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Conventional Electronic System Reliability Prediction

The history of reliability engineering goes back to 1950s when electronics played a major role for the first time. At that time, there was great concern within the US military establishment for the reliability and maintainability of the current electronic systems. Many meetings and ad hoc groups were created to cope with the problems. Developing better parts, finding quantitative reliability for parts, and collecting field data on actual part failures to determine the root cause of problems were three major fields of research in those days.

When the complexity of electronic equipment began to increase significantly, and new demands were placed on system reliability, a permanent committee (AGREE) was established to identify the actions that could be taken to provide more reliable electronic equipment (1952). The reliability era began when the first Radio Corporation of America (RCA) report on reliability of electronic parts was released in 1956, the first time when reliability was defined as a probability. On the other hand, one of the first reliability handbooks titled Reliability Factors for Ground Electronic Equipment was published in 1956 by McGraw-Hill under the sponsorship of the Rome Air Development Center (RADC); while the McGraw-Hill handbook gave information on design considerations, human engineering, interference reduction, and a section on reliability mathematics, failure prediction was only mentioned as a topic under development.

Reliability prediction and assessment are traced to November 1956 with publication of the RCA release TR-1100, titled "Reliability Stress Analysis for Electronic Equipment," which presented models for computing rates of component failures. It was the first time that the concepts of activation energy and the Arrhenius relationship were used in modeling component failure rates. However, in 1960s, the first version of a military handbook for the reliability prediction of electronic equipment (MIL-HDBK-217) was published by the US Navy [1]. It covered a broad range of part types, and since then, it has been widely used for military and commercial electronics systems.

Reliability Prediction for Microelectronics, First Edition. Joseph B. Bernstein, Alain A. Bensoussan, and Emmanuel Bender.

In July 1973, RCA proposed a new prediction model for microcircuits, based on previous work by the Boeing Aircraft Company. In the early 1970s, RADC further updated the military handbook and revision B was published in 1974. The advent of more complex microelectronic devices pushed the application of MIL-HDBK-2 17B beyond reason. This decade is known for development of new innovative models for reliability predictions. Then, RCA developed the physics-of-failure model, which was initially rejected because of the lack of availability of essential data.

To keep pace with the accelerating and ever-changing technology base, MIL-HDBK-217C was updated to MIL-HDBK-217D on January 15, 1982 and to MIL-HDBK-217E on October 27, 1986. In December 1991, MIL-HDBK-217F became a prescribed US military reliability prediction document. Two teams were responsible for providing guidelines for the last update. Both teams suggested:

1) that the constant failure rate (CFR) model could not be used;
2) that some of the individual wear-out failure mechanisms (like electromigration and time-dependent dielectric breakdown) could be modeled with a lognormal distribution;
3) that the Arrhenius-type formulation of the failure rate in terms of temperature should not be included in the package failure model; and
4) that stresses such as temperature change and humidity should be considered.

Both groups noticed that temperature cycling is more detrimental to component reliability than the steady state temperature at which the device is operating, so long as the temperature is below a critical value. This conclusion has been further supported by a National Institute of Standards and Technology (NIST), and an Army Fort Monmouth study which stated that the influence of steady-state temperature on microelectronic reliability under typical operating changes is inappropriately modeled by an Arrhenius relationship [2–4]. However, considering the ability to separate failure mechanisms by separate Arrhenius activation energies, it may be possible to return to the physics of failure (PoF) assumption that each mechanism will have a unique activation energy.

1.1 Electronic Reliability Prediction Methods

There are several different approaches to the reliability prediction of electronic systems and equipment. Each approach has unique advantages and disadvantages; several papers have been published on the comparison of reliability assessment approaches. However, there are two distinguishable approaches to reliability prediction, traditional/empirical, and PoF approach.

Traditional, empirical models are those that have been developed from historical reliability databases either from fielded applications or from laboratory tests [5].

Handbook prediction methods are appropriate only for predicting the reliability of electronic and electrical components and systems that exhibit CFRs. All handbook prediction methods contain one or more of the following types of prediction:

- Tables of operating and/or non-operating CFR values arranged by part type,
- Multiplicative factors for different environmental parameters to calculate the operating or non-operating CFR, and
- Multiplicative factors that are applied to a base operating CFR to obtain non-operating CFR [6].

MIL-HDBK-217 reliability prediction methodology which was developed under the activity of the RADC (now Rome Laboratory) and its last version released in February 1995 intended to "establish and maintain consistent and uniform methods for estimating the inherent reliability (i.e. the reliability of a mature design) of military electronic equipment and systems. The methodology provided a common basis for reliability predictions during acquisition programs for military electronic systems and equipment. It also established a common basis for comparing and evaluating reliability predictions or related competitive designs. The handbook was intended to be used as a tool to increase the reliability of the equipment being designed."

In 2001, the office of the US Secretary of Defense stated that ".... the Defense Standards Improvement Council (DSIC) decided several years ago to let MIL-HDBK-217 'die the death.' This is still the current OSD position, i.e. we will not support any updates/revisions to MIL-HDBK-217" [6].

Two basic methods for performing the prediction based on the data observation include the parts count and the parts stress analysis. The parts count reliability prediction method is used for the early design phases when not enough data is available, but the numbers of component parts are known. The information for parts count method includes generic part types (complexity for microelectronics), part quantity, part quality levels (when known or can be assumed), and environmental factors. Since equipment consists of the parts operating in more than one environment, the "parts count" equation is applied to each portion of the equipment in a distinct environment. The overall equipment failure rate is obtained by summing the failure rate for each component over its expected operating condition.

A part stress model is based on the effect of mechanical, electrical and environmental stress and duty cycles such as temperature, humidity, and vibration on the part failure rate. The part failure rate varies with applied stress and the

strength–stress interaction determines the part failure rate. This method is used when most of the design is complete, and the detailed part stress is available. It is applicable during later design phases as well. Since more information is available at this stage, the result is more accurate than the parts count method.

The environmental factor gives the influence of environmental stress on the device. Different prediction methods have their own list of environmental factors suitable for their device conditions. For instance, the environmental factor of MIL-HDBK-217F covers almost all the environmental stresses suitable for military electronic devices except for ionizing radiation. The learning factor shows the maturity of the device; it suggests that the first productions are less reliable than the next generations [7, 8]. The parts stress model is applied at component level to obtain part failure rate (λ_p) estimation with stress analysis. A typical part failure rate can be estimated as:

$$\lambda_p = \lambda_b \cdot \pi_Q \cdot \pi_E \cdot \pi_A \cdot \pi_T \cdot \pi_V \tag{1.1}$$

where λ_b is the base failure rate obtained from statistical analysis of empirical data, the adjustment factors include: π_T (temperature factor), π_A (application factor), π_V (voltage stress factor), π_Q (quality factor), and π_E (environmental factor). The equipment failure rate (λ_{EQUIP}) can be further predicted through parts count method:

$$\lambda_{EQUIP} = \sum_{i=1}^{n} N_i \left(\lambda_g \cdot \pi_Q\right)_i \tag{1.2}$$

where λ_g is the generic failure rate for the ith generic part, π_Q is the quality factor of the ith generic part, N_i is the quantity of ith generic part and n is the number of different generic part categories in the equipment. To accommodate the advancement of technology, a reliability growth model was introduced in the handbook approach to reflect the state-of-the-art technology.

$$\lambda_p \propto exp[G_r(t_2 - t_1)] \tag{1.3}$$

where G_r is the growth rate, t_1 is the year of manufacture for which a failure rate is estimated, t_2 is the year of manufacture of parts on which the data were collected. It takes time to collect field data and obtain the growth rate G_r especially when the growth is fast. Furthermore, the validity of applying a reliability growth model without taking technology generation into consideration is not confirmed. It is said that the predictions based on the handbook approach usually lead to conservative failure rate estimation. However, the data is very vague as to the actual validity of the calculated failure rate and no correlation with reality has ever been shown.

Telcordia SR-332, BT-HRD-5, NTT, CNET, RDF 93 and 2000, SAE, Siemens SN29500, prediction of reliability, integrity and survivability of microsystems (PRISM) [9] and FIDES are all the instances of traditional prediction models which provide their own sources of data environment from ground military, civil equipment, automotive, Siemens products, Telecom, commercial-military and aeronautical and military, respectively. Most of these models have gained popularity over time because of their ease of use and uniqueness [10].

The stated purpose of Telcordia SR-332 is "to document the recommended methods for predicting device and unit hardware reliability and for predicting serial system hardware reliability." The methodology is based on empirical statistical modeling of commercial telecommunication systems whose physical design, manufacture, installation, and reliability assurance practices meet the appropriate Telcordia (or equivalent) generic and system-specific requirements. In general, Telcordia SR-332 adapts the equations in MIL-HDBK-217 to represent what telecommunications equipment experience in the field. Results are provided as a CFR, and the handbook provides the upper 90% confidence-level point estimate for the CFR [6].

The basis of the Telcordia math models for devices is the Black Box Technique. This parts count method defines a black box steady-state failure rate for different device types and parts count steady-state failure rate for units; the system-level failure rate is simply the sum of all failure rates of the units contained in a system.

The main concepts in MIL-HDBK-217 and Telcordia SR-332 are similar, but Telcordia SR-332 also can incorporate burn-in, field, and laboratory test data, using a Bayesian analysis [7]. All these methods, in the end, continue to rely on the "π" model for adjusting a base failure rate, making mathematical justification quite illusive.

PRISM was developed in the 1990s by the Reliability Analysis Center (RAC) under contract with the US Air Force. The latest version of the method, which is available as software, was released in July 2001. RAC Rates is the name of PRISM mathematical model for component failure rates; the component models are based on filed data driven from several sources. PRISM applies Bayesian methods to the empirical data to get the system-level predictions. This methodology considers the failures of components as well as those related to the system. However, the component models are the heart of the analysis. It provides different models for capacitors, diodes, integrated circuits, resistors, thyristors, transistors, and software. The total component failure rate is composed of:

1) operating conditions,
2) non-operating conditions,
3) temperature cycling,
4) solder joint,
5) electrical overstress (EOS).

Each mechanism is treated independently.

For components not having RAC Rates models, PRISM provides Non-electronic Parts Reliability and Electronic Parts Reliability Data books. A multitude of part types can be found in these data books with failure rates for various environments.

Unlike the other handbook based on the CFR models, the RAC Rate models do not have a separate factor for part quality level. Quality level is implicitly accounted for by a method known as process grading. Process grades address factors such as design, manufacturing, part procurement, and system management, which are intended to capture the extent to which measures have been taken to minimize the occurrence of system failures [6-8, 11].

RDF 2000, released in July 2000, is a French Telecom standard that was developed by the Union Technique de l'Electricite (UTE). It is the last version of CNET reliability prediction methodology developed by the Centre National d'Etudes des Telecommunications (CNET). "RDF 2000 provides a unique approach to failure rate predictions in that it does not provide a parts count prediction. Rather component failure is defined in terms of an empirical expression containing a base failure rate multiplied by factors influenced by mission profiles." These mission profiles contain information about operational cycling and thermal variations during various working phases [7].

FIDES prediction method attempts to predict the CFR experienced in the useful life portion of the classic bathtub curve. The approach models intrinsic failures such as item technology and distribution quality. It also considers extrinsic failures resulting from equipment specification, design, production, and integration, as well as selection of the procurement route. The methodology considers failures resulting from development and manufacturing, and the overstresses linked to the application such as electrical, mechanical, and thermal.

Some proponents claim that FIDES predictions are "close" to the observed failure rate; its predictions are somewhere in between PRISM predictions that are more optimistic and those of MIL-HDBK-217 which are more conservative [11, 12]. RAC PRISM and FIDES are two methodologies which take place in two stages; the key element is applying the Bayesian statistical techniques to the initial reliability prediction.

Due to the wide range of available traditional reliability predictions, several articles have been published to study and compare the prediction models and methodologies. As an instance of these efforts, IEEE Std 1413-1998 was developed to identify the key required elements for an understandable and credible reliability prediction and to provide its users with sufficient information to evaluate prediction methodologies and to effectively use their results.

A comparison of some of the more popular electronic reliability prediction tools is shown in Table 1.1 [10, 13–16].

Table 1.1 Electronic reliability prediction tool comparator.

Attribute	Electronic prediction tool				
Methodology	**MIL-HDBK-217**	**IEC-TR-62380**	**TELCORDIA**	**PRISM**	**FIDES**
Version/date/ source	F, Notice 2, February 1995	Edition 1 August 2004	SR-332, Issue 1, May 2001	1.5 July, 2003	Issue A October, 2021
Distribution method	Handbook	Handbook	Handbook	Software	Handbook
Updates anticipated	No	Yes	Yes	Yes	Yes
Metric used	Failures per 10^6 operating hours	Failures per 10^6 operating hours	Failures per 10^9 operating hours	Failures per 10^6 calendar hours	Failures per 10^9 calendar hours
Software available	Yes	Yes	Yes	Yes	Yes
Environmental predefined choices	14	12	Limited to 5	37	7
Additional environmental modifiers	None	None	None	Operating temperature, dormant temperature, amplitude and frequency of thermal cycles, relative humidity, vibrational level	Operating temperature, amplitude and frequency of thermal cycles, relative humidity, vibrational level, ambient pollution level, overstress exposure
Part model type	Multiplicative	Multiplicative	Multiplicative	Additive	Additive
Operating profile	No	Yes	No	Yes	Yes

(*Continued*)

Table 1.1 (Continued)

Attribute	Electronic prediction tool				
Methodology	**MIL-HDBK-217**	**IEC-TR-62380**	**TELCORDIA**	**PRISM**	**FIDES**
Thermal cycling	No	Yes	No	Yes	Yes
Thermal rise in part	Yes	Yes	No	Yes	Yes
Solder joints failures	No	Yes	No	Yes	Yes
Induced failures	No	No	No	Yes	Yes
Failure rate data base for other parts	Limited	Limited	No	Yes	Yes
Infant mortality	No	No	Yes	Yes	No
Dormant failure rate	No	No	No	Yes	Yes
Test data integration	No	No	Yes	Yes	No
Bayesian analysis	No	No	No	Yes	No

Source: Reproduced with permission from [16]/Quanterion Solutions Incorporated.

The most controversial aspects of traditional approaches could be classified as the concept of CFR, the use of Arrhenius relation, the difficulty in maintaining support data, problems of collecting good-quality field data, and the diversity of failure rates with the source data are other limitations of traditional approaches [4].

Despite the disadvantages and limitations of traditional-/empirical-based handbooks, they are still used by engineers; strong factors such as good performance centered around field reliability ease of use as well as and providing approximate field failure rates make them still popular. Crane survey shows that almost 80% of the respondents use Mil handbook, while PRISM and Telcordia have second and third places in the chart [17].

The first publications on reliability predictions for electronic equipment were all based on curve fitting a mathematical model to historical field failure data to determine the CFR of parts. None of them could include a root-cause analysis of the traditional/empirical approach. The PoF approach received a big boost when the US Army Material Command authorized a program to institute a transition from reliance exclusively on MIL-HDBL-217. The command's Army Material System Analysis Activity (Amsaa), Communications-Electronic Command (Cecom), the Laboratory Command (Lab-com) and the University of Maryland's Computer-Aided Life-Cycle Engineering (CALCE) group collaborate on developing a physics-of-failure handbook for reliability assurance. The methodology behind the handbook was assessing system reliability based on environmental and operating stresses, the material used, and the packaging selected. Two simulation tools called Computer-Aided Design of Microelectronic Packages (CADMP-2) and CALCE were developed to help with the assessment; CADMP-2 assesses the reliability of electronics at the package level while CALCE assesses the reliability of electronics at the printed wiring board level. Together, these two models provide a framework to support a physics-of-failure approach to reliability in electronic systems design.

PoF uses the knowledge of root-cause failure to design and do the reliability assessment, testing, screening, and stress margins to prevent product failures. The main task of PoF approach is to identify potential failure mechanisms, failure sites, and failure modes, the appropriate failure models, and their input parameters, determine the variability for each design parameter, and compute the effective reliability function. In summary, the objective of any physics-of-failure analysis is to determine or predict when a specific end-of-life failure mechanism will occur for an individual component in a specific application. A physics-of-failure prediction looks at each individual failure mechanism such as electromigration, solder joint cracking, die bond adhesion, etc., to

estimate the probability of component wear-out within the useful life of the product. This analysis requires detailed knowledge of all material characteristics, geometries, and environmental conditions. The subject is constantly challenging, considering that new failure mechanisms are discovered and even the old ones are not completely explained. One of the most important advantages of the physics-of-failure approach is the accurate predictions of wear-out mechanisms and their cumulative effect on the time to fail. Moreover, since the acceleration test is one of the main aspects of finding the model parameters, it could also provide the necessary test criteria for the product. To sum up, modeling potential failure mechanisms, predicting the end-of-life, and using generic failure models effective for new materials and structures are the achievements of this approach [4].

The disadvantages of PoF approaches are related to their cost, complexity of combining the knowledge of materials, process, and failure mechanisms together, the difficulty of estimating the field reliability, and their inapplicability to the devices already in production as the result of its incapability of assessing the whole system [4, 18, 19]. The method needs access to the product materials, process, and data. Partly inspired and completed from Cushing et al. [15], Table 1.2 compares MIL-HDBK-217, FIDES approach and PoF.

Nowadays circuit designers have reliability simulations as an integral part of the design tools, like Cadence Ultrasim and Mentor Graphics Eldo. These simulators model the most significant physical failure mechanisms and help the designers meet the lifetime performance requirement. However, there are disadvantages which hinder designers to adopt these tools. First, the tools are not fully integrated into the design software because the full integration requires technical support from both the tool developers and the foundry. Second, they can't handle the large-scale design efficiently. The increasing complexity makes it impossible to exercise full-scale simulation considering the resources that simulation will consume. Chip-level reliability prediction only focuses on the chip's end-of-life, while the known wear-out mechanisms are dominant; however, these prediction tools do not predict the random, post-burn-in failure rate that would be seen in the field [5, 21].

By consideration of all the available reliability prediction tools and methods, they are all based on this original Mil-Handbook approach of assuming a base failure rate, λ_b, and multiplying that by what should be small correction factors, π. We will show in the following chapters that this fundamentally contradicts the presumption of a failure rate, λ, since failure rates add and do not multiply. This brings us to the established and known reliability assumption that linear rate mechanisms add and must be separated into a properly weighted sum-of-rates model.

Table 1.2 Comparison between MIL-HDBK-217 and physics of failure.

Issue	MIL-HDBK-217	FIDES	Physics of failure
Model development	The effectiveness of models in providing accurate design or manufacturing guidance is questionable since they have been developed based on assumed constant failure-rate data rather than root cause or time-to-failure data. As highlighted by Morris [20], the data available is often fragmented, requiring interpolation or extrapolation for the development of new models. Consequently, it is not appropriate to associate statistical confidence intervals with the overall model results.	FIDES and MIL-HDBK are both methodologies used for reliability prediction and analysis, but they have some key differences. FIDES offers advantages over MIL-HDBK in terms of utilizing real-world data, improving root cause analysis, and acknowledging the challenges of data completeness and quality. While statistical confidence intervals may not be directly associated with model results in FIDES, the emphasis on using real-world data helps mitigate some of the limitations observed in MIL-HDBK's model development approach. In addition, FIDES model is presented to be based on field failure data from few aerospace and military companies but is representing a small part of the worldwide original equipment manufacturers. The model assumes that each component has a constant failure rate, which is not relevant, in terms of part types failure.	Physics of Failure (PoF) models based on science and engineering first principles offer an alternative physical approach to reliability prediction and analysis compared to MIL-HDBK and FIDES models. PoF models rely on a deep understanding of the physical mechanisms and failure processes involved in a system, allowing for more accurate predictions and a clearer understanding of the underlying causes of failures. Unlike MIL-HDBK and FIDES, PoF models consider the fundamental physics and engineering principles governing the behavior of materials, components, and systems. This approach enables the modeling of complex interactions between different stress factors, such as temperature, mechanical stresses, humidity, and vibration, leading to a more comprehensive understanding of failure mechanisms. PoF models can support both deterministic and probabilistic applications. Deterministic PoF models focus on understanding and predicting specific failure modes, providing valuable insights into the system's weak

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Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
			points and guiding targeted mitigation strategies. On the other hand, probabilistic PoF models incorporate statistical variations and uncertainties in the inputs to provide a probabilistic assessment of reliability, considering the inherent variability in material properties, manufacturing processes, and operational conditions. By leveraging scientific principles and detailed knowledge of the system's behavior, PoF models can overcome some of the limitations of MIL-HDBK and FIDES approaches. They provide a solid foundation for reliability analysis, enabling engineers to make informed decisions based on the understanding of physical failure mechanisms rather than relying solely on empirical data or statistical models.
Device design modeling	The assumption of perfect designs in MIL-HDBK lacks substantiation as there is a notable absence of root-cause analysis for field failures. Additionally, MIL-HDBK-217 models fail to address wear-out issues adequately. Additionally, they do not adequately model the effects of derating rules, particularly concerning AC or RF	FIDES offers advantages over MIL-HDBK in terms of its emphasis on failure analysis, addressing wear-out issues, incorporating derating rules, and promoting adherence to industry standards. By considering these aspects, FIDES provides a more comprehensive and tailored approach to device design modeling, enhancing	Device Design Modeling involves the development of models that explicitly consider the impact of design, manufacturing, and operation on reliability by focusing on root-cause failure mechanisms. Among these models, thermal models play a crucial role and should be developed with utmost accuracy. It is essential to accurately determine and model

	dynamic stresses and on-off power cycling conditions, where the consideration of such rules is insufficient.	reliability assessments and supporting improved design practices. Even though FIDES offers advantages in device design modeling, there are a few notable drawbacks to consider: 1) Limited Adoption: FIDES may have a narrower adoption compared to other methodologies, which can impact the availability of resources and community support. 2) Data Availability and Quality: The reliance on failure data in FIDES can be challenging if comprehensive and accurate data is not readily available. Incomplete or inaccurate data can affect reliability predictions. 3) Complexity and Learning Curve: Implementing FIDES requires familiarity with the methodology and statistical analysis, leading to a potential learning curve and additional training requirements. 4) Customization for Specific Applications: FIDES may not fully capture the specific requirements and failure mechanisms of every application or industry, requiring additional customization and adaptation efforts.	temperature rises in hot spots, taking into account the true static and dynamic stress conditions experienced by the device. Additionally, it is important to model the biasing conditions, including voltage, current, and power excursions, as close as possible to the active area of the device. These biasing conditions can significantly impact the local variation in temperature, and accurately modeling them is crucial for a comprehensive understanding of the device's thermal behavior. By incorporating both the accurate modeling of temperature variations and biasing conditions, designers can gain a deeper insight into the thermal performance of the device. This enables them to identify potential reliability issues, optimize the design for improved performance, and make informed decisions regarding the selection of materials, architectures, and operational parameters. Such a comprehensive approach to device design modeling enhances the overall reliability and longevity of electronic devices.
Device defect modeling	Device defect modeling faces limitations that hinder its effectiveness in various aspects. Firstly, these models do not explicitly consider the impact of manufacturing variation on reliability.	FIDES approach in Device Defect Modeling has shown promise in assessing effectiveness. It considers manufacturing variation, provides guidelines for defect definition and	Failure mechanism models can be used to: (i) relate manufacturing variation to reliability, (ii) determine what constitutes a defect and how to screen/inspect. This rely on electrical failure modes which can be

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Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
	Secondly, they lack clear guidelines for defining defects and conducting effective screening and inspection processes. Furthermore, the electrical and thermal aspects of design are not accurately modeled, particularly for static and dynamic conditions, which play a crucial role in uncovering infant failure, random defects and wear-out failures.	screening/inspection, and accurately models electrical and thermal aspects. However, areas of improvement include ensuring data completeness and quality, continuous updates and adaptation to evolving technologies, and industry-specific considerations. By addressing these aspects, FIDES can further enhance its effectiveness in Device Defect Modeling, leading to improved reliability and reduced defects in devices. The FIDES methodology does not account for the variability of technical factors such as supplier selection, product performance related to process variability. It only provides a point estimate prediction that is subjectively adjusted for various factors. The process factor of the FIDES methodology is based on audit results and is calculated using an empiric formula subject to change with respect to the maturity of the product. FIDES divides the product development life-cycle into seven phases and assigns a weight to each, termed contribution phase. The user of the methodology can change the distribution of weights. The auditor can also determine whether some questions are irrelevant and omit them.	modeled in term of variation with time as the signature of a seed failure mechanism under activation. PoF is then a concrete tool to identify and survey hidden device defects. Such information can lead to precisely defined screening efficiency method.

		Potential areas for improvement in FIDES Device Defect Modeling include ensuring data completeness and quality, continuous updates and adaptation to evolving technologies, and addressing industry-specific considerations.	
Device screening	MIL-HDBK-217 promotes screening without recognition of potential failure mechanisms highlights potential limitations in its approach, which may lead to inadequate screening practices and compromised reliability assessments.	By considering a wide range of failure modes and mechanisms, FIDES aims to enhance screening methodologies and improve overall reliability predictions. The approach strives to maintain a comprehensive understanding of failure mechanisms, enabling accurate identification and mitigation of potential risks. FIDES also emphasizes the need to keep up with evolving technologies and industry standards to overcome limitations and maintain its effectiveness in promoting robust screening practices for enhanced reliability.	In order to effectively perform screening for device reliability, it is crucial to consider multiple factors and adopt a comprehensive approach. This involves utilizing failure mechanism models that relate manufacturing variation to reliability and provide insights into defect identification and screening. It is essential to accurately model the electrical and thermal stress conditions driving specific failure modes. This entails a thorough understanding of the device's electrical behavior and the variation in temperature. For instance, in the case of hot carrier effects, knowledge of their dependency on low-temperature stress conditions can help define appropriate voltage and current conditions for accelerated aging. Similarly, for scenarios involving RF swing in breakdown conditions or impact ionization, understanding the electrical stress conditions is crucial for accurate simulation and screening. Screening should also consider the impact of temperature fluctuations experienced by the device in real-world operating conditions. Incorporating the actual temperature
Device screening: lack of failure mechanism understanding	MIL-HDBK-217 primarily relies on empirical data and standardized formulas to estimate reliability. However, it does not emphasize the need for a thorough understanding of the underlying failure mechanisms. This omission limits the ability to accurately predict failure modes and develop targeted screening strategies.	FIDES recognizes the importance of understanding failure mechanisms and incorporates this knowledge into its approach. By considering failure mechanisms, FIDES aims to enhance the screening process and improve the overall reliability assessment of devices. This emphasis on failure mechanism understanding allows for a more thorough analysis of potential	

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Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
		failure modes and the implementation of appropriate screening practices. FIDES strives to ensure that failure mechanisms are adequately considered to mitigate risks effectively and improve device reliability.	variations into the screening process allows for more realistic reliability assessments. Moreover, screening efforts should account for the influences of mechanical stresses, humidity, vibration, and other critical stress factors that can significantly affect device reliability.
Device screening: insufficient consideration of stress factors	MIL-HDBK-217's screening recommendations often focus on generic stress factors, such as temperature and voltage, without delving into the specific failure mechanisms that might be affected. This approach overlooks the importance of considering stress factors that are directly relevant to the failure modes in question, resulting in ineffective screening practices.	The FIDES approach acknowledges the significance of precise modeling and understanding of the diverse stress factors that devices may experience throughout their operational lifecycle. By incorporating a comprehensive analysis of stress factors such as electrical, thermal, mechanical, and environmental stresses, FIDES aims to provide a more thorough and accurate assessment of device reliability. This consideration of stress factors enables FIDES to identify potential failure modes and implement appropriate screening practices that effectively address the specific stress factors relevant to each device. The user of the FIDES methodology can only include the stresses that FIDES lists for the particular component family. FIDES does not include for example, relative humidity as one of the stresses for capacitors, even though literature shows that humidity is a significant factor impacting the reliability of some capacitors.	As technology evolves, new failure modes and mechanisms emerge, requiring a flexible and adaptable screening approach. We need to implement a proactive approach to mitigate the potential for overlooking hidden failure modes by adopting a more comprehensive screening methodology. Standard screening procedures may not be sufficient to capture all possible failure modes, particularly those that are hidden or not explicitly recognized. PoF addresses the dynamic nature of technology and the continuous emergence of new failure modes and mechanisms. Unlike traditional approaches that rely on empirical data and statistical models, PoF focuses on understanding the fundamental physical and mechanistic aspects of failure. The dynamic nature of technology necessitates a flexible and adaptable screening approach. PoF recognizes this need and provides a framework that allows for the incorporation of new failure modes and mechanisms as they arise. By understanding the underlying physics and mechanisms behind failures, PoF enables engineers to

Device screening: neglect of application-specific considerations	Different applications have unique operating conditions and environmental factors that can significantly influence failure mechanisms. However, MIL-HDBK-217 does not sufficiently account for these application-specific considerations when promoting screening approaches. As a result, the screening efforts may not effectively target the relevant failure mechanisms for a given application.	FIDES is similar to MIL-HDBK-217 and may still have limitations in accounting for all application-specific considerations and environmental factors that can influence failure mechanisms. While FIDES aims to incorporate these factors into its approach, it may not comprehensively capture every possible influence on failure mechanisms in all scenarios. Therefore, despite its efforts to address application-specific considerations, there may still be instances where certain factors are not adequately accounted for in the screening process. Continuous improvement and refinement of the FIDES approach are necessary to enhance its ability to capture a wide range of application-specific influences on failure mechanisms. The methodology used in FIDES does not account for the part and assembly materials, geometry, and architecture, and will result in inaccurate and misleading predictions.	proactively identify and mitigate potential failure modes, even those that are hidden or not explicitly recognized. The comprehensive screening methodology offered by PoF goes beyond the limitations of standard procedures. It considers the interplay between various stress factors, such as thermal, electrical, and mechanical stresses, and their impact on the reliability of a device. This holistic approach helps uncover potential failure mechanisms that may not be captured by traditional methods, ensuring a more accurate assessment of reliability. Additionally, PoF emphasizes the importance of conducting root cause analysis and understanding the underlying physics governing failure mechanisms. By delving deeper into the fundamental causes of failures, PoF provides valuable insights into how failures occur, allowing for the development of targeted screening strategies and design improvements. Overall, the PoF approach is considered the best approach because it offers a proactive, adaptable, and comprehensive screening methodology that considers the evolving nature of technology and the need to mitigate the potential for overlooking hidden failure modes. By understanding the underlying physics and focusing on root cause analysis, PoF enables more accurate reliability

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Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
Device screening: potential for overlooking hidden failure modes	By not explicitly recognizing potential failure mechanisms, MIL-HDBK-217 may inadvertently lead to the oversight of hidden failure modes that are not captured by the standard screening procedures. This can result in unexpected failures in the field, impacting the reliability of the system.	FIDES, unlike MIL-HDBK-217, aims to address the potential for overlooking hidden failure modes by emphasizing a more comprehensive approach to screening. FIDES recognizes that standard screening procedures may not capture all possible failure modes, especially those that are hidden or not explicitly recognized. As a result, FIDES strives to incorporate advanced methodologies and techniques that allow for the identification and mitigation of these hidden failure modes. However, it is important to note that while FIDES makes efforts to address hidden failure modes, it may still have limitations in fully capturing all possible scenarios. There is always a potential risk of overlooking certain hidden failure modes due to the complexity and variability of different systems and environments. Therefore, continuous improvement and refinement of the FIDES approach, along with industry feedback and collaboration, are essential to enhance its ability to uncover and mitigate hidden failure modes effectively. FIDES contains a static list of basic	assessments and supports the development of robust and reliable electronic systems.
Device screening: limitations in addressing new technologies	MIL-HDBK-217 was initially developed for older technologies and may not adequately address the failure mechanisms and screening needs of emerging technologies. Without recognizing and adapting to the unique failure mechanisms associated with new technologies, the effectiveness of screening efforts may be compromised. Developing and maintaining current design reliability models for devices is an impossible task.		

		failure rates of components but does not provide any method of updating those failure rates using the user's reliability data or experience. It neither provides the data used to calculate the basic failure rates nor informs the user of the method for translating failure data to the tabulated basic failure rates. FIDES does not state the data collection timeline (for which generation of parts the models are meant, if any). Since electronic materials, designs, and processes change very rapidly, most of the models, even if they were correct, which they are not, would be outdated.	
Use of Arrhenius Model	The use of the Arrhenius Model in MIL-HDBK-217 presents both advantages and limitations. While it provides a simple framework with a focus on steady-state temperature, it may not readily accommodate temperature changes and might oversimplify the treatment of different failure mechanisms.	In the FIDES approach, the fluctuation of temperature is considered by allowing for explicit temperature change inputs in the modeling process. This means that instead of relying solely on steady-state temperature, FIDES considers the actual temperature variations experienced by the device in real-world operating conditions. In that statement, FIDES acknowledges that devices are subject to dynamic thermal environments where temperature can fluctuate over time. These fluctuations can be caused by factors such as changes in ambient temperature, operational conditions, power cycling, or other environmental factors. To accurately assess the device's reliability, FIDES incorporates these temperature variations explicitly in its modeling process. It takes into	While Arrhenius models provide a straightforward framework, PoF considers also the non-Arrhenius relation to accelerating parameters. PoF acknowledges the importance of experimental data and empirical observations to validate and refine reliability models. Through a combination of laboratory testing, field data analysis, and physical understanding, PoF provides a robust framework to assess reliability that goes beyond simplistic models like Arrhenius. By considering the specific failure mechanisms associated with a particular system or component, PoF allows for a more accurate and realistic assessment of reliability. This approach enables engineers to capture the complex dependencies between temperature, stress, and failure modes,
Use of Arrhenius Model – primary emphasis on steady-state temperature	Highlighting the significance of steady-state temperature set the primary stress factor to be reduced for improving reliability. This approach simplifies the design process by focusing on a single parameter that can have a significant impact on device performance and longevity.		
Use of Arrhenius Model – limitation in accepting	One limitation of MIL-HDBK-217 is that its models do not readily accept explicit temperature change inputs.		

(*Continued*)

Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
explicit temperature change inputs	This restriction hampers the ability to accurately account for transient temperature variations, which can occur in real-world operating conditions. Ignoring such temperature fluctuations may lead to less accurate reliability predictions.	account the specific temperature profiles or temperature cycles that the device is expected to encounter during its operational lifecycle. This enables a more accurate assessment of the device's performance and longevity, as it reflects the realistic temperature fluctuations that occur during operation. By explicitly accounting for temperature changes, FIDES provides a more comprehensive and accurate representation of the device's behavior under varying thermal conditions.	leading to improved predictions and more effective design decisions. PoF recognizes that different failure mechanisms can contribute to the overall reliability of a system. Instead of treating all failure mechanisms as a single entity, PoF allows for a mechanism-specific approach. It considers the unique characteristics, behaviors, and interactions of each failure mechanism, enabling a more accurate analysis of their impact on system reliability. PoF helps in identifying how different mechanisms may interact or influence each other, leading to a more comprehensive assessment of reliability. By conducting laboratory testing and analyzing field data, PoF can verify and refine the models that describe the behavior of different failure mechanisms. This empirical approach provides evidence for the interdependencies between failure mechanisms and helps in improving the accuracy of reliability predictions. PoF offers a flexible framework that can adapt to different types of failure mechanisms and their interdependencies: see chapter 5 of this handbook for the MTOL approach.
Use of Arrhenius Model – lumping acceleration models from different failure mechanisms	MIL-HDBK-217 employs a methodology that combines different acceleration models from various failure mechanisms into a single framework. This approach, although convenient from a modeling perspective, may overlook the distinct characteristics and dependencies of individual failure mechanisms. As a result, the reliability estimations may lack the necessary accuracy and precision required for specific failure modes.	While FIDES acknowledges the importance of addressing distinct characteristics and dependencies of individual failure mechanisms, one limitation is that it does not explicitly consider the simultaneous effects of multiple failure mechanisms. Unlike MIL-HDBK-217, which combines different acceleration models into a single framework, FIDES focuses on individual mechanisms separately. While this approach allows for a more detailed analysis of each mechanism, it may overlook the complex interactions and dependencies that can occur when multiple failure	
Use of Arrhenius Model – limited consideration of other stress factors	While MIL-HDBK-217 primarily emphasizes temperature, it may not adequately address the influence of		

	other stress factors that can significantly impact reliability, such as mechanical stresses, humidity, vibration, or electrical stresses. This limited consideration of multiple stress factors can lead to suboptimal reliability improvements if other critical stressors are not appropriately accounted for.	mechanisms act concurrently. As a result, the reliability estimations provided by FIDES may not fully capture the combined effects of multiple stress factors, potentially leading to a less comprehensive understanding of overall device reliability.	
Operating temperature	The consideration in MIL-HDBK-217 is confined to steady-state temperature alone. However, the accuracy of assessing the impact of steady-state temperature is questionable as it lacks a foundation in root-cause analysis and time-to-failure data.	Unlike MIL-HDBK-217, the FIDES approach recognizes the limitations of solely considering steady-state temperature in reliability assessments. FIDES aims to address this limitation by providing explicit support for the impact of operational temperature cycling on device reliability. Additionally, FIDES considers the combined effect of contaminants, such as ionic or hydrogen, and biasing conditions, which MIL-HDBK-217 does not explicitly address. Furthermore, FIDES acknowledges the need to account for the superposition of temperature cycling and vibration effects in reliability analysis. By incorporating these considerations, FIDES offers a more comprehensive approach to reliability assessment,	PoF is well-suited to address the constraints related to operating temperature, operational temperature cycling, and their combined effect with contaminants. Different failure mechanisms may exhibit varying sensitivities to temperature changes. By incorporating accurate temperature models and data, PoF can assess the impact of temperature variations on the reliability of a system. Repeated temperature fluctuations can induce additional stress on the components and accelerate certain failure mechanisms, such as fatigue or thermal fatigue. Contaminants, such as ionic or hydrogen species, can interact with the materials and components, leading to accelerated degradation or failure. By considering the interactions between contaminants and
Operational temperature cycling and combined to contaminants	MIL-HDBK-217 does not provide explicit support for considering the impact of operational temperature cycling on reliability, nor does it account for the combined effect of contaminants (such as ionic or hydrogen) and biasing conditions. Additionally, there is no provision for superposing the effects of temperature cycling and vibration in the reliability analysis within the handbook.		

(*Continued*)

Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
		considering multiple factors that can influence failure mechanisms and performance degradation. These differences in approach make FIDES a more robust methodology for capturing the complex interactions and effects of various stressors on device reliability. However, one drawback of the FIDES approach is that it may require more detailed and specific data compared to MIL-HDBK-217. The accurate modeling and analysis of operational temperature cycling, combined effects of contaminants and biasing conditions, and the superposition of temperature cycling, and vibration rely heavily on comprehensive and reliable data. Obtaining such data may pose challenges in certain situations, particularly for unique or specialized applications where limited or fragmented data is available. Therefore, while FIDES offers a more comprehensive approach, the availability and quality of data play a	temperature, PoF enables engineers to assess the synergistic effects and predict the impact on system reliability. Maximum Rating and Derating: PoF takes into account the maximum rating definitions and derating guidelines provided by component manufacturers. It recognizes the importance of operating components within their specified limits to ensure reliability and prevent premature failures.

		crucial role in its successful implementation and reliability assessments.	
Input data required	Does not model critical failure contributors, such as materials, architectures, and realistic operation stresses. Minimal data in, minimal data out. It is important to acknowledge that MIL-HDBK-217 was developed as a general reliability prediction handbook, aiming to provide broad guidance for a wide range of systems. While its simplicity may be advantageous in certain scenarios, it also introduces limitations in terms of accurately capturing the complexities associated with critical failure contributors.	For FIDES, there is a greater emphasis on capturing critical failure contributors, such as materials, architectures, and realistic operation stresses. The FIDES approach strives to incorporate more comprehensive and detailed input data, allowing for a more accurate representation of the system's reliability. By considering these critical factors, FIDES aims to provide more robust and tailored reliability predictions, addressing the limitations of MIL-HDBK-217 in capturing the complexities associated with failure contributors.	PoF considers the influence of input data required by promoting a comprehensive understanding of materials, architectures, and operating conditions. It emphasizes the importance of accessing relevant information from material datasheets, research publications, design documentation, environmental testing, failure analysis, and collaborative networks. PoF takes into account the influence of design factors such as materials and architectures on the time to failure and failure sites. It gives means to consider the specific failure modes and mechanisms relevant to the device or assembly and predicts their occurrence based on the design characteristics. By understanding how different design choices affect reliability, designers can make informed decisions to improve the performance and longevity of the system.
Output data	A quote from a proponent representative sheds light on the matter, stating that the handbook is not designed to predict field reliability and, overall, it does not perform well in providing accurate predictions in an absolute sense [20].	In terms of output data, FIDES aims to provide reliable predictions of field reliability. Unlike MIL-HDBK-217, FIDES do not suffer from the same limitation of not being designed to predict field reliability accurately. It focuses on providing more precise and meaningful output data, enabling engineers and decision-makers to	PoF considers the influence of output data required by providing designers with valuable insights into the impact of materials, architectures, loading conditions, and associated variations. It predicts the time to failure and failure sites for key failure modes and mechanisms, allowing designers to prioritize their efforts and make informed decisions to enhance reliability. Whether

(*Continued*)

Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
		make informed decisions regarding the system's reliability performance. This distinction highlights the commitment of FIDES to offer improved and more reliable predictions compared to the shortcomings of MIL-HDBK-217. However, it is important to note that the availability of comprehensive and accurate input data for FIDES can sometimes be a challenge. The limitation of requiring detailed information on materials, architectures, and realistic operation stresses can potentially impact the effectiveness and applicability of the FIDES approach, especially in cases where detailed data is limited or unavailable. Therefore, careful consideration should be given to data availability and quality when implementing FIDES for reliability predictions.	through deterministic or probabilistic treatment, PoF enables a comprehensive understanding of reliability factors and supports effective design improvements. PoF models enable the prediction of the time to failure for key failure modes and mechanisms. By considering the stress factors, material properties, and environmental conditions, PoF models can estimate the expected lifespan of the device or assembly. It provides insights into the locations or sites where failures are likely to occur within a device or assembly. It considers factors such as stress concentrations, weak points in the design, and potential failure mechanisms to identify the areas prone to failure.
DoD/industry acceptance	Mandated by government, 30-year record of discontent. Not part of the US Air Force Avionics Integrity Program (AVIP). No longer supported by senior US Army leaders.	FIDES has been introduced in 2004 by a consortium of French industrials (led by DGA (French DoD) and MBDA, including Thales, Eurocopter, Airbus, Nexter), with an update in 2009. See FIDES model coverage at: https://www.fides-reliability.org/en/node/555.	Adopting PoF as a best practice in industry offers a more accurate, comprehensive, and scientifically grounded approach to reliability assessment. While there may be initial investments in terms of expertise and resources, the long-term cost savings, prevention of failures, and optimization of

		The FIDES methodology models the failures whose origins are intrinsic (item technology or manufacturing and distribution quality) and extrinsic (equipment specification and design, selection of the procurement route, equipment production and integration) to the items studied. The FIDES methodology covers non-operating phases, whether standby periods between utilizations or actual storage.	design decisions make PoF a compelling choice over MIL and FIDES. PoF's dedication to continuous peer review, collaboration with industry leaders, and integration of Artificial Intelligence technologies positions it as a superior approach. These factors contribute to the refinement and advancement of PoF models, ensuring their relevance and effectiveness in addressing complex reliability challenges in the era of AI.
Conclusion	The models lack formal peer review as they have not been submitted to engineering societies or technical journals. Additionally, future tri-service coordination is a matter of concern.	Unlike MIL-HDBK, FIDES do not undergo formal peer review through submission to engineering societies or technical journals. This lack of external scrutiny and expert input may limit the ability to identify and address potential shortcomings or biases in the reliability models. In summary, FIDES offers the advantage of utilizing real-world data and promoting collaboration, while MIL-HDBK benefits from its long-standing use and simplicity. The choice between the two approaches depends on factors such as the availability of data, industry requirements, and the desired level of accuracy and customization in reliability assessments.	MIL and FIDES, with their reliance on empirical models or simplified approaches, may not provide the same level of accuracy and cost-effectiveness. They may overlook hidden failure modes or fail to adequately account for the complexities of modern technologies, potentially leading to unexpected failures and increased costs down the line. PoF is actively engaging with leading electronics companies, agencies, and industries worldwide to develop new software and documentation. The involvement of AI in PoF can contribute to automated data collection, analysis, and decision-making processes. AI algorithms can process vast amounts of data and extract valuable insights, enabling faster and more efficient reliability assessments. This

(*Continued*)

Table 1.2 (Continued)

Issue	MIL-HDBK-217	FIDES	Physics of failure
			combination of PoF and AI technologies has the potential to revolutionize the field of reliability engineering by providing advanced tools and methodologies.
Relative cost of analysis	Cost is high compared with value added. Can misguide efforts to design reliable electronic equipment.	The cost associated with implementing the FIDES methodology can be perceived as high when compared to the value it adds. It is important to carefully consider the cost-benefit ratio to ensure that the investments made in applying FIDES are justified. However, it is crucial to note that while the cost may be significant, it is intended to ensure more accurate reliability assessments and minimize the potential for misguided efforts in designing reliable electronic equipment. By investing in the appropriate resources and training, organizations can maximize the benefits of the FIDES approach and make informed decisions that lead to improved product reliability and customer satisfaction.	PoF offers flexibility in data acquisition, allowing for tailored approaches that align with specific project requirements and budgets. This flexibility in data acquisition translates to adaptable cost structures, making PoF accessible to a wider range of industries and organizations. By designing for reliability and minimizing defects throughout the operational life of a product, PoF enables organizations to achieve higher reliability, lower failure rates, and reduced costs, thereby enhancing the overall quality and performance of their products.

1.2 Electronic Reliability in Manufacturing, Production, and Operations

"Health Monitoring" covers the monitoring of the state of health of a system, continuously or intermittently, from direct or indirect observations, to anticipate and take the best decisions, whatever their nature. One can model a degradation process in various ways. In the absence of any observation of the phenomenon, reliability models, such as the Weibull law, can be obtained from statistical failure data on similar products. To estimate the probability of failure after a given duration of operation, these models can be supplemented by acceleration models and accelerated life tests.

The issue of reliability estimation turns out to be different when a product is subject to a degradation process that can be quantified over time and on which a threshold limit of acceptability can be set. It is then possible to follow the evolution of such a process during trials, to assess the predicted reliability of the product, or during the operational life. To know his state of health from day to day, estimates of the remaining useful life (RUL) can be generated and decisions about using the component can be processed accordingly. The conditions of use and the environment conditions can accelerate the degradation process based on the specific physics of the failure mechanism being activated.

The identification of a direct or indirect observable (indicator) of the degradation and the knowledge of the influential stress factors is the domain of the component expertise. The measurement of degradation can be carried out under different stress conditions or require a return to standard conditions. By observing the variations in degradation per unit of time, the phenomenon can be modeled by a Gamma process, if the degradation is always increasing (monotonic deterioration), or by a Wiener process if the degradation is decreasing temporarily by phenomena of recovery or even healing. The degradation phenomenon can be stationary or non-stationary and be influenced by environmental conditions.

In the absence of direct observation, certain degradation phenomena can be modeled by a hidden Markov process. The algorithm and the Hidden Markov models were first described in a series of articles by Baum [22] and his peers at the IDA Center for Communications Research, Princeton in the late 1960s and early 1970s. As written in Wikipedia, this describes a Markov process whose states, representative of levels of progressive degradation, are partially observable through probabilistic indicators (a vibrational spectrum or an oil color will, for example, provide information on the state of degradation of a mechanism). The Viterbi algorithm is then used to find the most probable sequence of transitions from a sequence of observations and the Forward-Backward, also called de Baum-Welch, to estimate the parameters of the model.

Other phenomena can be modeled by piecewise deterministic Markovian processes (PDMP). Developed by Davis [23], this type of hybrid dynamic reliability process makes it possible to associate random characteristics with continuous components in interaction (environmental variables that will influence and be influenced by the system, for example).

The use of dynamic Bayesian networks can also be considered to model degradation processes. These represent the evolution of random variables as a function of a discrete sequence.

1.2.1 Failure Foundation

Why and how high- or low-quality components can fail in comparable time scale? Of course, reducing temperature stress conditions can improve long-term mission operation but not only temperature. Indeed, applying lower bias voltage, current, and power are other options. How to manage Time-to-Failure for warranty and limits with predictable outcomes?

The failure event pattern is detailed in the following Figure 1.1a, the general failure pattern overview presents the alternatives a component or a structure may fail by way of a permanent or reversible mechanism, either from a sudden catastrophic malfunction or by a continuous degradation trend and in addition with or without partial recovery.

What are the root causes of component failure? What characterizes component failure? This is related to the definition of trackers as detailed.

The foundation of a failure is described in behind basic sequences:

- To identify the ***actors*** or the ***stressors*** (Figure 1.1b) (or in other terms, which stress parameters are the origin of the failures),
- The ***tracers*** or the ***observers*** (Figure 1.1c) (types of measurands whose evolution is a quantification correlated to the level of failure),
- The ***trackers*** or the ***signatures*** (Figure 1.1d) (a selected electrical or mechanical parameter which quantifies the type and level of failure).

Stressor levels (the actors) can be measured directly or indirectly, such as junction temperature from package temperature and thermal resistance, for example.

1.2.2 Reliability Foundational Models (Markovian, Gamma, Lévy, Wiener Processes)

A paper published in 2020 by Cabarbaye et al. [24] provides an example of how the degradation analysis method from experiments can be implemented. To characterize a degradation, two families of models can be considered: continuous models and state-space (or multi-state) models. The first relate to a physical quantity, such as a crack propagation, a current degradation, or a temperature rise, for example,

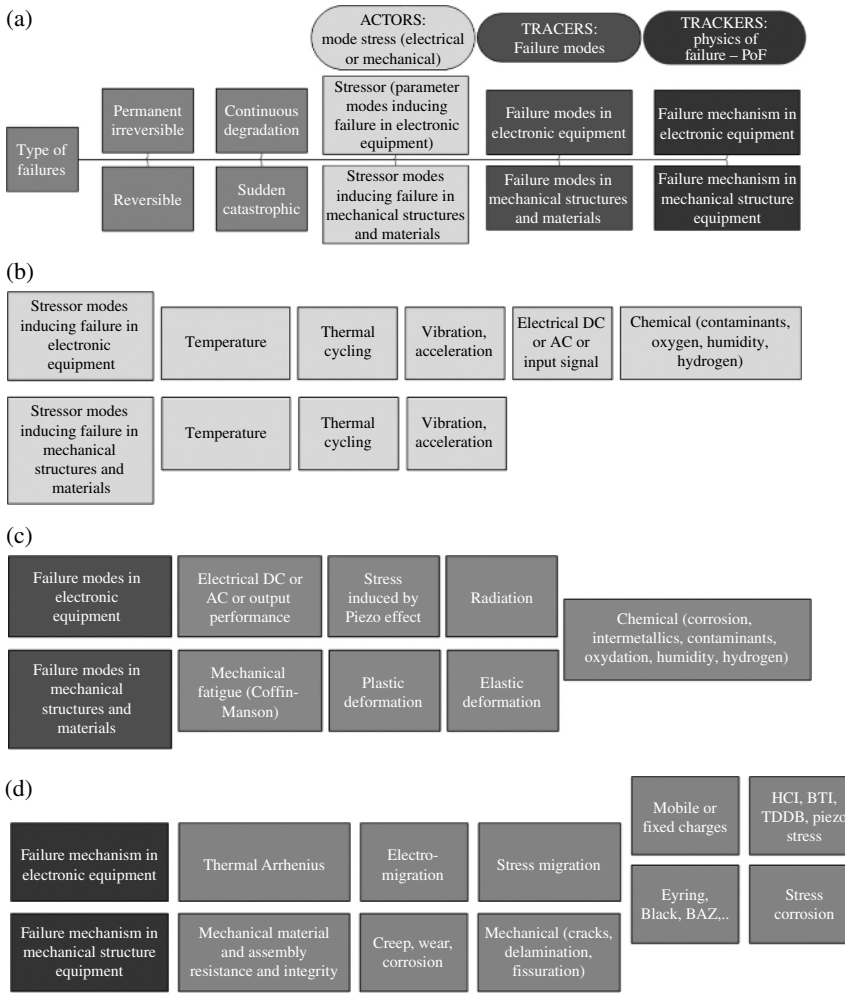


Figure 1.1 (a) General failure pattern overview. (b) How are failures induced by stress conditions (***tracer modes***). (c) Identify failure mode ***tracers***. (d) PoF based on ***trackers*** or ***signatures***.

whose evolution trajectory we seek according to a physics model. The second considers a series of pronounced states of degradation and transition laws between these states. They bring together members of the family of Markovian models such as PDMP.

The standard Accelerated Life Testing model (ALT), which includes most of the acceleration models used in reliability (Arrhenius, Eyring, Black, ...), can then be

used again on the assumption that only the scale factor of the degradation law is modified and not its form. The acceleration factor (AF) is then like the one considered for random failures but with different parameter values. If a threshold limit of acceptability can be set, the degradation model is transformed into a reliability model.

Continuous degradation models are generally based on the family of incremental Lévy processes [from the French mathematician (1886–1971)] independent and stationary (each increase depends only on the time interval), including the Gamma process, the Wiener process, and the compound Poisson process (degradation linked to an accumulation of shocks).

1.2.3 Correlation Versus Causation and Representativeness of Trackers

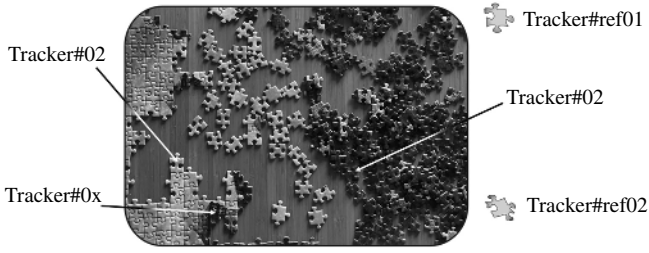
In reliability modeling, it is important to differentiate between correlation and causation: A correlation between variables, however, does not automatically mean that the change in one variable is the cause of the change in the values of the other variable. Causation is a cause-effect process and indicates that one event is the result of the direct influence of a variable stress parameter. In that sense, tracers are both types of correlated and causation parameters. While a tracker should be the "best parameter" showing causation to a failure mechanism. When several failure mechanisms are concurrent, several trackers can be identified and the trick consists in selecting, if possible, the most representative parameter of the existing multiple failure mechanisms.

Consequently, a physical model may be deduced from a tracker which could be biased so as not to accurately reflect the observed degradation of one (or several) failure mechanism(s). This adds "fuzzy" information which contributes to discrediting a failure mode model to predict the occurrence of failure. So, it looks like our quest to predict failures of a particular constituent being in a sub-system, an electronic card, or a component installed on it (of which it has its history of manufacturing, assembly process, and environmental applied stress conditions) may not yield the desired result. Hence, it is important to ask:

What is the representativeness of tracers and trackers?

The description of the allegory of the jigsaw puzzle given hereafter is a simplistic view of the situation.

Puzzle pieces can be similar in strength, stiffness, size, shape, and variability of colors, but at the same time, dissimilar with some drawbacks: indeed, this is because each puzzle piece is different in form, fit, and function (F3), and furthermore a single piece does not tell you the full sense of the picture.



Should a single valid Tracker be used to describe true component reliability figure?

There is something erroneous to describe the reliability of a product using one single representative element. Moreover, reliability is also influenced by variability, inherent in all manufacturing processes. To build a usable and accurate reliability model, you must start by observing the tracers, select those that are closest to a faithful description of reality, and validate a series that is the most representative in reliability signature.

We must pay attention to know what to measure and how to control this range of variation. The conditions of usage like bias voltage or input signal must be defined with respect to the maximum rating limits allowed for a product (note they are also distributed with some variability). Variation also exists in the environments that engineered products must withstand. Temperature, mechanical stress, vibration spectra, and many other varying factors must be considered.

The measurement conditions of trackers must be set as generic and reproducible as possible. In steady-state life test experiments, it is recommended to measure the trackers under typical bias at room temperature conditions. But in real life, it is not always possible to measure the trackers in such stable conditions and use of sensors can be an option to track the change in power consumption or local temperature provided the causation is established and validated.

What is the definition of a failure? How to quantify it? Is it better to describe failure in absolute or in relative value? How can a series of tracker models accurately represent the entire figure of a product? The trackers are buoys to know where the potential wells of poor reliability are and how an accumulation of trackers can inform about the total generic reliability level.

1.2.4 Functional Safety Standard ISO 26262

Saying that, the automotive Functional Safety Standard ISO 26262 introduced the concept of the Probabilistic Metric for random Hardware Failures (PMHF) associating it with the failure rate of the safety critical system or subsystem. In an SAE publication, Kleyner and Knoell [25] presented this concept and discussed

how to calculate both the failure rate and the average probability of failure per hour in terms of definitions, sources of the data, applications, and advantages and disadvantages.

Testing is an essential part of any engineering development program. There is one dilemma and conflict inherent in reliability testing as part of an integrated test program, however. To obtain information about reliability in a cost-effective way, that is also quick, it is necessary to generate failures. Only then can safety margins be ascertained. On the other hand, failures interfere with functional and environmental testing. In addition, lot-to-lot and device-to-device variability affects the probability of failure as well and another major source of variability is the range of production processes involved in converting designs into hardware. These considerations are exposed in the book "Practical Reliability Engineering" published by O'Connor and Kleyner [26] and assumes "*the old design concept of 'test-analyze-and-fix' (TAAF), in which reliance is placed on the test program to show up reliability problems, no longer has a place in modern design and manufacturing due to shorter design cycles, relentless cost reduction, warranty cost concerns, and many other considerations. Therefore, the reliability should be 'designed-in' to the product using the best available science-based methods. This process, called Design for Reliability (DfR) begins from the first stages of product development and should be well integrated through all its phases*."

Testing to demonstrate reliability when failures occur during tests can be analyzed using the life data analysis methods. The downside of the test-to-failure method is longer test times compared to equivalent success-run tests. Degradation analysis introduced is one way of demonstrating reliability within a relatively short period of time. Talking about parts reliability is not only considering the intrinsic reliability component capability but also defining the least stressful conditions of use taking into consideration extreme values external parameters can achieve during the mission. In other words, "a hammer blow can always destroy any good device." Consequently, it is equally important to select parts and assembly processes, and to have a good knowledge of the environment conditions (biasing/temperature). Knowing this, we enter the world of "Physics of Failures" (PoF) or "Physics of Health" (PoH).

The cause of a product failure is because of a disruption in the weakest link (a fragile part, a degraded aged part, or due to a sudden external overstress event). Either the breakage is foreseeable due to a parametric performance degradation with time, or it is catastrophic with now forewarning. In the wear-out case, statistical model variation with time is applicable (semi-Markovian or non-Markovian processes) and we can refer to wear-out failure mechanisms. In the case of a sudden break or catastrophic failure, it is by nature modeled as a random failure mechanism indicated only by a time to fail. Both may exit and must be combined to assess what we call the RUL of a product/device.

DfR is a set of approaches, methods, and best practices that are supposed to be used at the design stage of the product to minimize the risk that it might not meet the reliability requirements, objectives, and expectations. Statistical methods provide the means for analyzing, understanding, and knowing variation. These statistical representations can be only simplified models and we can't be sure they correctly describe the PoF or PoH. They help visualize mathematically some behavior, but the true life may be quite different.

As mentioned in chapter 12 of [26], *reliability testing should be considered part of an integrated test program, which should include:*

1) *Functional testing, to confirm that the design meets the basic performance requirements.*
2) *Environmental testing, to ensure that the design can operate under the expected range of environments.*
3) *Statistical tests, as described in Chapter 11, to optimize the design of the product and the production processes.*
4) *Reliability testing, to ensure (as far as is practicable) that the product will operate without failure during its expected life.*
5) *Safety testing, when appropriate.*

1.2.5 Additional Considerations

A component, however good as it may be, degrades under the effect of the applied stresses. A component is tested, manipulated, assembled, and embedded on an electronic card simply due to the manufacture of that electronic card. Then the accumulated effects of all the stressors evolve over time during the operational life of the equipment. How do the statistics related to the quality of the component batch, to the quality of the reporting and test processes, act and interact (signature statistics and environment statistics)? And how do these statistics change over time? Do they all evolve at the same rate? What impact do they have on the failure rate observed and described by the bathtub curve?

Until now, we measured the signature degrading over time when measured under reproducible conditions at room temperature and typical bias conditions (non-stress). During high-temperature endurance life tests, the components are biased under high-temperature conditions, which can induce stress levels different from the nominal operational ones. At high temperatures, the electrical characteristics of the components behave differently and the derating rates on the current or the voltage defined when cold are not the same as those when hot. They may, therefore, not be representative of the operational behavior of the components. The models deduced from these facts are therefore questionable. It is thus necessary to be extremely careful with the interpretation of the facts which can be distorted by this multi-statistical bias and high-temperature impact.

We must also mention another important concept which is the level of confidence of the trackers. What are the systematic drifts attached to them? And how to minimize them?

There are several definitions of systematic drifts and care must first be taken in defining what is called bias. We call bias the difference between the overall objective reliability measure (as a value deduced from the consideration of all the trackers) compared to the reliability deduced on a single tracker. The greater this difference, the more the measured reliability deviates from the overall objective reliability. When the bias is zero, there is no difference between the overall reliability and the reliability measured by a single tracker.

1.3 Reliability Criteria

Reliability is defined as the probability that a system (component) will function over some time period t. If T is defined as a continuous random variable, the time to failure of the system (component), then reliability can be expressed as:

$$R(t) = Pr\{T \geq t\} \tag{1.4}$$

where $R(t) \geq 0, \quad R(0) = 1$ and $lim_{t \to \infty} R(t) = 0$

For a given value of t, $R(t)$ is the probability that the time to failure is greater than or equal to t, and $F(t)$ could be defined as:

$$F(t) = 1 - R(T) = Pr\{T < t\}, F(0) = 0, lim_{t \to \infty} F(t) = 1 \tag{1.5}$$

Then $F(t)$ is the probability that a failure occurs before t.

$R(t)$ is referred to as the probability function and $F(t)$ as the cumulative distribution function (CDF) of the failure distribution. A third function is defined by:

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt} \tag{1.6}$$

is called the probability density function (PDF) and has two properties:

$$f(t) \geq 0, \quad \text{and} \quad \int_0^\infty f(t)dt = 1 \tag{1.7}$$

Both the reliability function and the CDF represent areas under the curve defined by $f(t)$. Therefore, since the area beneath the entire curve is equal to one, both the reliability and the failure probability will be defined so that:

$$0 \leq R(t) \leq 1, \text{ and } 0 \leq F(t) \leq 1 \tag{1.8}$$

The mean time to failure (MTTF) is defined by:

$$MTTF = E(T) = \int_0^\infty t \cdot f(t)dt \tag{1.9}$$

which is the mean or the expected value of the probability distribution defined by $f(t)$.

Failure rate or Hazard rate function provides an instantaneous rate of failure:

$$Pr\{t \le T \le t + \Delta t\} = R(t) - R(t + \Delta t) \tag{1.10}$$

The conditional probability of a failure in the time interval from t to $t + \Delta t$ given that the system has survived to time t is:

$$Pr\left\{t \le T \le t + \Delta t \middle| T \ge \mathrm{t}\right\} = \frac{R(t) - R(t + \Delta t)}{R(t)} \tag{1.11}$$

and then:

$\frac{R(t) - R(t + \Delta t)}{R(t)\Delta t}$ is the probability of failure per unit of time (failure rate). Set:

$$\lambda(t) = lim_{\,\Delta t \to \infty} \frac{-[R(t + \Delta t) - R(t)]}{\Delta t} \cdot \frac{1}{R(t)} = \frac{-dR(t)}{dt} \cdot \frac{1}{R(t)} = \frac{f(t)}{R(t)} \tag{1.12}$$

Then $\lambda(t)$ is known as the instantaneous hazard rate or failure rate function. The failure rate function $\lambda(t)$ provides an alternative way of describing a failure distribution. Failure rates in some cases may be characterized as increasing (instantaneous failure rate – *IFR*), decreasing (*DfR*), or constant (*CFR*) when $\lambda(t)$ is an increasing, decreasing, or constant function. Table 1.3 shows the relationship among the measures.

1.3.1 The Failure Rate Curve for Electronic Systems

An important form of the hazard rate is a bathtub curve. Systems having this hazard rate function experience decreasing failure rates early in their life cycle (infant mortality), followed by a nearly CFR (useful life), followed by an increasing failure rate (wear-out); this curve may be obtained as a composite of several failure distributions or as a function of piecewise linear and CFRs.

The reliability of electronic devices is represented by the failure rate curve (Figure 1.2) (called the "bathtub curve"). The curve can be divided into the three following regions: (i) initial failures, which occur within a relatively short time after a device starts to be used, (ii) random failures, which occur over a long period of time, and (iii) wear-out failures, which increase as the device nears the end of its life.

Table 1.3 The relationship among the measures.

	F(t)	***R(t)***	***f(t)***	***λ(t)***	
$F(t)$	$F(t)$	$1 - R(t)$	$\int_0^t f(x)dx$	$1 - exp - \left(-\int_0^t \lambda(x)dx\right)$	Cumulative distribution function (CDF) or probability of failure
$R(t)$	$1 - F(t)$	$R(t)$	$\int_t^\infty f(x)dx$	$exp\left(-\int_0^t \lambda(x)dx\right)$	Reliability (R)
$f(t)$	$\frac{dF(t)}{dt}$	$\frac{dR(t)}{dt}$	$f(t)$	$\lambda(t) \cdot exp\left(-\int_0^t \lambda(x)dx\right)$	Probability density function (PDF)
$\lambda(t)$	$\frac{\frac{dF(t)}{dt}}{1-F(t)}$	$\frac{d(ln\,R(t))}{dt}$	$\frac{f(t)}{\int_t^\infty f(x)dx}$	$\lambda(t) = \frac{f(t)}{R(t)}$	Instantaneous failure rate (IFR) or hazard function

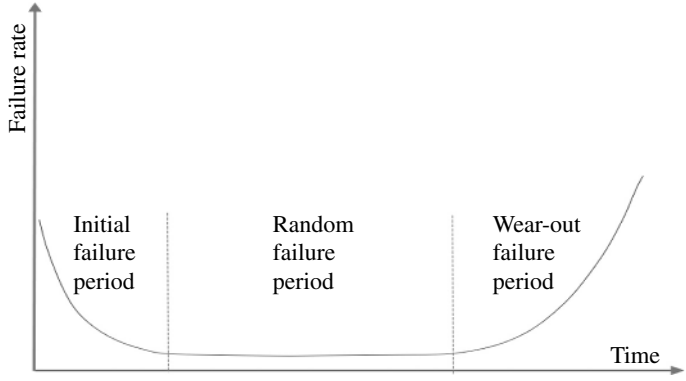


Figure 1.2 Failure rate curve.

"Initial failures" are considered to occur when a latent defect is formed, for example, during the device production process and then becomes manifest under the stress of operation. For example, a defect can be formed by having tiny particles in a chip in the production process, resulting in a device failure later. The failure rate tends to decrease with time because only devices having latent defects will fail, and these devices are gradually removed. At the start of device operation, there may be electronic devices with latent defects included in the set.

These will fail under operating stress, and as they fail, they are removed from the set based on the definition of the failure rate. The initial failure period can therefore be defined as the period during which devices having latent defects fail. The failure rate can be defined as a decreasing function since the number of devices having latent defects decreases as they are removed.

Most of the microelectronic device initial defects are caused by defects built into devices mainly in the wafer process. The most common causes of these defects are dust adhering to wafers in the wafer process and crystal defects in the gate oxide film or the silicon substrate, etc. The defective devices surviving in the sorting process (during the manufacturing process) may be shipped as passing products. These types of devices which are inherently defective from the start often fail when stress (voltage, temperature, etc.) is applied for a relatively short period. Finally, almost all of these types of devices fail over a short period of time and the failure rate joins the region called random failure part. The process of applying stresses for a short period of time (before shipping the product) to eliminate the defective devices is called screening ("burn-in").

"Random failures" occur once devices having latent defects have already failed and been removed. In this period, the remaining high-quality devices operate stably. The failures that occur during this period can usually be attributed to randomly occurring excessive stress, such as power surges, and software errors. Moreover, memory software errors and other phenomena caused by α rays and other high-energy particles are sometimes classified as randomly occurring failure mechanisms. There are also phenomena such as electrostatic discharge (ESD) breakdown, overvoltage (surge) breakdown (EOS), and latch-up which occur at random according to the conditions of use. However, these phenomena are all produced by the application of excessive stress over the device's absolute maximum ratings. So, these are classified as breakdowns instead of failures, and are not included in the random failure rate.

"Wear-out failures" occur due to the aging of devices from wear and fatigue. The failure rate tends to increase rapidly in this period. Semiconductor devices are therefore designed so that wear-out failures will not occur during their guaranteed lifetime. Accordingly, for the production of highly reliable electronic devices, it is important to reduce the initial failure rate to ensure the long life, or durability against wear-out failures. Wear-out failures are failures rooted in the durability of the materials comprising semiconductor devices and the transistors, wiring, oxide films, and other elements, and are an index for determining the device life (useful years). In the wear-out failure region, the failure rate increases with time until ultimately all devices fail or suffer characteristic defects.

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wear-out failure region, the failure rate increases with time until ultimately all devices fail or suffer characteristic defects.

1.3.2 Basic Lifetime Distribution Models

There are a handful of parametric models that have successfully served as population models for failure times arising from a wide range of products and failure mechanisms. Sometimes there are probabilistic arguments based on the physics of the failure mode that tend to justify the choice of model. Other times the model is used solely because of its empirical success in fitting actual failure data. Some of the models used in the electronic area are:

1) Exponential
2) Weibull
3) Extreme value
4) Lognormal

The exponential model, with only one unknown parameter, is the simplest of all life distribution models. The failure rate reduces to the constant for any time. The exponential distribution is the only distribution to have a CFR. The key factors are:

$$\begin{aligned}&\text{The probability density function (PDF),}\\&f(t)=\lambda e^{(-\lambda t)}\\&\text{The Cumulative Distribution Function (CDF),}\\&F(t)=1-e^{(-\lambda t)}\\&\text{Since } R(t)=1-F(t),\quad R(t)=e^{(-\lambda t)}\\&\text{The Instantaneous Failure Rate (IFR) function is given by}\\&h(t)=\frac{f(t)}{R(t)}=\lambda\end{aligned}\tag{1.13}$$

Although $1/\lambda$ is the average time of failure, it is not the same as the time when half the population would have failed. This median time to failure, or T_{50}, occurs in the interval for which the cumulative frequency distribution registers 50%. For a continuous population, the mean parameter is expressed by $Mean=\int_0^\infty x\cdot f(x)dx$. The variance of a random variable X is defined as the expected value of $(X-\mu)^2$, that is, $V(x)=E([X-\mu]^2)$.

So, for the exponential distribution, we get:

$$Mean=\frac{1}{\lambda}, Median=\frac{ln\,2}{\lambda}, Variance=\frac{1}{\lambda^2}\tag{1.14}$$

The CFR property, the exponential distribution is an excellent model for the long flat "intrinsic failure" portion of the Bathtub Curve. Since most components and systems spend most of their lifetimes in this portion of the Bathtub Curve, this justifies frequent use of the exponential distribution (when early failures or wear-out is not a concern). Its usefulness is to approximate a curve by piecewise straight-line segments. We can approximate any failure rate curve by week-by-week or month-by-month constant rates that are the average of the actual changing rate during the respective time durations. Then it would be possible to approximate any model by piecewise exponential distribution segments patched together. Some natural phenomena have a CFR (or occurrence rate), for example, the arrival rate of cosmic ray alpha particles or Geiger countertics. The exponential model works well for inter-arrival times (while the Poisson distribution describes the total number of events in each period). When these events trigger failures, the exponential life distribution model will naturally apply.

Weibull, on the other hand, is a very flexible life distribution model with two parameters.

The goal is to find a CDF that has a wide variety of failure rate shapes. With the constant $h(t) = \lambda$, we get just one possibility. Allowing any polynomial form of the type $\lambda(t) = \lambda \cdot \gamma \cdot (\lambda \cdot t)^{\gamma - 1}$ for a failure rate function achieves this objective. To derive $f(t)$, it is easier to start with the CDF $F(t)$. Setting

$$F(t) = 1 - exp\left(-\int_0^t \lambda(x)dx\right), \text{or } F(t) = 1 - exp\ -(\lambda \cdot t)^{\gamma} \tag{1.15}$$

We get the probability density function (PDF),

$$f(t) = \frac{dF(t)}{dt} = \frac{\gamma}{t} \cdot (\lambda \cdot t)^{\gamma} \cdot exp\ -(\lambda \cdot t)^{\gamma}$$

$$\text{Since} \quad R(t) = 1 - F(t), \quad R(t) = exp\ -(\lambda \cdot t)^{\gamma} \tag{1.16}$$

The Instantaneous Failure Rate (IFR) function is given by

$$h(t) = \frac{f(t)}{R(t)} = \frac{\gamma}{t} \cdot (\lambda \cdot t)^{\gamma}$$

For $t > 0$, other key formulas are given by:

$$Mean = \frac{1}{\lambda} \cdot \Gamma\left(1 + \frac{1}{\gamma}\right), Median = \frac{1}{\lambda}(ln\ 2)^{\frac{1}{\gamma}}$$

$$Variance = \frac{1}{\lambda^2}\Gamma\left(1 + \frac{2}{\gamma}\right) - \left[\frac{1}{\lambda}\Gamma\left(1 + \frac{1}{\gamma}\right)\right]^2 \tag{1.17}$$

with α the scale parameter (the Characteristic Life), γ (gamma) the Shape Parameter, and Γ the Gamma function with $\Gamma(N) = (N-1)!$ for integer N.

When $\gamma = 1$, the Weibull reduces to the Exponential Model. Depending on the value of the shape parameter, γ the Weibull model can empirically fit a wide range of data histogram shapes.

Weibull is widely used because of its flexible shape and ability to model a wide range of failure rates (Weibull has been used successfully in many applications as a purely empirical model); besides, Weibull model can be derived theoretically as a form of Extreme Value Distribution, governing the time to occurrence of the "weakest link" of many competing failure processes. This may explain why it has been so successful in applications such as capacitors, ball bearings, and relay and material strength failures. Another special case of the Weibull occurs when the shape parameter is 2. The distribution is called the Rayleigh Distribution and it turns out to be the theoretical probability model for the magnitude of radial error when the x and y coordinate errors are independent normal with 0 mean and the same standard deviation.

Extreme value distributions are the limiting distributions for the minimum or the maximum of a very large collection of random observations from the same arbitrary distribution. Gumbel [27] showed that for any well-behaved initial distribution (i.e. $F(x)$ is continuous and has an inverse), only a few models are needed, depending on whether you are interested in the maximum or the minimum, and if the observations are bounded above or below. In the context of reliability modeling, extreme value distributions for the minimum are frequently encountered. For example, if a system consists of n identical components in series, and the system fails when the first of these components fails, then system failure times are the minimum of n random component failure times. Extreme value theory says that independent of the choice of component model, the system model will approach a Weibull as n becomes large. The same reasoning can also be applied at a component level if the component failure occurs when the first of many similar competing failure processes reaches a critical level. The distribution often referred to as the Extreme Value Distribution (Type I) is the limiting distribution of the minimum of many unbounded identically distributed random variables. The PDF and CDF are given by:

$$f(x) = \frac{1}{\beta} e^{\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\beta}{\beta}}} \text{ where} - \infty < x < \infty, \ \beta > 0, \tag{1.18}$$

$$F(x) = 1 - e^{e^{\frac{x-\mu}{\beta}}} \text{ where} - \infty < x < \infty, \beta > 0 \tag{1.19}$$

If the x values are bounded below (as is the case with times of failure), then the limiting distribution is the Weibull.

Extreme Value Distribution model could be used in any modeling application for which the variable of interest is the minimum of many random factors, all of which can take positive or negative values, try the extreme value distribution

as a likely candidate model. For lifetime distribution modeling, since failure times are bounded below by zero, the Weibull distribution is a better choice. Weibull distribution and the extreme value distribution have a useful mathematical relationship. If t_1, t_2, ..., t_n are a sample of random times of fail from a Weibull distribution, then $ln(t_1)$, $ln(t_2)$, ..., $ln(t_n)$ are random observations from the extreme value distribution. In other words, the natural log of a Weibull random time is an extreme value random observation. If a Weibull distribution has shape parameter γ and characteristics life α, then the extreme value distribution value distribution (after taking natural logarithms) has $\mu = ln\ \alpha$, $\beta = 1/\gamma$.

Because of this relationship, computer programs and graph papers designed for the extreme value distribution can be used to analyze Weibull data. The situation exactly parallels using normal distribution programs to analyze lognormal data, after first taking natural logarithms of the data points.

The lognormal life distribution, like the Weibull, is a very flexible model that can empirically fit many types of failure data. The two-parameter form has parameters = the shape parameter and T_{50} = the median (a scale parameter). If time to failure, t_f, has a lognormal distribution, then the (natural) logarithm of time to failure has a normal distribution with mean $\mu = ln(T_{50})$ and standard deviation σ. This makes lognormal data convenient to work with; just take natural logarithms of all the failure times and censoring times and analyze the resulting normal data. Later on, convert back to real time and lognormal parameters using σ as the lognormal shape and $T_{50} = e^{\mu}$ as the (median) scale parameter.

$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\left(\frac{1}{2\sigma^2}\right)(ln\,t - ln\,T_{50})^2} \tag{1.20}$$

$$F(t) = \int_0^T \frac{1}{\sigma \cdot t\sqrt{2\pi}} \cdot e^{-\left(\frac{1}{2\sigma^2}\right)\cdot(ln\,t - ln\,T_{50})^2} dt = \Phi\left(\frac{ln\,t - ln\,T_{50}}{\sigma}\right) \tag{1.21}$$

$\Phi(z)$ denoting the standard normal CDF and $Mean = T_{50} \cdot exp\left(\frac{\sigma^2}{2}\right)$.

The lognormal PDF and failure rate shapes are flexible enough to make the lognormal a very useful empirical model. In addition, the relationship to the normal (just take natural logarithms of all the data and time points and "normal" data) makes it easy to work with mathematically, with many good software analysis programs available to treat normal data. The lognormal model can theoretically match many failure degradation processes common to electronic failure mechanisms including corrosion, diffusion, migration, crack growth, electromigration, and, in general, failures resulting from chemical reactions or processes. Applying the Central Limit Theorem to small additive errors in the log domain and justifying a normal model is equivalent to justifying the lognormal model in real time when a process moves toward failure based on the cumulative effect of many small "multiplicative" shocks. More precisely, if at

any instant in time, a degradation process undergoes a small increase in the total amount of degradation that is proportional to the current total amount of degradation, then it is reasonable to expect the time to failure (i.e. reaching a critical amount of degradation) to follow a lognormal distribution [28].

1.4 Reliability Testing

Reliability testing is a series of laboratory tests carried out under known stress conditions to evaluate the life span of a device or system. Reliability tests are performed to ensure that semiconductor devices maintain their performance and functions throughout their life. These reliability tests aim to simulate and accelerate the stresses that the semiconductor device may encounter during all phases of its life, including mounting, aging, field installation, and operation. The typical stress conditions are defined in the testing procedure described later in this document. Reliability tests are performed at various stages of design and manufacture. The purpose and contents differ in each stage. When testing semiconductor devices, (i) the subject and purpose of each test, (ii) the test conditions, and (iii) the judgment based on test results must be considered.

1.4.1 Reliability Test Methods

Reliability tests are performed under known stress conditions. A number of standards have been established including Japan Electronics and Information Technology Industries Association (JEITA) standards, US military (MIL) standards, International Electrotechnical Commission (IEC) standards, and Japan Industrial Standards (JIS). The testing procedures and conditions differ slightly from one another, but their purpose is the same. The test period including the number of cycles and repetitions, and test conditions are determined in the same manner as the number of samples, by the quality level of design and the quality level required by the customer. However, mounting conditions, operating periods, as well as the acceleration of tests are considered to select the most effective and cost-efficient conditions. Reliability tests must be reproducible. It is preferable to select a standardized testing method. For this reason, tests are carried out according to international or national test standards.

The definition of a device failure is important in planning reliability tests. It is necessary to clarify the characteristics of the device being tested and set failure criteria. These failure criteria must be used in determining whether any variations in the device characteristics before and after the test are in an allowable range. The reliability of a device is usually determined by its design and manufacturing process. Therefore, a reliability test is conducted by taking samples from a population

within the range that the factors of design and manufacturing process are the same.

The sampling standard for semiconductor devices is determined by both the product's reliability goal and the customer's reliability requirements to achieve the required level of "lot" tolerance percent defective (LTPD). The reliability tests for materials and processes are performed with the number of samples determined independently. For newly developed processes and packages, however, there are cases in which the existing processes or packages cannot be accelerated within the maximum product rating or in which new failures cannot be detected within a short period of time. In these cases, it is important to perform reliability testing based on the failure mechanism by means of Test Element Groups (TEGs). To ensure reliability during product design, we conduct testing according to the failure mechanism in the same process as the products, clarify the acceleration performance for temperature, electric field, and other factors, and reflect this in the design rules used in designing the product.

The standards and specifications related to the reliability of semiconductor devices can be classified as shown in Table 1.5. Reliability methods are often subject of standardization in several organizations. In those cases, the standards were usually derived from a common source, e.g. MIL-STD-883, and only minor differences exist between different standards.

The MIL standards have been used as industry standards for many years, and also today many companies still refer to the MIL standards. With the advent of new technologies, other standards have become more important. MIL-STD-883 establishes test methods and other procedures for integrated circuits. It provides general requirements, mechanical, environmental, durability and electrical test methods, and quality assurance methods and procedures for procurement by the US military. The test methods described in MIL-STD-883 include environmental test methods, mechanical test methods, digital electrical test methods, linear electrical test methods, and test procedures. MIL-STD-750 specifies mechanical, environmental, and electrical test methods and conditions for discrete semiconductor devices. MIL-STD-202 specifies mechanical and environmental test methods for electronic and electrical components. MIL-HDBK-217 is a US military handbook for reliability prediction of electronic equipment. This handbook introduces methods for calculating the predicted failure rate for each category of parts ion electronic equipment, including e.g. mechanical, components, lamps, and advanced semiconductor devices such as microprocessors.

Table 1.4 shows the subject, purposes, and contents of some reliability tests carried out at some laboratories.

The standards and specifications related to the reliability of semiconductor devices can be classified as shown in Table 1.5. Reliability methods are often subject of standardization in several organizations. In those cases, the standards were

Table 1.4 Examples of reliability testing conducted when new products are developed.

Phase	Purpose	Context	Contents
Development of semiconductor products	To verify that the design reliability goals and the customer's reliability requirements are satisfied	Quality approval for the product developed	The following and other tests are carried out as required 1) Standard tests 2) Accelerated tests 3) Marginal tests 4) Structural analysis
Development or change of materials and processes	To verify that the materials and processes used for the product under development satisfy the design reliability goals and the customer's reliability requirements To understand the quality factors and limits that are affected by materials and processes	Quality approval for wafer process/package developed or changed	Products are used to perform acceleration tests and other analyses as required with attention paid to the characteristics and changes of materials and processes
Pilot run before mass production	To verify that the production quality is at the specified level	Quality approval for mass production	This category covers reliability tests for examining the initial fluctuation of parameters that require special attention, as well as fluctuations and stability in the initial stage of mass production

Table 1.5 Classification of test standards.

Class	Example
International standard	IEC
National standards	USA (ANSI), CNES, DGA
Governmental standards	MIL, ESA
Industrial standards	EIA, JEDEC; JEITA, SIA, SAE
Standard by expert groups	ESDA, FIDES
Standards by semiconductor users	AEC Q100

usually derived from a common source, e.g. MIL-STD-883, and only minor differences exist between different standards.

The MIL standards have been used as industry standards for many years, and also today many companies still refer to the MIL standards. With the advent of new technologies, other standards have become more important. MIL-STD-883 establishes test methods and other procedures for integrated circuits. It provides general requirements; mechanical, environmental, durability, and electrical test methods; and quality assurance methods and procedures for procurement by the US military. The test methods described in MIL-STD-883 include environmental test methods, mechanical test methods, digital electrical test methods, linear electrical test methods, and test procedures. MIL-STD-750 specifies mechanical, environmental, and electrical test methods and conditions for discrete semiconductor devices. MIL-STD-202 specifies mechanical and environmental test methods for electronic and electrical components. MIL-HDBK-217 is a US military handbook for reliability prediction of electronic equipment. This handbook introduces methods for calculating the predicted failure rate for each category of parts ion electronic equipment, including e.g. mechanical, components, lamps, and advanced semiconductor devices such as microprocessors.

The IEC was founded in 1908 and is the leading global organization that prepares and publishes international standards (ISs) for electrical, electronic, and related technologies. IEC standards serve as a basis for national standardization and as references when drafting international tenders and contracts. IEC publishes IS, Technical specifications (TS), technical reports (TR), and guides. Examples of reliability-related IEC standards are IEC 60068 (which deals with environmental testing, this standard contains fundamental information on environmental testing procedures and severities of tests. It is primarily intended for electrotechnical products), IEC 60749 series (deals with mechanical and climatic test methods; these standards are applicable to semiconductor devices including discrete and integrated circuits), IEC 62047 (about micro-electromechanical devices), IEC 62373/74 on wafer level reliability, IEC/TR 62380 about reliability data handbook Universal model for reliability prediction of electronics components, printed circuit boards (PCBs) and equipment.

JEDEC Solid State Technology Association (formerly Joint Electron Device Engineering Council) is the semiconductor engineering standardization division of the Electronic Industries Alliance (EIA), a US-based trade association that represents all areas of the electronics industry. JEDEC was originally created in 1960 to cover the standardization of discrete semiconductor devices and later expanded in 1970 to include integrated circuits.

JEDEC spans a wide range of standards related to reliability. These standards are among the most referenced by semiconductor companies in the United States and Europe. The JEDEC committees for reliability standardization are JC-14

Committee on quality and reliability of solid-state products, JC-14.1 Subcommittee about reliability test methods for packaged devices, JC-14.2 Subcommittee on wafer level reliability, JC-14.3 Subcommittee about silicon devices reliability qualification and monitoring., JC-14.4 Subcommittee on quality processes and methods, JC-14.6 Subcommittee about failure analysis, JC-14.7 Subcommittee on Gallium Arsenide reliability and quality standards. JEDEC publishes standards, publications, guidelines, standard outlines, specifications, and ANSI and EIA standards.

JEITA was formed in 2000 from a merger of The Electronic Industries Association of Japan (EIAJ) and Japan Electronic Industry Development Association (JEIDA). Its objective is to promote the healthy manufacturing, international trade and consumption of electronics products. JEITA's main activities are supporting new technological fields, developing international cooperation, and promoting standardization.

Principal product areas covered by JEITA are digital home appliances, computers, industrial electronic equipment, electronic components and electronic devices (e.g. discrete semiconductor devices and ICs). JEITA standards related to semiconductor reliability are ED4701 which containing environmental and endurance test methods, ED4702 about mechanical tests, ED4704 on failure mode driven tests (wafer level reliability [WLR]), EDR4704 about guidelines for accelerated testing, EDR4705 on SER, EDR4706 about FLASH reliability JEITA standards are available online.

The Automotive Electronics Council and the ESD association are the most important examples of user groups and expert groups, respectively. Table 1.6 shows the reliability test standards [29, 30].

The purpose of semiconductor device reliability testing is primarily to ensure that shipped devices, after assembly and adjustment by the customer, exhibit the desired lifetime, functionality, and performance in the hands of the end user. Nevertheless, there are constraints of time and money. Because semiconductor devices require a long lifetime and low failure rate, testing devices under actual usage conditions would require a great amount of test time and excessively large sample sizes. The testing time is generally shortened by accelerating voltage, temperature, and humidity. In addition, statistical sampling is used, considering the similarities between process and design, so as to optimize the number of test samples. Temperature, temperature and humidity, voltage, temperature difference, and current are the accelerated stresses which can be applied to devices.

Reliability tests are performed under known stress conditions. The testing procedures and conditions differ slightly from one another although their purpose is the same. The test period including the number of cycles and repetitions, and test conditions are determined in the same manner as the number of samples, by the quality level of design and the quality level required by the customer. However,

Table 1.6 Reliability test standard.

Japan Electronics and Information Technology Industries Association (JEITIA) Standards	
EIAJ ED-4701/001	Environmental and endurance test method for Semiconductor Devices (General)
EIAJ ED-4701/100	Environmental and endurance test method for Semiconductor Devices (Lifetime Test I)
EIAJ ED-4701/200	Environmental and endurance test method for Semiconductor Devices (Lifetime Test II)
EIAJ ED-4701/300	Environmental and endurance test method for Semiconductor Devices (Strength Test I)
EIAJ ED-4701/400	Environmental and endurance test method for Semiconductor Devices (Strength Test I)
EIAJ ED-4701/50	Environmental and endurance test method for Semiconductor Devices (Other Tests)
US Military (MIL) Standards	
MIL-STD-202	Test method for Electronic and Electrical Parts
MIL-STD-883	Test method and Procedures for Microelectronics
International Electromechanical Commission (IEC) Standards	
IEC 60749	Semiconductor Devices – Mechanical and climatic test methods
IEC 60068-1	Environmental testing Part 1: General and guidance
IEC 60068-2	Environmental testing Part 2
Join Electron Devices Engineering (JEDEC) Standards	
JESD 22	Series Test Methods
JESD 78	IC Latch-Up Test
JEP 122	Failure Mechanisms and Models for Semiconductor Devices
European Cooperation for Space Standardization (ECSS) [26]	
ECSS-Q-ST-60-02C	Space product assurance – ASIC, FPGA and IP Core product assurance
ECSS-Q-30-08A	Components reliability data sources and their use
ECSS-Q-ST-30-11C	Derating – EEE components
Japanese Industrial Standards (JIS)	
JIS C 00xx	Environmental Testing Methods (Electrical and Electronics) Series
CENELEC Electronic Components Committee (CECC)	
CECC 90000	General Specification Monolithic Integrated Circuits
CECC 90100	General Specification Digital Monolithic Integrated Circuit

mounting conditions, operating periods, as well as the acceleration of tests are considered to select the most effective and cost-efficient conditions.

The definition of a device failure is important in planning reliability tests. It is necessary to clarify the characteristics of the device being tested and set failure criteria. These failure criteria must be used in determining whether any variations in the device characteristics before and after the test are in an allowable range. The reliability of a device is usually determined by its design and manufacturing process. Therefore, a reliability test is conducted by taking samples from a population within the range that the factors of the design and manufacturing process are the same. The sampling standard for semiconductor devices is determined by both the product's reliability goal and the customer's reliability requirements to achieve the required level of LTPD. The reliability tests for materials and processes are performed with the number of samples determined independently. For newly developed processes and packages, however, there are cases in which the existing processes or packages cannot be accelerated within the maximum product rating or in which new failures cannot be detected within a short period of time. In these cases, reliability testing based on the failure mechanism by means of TEGs is performed. To ensure reliability during product design, different tests are performed, according to the failure mechanism in the same process as the products, to clarify the acceleration performance for temperature, electric field, and other factors, and reflect this in the design rules used in designing the product [32].

1.4.2 Accelerated Testing

As mentioned by JEDEC, accelerated testing is a powerful tool that can be effectively used in two very different ways: in a qualitative or a quantitative manner. Qualitative accelerated testing is used primarily to identify failures and failure modes while quantitative accelerated testing is used to make predictions about a product's life characteristics (e.g. MTTF, B10 life, etc.) under normal use conditions. In accelerated testing, the quantitative knowledge builds upon the qualitative knowledge. Accelerated testing to be used in a quantitative manner for reliability prediction requires a physics-of-failure approach, i.e. a comprehensive understanding and application of the specific failure mechanism involved and the relevant activating stresses.

In general, accelerated lifetime tests are conducted under more severe stress conditions than actual conditions of use (fundamental conditions). They are methods of physically and chemically inducing the failure mechanisms to assess, in a short time, device lifetime, and failure rates under actual conditions of use.

By increasing the degree of stressors (e.g. temperature and voltage), like by increasing the frequency of the applied stress, using tighter failure criteria, or using test vehicles/structures specific to the failure modes, the degree of acceleration is increased.

The stress methods applied in accelerated lifetime tests are constant stress, and step stress methods. The constant stress method is a lifetime test where stress, such as temperature or voltage, is held constant and the degree of deterioration of properties and time to failure lifetime distribution are evaluated. In the step stress method, contrary to the constant stress method, the time is kept constant, and the stress is increased in steps and the level of stress causing failure is observed.

Typical examples of tests using the constant stress method, the step stress method, and the cyclic stress method, a variation of the constant stress method, are shown in Table 1.7.

An accurate quantitative accelerated test requires defining the anticipated failure mechanisms in terms of the materials used in the product to be tested. It is important to determine the environmental stresses to which the product will be exposed when operating and when not operating or stored, choosing a test or combination of tests based on the failure mechanisms that are anticipated to limit the life of the product. Acceleration models that should be considered include:

- Arrhenius Temperature Acceleration for temperature and chemical aging effects
- Inverse Power Law for any given stress
- Miner's Rule for linear accumulated fatigue damage
- Coffin-Manson non-linear mechanical fatigue damage
- Peck's Model for temperature and humidity combined effects
- Eyring/Black/Kenney models for temperature and voltage acceleration.

Table 1.8 describes each of these models, their relevant parameters, and frequent applications of each.

For a known or suspected failure mechanism, all stimuli affecting the mechanism based on anticipated application conditions and material capabilities are identified. Typical stimuli may include temperature, electric field, humidity, thermomechanical stresses, vibration, and corrosive environments. The choice of accelerated test conditions is based on material properties and application requirements; the time interval should be reasonable for different purposes as well. Accelerated stressing must be weighed against generating fails that are not pertinent to the experiment, including those due to stress equipment or material problems, or "false failures" caused by product overstress conditions that will never occur during actual product use. Once specific conditions are defined, a matrix of

Table 1.7 Typical example of accelerated lifetime tests.

Applied stress method	Purpose	Accelerated test	Main stressor	Failure mechanism
Constant stress method	Investigation of the effects of constant stress on a device	High-temperature storage test	Temperature	Junction degradation, impurities deposit, ohmic contact, inter-metallic chemical compounds
		Operating lifetime test	Temperature Voltage Current	Surface contamination, junction degradation, mobile ions, equilibrium molecular dynamic (EMD)
		High-temperature high humidity storage	Temperature Humidity	Corrosion surface contamination, pinhole
		High-temperature high humidity bias	Temperature Humidity Voltage	Corrosion surface contamination, junction degradation, mobile ions
Cyclic stress method	Investigation of the effects of repeated stress	Temperature cycle	Temperature difference Duty cycle	Cracks, thermal fatigue, broken wires and metallization
		Power cycle	Temperature difference Duty cycle	Insufficient adhesive strength of ohmic contact
		Temperature humidity cycle	Temperature difference Humidity difference	Corrosion, pinhole, surface contamination
Step stress method	Investigation of the stress limit that a device can withstand	Operation stress	Temperature Voltage Current	Surface contamination, junction degradation, mobile ions, EMD
		High-temperature reverse bias	Temperature Voltage	Surface contamination, junction degradation, mobile ions, TDDB

Table 1.8 Frequently used acceleration models, their parameters, and applications.

Model name	Description/ parameters	Application examples	Model equation
Arrhenius Acceleration Model	Life as a function of temperature or chemical aging	Electrical insulation and dielectrics, solid state and semiconductors, intermetallic diffusion, battery cells, lubricants and greases, plastics, incandescent lamp filaments	$Life = A_0 \cdot e^{-\frac{E_a}{k_B T}}$ where $Life$ = median Life of a population A_0 = scale factor determined by experiment e = base natural logarithms E_a = activation energy (unique for each failure mechanism) k_B = Boltzmann's constant = 8.62×10^{-5} eV/K T = temperature (in K)
Inverse Power Law	Life as a function of any given stress	Electrical insulation and dielectrics (voltage endurance), ball and roller bearings, incandescent lamp filaments, flash lamps	$\frac{Life\ at\ normal\ stress}{Life\ at\ accelerated\ stress} = \left(\frac{Accelerated\ stress}{Normal\ stress}\right)^N$ where $N = Acceleration\ factor$
Miner's Rule	Cumulative linear fatigue damage as a function of flexing	Metal fatigue (valid only up to the yield strength of the material)	$CD = \sum_{i=1}^{k} \frac{C_{Si}}{N_i} \leq 1$ where: CD = Cumulative damage C_{Si} = Number of cycles applied @ stress Si Ni = number of cycles to failure under stress Si (determined from a S-N diagram for that specific material) K = number of loads applied

(*Continued*)

Table 1.8 (Continued)

Model name	Description/ parameters	Application examples	Model equation
Coffin-Manson	Fatigue life of metals (ductile materials) due to thermal cycling and/or thermal shock	Solder joints and other connections	$Life = \frac{A}{(\Delta T)^B}$ where $Life$ = Cycles to failure A = scale factor determined by experiment B = scale factor determined by experiment ΔT = Temperature change
Peck's	Life as a combined function of temperature and humidity	Epoxy packaging	$\tau = A_0 (RH)^{-2.7} e^{\left(\frac{0.79}{k_B T}\right)}$ where τ = median life (time-to-failure) A_0 = scale factor determined by experiment RH = relative humidity
Peck's Power Law	Time to failure as a function of relative humidity, voltage and temperature	Corrosion	
Eyring/ Black/ Kenney	Life as a function of temperature and voltage (or current density – Black)	Capacitors, electromigration in aluminum conductors	$\tau = \frac{A}{T} e^{\left(\frac{B}{k_B T}\right)}$ where τ = median life (time-to-failure) A = scale factor determined by experiment B = scale factor determined by experiment
Eyring	Time to failure as a function of current, electric field and temperature	Hot carrier injection, surface inversion, mechanical stress	$TF = B \cdot I_{sub}^{-N} \cdot e^{-\frac{E_a}{k_B T}}$ where TF = time-to-failure B = scale factor determined by experiment I_{sub} = peak substrate current during stressing N = 2 to 4 E_a = −0.1 to −0.2 eV (apparent activation energy is negative) $TF = B \cdot (T_0 - T)^{-N} \cdot e^{-\frac{E_a}{k_B T}}$

Table 1.8 (Continued)

Model name	Description/ parameters	Application examples	Model equation
Thermo-mechanical stress	Time to failure as a function of change in temperature	Stress generated by differing thermal expansion rates	where TF = time-to-failure B = scale factor determined by experiment T_0 = stress-free temperature for metal (approximate metal deposition temperature for aluminum) N = 2–3 E_a = 0.5–0.6 eV for grain boundary diffusion, ≈1 eV for intra-grain diffusion

accelerated tests embodying these stimuli must be developed that allows separate modeling of each individual stimulus. A minimum of two accelerated test cells is required for each identified stimulus; three or more are preferred. Several iterations may be required in cases where some stimuli produce only secondary effects. For instance, high-temperature storage and thermal cycle stressing may yield similar failures, where high-temperature storage alone is the root stimulus.

Test sample quantity, the definition of failure criteria (i.e. the definition of a failure depends on the failure mechanism under evaluation and the test vehicle being used), and choosing an appropriate distribution (fitting the observed data to the proper failure distribution), together determine the AFs [29,30,32].