Research on Cable Reliability and Asset Management

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Estimation of Cable Lifetime: Introduction

- Estimation of cable lifetime is a problem as challenging as it is important
- Accelerating aging tests typically utilize only voltage stress and temperature as catalysts of degradation
- Lifetime model is simplified to reflect only those factors
- Leveraging different tests - a numerical challenge

Cable Aging Model (J. P. Crine)

$$L = A \cdot \frac{h}{2kT} \cdot e^{\frac{\Delta G}{kT}} \cdot \cos ech\left(\varepsilon_0 \varepsilon' \cdot \Delta V \cdot \frac{F^2}{2kT} \right) = A \cdot \frac{h}{2kT} \cdot e^{\frac{\Delta G}{kT}} \cdot \frac{2}{e^{\varepsilon_0 \varepsilon' \cdot \Delta V \cdot \frac{F^2}{2kT}} - e^{-\varepsilon_0 \varepsilon' \cdot \Delta V \cdot \frac{F^2}{2kT}}}$$

L = Life

F = Applied Voltage Stress

T = Temperature

A = Scaling Factor

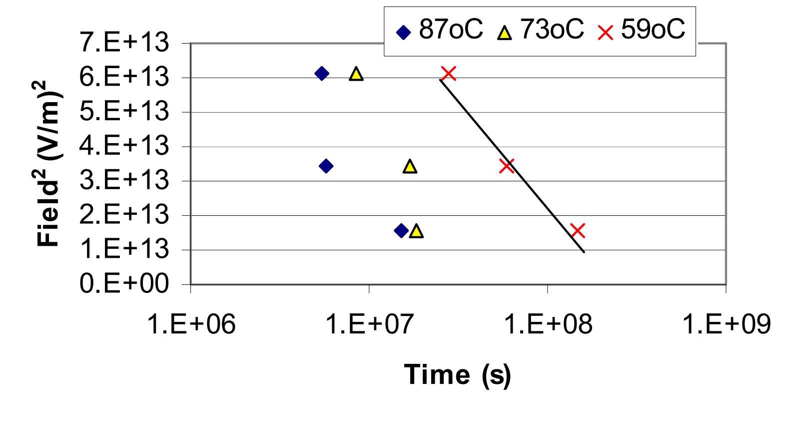
$\Delta G \rightarrow$ Represents the activation energy barrier generated by the electric field (somewhat temperature dependent).

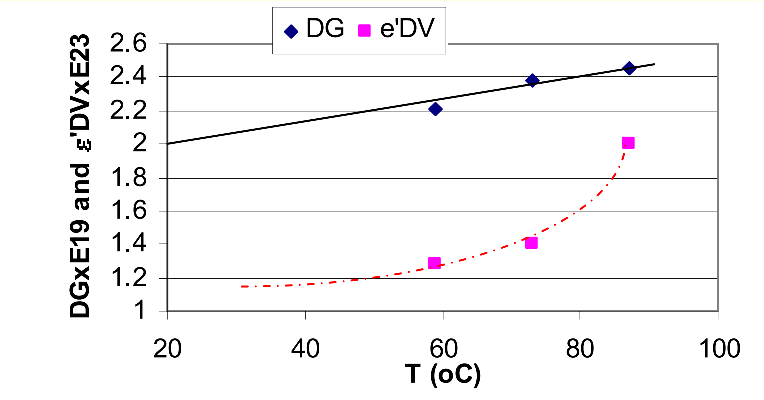
$\Delta V \rightarrow$ Represents the activation volume within which the degradation begins to develop.

Model development (cont.)

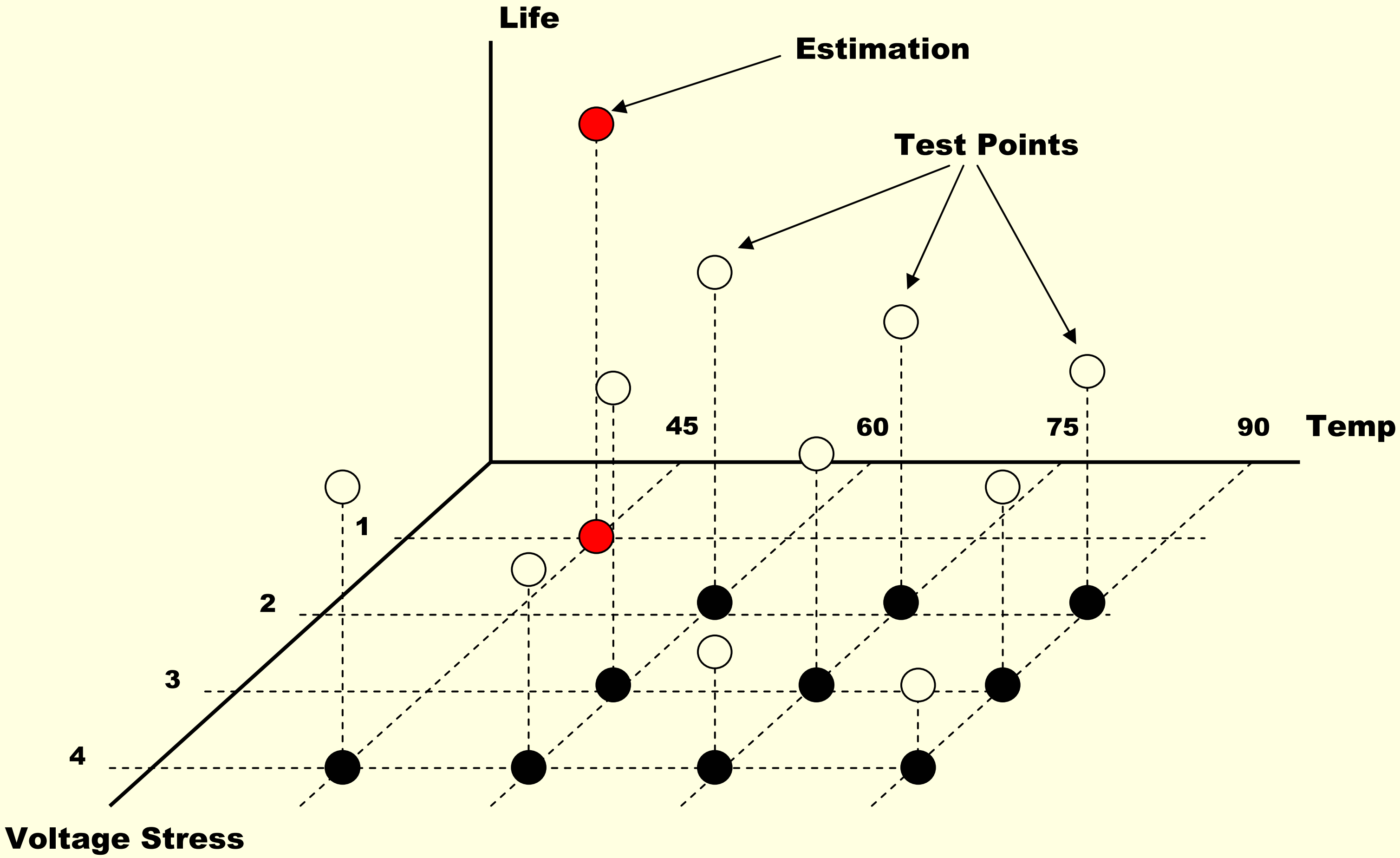
Accelerated Cable Life Test (ACLT) data on XLPE cable is used to solve for the unknown variable coefficients

$$\ln L = [\ln(A \cdot \frac{h}{2kT}) + \frac{\Delta G}{kT}] - \frac{\varepsilon_0 \varepsilon' \cdot \Delta V}{2kT} \cdot F^2$$

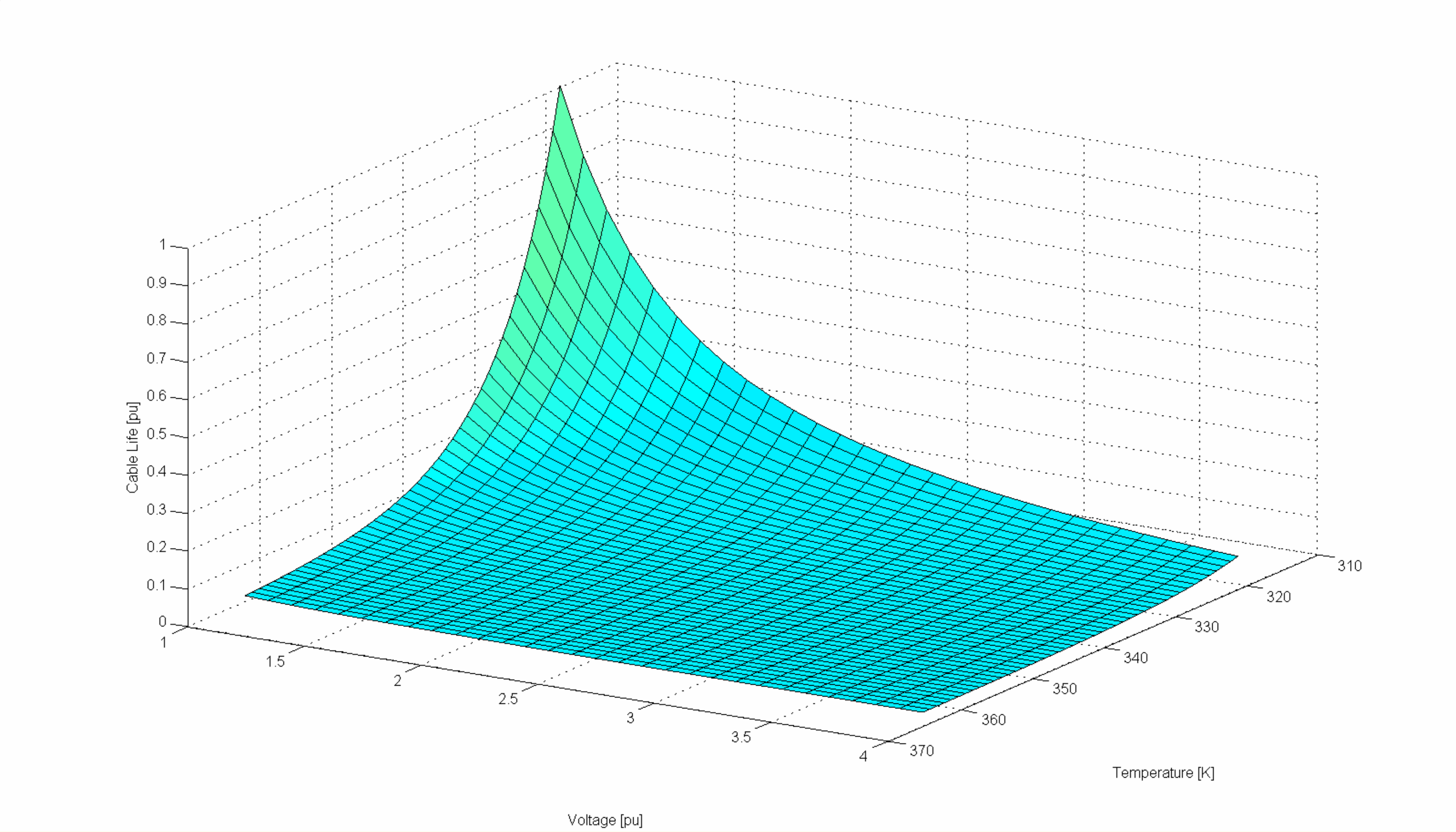




Lifetime Tests: Concept



Normalized Lifetime



- Slope of the curve is extremely high in (1,1) condition (normal operating regime)
- Most of the accelerated aging tests produce lifetimes which are orders of magnitude smaller than normal lifetime

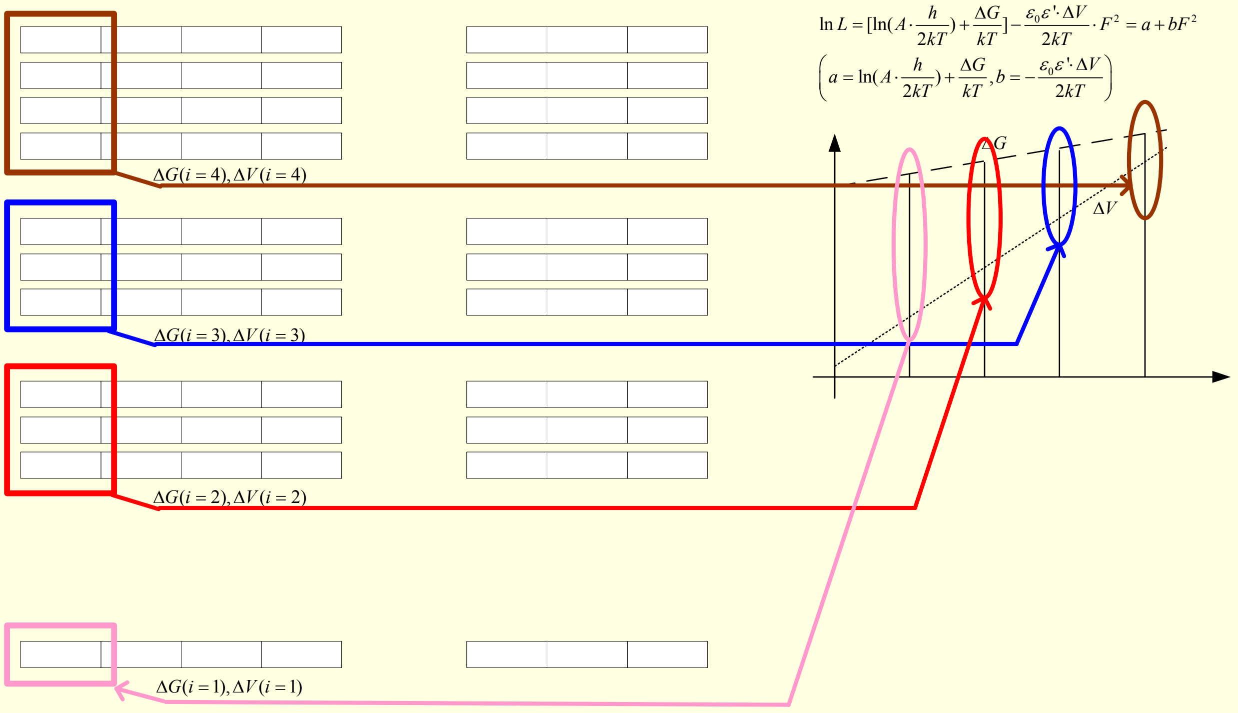
Impact on Measurement Accuracy

- Accelerated tests are characterized by small lifetimes whose errors may substantially influence the results
- Tests whose conditions are closer to normal operating regime may have more influence on the accuracy of estimation
- By perturbing (changing) the lifetime measurements from accelerated aging tests, it is possible to assess their impact on accuracy of lifetime estimates under normal conditions
- By selectively removing some accelerated aging tests, it is possible to rank them w.r.t. accuracy of lifetime estimation

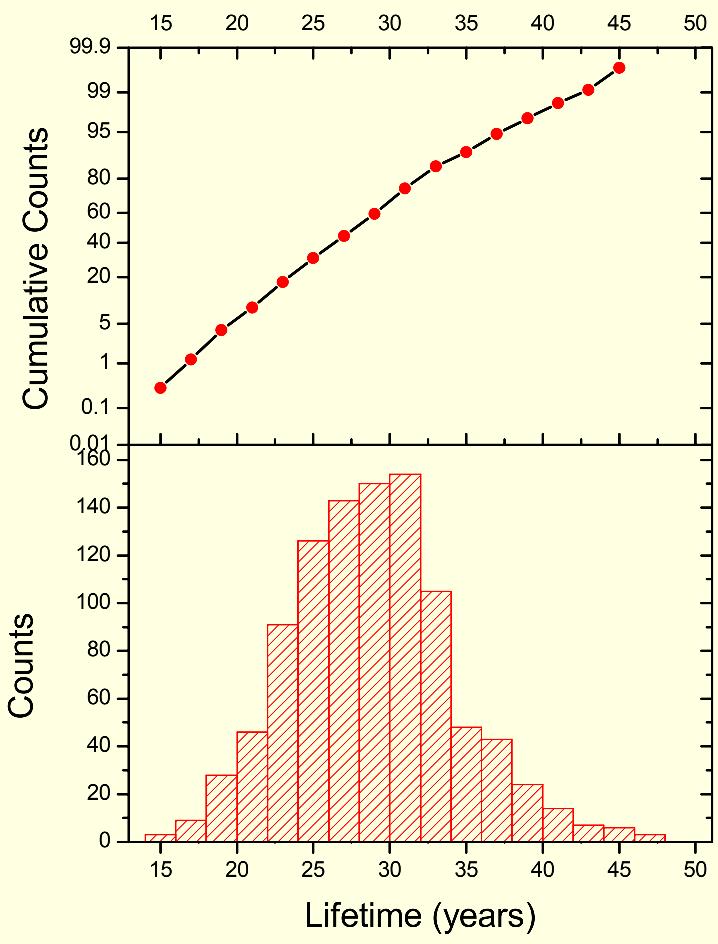
Model: Voltage Stress and Temperature Methodology: Probabilistic Simulation

- Characterization of parameters:

$$\ln L = [\ln(A \cdot \frac{h}{2kT}) + \frac{\Delta G}{kT}] - \frac{\varepsilon_0 \varepsilon' \cdot \Delta V}{2kT} \cdot F^2$$

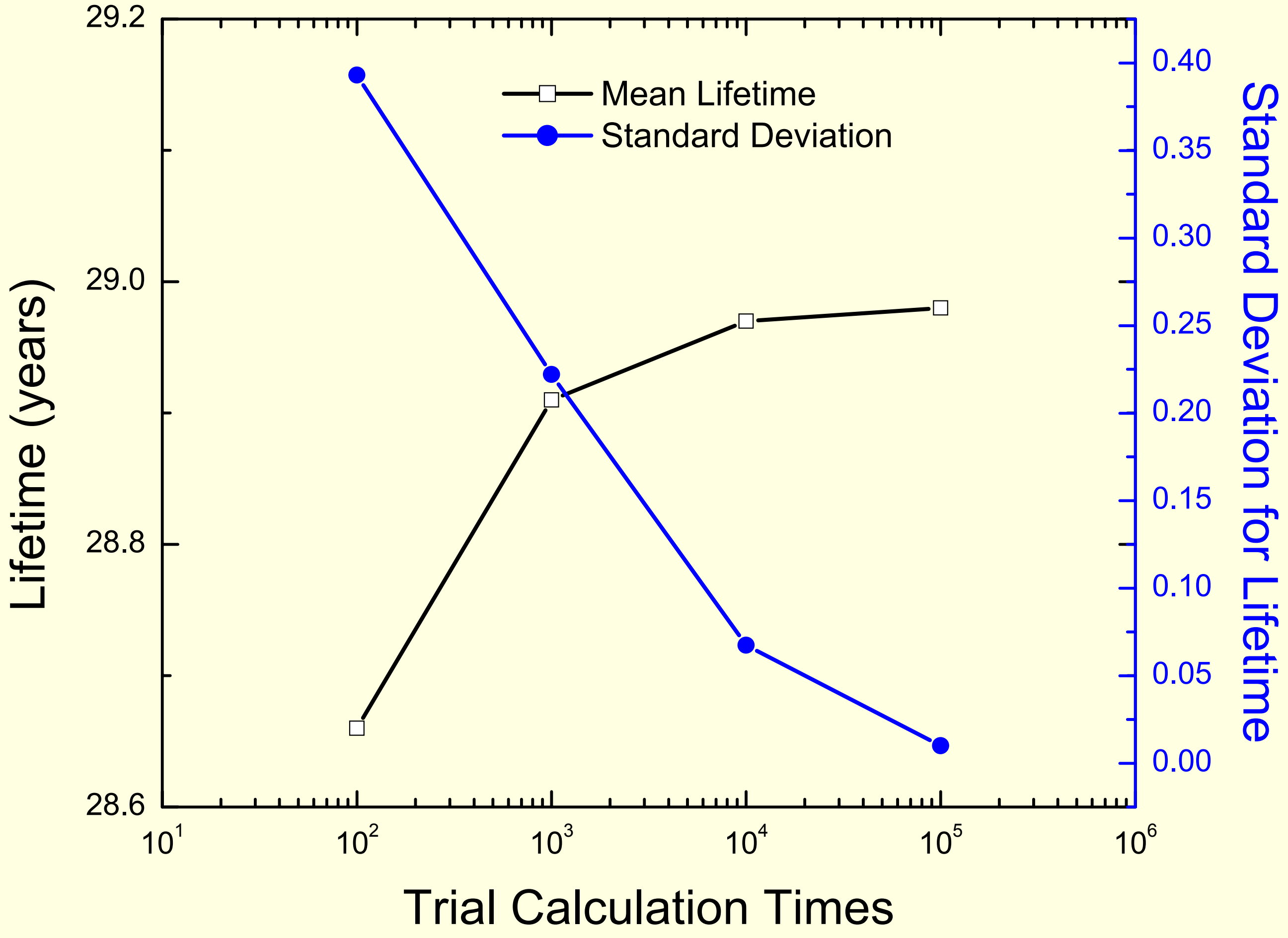


Monte Carlo Simulation for Lifetime Estimation

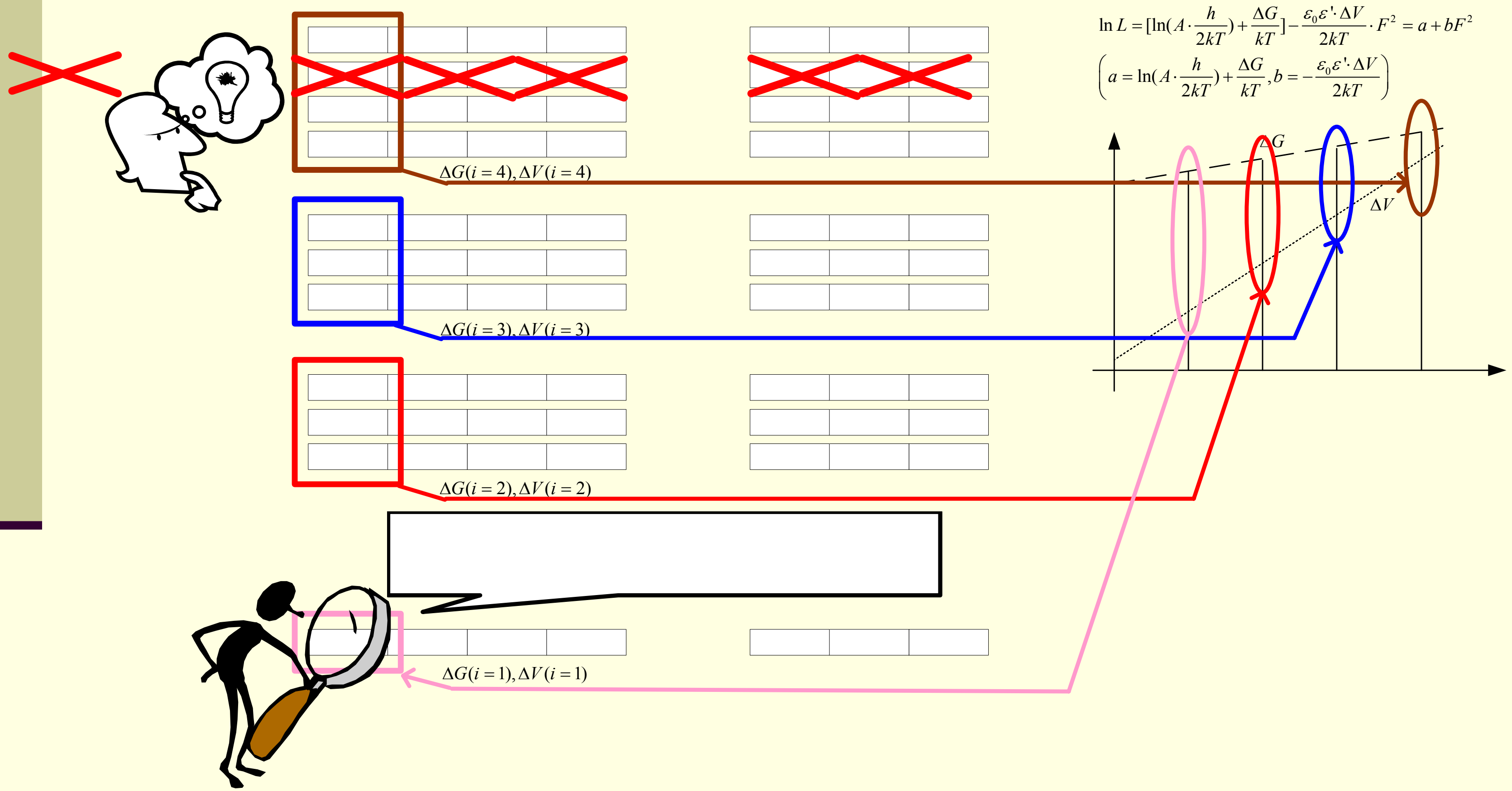


- Accelerated aging tests produce distributions of lifetimes
- Probabilistic simulation can produce a distribution of the lifetime estimate at normal conditions
- Verification of the procedure is only possible if normal condition lifetime data are available under comparable operating regimes
- Test model: EPRI data on aging of XLPE cables

Monte Carlo Simulation: Computation



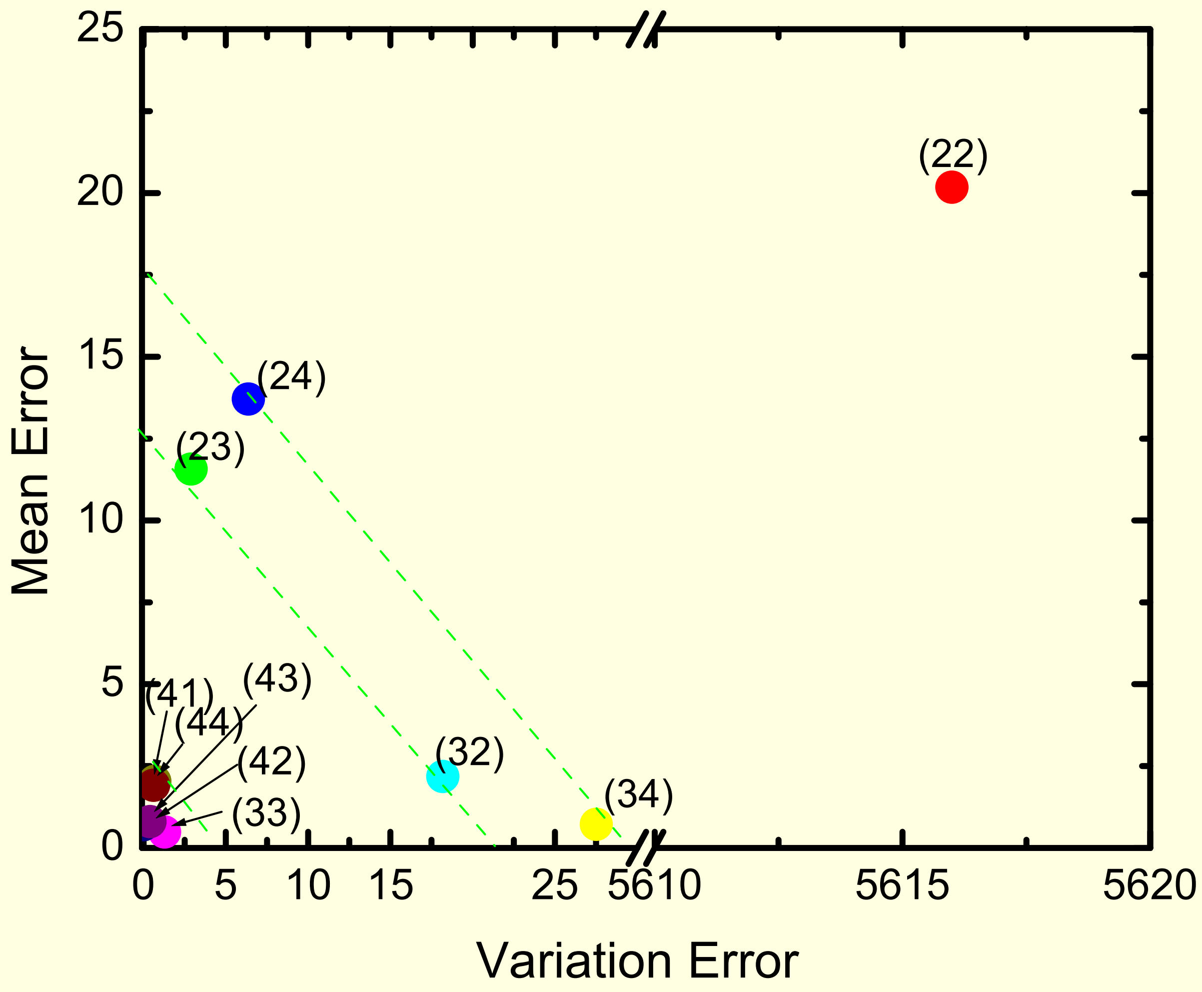
Lifetime Estimation Using Reduced Measurement Set



(Temp, Voltage Stress)

Random sa

Estimation Using Reduced Measurement Sets (Cont.)



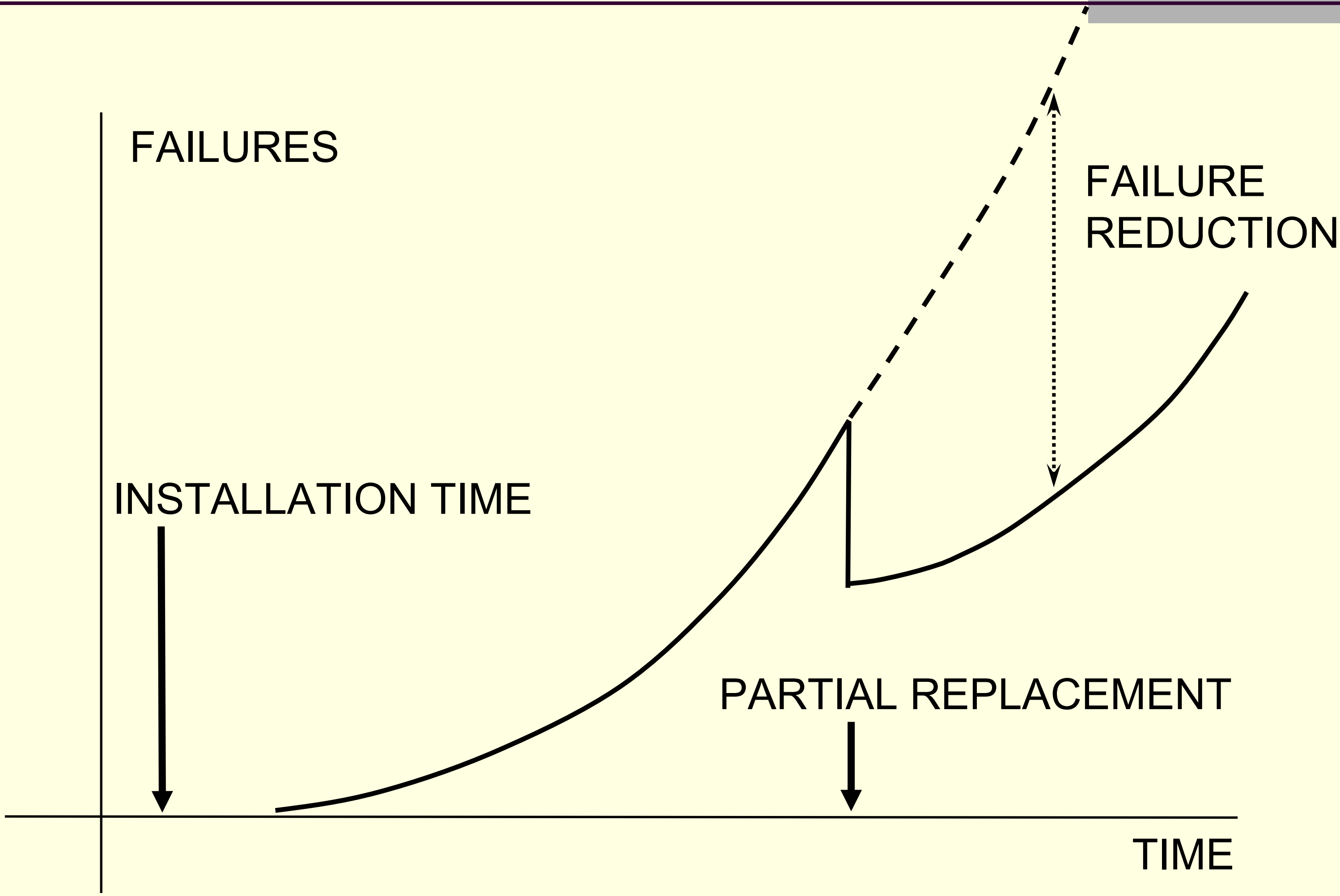
Cable Lifetime Estimation: Lessons Learned

- The starting point of aging model was very speculative – high risk project
- Model uncertainty could have invalidated the work – but didn't
- Experiments with reduced measurement sets have shown which tests are more influential on estimated cable life and allow for test prioritization

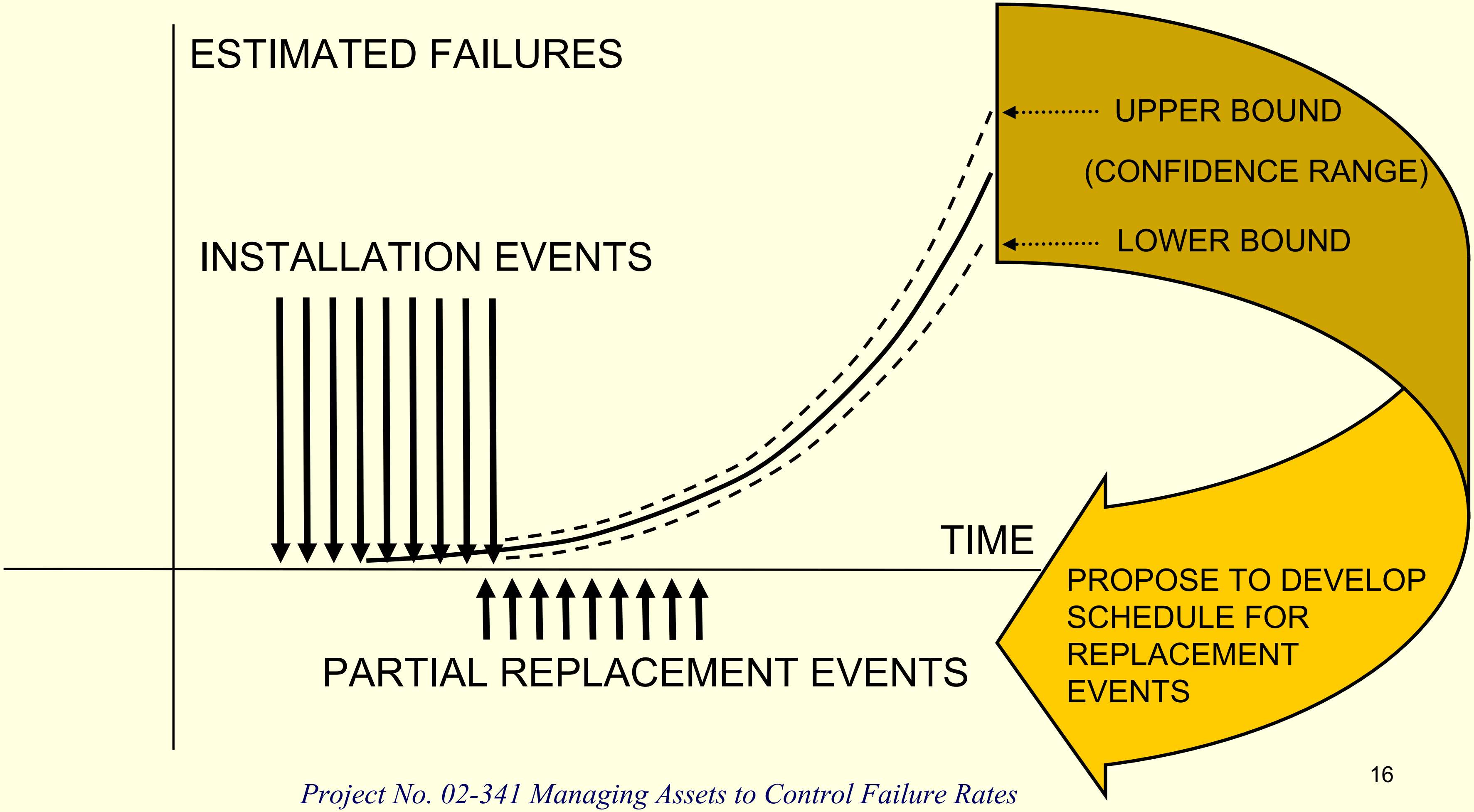
Cable Asset Management Effect of Replacements on Failure Rates

- Assumes homogeneous sample set, all aging at the same conditions, will have the same statistical aging parameters
- Failure data collected by utilities are incomplete – failures are not associated with vintages of populations in databases
- Prior work: Bill Forrest’s model
- Our approach: nonlinear model, probabilistic simulation, development of replacement schedules with a desired forecasted failure performance

Concept: Cable Asset Management Effect of Replacements on Failure Rates



Estimation and Control of Failures in Composite Populations of Cables



Formulation of the Failure Model

$$f(t) = X^{1/a} \cdot K \cdot (t-g)^b$$

Parameters a,K,g,b represent the description (model) of the failures for population X (in miles)

When there are *multiple* populations X_i installed in years i = 0, 1, 2, …, k, the *cumulative* failure model F(*t,a,g,b,K*) becomes a sum:

$$F(t,a,g,b,K) = \sum_{i=0}^{k} X_i^{1/a} \cdot K \cdot (t-g-i)^b$$

Observations on the Failure Model

- Failures do not necessarily increase linearly with length of cable population (due to coefficient *a*, having twice as long a cable does not necessarily mean that the population would experience twice as many failures)

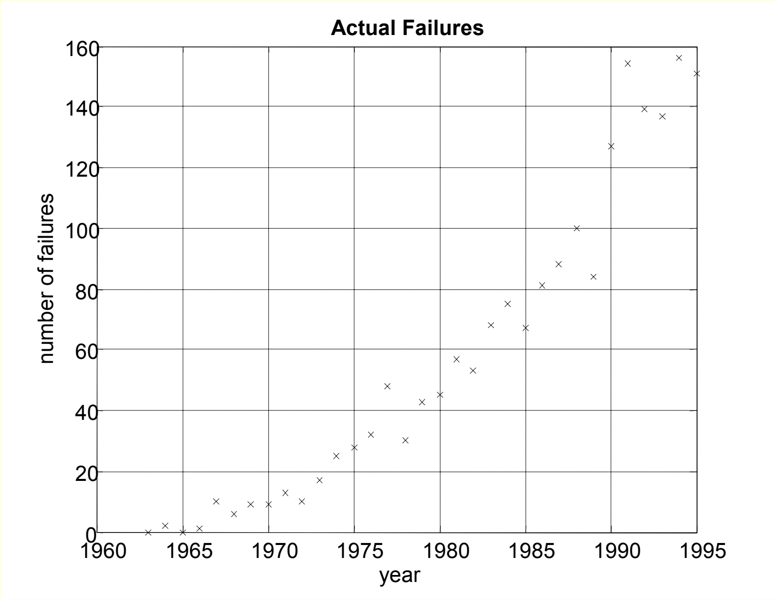
- Model allows for a gap of *g* years before the onset of the first failures

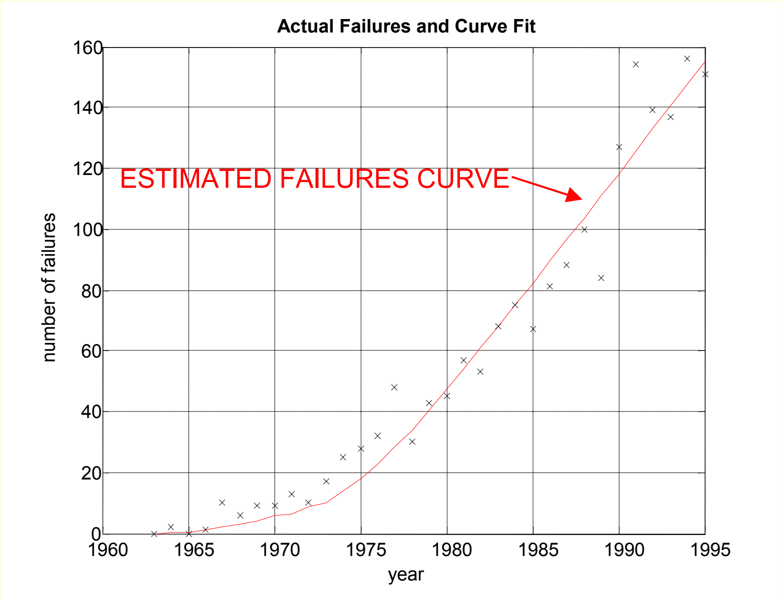
- Failures increase with the exponent *b* over time (i.e. if $b = 2$, failures will increase with the square of the time elapsed since the initial installation)

- Coefficient *K* allows additional flexibility (scaling) in the equation and is not part of the statistical description, strictly speaking

- If two (or more) populations of cable of identical lengths *X* were installed under identical conditions, they would produce different numbers of failures over time.

Methodology for Identification of Statistical Coefficients

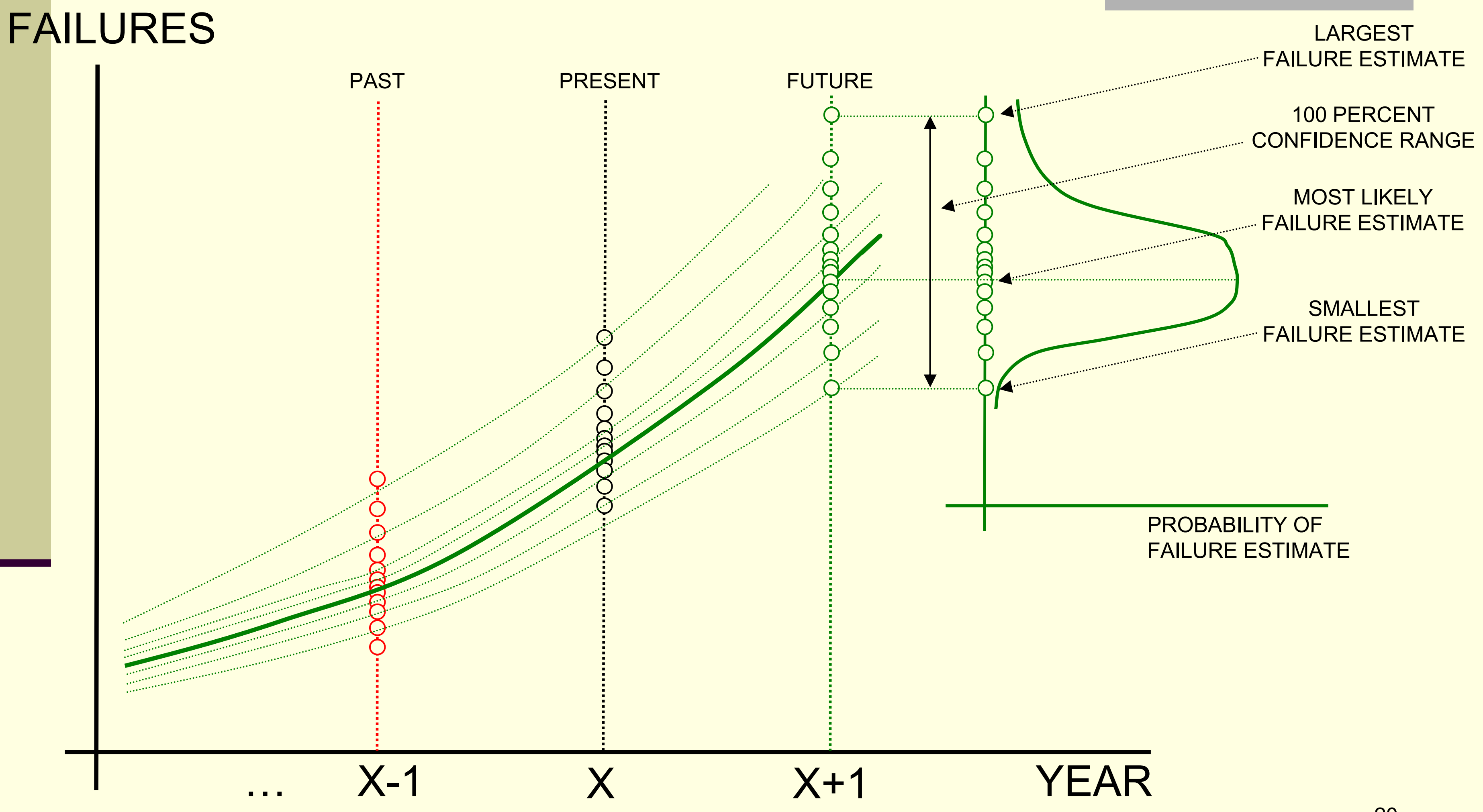




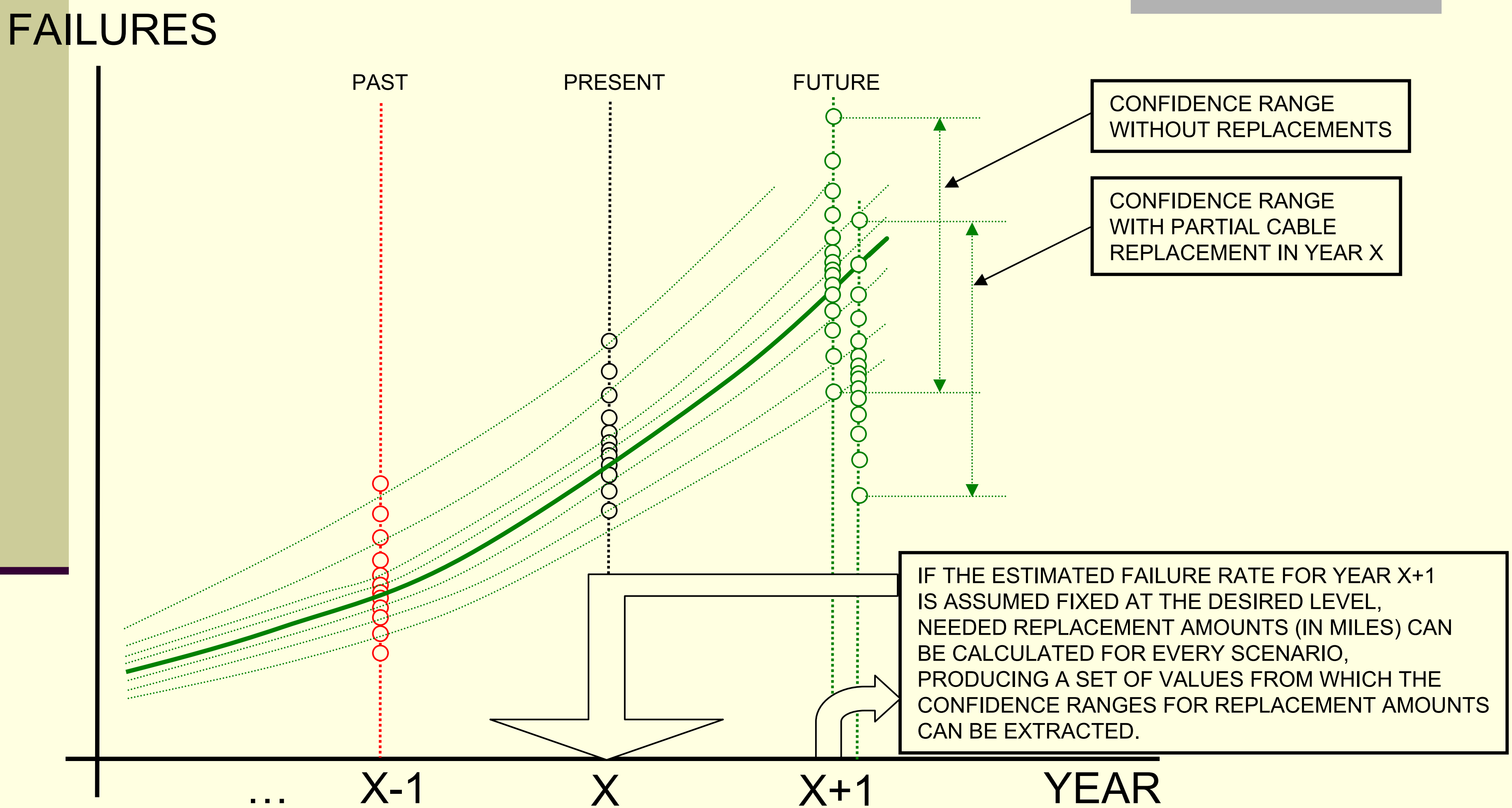
IDENTIFICATION OF {a,g,b,K} STATISTICAL PARAMETERS

CALCULATION OF ESTIMATED FAILURES USING {a,g,b,K}

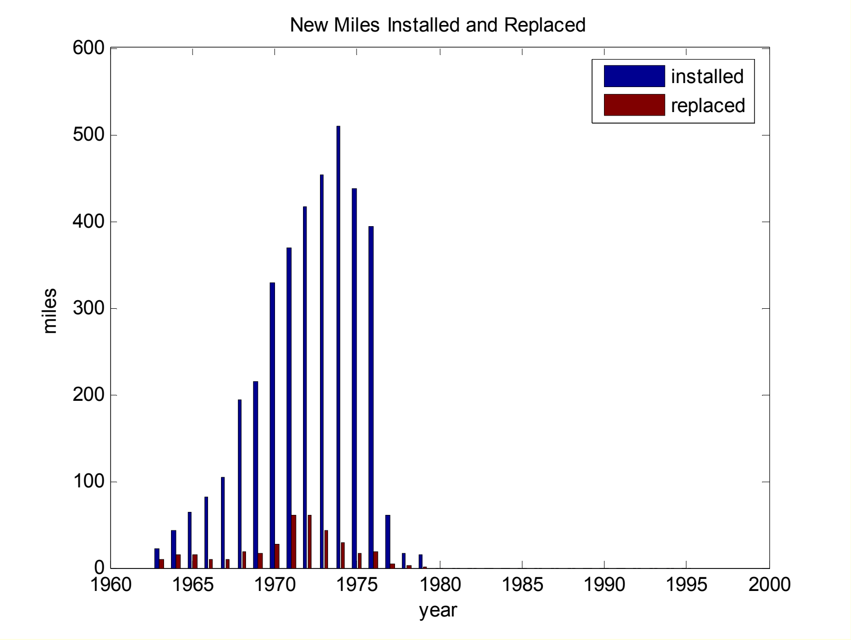
Concept of Failure Estimation

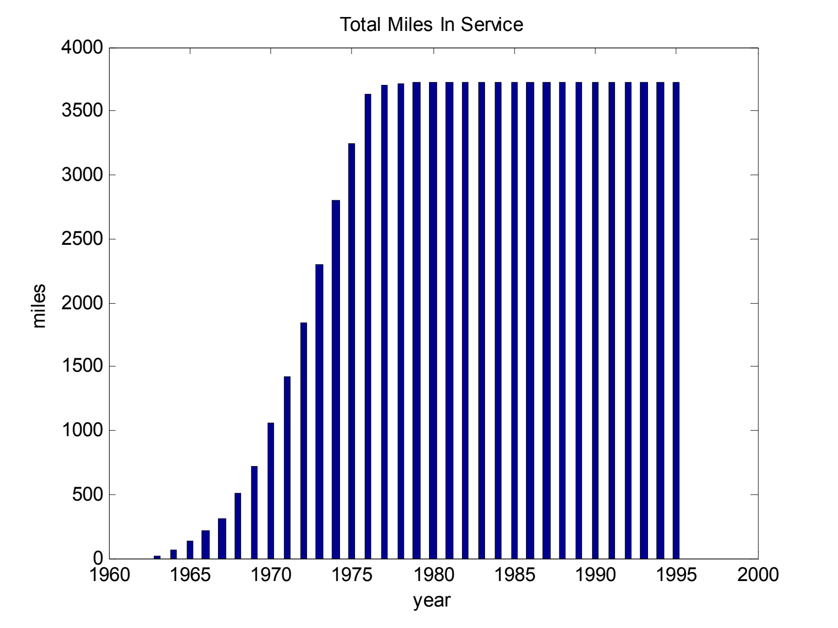


Effect of Partial Cable Replacement

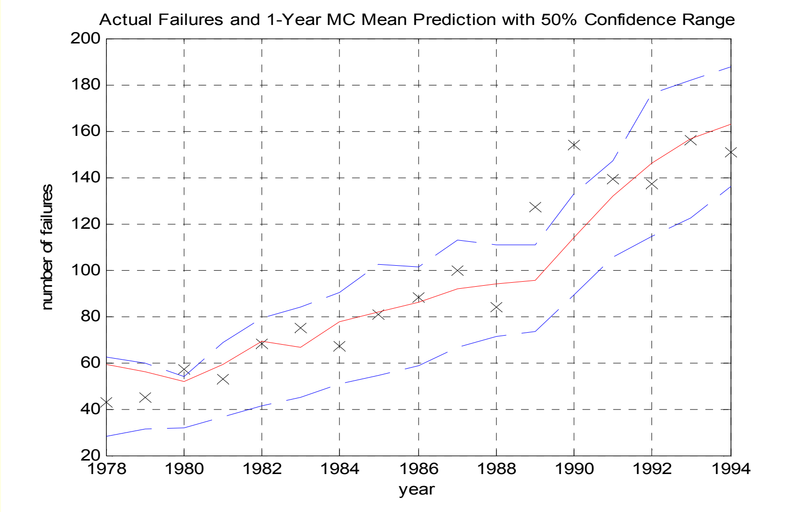


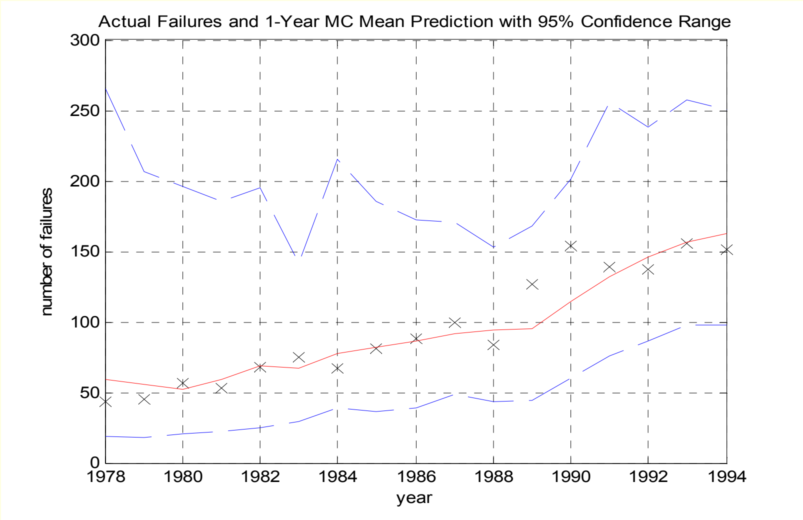
Test Data Set: New Cable Installation and Replacements

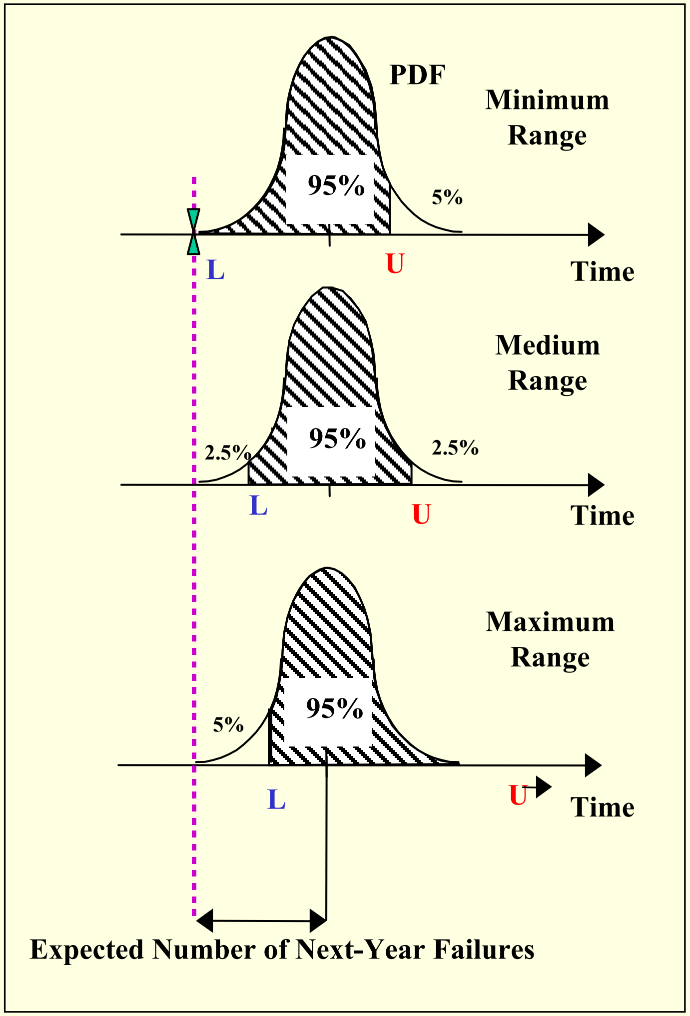




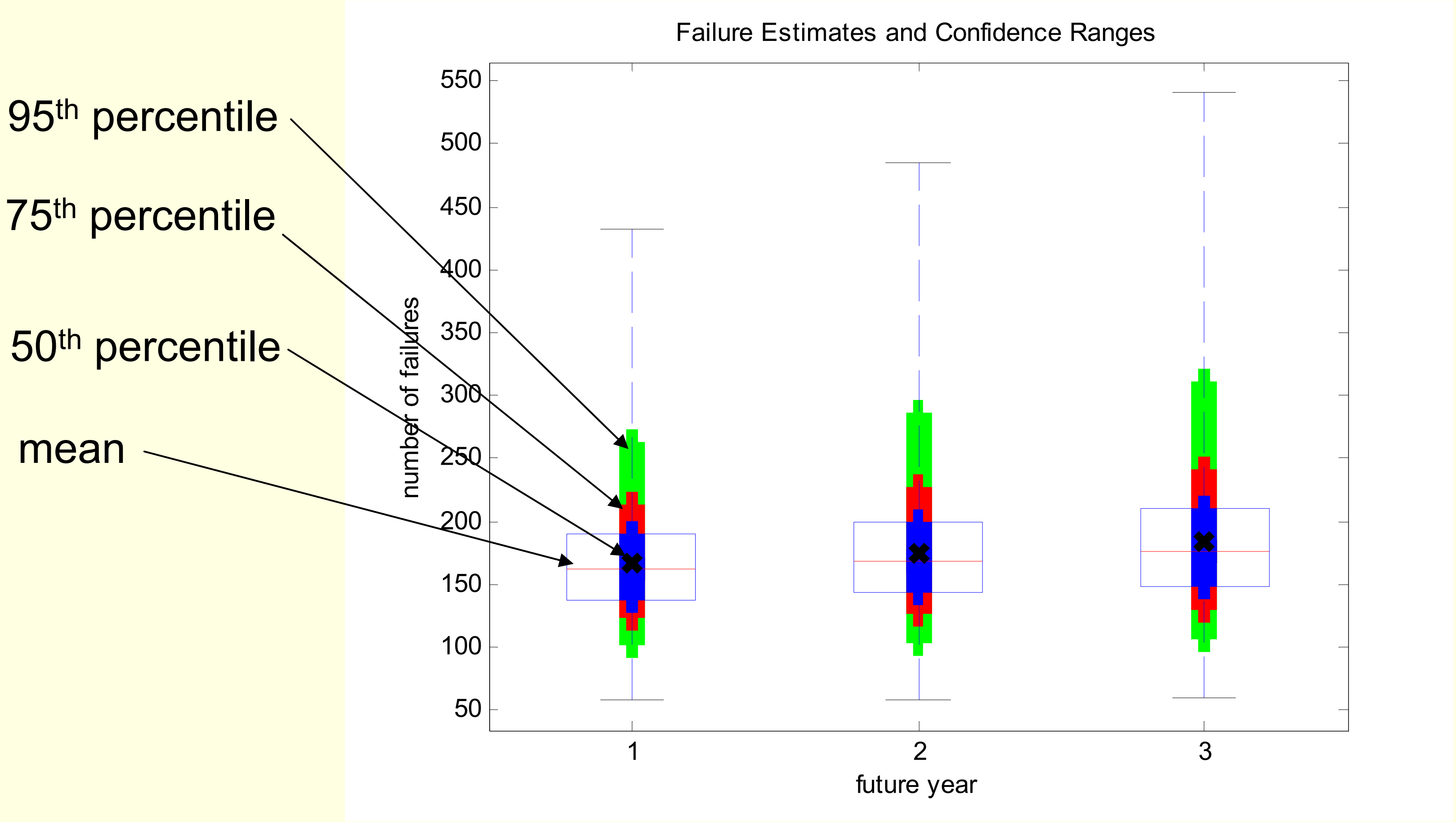
1-Year Prediction Test – 100 MC Simulations Per Year, 50% and 95% Confidence



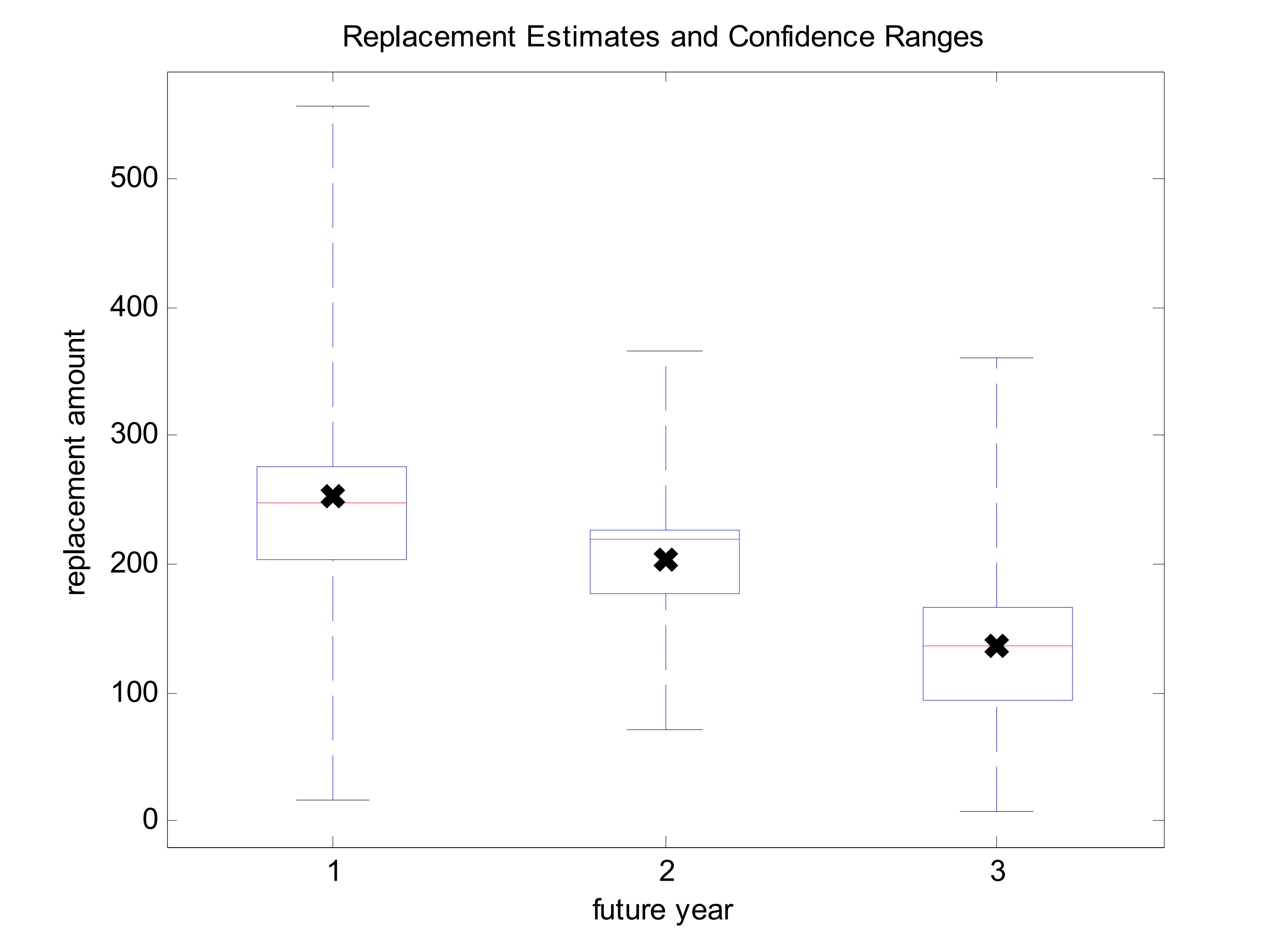




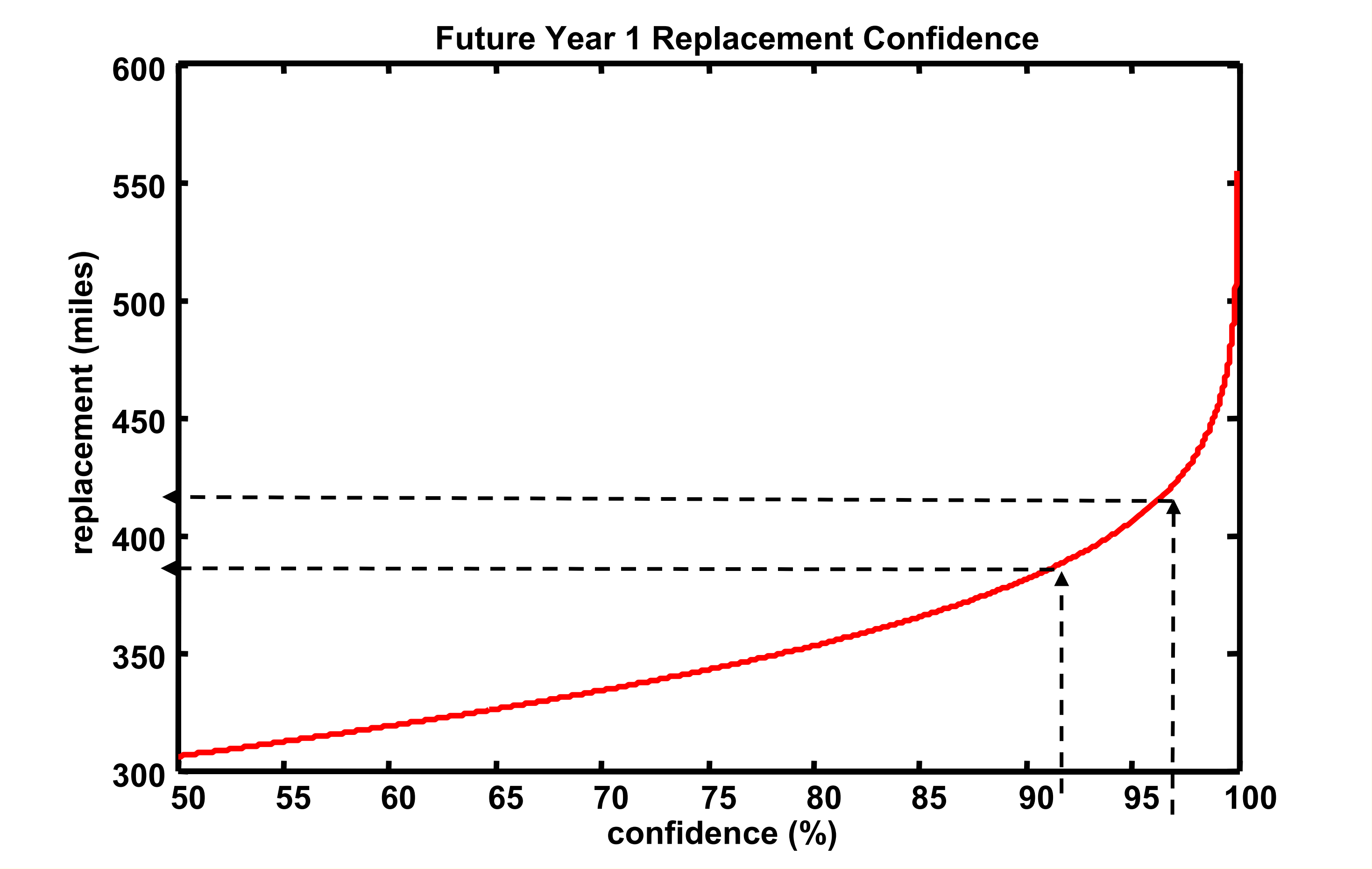
3-Year Failure Prediction and 50%, 75%, 95% Confidence Ranges for Constant Failure Rate



3-Year Replacement and 50% Confidence Range for Constant Failure Rate



Bottom Line: 1-Year Replacement Upper Bound



Conclusions

- Historical records of cable failures are incomplete
- Optimal approach – building statistical failure model based on the available data
- Monte Carlo simulations allow not only the estimation of future failures and replacement rates, but also their confidence ranges
- Asset management goal: to build a decision support tool which can approach the replacement strategy from the statistical viewpoint and build the decision with the desired level of certainty
- Better tracking of failure performance could significantly improve the performance of the algorithm