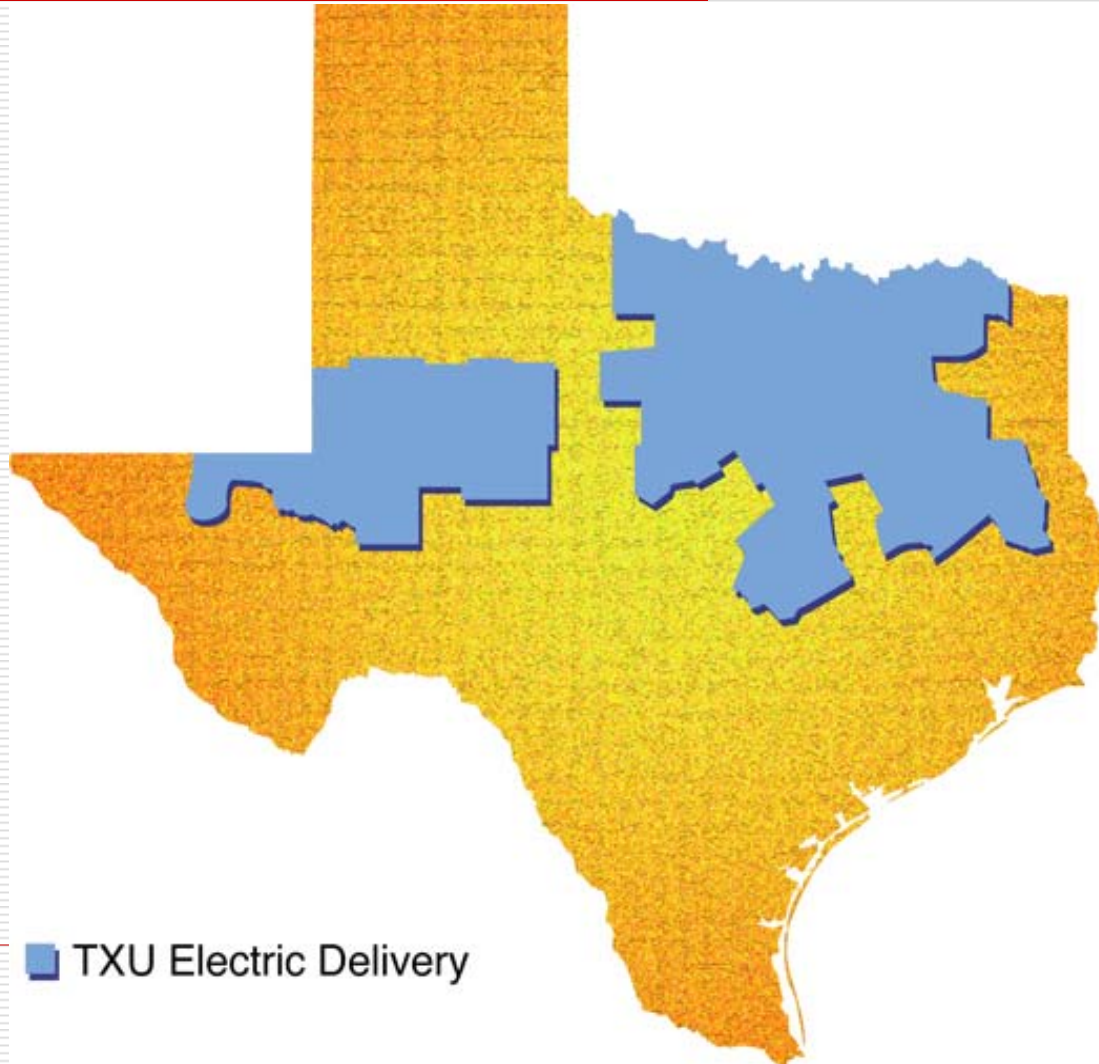

Cable Failure Statistics and Analysis at TXU Electric Delivery Company

by Richie Harp – TXU Electric Delivery
and John T. Smith, III – General Cable

History of TXU Electric Delivery Cables

- Present TXU Electric Delivery system is composed of the merger of three independent electric utilities in 1984
 - Dallas Power & Light
 - Texas Electric Service
 - Texas Power & Light
 - Consolidated to one cable standard in 1990
-

Service Territory



Dallas Power & Light

- ❑ Service Territory – within the city limits of Dallas
 - ❑ Approximately 1/6 of the system cable
 - ❑ PILC cable in downtown network and many substation getaways
 - ❑ 220-mil HMWPE beginning in mid 1960s
 - ❑ 220-mil XLPE beginning in early 1970s
 - ❑ Standardized cable in 1990
-

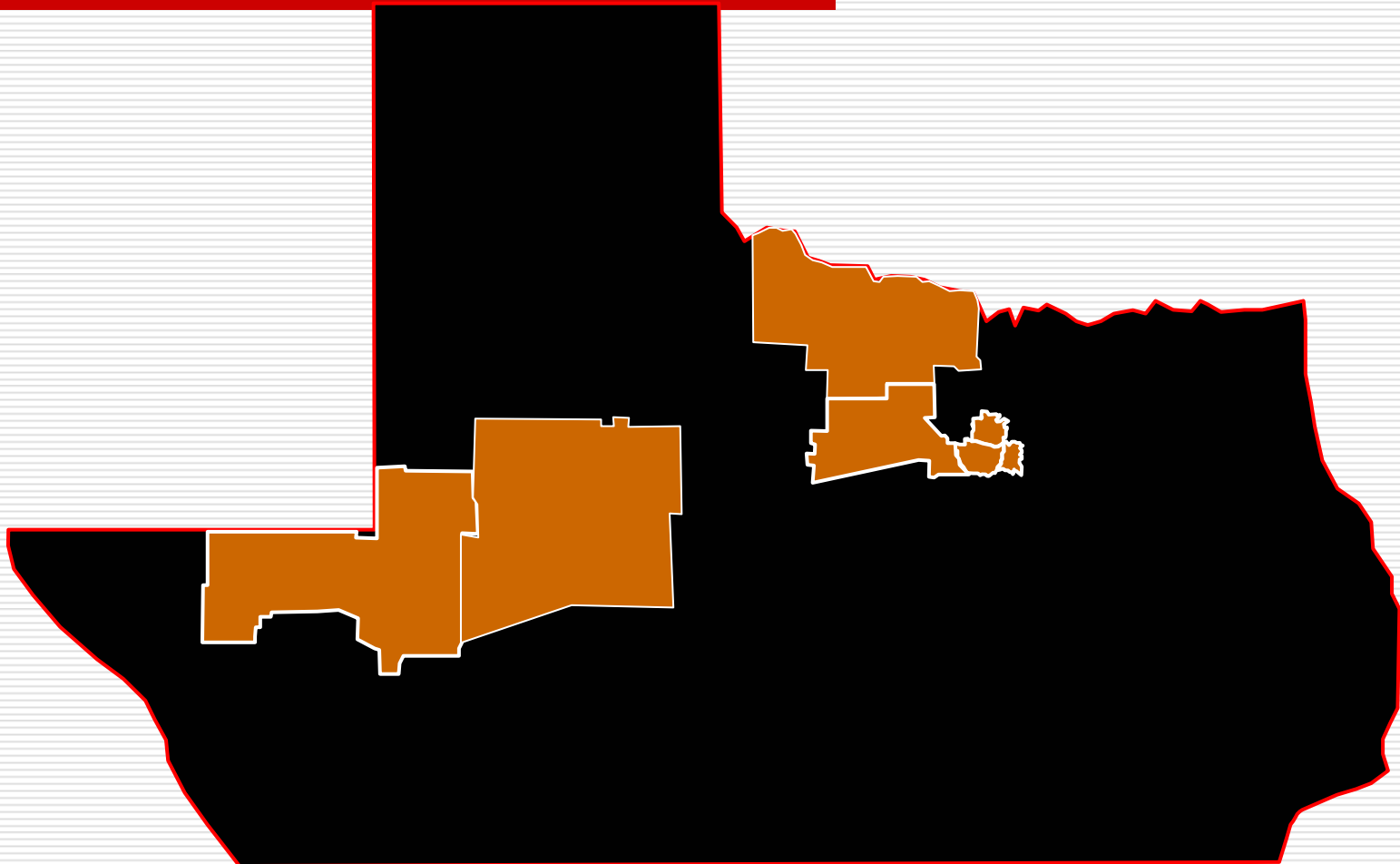
Service Territory – DP&L



Texas Electric Service

- ❑ Service Territory – west part of D/FW Metroplex, Ft Worth and west past Midland/Odessa
 - ❑ Approximately 1/3 of the system cable
 - ❑ PILC cable in downtown network only
 - ❑ 220-mil HMWPE beginning in mid 1960s
 - ❑ 175-mil XLPE beginning in early 1970s
 - Jacketed XLPE cable in mid 1980s
 - ❑ Standardized cable in 1990
-

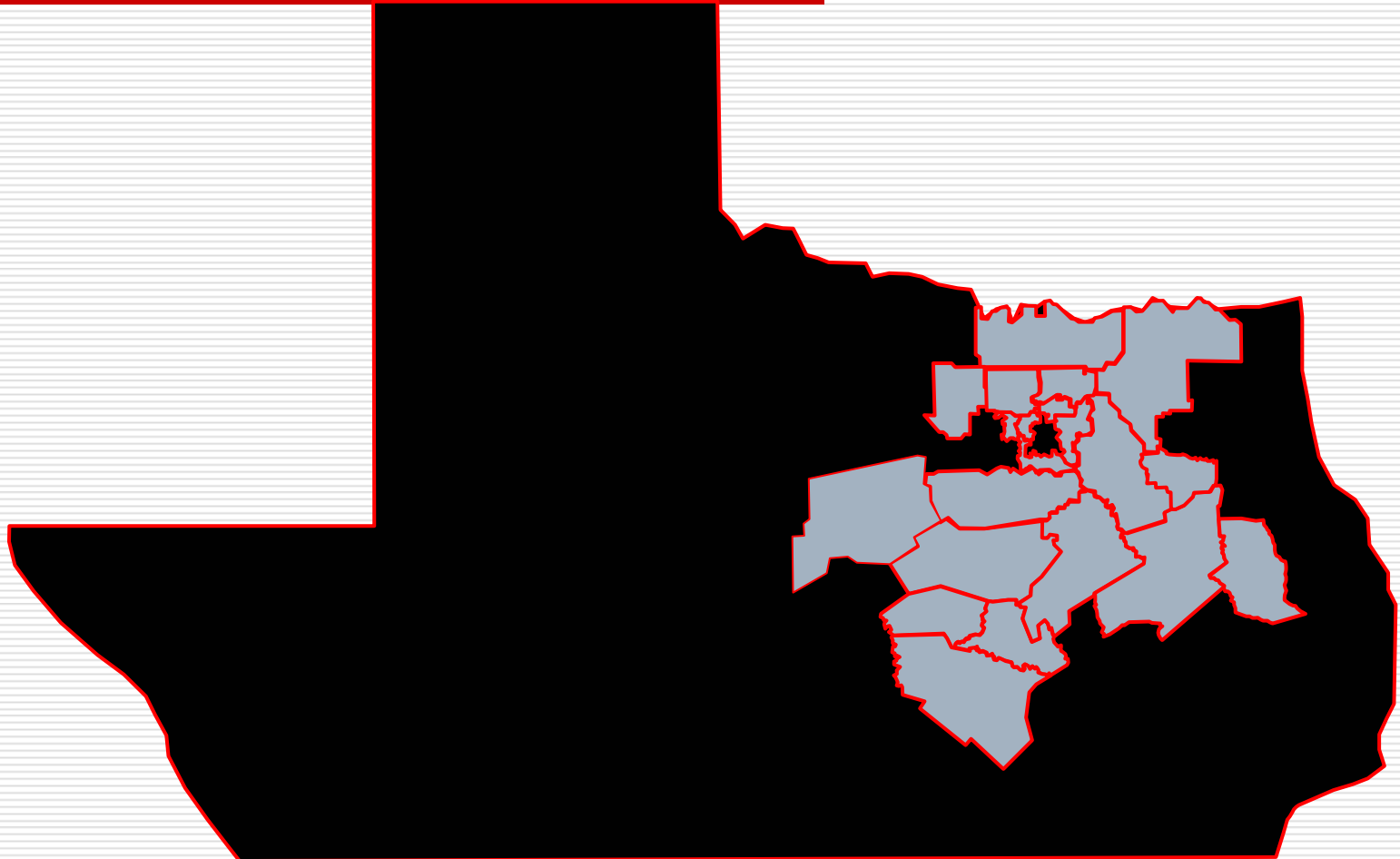
Service Territory - TES



Texas Power & Light

- ❑ Service Territory – east part of D/FW Metroplex (outside Dallas city limits), North, Central, and East Texas
 - ❑ Approximately 1/2 of the system cable
 - ❑ PILC cable at D/FW Airport installed in 1991 to replace XLPE cable
 - ❑ 220-mil HMWPE beginning in mid 1960s
 - ❑ 175-mil XLPE beginning in early 1970s
 - ❑ Standardized cable in 1990
-

Service Territory – TP&L



TXU Electric Delivery

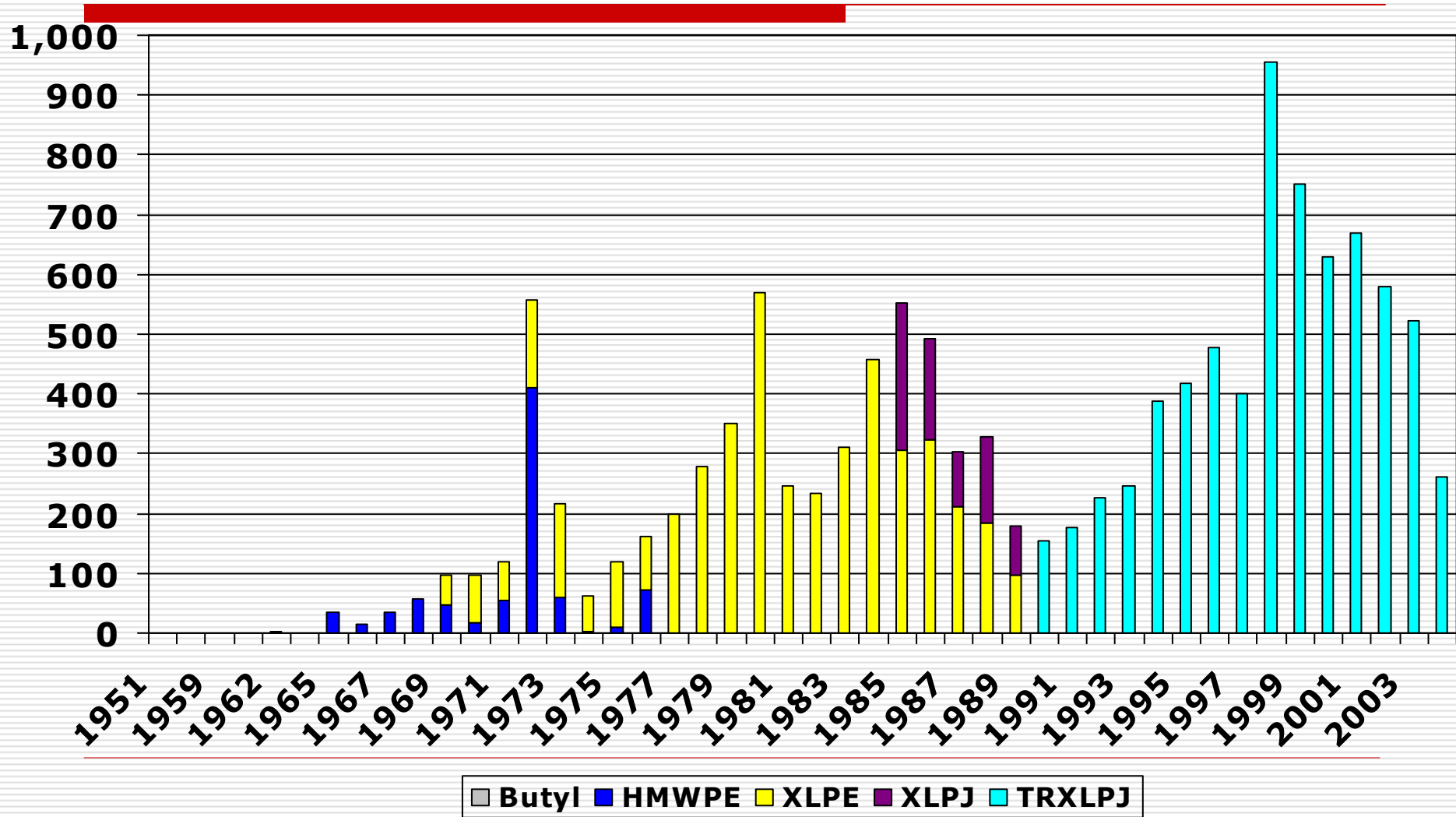
- 18,000 cable miles – Extruded cables
 - Beginning in 1990 – Standardized Cable
 - Strand-filled Conductors
 - 260-mil TRXLPE Insulation (25 kV)
 - #1/0 Al 175-mil added later for 15 kV applications
 - LLDPE Encapsulating Jacket
 - Centralized Cable Testing
 - Separate testing previously by two of the divisions since mid 1970s
-

Cable In Service (as of 8/31/04)

Cable	Cable-Miles	Year Began Installing	Average Age
Butyl Rubber	6	Early 60s	42
HMWPE	1,179	Mid 60s	33
XLPE	6,502	Early 70s	23
XLPE Jkt	1,058	Mid 80s	18
TRXLPE Jkt	9,870	1990	6

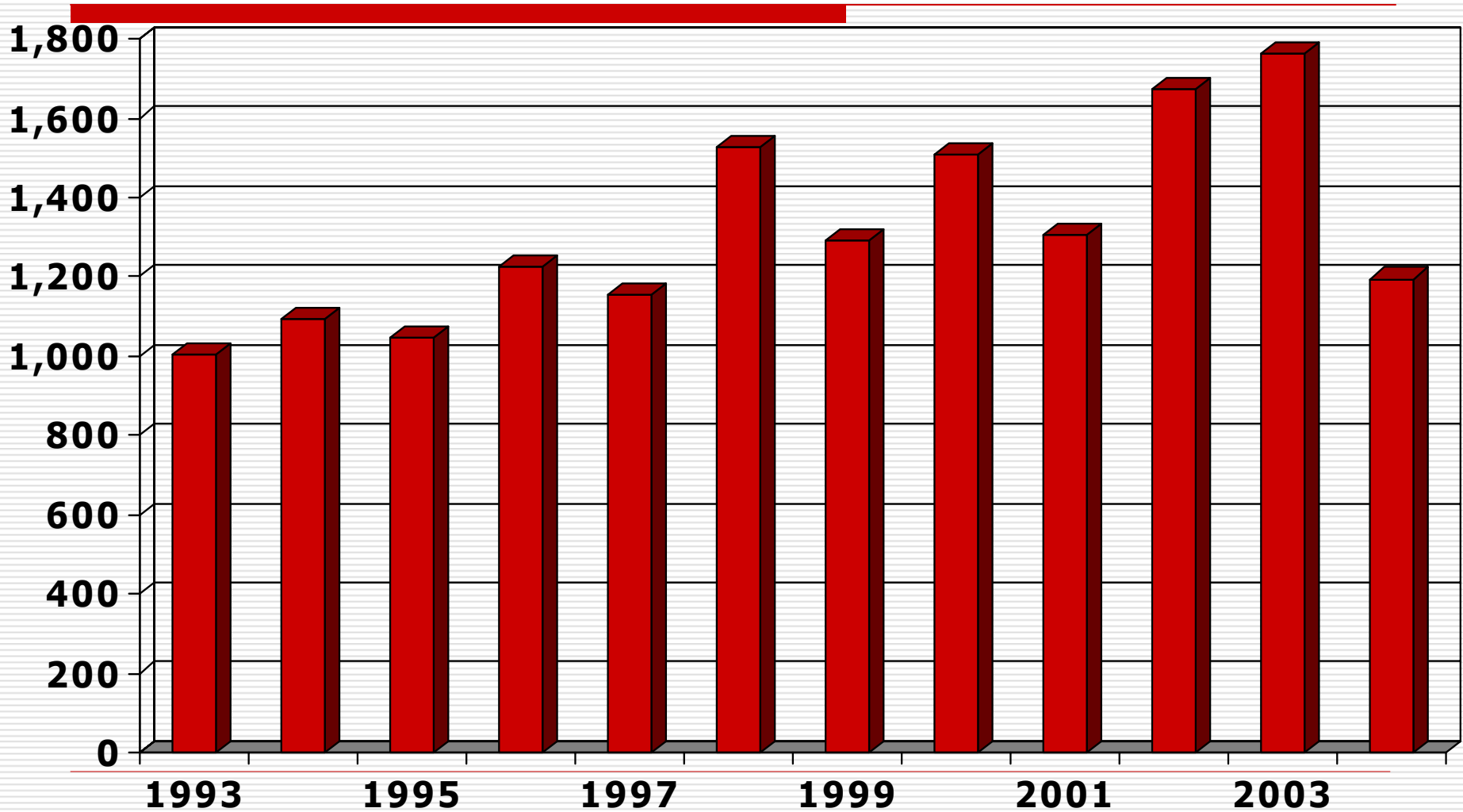
Cable In Service by Insulation Type

(Cable Miles by Vintage Year – 8/31/04)

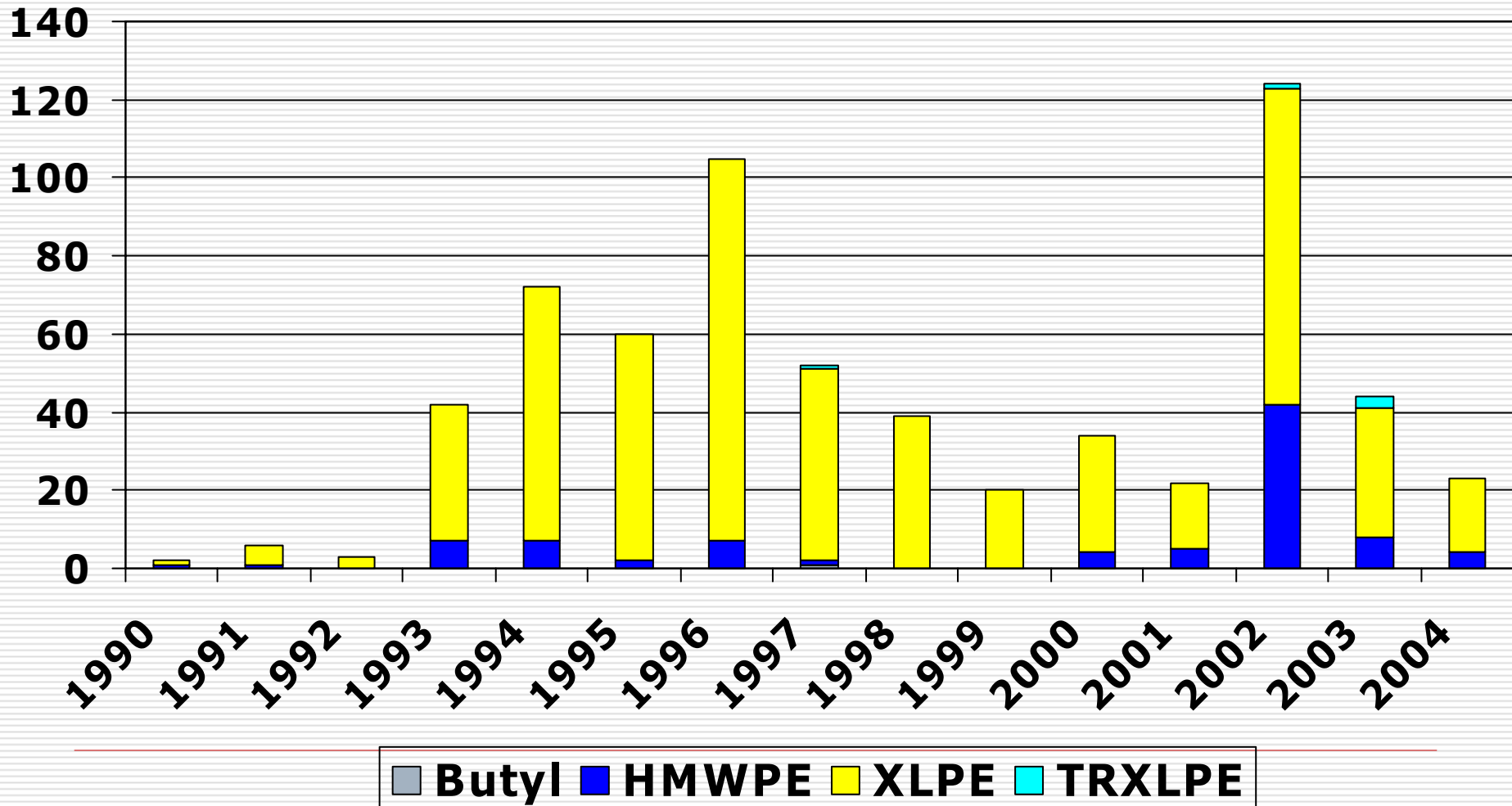


Number of Failures by Year

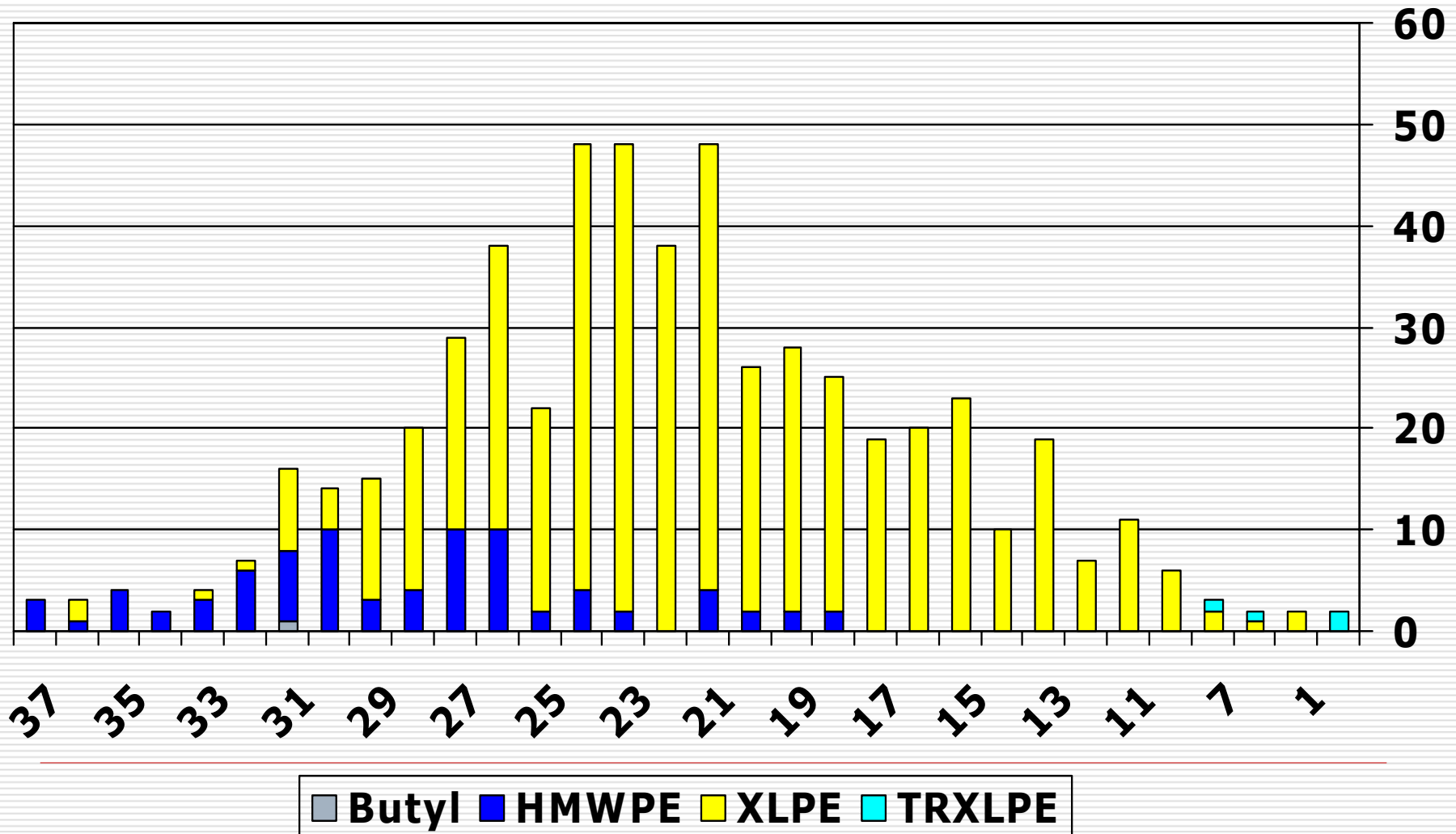
(as of Aug 31, 2004)



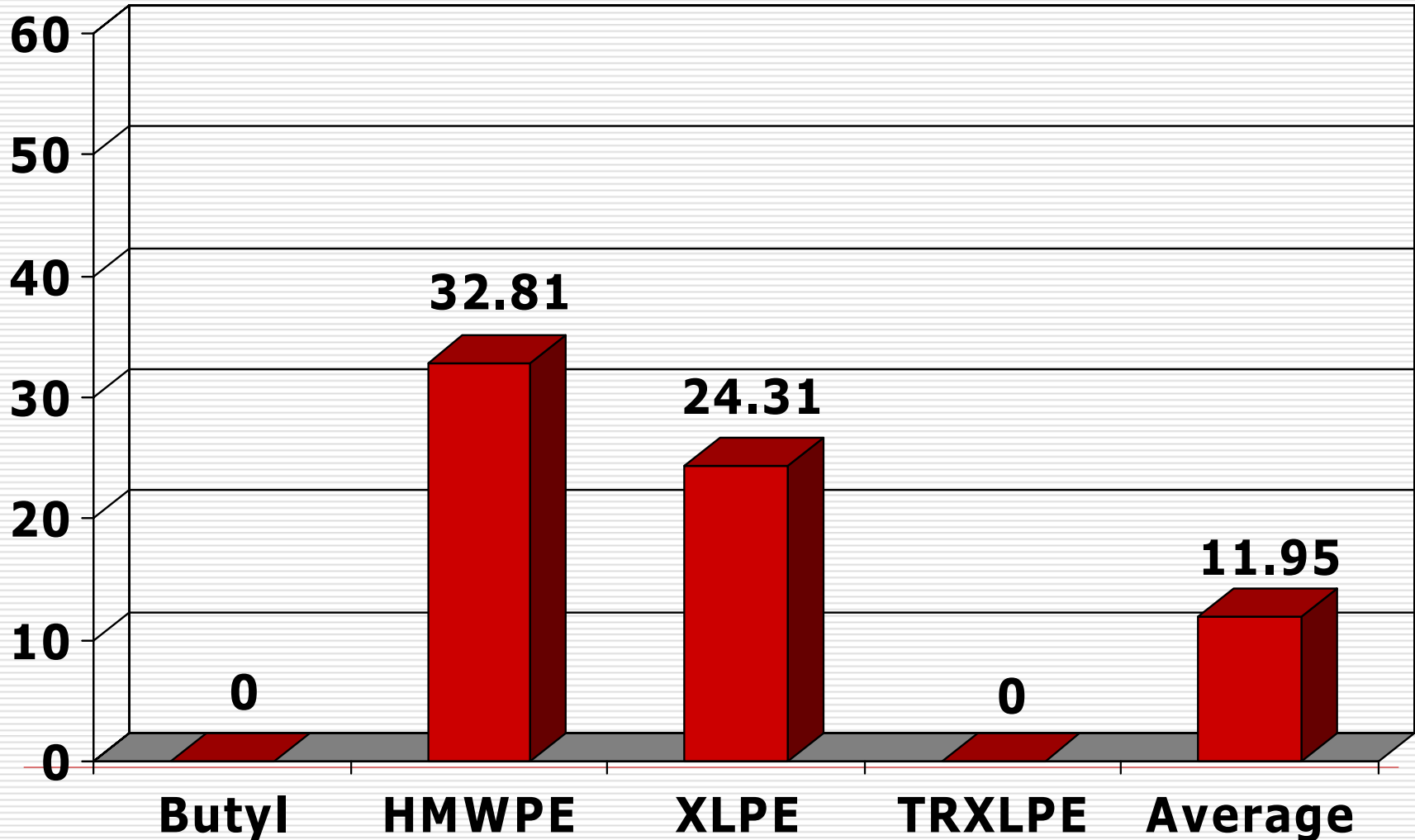
Failures Analyzed by Year of Failure and Insulation Type



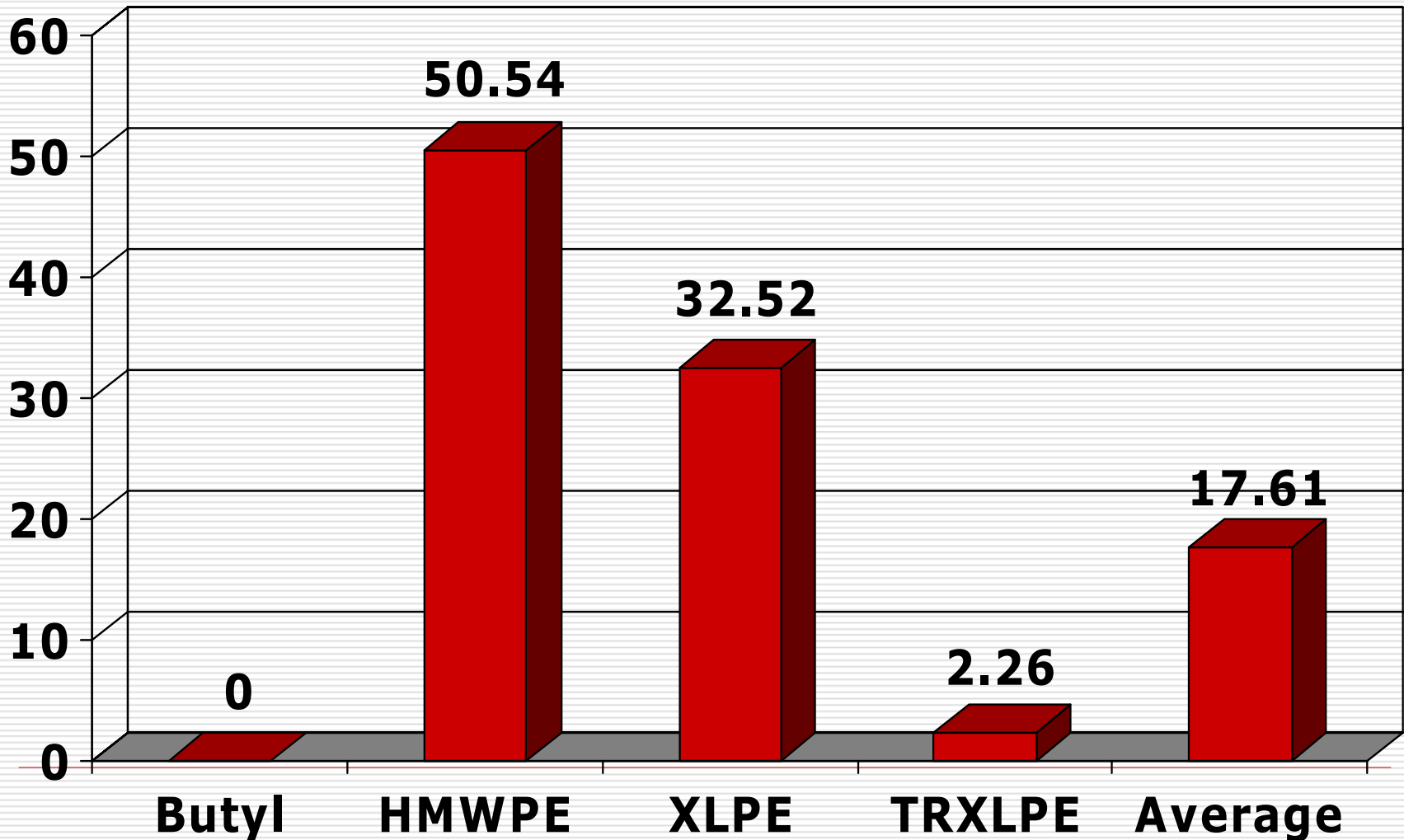
Failures Analyzed by Age and Insulation Type



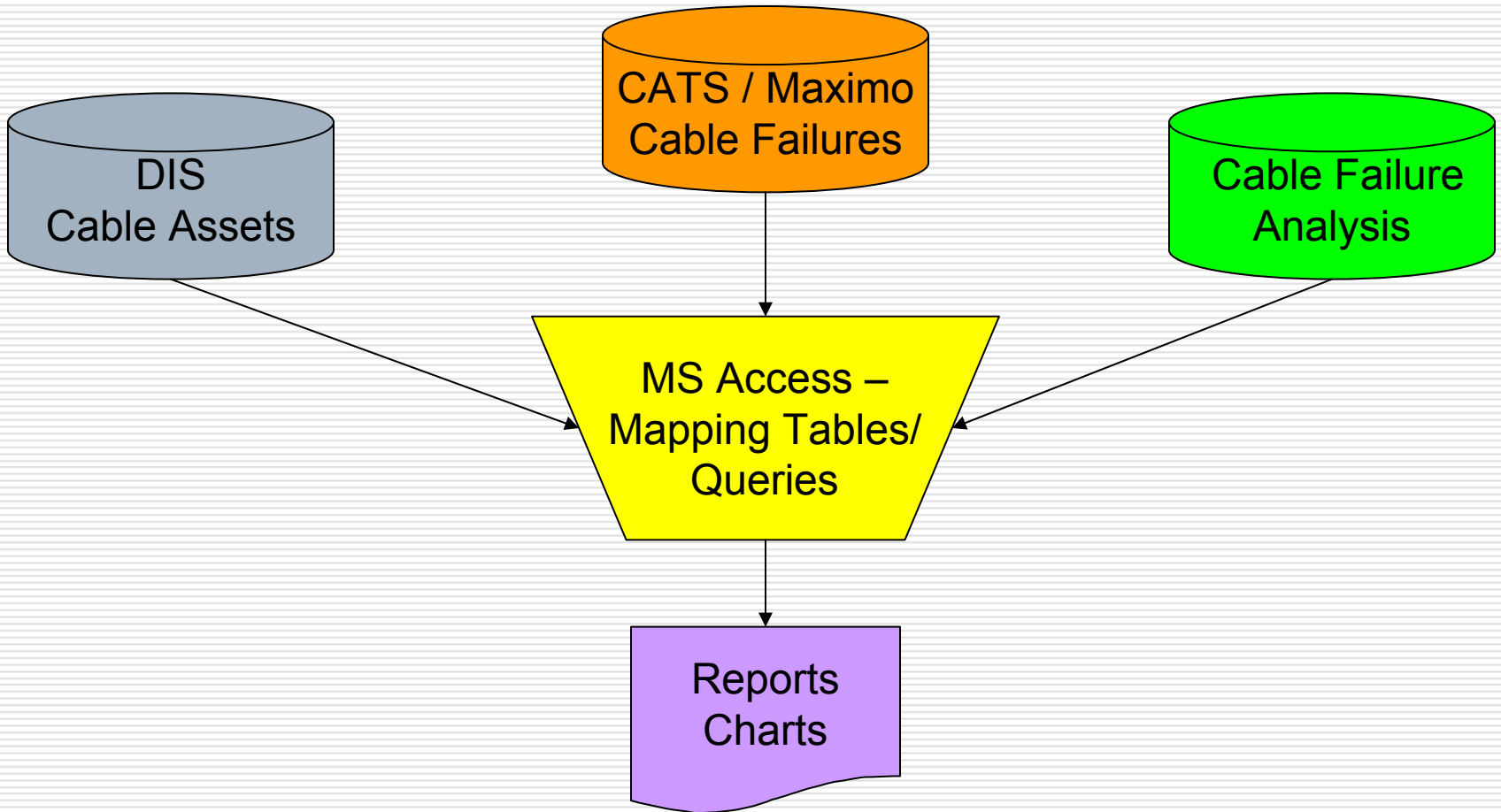
Failures per 100 Miles in 2004 by Insulation Type (as of 8/31/04)



Failures per 100 Miles in 2003 by Insulation Type



Databases



Conclusions on TXU Electric Delivery Cable Failures

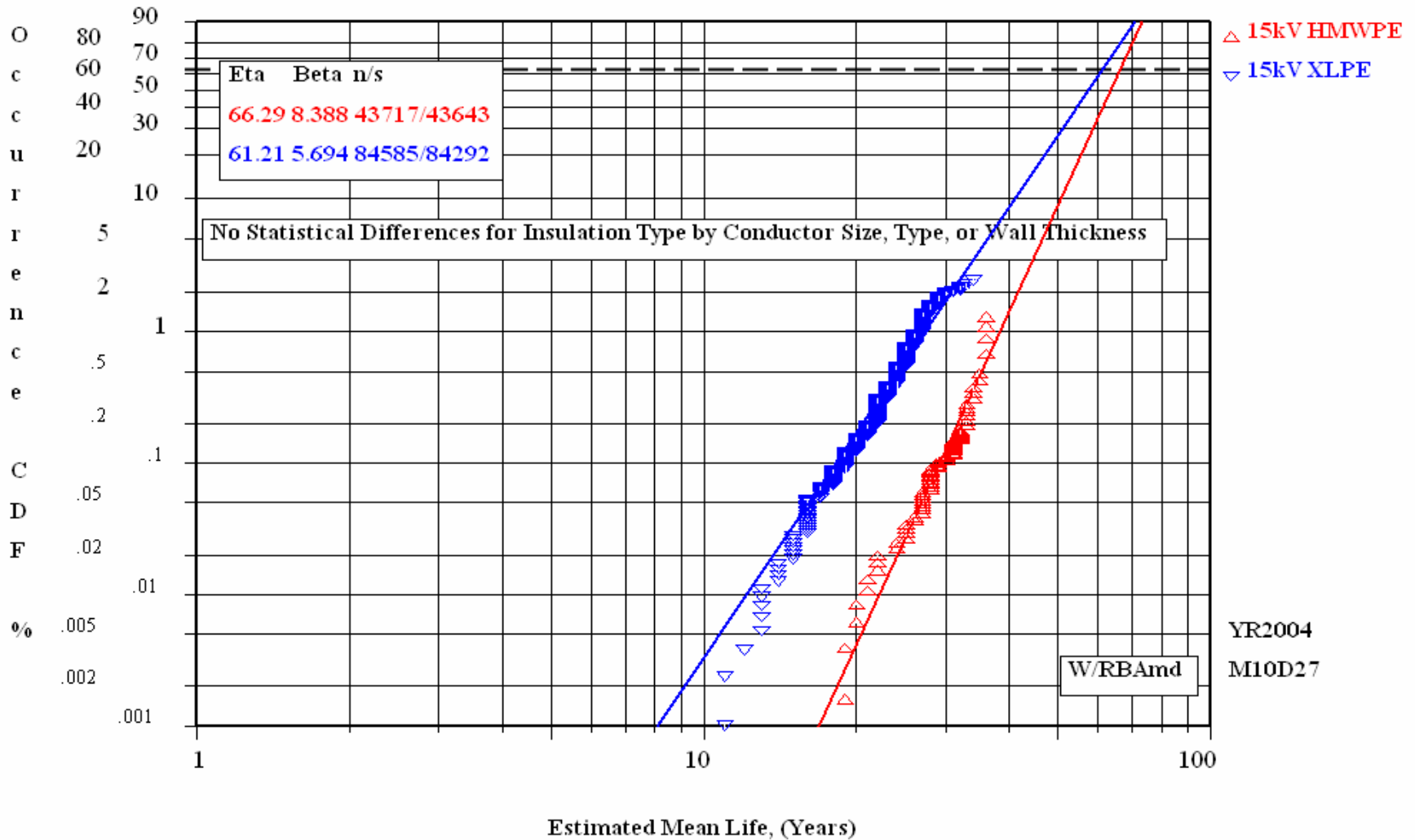
- For HMWPE cables that have been analyzed, the age is about 5 years more than that of XLPE cables.
 - More on this in data analysis (next)
 - It is possible to link various cable databases so that some cable replacement decisions can be made.
-

TXU Cable Failures Analysis

**Weibull Analysis & Crow-AMSAA Modeling
(Crow-Army Materials Systems Analysis
Activity) w/Failure Forecasting**

Weibull Analysis of Only 2% of Total Failures: 1991 - 2004

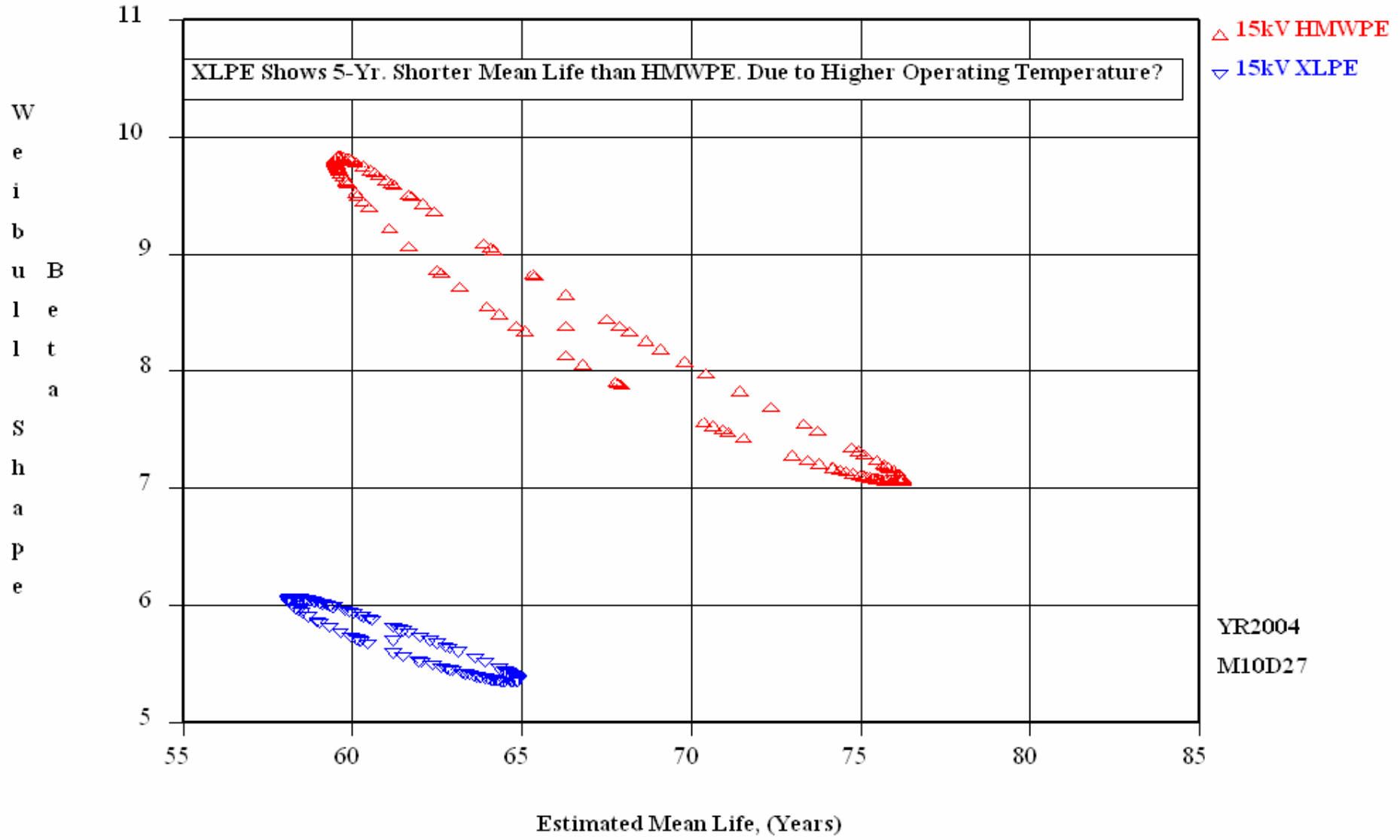
TXU 15kV Cables- All Conductors, 175/220-mil Insulation
Aluminum & Copper



$\beta < 1$ = infant mortality; $\beta = 1$ implies random failure; $1.0 < \beta < 4.0$ implies early wear out; $\beta > 4.0$ implies old age (rapid) wear out. Both HMWPE and XLPE show $\beta > 4.0$.

Contour Plots of Weibull Plots: Large Number of Suspensions

TXU 15kV Cables- All Conductors, 175/220-mil Insulation
Aluminum & Copper



YR2004
M10D27

Failure Forecasts for HMWPE from Weibull Plot

Weibull Quantity Expected - Abernethy Risk

Present Risk Quantity (RBA) = 79.63845 ***Present Actual Failures = 78***

Date: M10-D27-YR2004

TXU 15kV Cables- All Conductors, 175/220-mil Insulation Aluminum

{No Renewal}

Eta = 66.28787 Beta = 8.388062 Total/Suspension = 43717/43643

Set: #1 15kV HMWPE Next Expected Occurrence (Day) = +17

Usage Rate [Estimated Mean L (Years) Each Item Each Month] = .083

Expected Additional Occurrence (Cumulative):

Month.....Risk	Month.....Risk	Month.....Risk	Month.....Risk
1	1.747	16	32.34
2	3.528	17	34.7
3	5.344	18	37.11
4	7.194	19	39.56
5	9.08	20	42.05
6	11	21	44.59
7	12.96	22	47.18
8	14.96	23	49.81
9	16.99	24	52.49
10	19.06	25	55.23
11	21.17	26	58.01
12	23.33	27	60.84
13	25.52	28	63.72
14	27.75	29	66.66
15	30.03	30	69.64
		31	72.69
		32	75.78
		33	78.93
		34	82.14
		35	85.41
		36	88.73
		37	92.11
		38	95.55
		39	99.06
		40	102.6
		41	106.2
		42	109.9
		43	113.7
		44	117.5
		45	121.4
		46	125.3
		47	129.4
		48	133.5
		49	137.6
		50	141.9
		51	146.2
		52	150.5
		53	155
		54	159.5
		55	164.1
		56	168.8
		57	173.6
		58	178.4
		59	183.4
		60	188.4

**Good agreement between actual failures and predicted present risk quantity predicted by the Weibull plot.
Next failure of HMWPE predicted to be within 17 days of last failure. Failures are predicted at a rate of ~ 2/day.**

Failure Forecasts for XLPE from Weibull Plot

Weibull Quantity Expected - Abernethy Risk

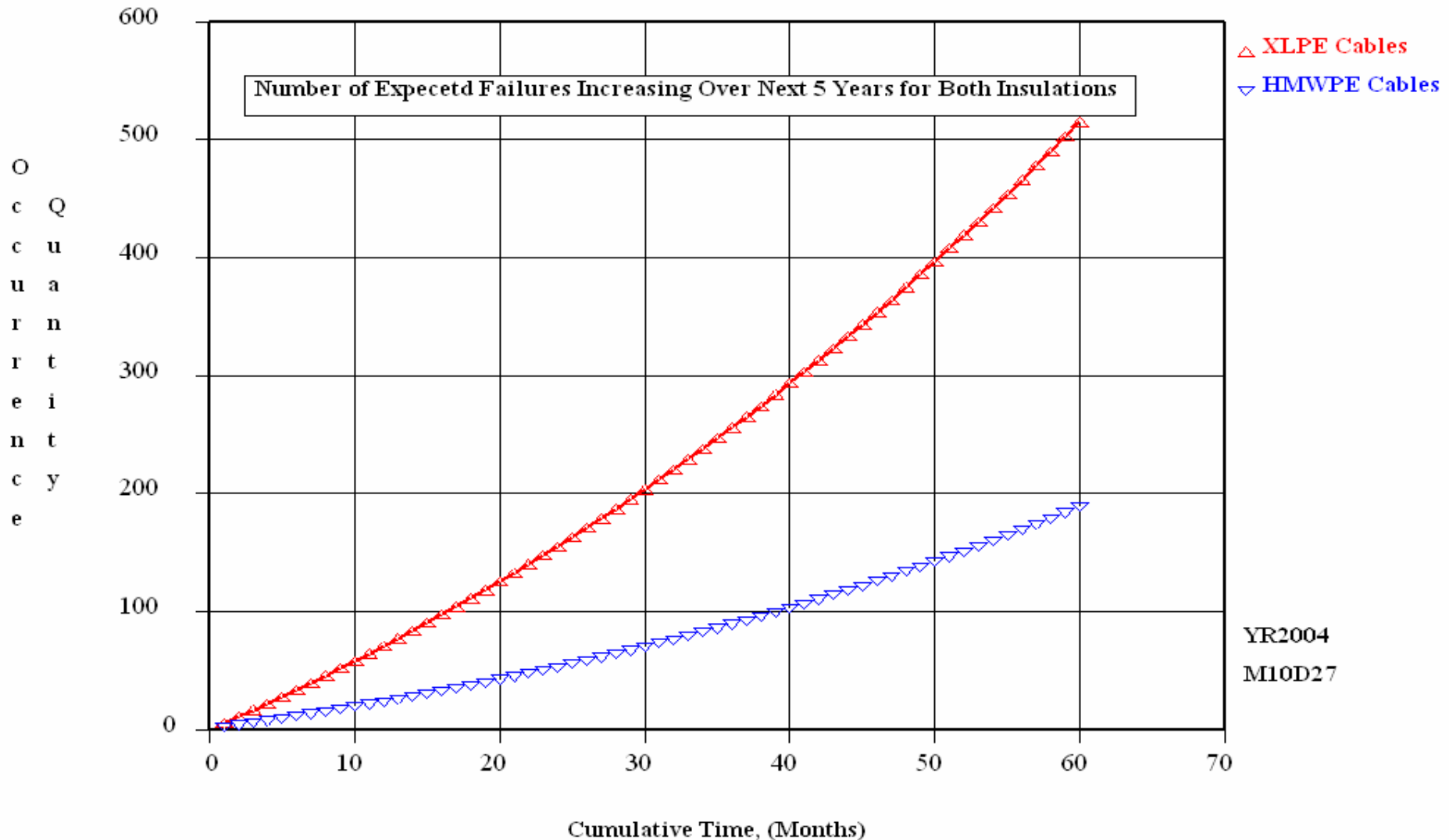
Present Risk Quantity (RBA) = 296.7281 ***Present Actual Failures = 295*** Date: M10-D27-YR2004
 TXU 15kV Cables- All Conductors, 175/220-mil Insulation Aluminum {No Renewal}
 Eta = 61.20765 Beta = 5.693864 Total/Suspension = 84585/84292
 Set: #2 15kV XLPE Next Expected Occurrence (Day) = +6
 Usage Rate [Estimated Mean L (Years) Each Item Each Month] = .083
 Expected Additional Occurrence (Cumulative):

Month.....Risk	Month.....Risk	Month.....Risk	Month.....Risk
1	5.405	16	97.2
2	10.89	17	104.1
3	16.47	18	111.1
4	22.13	19	118.2
5	27.88	20	125.4
6	33.71	21	132.7
7	39.64	22	140.1
8	45.66	23	147.6
9	51.77	24	155.2
10	57.97	25	163
11	64.26	26	170.8
12	70.66	27	178.8
13	77.14	28	186.9
14	83.73	29	195.1
15	90.41	30	203.4
		31	211.8
		32	220.4
		33	229.1
		34	237.9
		35	246.8
		36	255.8
		37	265
		38	274.3
		39	283.8
		40	293.4
		41	303.1
		42	312.9
		43	322.9
		44	333
		45	343.3
		46	353.7
		47	364.2
		48	374.9
		49	385.7
		50	396.7
		51	407.9
		52	419.1
		53	430.6
		54	442.2
		55	453.9
		56	465.8
		57	477.9
		58	490.1
		59	502.5
		60	515

Good agreement between actual failures and predicted present risk quantity predicted by the Weibull plot.
 Next failure of HMWPE predicted to be within 6 days of last failure. Failures are predicted at a rate of ~ 5/day.

Failure Forecast Plots for HMWPE and XLPE from Weibull Risk Analysis

Risk: No. of Expected Failures



XLPE cables failing at faster rate than HMWPE. May be related to how XLPE cables are operated.

Conclusions of Weibull Analysis and Failure Forecasts

- ❑ Weibull plots indicate that both XLPE and HMWPE are in old age wear-out mode
 - β values of both insulations are > 4.0
 - Failure rates are increasing
 - β value for XLPE (5.7) is less than value for HMWPE (8.4); earlier failures predicted for XLPE
 - ❑ Estimated mean life for HMWPE is 5 years greater than XLPE (based on analysis of $\sim 2\%$ of all failures observed)
 - ❑ XLPE cable should be focus of cable replacement program
 - ❑ Unable to do accurate failure forecasting via Abernethy risk analysis due to only small percentage ($\sim 2\%$) of actual failures being available for life analysis
-

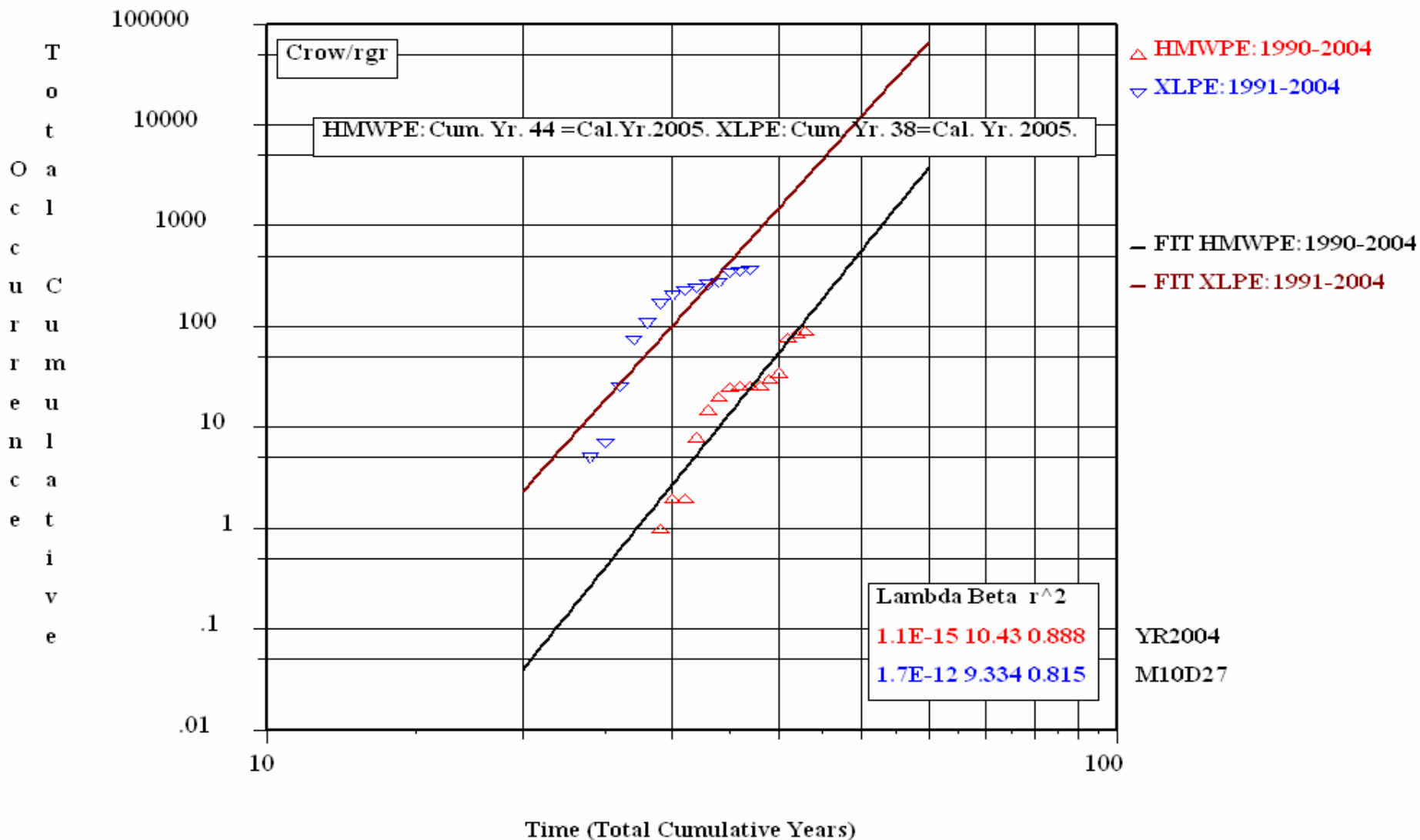
Introduction and Interpretation of Crow-AMSAA Modeling and Plots

- James T. Duane at GE pioneered development of reliability modeling by plotting failure rates on a time scale on logarithmic paper
 - Dr. Larry H. Crow of the Army Material Systems Analysis Activity (AMSAA) improved the growth model and added a goodness of fit test, resulting in MIL-HDBK-189
 - IEC 1164 recognizes Crow-AMSAA model as best practice for tracking reliability growth
 - Crow-AMSAA model, $n(t) = \lambda t^\beta$, includes 2 parameters, Lambda (λ) and Beta (β)
 - where $n(t)$ = cumulative failure events at time t ,
 - lambda, λ = scale parameter and intercept at $t = 1$,
 - and beta, β = slope when, $\text{Ln } n(t) = \text{Ln } \lambda + \beta \text{Ln } t$ on a log-log plot
-

Introduction and Interpretation of Crow-AMSAA Modeling and Plots (Cont)

- Crow-AMSAA models processes where overall system reliability may be changing with time
 - Models non-Homogenous Poisson processes, multiple failure modes
 - Interpretation of β , the failure rate or hazard rate, is same as with Weibull plots
 - $\beta < 1$, means failure rate is decreasing
 - $\beta \sim 1$, means failure rate is constant/not changing
 - $\beta > 1$, means failure rate is increasing
 - Goodness of Fit
 - r^2 value of log-log plot must be ≥ 0.90
 - Corners, cusps and curvature in log-log plots indicate changes in failure rates/modes of system being investigated
 - Crow-AMSAA model is used to forecast future cumulative and interval failures or events
-

CROW-AMSAA: Failures Only



β Values for HMWPE and XLPE are > 1.0 and almost equal. Fits are not good; r^2 values < 0.90 . Corners and Cusps observed in both plots. Analysis of data by segmenting reveals better fits, indicating failure modes are changing.

Crow-AMSAA Failure Forecasts-HMWPE and XLPE (Based on ~2% Sampling)

□ HMWPE Predicted Cumulative Failures

■ By 2005 = 148

148 – current 90 in 2004 = **58** failures in 2005

■ By 2010 = 455

455 – (367 in 2009) = **88** failures in 2010

□ XLPE Predicted Cumulative Failures

■ By 2005 = 932

932 – current 364 in 2004 = **568** failures in 2005

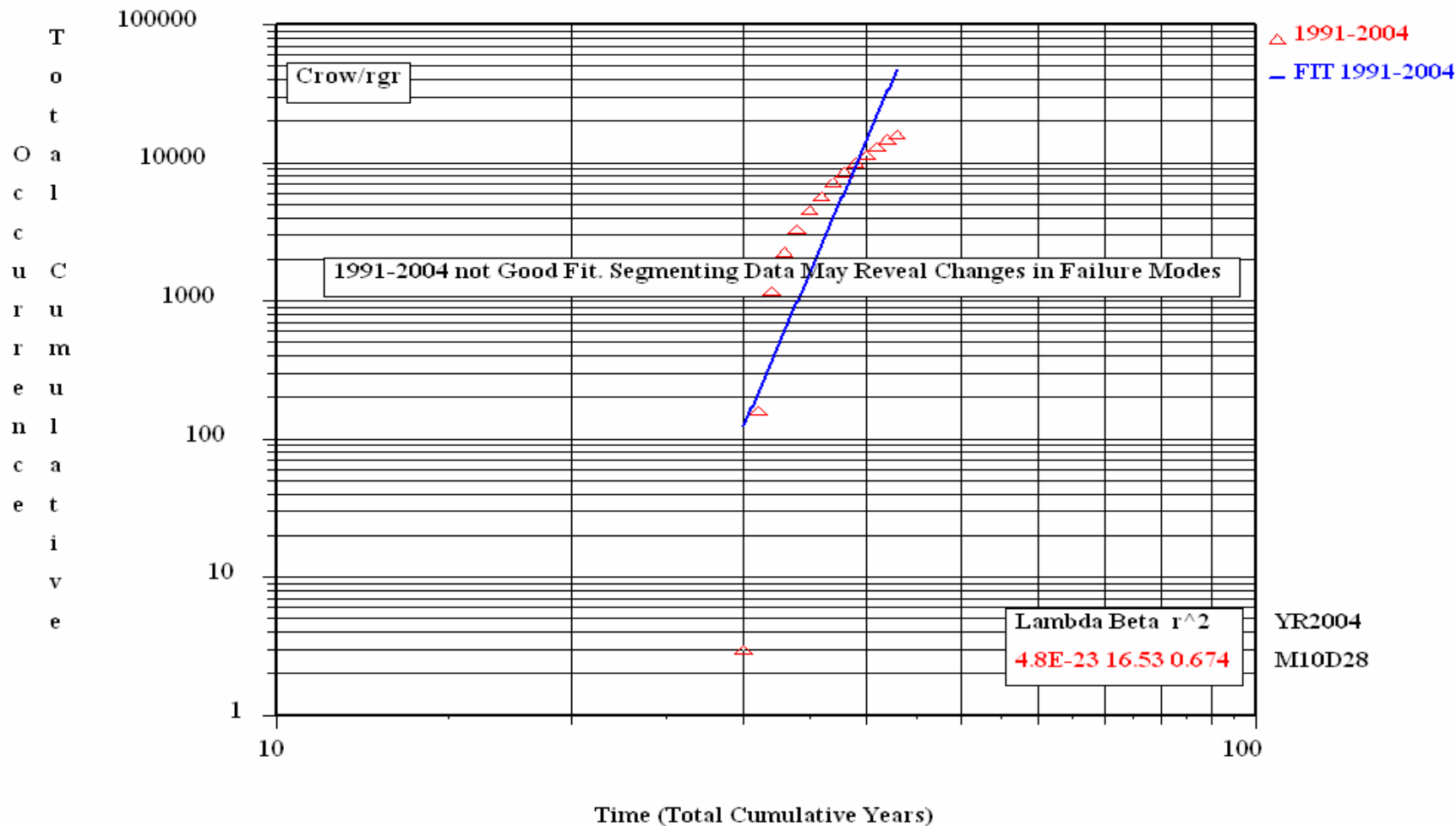
■ By 2010 = 2,954

2,954 – (2,372 in 2009) = **582** failures in 2010

Crow-AMSAA Plots for All Insulation Types of Cable Failures

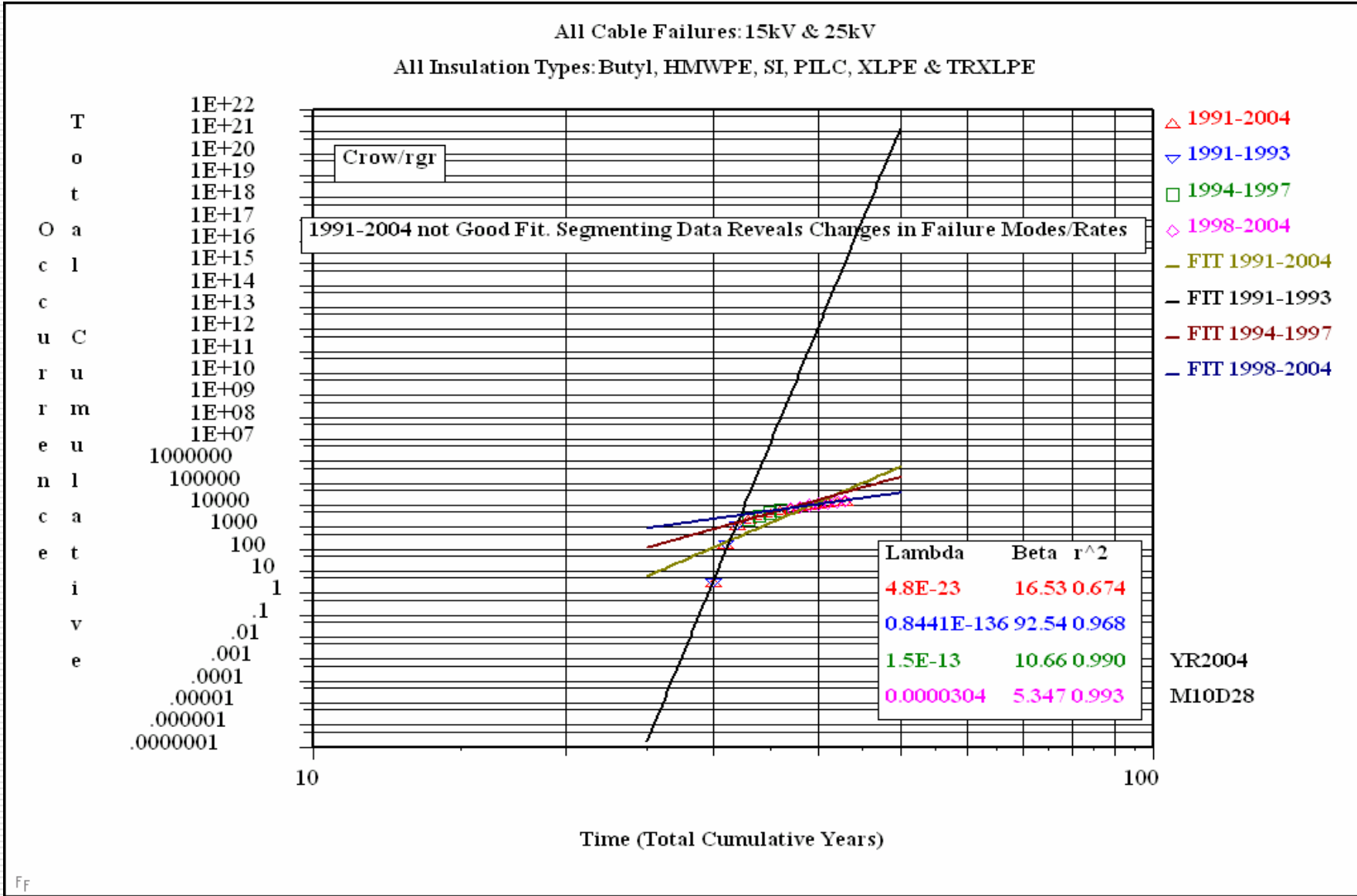
All Cable Failures: 15kV & 25kV

All Insulation Types: Butyl, HMWPE, SI, PILC, XLPE & TRXLPE



β Value > 1.0; hazard rate/instantaneous failure rate increasing. r^2 , Goodness of Fit value < 0.90. Corners, curves and cusps observed in plots; failure modes of system are changing.

Crow-AMSAA Plots for All 15,943 Cable Failures for All Insulation Types



All β Values are > 1.0 ; hazard rates/instantaneous failure rates increasing. Corners and Cusps observed in plots; failure modes of system are changing. When segmented, fits are good; r^2 values $\gg 0.90$. Last fit (1998 – 2004) should be used to make failure forecasts.

Crow-AMSAA Model and Plot Parameters for All Insulation Types

Crow-AMSAA (Duane) Fit

$\log(\text{Cumulative Occurrence}) = \log(\text{Lambda}) + \text{Beta} * \log(\text{Cumulative Time})$ (rgr)

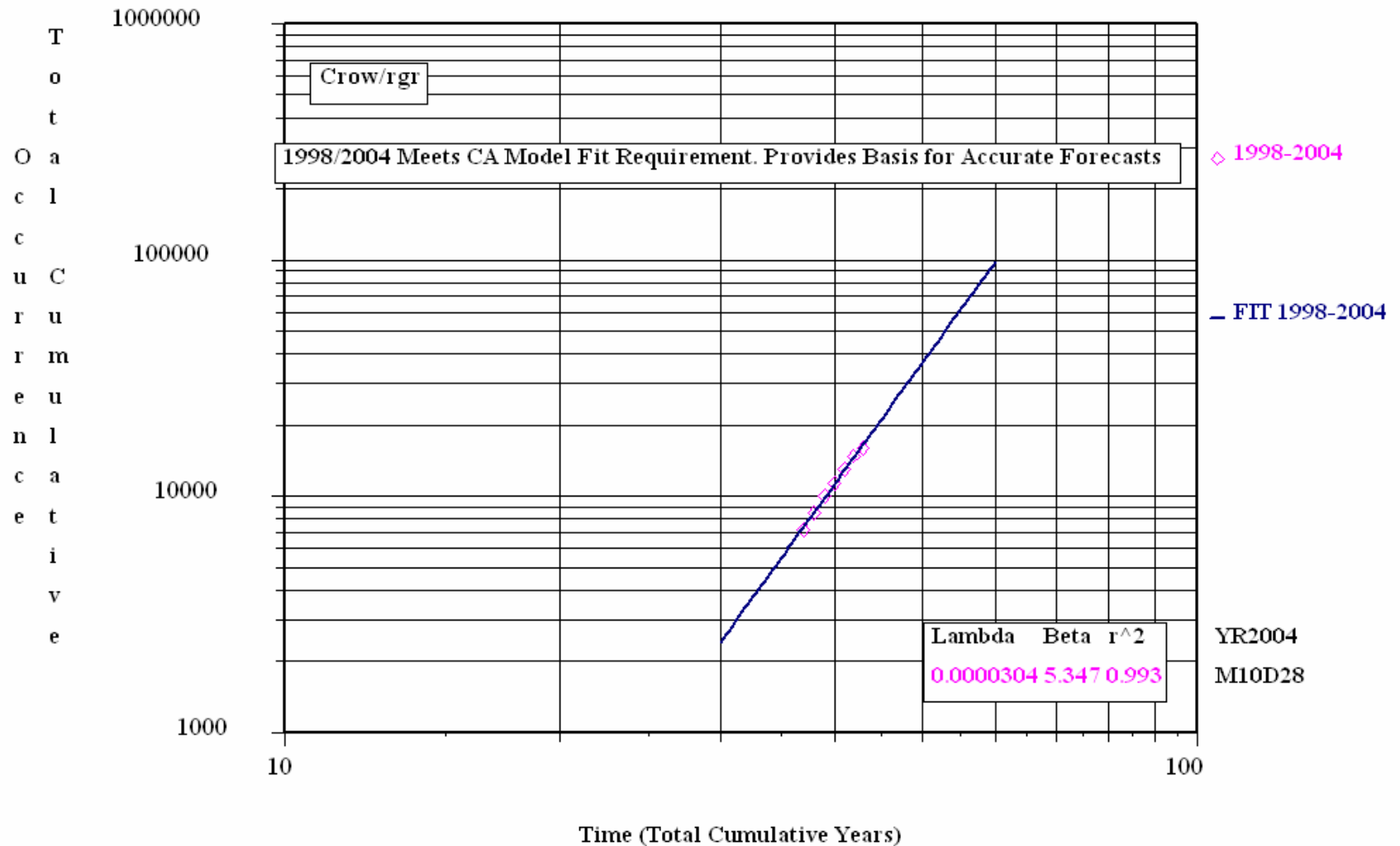
Set/Name	Lambda Scale Parameter	Beta Slope Parameter	Cumulative Occurrence Rate	Instantaneous Occurrence Rate
1/1991-2004	4.77E-23	16.53	370.8	18,182.4
2/1991-1993	0.00	92.54	36.4	4,653.4
3/1994-1997	1.53E-13	10.66	157.9	1,744.0
4/1998-2004	3.04E-05	5.35	370.8	2,052.2

Crow-AMSAA Plots of All Insulation Types of Cable Failures

All Cable Failures: 15kV & 25kV



All Insulation Types: Butyl, HMWPE, SI, PILC, XLPE & TRXLPE



F_F

$\beta > 1.0$; hazard rate/instantaneous failure rate increasing. Last fit (1998 – 2004) should be used to make accurate failure forecasts.

Crow-AMSAA Failure Forecasts for TXU System: All Insulation Types

- Predicted cumulative failures based on last fit: 1998 - 2004
 - By 2005 = 18,861 total failures; 18,861 – current 15,943 in 2004 = **2,918** predicted failures in 2005
 - By 2010 = 33,182 total failures; 33,182 – (29,717 in 2009) = **3,465** predicted failures in 2010
-

Conclusions of Crow-AMSAA Analysis and Failure Forecasts

- Crow-AMSAA plots indicate that both XLPE and HMWPE are in an increasing failure rate condition
 - β values of both insulations are > 1.0 ; failure rates are increasing
 - β value for XLPE and HMWPE are almost equivalent
 - Although failure rate is greater for HMWPE, smaller number of failures is forecast because there was less failure data available for HMWPE; 78 vs. 295
-

Conclusions of Crow-AMSAA Analysis and Failure Forecasts (Cont)

- ❑ Unable to do accurate failure forecasting for insulation types via Crow-AMSAA modeling due to only small percentage ($\sim 2\%$) of actual failures being available for analysis
 - ❑ Crow-AMSAA plot for ALL insulation failures between 1991 – 2004 shows adequate modeling of system
 - Failure rate increasing, $\beta > 1.0$
 - Curvature and cusps observed in plot
 - Plot segmented and analyzed resulting in good fits
 - Adequate failure forecasts for the system provided by Crow-AMSAA
 - Crow-AMSAA modeling and failure forecasts not dependent on age of failures
-

Summary of Analysis of Cable Failures

- Both analysis techniques (Weibull and Crow-AMSAA) indicate HMWPE and XLPE cables are in old age wear out and are in an increasing instantaneous failure rate mode
 - XLPE shows to be in a worse state/condition than HMWPE
 - This cable insulation type should be the focus of cable replacement
 - Weibull analysis requires age of all failures (by insulation type, conductor size, insulation thickness) to be able to provide accurate failure forecasts
-

Summary of Analysis of Cable Failures (Cont)

- Crow-AMSAA does not require age of failures to make accurate failure forecasts
 - Crow-AMSAA does require identification of insulation types in order to be specific about which cable insulation type should be prioritized for replacement
 - Accurate analysis and failure forecasts require accurate data
-