

Modeling Underground Cable Faults Utilizing Weibull and Crow-AMSAA





Model Differences

- Weibull: Models a failure mode distribution of a replaceable system.
- Crow-AMSAA: Models the reliability growth of a repairable system.



Model Differences

- Weibull distributions use the individual times-to-failure.
- Weibull models one, perhaps two failure modes at most.
- The weibull failure mode is considered static/unchanging.
- CA uses the cumulative times-to-failure.
- CA can handle a mixture of failure modes.
- CA models a reliability process where the overall reliability can change with cumulative time.

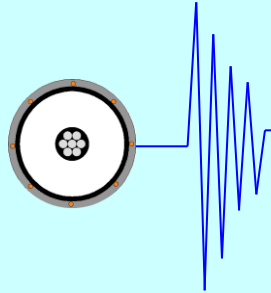
Weibull

- Weibulls can not be determined by arbitrarily fitting failure data to the weibull equation.

$$F(t) = 1 - e^{-\left(\frac{t}{\gamma}\right)^\beta}$$

- $F(t)$ = fraction failing (CDF)
- t = failure time
- γ = characteristic life or scale parameter
- β = slope or shape parameter

Weibull

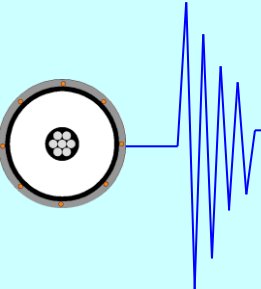


To determine the weibull distribution from time-to-failure data:

- 1) For each failure mode, rank the times from earliest to latest for both the failures and suspensions of the population.
- 2) Calculate the adjusted ranks for the failures.

$$\text{Adjusted Rank} = \frac{(\text{Reverse Rank}) \times (\text{Previous Adjusted Rank}) + (N + 1)}{(\text{Reverse Rank} + 1)}$$

Weibull

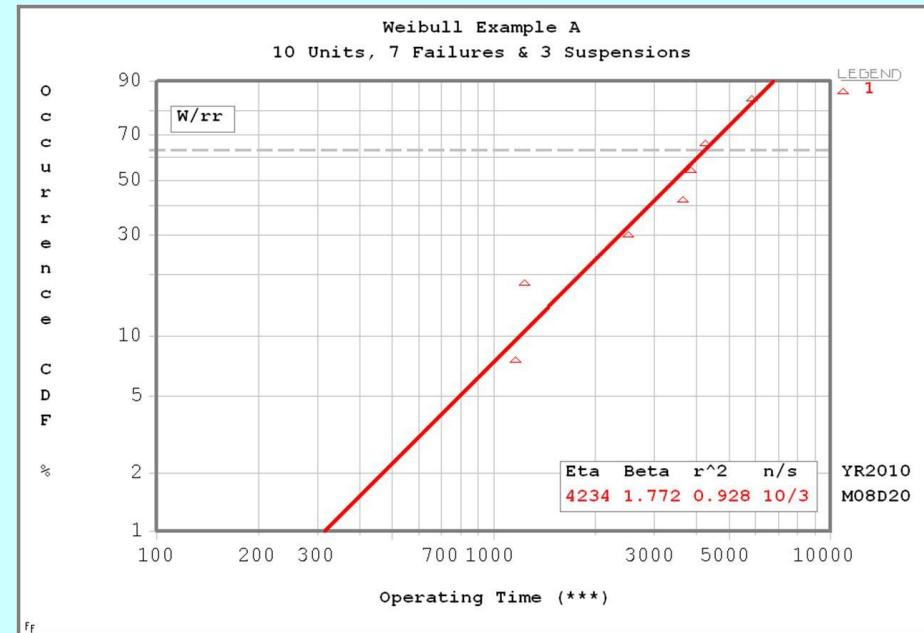
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- 3) Use Benard's approximation to determine the median ranks of the failures.

$$\textit{Benard's Median Rank} = \frac{(i - 0.3)}{(N + 0.4)}$$

- 4) Plot failure times on X versus median ranks on Y.
- 5) Determine β and γ by linear regression or maximum likelihood estimate (MLE).

Weibull Example A

Time	Rank	Reverse Rank	Adjusted Rank	Median Rank
1000-S	1	10	Suspension	***
1159-F	2	9	1.10	7.69%
1234-F	3	8	2.20	18.27%
1489-S	4	7	Suspension	***
2513-F	5	6	3.46	30.36%
3655-F	6	5	4.71	42.45%
3852-F	7	4	5.97	54.53%
4261-F	8	3	7.23	66.62%
5639-S	9	2	Suspension	***
5847-F	10	1	9.11	84.75%



Weibull

Once the weibull distribution is determined, future failures can be forecast as follows:

- 1) Determine the Now Failures.

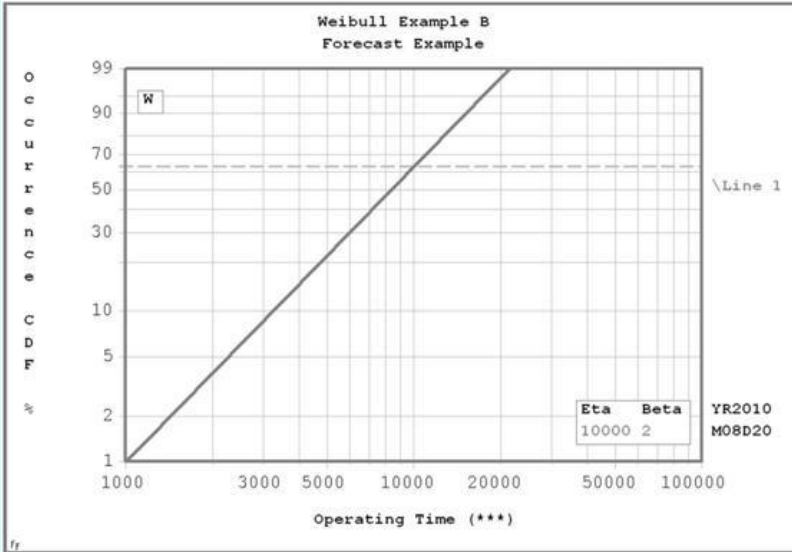
$$\text{Now Failures} = \sum_i^{\text{failures}} 2(F(t_i)) + \sum_j^{\text{suspensions}} F(t_j)$$

Weibull

2. Forecast the failures from the suspensions over a predetermined time interval.

$$\mathbf{Failure\ Forecast} = \sum_j^{\mathbf{suspensions}} \frac{[F(t_j + u) - F(t_j)]}{[1 - F(t_j)]}$$

Weibull Example B



Number of Units	Time on Each Unit	F(t)	F(t) * N
4-S	1000	0.01	0.04
1-F	4000	0.15	0.15
2-S	5000	0.22	0.44
2-S & 1-F	6000	0.3	0.9
8-S + 2-F = 10 total	Now Failures		1.53
	Bias Adjusted Now Failures		1.98

Number of Units	Start Time	End Time	F(t + j)	F(t)	Forecasted Failures
4-S	1000	3000	0.08	0.01	0.28
2-S	5000	7000	0.38	0.22	0.41
2-S	6000	8000	0.48	0.3	0.51
N = 8	Expected Failures in $\Delta T = 2000$				1.21



Weibulls of Underground Cable

- To construct weibulls for underground cable, weibulls have to be developed for each failure mode on each component.
 - Elbows
 - Splices
 - Cable Segment (Device to Device) Note, you can not discretely divide the segment into smaller units.
- Only the first fault is modeled and the repair is replacement with a like unit.

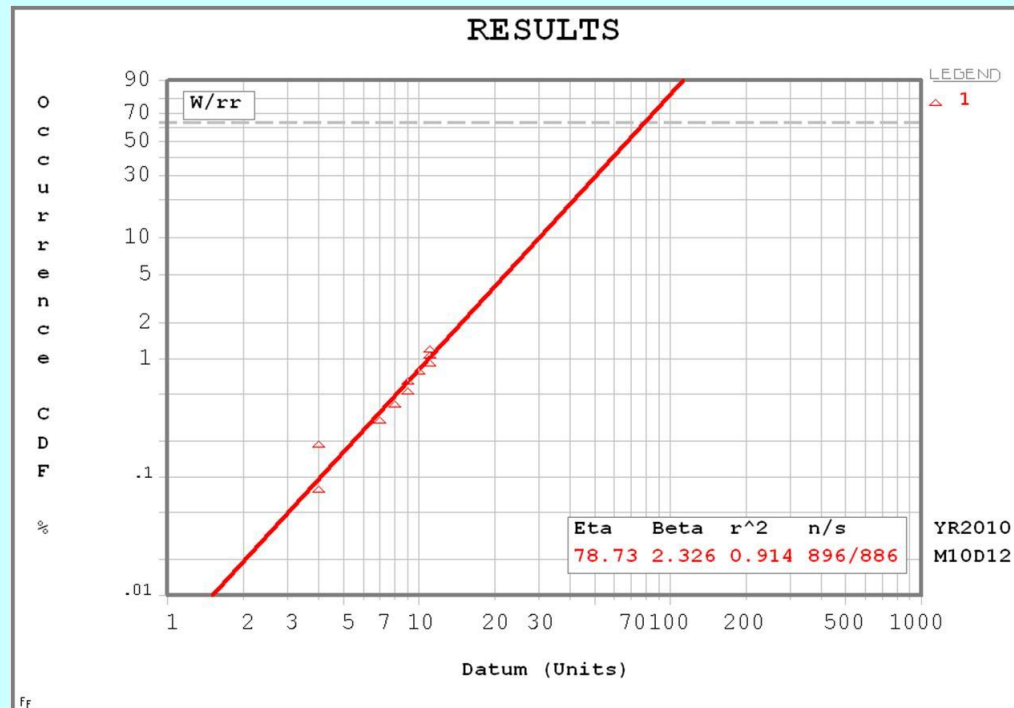


Weibull of 500 kcmil in Conduit

- Roughly 450,000 ft installed 92 to 99.
- Approximately 896 segments.
- All cable in conduit.
- All faults are assumed to be first faults.
- All faults assumed to be insulation failures on individual segments.
 - Exception, suspended 1996 fault from 1995 vintage cable in analysis.

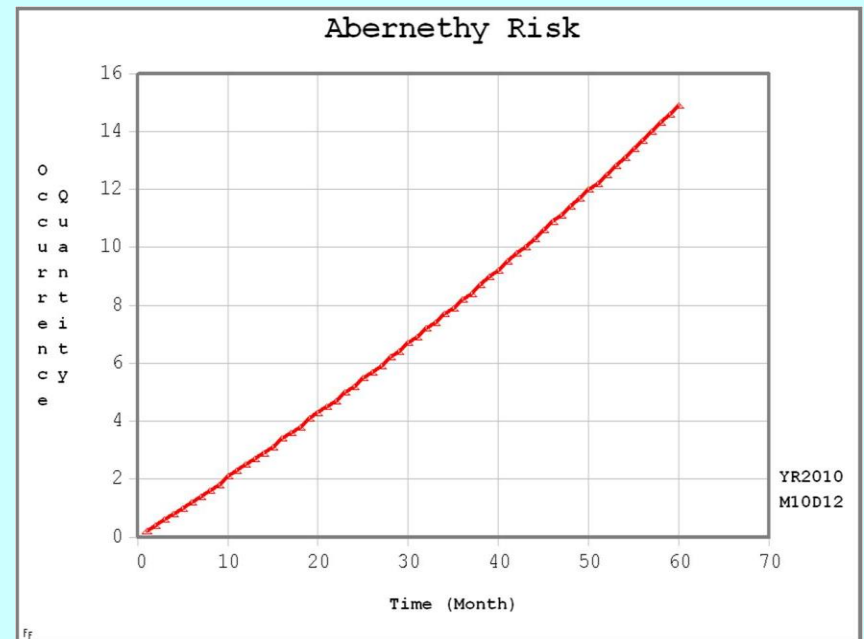
Weibull of 500 kcmil in Conduit

500 kcmil		Calendar Yr/Faults											
Vintage Year	Segment Count	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1992	354						1	1					
1993	144									1			
1994	38												
1995	110	1			1				1				
1996	47												2
1997	74						1			1		1	
1998	63												
1999	67												



Weibull of 500 kcmil in Conduit

- Present Risk Quantity (RBA) = 13.735
- Next Expected Occurrence (Month) = +5
- 14.9 faults are forecasted over next 60 months
- No renewal





Crow-AMSAA

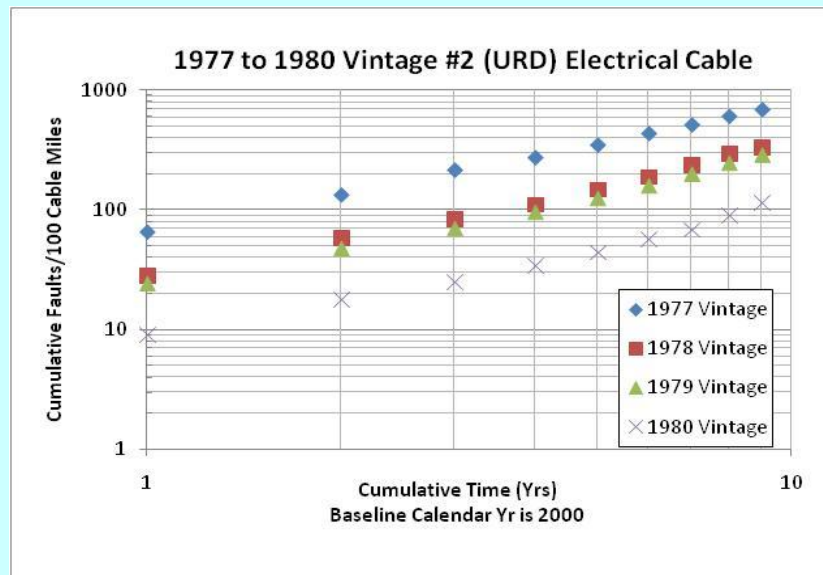
- The Crow-AMSAA reliability growth model is given below:

$$n(t) = \lambda t^{\beta}$$

- $n(t)$ is the cumulative number of faults or faults/100 cable miles
- t is the cumulative time
- λ and β are the Crow-AMSAA parameters

Crow-AMSAA

- Graphically the CA model is a log-log plot of cumulative faults versus cumulative time. If the model applies the resulting plot is linear. However, if cumulative faults/100 cable miles are utilized, future faults can be forecast as a function of cable replacement.



Crow-AMSAA

- The accepted method of determining the Crow-AMSAA parameter β , is by the Maximum Likelihood Estimate (MLE). Note there are several MLE formulations based upon data type. The data type normally encountered with underground cable is grouped data.

$$\sum_{i=1}^k n_i \left[\frac{T_i^{\hat{\beta}} \ln T_i - T_{i-1}^{\hat{\beta}} \ln T_{i-1}}{T_i^{\hat{\beta}} - T_{i-1}^{\hat{\beta}}} - \ln T_k \right] = 0$$

Crow-AMSAA

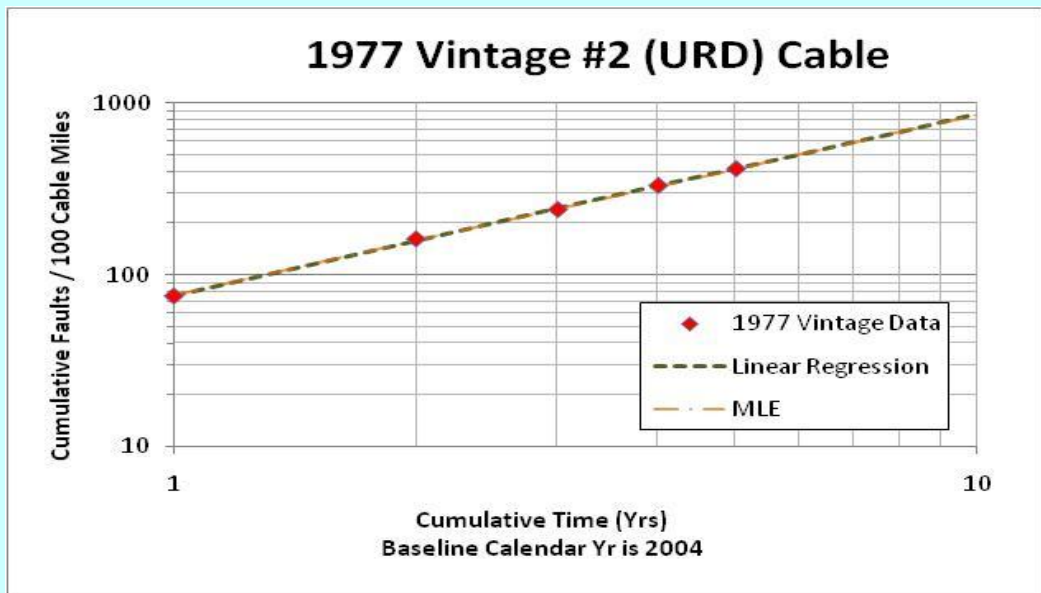
- Once β is determined the scale parameter λ is estimated with the following equation:

$$\hat{\lambda} = \frac{\sum_{i=1}^k n_i}{T_k^{\hat{\beta}}}$$

- For small, well behaved data sets, the Crow-AMSAA parameters, λ and β , can also be estimate from Linear Regression.

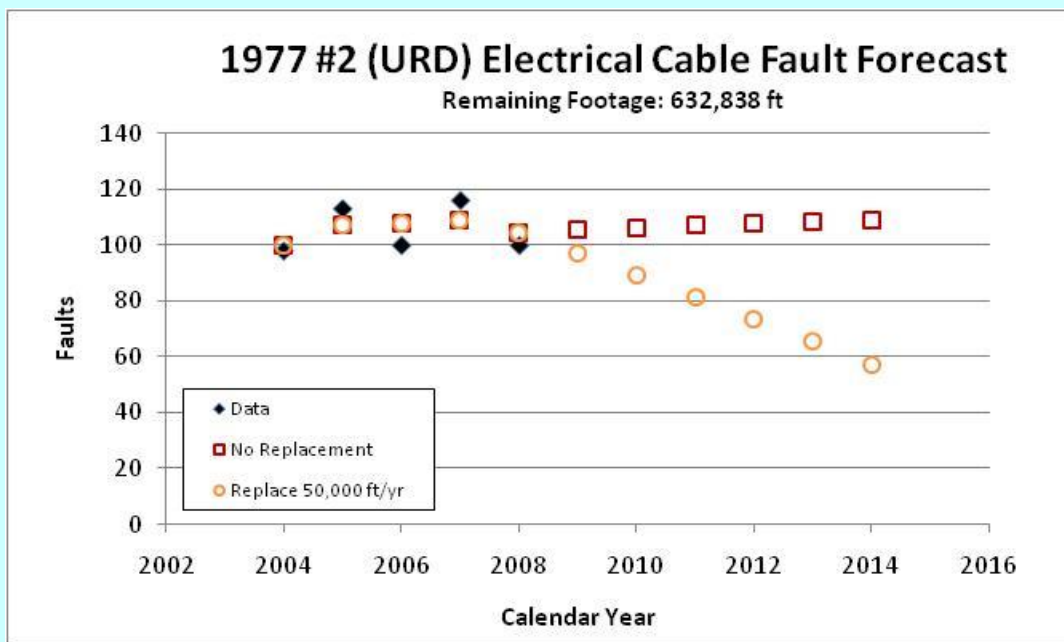
Crow-AMSAA

Cable Type	#2	Data Analysis					
Vintage	1977						
		From	2004				
		To	2008				
Calendar Yr	Cum Time (Yrs)	Cum Faults/100 cable mile	Parameters	λ	β	R ²	SEy/x
2004	1	98	Regression	99.4457	1.0449	0.9992	1.0213
2005	2	211					
2006	3	311	Parameters	λ	β	chi ²	Fit (0.05)
2007	4	427	MLE	101.1293	1.0257	2.4073	OK
2008	5	527					



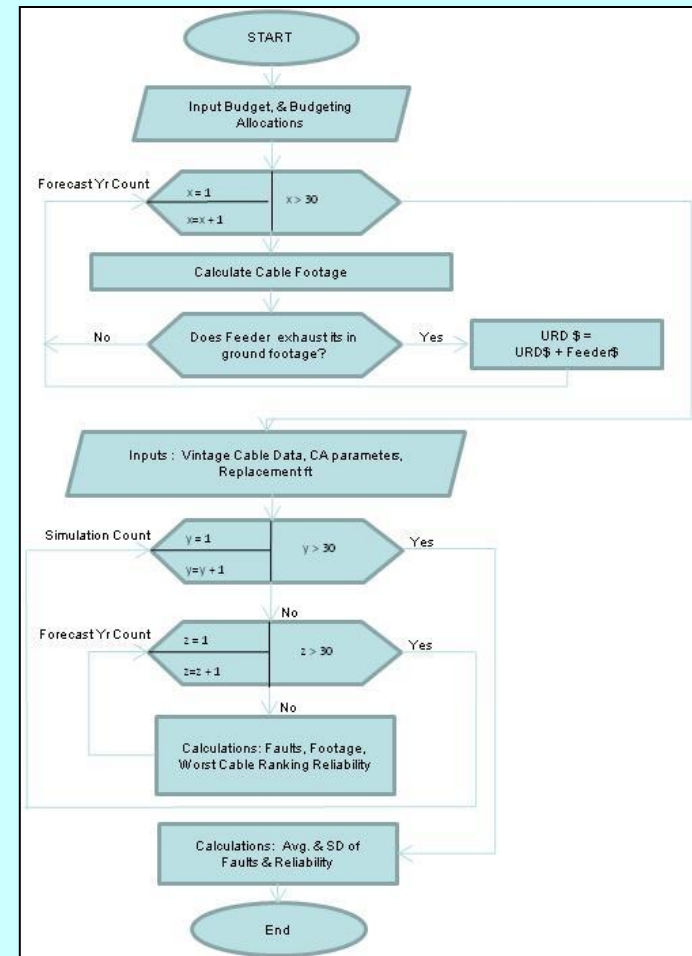
Crow-AMSAA

- Faults are forecasted by reducing the cumulative faults/100 cable miles to discrete faults/100 cable miles and multiplying this value by the footage.



Cable Replacement Simulation

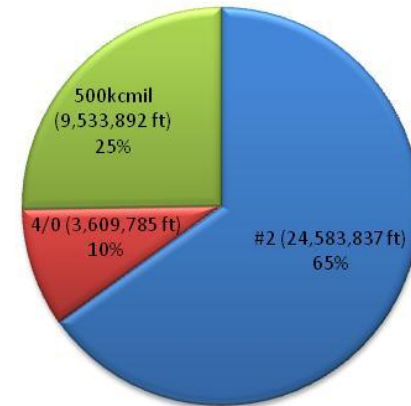
- Since cable faults can be determined as a function of cable replacement, the entire primary cable replacement process can be simulated.
- The primary cable replacement simulation developed at SRP, known as the Long Range Fault & Reliability (LRFR) Model, forecast primary cable faults and reliability over a 30 yr period.



Cable Replacement Simulation

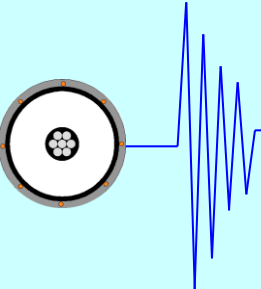
- **WHY...** To effectively manage long term cable replacement requires insight into how today's budgeting decisions impact future cable faults and reliability.

Direct Buried Primary Cable Footage As Of
Fiscal Yr 2010/Calendar Yr 2009



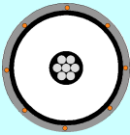
Simulation Example

Budget Parameters

- 
- Budgets and cost are fixed for all 30 forecast years.
 - Cost: \$35/ft 500 & 4/0 & \$45/ft #2
 - Budget Allocations: 45% 500, 20% 4/0, 35% #2
 - Time value of money not considered.
 - Footage:
 - 9,760,431 ft - 500
 - 3,722,797 ft - 4/0
 - 24,132,955 ft - #2

Simulation Example

Input Parameters #2 (URD)



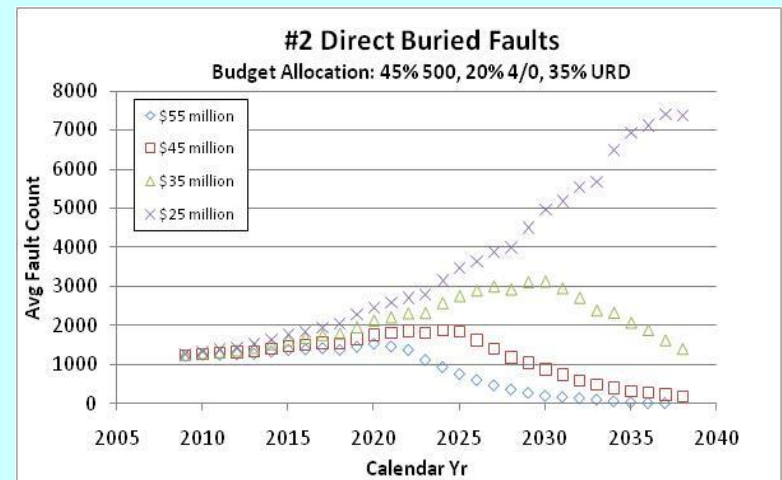
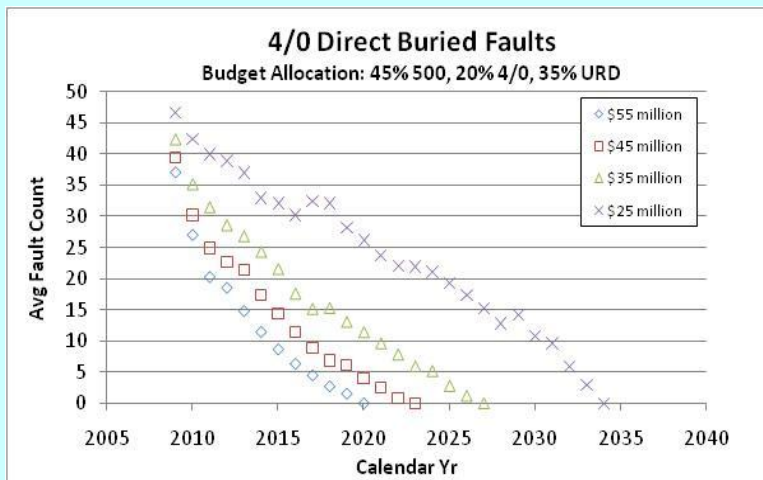
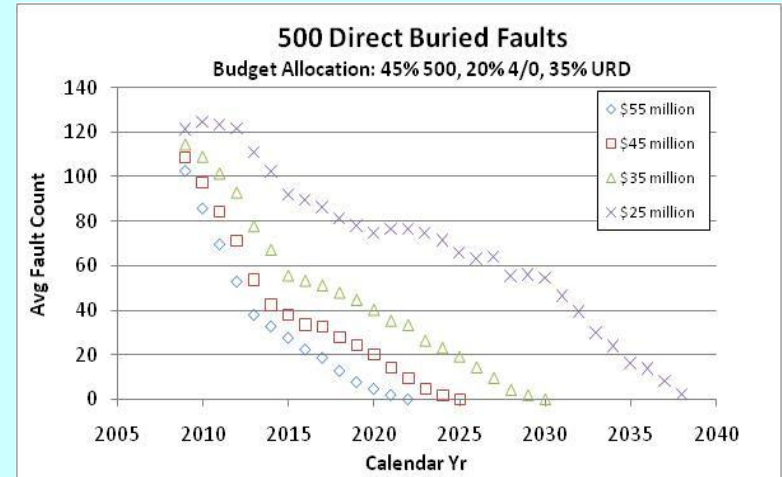
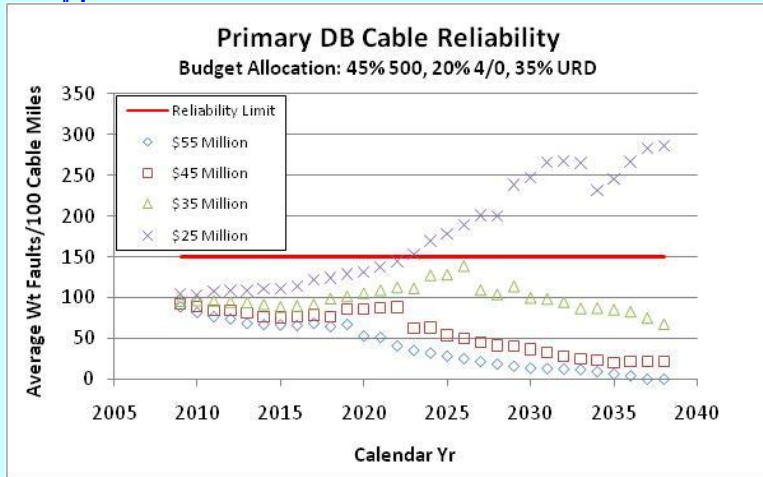
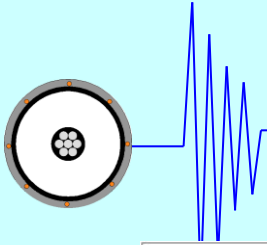
Replacement Yr	Replacement Footage
1	217,778
2	217,778
3	217,778
4	217,778
5	217,778
6	217,778
7	217,778
8	217,778
9	217,778
10	217,778
11	217,778
12	217,778
13	217,778
14	217,778
15	217,778
16	295,556
17	295,556
18	295,556
19	295,556
20	295,556
21	295,556
22	440,380

UG Cable Type	Beginning Yr of Replacement
#2	2009
Max Beta Bump: 25 to 60 Yrs	Min Beta Bump: 25 to 60 Yrs
0.2	0.02
Max Wt Factor for Fault/100 Cable Mile	Min Wt Factor for Fault/100 Cable Mile
1	1
Replacement Cost (\$/ft)	Maintenance Cost (\$/fault)
\$45	\$2,500
Annual Inflation (%)	T ₀ Yr
1.50%	2005

Vintage	β	λ	Footage
1965	1	32.04	16,481
1966	1	19.24	27,444
1967	1	25.51	20,701
1968	1	7.51	70,328
1969	1.28	65.581	266,156
1970	1	63.197	442,506
1971	1.01	45.48	771,971
1972	1.16	60.77	1,106,960
1973	1.01	77.34	1,061,468
1974	1.06	54.32	780,541
1975	1.01	41.7	644,886
1976	1.18	44.58	410,339
1977	1.01	86.76	632,838
1978	1.09	42.92	1,225,997
1979	1.04	40.82	1,542,228
1980	1.03	20.79	1,122,068
1981	1.05	30.18	927,196
1982	1.11	16.76	774,710
1983	1.14	9.18	1,332,063
1984	1.08	4.61	2,115,031
1985	1.04	2.39	2,070,853
1986	1.1	1.27	2,073,088

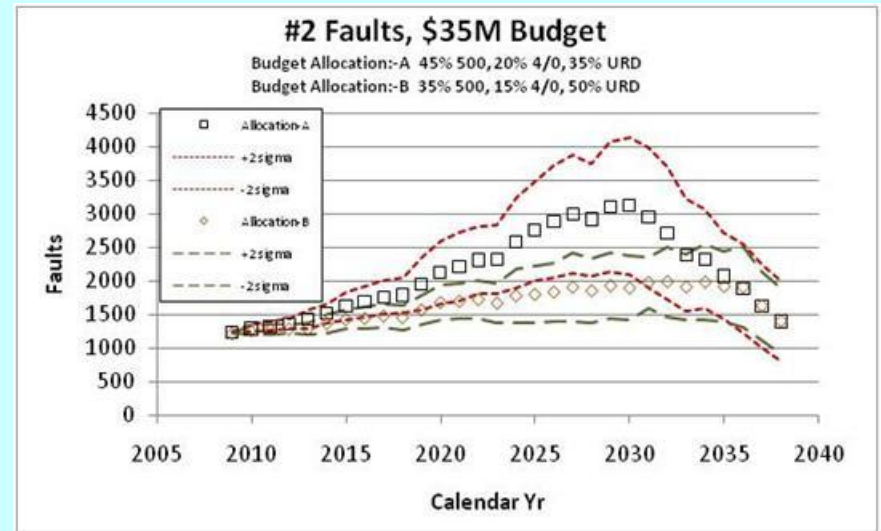
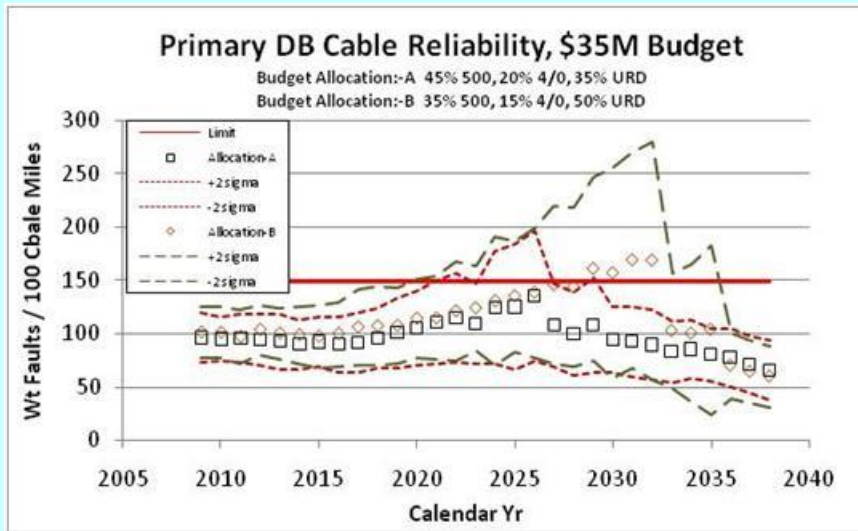
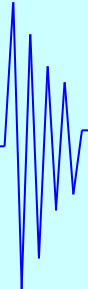
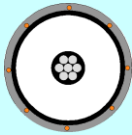
Simulation Example

Results



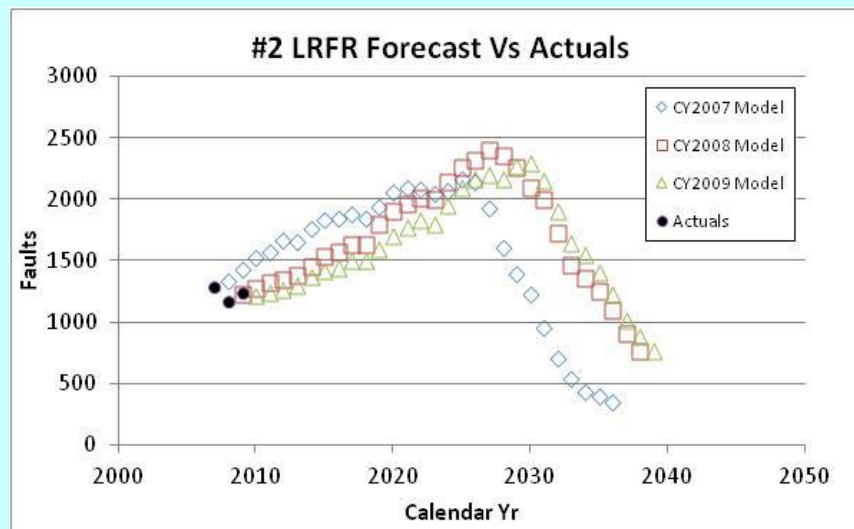
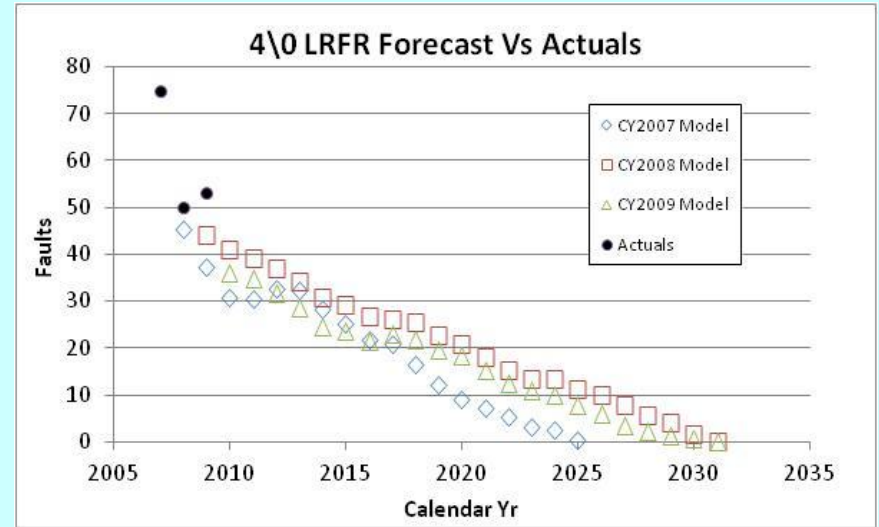
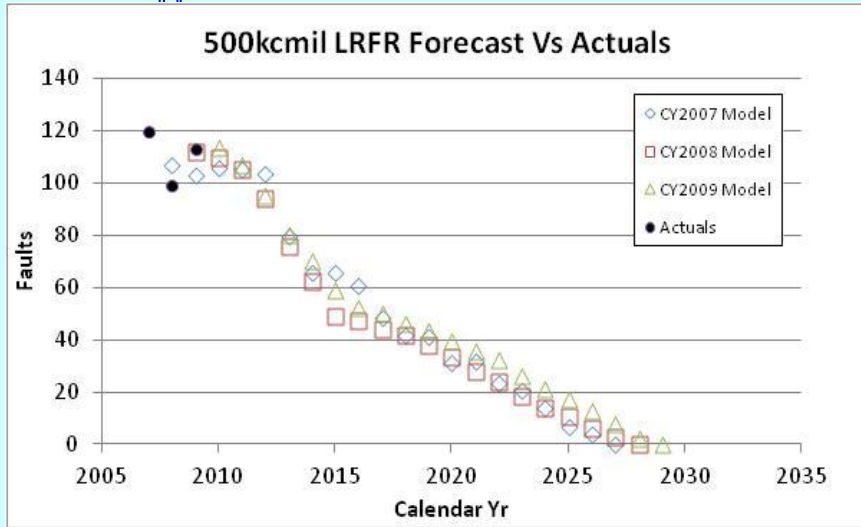
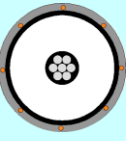
Simulation Example

Results



Simulation Example

Fault Data Vs Simulations

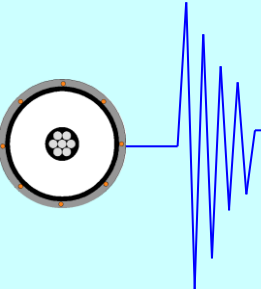


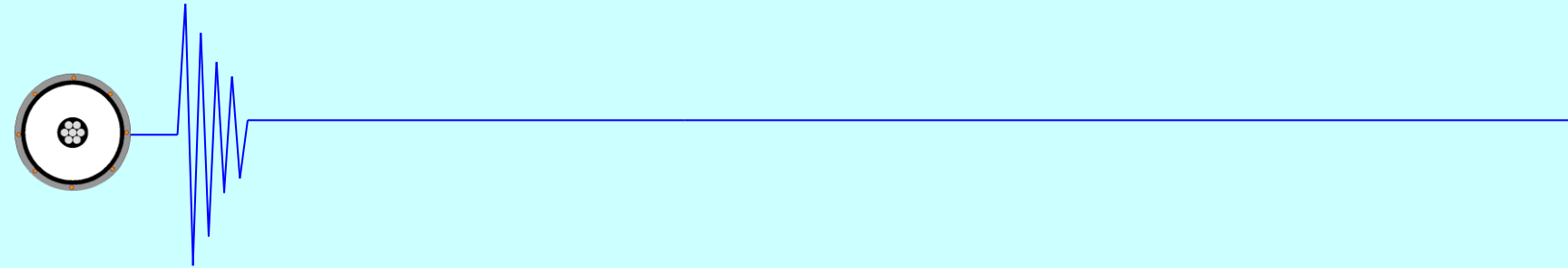


Final Remarks

- **Data is king.** The best models in the world are of little value if derived from inaccurate data.
- Not only do you need good data, you need the right data to support the chosen model.
- Both weibull and Crow-AMSAA are capable of forecasting primary cable faults and being integrated into primary cable replacement simulation models.

Final Remarks

- 
- For direct buried primary cable, the Crow-AMSAA model is preferable since it models a repairable system.
 - Weibulls will give good results from just a few failures within the population under evaluation.
 - Weibulls allow a risk level to be set as part of a preventative maintenance program.



Questions

