“Accelerated Cable Life Testing”

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History of ACLT Activities at the MTC

- 1977-1978 - Testing Begun in 3 Tanks
- 1981 - Lyle and Kirkland Paper - “An Accelerated Life Test For Evaluating Power Cable Insulation” - IEEE PES Winter Power Meeting
- 1982 - Started Testing for Outside Material Suppliers - 8 Tanks in Use
- 1986 - 1988
  - 20 Tanks Added for EPRI Proj. RP2713-02
  - 15 Tanks Added for Outside Material Supplier Testing
- 1992 - 26 Tanks Added For Internal Material Development Testing
- 1993-1998 - Participated in 12-35 Task Force To Develop Guide For Accelerated Aging Tests in Water-Filled Tanks

IEEE Guide P1407

- "Guide for Accelerated Aging Tests for Medium-Voltage Extruded Electric Power Cables Using Water-Filled Tanks"
- Good Information - USE IT!!!
- Presently Being Considered for Modification in ICC Working Group A13W

Qualitative vs. Quantitative Accelerated Testing

- Qualitative Tests (Shake & Bake, Torture Tests, Elephant Tests, etc.)
  - Do not Quantify the Life Characteristics of the Product
  - May Increase Reliability by Revealing Probable Failure Modes
  - May Assist in Design of Qualitative Test
  - Will Not Help You Determine Reliability of the Product Under Normal Use Conditions
- Quantitative Tests
  - Tests Are Designed to Quantify the life characteristics of the product under normal use conditions and provide reliability information
  - Time-to-failure information (or time to an event) is required since the failure of the product is what we are interested in.

Accelerated Aging in Water-Filled Tanks

- Designed to Reduce The Amount of Time Required for:
  - Dielectric Failures <u>During</u> Aging
  - Reductions in AC Breakdown Strength
  - Changes in Some Other Diagnostic Measurement (i.e., Impulse Breakdown Strength)
- An Attempt to Simulate <u>Worst-Case</u> Field-Aging Conditions
  - Wet Environment
  - Elevated Conductor Temperatures
  - Elevated Electrical Stress
  - Surges
- Underlying Assumption is That Aging Mechanism In Tanks Under Accelerated Conditions Is Similar To Aging Mechanism in a Wet Field Environment

Prior ACLT Testing Applications

- Basic Research (EPRI Sponsored)
  - Development of Aging Models
  - Develop Correlation Between AC Breakdown Data and Cable Life
  - Remaining Life Estimates of Field-Aged Cables
  - Evaluation of Diagnostic Test Methods
- Material Evaluations
  - Insulations
  - Shields
    - Conventional vs. Supersmooth Conductor Shield
    - EVA vs. EEA Base Resins
  - Peroxides

Prior ACLT Testing Applications (Continued)

- Cable Production Method Evaluations
  - Steam Cure vs. Dry Cure
  - True Triple vs. Dual Tandem
- Cable Design Evaluations
  - Jacket vs. No Jacket
  - Strand Fill vs. No Strand Fill
  - Reduced Insulation Thickness

ACLT Acceleration Factors

- Water
  - Deionized Water in Strands (Some Labs Use Tap Water)
  - Deionized Water in Tanks (Some Labs Use Tap Water)
- Temperature
  - Daily 8 Hr. Heat Cycles (Cycle Time May Vary)
  - 45-90°C Conductor Temperature During Heat Cycle
- Voltage
  - 60 Hz.
  - Continuously Applied
  - 2 to 4 Times Rated Voltage to Ground
  - Reduced Voltage Level at Elevated Frequency is an Option

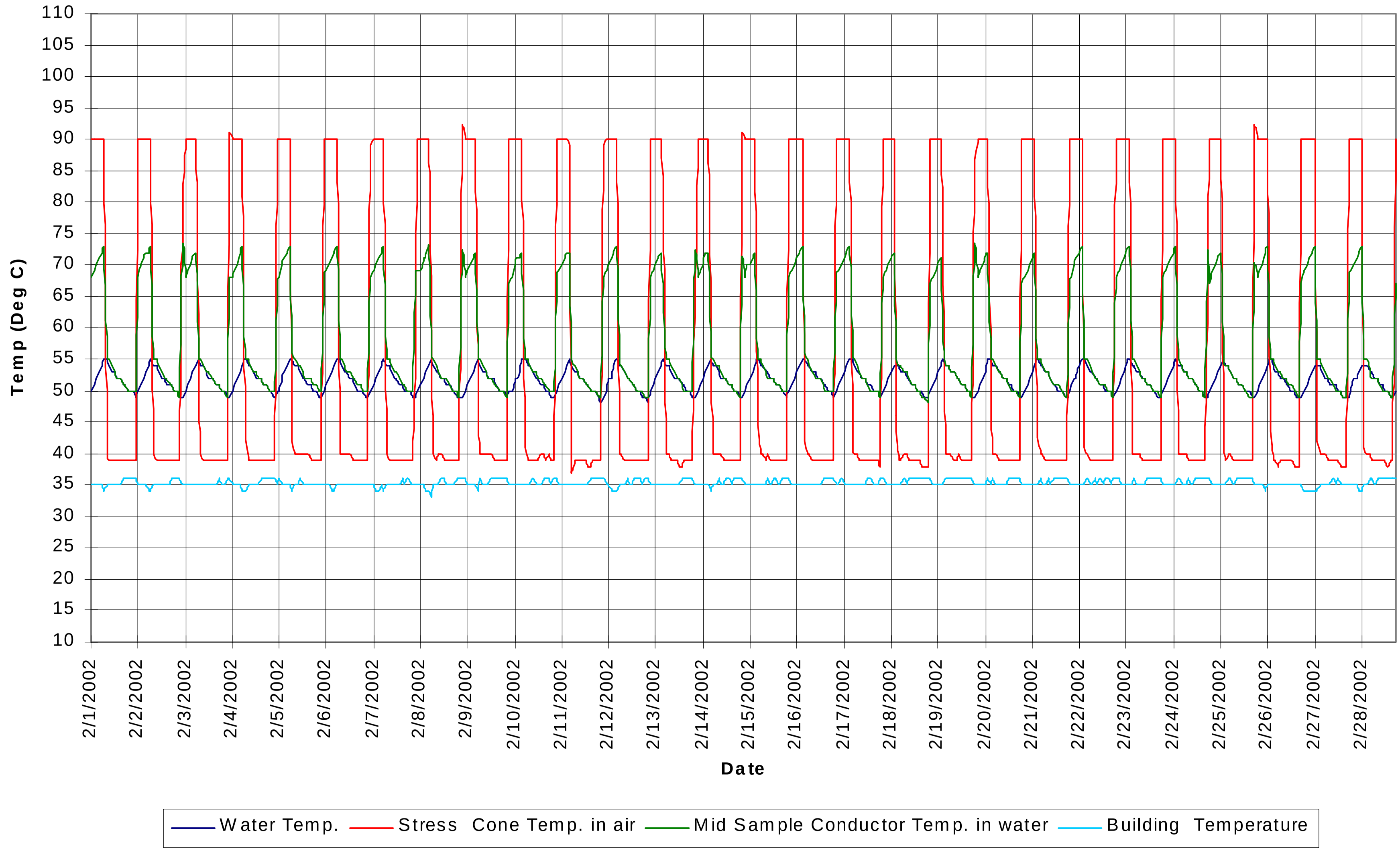
Preconditioning

- An Attempt to Normalize Peroxide Decomposition By-Product Levels Prior to ACLT By Heating the Cable Conductor in Free Air for a Period of Time
- Similar to Dry Cyclic Aging Test in AEIC Specifications
- Peroxide Decomposition By-Product Level Will Affect ACLT Results - (Just As It Affects AC Breakdown Results on New Cables)
- Many Preconditioning Schemes Utilized
- Touchy Subject!

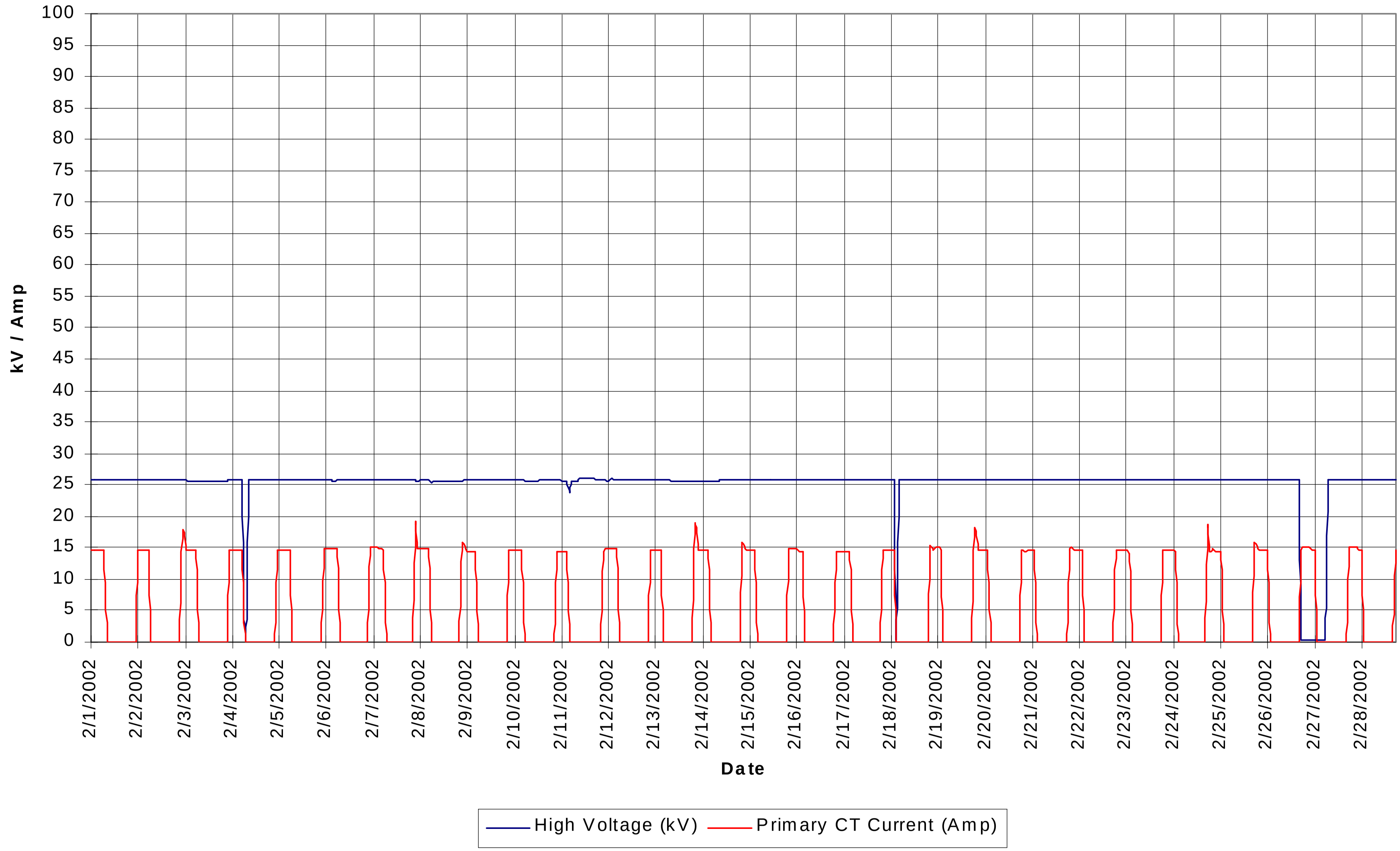
Data Acquisition and Monitoring

- Follow Guidelines Outlined in IEEE Guide P1407 "Guide for Accelerated Aging Tests for Medium-Voltage Extruded Electric Power Cables Using Water-Filled Tanks"
- Reproducibility of ACLT Data Will Depend on Precise Control of Factors That Accelerate Aging
- These Factors Should Be Controlled Over the Entire Duration of the ACLT
- Control Can and Should Be Demonstrated With Good Data Acquisition and Monitoring

Tank 49 Temperature Profile



Tank 49 Voltage & Current Profile

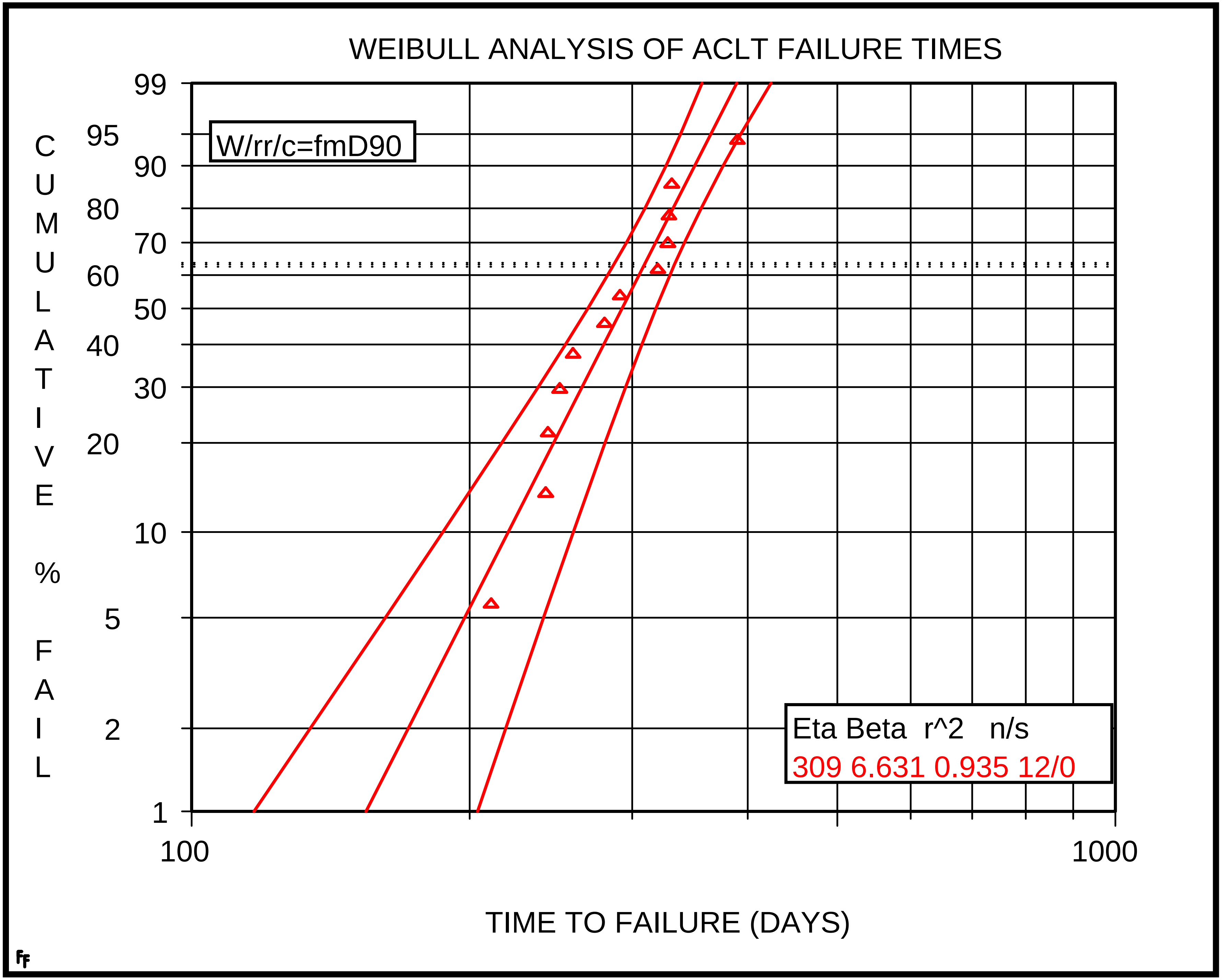


Cables Used in MTC ACLT's

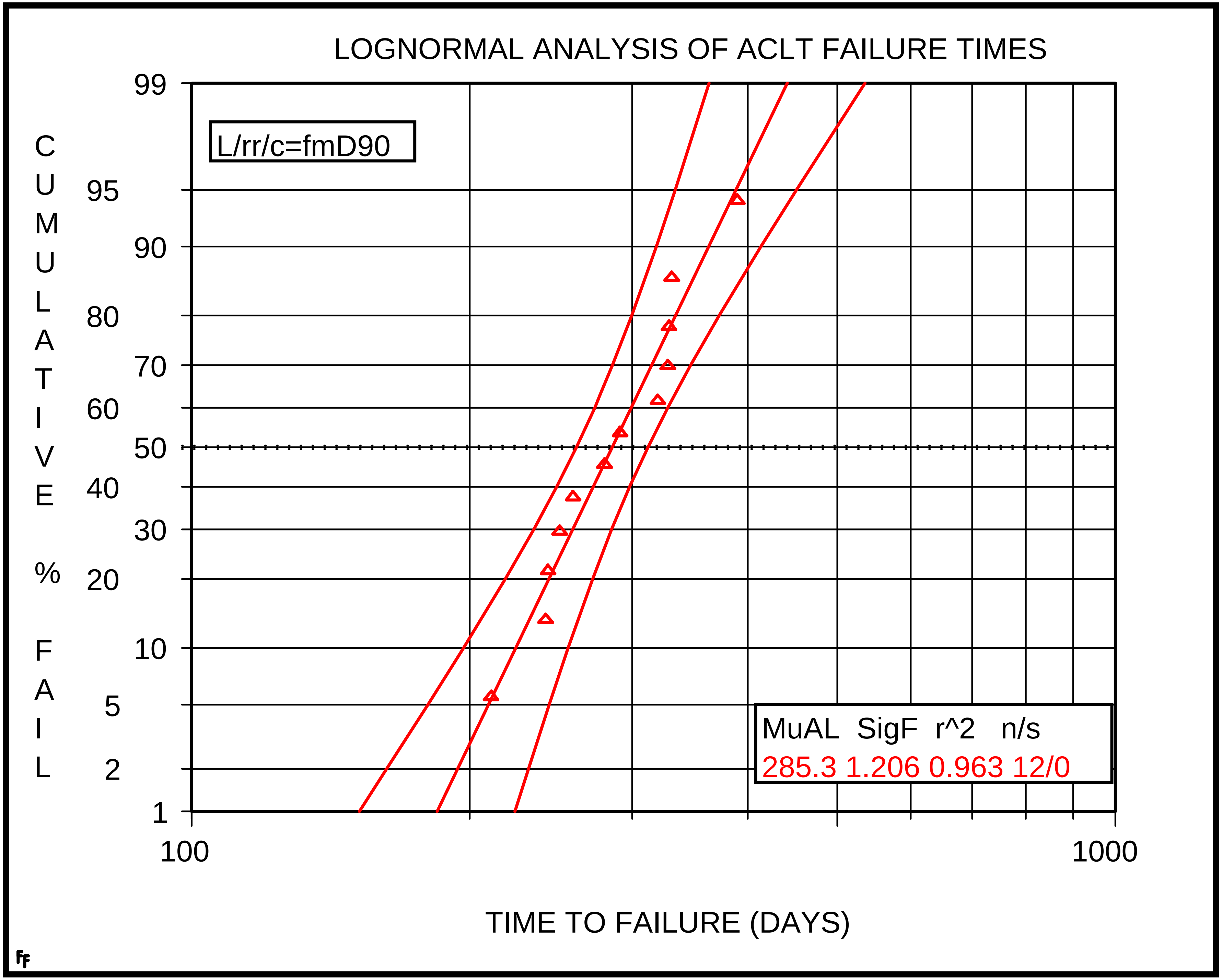
- Full-Size Cables
  - 15 kV Rating
  - Conductor
    - #2 - 1/0 AWG Conductor
    - Aluminum or Copper
- Reduced Wall Thickness Cables
- Cables Cut Into 16.5 ft to 30 ft. Sample Lengths Depending on Test Protocol

Time-to-Failure ACLT Test Protocol

- Population Size: Usually 12 Samples
- Age Samples to Dielectric Failure
- Record the Failure Times For Each Sample
- Failure Analysis
  - Statistically Analyze the Failure Times
  - Perform Microscopic Exams on Failure Sites to Gain Knowledge About Failure Modes



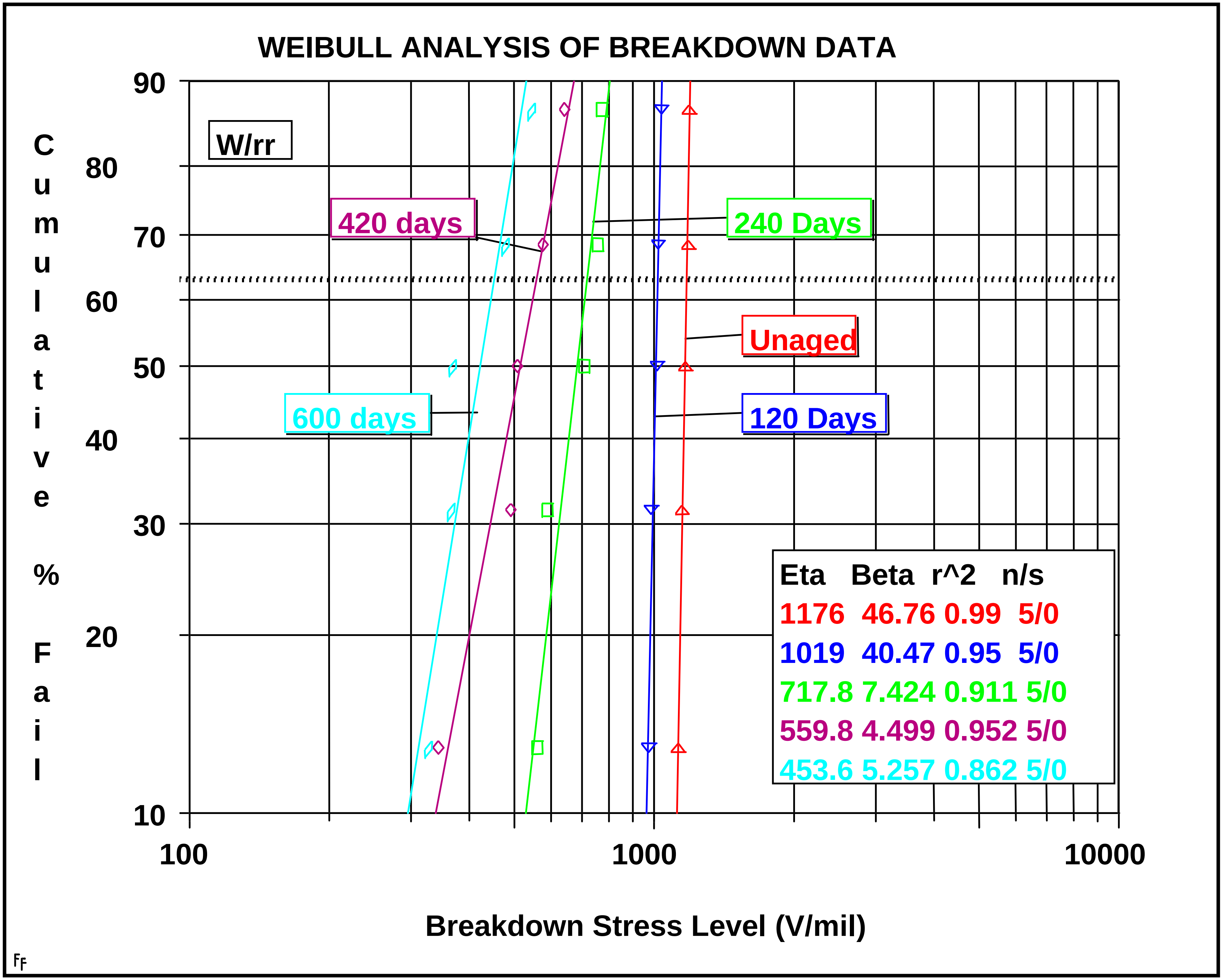
WEIBULL ANALYSIS OF ACLT FAILURE TIMES
W/rr/c=fmD90
CUMULATIVE % FAIL
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
TIME TO FAILURE (DAYS)
Eta Beta r^2 n/s
309 6.631 0.935 12/0

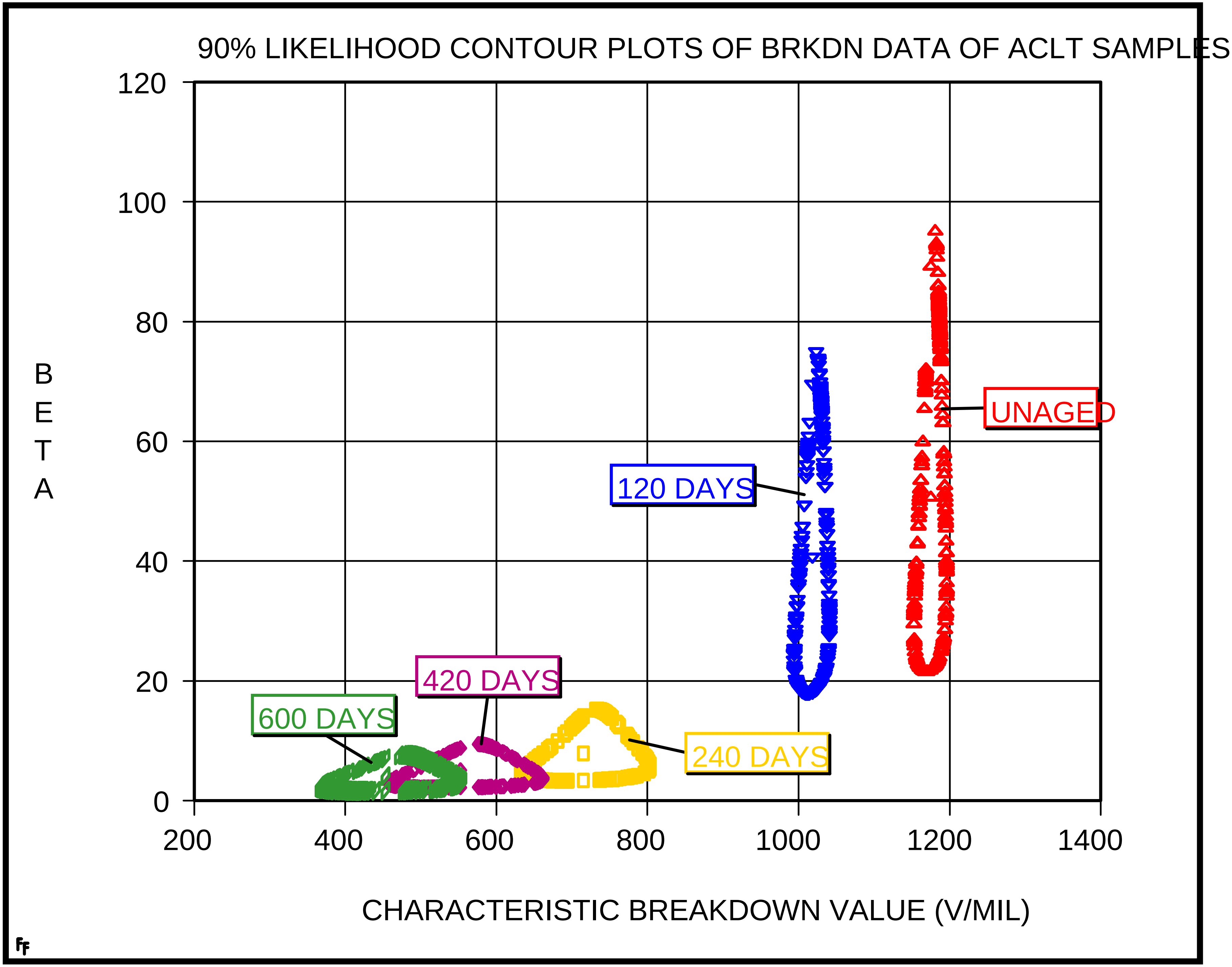


LOGNORMAL ANALYSIS OF ACLT FAILURE TIMES
L/rr/c=fmD90
CUMULATIVE % FAIL
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
MuAL SigF r^2 n/s
285.3 1.206 0.963 12/0
TIME TO FAILURE (DAYS)

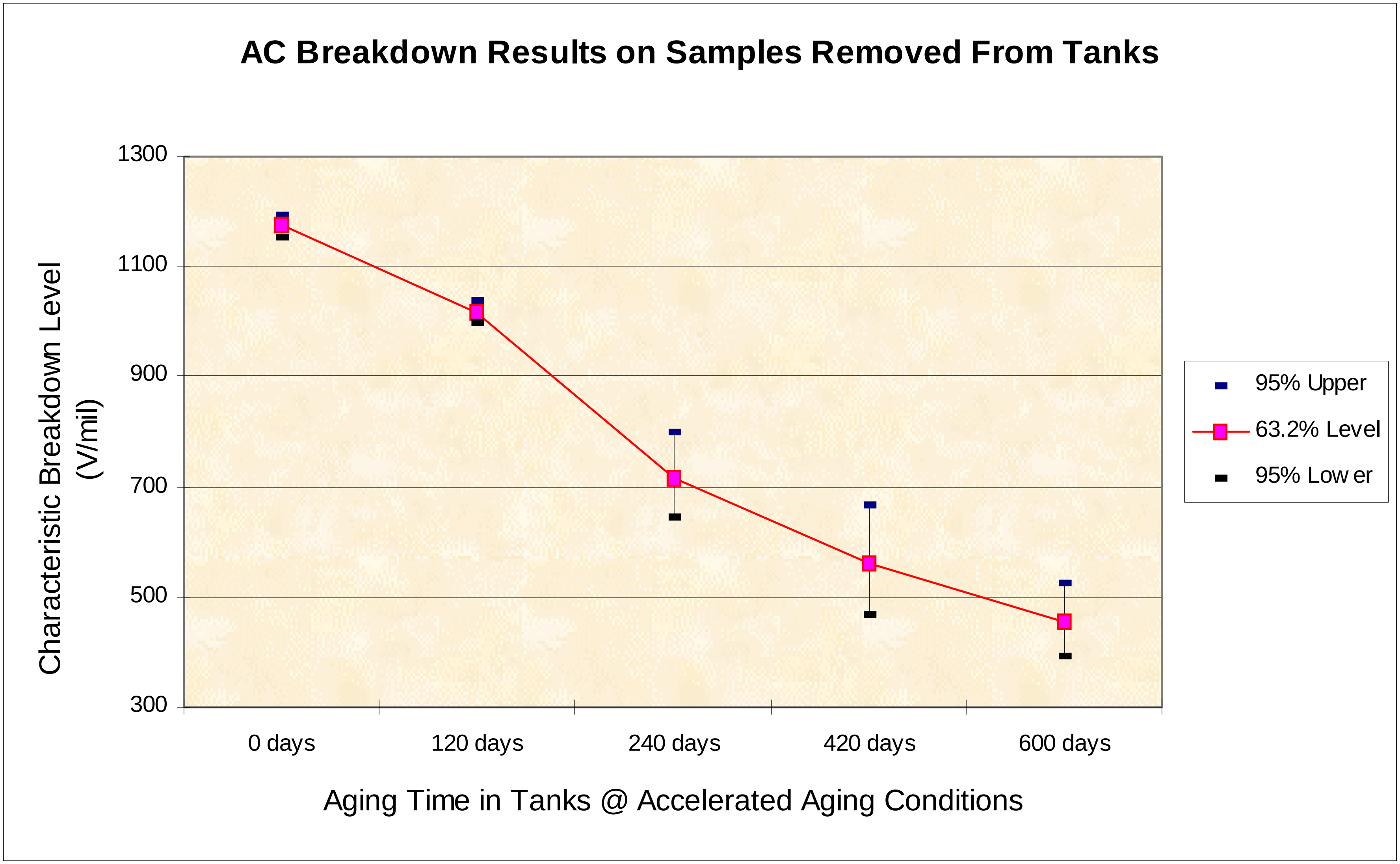
Retained Breakdown Strength Test Protocol (Not a Life Test!)

- Accelerates Degradation of AC Breakdown Strength
- Population Size: Usually 25 Samples
- One Group of 5 Samples - Unaged
- Age 4 Groups of 5 Samples In Tanks For Different Time Periods (120, 240, 420, 600 Days)
- At End of Each Aging Period, Remove 5 Samples for AC Breakdown Tests and Perform Statistical Analysis of Breakdown Values
- Plot Curve Showing Degradation of Breakdown Strength vs. Aging Time in Tanks Under Accelerated Aging Conditions
- Perform Microscopic Exams on Breakdown Sites to Gain Knowledge About Failure Modes


WEIBULL ANALYSIS OF BREAKDOWN DATA
W/rr
420 days
240 Days
Unaged
600 days
120 Days
Eta Beta r^2 n/s
1176 46.76 0.99 5/0
1019 40.47 0.95 5/0
717.8 7.424 0.911 5/0
559.8 4.499 0.952 5/0
453.6 5.257 0.862 5/0
90
80
70
60
50
40
30
20
10
100
1000
10000
Cumulative % Fail
Breakdown Stress Level (V/mil)



90% LIKELIHOOD CONTOUR PLOTS OF BRKDN DATA OF ACLT SAMPLES
120
100
80
60
40
20
0
BETA
UNAGED
120 DAYS
420 DAYS
600 DAYS
240 DAYS
200
400
600
800
1000
1200
1400
CHARACTERISTIC BREAKDOWN VALUE (V/MIL)


AC Breakdown Results on Samples Removed From Tanks
1300
1100
900
700
500
300
Characteristic Breakdown Level
(V/mil)
0 days
120 days
240 days
420 days
600 days
Aging Time in Tanks @ Accelerated Aging Conditions
95% Upper
63.2% Level
95% Low er

Development of Aging Model For XLPE-Insulated Cables (EPRI Project RP2713-02)

ACLT Test Matrix Designations

CONDUCTOR TEMPERATURE

TEST VOLTAGE	90°C LEVEL 4	75°C LEVEL 3	60°C LEVEL 2	45°C LEVEL 1
34.6 kV (4 X Vg)	44	43	42	41
26.0 kV (3 X Vg)	34	33	32	31
17.3 kV (2 X Vg)	24	23	22	21
8.7 kV (1 X Vg)	14	13	12	11

Formula For Wet Aging Model For XLPE-Insulated Cables (EPRI Project RP2713-02)

y_p = - 18.78244

+10.5551633 * (1000/(273.2 + *T*))

+0.62568007 * (1000/(273.2 + *T*))*ln(1/*V*)

+0.48102162 * ln{[-ln(1-*p*)](30/*L*)}

y_p = pth percentile for natural log failure time, thus

t_p = exp(y_p) = DAYS = predicted number of days for the pth percentile of the failure time distribution

YEARS = DAYS/365

V = Test Voltage in kV

T = Conductor Load Cycle Temperature in °C

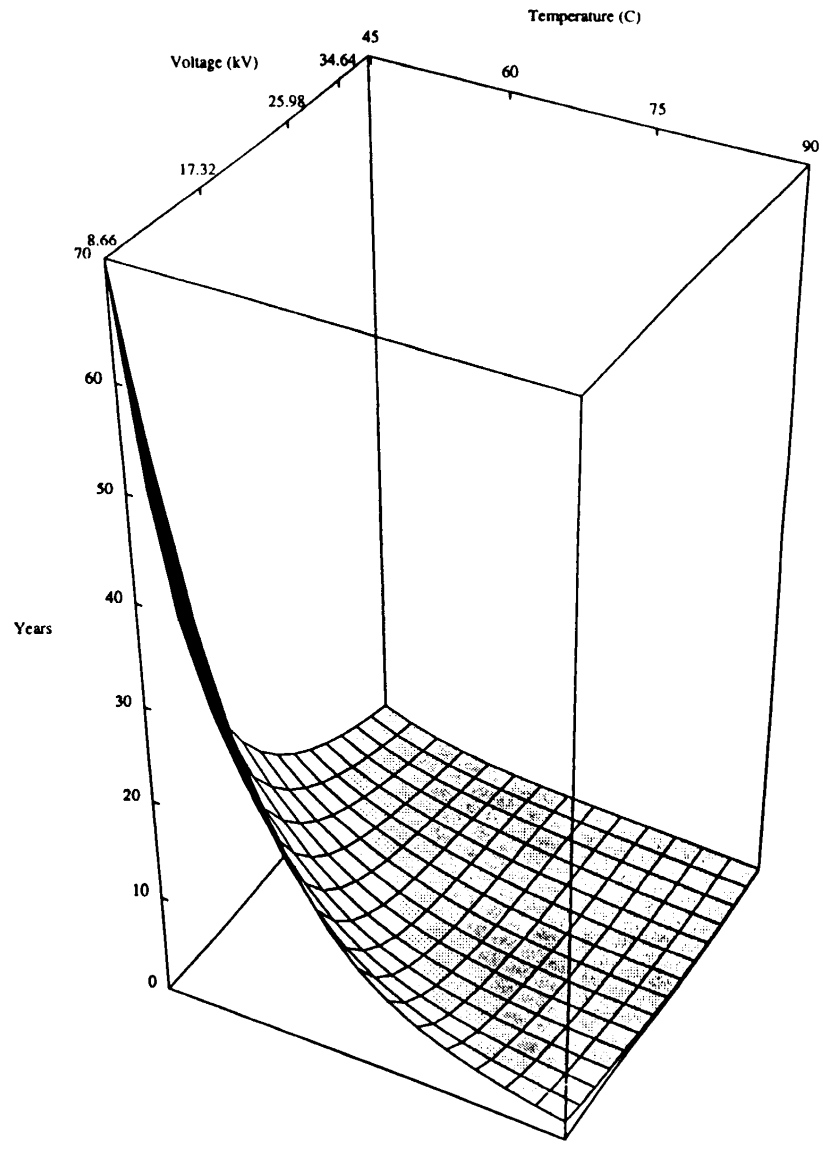
L = Cable Length in feet

p = failure percentile of the failure distribution

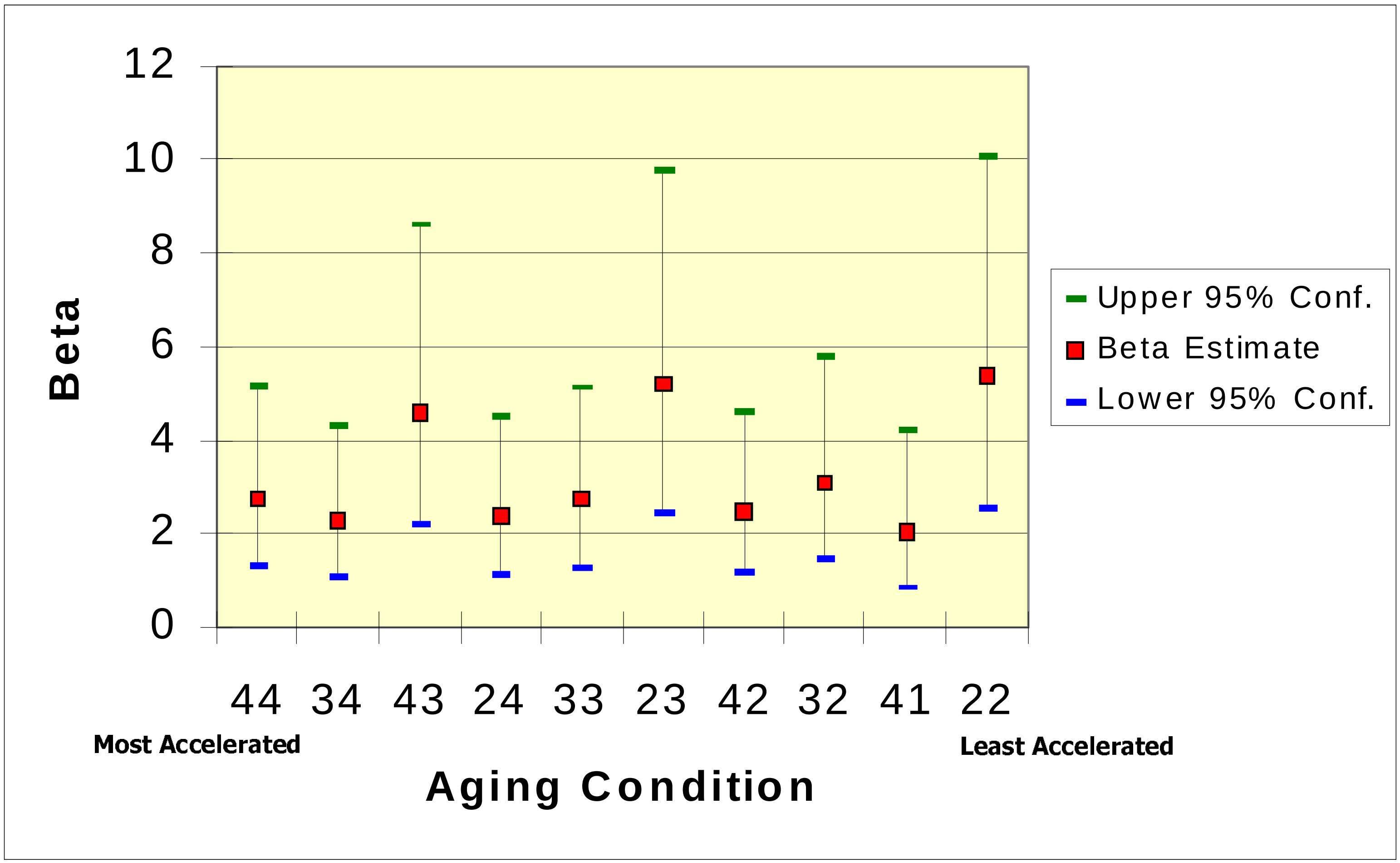
Predicted Characteristic Life (p = 0.632) of XLPE Insulated Cable For Selected Voltages and Temperatures (L = 30 ft)

V (kV)	*T* (°C)	Predicted YEARS	LOWER 90% Limit	UPPER 90% Limit
34.6	90	0.18	0.16	0.20
34.6	75	0.48	0.43	0.54
34.6	60	1.40	1.21	1.63
34.6	45	4.56	3.65	5.71
26.0	90	0.29	0.26	0.32
26.0	75	0.80	0.75	0.86
26.0	60	2.41	2.14	2.71
26.0	45	8.04	6.59	9.81
17.3	90	0.59	0.50	0.69
17.3	75	1.66	1.43	1.93
17.3	60	5.16	4.32	6.16
17.3	45	17.84	14.00	22.72
8.7	90	1.94	1.36	2.76
8.7	75	5.77	4.03	8.25
8.7	60	18.95	12.93	27.78
8.7	45	69.71	45.45	106.91

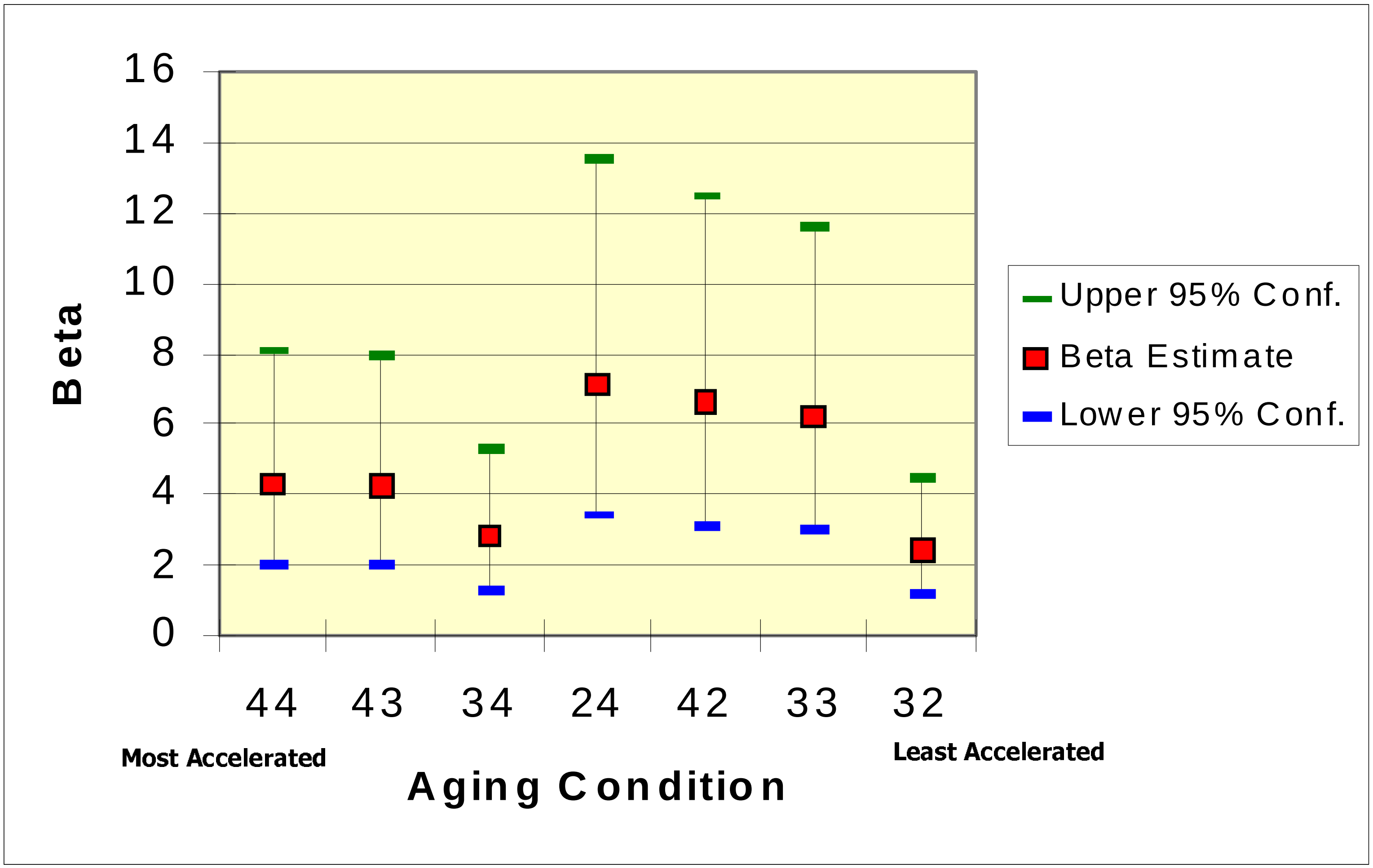
3-D Representation of Wet XLPE Aging Model
(p = 0.632, L = 30 ft.)



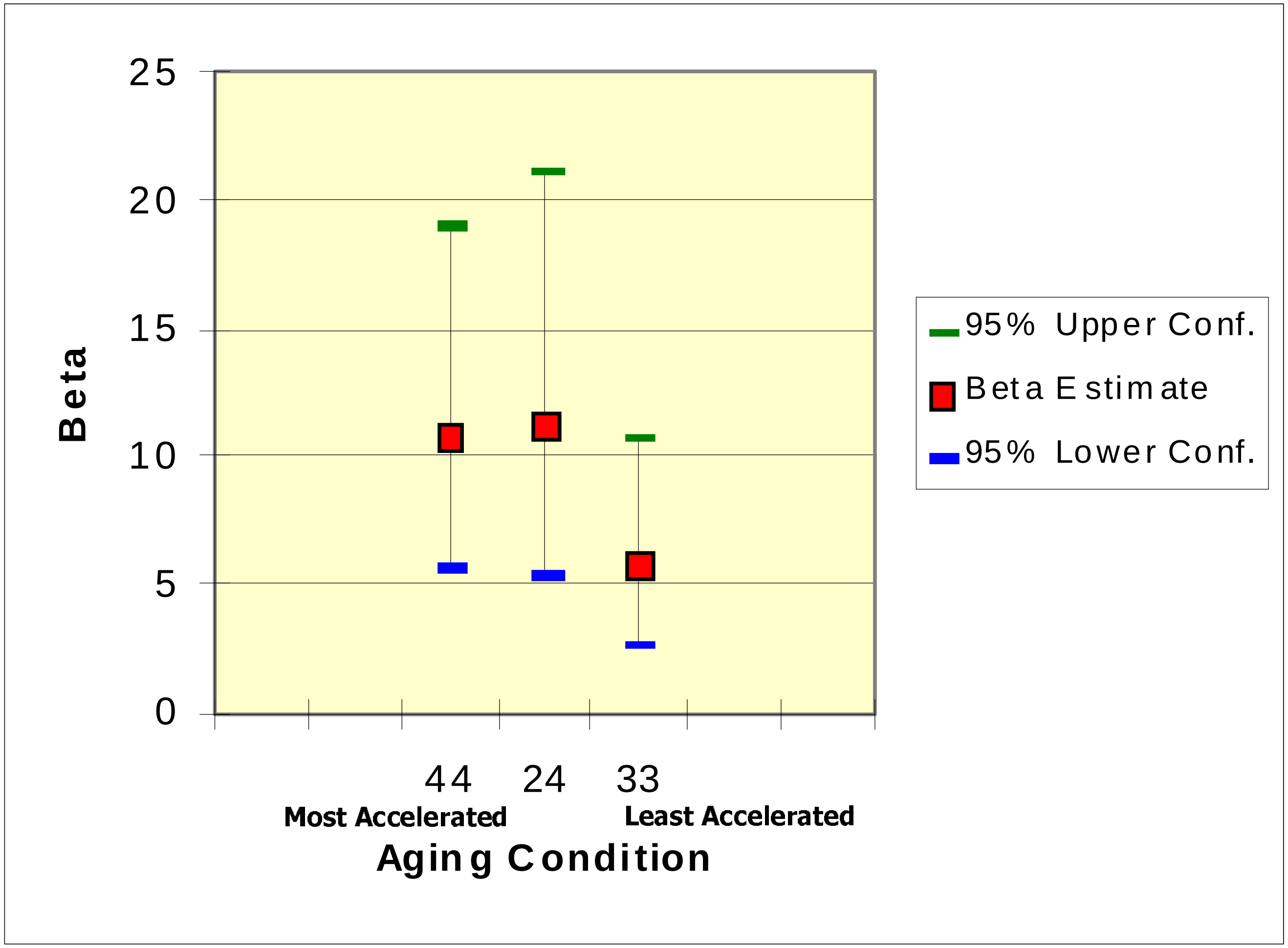
Run 1 XLPE Failure Mode Investigation At Different ACLT Aging Conditions



Run 2 XLPE Failure Mode Investigation At Different ACLT Aging Conditions



Run 3 XLPE Failure Mode Investigation At Different ACLT Aging Conditions



90% Confidence Intervals on β

- Monte Carlo Pivotal Bounds Were Used - (Best Practice for Small Samples - Refs. Lawless [1982], Abernethy [2000])
- Intervals Will Contain the True Unknown β With Frequency of 90% (a Measure of the Estimated β's Repeatability in Many Trials)
- Intervals Will Contain 90% of the Expected Variation in β That Is Solely Due to Statistical Uncertainty
- Overlap of 90% Confidence Intervals for Each Aging Condition Indicates No Significant Difference in β at 90% Confidence Level   (Failure Mechanism Is Not Changing As You Approach Field-Aging Conditions)

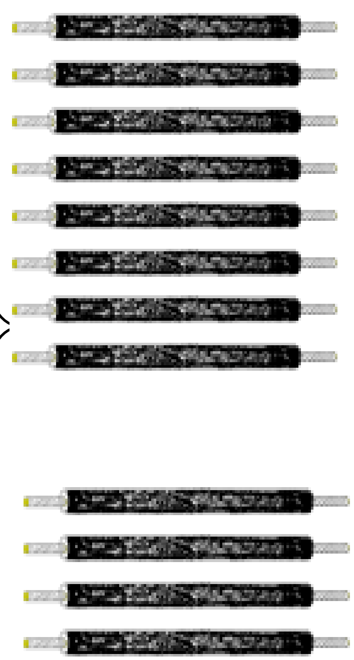
Prior EPRI-Sponsored Work RP2713-02 (1985-1997)

- Correlation Between Cable Life in ACLT (GMTF - Geometric Mean Time to Failure) and Remaining AC Breakdown Strength (GMBD - Geometric Mean Breakdown Strength) Was Established For XLPE Cables
  - GMTF - From Lognormal Analysis of ACLT Failure Times
  - GMBD - From Lognormal Analysis of AC Breakdown Results
- Results Were Extrapolated to Aging Conditions Seen in the Field

Methodology Used To Relate Cable Life to AC Breakdown Strength

30 Ft.
Samples

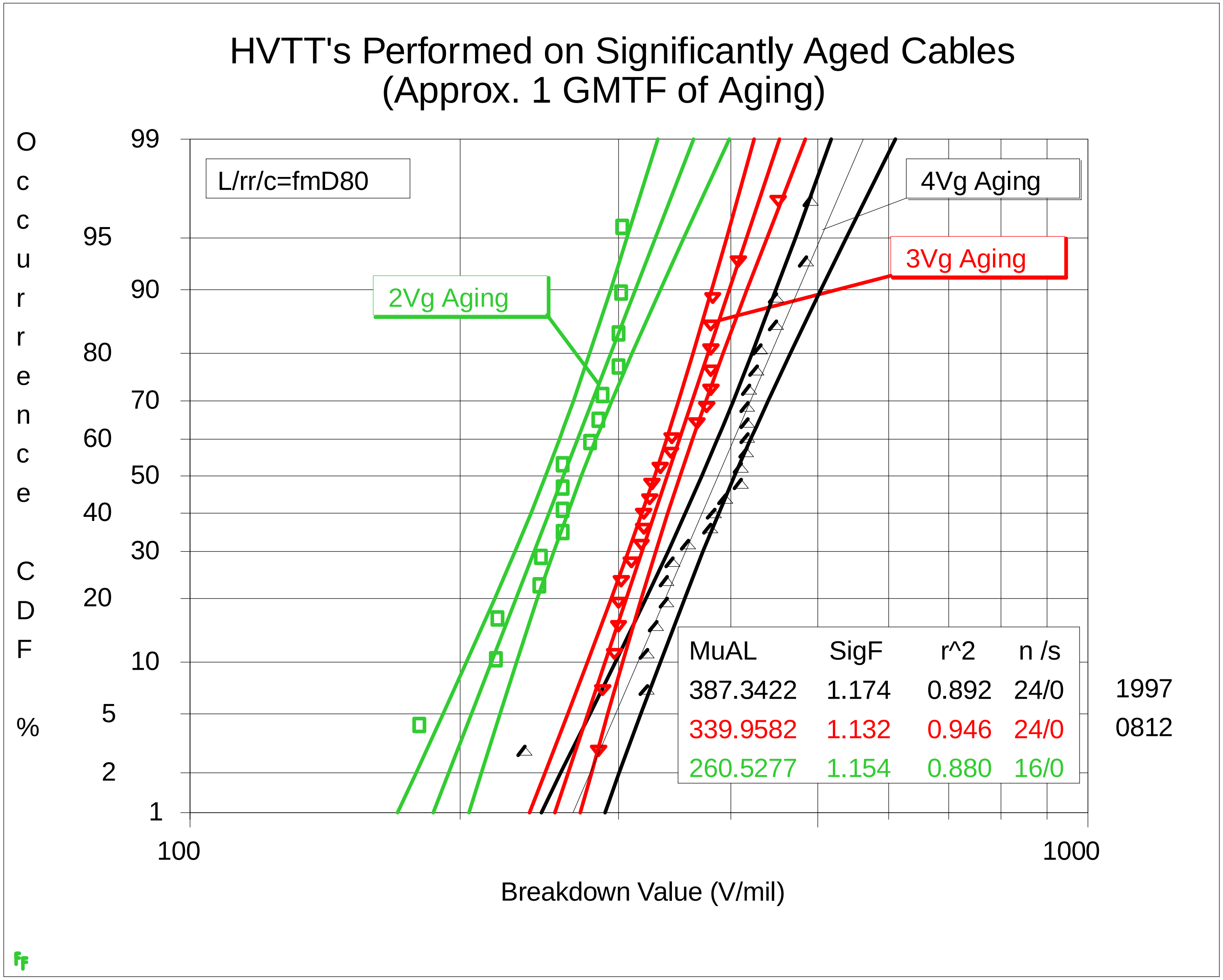
ACLT Population (12 Samples for Each Aging Condition)



Age 8 Samples to Failure - Calculate Lognormal GMTF - Measure of Cable Life

Remaining 4 Samples Subjected to AEIC HVTT Procedure - Calculate Lognormal GMBD - Measure of AC Breakdown Strength

You Now Have a Relationship at Each Aging Condition Between GMTF (A Measure of Cable Life) and GMBD (A Measure of AC Breakdown Strength)
For Significantly Aged Cables (**Significantly Aged** Since 8/12 Samples Had Failed)

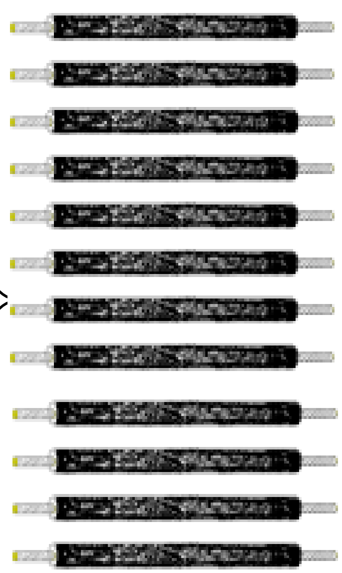


HVTT's Performed on Significantly Aged Cables
(Approx. 1 GMTF of Aging)
Occurrence CDF %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
Breakdown Value (V/mil)
L/rr/c=fmD80
4Vg Aging
3Vg Aging
2Vg Aging
MuAL SigF r^2 n /s
387.3422 1.174 0.892 24/0
339.9582 1.132 0.946 24/0
260.5277 1.154 0.880 16/0
1997
0812

Methodology Used To Relate Cable Life to AC Breakdown Strength (Continued)

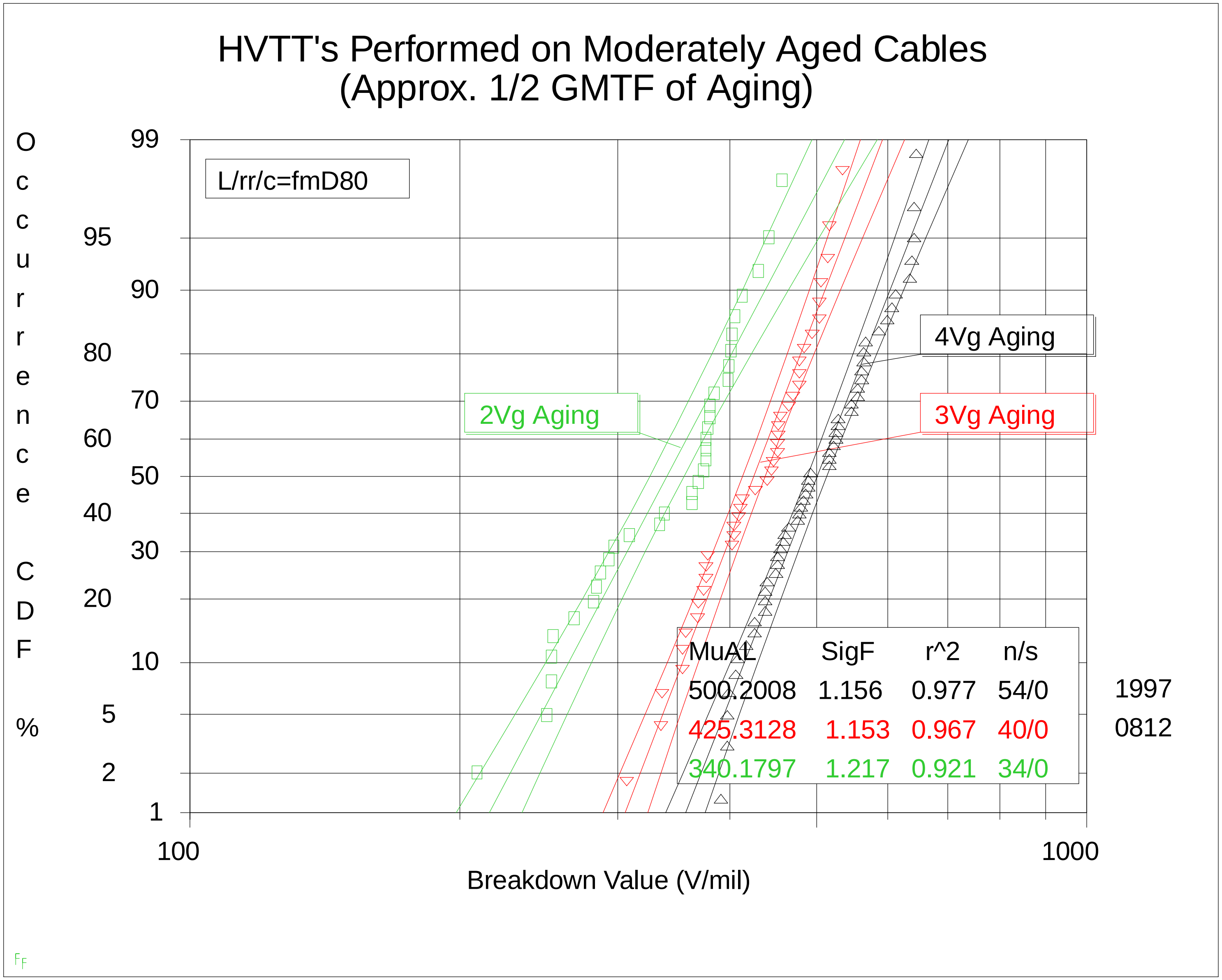
30 Ft.
Samples

ACLT
Population
(12 Samples
for Each
Aging
Condition)



Age Samples For 1/2 of GMTF
Value Calculated From Prior ACLT
Populations Which Were Allowed
to Go to 8 Failures
Call These Samples
Moderately Aged

Perform AC
Breakdowns on All
Samples That
Survive the 1/2
GMTF Aging Period
and Calculate the
GMBD Value

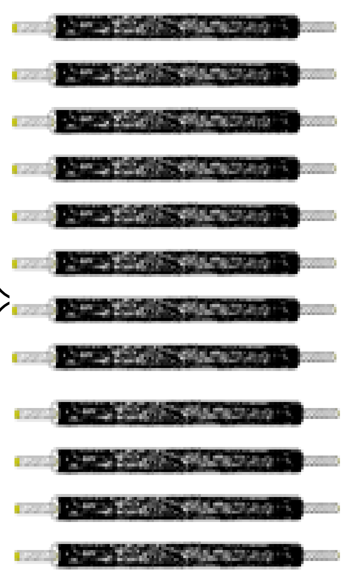


HVTT's Performed on Moderately Aged Cables
(Approx. 1/2 GMTF of Aging)
L/rr/c=fmD80
Occurrence CDF %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
Breakdown Value (V/mil)
2Vg Aging
3Vg Aging
4Vg Aging
MuAL SigF r^2 n/s
500.2008 1.156 0.977 54/0
425.3128 1.153 0.967 40/0
340.1797 1.217 0.921 34/0
1997
0812

Methodology Used To Relate Cable Life to AC Breakdown Strength (Continued)

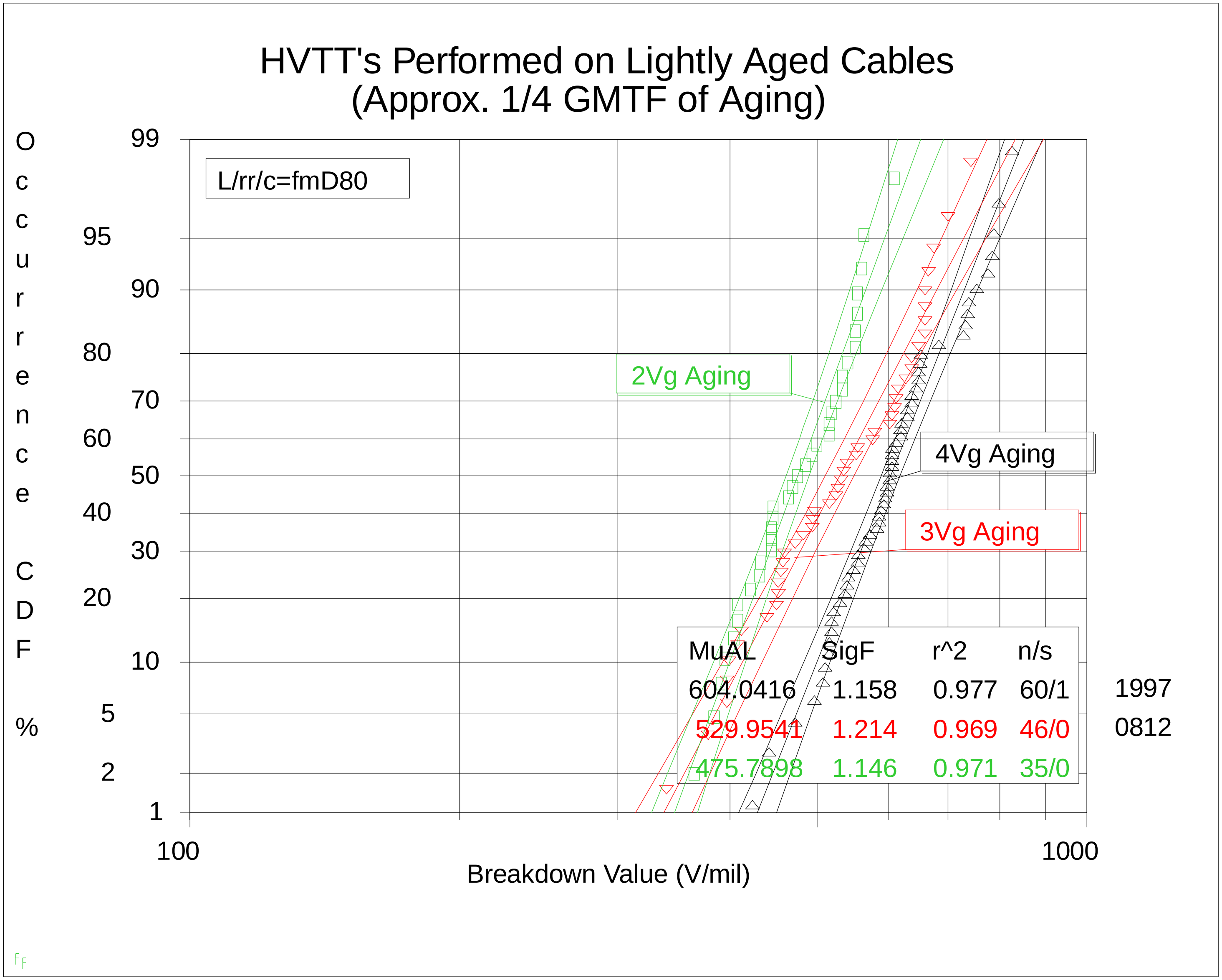
30 Ft.
Samples

ACLT
Population
(12 Samples
for Each
Aging
Condition)



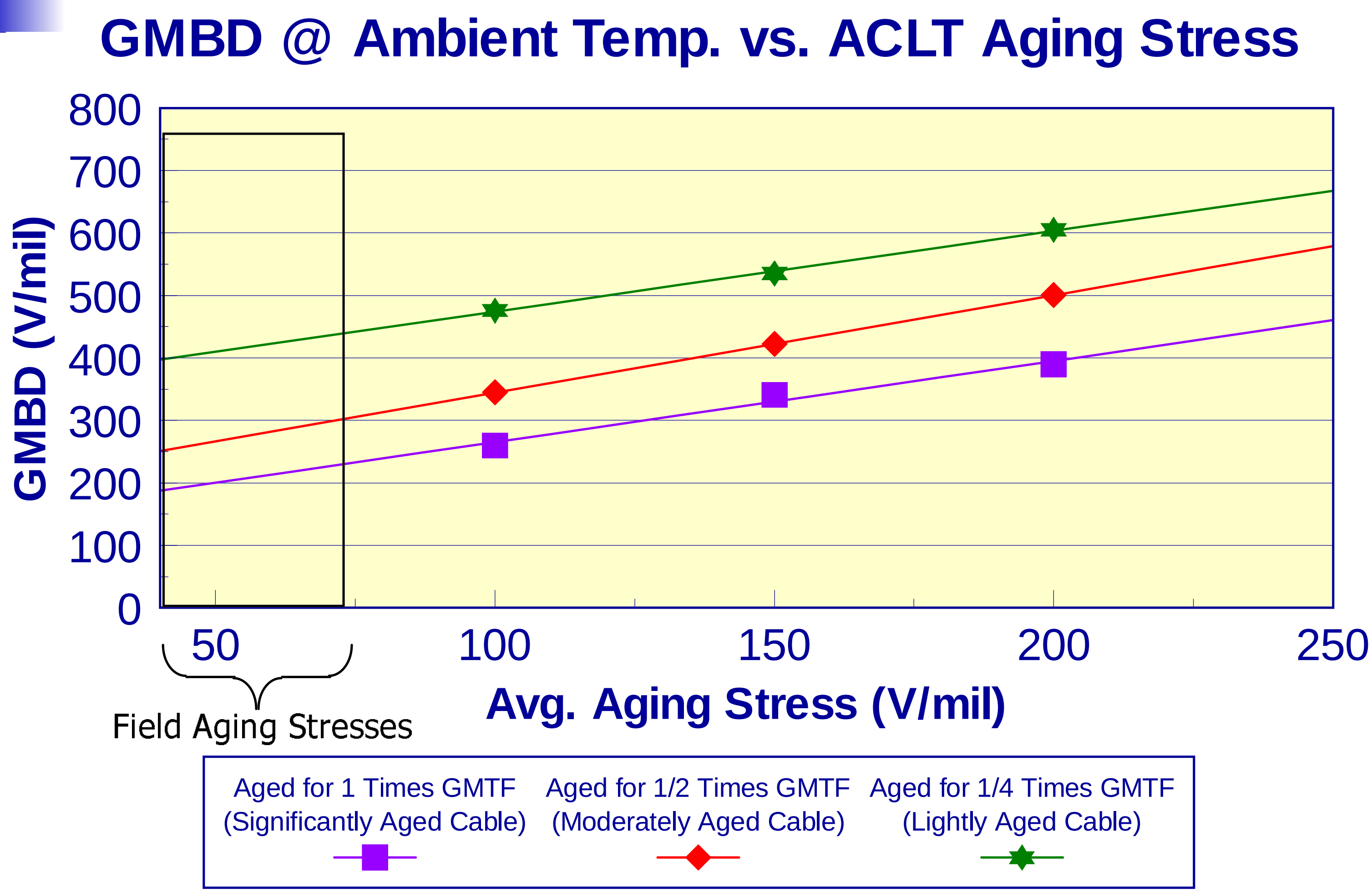
Age Samples For 1/4 of GMTF
Value Calculated From Prior ACLT
Populations Which Were Allowed
to Go to 8 Failures
Call These Samples
Lightly Aged

Perform AC
Breakdowns on All
Samples That
Survive the 1/4
GMTF Aging Period
and Calculate the
GMBD Value



HVTT's Performed on Lightly Aged Cables
(Approx. 1/4 GMTF of Aging)
L/rr/c=fmD80
2Vg Aging
4Vg Aging
3Vg Aging
MuAL SigF r^2 n/s
604.0416 1.158 0.977 60/1
529.9541 1.214 0.969 46/0
475.7898 1.146 0.971 35/0
1997
0812
Occurrence CDF %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
Breakdown Value (V/mil)

Relationship Between AC Breakdown Strength and Remaining Life of Cable



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