Accelerated Testing
Obtaining Reliability Information Quickly

William Q. Meeker
Department of Statistics and
Center for Nondestructive Evaluation
Iowa State University
Ames, IA 50011

Accelerated Testing Background

- Today's manufacturers face strong pressure to:
  - Improve productivity, product field reliability, and overall quality using new technology.
  - Develop newer, higher technology products in record time.
- Implies increased need for up-front testing of materials, components and systems.
- Accelerated tests provide timely information for product design and development.
- Users must be aware of potential pitfalls

What is Reliability?

- $R(t) = 1 - F(t)$
- The probability that a system, vehicle, machine, device, and so on, will perform its intended function under encountered operating conditions, for a specified period of time.
- Quality over time
- A powerful marketing tool
- An engineering discipline requiring support from
  - Physics and chemistry
  - Statistics

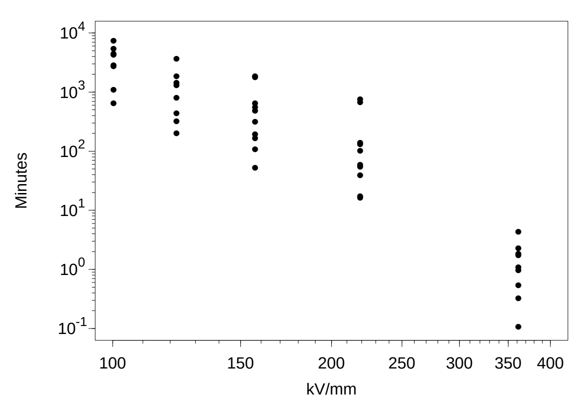
Overview

- Different kinds of accelerated tests
- Example 1—Evaluation of an insulating structure
- Example 2—New-technology microelectronic logic device
- Accelerated Degradation Tests
- Importance of physics of failure and physical/chemical models (and sensitivity analysis)
- Example 3—Microelectronic RF amplifier device
- Connecting with the field
- Example 4—Appliance field reliability
- Areas for further research

Some Applications of Accelerated Tests

- Assess component or material reliability or durability.
- Make design decisions to improve reliability or lower cost
- Verify predictions produced with physical models (e.g. FEM)
- System test to simulate field-use at accelerated conditions.
- Predict product field performance.
- Identify and fix potential failure modes at system/subsystem level (HALT and STRIFE tests).
- Screening (100% or audit) testing of manufactured product (e.g. ESS and burn-in).

Breakdown Times in Minutes of a Mylar-Polyurethane Insulating Structure (from Kalkanis and Rosso 1989)



Inverse Power Relationship-Lognormal Model

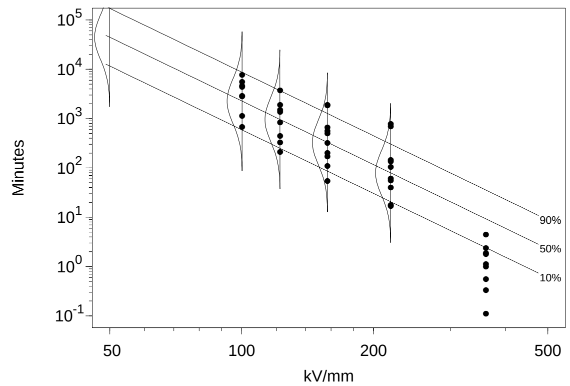
The inverse power relationship-lognormal model is

$$\Pr[T \le t; \mathtt{volt}] = \Phi_{\text{nor}}\left[\frac{\log(t)-\mu}{\sigma}\right]$$

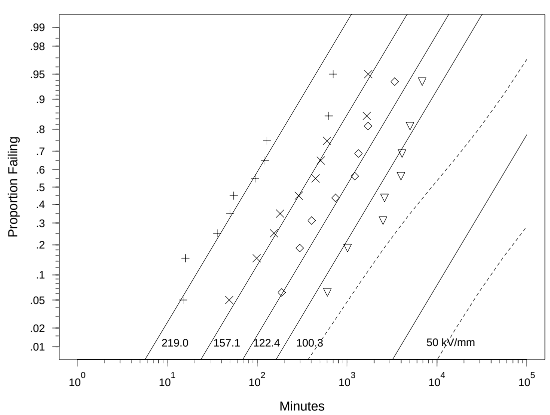
where

- $\mu = \beta_0 + \beta_1 x$, and
- $x = \log(\text{Voltage Stress})$.
- σ assumed to be constant.

Plot of Inverse Power Relationship-Lognormal Model Fitted to the Mylar-Polyurethane Data (also Showing 361.4kV Data Omitted from the ML Estimation)



Lognormal Probability Plot of the Inverse Power Relationship-Lognormal Model Fitted to the Mylar-Polyurethane Data



Methods of Acceleration

Three fundamentally different methods of accelerating a reliability test:

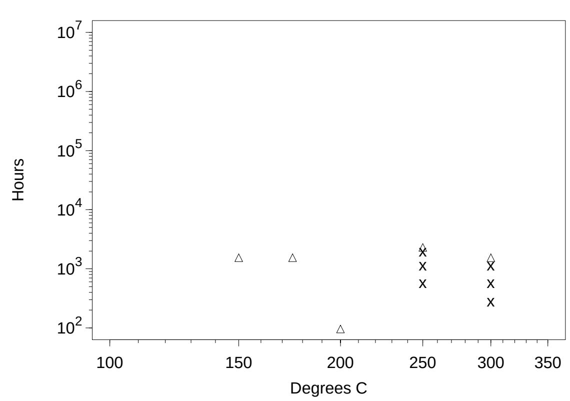
- Increase the use-rate of the product (e.g., test a toaster 400 times/day). Higher use rate reduces test time.
- Use elevated temperature or humidity to increase rate of failure-causing chemical/physical process.
- Increase stress (e.g., voltage or pressure) to make degrading units fail more quickly.

  Use a physical/chemical (preferable) or empirical model relating degradation or lifetime at use conditions.

Interval ALT Data for a New-Technology IC Device

- Tests run at 150, 175, 200, 250, and 300°C.
- Developers interested in estimating activation energy of the suspected failure mode and the long-life reliability.
- Failures had been found only at the two higher temperatures.
- After early failures at 250 and 300°C, there was some concern that no failures would be observed at 175°C before decision time.
- Thus the 200°C test was started later than the others.

New-Technology Integrated Circuit Device ALT Data



Elevated Temperature Acceleration of Chemical Reaction Rates

- The Arrhenius model Reaction Rate, $\mathcal{R}(\texttt{temp})$, is

$$\mathcal{R}(\texttt{temp}) = \gamma_0 \exp\left(\frac{-E_a}{k_B(\texttt{temp}\,^\circ\text{C} + 273.15)}\right) = \gamma_0 \exp\left(\frac{-E_a \times 11605}{\texttt{temp}\,\text{K}}\right)$$

  where $\texttt{temp}\,\text{K} = \texttt{temp}\,^\circ\text{C}+273.15$ is temperature in Kelvin and $k_B = 1/11605$ is Boltzmann's constant in units of electron volts per K. The reaction activation energy, E_a, and γ_0 are characteristics of the product or material being tested.

- The reaction rate Acceleration Factor is

$$\begin{aligned}\mathcal{AF}(\texttt{temp}, \texttt{temp}_U, E_a) &= \frac{\mathcal{R}(\texttt{temp})}{\mathcal{R}(\texttt{temp}_U)} \\ &= \exp\left[E_a\left(\frac{11605}{\texttt{temp}_U\,\text{K}} - \frac{11605}{\texttt{temp}\,\text{K}}\right)\right]\end{aligned}$$

- When $\texttt{temp} > \texttt{temp}_U$, $\mathcal{AF}(\texttt{temp}, \texttt{temp}_U, E_a) > 1$.

The Arrhenius-Lognormal Regression Model

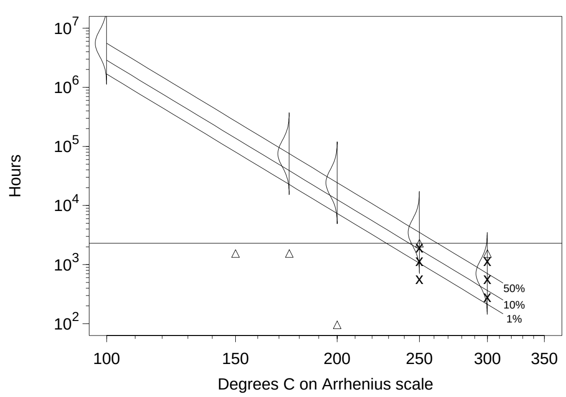
The Arrhenius-lognormal regression model is

$$\Pr[T \le t; \texttt{temp}] = \Phi_{\text{nor}}\left[\frac{\log(t) - \mu}{\sigma}\right]$$

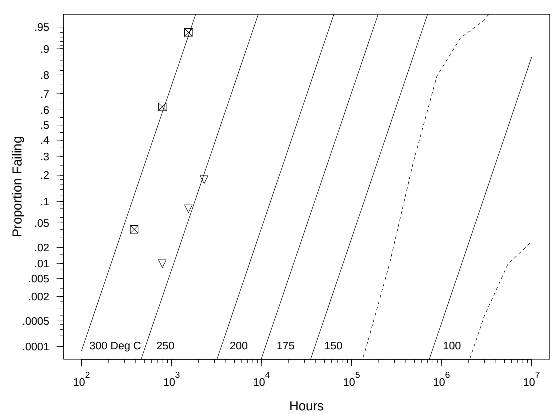
where

- $\mu = \beta_0 + \beta_1 x$,
- $x = 11605/(\texttt{temp}\,\text{K}) = 11605/(\texttt{temp}\,^\circ\text{C} + 273.15)$
- and $\beta_1 = E_a$ is the activation energy
- σ is constant

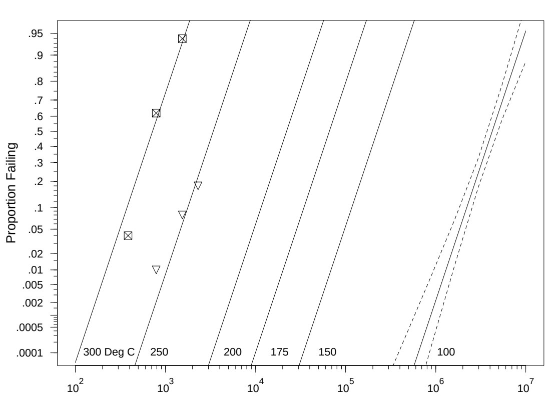
Arrhenius Plot Showing ALT Data and the Arrhenius-Lognormal Model ML Estimation Results for the New-Technology IC Device.



Lognormal Probability Plot Showing the Arrhenius-Lognormal Model ML Estimation Results for the New-Technology IC Device



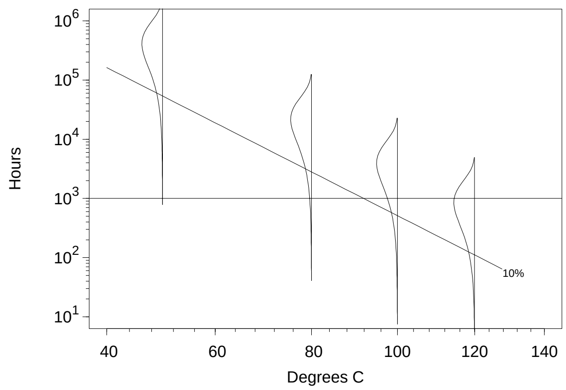
Lognormal Probability Plot Showing the Arrhenius-Lognormal Model ML Estimation Results for the New-Technology IC Device with Given $E_a = .8$



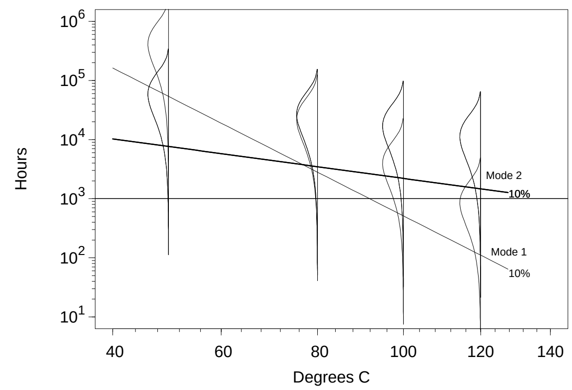
Pitfall 4: Masked Failure Mode

- Accelerated test may focus on one known failure mode, masking another!
- Masked failure modes may be the first one to show up in the field.
- Masked failure modes could dominate in the field.

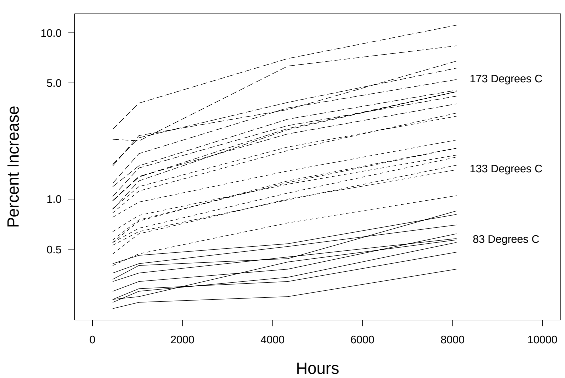
Possible results for a typical temperature-accelerated failure mode on an IC device



Unmasked Failure Mode with Lower Activation Energy



Percent Increase in Resistance Over Time for Carbon-Film Resistors (Shiomi and Yanagisawa 1979)



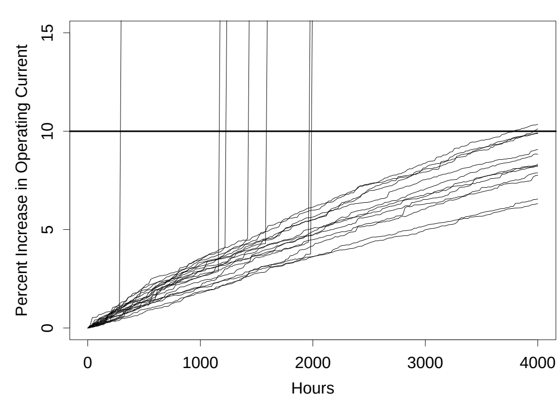
Advantages of Using Degradation Data Instead of Time-to-Failure Data

- Degradation is natural response for some tests.
- Can be more informative than time-to-failure data. (Reduction to failure-time data loses information)
- Useful reliability inferences even with 0 failures.
- More justification and credibility for extrapolation. (Modeling closer to physics-of-failure)

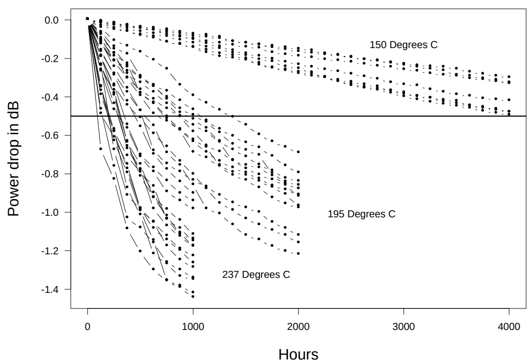
Limitations of Degradation Data

- Degradation data may be difficult or impossible to obtain (e.g., destructive measurements).
- Obtaining degradation data may have an effect on future product degradation (e.g., taking apart a motor to measure wear).
- Substantial measurement error can diminish the information in degradation data.
- Analyses more complicated; requires statistical methods not yet widely available.
  (Modern computing capabilities should help here)
- Degradation level may not correlate well with failure.

Percent Increase in Operating Current for GaAs Lasers Tested at 80°C



Device-B Power Drop
Accelerated Degradation Test Results
at 150°C, 195°C, and 237°C
(Use conditions 80°C)



Arrhenius Model
Temperature Effect on Chemical Degradation

$$A_1 \xrightarrow{k_1} A_2$$

and the rate equations for this reaction are

$$\frac{dA_1}{dt} = -k_1 A_1 \quad \text{and} \quad \frac{dA_2}{dt} = k_1 A_1, \quad k_1 > 0. \tag{1}$$

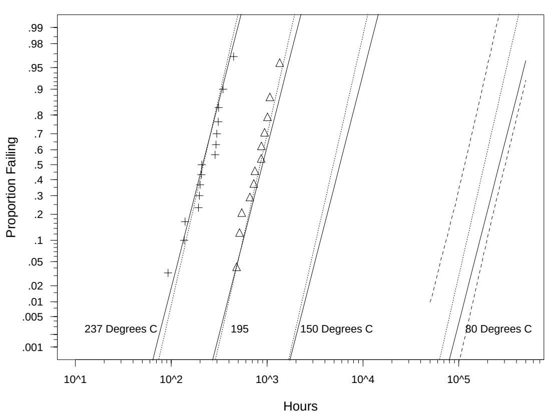
Solving these gives

$$\begin{aligned} A_1(t) &= A_1(0)\exp(-k_1 t) \\ A_2(t) &= A_2(0) + A_1(0)[1 - \exp(-k_1 t)] \end{aligned}$$

where $A_1(0)$ and $A_2(0)$ are initial conditions. The Arrhenius model describing the effect that temperature has on the rate of a simple first-order chemical reaction is

$$k_1 = \gamma_0 \exp\left[\frac{-E_a}{k_B \times (\texttt{temp} + 273.15)}\right]$$

Lognormal-Arrhenius Model Fit to the Device-B Time-to-Failure Data with Degradation Model Estimates



What Do Accelerated Test Results Tell Us About Field Reliability?

Need information on:

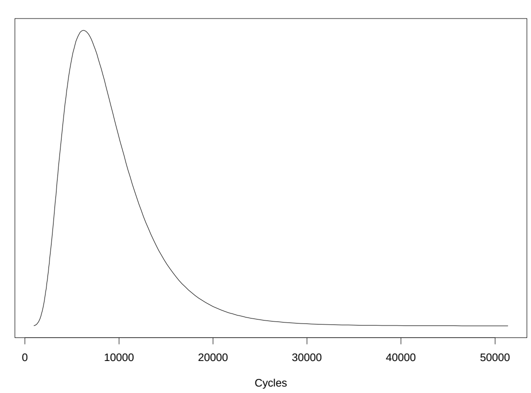
- Effects of acceleration (e.g., cycling rate).
- Distribution of use-rates in actual use.
- Distribution of environmental conditions (e.g., stress spectra distributions).

These factors may be given or, in some situations, inferred from the available data.

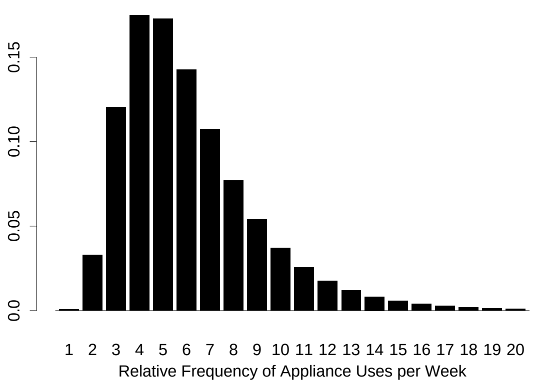
Establish a Transfer Function Relating Laboratory Tests and Field Performance

- Carefully compare laboratory tests results and field failures.
  - ▶ Same failure mechanisms operating in laboratory tests?
  - ▶ Same factors (environmental noises) exciting the failure mechanisms?
  - ▶ Identify laboratory/field discrepancies to improve test procedures. Seek understanding of reasons for lack of agreement.
- Find a model (transfer function) to relate laboratory test to field use.
- Understanding the relationship between the laboratory test results and product field reliability will provide stronger basis for using future laboratory tests to predict field performance.

Component-A
Laboratory Test Cycles to Failure



Appliance Use-Rate Distribution (discretized lognormal distribution)



Example Use-Rate Model

- Life of a component in cycles of use, has a distribution

$$F_C(c) = P(C \le c) = \Phi\left[\frac{\log(c) - \mu}{\sigma}\right]$$

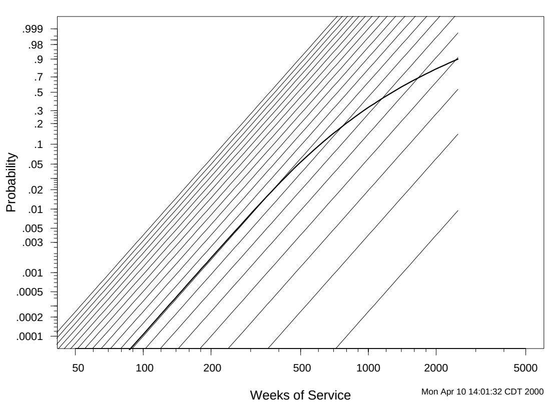
- Actual use-rate has a distribution given by the proportion of users π_i $(i = 1, \ldots, k)$ that use the appliance at constant rate R_i, where $\sum_{i=1}^{k} \pi_i = 1$.

- Then the failure probability as a function of time is

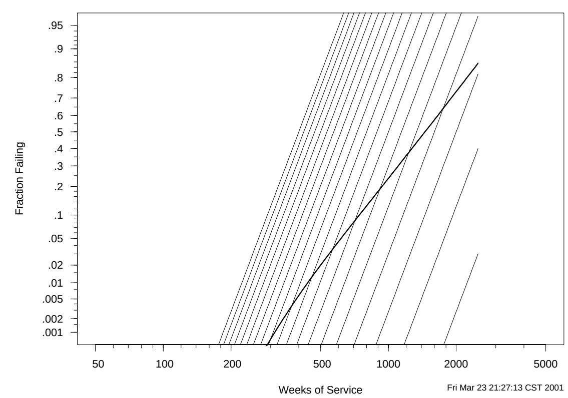
$$F_T(t; \boldsymbol{\theta}) = P(T \le t) = \sum_{i=1}^{k} \pi_i \, \Phi\left[\frac{\log(t) - \mu_i}{\sigma}\right]$$

where $\boldsymbol{\theta} = (\mu_1, \ldots, \mu_k, \sigma)$ and $\mu_i = \mu - \log(R_i)$.

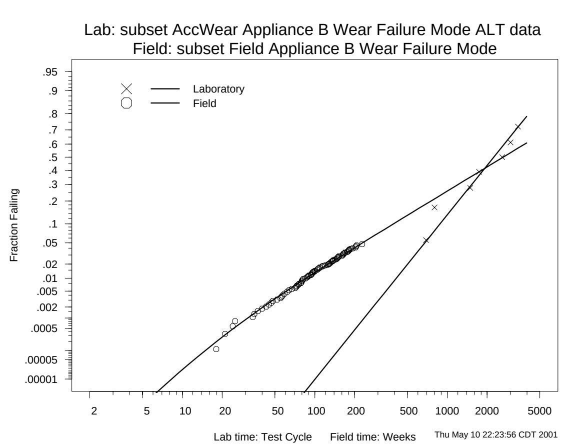
Predicted Field Reliability of Component-A as a Weighted Average of Weibull Distributions



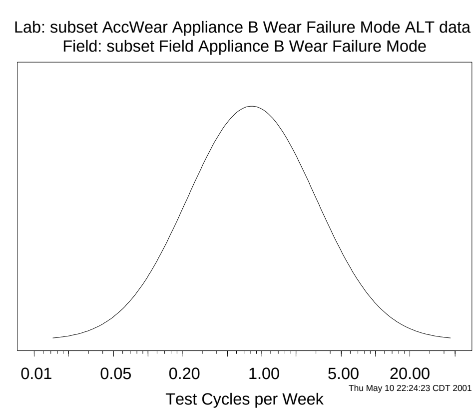
Predicted Field Reliability of Component-A as a Weighted Average of Lognormal Distributions



Fitted Use-Rate Model for the Wear Failure Mode



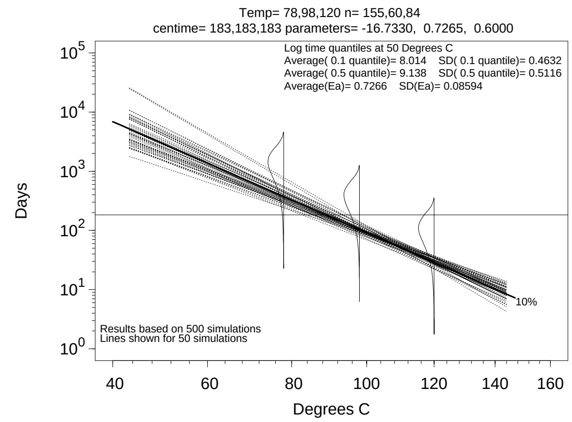
Field Variability Lognormal $f(r; \eta_R, \sigma_R)$ Density for the Wear Failure Mode (unloaded cycles relative to field days of use)



Planning Accelerated Tests

- Most basic ideas of traditional DOE still hold
- Limit, as much as possible the amount of extrapolation used.
- In censored accelerated life tests (failure time is response) allocate more test units to low acceleration factor level than high acceleration factor levels.
- Consider including some tests at the use conditions.
- Use simulation to investigate properties of alternative ALT plans.

Simulation of a Proposed Accelerated Life Test Plan



Areas for Further Research

- Physical/statistical models for failure acceleration
- Methods for sensitivity analysis when empirical models must be used
- Prediction of service life in complicated environments
- Physical/statistical models the field environment
- Bayesian methods for analysis and planning (especially adaptive test plans)
- Accelerated degradation test planning
- Degradation analysis and planning with coarse (e.g. ordered categorical and censored) data.
- Physical comparison of lab and filed failures to validate testing methods

Concluding Remarks

- Accelerated Testing can be valuable tool when used carefully
- There is no magic in Accelerated Testing
- Cross-disciplinary teams are needed to deal effectively with all issues
  - ▶ Product/reliability/design engineers to identify product-use profiles, environmental considerations, potential failure modes or weaknesses that need to be evaluated, etc.
  - ▶ Experts in materials and the chemistry/physics of failure to help in the understanding of an suggest/develop appropriate models for acceleration of particular failure modes.
  - ▶ Statisticians to help with stochastic modeling, plan tests, fit models, and to help quantify uncertainty in results.
- Users of Accelerated Testing must beware of pitfalls

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