Accelerated Test Methods for Reliability Prediction

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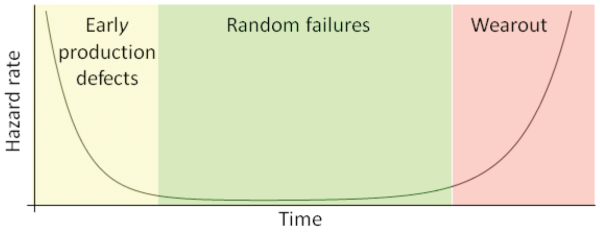
Traditional testing methods are costly and inefficient for predicting the lifetimes of materials that are expected to function reliably over many years, such as components in the nuclear stockpile. Alternatives to traditional tests accelerate the aging of components by subjecting them to conditions outside normal service or storage ranges, which, in principle, provides test data within a compressed time frame. Alternatives include accelerated life testing (ALT), accelerated degradation testing (ADT), highly accelerated life testing (HALT), highly accelerated stress screening (HASS), and variants on these methods.

Use of accelerated methods is often hindered by organizational conflicts between testing as part of an iterative process of finding and removing defects and testing as a means of estimating or predicting reliable life. We are developing a taxonomy for classifying types of accelerated tests and a statistical framework for reconciling conflicting objectives and optimizing the use of testing resources.

Many systems are subject to requirements for extremely high reliability over long periods of operation or storage—the nuclear stockpile is a prime example. In addition, systems and components often need to be developed within a time frame that is much shorter than their required reliable operating lives. These requirements present a challenge to traditional reliability engineering, in which items are tested to failure under expected operating conditions in order to predict the reliable lifetime of a deployed system. When lifetimes are measured in years or decades, this approach is no longer feasible.

Reliability can be defined as "the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time" [1]. Formally, if $F(t)$ is the probability of failure at or before time t, the reliability function $R(t) = 1-F(t)$ gives the probability that the item will still be functional at time t. Derived quantities include the probability density of failure, $f(t) = dF(t)/dt$, and the hazard rate, $h(t) = f(t)/R(t)$. The hazard rate gives the failure rate at time t, given survival up to t—knowing whether $h(t)$ is increasing, decreasing, or constant is helpful in predicting an item's useful life.

Fig. 1. "Bathtub curve" of lifetime hazard rate.



A standard engineering rule of thumb is that the hazard rate for a complex system follows a "bathtub curve," as shown in Fig. 1. Early in the life of a system it may exhibit a high failure rate due to production defects or design flaws. It is expected that these problems will be corrected, leading to a period where the failure rate is constant (and low). Near the end of its useful life, the failure rate is increasing due to "wearout," which might be wearing out of mechanical components, or some physical or chemical degradation process.

Reliability engineering has several goals, which can be characterized in terms of the bathtub curve. Ideally, the early part of the curve would occur before deployment of the system–this involves a planned process of reliability growth [2], illustrated in Fig. 2, where progress is measured by testing against a series of "learning curves" [3] as defects are identified and corrected, with major problems deferred to separate corrective action phases. This process requires predictive models for reliability growth and testing methods that rapidly identify defects—both of these areas are part of our ongoing research.

Testing during development should verify that the system can be deployed with an acceptably low failure rate. Assuming this can be done, an additional important requirement is to understand aging characteristics in order to predict the onset of wearout or degradation failures, either in operation or when the system is stored in a ready state. Figure 3 plots data from a degradation test, where metal alloy components are prepared with a small notch, then subjected to repeated flexing until fatigue cracks form and lengthen. The inset plot at the top is the estimated probability density of time (flex cycles) to reach a critical length where failure is imminent. This density can be used to predict the service life of the component before it must be replaced [4].

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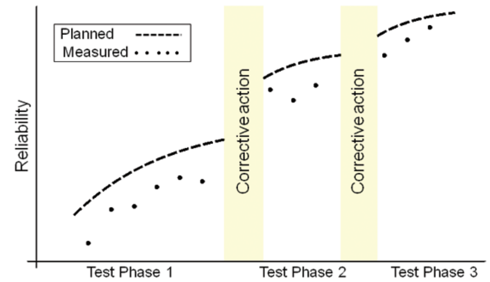
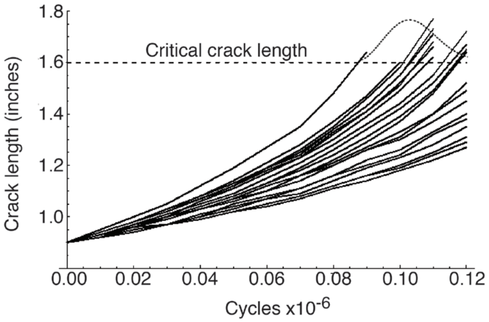


Fig. 2. Reliability growth over a product development cycle.

For highly reliable components and systems, testing of the sort just described cannot be completed within an acceptable time frame if it is performed under normal service conditions—collecting a sizable number of failures or sample degradation paths might take years. Approaches to avoiding this problem are accelerated life testing (ALT) and accelerated degradation testing (ADT), where items are tested under stress conditions of temperature, mechanical loading, vibration, power cycling, etc., that are outside the normal operating range, in order to produce degradation or failure in a shorter time [5]. ALT may include progression through a range of stresses, or application of multiple stressors simultaneously. At LANL, ALT/ADT has been applied to materials ranging from organic polymers [6] to plutonium [7] in order to predict how the aging of these materials will affect the components in which they are used.

The intent of ALT/ADT is to accelerate the production of failures or degradation that could occur in normal usage, so the range of stressors must not initiate novel failure modes–for example, a temperature high enough to melt solder on an electronic circuit board. In addition, for accelerated tests to have predictive value, the experimenter must be able to model how stress reduces the life of the item. As a typical example, the exponential distribution is often used to predict the life of electronic components: $R(t) = \exp(-\lambda t)$, where λ is the mean failure rate. The Arrhenius model for temperature dependence of reaction rates is used to predict changes in reliability when temperature is increased, by setting $\lambda = \lambda(\tau) = \alpha\exp(-\beta/\tau)$, where α and β are experimentally determined. Other models, such as the Eyring, can be used to account for the effect of multiple stressors.

Fig. 3. Sample paths for fatigue crack growth.



Highly accelerated life testing (HALT), which uses combinations of stressors at progressively higher levels, while superficially similar to ALT, is aimed only at finding and correcting design faults during product development [8]. As practiced, it does not yield predictive statistical models [9]. Highly accelerated stress screening (HASS) is a related method applied to the elimination of defective items from a production process.

Our research suggests that although ALT and HALT testing involve similar experimental setups, and could in principle provide similar data, they are performed by different organizational units for different purposes. HALT has been shown to be effective for accelerating reliability growth, but contractual requirements for a demonstrated level of reliability may mandate statistically oriented methods such as ALT. This creates an organizational conflict and may result in suboptimal allocation of limited testing budgets.

We believe there are synergies waiting to be exploited between the various accelerated methods and are currently classifying types of accelerated tests and cataloging experimental design and analysis techniques. Based on these efforts, we hope to develop experimental protocols that provide results usable both by product engineers who are testing in order to find bugs in the design and by statisticians collecting data for lifetime prediction. In addition, we hope to develop robust models for accelerating factors that reduce the effort required to analyze ALT and HALT results. This effort will benefit the current B61 life extension program (LEP) as well as future LEPs and other long-term aging studies.

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