MV Cables'
Field Aged Test and Reliability Results

ICC Educational Session

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Outline

- Typical Constraints
- Sources for this presentation
- Examples from North America, with limited comparison to accelerated cable aging
- Examples from ex- North America
- Summary / Conclusions

“Field aging data”

Constraints / Reality

- Involves time, $$, Commitment, Data gathering / analysis

- Operating cables:

    - Lack of continuous monitoring techniques
    - $$ for tracking on-going data gathering
    - Challenge to take operating circuits out of line
    - $$ for replacement of ‘test’ sections
    - In many instances, even lack of information for cables’ location
    - Etc. etc…..

- ‘Failed’ cables

    - Lack of consistent data gathering processes / protocols
    - Need for data isolation of ‘cables’ vs. ‘Accessory’ vs. ‘other’ failures
    - Etc, etc……

Field Reliability Evaluation

Examples - North American utilities…….

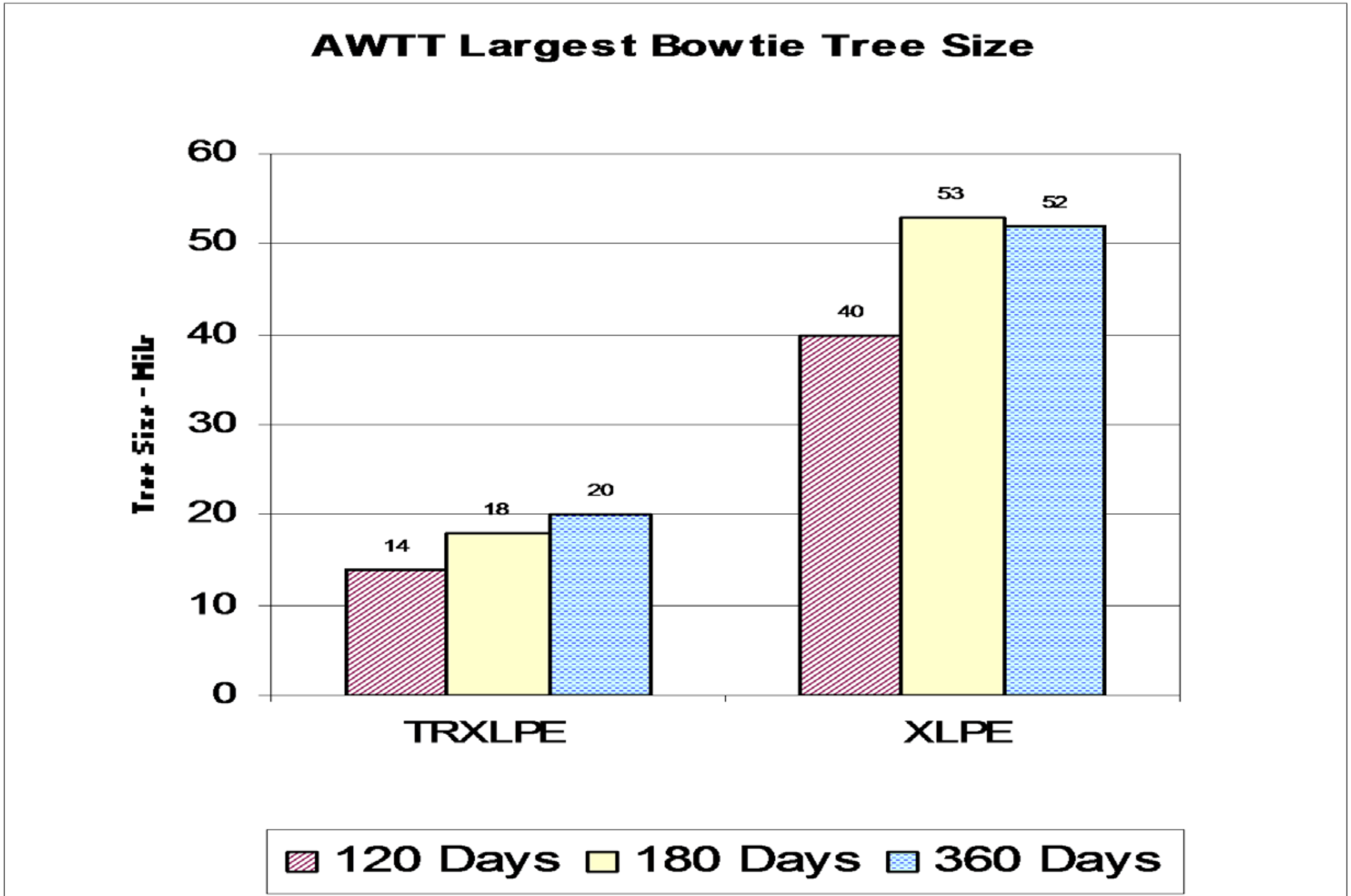
Treeing (Wisconsin Public Service)

Electrical Strength (Alabama / CenterPoint)

Cable Faults (Oncor Delivery)

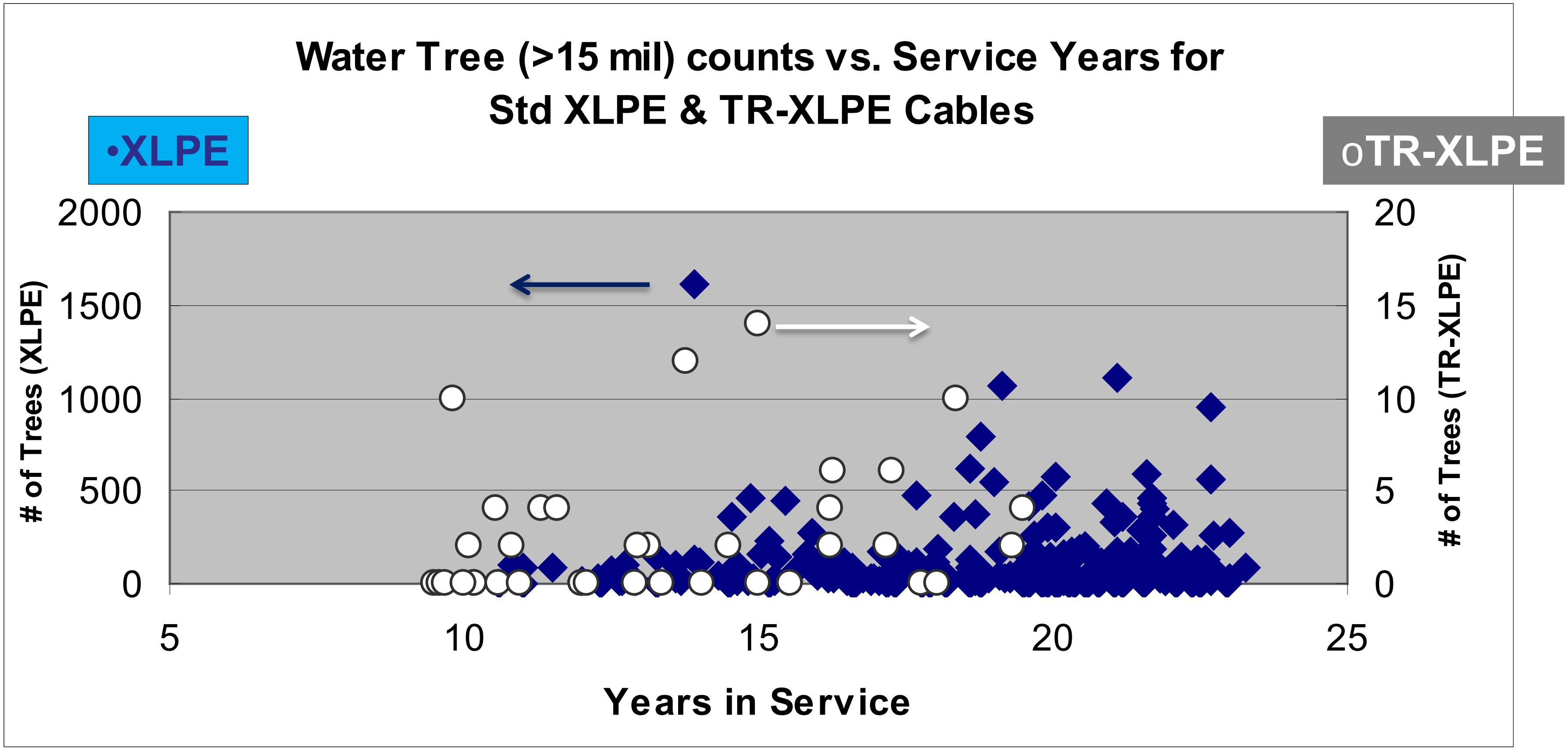
Asset management (Hydro Ottawa)

AWTT Test- Water Treeing Performance



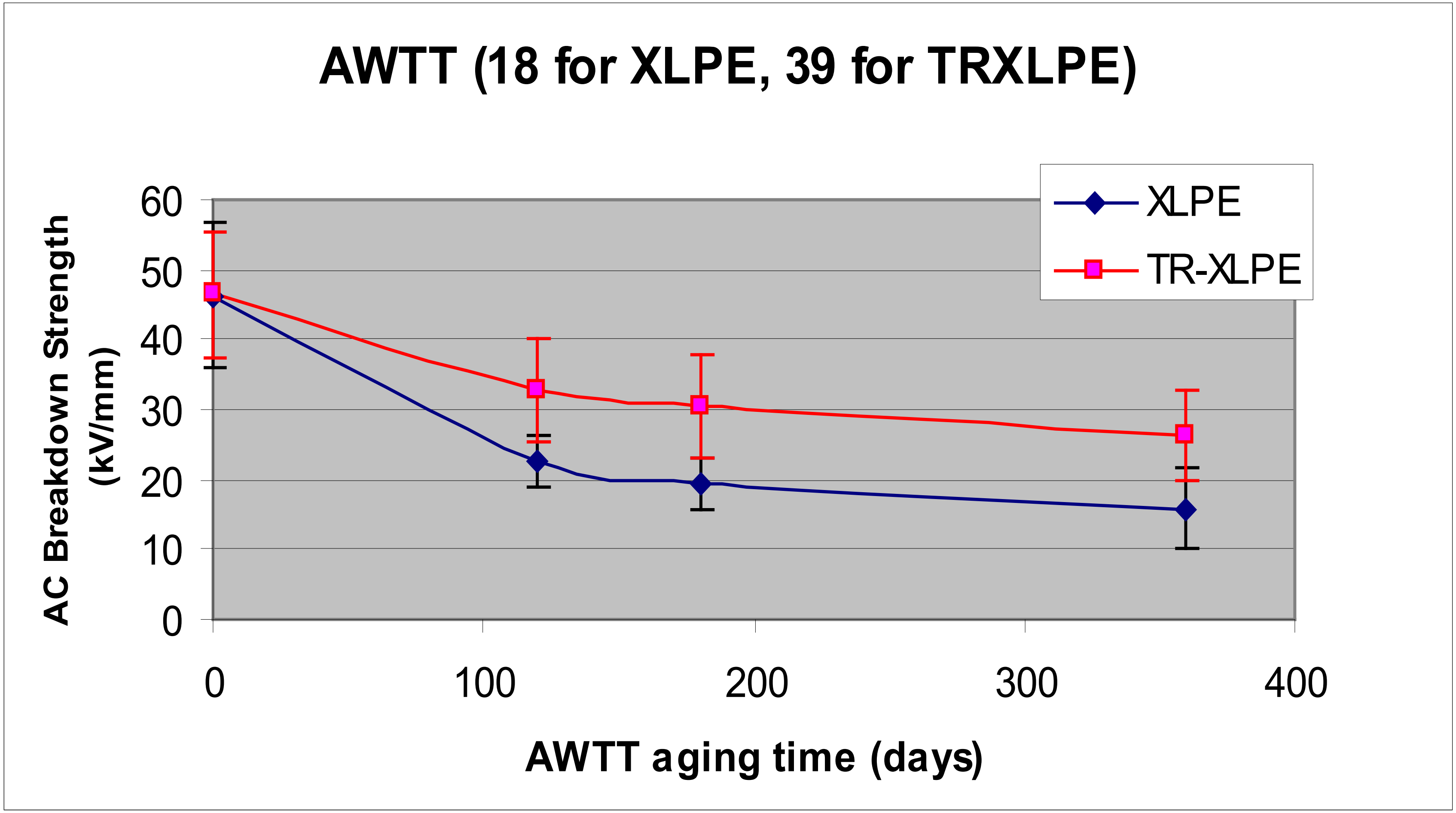
Courtesy - NEETRAC

Wisconsin Public Service Corp. Experience Related to Water Trees



From: CIGRE Canada Paper, 2008

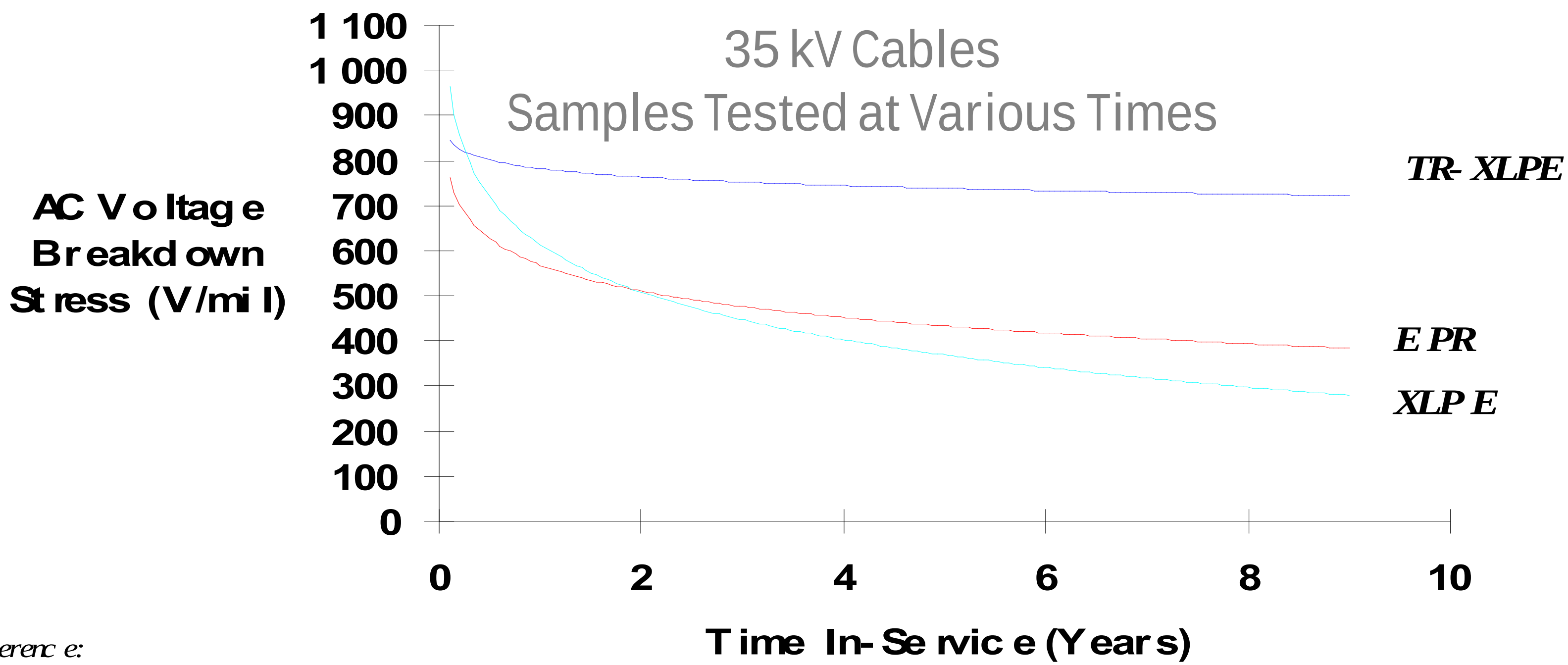
AWTT Qualification Tests Conducted in the 90's



The error bars represent +/- 1 standard deviation.

Courtesy - NEETRAC

Field Aged Performance - CenterPointe Energy (Houston Lighting & Power)



Reference:
“Evaluation of Service Aged 35 kV TR-XLPE URD Cables,”
C. Katz, M. Walker, September 1996 T&D Conference

Field Aged Cable Testing – Alabama Power and HL&P

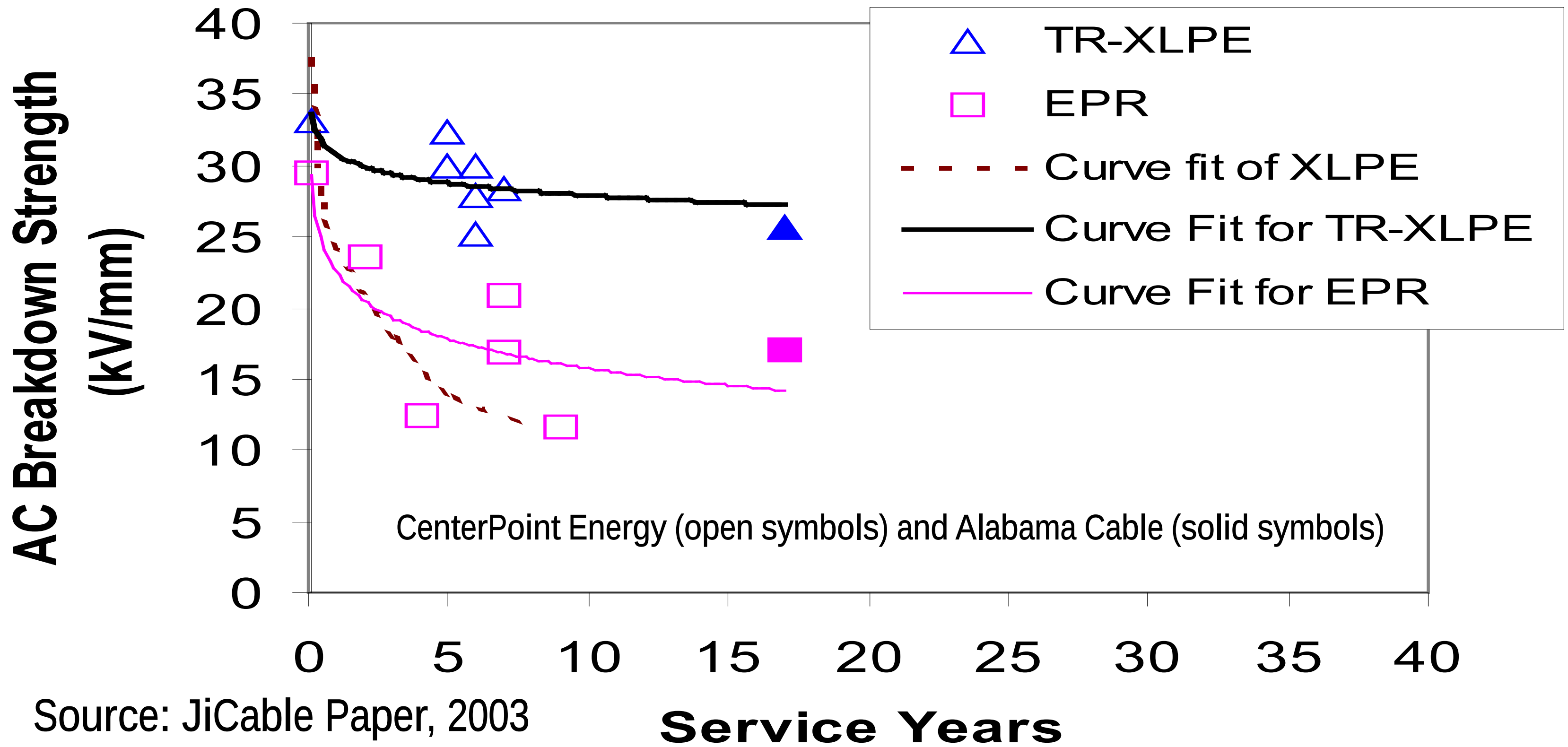
- Similar cable designs and installations at both utilities
- 35kV, 345 mil insulation, installed in PVC ducts
- Same EPR and TR-XLPE at both sites
- Alabama Power cables tested 17-year-old cables in 2003
- HL&P tested nine-year-old cables in 1997

Presented at Jicable 2003

Alabama Power & CenterPoint Energy

35kV TR-XLPE & EPR Cables

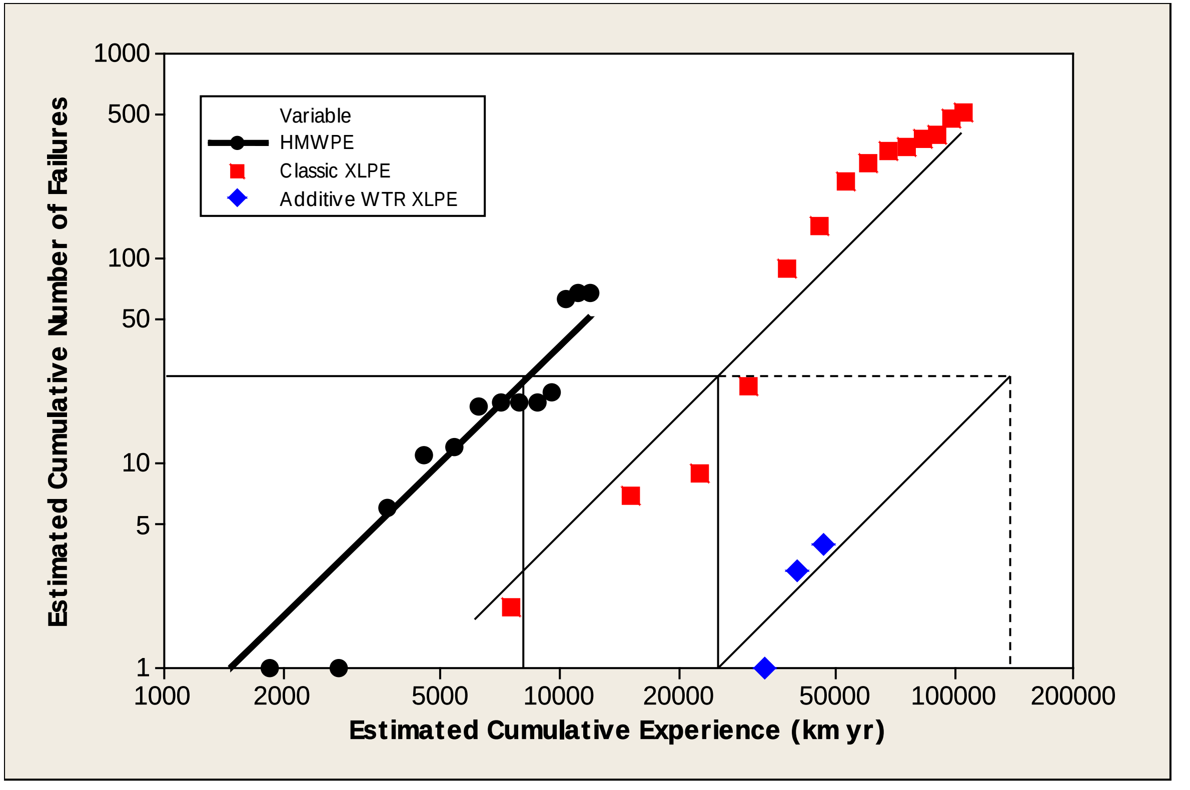
Good relative stability of AC breakdown strength after 17 years of field operation



Source: JiCable Paper, 2003

TXU (Oncor) TX, USA – Fault History
Three historical insulation systems

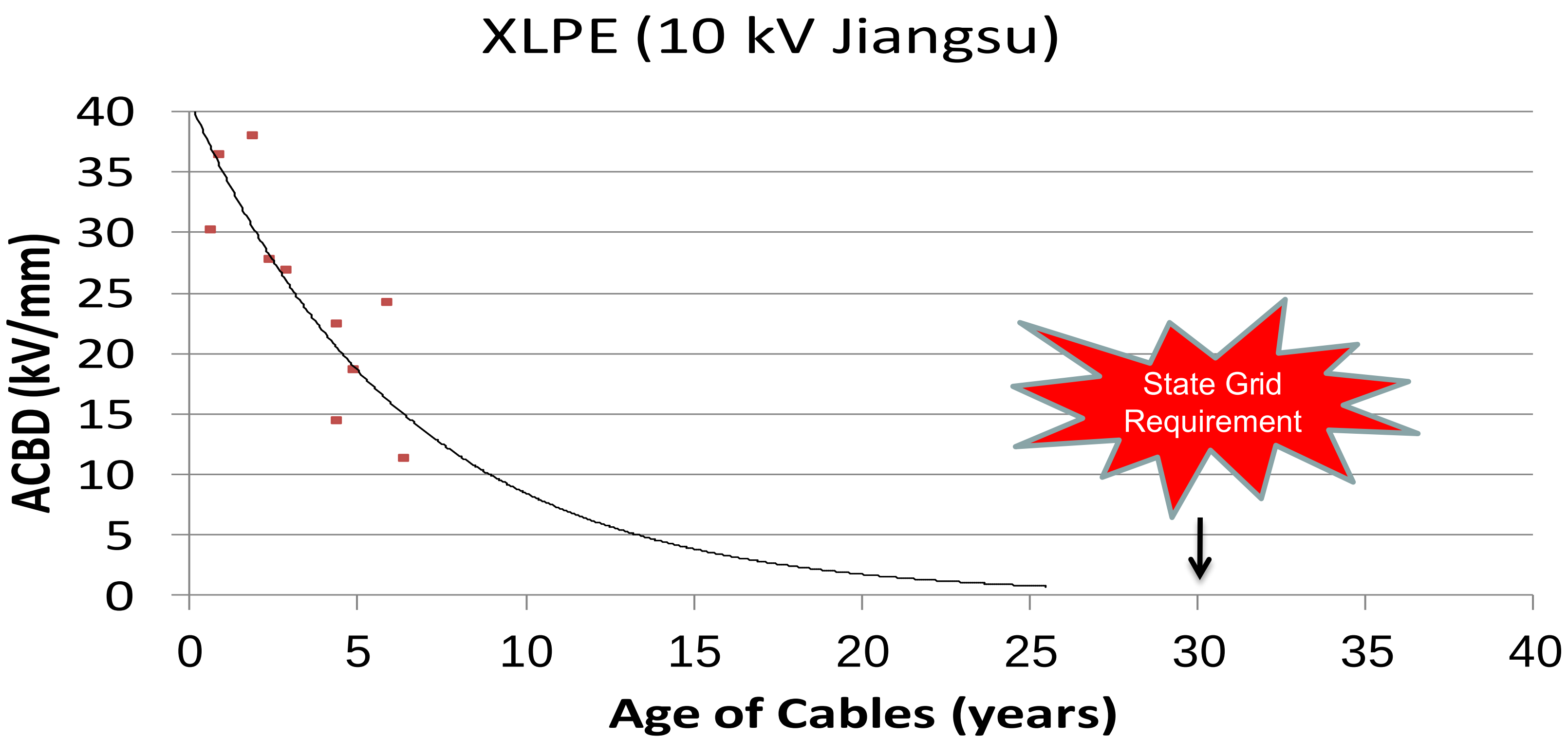
30 failures occurred after:
9,000 km-years for HMWPE.
22,000 km-years for XLPE
>>100,000 km-years for
“Additive” WTR XLPE cable (est.)



Crow-AMSA Analysis

Ref: “Long-life XLPE Insulated Power Cables”., Ed. by Harry Orton and Rick Hartlein , 2006

Cable Aging – Jiangsu, China



Jiangsu: XLPE (Source of data: CIGRE 2010 B1-112 paper)

Summary / Conclusions

- Collection of on-going field aged cable performance is spotty for a host of valid reasons
- Similarly, rigorous collection practices and analysis of field cable fault data are not very robust
- However, collection of data allows utilities to make reasonable decisions on asset management
- North American utilities have had very good performance for past several years
- Similar experience is seen from Germany
- Broader, global perspective is a challenge, with limited data
- NOTE: Fall 2004 ICC Educational Session had several utility presentations …..including: SDG&E, WPS, Oncor, OG&E, HL&P etc.
- In addition, there may have been other ICC presentations over the years……Puget Sound & Energy, Hydro Quebec etc. that may be of use.

Field Aged Cable Performance Data and Correlation to Accelerated Aging Data, HV Paper Cables

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ICC Educational Program

March 28, 2012

Seattle, WA

Outline

- HV Paper Cables, focus on HPFF cables
- AEIC/EEI Cornell (345 kV) & AEIC/EEI/ERC Waltz Mill (550kV & above) Accelerated Paper Cable Testing
- EPRI Waltz Mill (138/345 kV) Accelerated Paper Cable Testing
- Field Aged Performance Data (life/paper/fluid), both from Waltz Mill Accelerated Testing and Cables Removed after Long Service
- Despite exceedingly long life expected/predicated under typical operating conditions, and long measured and very sound radial Paper as well as Fluid properties of in-service cables along with quite satisfactory visual inspections, failures have at times been encountered in cables per se. Why? Potential Reasons. A better understanding & substantiation toward this end will be valuable
- General Conclusions/Recommendations

HV Paper Cables

- HPFF (110 – 138 kV) and HPGF (120 – 138 kV) cables were commercially introduced, respectively, in 1935 and 1941 in the US. General construction has remained essentially the same, however, gradual refinements in materials and processing have been made, resulting in reliable higher voltage levels and power capabilities. The first 230 KV HPFF cable was installed in 1954 by USACE at Garrison Hydro-dam, ND. The first 345 kV HPFF cable system was energized on May 1, 1964 at Con Ed, NY – still the highest voltage level in the US for HPFF cable systems
- Of the nearly 4,500 circuit-miles of the US underground transmission system - mostly 69-345 kV HPFF cables (over 75%) - with limited HPGF but presently only up to 138 kV & still less SCFF cables (69-525 kV; submarine ones pretty much intact). HPFF cables continue to be our workhorse
- Over 50% of HPFF cables are approaching/have exceeded their assumed design life of 40 years, hence increasing emphasis on the performance of operating cables, including regular maintenance
- Performance record under operating conditions excellent, all the more for HPFF/HPGF cables per se – quite true for accessories as well, after taking care of some earlier 345 kV paper splice problems in the field

Cornell Accelerated Testing, 345 kV

- First accelerated field test program involving four 345 kV HPFF cable systems (2 HPFF & 2 SCFF) from 4 cable and 2 termination manufacturers over 3 ½ years (1961-1964); each cable had 2 joints
- Load-cycling (32 hours on and 16 hours off) with increasing conductor temperatures (45-115 ^{0}C,) and applied voltages (100-145% rated) over well-defined periods in 3 phases
- The testing protocol was deemed to simulate/exceed 40-year life
- At the end of the testing, cables were returned to the respective manufacturers for a through examination, necessary measurements and tests to determine whether visible or measurable changes have occurred in any part of the cable system

Cornell………

- The electrical tests on full-size cables included both power factor- temperature and voltage time tests per applicable AEIC Specifications. In addition, radial paper tape (PF @80 ^{0}C, tensile and elongation, folding, moisture, dielectric strength) and impregnating fluid (PF @100 ^{0}C , IR spectrum, viscosity) evaluations were made and the results compared to the initial values.
- Based on both visual inspection and detailed testing, little or no changes were found in either the cable as a whole or its insulation system comprised of paper and fluid after 3 ½ yeas of over-voltage and high-temperature cycles, assuring a reliable in-service life

Waltz Mill Accelerated Testing, 550-765 kV

- Drawing from the experience of Cornell testing, under contract to EEI Westinghouse built Waltz Mill accelerated HPFF cable testing facility in 1968, operating it until it was transferred to EPRI in 1973
- This extensive facility was designed to test 12 prototype cables in the 138 -1100 kV range
- The accelerated testing at 500/550 kV HPFF cables included the same 4 cable & 2 termination suppliers. The initial 2 years program(Phase 1), was extended to perform further testing (Phase 2) involving overload testing for two cables at both continuous and cyclic periods at conductor temperatures of 110 ^{0}C, 120 ^{0}C & 130 ^{0}C, requiring 2 months at each temperature, applied voltage being 690 kV (L to L), and overvoltage testing up to 930 kV at conductor temperatures of 90 ^{0}C and 100 ^{0}C.
- The objective of Phase 2 was the evaluation of 765 kV cellulosic cable
- Forced-cooled testing was later done for this design for voltages up to 765 kV for cable(s) systems surviving Phase 2
- Unlike Cornell, both continuous & cyclic loading modes were applied over 2 years. The former resulted in thermal aging of cable insulation, while the latter also afforded mechanical working of the cable assembly.

500/550 Test Protocol

Test Period	Test Percentage	3 Ph/1 Ph Voltage kV	Conductor Temp. ^{0}C	Type of Test
1	110	550/317	75	Continuous
2	110	550/317	75	Cyclic
3	125	626/360	75	Continuous
4	125	626/360	90	Continuous
5	125	626/360	90	Cyclic
6	125	626/360	90	Continuous
7	125	626/360	100	Continuous
8	125	626/360	100	Cyclic
9	125	626/360	100	Continuous
10	137.5	690/400	75	Continuous
11	137.5	690/400	90	Continuous
12	137.5	690/400	100	Continuous

Note: The shield temperature was to be maintained between 60 ^{0}C and 70^{0}C.
One Period = 2 months under voltage and load.

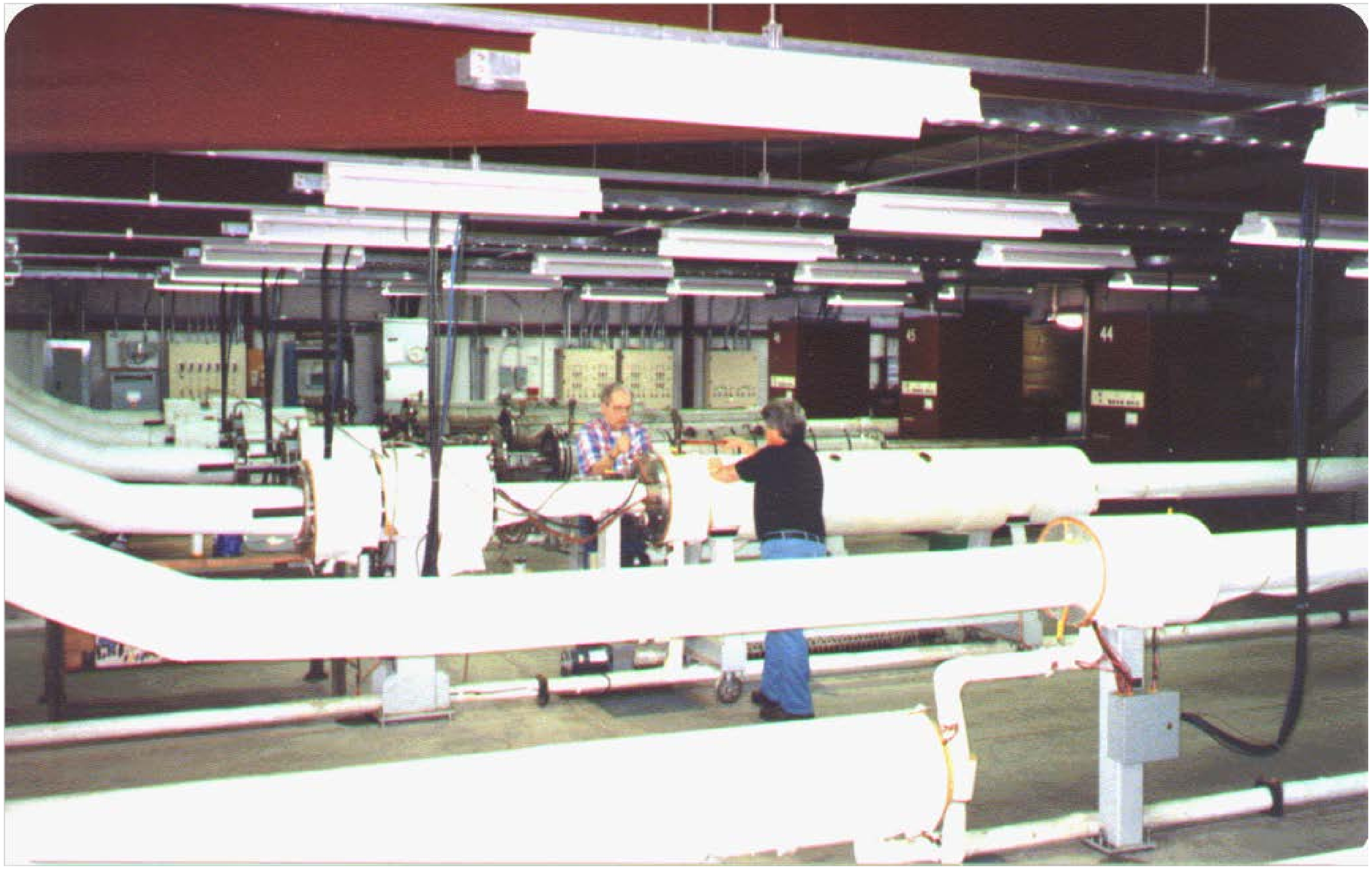
500/550 kV………

- The test program was based on an equivalent 40-year life, per $V^n t$ relationship (n=10) and temperature-time equivalent with 8 ^{0}C rule
- All cables (1000 ft., one splice) successfully passed the 2-year plus testing (2 year period, July 1969 to August 1972). Cable systems were well monitored during the testing period for DF as a function of voltage, conductor temperature & time. In addition, the samples returned to the manufacturers were visually inspected, including electrical testing of samples & testing of paper tapes (TS, tear, folding, dielectric & moisture – DP only for one of the cables) and pipe fluid/impregnant (DF, moisture, IR, BD, peroxide, neutralization & resistivity). This varied data indicated that the conditions of the cable has remained basically the same
- It is noteworthy that the cables were returned after phase 2 & thus the above tests included testing beyond the original 2 years
- Based on this detailed testing, it was concluded that the cellulosic paper systems have maintained their integrity & are acceptable for commercial operation at 550 kV, and even 765 kV – a minimum of 40 years life under typical operating conditions
- The outcome of the 550 kV program singularly strengthened the commercial acceptability of HPFF cable systems at 345 kV in the US

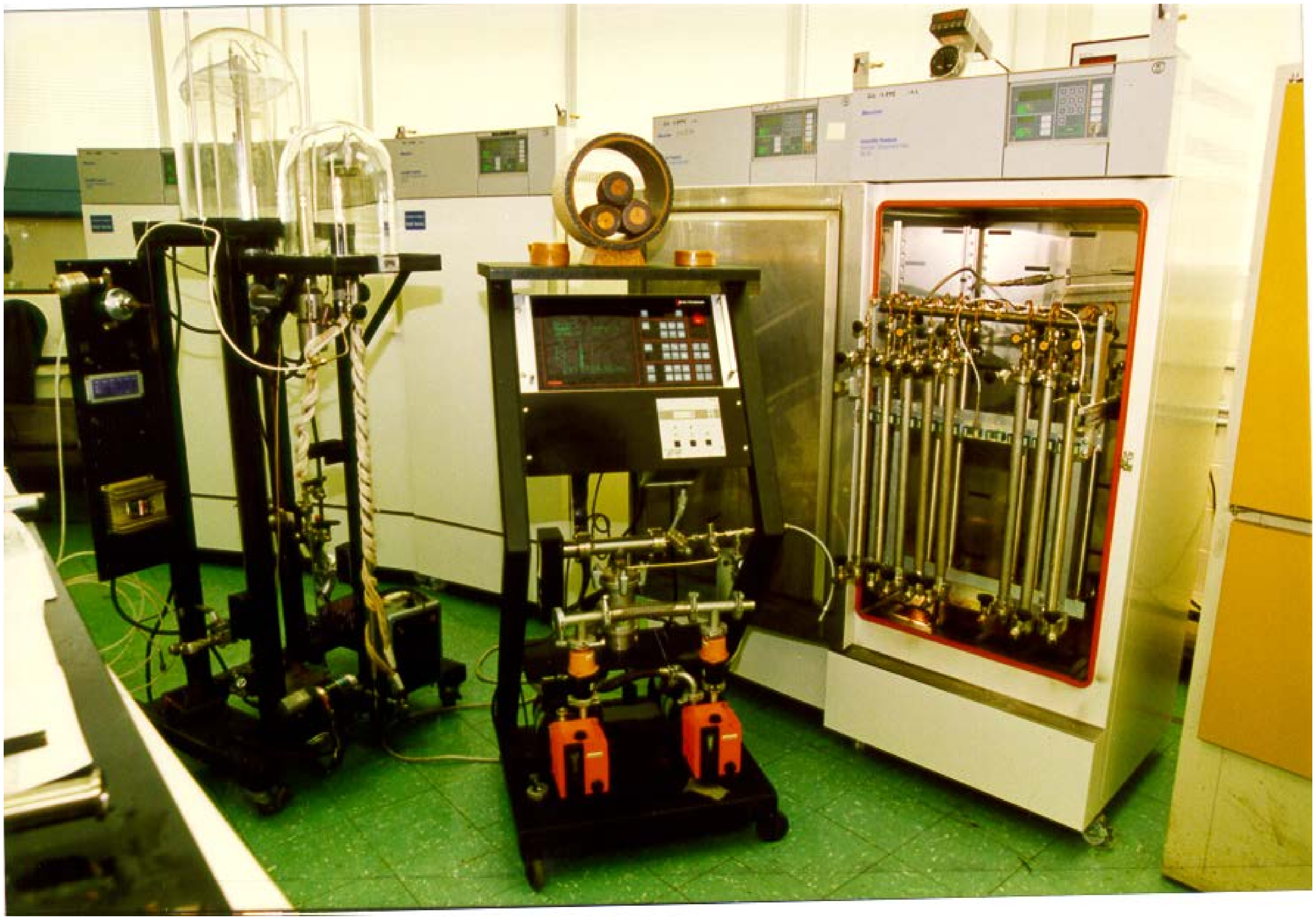
EPRI Waltz Mill Accelerated Testing, 138-345kV

- This 1992-1998 project was comprised of 3 independent but related areas based on both laboratory and field investigations :
- #1: Accelerated aging of six 138 kV and six 345 kV warehoused HPFF cables of different vintages at elevated and cyclic temperatures (125-137.5 ^{0}C), with and without motion, for 26 months at Waltz Mill but at 105% rated voltage. The original 125 ^{0}C conductor temperature was raised to 135 ^{0}C (138 kV) & 130 ^{0}C (345 kV) due to lack of cable failures up to 14 months. This area determined the basic aging failure mechanism to define the end-of-life criteria , establishing paper property magnitudes representing end-of-life under the influence of mechanical motion of a cable.
- #2:Development of a diagnostic tool(s) to evaluate the aging process in an HPFF cable & the relationship of several pipe fluid chemical, physical and electrical measurements to changes in the property of paper insulation during the aging process, at periodically specified intervals
- #3:Determination of the mechanical, chemical & electrical properties of paper tapes removed from the 12 cables as a function of time & temperature, seeking which paper properties best relate to end-of-life, retention (%) of the most important property at the end-of-life and its radial location and how to account for this location

Indoor 345 kV Test Bays at Waltz Mill



Area #3 Paper Tape Aging Set-Up for Waltz Mill



Area #1 & #3 Paper Testing Set-Up

Test Program

Test Bay	Voltage	Year Of Mfg.	Temperature	Bending
11	138	1957	CONSTANT	NO
12	138	1979	CONSTANT	NO
13	138	1957	CONSTANT	YES
14	138	1979	CONSTANT	YES
15	138	1957	CYCLIC	YES
16	138	1979	CYCLIC	YES
41	345	1964	CONSTANT	NO
42	345	1991	CONSTANT	NO
43	345	1964	CONSTANT	YES
44	345	1991	CONSTANT	YES
45	345	1964	CYCLIC	YES
46	345	1991	CYCLIC	YES

Periodic Fluid & Paper tests

- Fluid testing of pipe fluid included: DGA of 16 gases, furfural content, moisture content, DF @100 ^{0}C, neutralization no., volume resistivity, molecular weight, IR, color, peroxide content, dielectric strength, viscosity and RI (397 samples vs. 108 specified), Area #2
- Paper tests on samples from Area#2 and Area#1 (both failed & un-failed cables) included: Degree of Polymerization (DP), Tensile Strength (TS) – also Wet-Tensile Strength (WTS), Folding Endurance (FE), Dissipation Factor (DF) @80 ^{0}C and Dielectric Strength (DS)

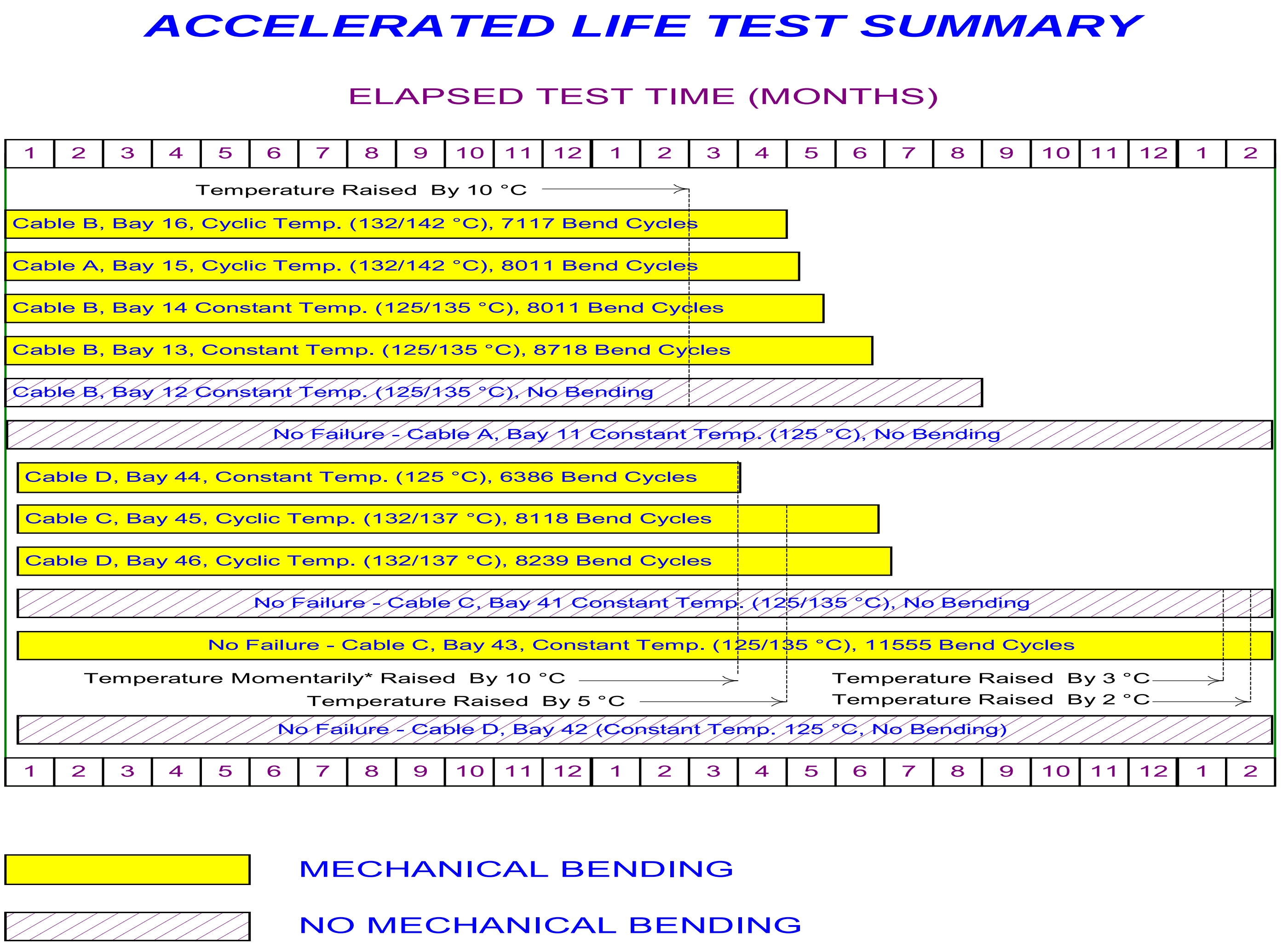
Key Fluid & Paper testing Conclusions

- Of the 13 tests performed on the fluid samples – only the carbon oxides from DGA and furfural content – kept gradually increasing , right up to breakdown and/or test termination, demonstrating that both measurements can be utilized to monitor the paper aging process, and potential remaining life. The rest of 11 fluid properties hardly changed from the original values
- While TS (dry), FE and DP decreased steadily as aging progressed and were evaluated to serve as the end of useful life, the remaining DP adjacent to the conductor offers the best correlation with cable failures experienced at Waltz Mill, hence was selected to estimate remaining cable life
- DP was identified as the end of transformer life as early as the late 1950s by the French.   However, Paper Aging and its relationship to mechanical properties and temperature, including the long proposed (late 1920s) 10 ^{0}C is due to an American (Montsinger)

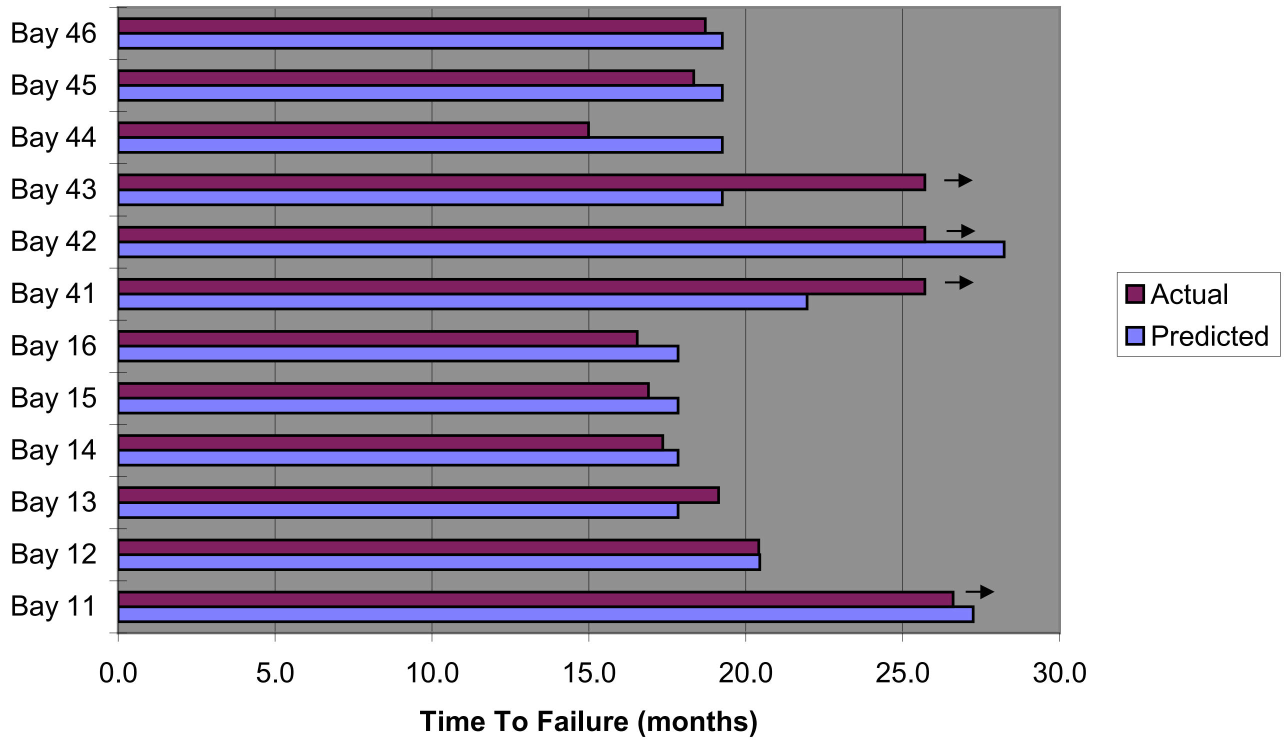
Key Fluid/Paper testing Conclusions……..

- 10% retention of any physico-chemical property of paper has been suggested. The Waltz Mill work concluded that DP is the way to go. Being a fundamental rather than a bulk property compared to others, it shows less scatter in measurements and its initial values represent a narrower range. A DP of about 350 signifies the end of useful cable life – for transformers the accepted value is 150-200
- Compared to carbon oxides and furfural, DP offers a much more accurate aging marker
- The retained DP at the conductor in a 138 kV HPFF cable of 1969 vintage was found to be 95% (1146 vs. 1208), giving a life prediction of 673 years under current operating conditions. Making allowances inherent in such computations, a life exceeding 100 years looks reasonable . Accordingly, we should focus on other factors (e.g., maintenance, accessories/auxiliaries, integrity of the steel pipe) to realize long life in such cables rather than meager loss of life – the “graceful aging” of the dielectric system

Test Program Results



Life-Time Model, Actual vs. Predicted



Paper Properties of a 1959, 138 kV HPFF Cable

								DRY TENSILE	WET-TENSILE	FOLDING ENDURANCE
TAPE	DIST.	THICKNESS	WIDTH	CROSS SECTION	MOISTURE	DF	DP	STRENGTH	STRENGTH	1 KG
#	(MILS)	(MILS)	(IN)	(IN^2)	(PPM)	(%)		(PSI)	(PSI)	(# FOLDS)
1	528	6.0	1.000	0.0060	543	0.58	995	11,339		
2	522	6.0	1.000	0.0060					3,483	2,415
10	474	6.0	1.000	0.0060	389	0.46	996	12,747		
11	468	6.0	1.000	0.0060					3,450	2,356
20	414	6.0	1.000	0.0060	410	0.29	994	12,092		
21	408	6.0	1.000	0.0060					4,010	2,251
30	355	6.0	0.875	0.0053	420	0.30	843	15,208		
32	350	6.0	0.875	0.0053					4,182	2,984
40	305	5.0	0.875	0.0044	306	0.26	831	15,086		
41	300	5.0	0.875	0.0044					4,804	2,815
50	255	5.0	0.875	0.0044	322	0.25	866	17,080		
51	250	5.0	0.875	0.0044					5,523	2,715
60	205	5.0	0.750	0.0038	435	0.27	841	15,792		
61	200	5.0	0.750	0.0038					5,347	2,345
70	155	5.0	0.750	0.0038	420	0.26	840	16,701		
71	150	5.0	0.750	0.0038					5,685	2,645
80	105	5.0	0.750	0.0038	544	0.25	842	16,673		
81	100	5.0	0.750	0.0038					5,729	2,345
90	55	5.0	0.750	0.0038	509	0.36	838	16,699		
91	50	5.0	0.750	0.0038					6,095	2,456
99	10	5.0	0.750	0.0038					5,775	2,345
100	5	5.0	0.750	0.0038	569	0.89	833	16,634		
Average					421	0.328	889	14,942	4,831	2,533

Paper Properties a 1970, 230 kV HPFF Cable

TAPE #	DIST. (MILS)	THICKNESS (MILS)	WIDTH (IN)	CROSS SECTION (IN^2)	MOISTURE (PPM)	DF (%)	DP	DRY TENSILE STRENGTH (PSI)	WET-TENSILE STRENGTH (PSI)	FOLDING ENDURANCE 1 KG (# FOLDS)	Copper Number	DIELECTRIC STRENGTH (V/mil)
1	754	8.0	1.250	0.0100	380	0.280	764	12,022			0.6349	1899
2	746	8.0	1.250	0.0100					6,326	2,692		
8	698	8.0	1.250	0.0100	240	0.230	769	11,497			0.6182	
9	690	8.0	1.250	0.0100					6,233	2,668		
20	602	8.0	1.250	0.0100	241	0.220	777	12,163			0.6037	1987
21	594	8.0	1.250	0.0100					6,191	2,245		
31	514	7.0	1.000	0.0070	277	0.220	757	14,035			0.6148	
32	507	7.0	1.000	0.0070					7,473	2,582		
45	416	7.0	1.000	0.0070	270	0.220	810	14,530			0.6137	2025
46	409	7.0	1.000	0.0070					7,158	2,692		
56	339	7.0	1.000	0.0070	249	0.220	758	14,062			0.6354	
57	332	7.0	1.000	0.0070					8,190	2,601		
67	274	5.0	0.825	0.0041	241	0.210	756	18,182			0.6513	2065
68	269	5.0	0.825	0.0041					9,431	2,412		
79	214	5.0	0.825	0.0041	250	0.210	757	18,330			0.6462	
80	209	5.0	0.825	0.0041					9,770	2,398		
90	159	5.0	0.825	0.0041	327	0.220	809	18,244			0.6340	2098
91	154	5.0	0.825	0.0041					8,924	2,469		
100	116	4.0	0.725	0.0029	296	0.260	740	15,361			0.6258	
101	112	4.0	0.725	0.0029					9,027	2,412		
109	80	4.0	0.725	0.0029	343	0.240	760	15,361			0.6096	2056
110	76	4.0	0.725	0.0029					7,488	2,409		
118	44	4.0	0.725	0.0029	345	0.250	759	15,376			0.6154	
119	40	4.0	0.725	0.0029					7,407	2,346		
127	8	4.0	0.725	0.0029				15,678				
128	4	4.0	0.725	0.0029	371	0.260	755		7,654	2,415	0.6186	1998
Average					295	0.234	767	14,988	7,790	2,488	0.6247	2,018

Paper Properties of a 1973, 345 kV HPFF Cable

Tape	Dist.	Thickness	Width	Cross Section	Moisture	DF	DP	Dry-Tensile Strength	Wet-Tensile Strength	Folding Endurance I kg
#	(mils)	(mils)	(in)	(in^2)	(ppm)	(%)		(psi)	(psi)	(#folds)
1	1029	8.0	1.125	0.0090	726	0.270	789	15,460	4,860	4,058
13	933	8.0	1.125	0.0090	694	0.240	764	15,413	5,288	4,497
25	837	8.0	1.125	0.0090	490	0.240	755	15,120	5,070	3,954
39	733	8.0	1.125	0.0090	505	0.220	768	16,113	5,446	4,069
54	613	8.0	1.125	0.0090	486	0.220	751	15,157	5,174	3,348
68	523	6.0	1.000	0.0060	548	0.240	762	17,898	5,915	3,499
83	433	6.0	1.000	0.0060	486	0.280	734	17,817	5,467	3,241
97	350	5.0	0.875	0.0044	536	0.320	741	17,380	5,995	3,548
110	285	5.0	0.875	0.0044	449	0.300	762	16,117	6,041	2,584
125	210	5.0	0.875	0.0044	398	0.280	757	16,069	7,246	2,718
138	145	5.0	0.750	0.0038	402	0.270	730	18,408	6,870	2,383
149	90	5.0	0.750	0.0038	409	0.280	749	18,069	7,393	2,936
158	45	5.0	0.750	0.0038	612	0.340	748	18,538	7,465	2,463
166	5	5.0	0.750	0.0038	649	0.600	738	18,072	7,329	2,255
Average					528	0.293	753	16,831	6,111	3,254

Why HPFF Cable Per Se Failures

- Despite exceedingly long life expected/predicated under typical operating conditions, and long measured and very sound radial Paper as well as Fluid properties of in-service cables along with satisfactory visual inspections as discussed, failures have at times been encountered in cables proper. The potential reasons may range from obvious to subtle, and are often hard to identify in many cases at HV cables
- The oft-mentioned reasons, and may not be limited to, include: inadvertent loss of pressure, installation irregularities, sloping profile, excessive road traffic & vibrations, soil thermal conditions & potential changes over time, excessive tape movement and unacceptably wide butt-gaps, extensive dilution of the impregnant by pipe fluid, material deficiency, any potential manufacturing anomaly, rare but could exist, thermo-mechanical effects etc.

- These reasons have been frequently suggested – some more logical than others - but the evidence to tie up a failure to any of such reasons is lacking. With the acknowledged long life of HPFF cables, such a substantiation would be valuable toward this end – few of the last remaining needs for HPFF cables, failures can be a challenge in any HV equipment Good record-keeping of the many and varied aspects involved will be helpful

Conclusions & Recommendations

- HPFF cables are characterized by an exceedingly long life under typical loading conditions – a life exceeding 100 years expected under most conditions encountered in service
- The aging process “graceful aging” in HV taped cables can be related to physico-chemical properties of paper, carbon oxides and furfural content. DP at the conductor is the best aging marker, and most appropriate to estimate life through algorithms developed in the referenced EPRI project for operating conditions
- Loss of mechanical properties of paper tapes along with cable bending results in failure
- DP of the innermost tapes is the best indicator for remaining life - a DP value of about 350 signifies the end of useful life, about 3 times more than previously suggested by cable engineers in Italy
- DP retention in the investigation of over 100 dissected cables removed from service was mostly over 95%, signifying minimal aging
- Loss of dielectric strength is not a primary failure mode
- Periodic maintenance of the dielectric system and the pipe is recommended
- DGA offers an economical & effective means to access the condition of the cable and its accessories, including a rough estimate of life through carbon oxides
- EPRI’s DF measurement procedure can detect advanced aging

Acknowledgements

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The other key individuals who played indispensable role include: Dr. Oscar O. Morel (formerly DECo/now Utilx), Sandeep K. Singh (DECo), John H. Cooper (PDC) and Walter Zenger (formerly EPRI/now PGE). In addition, thanks are due to so many cable engineers at North American and foreign utilities as well as EPRI (past & present), who have vitally contributed to the Oil and Paper efforts at The Detroit Edison Company since the early 1980s in many ways.

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