Accelerated Cable Life Test (ACLT) Results with Reduced Insulation Wall Thickness Specimens

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Subcommittee A: Cable Construction and Design
Fall 2007 ICC Meeting
November 5, 2007
9:15AM – 12:30PM
Scottsdale, Arizona

Presentation Outline

- Brief History of ACLT: 1981 - 2007
- Typical Historical ACLT Results of Full-Size (175-mil) Wall TRXLPE Cable Cores
- ACLT Results with 125-mil Wall TRXLPE Cable Cores
- ACLT Results with 60-mil Wall TRXLPE Cable Cores
- Possible Insulation System Comparisons via Inverse Power Law Under Wet-Aging Conditions with Reduced Wall Cable Cores
- Life Comparison Implications with Reduced Wall Cable Cores
- Conclusions
- Future Work

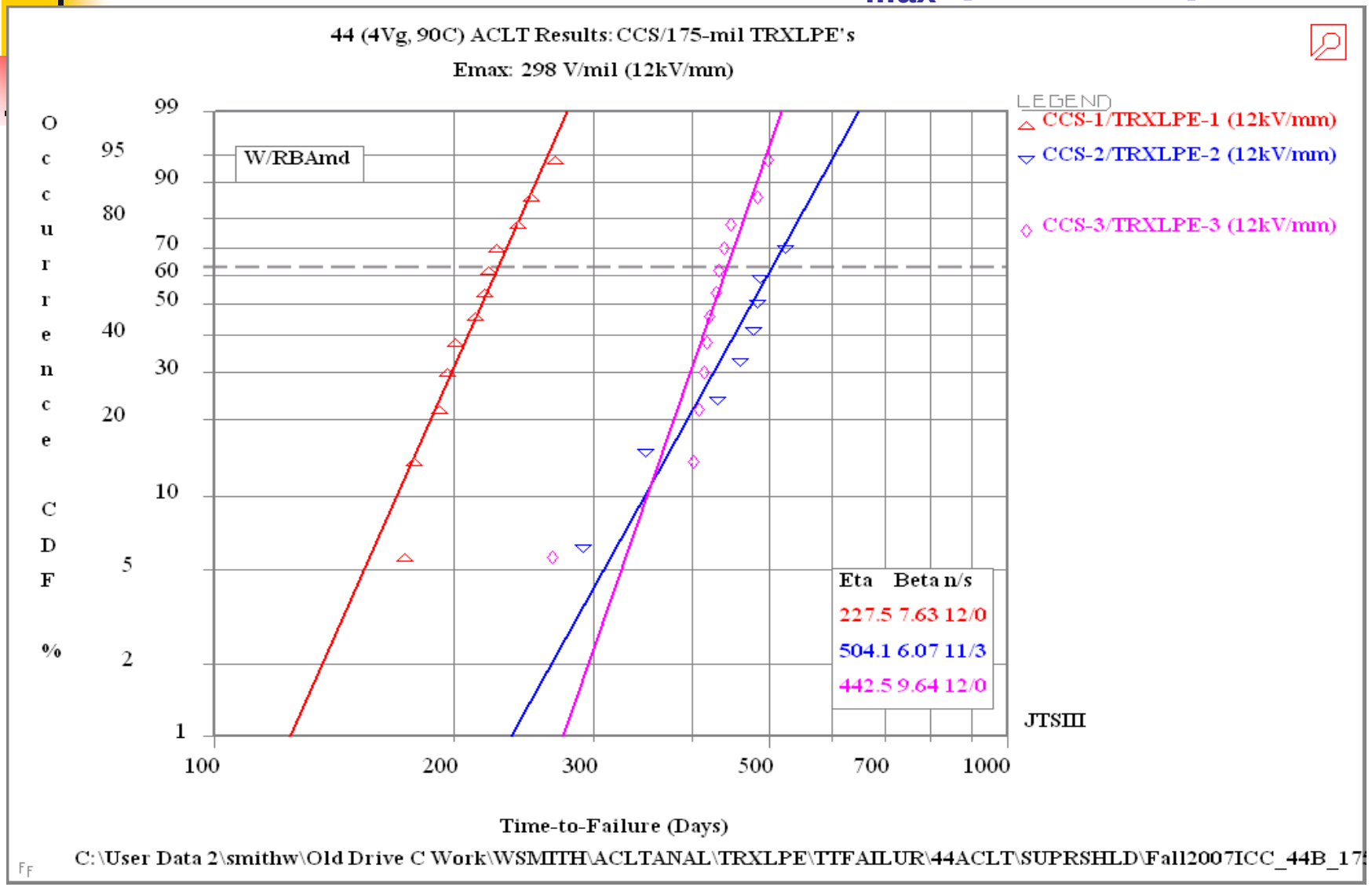
Brief History of ACLT – 1981

- First ACLT Results on Full-Size Cable Cores Reported at 1981 Winter Power Meeting in Atlanta, GA by Robert Lyle
  - Test Specimens: #2 AWG-7W, 175-mil Wall, 15kV-Rated
  - Preconditioning = 72 Hrs. @ 90°C in Air
  - Test Voltage = 34.6kV
  - Maximum Stress @ Conductor Shield = 298 V/mil (12kV/mm)
  - Insulation Average Stress = 200 V/mil (8kV/mm)
  - Test Temperature = 90°C @ Hot Spot in Air Under Stress Cone
  - Load-Cycled (200 Amps), 8 Hrs. On/16 Hrs. Off, seven (7) days/Week
  - Test Environment Temperature = 35C ± 2°C
  - Tank Water Temperature: Uncontrolled (Tracked Load-Cycle)
  - Deionized Tank Water; Deionized Water in Conductor Strands
  - Insulations = HMWPE, Tree Retardant HMWPE and Natural XLPE
  - Shields = Extruded Conventional Conductor (CCS) and Extruded Strippable Insulation
  - Cable Manufacture = Dual Tandem Extrusion, 2-Pass
  - Diagnostic = Life, Lognormal Geometric Mean Time-to-Failure (GMTF)
    - HMWPE = 36 Days; TR-HMWPE = 75-85 Days; Natural XLPE = 37Days

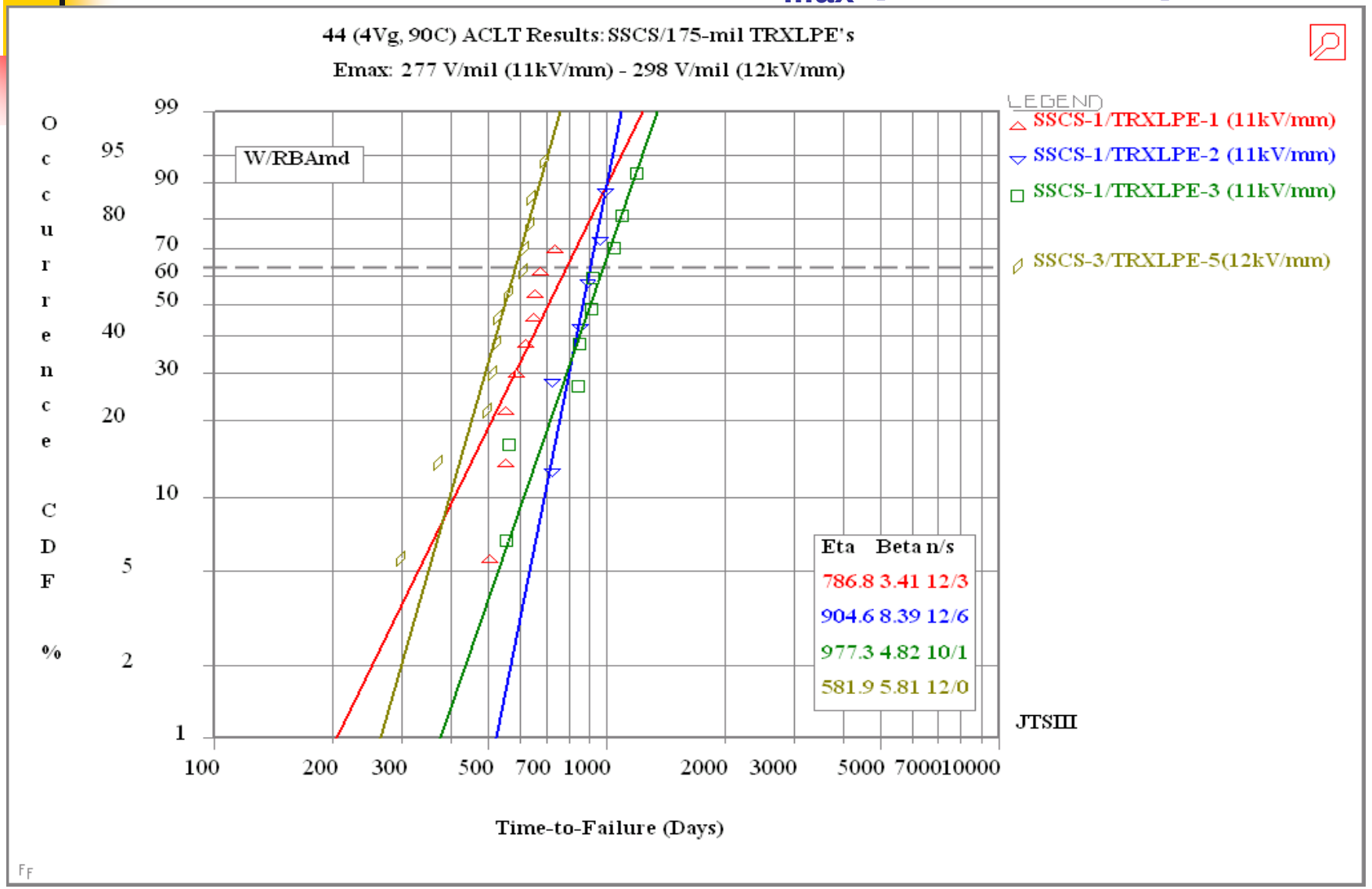
Current Status of ACLT – Today

- **Full-Size Cable Cores Still Employed in Insulation and Conductor Shields ACLT Life Performance Comparisons**
  - **Test Specimens: #1/0 AWG-19W, 175-mil Wall, 15kV-Rated**
  - **Preconditioning = 72 Hrs. @ 90°C in Air (Still Predominant, but Changing)**
  - **Test Voltage = 34.6kV (Still Predominant, but Changing)**
  - **Max. Stress @ Cond. Shld. = 277 V/mil (11kV/mm)**
  - **Avg. Ins. Stress = 200 V/mil (8kV/mm)**
  - **Conductor Test Temperature = 75°C in Water, or 90°C in Air**
  - **Load-Cycled 8 Hrs. On/16 Hrs. Off, seven (7) days/Week**
  - **Test Environment Temperature = 35C ± 2°C and 25C ± 2°C**
  - **Tank Water Temperature: Uncontrolled (Tracks Load-Cycle) and 50C Controlled**
  - **Deionized Tank Water; Deionized Water in Conductor Strands**
  - **Insulation = Natural XLPE (as Controls) and Tree Retardant XLPE**
  - **Shields = Extruded Conventional and SuperSmooth Conductor (SSCS), and Extruded Strippable Insulation Shield**
  - **Cable Manufacture = True Triple and Dual Tandem Triple Extrusion, Single Pass**
  - **Diagnostic = Life, Weibull Characteristic Life, Eta, and Weibull Shape, Beta**
    - **Natural XLPE (with Conventional Conductor Shields) = 80 – 120 Days**
    - **Natural XLPE (with SuperSmooth Conductor Shields) = 300 – 400 Days**
    - **TRXLPE (with Conventional Conductor Shields) =200 – 800 Days**
    - **TRXLPE (with SuperSmooth Conductor Shields) = 600 – 900 Days**

Typical Historical ACLT Results of Full-Size (175-mil) Wall CCS/TRXLPE Cable Cores vs. E_{max} (#2 AWG)



Typical Current ACLT Results of Full-Size (175-mil) Wall SSCS/TRXLPE Cable Cores vs. E_{max} (#1/0 AWG)



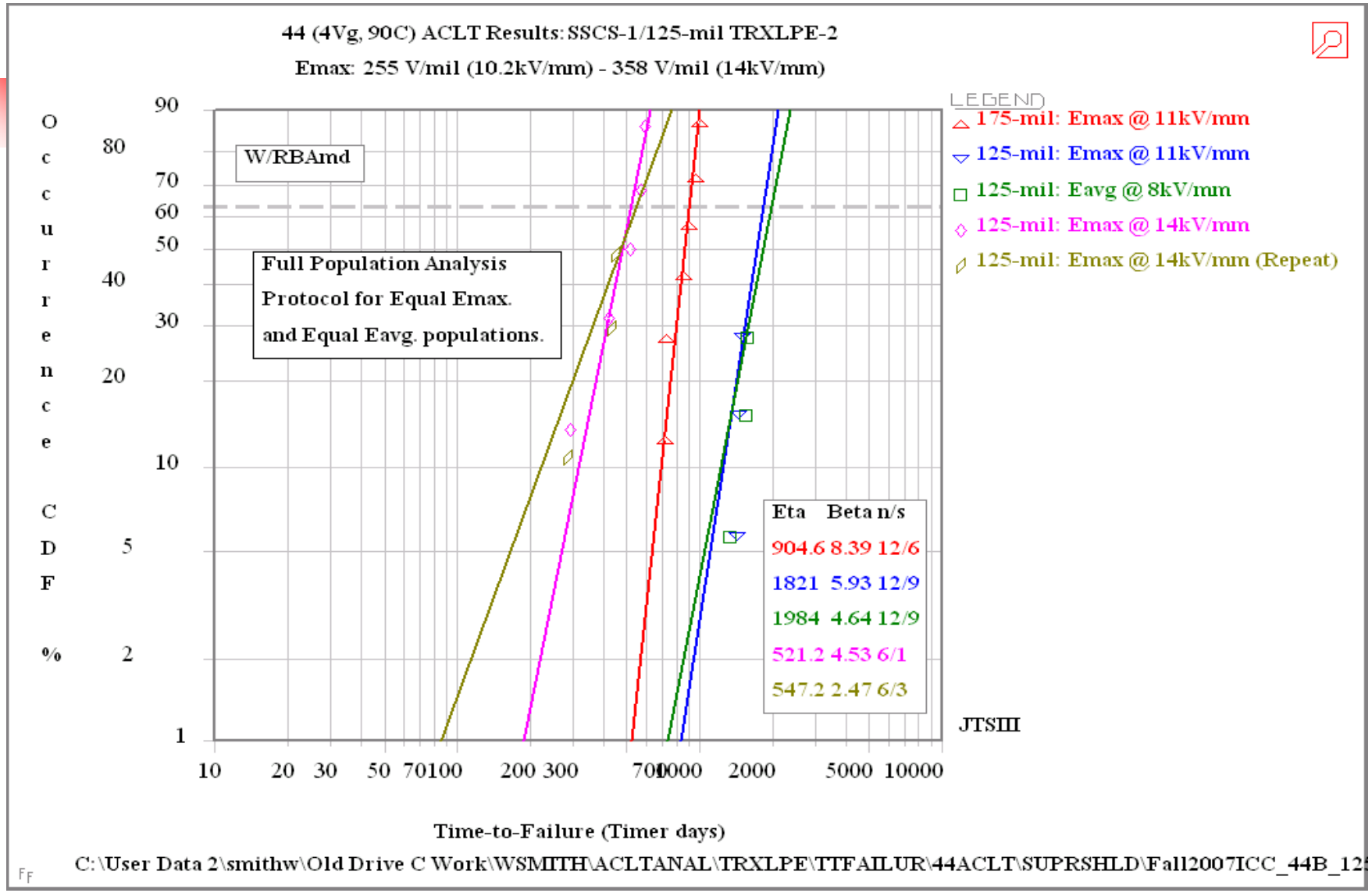
ACLT Test Time Reductions with Today's Conductor Shields and TRXLPE Insulation Systems are Desirable for Faster Materials Approvals

- With Current MV Cable Materials Design and Quality, ACLT Evaluations at Conventional Test Stresses with 1/0 AWG Full-Size (175-mil Wall) Cables Provide Excessively Long Test Times
  - 2 – 4 Years Characteristic (Mean) Life
  - 3 – 5 Years Calendar (Total) Test Time
- Reduced Insulation Wall of ACLT Specimens Might Provide Reductions in Test Times
- AEIC Currently Allows Reduced Insulation Wall Cable Design for 15kV-Rated MV Cables
  - AEIC CG11-02, Guide for Reduced Diameter Extruded Dielectric Shielded Power Cables Rated 5 through 46kV, and
  - AEIC CG12-05, Guide for Minimizing the Cost of Extruded Dielectric Shielded Power Cables Rated 5 through 46kV
- GCC Initiated a Reduced Insulation Wall ACLT Test Program with 125-mil Insulated TRXLPE Cable in 1999/2000 with the Assumption that Reduced ACLT Life Would be Obtained

Details of ACLT with 125-mil Wall TRXLPE Cable Cores

- **125-mil Wall Cable Core ACLT Protocol Test Specimen and ACLT Details**
  - **Test Specimens: #1/0 AWG-19W, 125-mil Wall, 15kV-Rated, TRXLPE-2**
  - **Preconditioning = 72 Hrs. @ 90°C in Air**
  - **Test Voltages = Calculated to Duplicate E_{max} and E_{avg} stresses of 1/0 AWG, 175-mil Wall Cable Core**
    - **24.7kV = 255 V/mil (10.2kV/mm) E_{max}, E_{avg} = 198 V/mil (8kV/mm)**
    - **26.8kV = 277 V/mil (11kV/mm) E_{max}, E_{avg} = 214 V/mil (8.6kV/mm)**
    - **34.6kV = 358 V/mil (14kV/mm) E_{max}, E_{avg} = 277 V/mil (11kV/mm)**
  - **Conductor Test Temperature = 90°C in Air**
  - **Load-Cycled 8 Hrs. On/16 Hrs. Off, seven (7) days/Week**
  - **Test Environment Temperature = 35C ± 2°C**
  - **Tank Water Temperature: Uncontrolled (Tracks Load-Cycle)**
  - **Deionized Tank Water; Deionized Water in Conductor Strands**
  - **Insulation = Tree Retardant XLPE**
  - **Shields = Extruded SuperSmooth Conductor (SSCS-1) and Extruded Strippable Insulation**
  - **Cable Manufacture = Dual Tandem Triple Extrusion, Single Pass**

ACLT Results of 125-mil Wall SSCS-1/TRXLPE-2 Cable Cores vs. E_{max} (#1/0 AWG)



Conclusions from ACLT Results with 125-mil Wall TRXLPE Cable Cores

- **ACLT Test Times are NOT Reduced When Tested at Conventional Insulation Voltage Stresses (< 300 V/mil (12kV/mm))**

- **ACLT Test Times ARE Reduced by ~ 40% (900 to 500 days) for TRXLPE-2 When Tested at Stresses Exceeding the IEEE P1407 Recommended Maximum Test Stress Level of 300 V/mil**
  - **Maximum Insulation Voltage Stress at Conductor Shield of 358 V/mil (14kV/mm))**
  - **Average Insulation Stress of 277 V/mil (11kV/mm)**

- **Insulation Reductions Must Be Greater or Test Stresses Must Be Higher (or Both) to Get Meaningful Reductions in ACLT Test Times**

Investigate ACLT with 60-mil Wall TRXLPE Cable Cores at Conventional Stresses and at Stresses >> 300 V/mil (12kV/mm)

- **60-mil Wall Cable Core ACLT Protocol Test Specimen and ACLT Details**
  - **Test Specimens: #1/0 AWG-19W, 60-mil Wall, 15kV-Rated, TRXLPE-4**
  - **Preconditioning = 72 Hrs. @ 90°C in Air (B) and 500 Hrs. @ 90°C in Air (J)**
  - **Test Voltages = Calculated to Duplicate E_{max} and E_{avg} stresses of 1/0 AWG, 175-mil Wall Cable Cores**
    - **11.2kV = 223 V/mil (9kV/mm) E_{max}, E_{avg} = 196 V/mil (8kV/mm): Equivalent Avg. Stress**
    - **14.2kV = 282 V/mil (11kV/mm) E_{max}, E_{avg} = 249 V/mil (10kV/mm): Equivalent Maximum Stress**
    - **26.0kV = 517 V/mil (21kV/mm) E_{max}, E_{avg} = 456 V/mil (18kV/mm)**
  - **Conductor Test Temperature = 90°C in Air and 75°C in Water**
  - **Load-Cycled 8 Hrs. On/16 Hrs. Off, seven (7) days/Week**
  - **Test Environment Temperature = 35°C ± 2°C and 25°C ± 2°C**
  - **Tank Water Temperature: Uncontrolled (Tracks Load-Cycle) and Controlled**
  - **Deionized Tank Water; Deionized Water in Conductor Strands**
  - **Insulation = Tree Retardant XLPE**
  - **Shields = Extruded Supersmooth Conductor (SSCS-3 thru 10) and Extruded Strippable Insulation**
  - **Cable Manufacture = Dual Tandem Triple Extrusion, Single Pass**

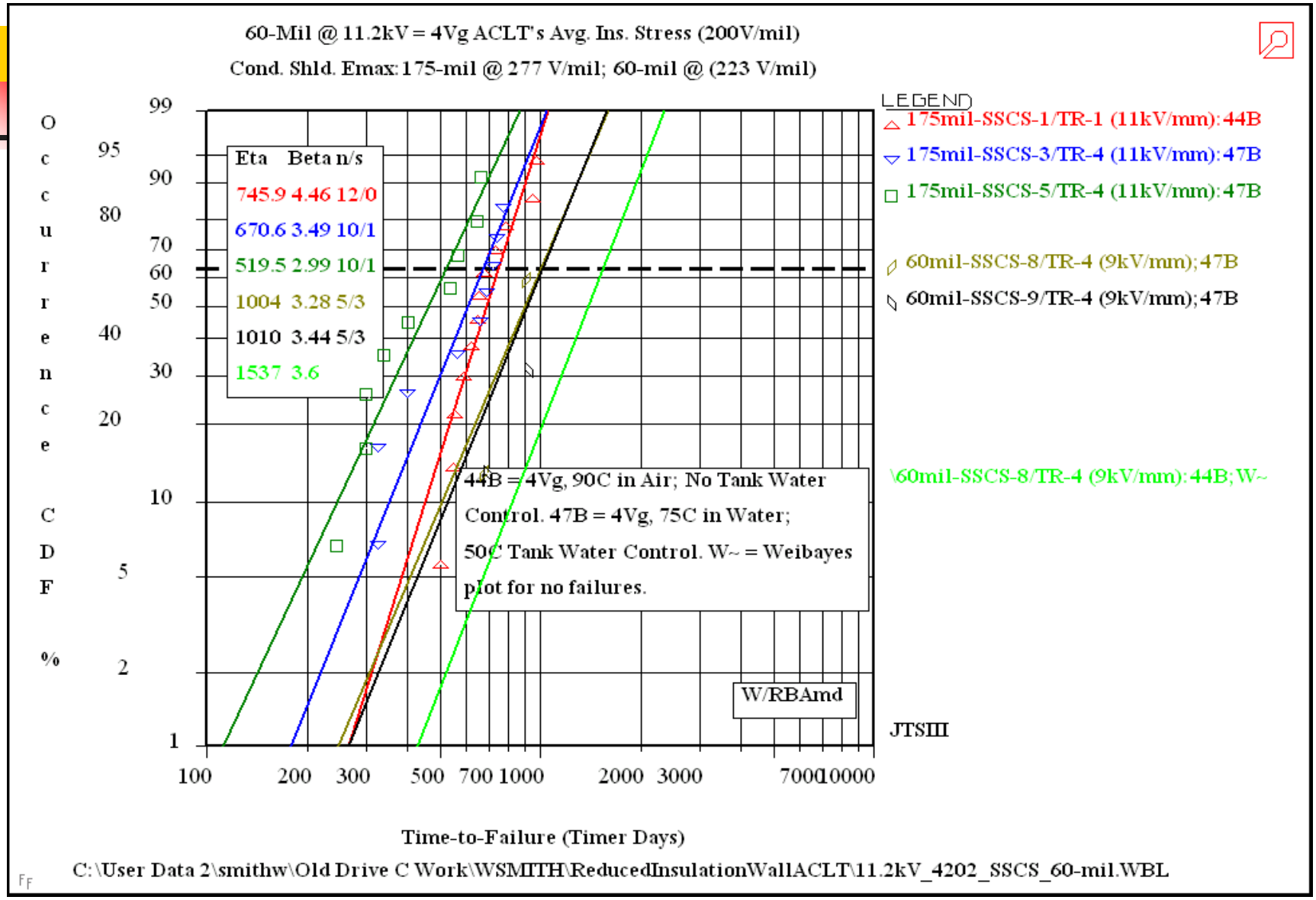
Rationale for 60-mil Wall ACLT @ 44B, 47B, 34W and 37W (11.2kV, 14.2kV and 26kV)

- Test 60-Mil Wall Cables in Controlled and Non-Controlled Tank Water Temperature Protocols at Equivalent E_{avg} and E_{max} as Full-Size 175-mil Wall Cables, and at E_{avg} and E_{max} >> Typical Stresses

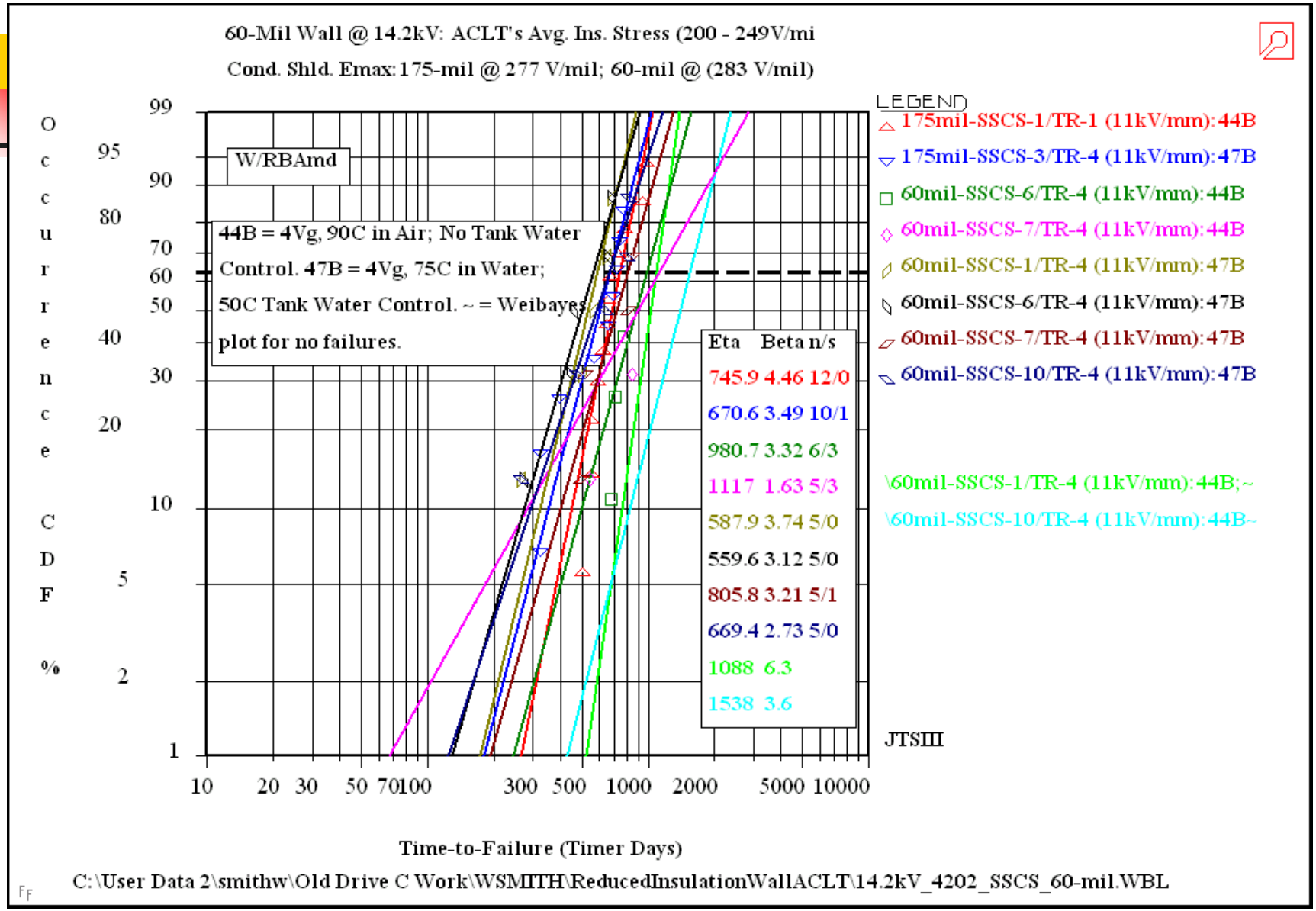
- What is Effect of Typical ACLT Test Stresses on 60-Mil Wall Cables?
  - Is Testing Time Reduced or Extended
  - If so, by How Much?

- What is Effect of >> Typical Stresses in ACLT on 60-Mil Wall Cables?
  - Is Testing Time Reduced or Extended
  - If so, by How Much?

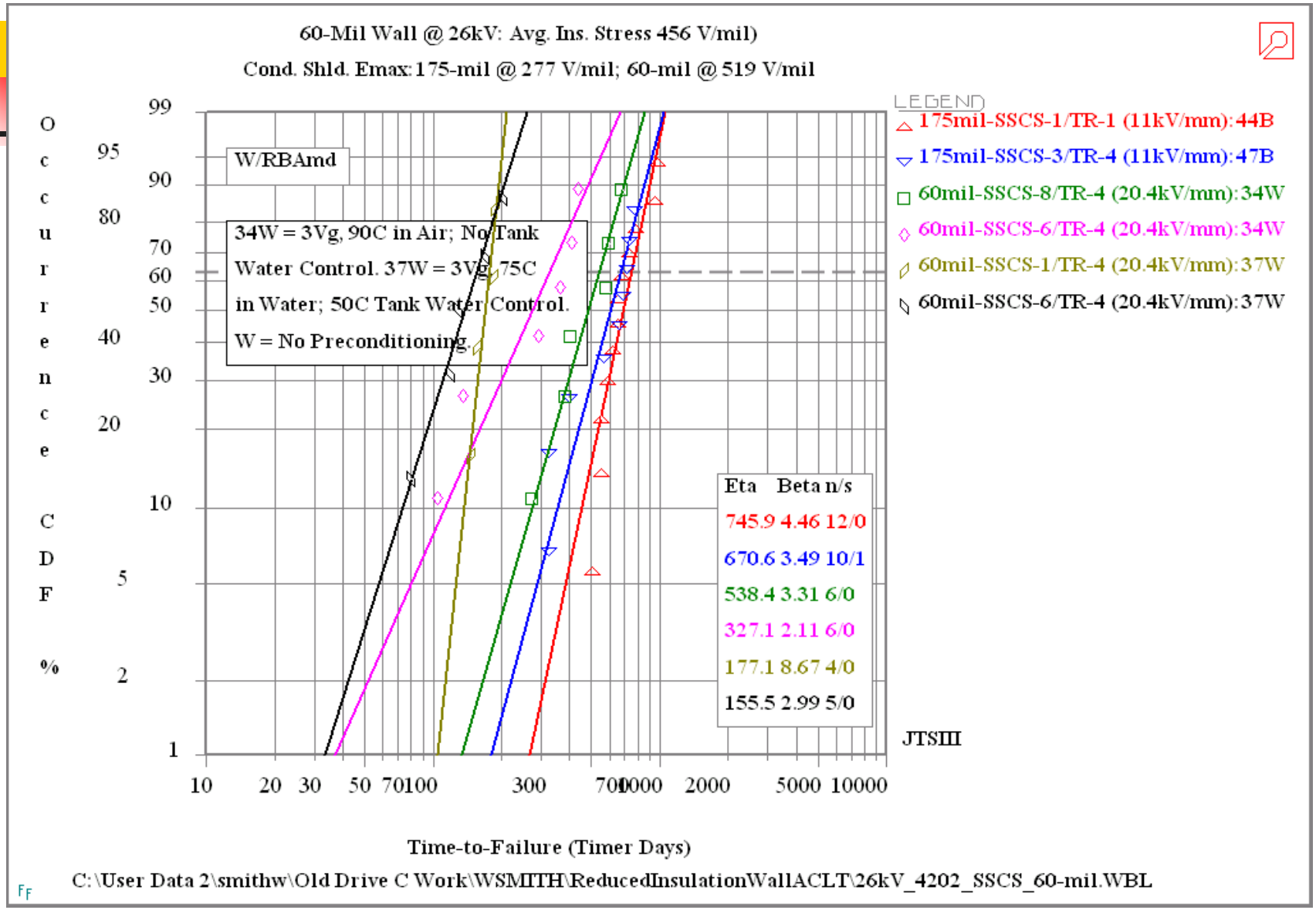
11.2kV ACLT Results of 60-mil Wall SSCS/TRXLPE Cable Cores @ Equivalent E_{avg} 200 V/mil (8kV/mm)



14.2kV ACLT Results of 60-mil Wall SSCS/TRXLPE Cable Cores @ Equivalent E_{max} 277 V/mil (11kV/mm)



26kV ACLT Results of 60-mil Wall SSCS/TRXLPE Cable Cores @ 517 V/mil (20.4kV/mm) E_{max}



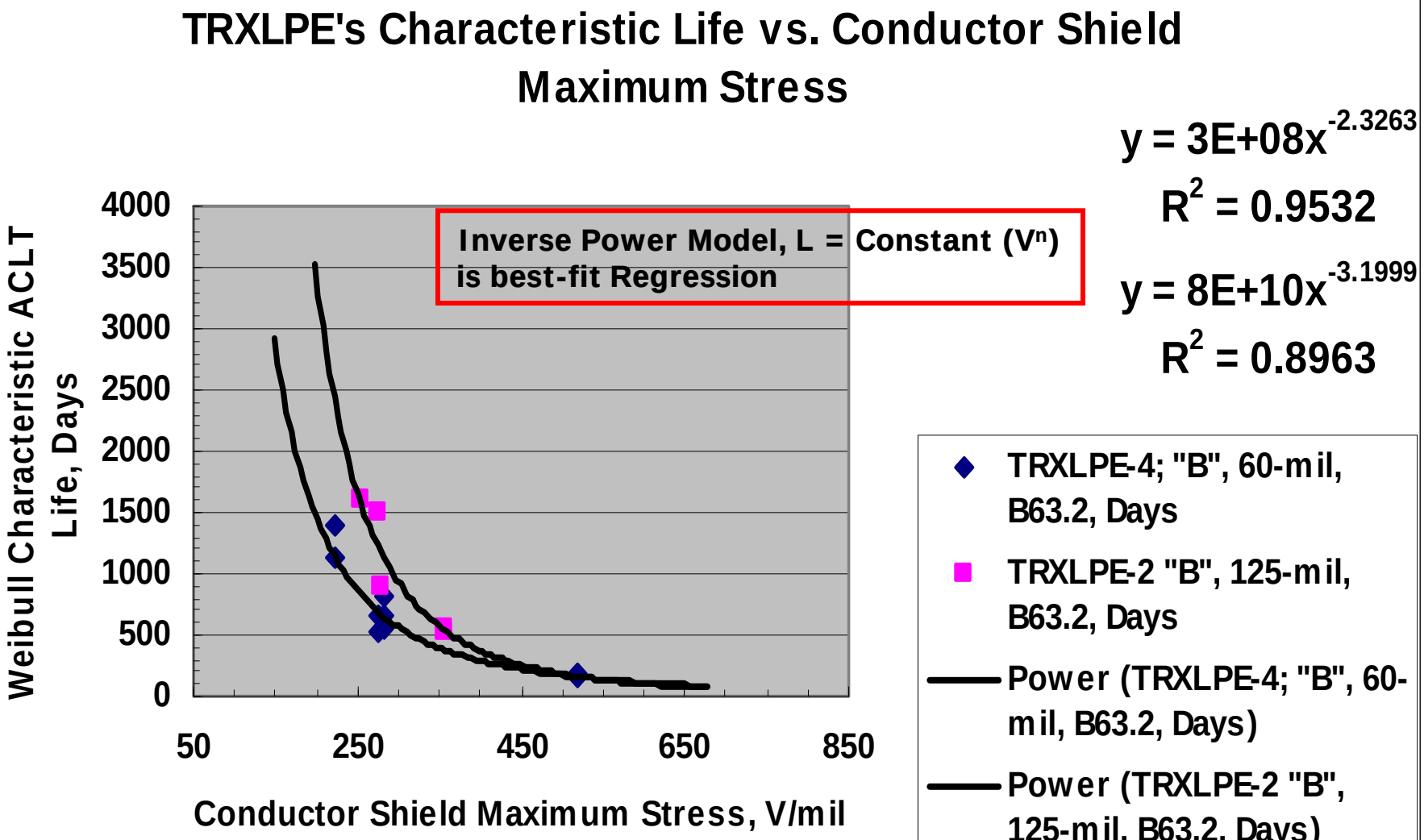
Conclusions from 11.2kV, 14.2 and 26kV ACLT Results of 60-mil Wall SSCS's/TRXLPE Cable Cores

- **ACLT Test Times at 11.2kV and 14.2kV Test Voltages of 60-mil Cable Specimens are NOT Reduced, But Extended by 1.4 to >2X for 60-Mil Wall Cables in Non-Controlled and Controlled Tank Water Temperature Protocols at Equivalent Maximum and Equivalent Average Insulation Stress as 175-Mil Wall Cables**
  - **Majority of Significant Increase in Life Performance at Typical Conventional Insulation Test Stresses is Thought to be Attributable to Reduced Insulation Volume**
  - **For a Given Family Type of SSCS's with Small Differences in Formulation Chemistry)**
- **ACLT Test Times at 26kV Test Voltage of 60-mil Cable Specimens ARE Reduced Significantly (30 – 80%)**
  - **Higher Test Voltages Required to Overcome Reduced Insulation Volume Effect**
  - **Maximum Stresses and Average Insulation Stress Obtained at 26kV Test Voltage with 60-mil Cables are Equivalent to Range of Operating Stresses Observed in High Voltage (HV) and Extra High Voltage (EHV) Transmission Class Cables**
- **Controlled (Constant Temperature) Tank Water ACLT Protocols Maintain their Accelerating Advantage Over Non-Controlled Tank Water Protocols at Equivalent Test Voltages Over the Test Voltage Range of 11.2 – 26kV with 60-mil Wall Test Specimens**

Wet-Aged Voltage Endurance Implications of ACLT Results of Reduced Wall SSCS's/TRXLPE Cable Cores

- The Use of 60-mil Cable Specimens In ACLT Protocols Now Provides a Method of Determining Wet-Aged Voltage Endurance Characteristics of Insulation Systems in a Relatively Quick Timeframe Based on Life Performance
  - **Typically Reported Inverse Power Law Life Exponent Values of "n" for XLPE of 5 – 12 Determined Under Dry Conditions Using Pressed Slabs or Model Cables (In the Absence of Shields) Can be Evaluated Under Wet Aging Conditions WITH Shields in a Relatively Quick Timeframe**
- The Method Can Allow Comparison Between Insulations, Conductor Shields and Combinations Thereof
- The Techniques May Be Useful for Unfilled and Filled Insulation Systems

Wet-Aged Voltage Endurance Implications of ACLT Results of Reduced Wall SSCS's/TRXLPE Cable Cores



Wet-Aged Voltage Endurance Implications of ACLT Results of 125-mil Wall SSCS-1/TRXLPE-2 Cable Cores

Conductor Shield Max. Stress, X (V/mil)	n	X^n	A	Insulation Life y, Days	Insulation Life y, Years
40	-3.1999	7.47426E-06	8.00E+10	597941	1638.2
50	-3.1999	3.65987E-06	8.00E+10	292790	802.2
100	-3.1999	3.98291E-07	8.00E+10	31863	87.3
255	-3.1999	1.9921E-08	8.00E+10	1594	4.4
277	-3.1999	1.52865E-08	8.00E+10	1223	3.4
279	-3.1999	1.49386E-08	8.00E+10	1195	3.3
306	-3.1999	1.11158E-08	8.00E+10	889	2.4
358	-3.1999	6.72713E-09	8.00E+10	538	1.5
299	-3.1999	1.19702E-08	8.00E+10	958	2.6
517	-3.1999	2.0754E-09	8.00E+10	166	0.5

Wet-Aged Voltage Endurance Implications of ACLT Results of 60-mil Wall SSCS's/TRXLPE-4 Cable Cores

Conductor Shield Max. Stress, X (V/mil)	n	X^n	A	Insulation Life y, Days	Insulation Life y, Years
40	-2.3263	1.88E-04	3.00E+8	56266	154.2
50	-2.3263	1.12E-04	3.00E+8	33482	91.7
100	-2.3263	2.23E-05	3.00E+8	6676	18.3
223	-2.3263	3.44E-06	3.00E+8	1033	2.8
277	-2.3263	2.08E-06	3.00E+8	624	1.7
283	-2.3263	1.98E-06	3.00E+8	594	1.6
306	-2.3263	1.65E-06	3.00E+8	495	1.4
358	-2.3263	1.15E-06	3.00E+8	344	0.9
299	-2.3263	1.74E-06	3.00E+8	522	1.4
517	-2.3263	4.87E-07	3.00E+8	146	0.4

Final Conclusions

- **ACLT Characteristic Life of Reduced Insulation Wall Cables with Currently Commercially-Available and Past Commercial TRXLPE's with Currently Commercial and Experimental SSCS's is Increased by ≥ 1.3 - ≥ 2X in Controlled or Non-Controlled Tank Water Temperature Protocols With or Without Prior Thermal Preconditioning**
- **ACLT Characteristic Life of Reduced Insulation Wall Cables with SSCS's and TRXLPE's is Decreased by a Factor of 1.4 – 4.3 when Conductor Shield Maximum Test Stress in ACLT Exceeds the 300 V/mil (12kV/mm) IEEE Guide 1407 Recommended Maximum Stress Level**
- **Reduction in ACLT Testing Times and Testing Costs Are Possible with Reduced Insulation Wall (60 – 125-mil) ACLT Specimens at Test Stresses Between 300 – 500 V/mil (12kV/mm – 20kV/mm)**
- **Comparative Evaluation of TRXLPE's and SSCS's is Possible with Reduced Insulation Wall/High Stress Design ACLT Specimens**

Current Work In Progress with Reduced Insulation Wall ACLT Specimens

- **Evaluate Possible Changes in Failure Mechanism of Reduced Insulation Wall Specimens vs. Full-Size (175-mil) Wall Specimens**
  - **Evaluation of Treeing Performance Attributes; Tree Type, Density, Length**
  - **Comparative Evaluation of Weibull Shape Parameter, Beta**
- **Determine Materials Combination (Conductor Shields/XLPE/TRXLPE) Ranking Correlation Between Reduced Insulation Wall Specimens and Full-Size (175-mil) Specimens**
- **Evaluate Preconditioning Effects on Life (Eta) and Failure Mechanism (beta) in More Detail**
- **Verify Wet-Aged Voltage Endurance Attributes Over Wider Range of ACLT Stresses (100 – 625 V/mil) to Confirm Initial Inverse Power Law Life Exponents, "n" of 2 - 4**