Accelerated Reliability Testing Applications and Pitfalls

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

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Much of the material in this talk has been taken from Meeker and Escobar (1998).

Accelerated Testing Background

- Reliability is a powerful marketing tool
- Today's manufacturers face strong pressure to:
  - Develop newer, higher technology products in record time.
  - Improve productivity, product field reliability, and overall quality using new technology.
- 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

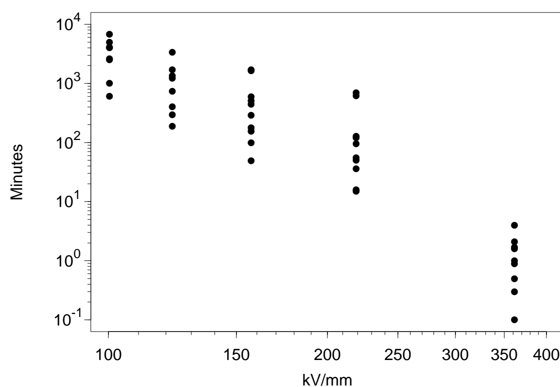
Overview

- Different kinds of accelerated tests
- Example 1—Evaluation of an insulating structure
- Example 2—New-technology microelectronic logic device
- Accelerated Life Tests versus Accelerated Degradation Tests
- Importance of physics of failure and physical/chemical models (and sensitivity analysis)
- Example 3—Microelectronic RF amplifier device
- Other problems and pitfalls
- Links with six-sigma.
- Concluding remarks

Types of Accelerated Tests

- Assess component or material reliability or durability.
- Identify and fix potential failure modes at system/subsystem level (STRIFE TESTS).
- Screening (100% or audit) testing of manufactured product (e.g. ESS and burn-in).
- System test to simulate field-use at accelerated use-rates.

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



Inverse Power Relationship-Lognormal Model

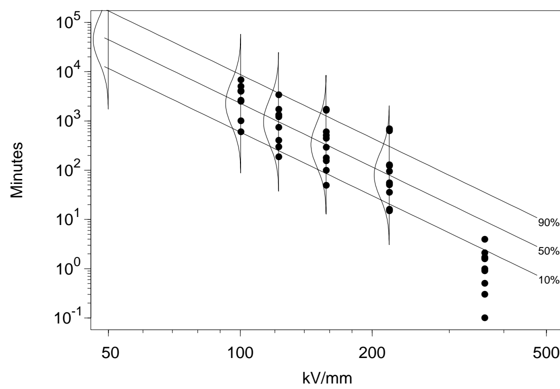
The inverse power relationship-lognormal model is

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

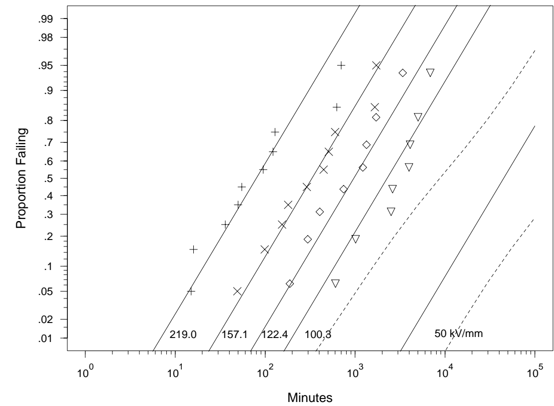
where

- $\mu = \beta_0 + \beta_1 x$, 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:

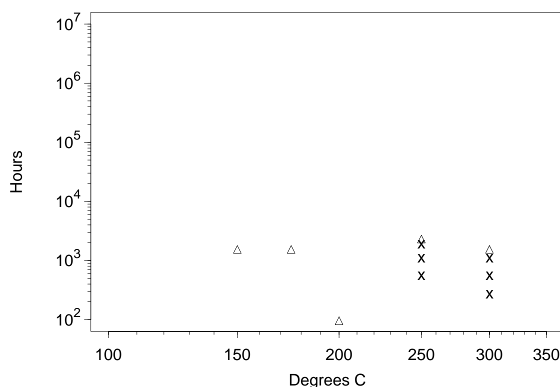
- Increase the use-rate of the product (e.g., test a toaster 400 times/day). Higher use rate reduces test time.
- Use elevated temperature or humidity to increase rate of failure-causing chemical/physical process.
- Increase stress (e.g., voltage or pressure) to make degrading units fail more quickly.

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

Analysis of 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.

Lognormal New-Technology Integrated Circuit Device ALT Data



Elevated Temperature Acceleration of Chemical Reaction Rates

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

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

  where $\texttt{temp}\,\text{K} = \texttt{temp}\,°\text{C} + 273.15$ is temperature in degrees 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

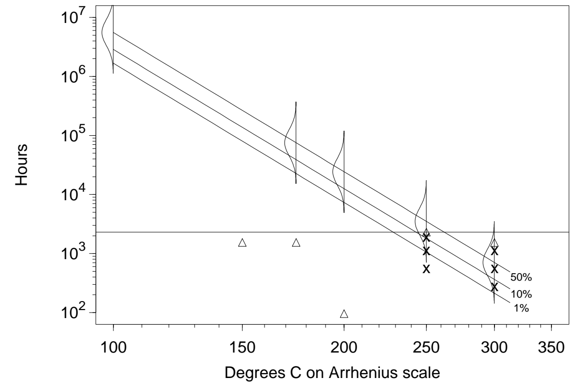
The Arrhenius-lognormal regression model is

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

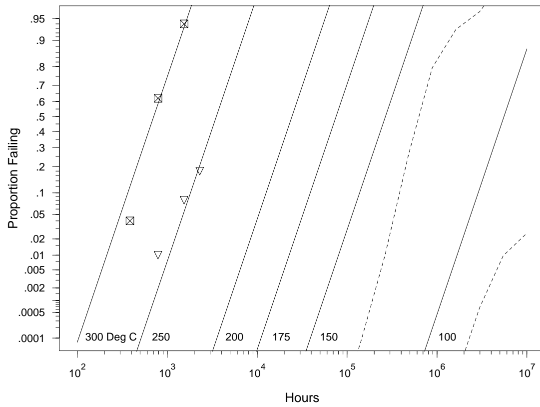
where

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

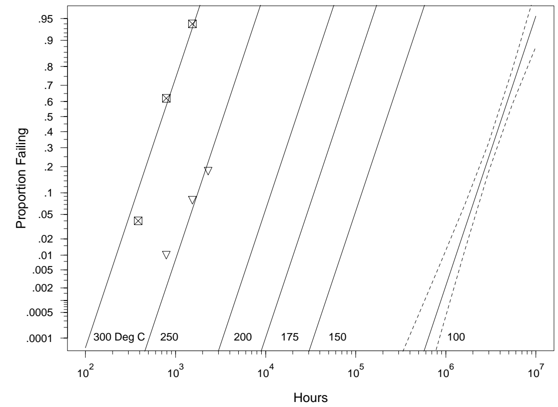
Arrhenius Plot Showing ALT Data and the Arrhenius-Lognormal Model ML Estimation Results for the New-Technology IC Device.



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



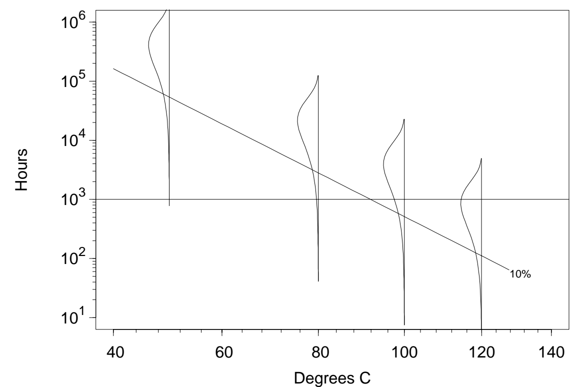
Lognormal Probability Plot Showing the Arrhenius-Lognormal Model ML Estimation Results for the New-Technology IC Device with Given $E_a = .8$



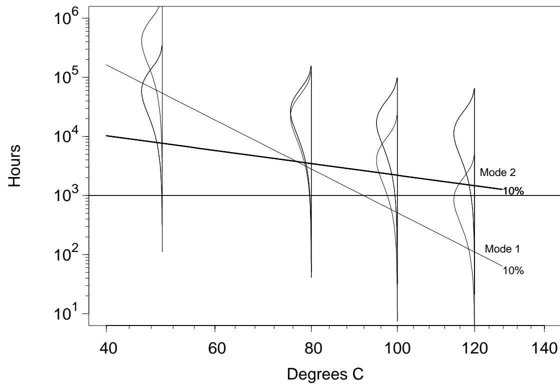
Pitfall 4: Masked Failure Mode

- 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



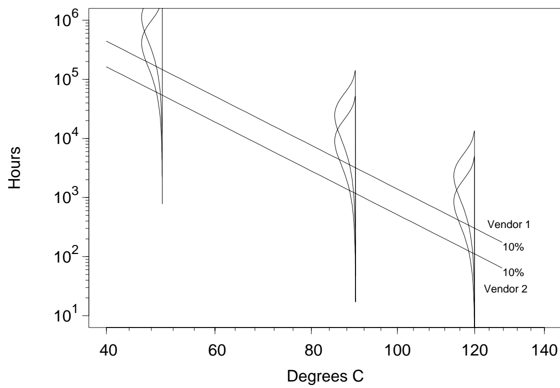
Unmasked Failure Mode with Lower Activation Energy



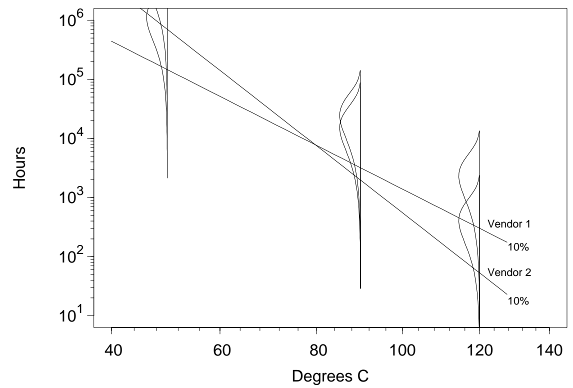
Pitfall 5: Faulty Comparison

- It is sometimes claimed that Accelerated Testing is not useful for predicting reliability, but is useful for comparing alternatives.
- Comparisons, however, are subject to some of the same difficulties.
- Beware of comparing products then the have different kinds of failures.

Comparison of Two Products I



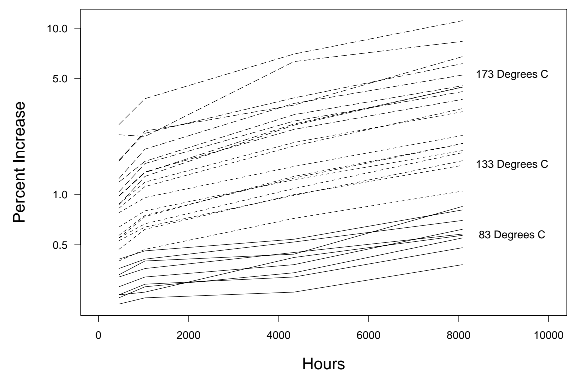
Comparison of Two Products II



Some Practical Suggestions

- Build on previous experience with similar products and materials.
- Use pilot tests
- Use results from failure mode analysis.
- Seek physical understanding of cause of failure.
- Seek physical justification for life/stress relationships.
- Limit the amount extrapolation used
- Use degradation data, if possible

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



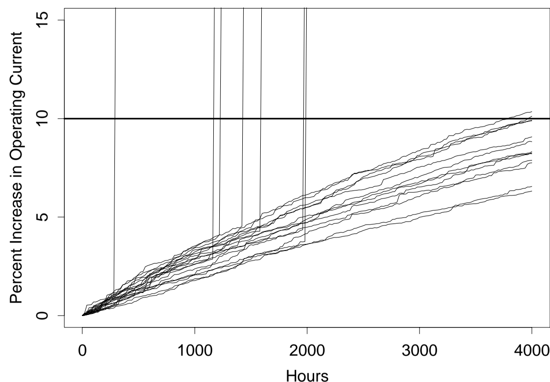
Advantages of Using Degradation Data Instead of Time-to-Failure Data

- 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)

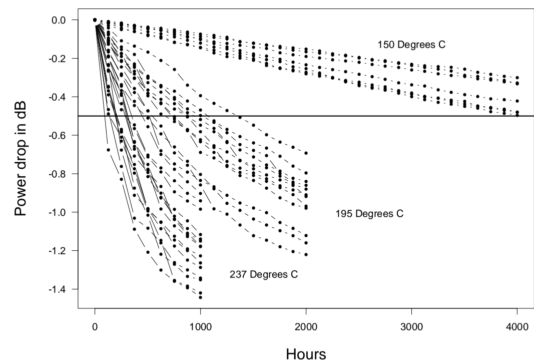
Limitations of Degradation Data

- 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

$$\frac{dA_1}{dt} = -k_1 A_1 \quad \text{and} \quad \frac{dA_2}{dt} = k_1 A_1, \quad k_1 > 0. \qquad (2)$$

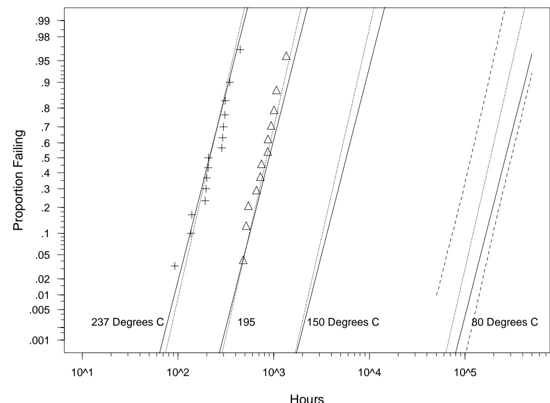
Solving these gives

$$A_1(t) = A_1(0)\exp(-k_1 t)$$
$$A_2(t) = A_2(0) + A_1(0)[1 - \exp(-k_1 t)]$$

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

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

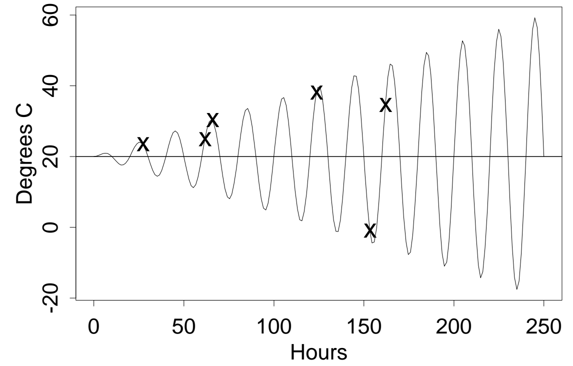
Lognormal-Arrhenius Model Fit to the Device-B Time-to-Failure Data with Degradation Model Estimates



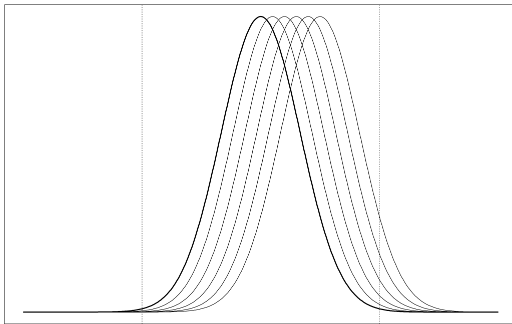
Pitfall 8: Predictions of Variable Environments is Complicated

- Most accelerated tests are run under carefully controlled, usually constant, conditions.
- Prediction of life in environments (e.g., effects of outside weathering) is complicated.
- For example, manufacturers of paints and coatings still rely on outdoor testing.
- Substituting "average" conditions into simple acceleration modes can give misleading results in predicted spread and location.
- There is some hope of using kinetics cumulative damage models to make useful predictions.

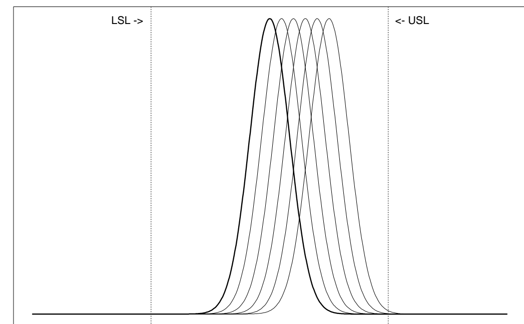
Strife Test



Effect of Component Drift Over Time 3-σ process



Effect of Component Drift Over Time 6-σ process



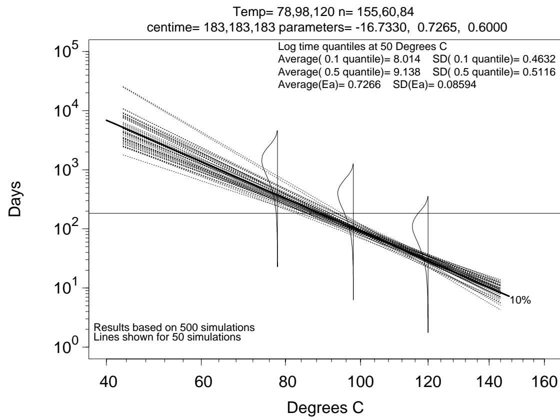
Relationship to 6-σ-Type Strategy

- **Measure** critical (failure-related) reliability variables at time 0 and over time.
- **Analyze** causes of failure, sources of variability (identify important ones), and effect of critical reliability variables on failure.
- **Improve** by using designed experiments, searching for robust design options, degradation reduction alternatives, strengthening critical components, etc.
- **Control** manufacturing processes to maintain reduced variability.

Planning Accelerated Tests

- Limit, as much as possible the amount of extrapolation used.
- In 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



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 and land mines

References

- D. Byrne, J. Quinlan, Robust function for attaining high reliability at low cost, *1993 Proceedings Annual Reliability and Maintainability Symposium*, 1993, pp 183-191.
- L. W. Condra, *Reliability Improvement with Design of Experiments*, 1993, New York: Marcel Dekker, Inc.
- M. Hamada, Using statistically designed experiments to improve reliability and to achieve robust reliability, *IEEE Transactions on Reliability* R-44, 1995 June.
- M. Hamada, Analysis of experiments for reliability improvement and robust reliability, in *Recent Advances in Life-Testing and Reliability*, 1995, N. Balakrishnan, editor, Boca Raton: CRC Press.
- Meeker, W.Q. and Hamada, M. (1995), Statistical Tools for the Rapid Development & Evaluation of High-Reliability Products, *IEEE Transactions on Reliability* R-44, 187-198.

References

- Meeker, W.Q. and Escobar, L.A. (1998a), *Statistical Methods for Reliability Data*. John Wiley and Sons, Inc.
- Meeker, W.Q. and Escobar, L.A. (1998b), Pitfalls of Accelerated Testing. , *IEEE Transactions on Reliability* R-47, 114-118.
- W. Nelson, *Accelerated Testing: Statistical Models, Test Plans, and Data Analyses*, 1990, New York: John Wiley & Sons, Inc.
- G. Taguchi, *System of Experimental Design*, 1987; White Plains, NY: Unipub/Kraus International Publications.
- T. S. Tseng, M. Hamada, C. H. Chiao, (1995), Using degradation data from a factorial experiment to improve fluorescent lamp reliability, *Journal of Quality Technology*, 363-369.