Why the traditional reliability prediction models do not work - is there an alternative?

by Michael Pecht

Introduction

While it is generally believed that reliability prediction methods should be used to aid product design and product development, the integrity and auditability of the traditional prediction methods have been found to be questionable, in that the models do not predict field failures, cannot be used for comparative purposes, and present misleading trends and relations. This paper presents a historical overview of reliability predictions for electronics, discusses the traditional reliability prediction approaches, and then presents an effective alternative which is becoming widely accepted.

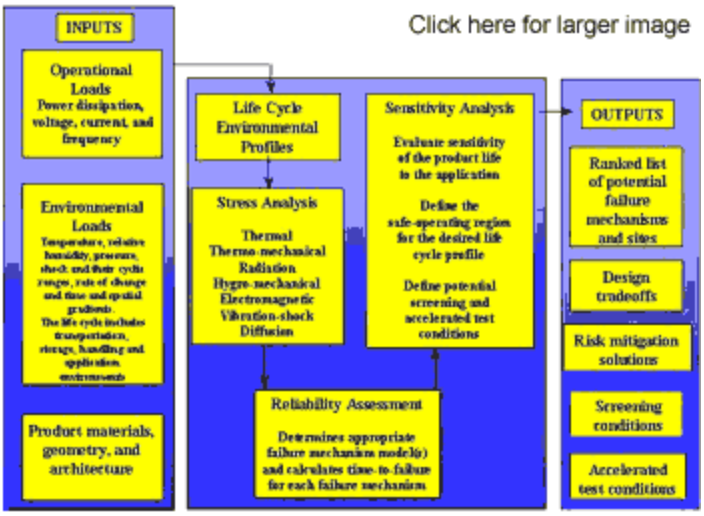

Figure 1 - Physics of Failure Process

What Is The Historical Perspective For Reliability Prediction of Electronics

Product and system reliability emerged as an identified engineering discipline in the late 1940's. This does not suggest that engineers and designers did not always strive for reliable designs. Engineers have naturally designed and operated equipment to "succeed" and they typically did so by providing a margin of strength over the anticipated loads (stresses). For example, in 1860, A. Wohler presented some of the earliest fatigue failure information, which occurred on stagecoach and railroad axles. The S-N (applied load versus cycles to failure) diagrams, which resulted from Wohler's work, were used to identify the load condition (called a fatigue limit) below which "no failures" should be expected.

Reliability engineering for electronics started with the establishment of the Ad Hoc Group on Reliability of Electronic Equipment on December 7, 1950, and the subsequent Advisory Group on the Reliability of Electronic Equipment (AGREE) formed by the US Department of Defense in 1952. One of the first reliability handbooks was titled "Reliability Factors for Ground Electronic Equipment" published in 1956 by McGraw-Hill under the sponsorship of the Rome Air Development Center (RADC). This publication contained 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 for electronics is traced to November 1956 with publication of the RCA release TR-ll00, titled "Reliability Stress Analysis for Electronic Equipment," which presented models for computing rates of component failures. This was also the first formal publication in which the concept of activation energy and the Arrhenius relationship were used in modeling electronic component failure rates. This publication was followed by the "RADC Reliability Notebook" on October 30, 1959; a report titled "Reliability Applications and Analysis Guide," by D. R. Earles of the Martin Company, in September 1960; and a report titled "Failure Rates," by D. R. Earles and M. F. Eddins, of AVCO Corporation, in April, 1962.

In December 1965, the U. S. Navy introduced the first reliability prediction handbook for electronics, MIL-HDBK-217A. In this first version, there was only a single point failure rate of 0.4 failures per million hours for all monolithic integrated circuits, regardless of the materials, the design, the manufacturing processes or the life cycle condition (environment and usage). This single-valued failure rate was illustrative of the infancy of the reliability models, and the fact that accuracy was less of a concern than standardization to the U. S. Department of Defense (*).

In July 1973, RCA proposed a prediction model for microcircuits, based on previous work by the Boeing Aircraft Company. The proposed model consisted of two additive portions: one reflecting a steady-state-temperature-related failure rate, and the second a mechanical-related failure rate. It was clear to RCA researchers, that any reliability model should reflect design, device and fabrication techniques, manufacturing, materials, and geometries. Unfortunately, this attitude was not shared by the RADC, and the model was greatly simplified in-house by modeling the device reliability with a pair of complexity factors, and assuming an exponential failure distribution during the operational life of the device. This model was then published as MIL-HDBK-217B under the preparing activity of the Air Force. The exponential distribution assumption still remains in many handbooks today, in spite of overwhelming evidence suggesting that it is often not appropriate [1].

Rapid improvements and increased complexity of microelectronic devices pushed the application of MIL-HDBK-217B beyond reason. A good example was the limitations of the early models to address a 64K RAM. In fact, when the RAM model was extrapolated to include at that time the common 64K capability, the resulting mean time between failures was 13 seconds [2]. As a result of this type of incident, on April 9, 1979 MIL-HDBK-217C was published to "band-aid" the problems. Although MIL-HDBK-217C was updated to MIL-HDBK-217D on January 15, 1982, to MIL-HDBK-217E on October 27, 1986, and to MIL-HDBK-217F [3] in December 1991, the handbook could never keep up-to-date with the technology advances; the field data took too long to collect and the models were not based on sound engineering fundamentals.

In the last version of the document, two teams were under contract to provide guidelines for this update. The IIT Research Institute/Honeywell SSED team developed reliability models for CMOS, VHSIC, and VHSIC- like devices, and the University of Maryland (CALCE Electronic Products and Systems Center) /Westinghouse team developed reliability models for advanced technology microelectronic devices to include high gate count devices such as VHSIC, VLSI, and complex packaging approaches such as surface mount, ASIC, and hybrids. Both teams suggested:

- that the constant failure rate model not be used;
- that some of the individual wearout failure mechanisms (i.e., electromigration and time-dependent dielectric breakdown) be modeled with a lognormal distribution;
- that the Arrhenius type formulation of the failure rate in terms of temperature should not be included in the package failure model; and
- that stresses such as temperature change and humidity be considered. In particular, both the IIT/Honeywell study and the University of Maryland/Westinghouse study noted that temperature cycling was becoming 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 was further supported by a National Institute of Standards and Technology (NIST) study [4], and an Army Fort Monmouth [5] study, which stated that the influence of steady-state temperature on microelectronic reliability under typical operating changes was being inappropriately modeled by an Arrhenius relationship.

Reliance on MIL-HDBK-217 proved costly. For example, the use of MIL-HDBK-217 upfront in the design process, had initially led to design decisions maximizing the junction temperature in the F22 Advanced Tactical Fighter electronics to 60°C and in the Comanche Light Helicopter to 65°C. In fact, 125°C might have been acceptable and could have resulted in substantial improvements in life cycle cost, weight, volume, support, and reliability. Furthermore, cooling temperatures as low as -40°C at the electronic's rails were at one time required to obtain the specified junction temperatures; the resulting temperature cycles are known to precipitate many unique failure mechanisms.

Problems with the Traditional Approach to Reliability Prediction
Problems that arise with the traditional reliability prediction methods and some of the reasons these problems exist are described below .

1) Up-to-date collection of the pertinent reliability data needed for the traditional reliability prediction approaches is a major undertaking, especially when manufacturers make yearly improvements. Most of the data used by the traditional models is out-of-date. For example, the connector models in MIL-HDBK-217 have not been updated for at least 10 years, and were formulated based on data 20 years old.

Nevertheless, reliance on even a single outdated or poorly conceived reliability prediction approach can prove costly for systems design and development. For example, the use of military allocation documents (JIAWG), which utilizes the MIL-HDBK-217 approach upfront in the design process, initially led to design decisions maximizing the junction temperature in the F-22 advanced tactical fighter electronics to 60°C and in the Comanche light helicopter to 65°C. Boeing noted that, "The System Segment Specification normal cooling requirements were in place due to military electronic packaging reliability allocations and the backup temperature limits to provide stable electronic component performance. The validity of the junction temperature relationship to reliability is constantly in question and under attack as it lacks solid foundational data."

For the Comanche, cooling temperatures as low as -40°C at the electronic's rails were at one time required to obtain the specified junction temperatures; even though the resulting temperature cycles were known to precipitate standing water as well as many unique failure mechanisms. Slight changes have been made in these programs when these problems surfaced, but scheduling costs cannot be recovered.

2) In general, equipment removals and part failures are not equal. Often field removed parts are re-tested as operational (called re-test OK, or fault-not-found, or could-not duplicate) and the true cause of "failure" is never determined. As the focus of reliability engineering has been on probabilistic assessment of field data, rather than on failure analysis, it has generally been perceived to be cheaper for a supplier to replace a failed subsystem (such as a circuit card) and ignore how the card failed.

3) Many assembly failures are not component-related but due to an error in socketing, calibration or instrument reading or due to the improper interconnection of components during a higher level assembly process. Today, reliability limiting items are much more likely to be in the system design (such as misapplication of a component, inadequate timing analysis, lack of transient control, stress-margins oversights), than in a manufacturing or design defect in the device.

4) Failure of the component is not always due to a component-intrinsic mechanism but can be caused by: (i) an inadvertent over-stress event after installation; (ii) latent damage during storage, handling or installation after shipment; (iii) improper assembly into a system; or (iv) choice of the wrong component for use in the system by either the installer or designer. Variable stress environments can also make a model inadequate in predicting field failures. For example, one Westinghouse fire control radar has been used in a fighter aircraft, a bomber, and on the top mast of a ship, each with its unique configuration, packaging, reliability and maintenance requirements.

5) Electronics do not fail at a constant rate, as predicted by the models. The models were originally used to characterize device reliability because earlier data was tainted by equipment accidents, repair blunders, inadequate failure reporting, reporting of mixed age equipment, defective records of equipment operating times, mixed operational environmental conditions. The totality of these effects conspired to produce what appeared to be an approximately constant hazard rate. Further, earlier devices had several intrinsic failure mechanisms which manifested themselves as several subpopulations of infant mortality and wear-out failures resulting in a constant failure rate. The above assumptions of constant failure rate do not hold true for present day devices.

6) The reliability prediction models are based upon industry-average values of failure rates, which are neither vendor- nor device-specific. For example, failures may come from defects caused by uncontrolled fabrication methods, some of which were unknown and some of which were simply too expensive to control (i.e. the manufacturer took a yield loss, rather than putting more money to control fabrication). In such cases, the failure was not representative of the field failures upon which the reliability prediction was based.

7) The reliability prediction was based upon an inappropriate statistical model. For example, a failure in a lot of radio-frequency amplifiers was detected at Westinghouse in which the insulation of a wire was rubbed off against the package during thermal cycling. This resulted in an amplifier short. X-ray inspection of the amplifier during failure analysis confirmed this problem. The fact that a pattern failure (as opposed to a random failure) existed under the given conditions, proved that the original MIL-HDBK-217 modeling assumptions were in error, and that either an improvement in design, improved quality, or inspection was required.

8) The traditional reliability prediction approaches can produce what are likely to be highly variable assessments. As one example, the predicted reliability, using different prediction handbooks, for a

memory board with 70 64k DRAMS in a "ground benign" environment at 40°C, varied from 700 FITS to 4,240,460 FITS. Overly optimistic predictions may prove fatal. Overly pessimistic predictions can increase the cost of a system (e.g., through excessive testing, or a redundancy requirement), or delay or even terminate deployment. Thus, these methods should not be used for preliminary assessments, baselining or initial design tradeoffs.

An Alternative Approach: Physics-of-Failure

Many of the leading US commercial electronics companies have now abandoned the traditional methods of reliability prediction. Instead, they use reliability assessment techniques, that are based on the root-cause analysis of failure mechanism, failure modes and failures causing stresses. This approach, called physics-of-failure, has proven to be effective in the prevention, detection, and correction, of failures associated with design, manufacture and operation of a product.

The physics-of-failure (PoF) approach to electronics products, is founded on the fact that failure mechanisms are governed by fundamental mechanical, electrical, thermal, and chemical processes. By understanding the possible failure mechanisms, potential problems in new and existing technologies can be identified and solved before they occur.

The PoF approach begins within the first stages of design (see Figure 1). A designer defines the product requirements, based on the customer's needs and the supplier's capabilities. These requirements can include the product's functional, physical, testability, maintainability, safety, and serviceability characteristics. At the same time, the service environment is identified, first broadly as aerospace, automotive, business office, storage, or the like, and then more specifically as a series of defined temperature, humidity, vibration, shock, or other conditions. The conditions are either measured, or specified by the customer. From this information, the designer, usually with the aid of a computer, can model the thermal, mechanical, electrical, and electrochemical stresses acting on the product.

Next, stress analysis is combined with knowledge about the stress response of the chosen materials and structures to identify where failure might occur (failure sites), what form it might take (failure modes), and how it might take place (failure mechanisms). Failure is generally caused by one of the four following types of stresses: mechanical, electrical, thermal, or chemical, and it generally results either from the application of a single overstress, or by the accumulation of damage over time from lower level stresses. Once the potential failure mechanisms have been identified, the specific failure mechanism model is employed. The reliability assessment consists of calculating the time to failure for each potential failure mechanism, and then, using the principle that a chain is only as strong as its weakest link, choosing the dominant failure sites and mechanisms as those resulting in the least time to failure. The information from this assessment can be used to determine whether a product will survive for its intended application life, or it can be used to redesign a product for increased robustness against the dominant failure mechanisms. The physics-of-failure approach is also used to qualify design and manufacturing processes to ensure that the nominal design and manufacturing specifications meet or exceed reliability targets.

Computer software has been developed by organizations such as Phillips and the CALCE EPRC at the University of Maryland, to conduct a physics-of-failure analysis at the component level. Numerous organizations have PoF software which is used at the circuit card level. These software tools make

design, qualification planing and reliability assessment, manageable and timely.

Summary and Comments
The physics-of-failure approach has been used quite successfully for decades in the design of mechanical, civil and aerospace structures. This approach is almost mandatory for buildings and bridges, because the sample size is usually one, affording little opportunity for testing the completed product, or for reliability growth. Instead, the product must work properly the first time, even though it often relies on unique materials and architectures placed in unique environments.

Today, the PoF approach is being demanded by (1) suppliers to measure how well they are doing and to determine what kind of reliability assurances they can give to a customer and (2) by customers to determine that the suppliers know what they are doing and that they are likely to deliver what is desired. In addition, PoF is used by both groups to assess and minimize risks. This knowledge is essential, because the supplier of a product which fails in the field loses the customer's confidence and often his repeat business, while the customer who buys a faulty product endangers his business and possibly the safety of his customers.

In terms of the US military, the U.S. Army has discovered that the problems with the traditional reliability prediction techniques are enormous and have canceled the use of MIL-HDBK-217 in Army specifications. Instead, they have developed Military Acquisition Handbook-179A which recommends best commercial practices, including physics-of-failure.

References
The traditional approach to predicting reliability is common to various international handbooks.

[MIL-HDBK-217 1991; TR-TSY-000332 1988; HRDS 1995; CNET 1983; SN 29500 1986]; all derived from some predecessor of MIL-HDBK-217.

[1] F. R. Nash, Estimating Device Reliability: Assessment of Credibility. Boston, MA: Kluwer, 1993, ch. 6. (back to article)

[2] L. Phaller, Westinghouse Electric, private communication, 1991. (back to article)

[3] Reliability Prediction of Electronic Equipment, MIL-HDBK- 217F. Washington, DC: US Gov. Printing Office, Dec. 1991. (back to article)

[4] J. Kopanski, D. L. Blackbum, G. G. Harman, and D. W. Berning, "Assessment of reliability concerns for wide temperature operation of semiconductor device circuits," in Trans. 1st Int. High Temperature Electronics Conf. (Albuquerque, NM, 1991), pp. 137-142. (back to article)

[5] M. Pecht, P. Lall, and E. Hakim, Temperature Dependence on Integrated Circuit Failure Mechanisms: Advances in Thermal Modeling III, A. Bar-Cohen and A. D. Kraus, Eds. New York: IEEE and ASME Press, Dec. 1992, ch. 2. (back to article)

(*) Stemming from a perceived need to place a figure of merit on a system's reliability, US government procurement agencies sought standardization of requirement specifications and a prediction process.

Without such standardization the military was concerned that each supplier would develop their own predictions based on its own data, and it would be difficult to evaluate system predictions against requirements based on components from different suppliers or to compare competitive designs for the same component or system. Thus, even though the values calculated from the models were unrealistic and often orders of magnitude in error, the view was that there was commonality. (back to article)

Michael Pecht, George E. Dieter Professor of Mechanical Engineering and founder and director of the CALCE Electronic Product and Systems Center of the University of Maryland, College Park, MD 20742, USA. The Center provides a knowledge and resource base to support the development of competitive electronic components, products and systems. The Center is supported by more than 100 electronic product and systems companies from all sectors, including telecommunications, computer, avionics, automotive, and military manufacturers. Mr. Pecht's contact information: tel: +1 (301) 405 5323 - FAX: +1 (301) 314 9269 - e-mail: pecht@eng.umd.edu
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