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A Review of Common Acceleration Models in Accelerated Life Testing

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Abstract: The core of accelerated life testing (ALT) is the development of acceleration models. These models can be classified into three types based on their underlying methodologies: physics-based, empirical inductive, and statistical inference models. This paper primarily examines the acceleration models that are commonly applied in engineering practice and presents the relevant computational formulas to highlight the fundamental research methodologies of ALT. Additionally, the paper underscores that ALT is increasingly recognized as a vital and emerging trend, driven by its role in shortening design cycles, enhancing product reliability, and managing costs.

Keywords: Accelerated life testing, acceleration mode, reliability, accelerated lifetime.

1. Introduction

Advances in technology have significantly extended product lifespans and greatly enhanced reliability. However, for reliability engineering professionals, acquiring accurate lifespan data for products under normal operating stress conditions has become increasingly difficult, making it challenging to accurately assess product lifespan and reliability. To address this, Accelerated Life Testing (ALT) was developed[1,2]. ALT seeks to obtain more comprehensive product information within a shorter test period by applying elevated stress levels, without altering the product's failure mechanism under normal conditions. The fundamental assumption underlying these techniques is that the applied stress does not change the failure mechanism of the product[3-5]. ALT is a testing methodology that, based on sound engineering and statistical assumptions, employs statistical models linked to physical failure mechanisms to translate life data obtained under accelerated stress conditions—where stress levels exceed normal operating conditions—into reliable estimates of a product’s lifespan under nominal stress. ALT is typically classified into three categories: constant stress tests, step-stress tests, and progressive stress tests, depending on how the stress is applied[6-8]. Extensive research on ALT has been conducted by scholars worldwide[9-19], encompassing areas such as ALT types, model development, optimal design, and data analysis. ALT has broad applications in key fields such as the military, aviation, aerospace, machinery, and electronics. By applying accelerated stress during testing, ALT not only shortens test time and enhances efficiency but also reduces testing costs, making the reliable evaluation of high-reliability, long-life products feasible. Once the mathematical relationship between product lifespan and stress is determined—through the development of an acceleration model—the data obtained from ALT can be effectively extrapolated to predict product reliability under normal usage conditions. Therefore, the development of acceleration models has become the central focus of ALT research.

2. Development of Acceleration Models

Acceleration models are typically categorized into three main types based on their methodological foundations: physical acceleration models, empirical acceleration models, and statistical acceleration models.Physical acceleration models are built on a deep understanding of the physicochemical mechanisms that govern product failure. A prime example is the Arrhenius model[9], which describes the relationship between product lifespan and temperature stress. Similarly, the Eyring model [9], grounded in quantum mechanics, explains the relationship between product lifespan and temperature stress. Glasstone and colleagues extended the Eyring model to account for the complex relationship between product lifespan, temperature stress, and voltage stress[9].Empirical acceleration models are derived from engineers’ long-term observations and analyses of product performance. Common examples include the inverse power law model and the Coffin-Manson model. The inverse power law model investigates the relationship between voltage or pressure stress and product lifespan[9], while the Coffin-Manson model examines the effects of thermal cycling stress on product lifespan[20]. However, Fallou’s exponential model, introduced in 1979[21], which describes the combined influence of temperature and electrical stress on product lifespan, has limitations, as it fails to account for electrical stress limits. To address these limitations, Simoni proposed a more comprehensive compound stress-life model that includes both electrical and thermal stress limits[22]. Furthermore, Montanari introduced an inverse power law limit model based on probabilistic statistical theory[23], while Peck developed the generalized Eyring-Peck model, which describes the joint effects of temperature and humidity on product lifespan in high-stress accelerated testing of components[24]. Notably, although Silverman applied temperature and vibration as acceleration factors in the reliability screening of printed circuit boards, he did not construct a corresponding acceleration stress model[25]. In contrast, Srinivas and Ramu used the Paris fracture fatigue law to model fatigue damage caused by mechanical stress and developed an acceleration model that considers the combined effects of thermal, mechanical, and electrical stress, based on fracture mechanics fatigue life theory [26]. Statistical acceleration models, which rely on statistical analysis techniques, are often used to handle data that cannot be explained through physicochemical methods. These models are further divided into parametric and non-parametric models. Parametric models have a fixed number of parameters with predefined characteristics, while non-parametric models are more flexible, as they do not require prior parameter specification. Parametric models assume a predetermined product lifetime distribution, whereas non-parametric models do not, making the latter more attractive to researchers. However, non-parametric models are less commonly applied in engineering contexts. This paper focuses on physical and empirical acceleration models, leaving non-parametric acceleration models outside the scope of discussion.

3. Accelerated Life Testing Methods

Accelerated Life Testing (ALT) shortens the testing duration by increasing the stress levels applied to the product, serving as a foundation for the reliability evaluation of high-reliability, long-lifespan products. Among the various ALT methods, the following three are the most commonly employed:

(1) Constant Stress Accelerated Life Testing (Constant Stress Testing): In this method, a set of predetermined stress levels $S_1, S_2, \cdots, S_k$,and applied to different groups of samples $S_0 < S_1 < S_2 < \cdots < S_k$. Each group undergoes life testing at a specific stress level until a defined number of failures is observed. As shown in Figure 1.

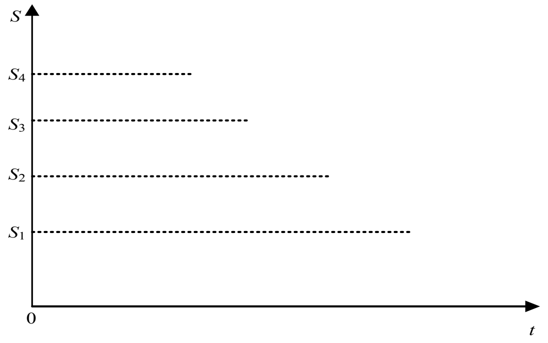

Figure 1. Constant Stress Accelerated Life Testing

The key advantages of constant stress testing are as follows:1)Modeling Stress-Lifetime Relationships: This method facilitates the development of models that link product lifespan to stress levels, enabling the identification of critical stress factors or combinations that significantly impact lifespan. These models provide a reliable estimate of the product's lifetime distribution.2)High Precision in Statistical Analysis: Constant stress testing benefits from a well-established theoretical framework, allowing for the highest precision in statistical analysis.3)Extensive Validation in Engineering Practice: This method has been widely validated in real-world applications, making it highly reliable and practical for engineering use.

However, constant stress testing has some notable limitations:1)Reduced Acceleration Efficiency: To minimize uncertainties in lifespan extrapolation, the lowest stress level is often set close to the normal operating conditions, leading to relatively long failure times and reduced acceleration efficiency.2)Requirement for Preliminary Testing: When prior knowledge about the product is limited, exploratory testing may be necessary to identify the maximum stress level while ensuring consistency in failure mechanisms. This can add complexity and cost to the testing process.

(2) Step-Stress Accelerated Life Testing (commonly referred to as Step-Stress Testing): This method involves selecting a set of accelerated stress levels $S_1 < S_2 < \cdots < S_k$, all of which exceed the normal stress level S_0 . The test begins by placing a specific number of samples under the initial stress level for life testing. After a predetermined period, the stress level is increased to the next level to continue the testing process. This sequence is repeated by raising the stress level until a predetermined number of failures occur.As shown in Figure 2.

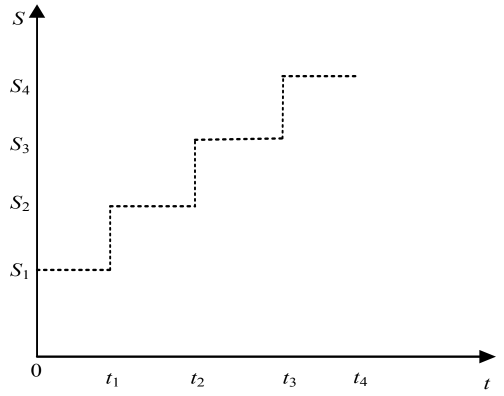

Figure 2. Step-Stress Accelerated Life Testing

(3) Decreasing Step-Stress Accelerated Life Testing. This approach is based on the concept of reliability growth testing with time-to-censoring. The test commences at the highest stress level, and at specified intervals, the test stress is reduced by one level. The data collected from this testing can be used to extrapolate lifetime or reliability at lower stress levels, analogous to extrapolating reliability from growth test results over subsequent testing periods.As shown in Figure 3.

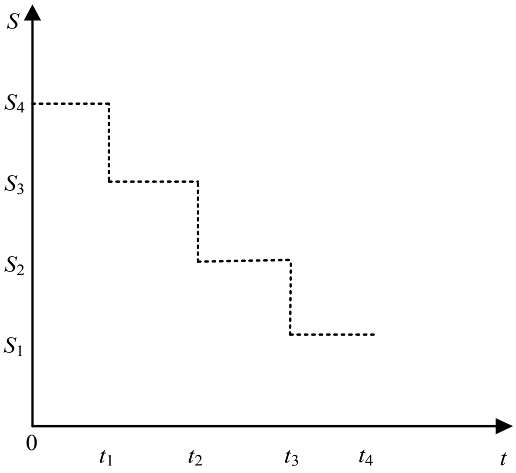

Figure 3. Decreasing Step-Stress Accelerated Life Testing

Step-Stress/Decreasing Step-Stress Testing offers several notable advantages. First, it delineates the range of stress levels experienced by the specimen while preserving consistency in the failure mechanism. Second, it facilitates qualitative comparative analysis for reliability levels. Additionally, when addressing high reliability and long lifespan assessment issues, step-stress testing exhibits greater acceleration efficiency compared to constant stress testing, while significantly reducing the required sample size, thereby lowering testing costs substantially.

However, Step-Stress/Decreasing Step-Stress Testing also has several limitations. On one hand, from an engineering perspective, implementing step-stress testing is more complex than constant stress testing, as sample failures often result from the combined effects of multiple accelerated stress levels. Consequently, accurately extracting lifetime information for products at each stress level from such complex failure data presents a core challenge for statistical analysis in step-stress testing. On the other hand, the statistical analysis methods for step-stress testing are not yet fully developed, and the complexity of its statistical algorithms undoubtedly increases the difficulty of data processing.

4. Commonly Used Acceleration Models

The core principle of accelerated life testing involves leveraging the lifetime characteristics observed at elevated stress levels to extrapolate the lifetime characteristics at normal stress levels. The essential aspect of this principle is the establishment of a relationship between lifetime characteristics and stress levels, referred to as the acceleration model. The commonly used acceleration models are outlined below, as illustrated in Figure 4.

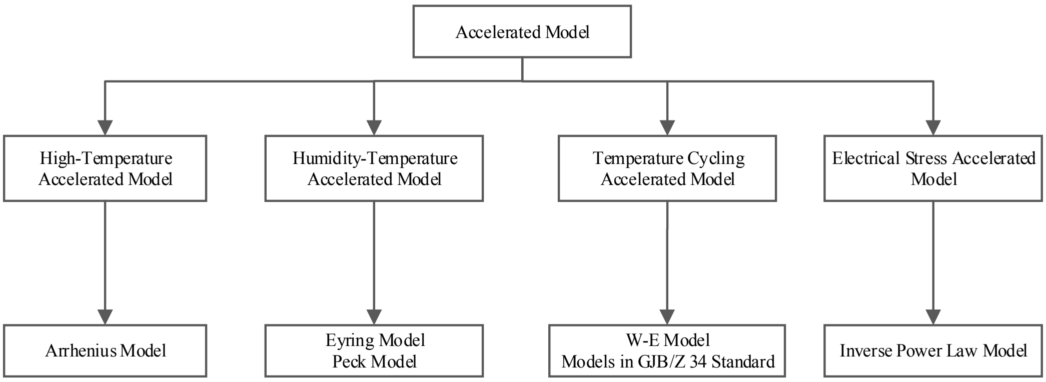

Figure 4. Overview of Acceleration Models.

4.1. High-Temperature Acceleration Model

The high-temperature acceleration model is predominantly represented by the Arrhenius model. In accelerated life testing, it is common to use temperature as an acceleration stress because elevated temperatures can enhance chemical reactions within products, such as electronic components and insulation materials, thereby leading to premature failure. The model and its acceleration factor are expressed as follows:

$$\xi = A\exp^{E/KT} \tag{1}$$

$$AF = \exp(\frac{E_a}{k}(\frac{1}{T_{noraml}} - \frac{1}{T_{stress}})) \tag{2}$$

In the equation, ξ represents a specific lifetime characteristic, such as median lifetime or mean lifetime. The constant A satisfies $A > 0$. The activation energy, denoted as E_a, is material-dependent and measured in electron volts (ev). The Boltzmann constant, K, is equal to $8.617\times10^{-5} ev/K$. The variable T represents the absolute temperature, T_{normal} indicates the absolute temperature at room temperature, and T_{stress} signifies the absolute temperature at elevated conditions.

The Arrhenius model posits that lifetime characteristics decrease exponentially with rising temperature. By taking the logarithm of both sides, we derive the following equation:

$$\ln\xi = a + b/T \tag{3}$$

where $a = \ln A, b = E/K$ are unknown parameters. This model illustrates that the logarithm of the lifetime characteristic is a linear function of the inverse of the temperature.

4.2. Humidity-Temperature Acceleration Models

4.2.1. Peck Model

The Peck model is expressed as follows:

$$u_l = Ae^{-E_a/KT_L} \cdot RH^{-n} \tag{4}$$

In this equation, μ_l represents the degradation rate under temperature stress T(in Kelvin) and relative humidity stress RH%; A is the frequency factor; E_a is the activation energy, measured in electron volts (eV), with an empirical value ranging from 0.6 to 2.51; K is the Boltzmann constant, equal to $8.617\times10^{-5} eV/K$; and n is the inverse power index.

4.2.2. Eyring Model

The Eyring model is represented as follows:

$$u_l = Ae^{-\frac{E_a}{KT_l}+\frac{B}{RH}} \tag{5}$$

In this equation, A is the frequency factor; E_a is the activation energy, also measured in electron volts (eV), with an empirical range of 0.6 to 2.51; K is the Boltzmann constant, valued at $8.617\times10^{-5}eV/K$; and B is a constant.

The Peck model includes three parameter (E_a, A, n) while the Eyring model comprises three parameters (E_a, A, B) . The parameters for both models can be determined using the least squares method: 1) logarithmically transform the model; 2) adjust the model parameters; 3) calculate the slope and intercept; 4) derive the model parameters.

4.3. Temperature Cycling Acceleration Models

There are two types of temperature cycle models. One type addresses solder joint fatigue, including the M-C model, N-L model, and W-E model, with the W-E model demonstrating the highest accuracy. The other type is the inverse power law model. This section introduces the W-E model, the inverse power law model, and the models outlined in the GJB/Z34 standard.

4.3.1. W-E Model

The W-E model is defined as follows:

$$N_f(50\%)=\frac{1}{2}\left[\frac{2\varepsilon_f'}{\Delta D}\right]^m \tag{6}$$

In this equation, ε_f' represents the fatigue toughness index, which has a value of 0.325 for tin-lead solder; ΔD is the amount of creep fatigue damage; and m is the temperature and time-dependent index.

The calculation for the temperature and time-dependent index is given by:

$$\frac{1}{m}=0.442+6\times10^{-4}T_{sj}-1.74\times10^{-2}\ln\left(1+\frac{360}{t_D}\right) \tag{7}$$

In this equation, T_{sj} represents the average temperature for each cycle, while t_D denotes the dwell time at high and low temperatures during the temperature cycle. Some parameters of this model, such as ΔD and ε_f' , are not readily obtainable.

4.3.2. Models in the GJB/Z 34 Standard

The GJB/Z 34 standard provides a temperature cycle acceleration model, expressed as follows:

$$AF=\left(\frac{R_a+0.6}{R_u+0.6}\right)^{0.6}\left(\frac{\ln(e+v_a)}{\ln(e+v_u)}\right)^3 \tag{8}$$

In this equation, R_a is the difference between the accelerated high-temperature value and the normal temperature; R_u is the difference between the normal high-temperature value and the normal temperature; v_a is the rate of temperature change during the accelerated temperature cycle; and v_u is the rate of temperature change during conventional temperature cycling.

A drawback of this model is that the parameters are fixed and tend to be conservative. While the model is user-friendly and can be directly applied, it is crucial to recognize that discrepancies may exist between its accelerated effects and actual conditions.

4.4. Electric Stress Acceleration Model

The electric stress acceleration model is represented by the inverse power law model. In accelerated life testing, when electric stress (such as voltage, current, power, etc.) serves as the acceleration stress, certain lifetime characteristics of the product exhibit relationships that conform to the inverse power law model, expressed as follows:

$$\xi = Av^{-c} \tag{9}$$

In this equation, ξ denotes a specific lifetime characteristic, such as median lifetime or mean lifetime; A is a constant with $A>0$; c is a normal constant related to activation energy; and v is the electric stress. The inverse power law model indicates that the lifetime characteristic is a negative power function of the stress vvv. Taking the logarithm of both sides of this model yields:

$$\ln\xi = a+b\ln v \tag{10}$$

where $a=InA, b=-c$ are unknown.

The linearized forms of the Arrhenius model and the inverse power law model can be uniformly expressed as follows:

$$\ln\xi = a+b\varphi(s) \tag{11}$$

In this equation, ξ represents a certain lifetime characteristic, and $\varphi(s)$ is a known function of the stress level s .

5. Analysis of the Current Status and Future Prospects

This paper analyzes the current state of research in accelerated life testing, emphasizing the acceleration models employed internationally. The review focuses on classical acceleration models that have gained widespread adoption and are representative of the field.The analysis indicates that the development of any acceleration model relies on specific assumptions. When these assumptions hold, the models typically produce accurate assessments. However, deviations from these assumptions can result in significant discrepancies in the outcomes. Consequently, future research will aim to enhance existing models and propose innovative acceleration models to broaden their applicability.

While these improved acceleration models provide wider applicability, they also introduce additional parameters, which increase the complexity of model structures and pose computational challenges. Therefore, the use of computer-aided calculation methods will be essential to ensure accurate assessments of model parameters.Moreover, research in accelerated life testing primarily addresses two core issues: optimal design prior to testing and statistical analysis after testing. Key considerations in optimal design include: 1) determining appropriate levels of acceleration stress; 2) allocating sample proportions across groups and establishing truncation methods in constant stress testing; 3) developing strategies for step stress testing; and 4) defining termination criteria for step and sequential stress tests. The primary objective of statistical analysis is to process product lifespan data under accelerated stress conditions, estimate unknown parameters within acceleration models, and derive performance and reliability metrics for products under normal conditions. Research will mainly focus on the application of statistical analysis methods in constructing acceleration models and conducting extrapolation predictions based on established models.

This comprehensive analysis highlights the significance of ongoing research in accelerated life testing and lays the groundwork for future innovations in this field.

6. Conflicts of Interest

The authors declare that they have no conflict of interest.

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