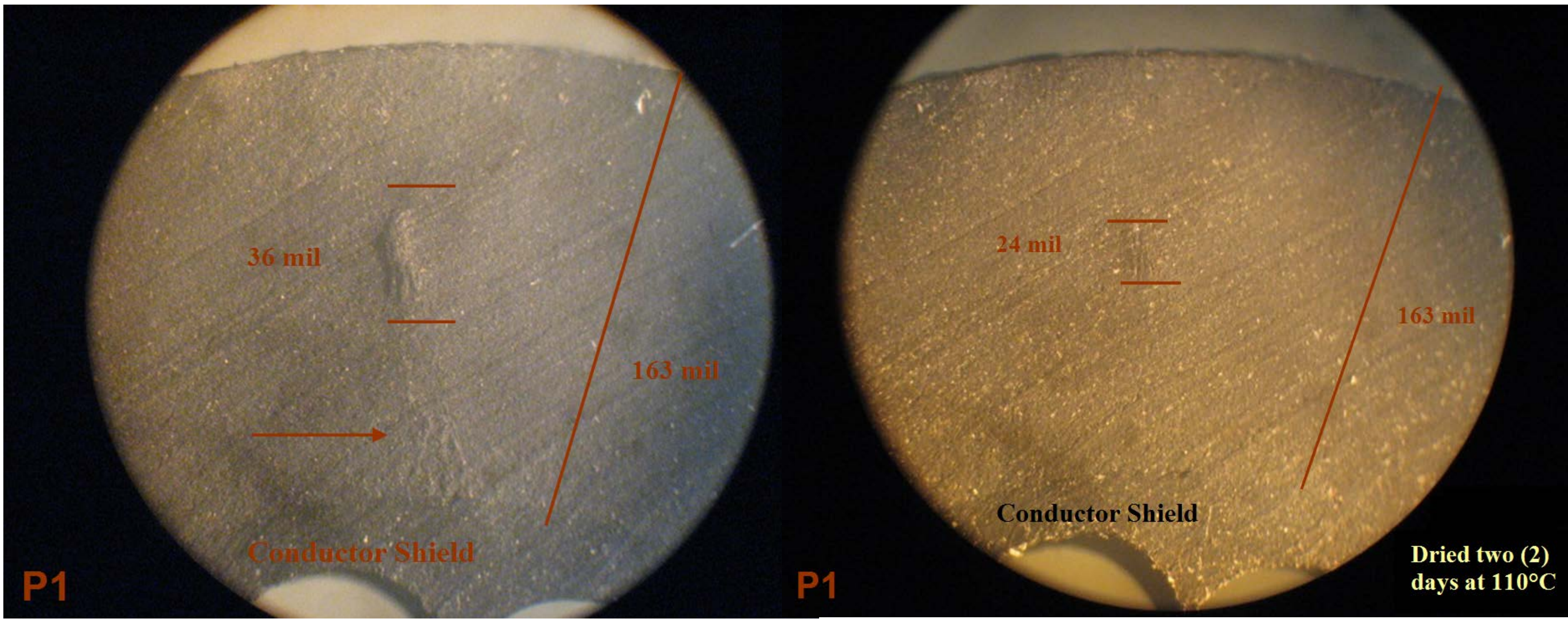
Search for Low Resistance Points *(another view)*



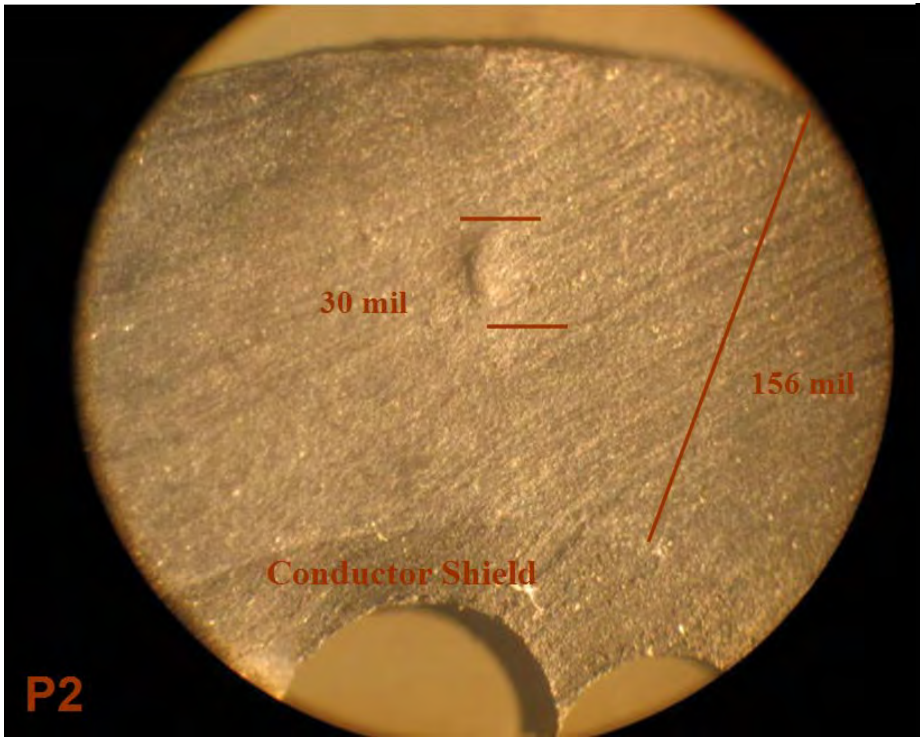
View of Insulation Surface at Low Resistance Location

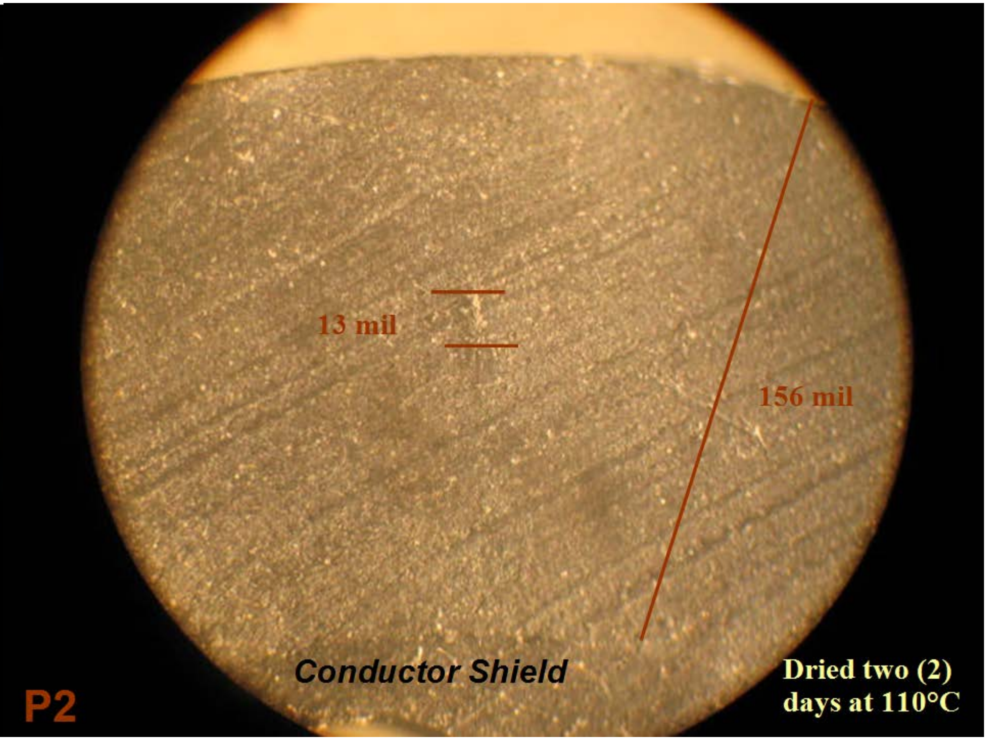


P1 Low Resistance Insulation Wafers after Wetting & Drying

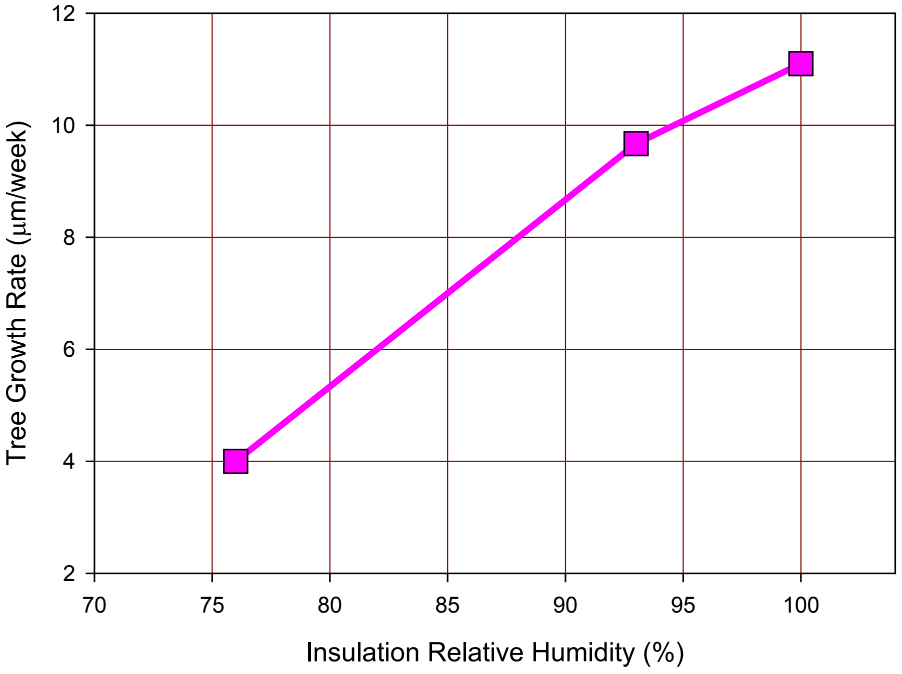


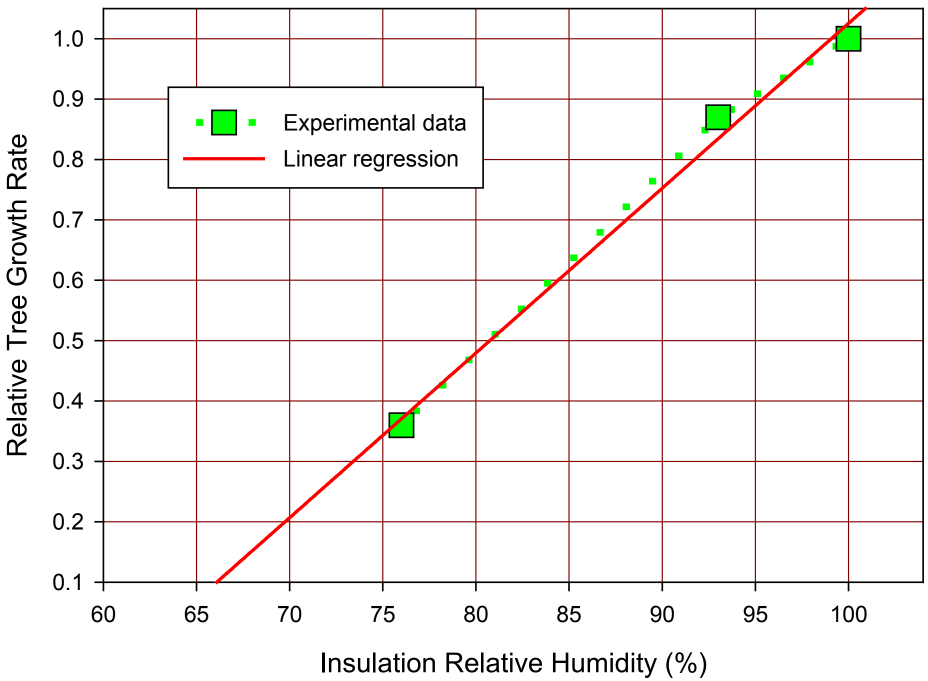
P2 Low Resistance Insulation Wafers after Wetting & Drying





Water Tree Growth Rate in XLPE vs. Insulation Relative Humidity

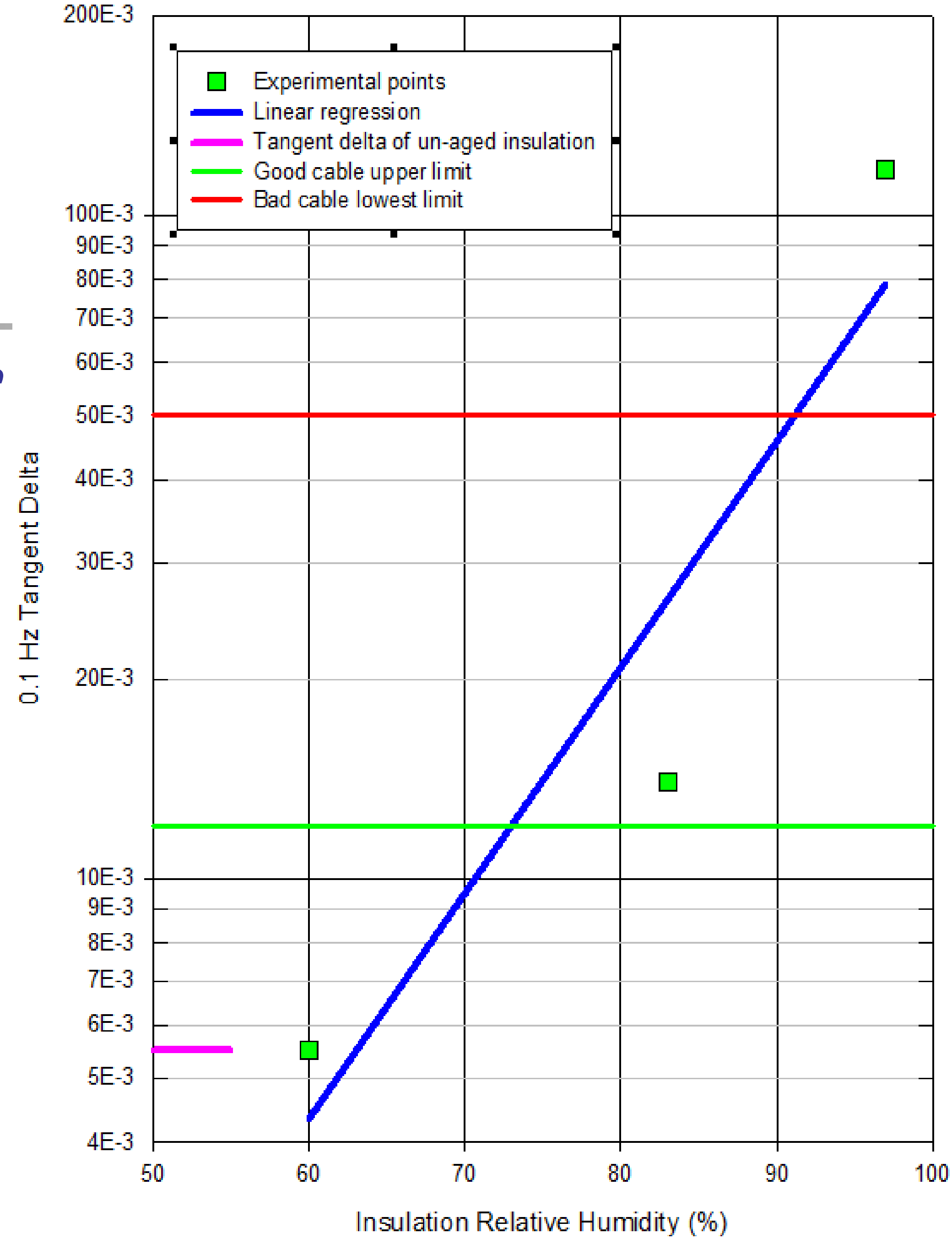




1. Hvidsten, S, Svein Magne Hellesø, Ståle Nordås and Torbjørn Ve. "Water Diffusion in Wet Designed High Voltage Polymer Subsea Cables," *Proceedings of the IEEE/PES Insulated Conductors Committee Meeting,* Orlando, Fl (November 2009)

0.1 Hz Tan Delta vs. Insulation Relative Humidity

(Black EPR insulated cable after 35 years of service)



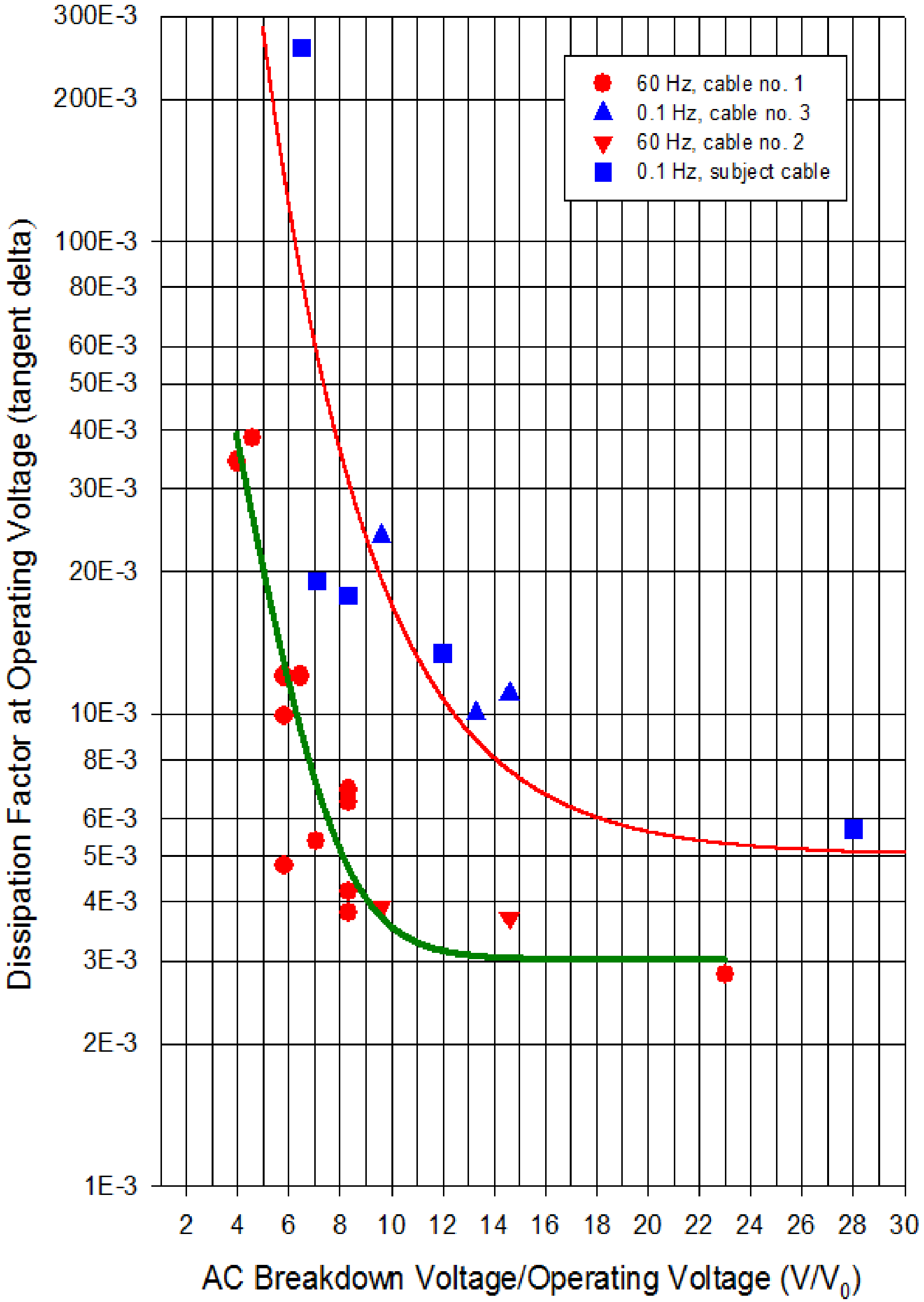
Results of AC Step-Voltage Breakdown Tests of Black EPR Cable

Section Designation	Section Active Length, ft (m)	Tan Delta (E-3)	AC Voltage Breakdown		
			(kV)	V/V_0	V/mil
H4 E-EA	8 (2.4)	5.7	68	28	425
H3	106 (32)	120	6.5	2.7	41
H2 K-L	8 (2.4)	13.4	29	12	180
H2 Y-Z	8 (2.4)	17.8	20	8.3	125
H2 O-P	8 (2.4)	19.1	17	7.1	106
H2 AA-AB	10.3 (3.1)	257	15.5	6.5	97
H4 E-D*	18 (5.5)	5.4	59	25	370
Probable strength of black ERP insulation when manufactured			~104	~43	~650

** Section dried 11 days in 135°C oven*

0.1 Hz and 60 Hz Tan Delta vs. AC Breakdown Voltage

- Dissipation factor correlates well with voltage of AC breakdown
- To estimate from the graph the AC breakdown voltage, the cable has to be uniformly aged or of short length
- TD at 0.1 Hz much better evaluation tool than TD at 60 Hz



Remarks

- Cable failed at low test voltage of 6.5 kV (2.7 V_0) without observable partial discharge
- Low insulation resistance channels were present in the insulation. Lowest single channel resistance ~ $1 \times 10^9\ \Omega$
- At operating voltage, power dissipated in such a channel:

$$(2.4\ \text{kV})^2 / 1 \times 10^9\ \Omega = 5.8\ \text{mW}$$

- Diameter of low resistance channel ~20 mil → $S = 0.2\ \text{mm}^2$
- Density of Dissipated power in a channel:

$$5.8 \times 10^{-3}\ \text{W} / 0.2\ \text{mm}^2 = 29\ \text{mW} / \text{mm}^2$$

Remarks (cont'd)

- To raise cable insulation temperature by 60 C, power density of 0.67 mW / mm^2 is required
- Dissipated power density in low resistance channel is 29 mW/mm^2:0.67 mW/mm^2 = 43 x higher than power density required to raise insulation temperature by 60 C.
- Thermal run-away seems to be a mechanism of wet-aged 5 kV cable's final demise.

Black EPR Cable After 35 Years in Wet to Dry Environment

- Very advanced aging of phase B indicated by high TD at voltages as low as 0.25 V_0 and low insulation resistance
- Sections of B phase affected to a different degree by water
- Degree of insulation degradation correlates with insulation (air) relative humidity
- Cable failed in laboratory without observable partial discharge
- Cable's final "bucket kick" seems to be thermal runaway.

Laboratory Evaluation: Black EPR, 5 kV Cable, in Service about 32 Years

X Phase

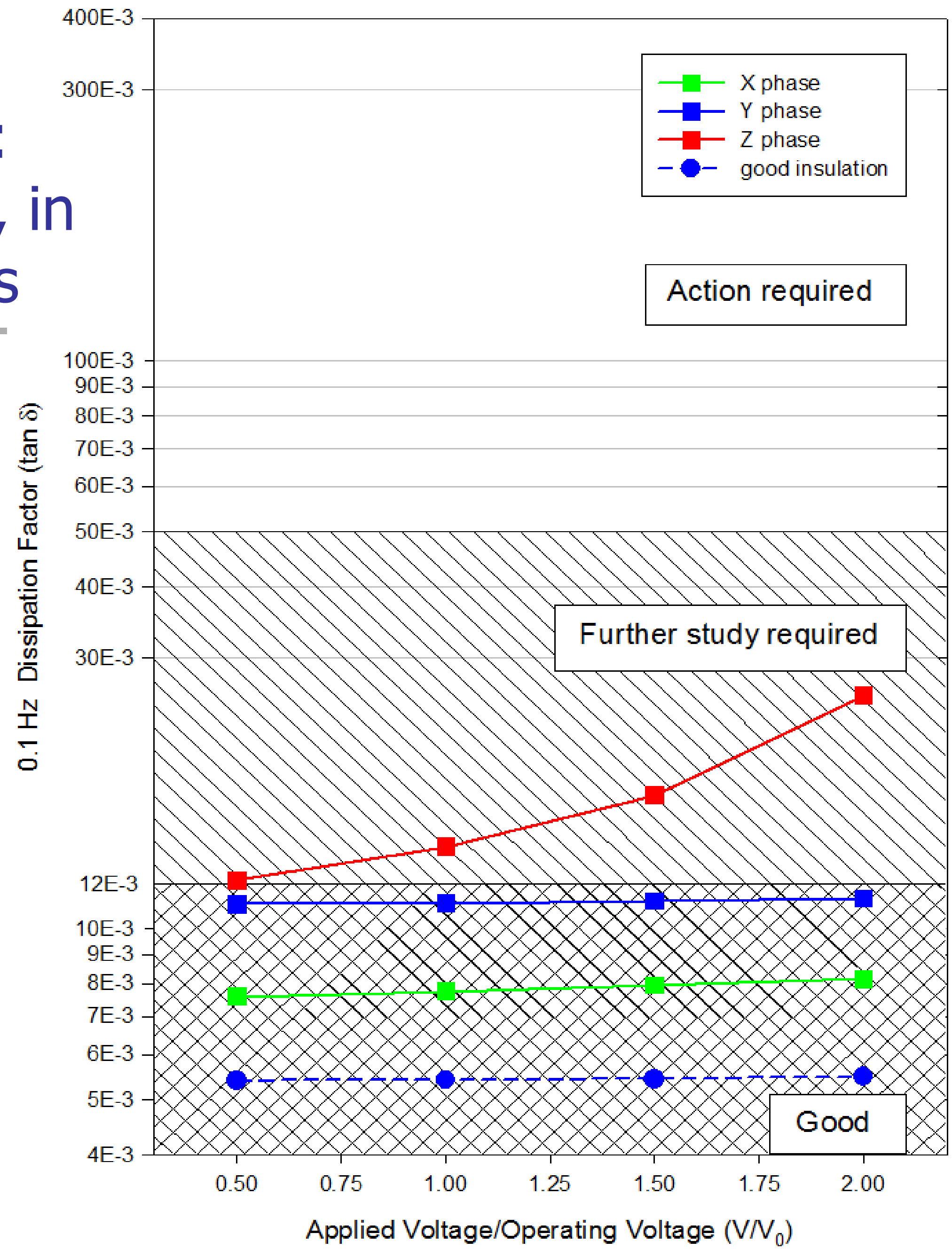
140 ft

Y Phase

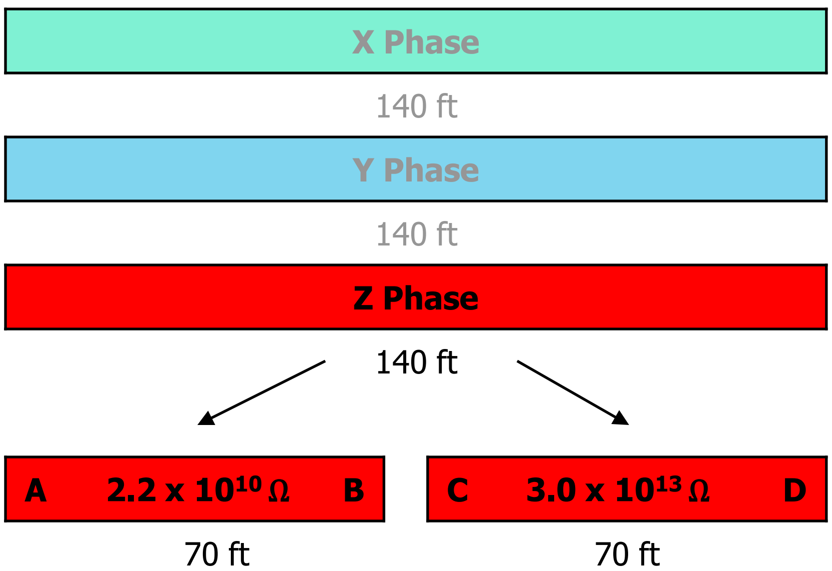
140 ft

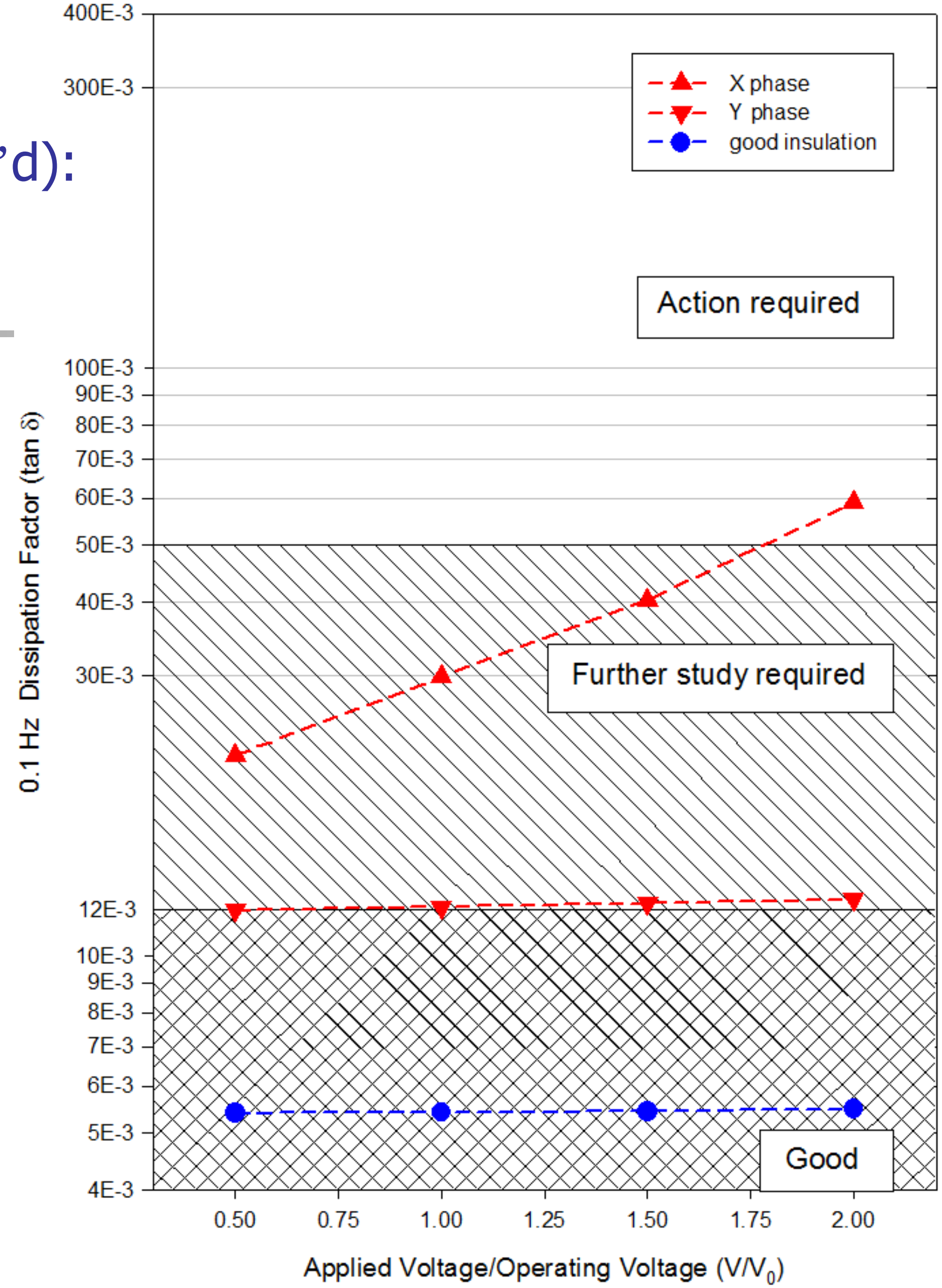
Z Phase

140 ft

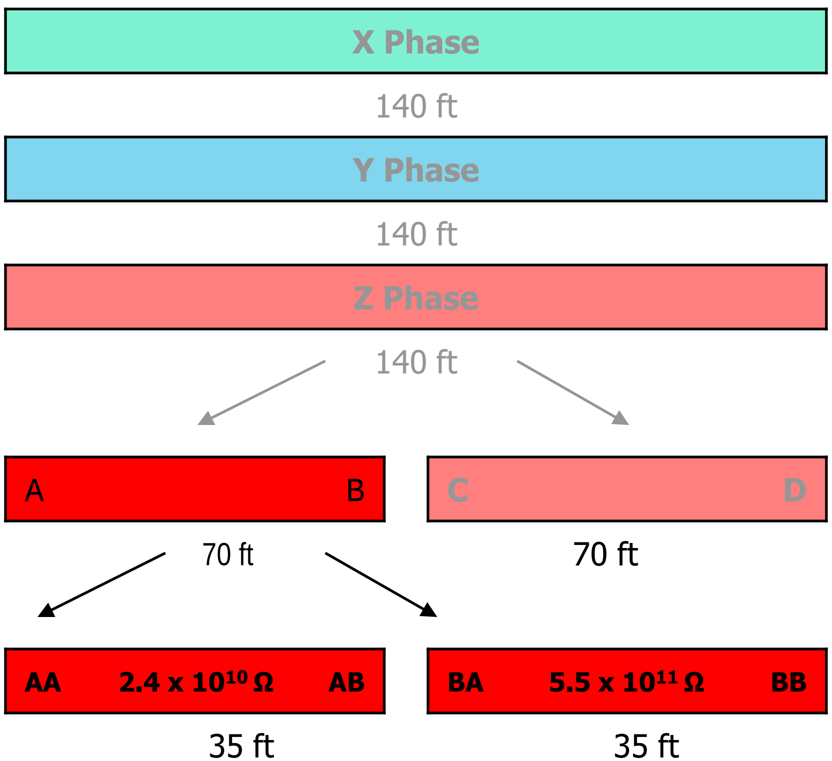


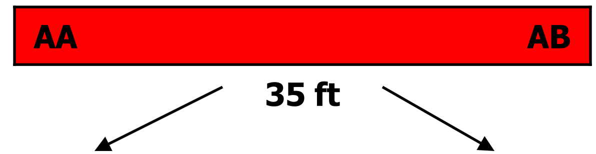
Laboratory Evaluation (cont'd): Black EPR, 5 kV Cable, in Service about 32 Years





Laboratory Evaluation (cont'd): Black EPR, 5 kV Cable, in Service about 32 Years



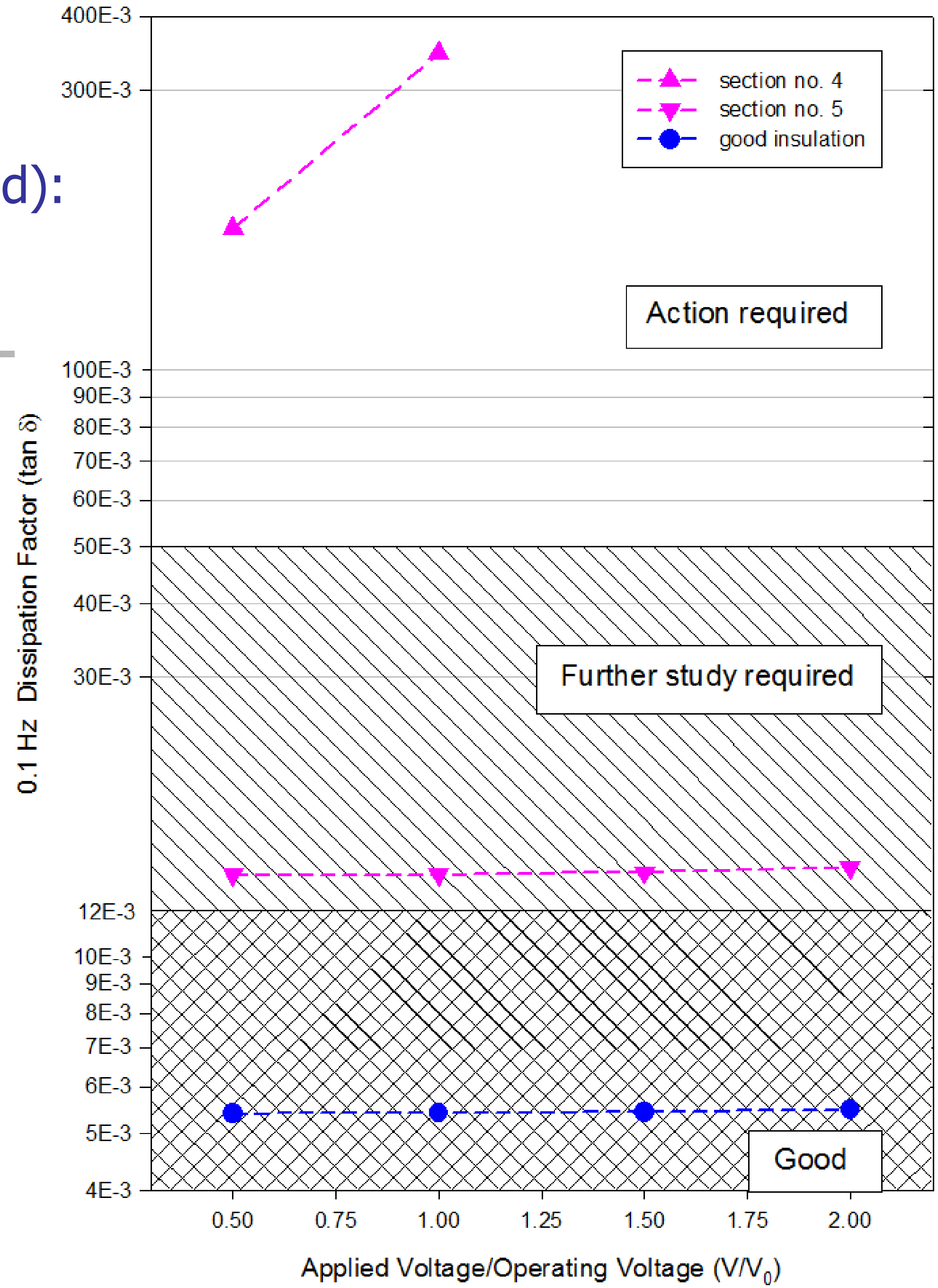


Section Number	Insulation Resistance, MΩ
1	9E6
2	3E6
3	6E6
4	3E4
5	4E6
6	4E6
7	3E6

Laboratory Evaluation (cont'd): Black EPR, 5 kV Cable, in Service about 32 Years

Each section, 7 ft long

Section Number	Insulation Resistance, MΩ
1	9E6
2	3E6
3	6E6
4	**3E4**
5	4E6
6	4E6
7	3E6



0.1 Hz and 60 Hz Tan Delta vs. AC Breakdown Voltage

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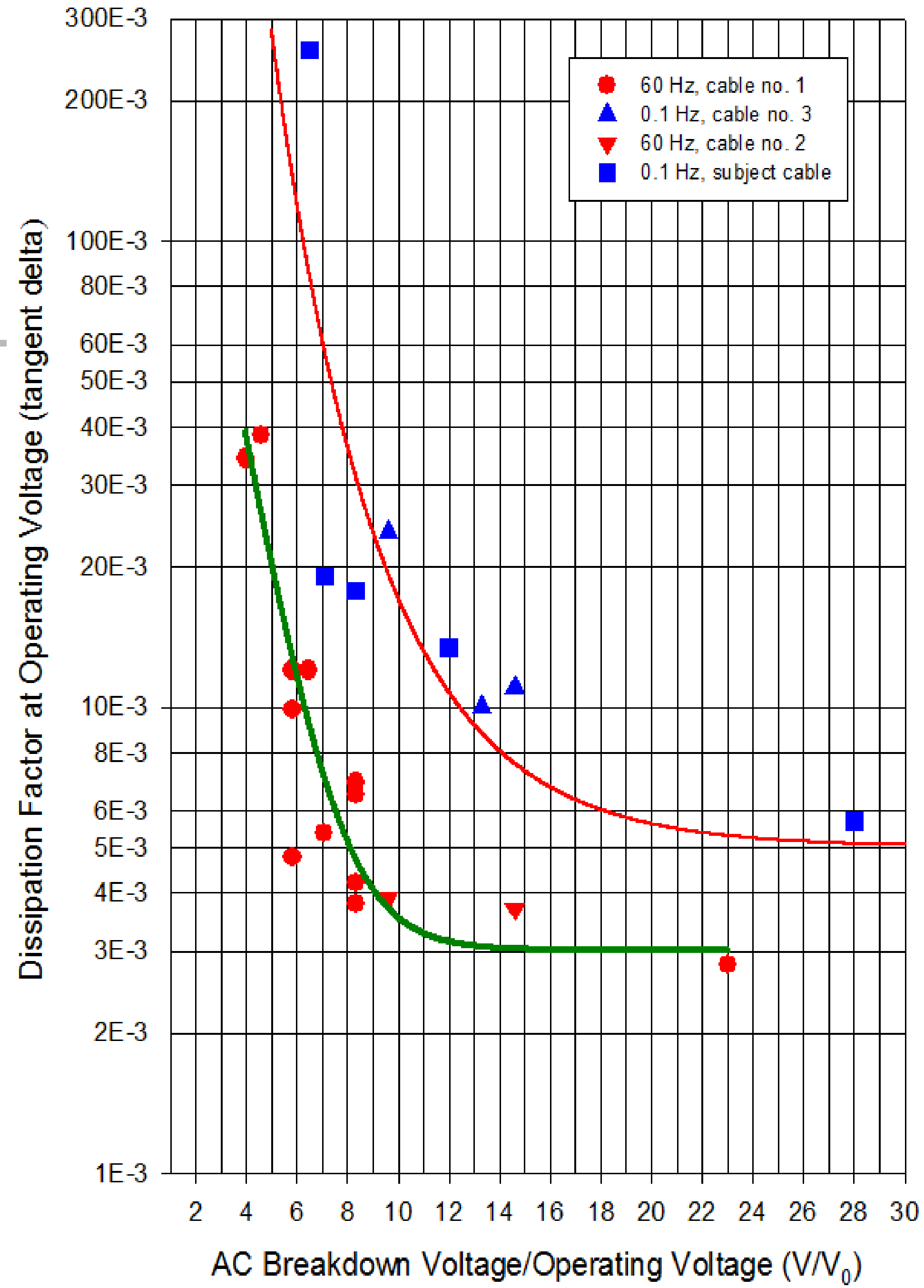

Cable Length and Tan Delta

1. If Tan δ is flat with voltage ≈ cable uniformly degraded along its length
2. If Tan δ increases "significantly" with voltage ≈ part of the cable is degraded much more than the rest
3. Not degraded length of cable washes-out the effect of insulation degradation on tan delta
4. Because of 3, if possible, test as short length of a cable as practical (if six conductors per phase, try to measure one conductor at a time)