Predicting the Reliability of Electronic Equipment

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The use of reliability predictions in the design and operation of electronic equipment has been an evolutionary and very controversial process, and over the past decade, reliability prediction methods have been a focal point for a flurry of books, papers, editorials, opinions, special sessions, and workshops. While it is generally believed that reliability assessment methods should be used to aid in product design and development, the integrity and auditability of the reliability 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 discusses the role of reliability prediction and assessment in design, development, and deployment of electronic equipment; overviews the history of reliability predictions for electronics; discusses the advantages and disadvantages of some current methods; and presents some of the key research questions which need to be addressed.

I. The Role of Reliability Assessment and Prediction in the Design, Development, and Deployment of Electronic Equipment

Reliability assessment (based on the root-cause analysis of failure mechanisms, failure sites, failure modes, and failure-causing stresses) has proven to be effective in the prevention, detection, and correction of failures associated with design, manufacture, and operation of a product. Traditional reliability prediction methods (based on the statistical curve fitting of field failure data) have also been used to address design and operation, as well as various supportability issues, but, as will be subsequently discussed, have not been very effective.

Figure 1 depicts the interactions between reliability assessment and prediction inputs with design, development, and support tasks. An overview of various tasks and the reliability inputs is given below.

Allocation: Allocation entails the assignment of reliability goals to the equipment and the subsequent assimilation of reliability goals to subsystems, assemblies, and parts. That is, commencing with an overall goal for product reliability, allowable reliabilities are apportioned. The reliability goal must be based on the expected application, in terms of the life-cycle product profile.

Reliability predictions are often used to define the attainable minimum needs for system success, and allocation information often goes to the contractor as a minimum prediction of the "deliverable reliability." In some cases, allocation information becomes the assumed limit for reliability growth. This can be a mistake if this information limits, in any way, reliability improvement.

System Architecture and Device Specification: As the physical design begins, reliability assessments will guide tradeoffs in the system architecture and part selection, although functional and performance characteristics play the dominant role. Individual components must not be considered to be the only, or necessarily the major, source of failures. Interconnections and structures must also be selected properly. Redundancy may be deemed necessary for mission completion when consequences of failure are severe and when there is a lack of understanding of the actual reliability drivers.

While reliability predictions are often recommended (by the U.S. military) for selecting and comparing alternative architectures and parts, because of the time delays in collecting field data, the advantages of new technologies and cost-effective methods are not exploited. For example, use of the reliability prediction method MIL-HDBK-217F can lead the designer to select ECL for high-speed and high-reliability applications over Bi-CMOS, when in fact Bi-CMOS is now a mature and more highly reliable technology.

Stress Analysis: Given the system architecture and parts, reliability prediction models are used to assess the influence of the magnitude and duration of the stresses on the reliability of the parts and systems, so that stress and environment-controlling systems (i.e., vibration and cooling systems) and derating techniques can be implemented. Temperature, humidity, electrical fields, vibration, and radiation are major stress variables affecting reliability.

Derating: Derating is based on the concept that operating electrical, thermal-mechanical and chemical stresses accelerate failures in a predictable manner, which if controlled, will improve reliability. For electronics, typical derating parameters include current, voltage, power, fanout, fre-

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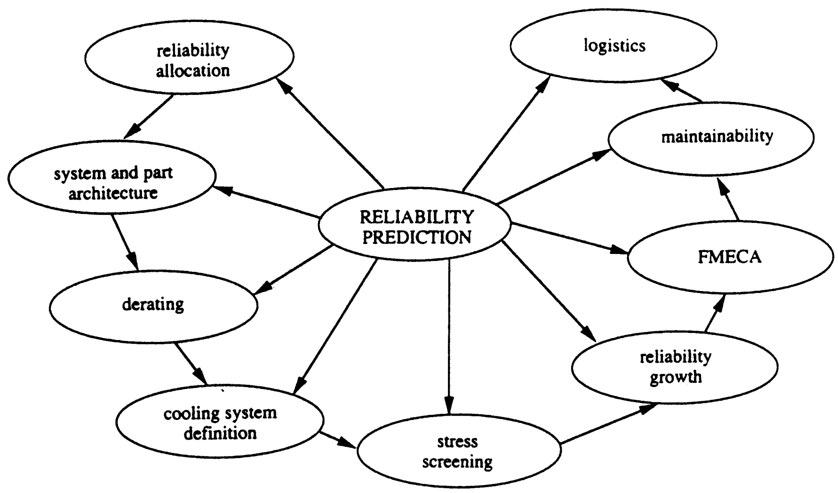

Fig. 1. Impact of reliability tasks on electronics.

quency, and operating (i.e., junction) temperature. Using the mathematical expressions of reliability prediction, one can often derive a derate schedule. Such schedules must be based on the dominant failure mechanisms for the particular electronics and must include the mechanical and structural elements, and device interactions, as well as the devices themselves.

Environmental Controls: There are various ways in which both the operating and environmental stresses can be controlled to improve reliability. Methods can be applied to keep harmful stresses (i.e., high and low temperatures, temperature cycles, high shock loads, high humidity, high radiation) away from sensitive devices and structures. Methods can also be applied to manage the system environment to obtain specific stress conditions. However, the cost and complexity of lowered stresses must be balanced against the cost and complexity of electronic complications to improve reliability by improved architectures and parts.

For example, steady-state temperature is often considered a major reliability factor, and much effort goes into lowering the temperature of the electronics. Although the traditional reliability prediction methods provide a model relating steady-state temperature to reliability, recent studies show that these relations are false [3], [4]. The apparent agreement between elevated temperatures and high failure rates should not necessarily lead to the conclusion that steady-state temperature is the cause of the failures, when in fact, temperature cycling may be the culprit [1], [2].

Stress Screening: Screening is the process by which defective parts, resulting from improper or out-of-control manufacture and assembly processes are detected and eliminated from a production batch. The principle involves inducing failures only in a population that already has "weak" parts, without reducing the reliability in the population of "strong" parts. The assumption is that through the application of short-term stresses, failures in the weak population can be precipitated, leaving a highly reliable population. Stress screening and burn-in (i.e., high-temperature screen) methods should not be based on reliability prediction models, but on acceleration stress levels that are often derived from the models for the potential failure mechanisms associated with potential problems in quality.

One type of screen is called burn-in, whereby the parts are operated for a period of time at high temperatures in order to precipitate defects, and hence failures, in the weak population of parts. For parts with low failure rates (i.e., below 10 failures per million device hours) Motorola noted that burn-in prior to usage does not remove many failures. On the contrary, it may cause failures due to handling [3].

Failure Modes, Effects and Criticality Analysis (FMECA): FMECA is a method to assess the interoperability of the parts, subassemblies, assemblies, and subsystems comprising the system. The objectives are: to determine the effects of failures on system operation; to identify the failures (especially "single-point" failures) critical to operational success and personnel safety; and to rank each potential failure according to the effects on other portions of the system, the probability of the failure occurring, and the criticality of the failure mode. Reliability predictions are often used to determine the probability of failure for each potential failure mode of each element in the system.

Maintainability and Logistics: Maintainability assessment often uses failure rate data from reliability prediction models to determine a mean-time-to-repair (MTTR) from element times-to-repair. The MTTR and metrics associated with acquisition, personnel, business, and other issues are then used, along with reliability predictions, to calculate logistics parameters such as availability and supportability. It is critical that the design team realizes that errors in the reliability predictions can be multiplied many times in the calculation of logistics metrics.

Certification: This is the culmination of the product development process, where it is agreed that the product is ready to be introduced to the market, having met or exceeded marketing, contractual, regulatory, or other goals for performance. Where reliability is an item affecting the final decision, many, if not all, of the foregoing reliability tasks will be involved.

Warranty: The expectations of reliability often affect the warranty terms. In some cases, suppliers may be required only to meet contractual goals without incentive for, or interest in, continued reliability improvement. That is, the concept of "attainable maximum" often provides an easily achieved cap on expectations. There are many other warranty arrangements, often intended to encourage suppliers to treat product reliability seriously. For example, the desired reliability goal bears economic considerations that affect life-cycle cost. Those costs are usually included in the fundamental economic analysis to determine economic feasibility of the total program, and in some cases can be an important item in total costs of ownership.

Failure Diagnosis and Corrective Actions: Failure diagnosis and corrective actions may be involved as part of a continuous product improvement program. When the goal is only to meet warranty requirements, there is seldom any interest in further diagnosis and corrective action after the goal has been met. In such an instance, reliability prediction may provide the basis for a hindrance to continued improvements in reliability. Reliability growth is associated with the continuous improvement in product reliability [4]. However, once again, the calculated reliability should not necessarily be considered to be the maximum achievable reliability.

Cost Effectiveness: Many variables affect cost effectiveness. Cost, weight, volume, dependability, and a myriad of other factors can all have a role, and thus cost effectiveness studies can be quite complex. When reliability is a major element, as is the case with aviation equipment, dollar cost can be less significant than other factors such as weight, volume, and power consumption in an unmanned space application. All costs must be defensible in terms of product value.

II. What is the Historical Perspective for Reliability Prediction

Only since World War II has product and system reliability emerged as an identified engineering discipline. This does not suggest that engineers and designers did not always strive for "failure-free" 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 or 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 stress versus cycles to failure) diagrams which resulted from Wohler's work, were used only to identify the fatigue limit, or the stress, below which "no failures" should be expected.

During and after World War II, electronic equipment complexity began to increase significantly. New demands were placed on system reliability, while new electronic components pushed the state of the art in terms of performance, packaging, and reliability. Stemming from a perceived need to place a figure of merit on a system's reliability, U.S. government procurement agencies sought standardization of requirement specifications and a prediction process. Without such standardization, each supplier could develop its 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. It was in this environment that engineers were asked to predict system reliability, even though the values calculated from the models were unrealistic and often orders of magnitude in error.

Reliability engineering for electronics started with the establishment of the Ad Hoc Group on Reliability of Electronic Equipment on December 7, 1950, although the modern field of reliability is often traced back to the Advisory Group on the Reliability of Electronic Equipment (AGREE) formed by the U.S. 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). While this publication did contain 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 is 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. This was the first formal publication in which the concept of activation energy and the Arrhenius relationship were used in modeling component failure rates. This publication was followed by the "RADC Reliability Notebook" on October 30, 1959, compendiums of failure rate models by D. R. Earles, "Reliability Applications and Analysis Guide," The Martin Company, September 1960, and D. R. Earles and M. F. Eddins, "Failure Rates," AVCO Corporation, April, 1962, and the publication of a military handbook format known as MIL-HDBK-217.

In the MIL-HDBK-217A document published on December 1, 1965 under the preparing activity of the Navy, there was only a single point failure rate of 0.4 failures per million hours for all monolithic integrated circuits, regardless of the stresses, the materials, or the architecture. This single-valued failure rate was illustrative of the infancy of the reliability models for integrated circuit technology, and the fact that accuracy was less of a concern than consistency or standardization.

In July 1973, RCA proposed a new 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 also clear to RCA researchers, that any reliability model should reflect device fabrication techniques, materials, and geometries. Unfortunately, this attitude was not shared by the RADC, and the model was greatly simplified in-house at the RADC by presenting characteristics of the devices as 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 the handbook today, in spite of overwhelming evidence suggesting that it is not appropriate [5].

The advent of more complex 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 or 256K 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 s [6]. As a result of this type of incident, a variety of notice changes to MIL-HDBK 217B appeared, and on April 9, 1979 MIL-HDBK-217C was published to "band-aid" the problems. 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 [7] became a prescribed U.S. military reliability prediction document, as a result of the RADC (now renamed Rome Laboratory) efforts on updating this version of the handbook. Two teams were under contract to provide guidelines for this update. The IIT Research Institute/Honeywell SSED team proposed new reliability models for CMOS, VHSIC, and VHSIC-like devices, and the Westinghouse/University of Maryland team proposed 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: 1) that the constant failure rate model not be used; 2) that some of the individual wearout failure mechanisms (i.e., electromigration and time-dependent dielectric breakdown) 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 be considered. In particular, both the IIT/Honeywell study and the University of Maryland/Westinghouse study noted 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) study [2], and an Army Fort Monmouth [1] study which stated that the influence of steady-state temperature on microelectronic reliability under typical operating changes is inappropriately modeled by an Arrhenius relationship.

Reliance on MIL-HDBK-217 can prove 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 would 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. Changes have been made in these programs, but costs in scheduling cannot be re-cooped.

III. The Current Practice of Reliability Prediction

Today, the U.S. Government (i.e., FAA) and the military, as well as some U.S. commercial manufacturers of electronic components, printed wiring and circuit boards, and electronic equipment and systems, subscribe to reliability prediction techniques (especially MIL-HDBK-217) in some manner; although sometimes unknowingly. In Japan, Taiwan, Singapore, Malaysia, and some of the leading U.S. electronics companies, the traditional methods of reliability prediction have been abandoned. Instead, they use reliability assessment techniques such as physics-of-failure whereby the root causes of failure are detected and corrected, rather than predicted [8], [9].

A. Traditional Approach [5]

The traditional approach to predicting the long-term reliability of devices in field use, involves implementing statistical models, using the exponential, or constant failure rate, model [10]. This model is common to six widely used reliability prediction procedures [11]–[16].[1] In a previous review [17] of reliability prediction procedures, it was suggested that many of the existing procedures derive from some predecessor of MIL-HDBK-217, the first version which appeared in 1965 [18]. This standard applies to microelectronic devices, discrete semiconductors, tubes, lasers, resistors, capacitors, relays, switches, connectors, printed wiring boards, etc. It is not difficult to reconstruct the rationale for the use of the constant failure rate (exponential) model as a description of the useful life of some component.

1) Data acquired several decades ago were "tainted by equipment accidents, repair blunders, inadequate failure reporting, reporting of mixed age equipment, defective records of equipment operating times, mixed operational environmental conditions..." [19]. The totality of these effects conspired to produce what appeared to be an approximately constant failure rate.

2) The first generations of components in the early days of the electronic era also contained many intrinsically high failure rate mechanisms [20]. The manifestation of different infant mortality and wearout failure mechanisms, varyingly

[1] Mentor Graphics Corporation, Wilsonville, OR, studied the availability of CAD tools for electronic reliability assessment from the following companies/products: Management Sciences, Inc.; System Effectiveness, Inc.; Power Tronics, Inc.; Item Software, Ltd.; Advanced Logistics Developments, Ltd.; Innovative Software Designs, Inc.; Technicomp, Inc.; Dynamic Soft Analysis, Inc.; and Rome Laboratory products, including RL-Oracle, R&MAT, REST, FASTER, RAMP, and noted that available CAD tools are all MIL-HDBK-217 based failure predictions.

present in subpopulations, might tend to produce a roughly constant failure rate during service life.

3) Even in the absence of significant intrinsic failure mechanisms, fragile early product subject to temporally random overstressing of external (environmental) origin would be expected to exhibit a useful life period in which the failure rate was more or less constant [21].

4) By the time equipment has been overhauled or repaired several times (substitution of new components for those that failed because of intrinsic wearout mechanisms) "it consists of components in a scattered state of wear" [22]. Even though the wearout of each component may be governed by a time-dependent distribution (e.g., lognormal or Weibull), the combination of devices, now with varyingly different projected lifetimes, could produce failures equally likely to occur during any interval of service life, and hence a time-independent failure distribution might result. For maintained systems in which failed units are replaced, this outcome is predicted by Drenick's limit theorem [23], [24] which states that under suitable conditions the reliability of any system approaches the limit given by $S(t) = \exp(-\lambda t)$, where λ, the failure rate, is a constant and $S(t)$ is the survival function. In a practical sense, however, most systems do not last long enough to reach this steady state [24]. For example, a simple system, in which a large number of light bulbs was put into service at $t = 0$, was examined using a computer simulation [25]. The lifetimes of the bulbs were assumed to be normally distributed with a mean lifetime $\tau = 7200$ h = 10 months = 0.83 years, and a $\sigma = 600$ h = 25 days. It was imagined that each failure was immediately detected and replaced. Steady state was not observed until 13.3 years.

5) The addition of a decreasing (infant mortality) failure rate curve with an increasing (wearout) failure rate curve can give a crudely constant rate for some period of time, even in the absence of external temporally random-failure-producing events [26].

B. Modified Traditional Approach [5]

With the passage of time, two facts became evident for microelectronic devices. The first was that infant mortality failures were found to follow a time-dependent failure rate curve that decreased with time for $\sim 10^4$ h, at which time the failure rates were low ($\sim$10 FIT's[2]) in some cases [27]. The thermal activation energies appeared relatively low ($E_a = 0.25$–0.42 eV) for the infant population [27], so that in general it could be expected that even after a burn-in screen at elevated temperatures prior to shipment, an installed population of devices might exhibit some infant mortality failures in the first year or so, prior to the time at which relatively low failure rates would be witnessed. Infant mortality failures are due predominantly to mistakes made during manufacture, and they tend to affect only a small subpopulation of shipped product. Presumably, perfect manufacture would significantly reduce the incidence of such failures.

Wearout failures, by contrast, relate to mechanisms that affect the entire population. The second important fact was that after the wearout mechanisms were understood, it proved possible to "design them out," with the result that wearout failures were no longer likely to occur during the normal service life of microelectronic devices [19]–[21], [26]–[34].

The absence of wearout, and likely persistence of infant failures in the first year, or so, of field use prompted an alternative [26], [35] to the constant failure rate model, whereby the decreasing failure rate of the infant mortality period is modeled by a declining-in-time two-parameter Weibull model, where in simplified notation

$$\lambda(t) = \lambda_1 t^{-\alpha}, \quad 0 < \alpha < 1 \tag{1}$$

and $\lambda_1 = \lambda(t = 1 \text{ h})$. Somewhat arbitrarily, it was assumed that at $t = 10^4$ h, there is a crossover to the constant failure rate model which controls the remainder of the service life. (Of the existing cited [10] procedures, three [11], [13], [14] assume that no infant mortality occurs in shipped product, while three [12], [15], [16] make allowances for such failures.)

The modified traditional approach [26], [35] appears to be doubly conservative. After a time of approximately 10^4 h ($\sim$1 year), it fixes the failure rate to be constant. There is evidence, however, that the observed failure rates in field use [5], [19]–[21], [28]–[33] continue to decline well beyond a year. It also seems conservative because it fixes the constant failure rate at a value that is the approximate equivalent of the maximum failure rate for lognormally distributed wearout mechanisms, where that maximum occurs at approximately 10^6 h ($\sim$100 years).

C. Critique of Traditional Approaches [5]

One goal of the traditional conservative approaches, is to provide safety factors to protect against the inaccuracies present in reliability estimates [17]. A difficulty, however, is that these approaches can produce what are likely to be variable (depending upon the differences and numbers of conservative assumptions) and overly pessimistic assessments. As one example, the predicted reliability [17], using different prediction handbooks, for a memory board with 70 64K DRAM's in a "ground benign" environment at 40°C, varied from 700 FIT's [36]) to 4 240 460 FIT's [37]. As another example [10], it has been calculated that the predicted reliability of one 64K DRAM, in the same environment, varied from 8 FIT's [13] to 1950 FIT's [15]. 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.

The exponential model, which is common to all of the cited traditional prediction procedures [11]–[16], [18], [36], [37], may not, of course, be responsible for all of the incredible variations found [10], [17] among the procedures. Some part of the variations found may be based upon differences in field studies [17], or the sensitivity of the

[2] One FIT is equivalent to one failure in 10^9 operating hours

exponential model to temperature and choice of thermal activation energy [5], [38].

The connection between predicted and actual failure rates may be uncertain for many legitimate and unsurprising reasons.

1) Neither the assemblage of components, nor the component of interest actually failed. The apparent failure was due to an error in socketing, calibration, or instrument reading.

2) The assemblage failure was *not* component-related but due to the improper interconnection of components during a higher level assembly process.

3) The failure of the component was *not* due to a component-intrinsic mechanism but caused by: i) an inadvertent overstress event after installation; ii) latent damage during storage, handling, or installation after shipment; iii) improper assembly into a system; iv) choice of the wrong component for use in the system by either the installer or designer, etc.

4) The component failure was due to a poorly understood mechanism affecting only a small subpopulation of shipped units, and *not* due to one of the well-suited normal mechanisms upon which the reliability prediction was based. Failures may also 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 [39]).

5) The reliability prediction was based upon industry-average values of failure rates found in standards such as MIL-HDBK-217 or its various progeny (e.g., Bellcore TR-NWT-000332), which are neither vendor- nor device-specific.

6) The reliability prediction was based upon vendor-specific and device-specific laboratory-acquired data, but an inappropriate statistical model (e.g., the constant failure rate or exponential model) was used.

7) The predicted failure rate, determined from the use of vendor- and device-specific data in a physically supportable model, turned out to be substantially in excess of the observed field-use failure rate because there was not enough time prior to deployment for the accumulation of the requisite quantity of data to make a more accurate assessment.

Predictions about the future of the weather, the stock market, or the chances of recovery from a potentially fatal disease are of enormous interest and value, even though they may be imperfect in many respects. Despite the recognized deficiencies, items 1)–7) above, associated with making reliability predictions about electronic components, accurate quantitative predictions are considered necessary for making intelligent decisions relating to the deployment and operation of a system. Inventories of spare parts must be gauged, replacement/repair strategies must be implemented, and downtime exposures must be assessed.

The component supplier cannot be responsible for events, 1)–3), that occur subsequent to delivery. For example, it is uneconomical and impractical for a supplier to assure continual operation in the face of arbitrarily large overstress incidents. The component supplier can, however, assist the customer in the failure-mode-analysis process. Item 4), above, which has more to do with making the product reliable than with demonstrating/predicting reliability, requires that the supplier exercise exacting quality control in manufacture, continual surveillance testing/aging on a sample basis, and rigorous certification screening of all shipped product.

Recognizing the potentials for assessment discrepancies and inaccurate predictions of field service reliability connected with 5)–7), the challenge for the vendor's reliability engineer is to make a persuasively accurate quantitative reliability prediction by incorporating current and relevant data with reasonable assumptions into a physically plausible model, and, if possible, to accomplish this prior to field use.

Example One, below, involving the reliability assessment of an electrooptic device, illustrates the use of three well-known prediction methods for the purpose of addressing items 5) and 6). Example Two, connected with item 7), deals with the use of redundancy to demonstrate the required reliability prior to deployment in the face of a severe time constraint.

As noted at the beginning of this section, the existing 217-type reliability standards [11]–[16] have yielded failure rate predictions for the same device that differed by a factor of 6000 in one case [17], and a factor of 240 in another case [10]. These results suggest that, as a general rule, the different 217-type standards will *not* yield comparable failure rate predictions. However, for a particular set of circumstances pertinent to the laser of Example One, the three standards considered, with some qualification, can give failure rates that are in substantial agreement. This chance agreement is seen as an exception to the general rule given above.

1) Example One: Comparisons of Three Prediction Methodologies: A potential customer asks whether a semiconductor laser manufacturer can supply lasers satisfying the following specifications:

Optical output power	$= 3$ mW
Ambient temperature	$= 25°\text{C}$
System lifetime	$= \tau_s(25°\text{C}) = 10^5\text{h}$
Time-averaged failure rate	$= \langle\lambda\rangle = 500$ FIT's
Confidence level	$= C = 50\%$

The deployed lasers are to be operated in a "ground benign" environment, i.e., one that is electrically, mechanically, and thermally tranquil. Thus if field failures occur, it is expected that they will be due to intrinsic device defects. A good deal hinges, therefore, on the credibility of the reliability assessment. To gain added confidence, the customer asks the supplier to employ, and compare the results of, all of the failure prediction methodologies (standards) currently used in the United States.

US MIL-HDBK-217 [7]: The steady-state failure rate prediction for an InGaAs/InGaAsP semiconductor laser can

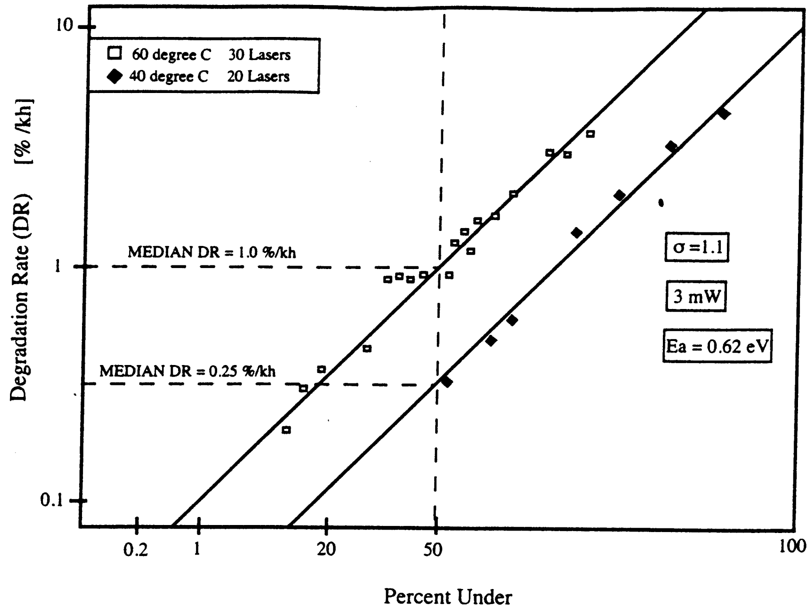

Fig. 2. Temperature accelerated laser aging.

be determined from

$$\lambda = \lambda_b \Pi_T \Pi_Q \Pi_I \Pi_A \Pi_P \Pi_E \tag{2}$$

in which λ_b is the base failure rate, and the Π_i are various multiplying factors whose values depend upon the use conditions. The relevant quantities are [7]

$\lambda_b = 5650$ FIT's

$\Pi_T = 1.0\,(25°\text{C})$

$\Pi_Q = 1.0$ (hermetic package)

$\Pi_I = 0.08$ (peak forward current $I = 25\,\text{mA}$)

$\Pi_A = 0.71$ (50% duty cycle)

$\Pi_P = 1.5$ (in constant optical power operation, end-of-life is defined as a 50% increase in drive current)

$\Pi_E = 1.0$ (ground benign environment).

The resulting value for the steady-state or time-average failure rate is determined from (2) to be

$$\lambda = 480 \text{ FIT's}. \tag{3}$$

Bellcore TR-NWT-000332 [40]: Another well-known standard [40] follows a similar path in which the steady-state failure rate is determined from

$$\lambda = \lambda_b' \Pi_Q' \Pi_S' \Pi_T' \tag{4}$$

The relevant parameters are [40]

$\lambda_b' = 5000$ FIT's

$\Pi_Q' = 0.5$ (hermetic package)

$\Pi_S' = 1.0$ (no electrical stress specification)

$\Pi_T' = 0.15$ (25°C).

Substitution into (4) produces

$$\lambda = 375 \text{ FIT's}. \tag{5}$$

It seems remarkable that (3) and (5) are within 30% of one another, given that the pi-factors are so different in the two schemes.

It is specifically noted in [40] that significant differences in failure rates of optoelectronic devices can be expected among different suppliers. Bellcore, therefore, recommends that field and/or laboratory data be used to support any reliability predictions for components such as lasers. Consequently, the manufacturer's reliability engineer is led to a second Bellcore standard [41], one specifically designed for semiconductor lasers (and other optoelectronic components such as LED's and photodiodes). A testing procedure is provided [41] in which vendor-acquired data for a particular laser are employed in two separate prescribed models to give two kinds of failure rates. The following application of [41] should demonstrate that vendor- and device-specific data alone do not automatically produce credible reliability predictions. The choice of the model to produce a numerical assessment is also important.

Bellcore TA-TSY-000983 [41]:

a) Gradual degradation failures: In the absence of electrical overstressing, the manufacturer knows that the only source of laser failure is that due to gradual degradation which cannot be eliminated by design. Figure 2 shows lognormal distributions of degradation rates (DR) for two populations of lasers, each operated at optical outputs of 3 mW. The degradation rates are a measure of the rate of increase in current required to maintain 3-mW outputs. The analysis that follows is in substantial compliance with [41]. In more detail, including a critical examination of underlying assumptions, an analysis similar to the following has been given in [42].

It is assumed that the temperature dependence of the degradation rates is given by

$$\text{DR} \propto \exp\left[-\frac{E_a}{KT}\right] \tag{6}$$

where E_a is a thermal activation energy, k is Boltzmann's constant = 0.862×10^{-4} eV/K, and T is the absolute temperature. The parallel straight-line fits to the distributions at 40 and 60°C in Fig. 2 yield the values, $\mathrm{DR}_{\mathrm{median}}(60°\mathrm{C}) = 1.0\%/\mathrm{kh}$, $\mathrm{DR}_{\mathrm{median}}(40°\mathrm{C}) = 0.25\%/\mathrm{kh}$, and the lognormal sigma, $\sigma = 1.1$. Using (6), it is found that

$$E_a = 0.62 \text{ eV}. \tag{7}$$

In terms of the initial operating current, $I(0)$, and the increase in current, ΔI, needed to maintain a constant optical output, a conservative definition of end-of-life (EOL) is

$$\left[\frac{\Delta I}{I(0)}\right]_{\mathrm{EOL}} = 50\%. \tag{8}$$

Consequently, the median time to failure at 60°C is

$$\tau_{\mathrm{median}}^{60°\mathrm{C}} = \left[\frac{\Delta I/I(0)}{\mathrm{DR}_{\mathrm{median}}^{60°\mathrm{C}}}\right] = \frac{50\%}{1(\%/\mathrm{kh})} = 50 \text{ kh}. \tag{9}$$

The acceleration factor between 60°C and 25°C is the ratio DR(60°C)/DR(25°C), which can be found using (6) and (7) to be $A(60, 25°\mathrm{C}) = 12.6$. Multiplying (9) by this acceleration factor yields

$$\tau_{\mathrm{median}}^{25°\mathrm{C}} = 632 \text{ kh}. \tag{10}$$

The lognormal sigma is defined by

$$\sigma = \ln\left[\frac{\tau_{50\%}}{\tau_{16\%}}\right] \tag{11}$$

so that with $\tau_{50\%} = \tau_{\mathrm{median}}$, and $\sigma = 1.1$

$$\tau_{16\%}^{25°\mathrm{C}} = 210 \text{ kh}. \tag{12}$$

The values in (10) and (12) are used to draw the straight line on the lognormal probability plot of Fig. 3, from which it is determined that the probability of failure (p) for $\tau_s(25°\mathrm{C}) = 10^5$ h is $p = 5 \times 10^{-2} (5\%)$. Therefore, in units of FIT's obtained by multiplying by 10^9, the time-averaged failure rate due to gradual degradation is

$$\langle\lambda\rangle_{\mathrm{gradual}} = \frac{p}{\tau_s{}^{25°\mathrm{C}}} 10^9 = 500 \text{ FIT's}. \tag{13}$$

b) Random failures: There is, however, an additional requirement contained in the Bellcore standard. A failure rate estimate must be made for all remaining failure modes, for example, a debonding of the laser due to poor soldering, a workmanship issue. The failures other than due to gradual degradation are denominated as "random" failures because the model required for making the reliability determination is the constant failure rate or exponential model.

Assuming that none of these other types of failures was observed during the 3000-h aging of the two populations (one at 40°C and the other at 60°C), it may be shown [42] using the exponential model that the associated random failure rate is given by

$$\lambda_{\mathrm{random}}[\mathrm{FIT's}] = \frac{10^9}{\sum n_i t_i} \ln\left[\frac{1}{1-C}\right]. \tag{14}$$

The Bellcore standard requires using an $E_a = 0.35$ eV for random failures, in the absence of evidence to the contrary,

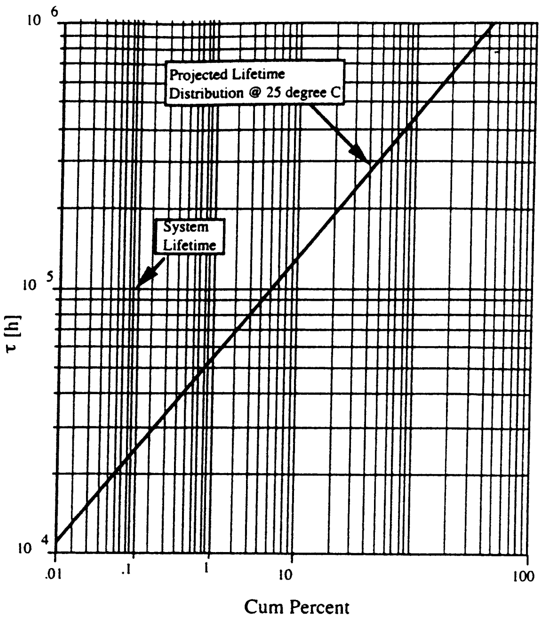

Fig. 3. Projected lifetime distribution at 25°C.

Table 1 Summary of Failure Rates

λ [FITS]			
US [7] MIL-HDBK-217	Bellcore [40] TR-NWT-000332	Bellcore [41] TA-TSY-000983	
480 (total)	375 (total	500 (gradual)	1400 (random)
		1900 (total)	

in order to convert the products $n_i t_i$ at 40 and 60°C into their 25°C equivalents. Using the relevant acceleration factors, the result is

$$\sum_i n_i t_i = (3000 \text{ h})[30\ A(60, 25°\mathrm{C}) + 20\ A(40, 25°\mathrm{C})]$$
$$= 4.92 \times 10^5 \text{ device-hours}. \tag{15}$$

For a confidence level $C = 50\% = 0.5$, substitution into (14) yields

$$\lambda_{\mathrm{random}} = 1400 \text{ FIT's}. \tag{16}$$

The total failure rate is given by the sum of (13) and (16).

$$\lambda_{\mathrm{TOTAL}} = \langle\lambda\rangle_{\mathrm{gradual}} + \lambda_{\mathrm{random}} = 1900 \text{ FIT's}. \tag{17}$$

Comparisons and Critiques: Table 1 summarizes the results previously given in (3), (5), (13), (16), and (17).

The third methodology [41] produced a credible risk assessment for the well-known gradual degradation "wearout" failure mode for semiconductor lasers, because the vendor-manufacturer was permitted to use its own laser degradation data, and a physically supportable (lognormal) model [42]. The approximate agreement of the 500-FIT estimate in Table 1 with the estimates from the first [7] and second [40] methodologies is consistent with the conclusions that the first two methodologies assessed, by some means, *only* the gradually occurring wearout mode, and that the reliability of semiconductor lasers with respect to this mode was similar from one manufacturer to another.

The fact of agreement between the 500-FIT estimate [41] and the 480-FIT estimate [7] should *not* be taken as an endorsement of [7] with regard to any component other than one particular kind of semiconductor laser. For microelectronic components, generally, [7], and its progeny [12]–[16], have been subjected to considerable criticism [10], [17], [43]–[48] a discussion of which is beyond the scope of this paper.

The assessment that appears anomalous, and which *appears* to prevent satisfying the customer's 500-FIT requirement, is the 1400 FIT's from [41] for the so-called "random" failures, i.e., failures due to all causes *other* than gradual degradation. The credibility of such an estimate can be examined in light of answers to the following questions.

1) Has the chosen testing/aging regimen been designed to detect the failures that are most likely to occur?
2) What class of failures are likely to be detected in the regimen in question?
3) For the class of failures to be detected in the chosen aging regimen, what model is appropriate for quantifying the reliability?

Plausible answers appear below.

1) The failures that are most likely to befall a shipped population of lasers, apart from gradual degradation, include errors in laser manufacture, handling, and assembly into a module. Examples include chip debonding due to a partial solder attachment, metal particle shorting in a module with loose wire tails, corrosion due to condensation in a nonhermetic module, ESD-induced leakage paths, and unacceptable increases in the lasing spectral width due to back-reflections. Most of these failures are "seeded" after the laser has been sent to be packaged. Isothermal aging (burn-in) of pre-packaged lasers under laboratory conditions similar to a ground benign environment will *not* detect such failures. The key to eliminating "freak" failures that exist in only a small subpopulation, and which are lot- and time-of-manufacture-dependent is continuous quality improvement [43], [49], [50]. Examples are: a) tightened in-process pass/fail specifications; b) lot yield limits; c) multistage visual inspections; d) temperature cycling and burn-in aging under maximum stresses; e) thorough analysis of in-process fallout and field failures to establish root causes and implement corrective actions; f) establishment of strict change control and supplier monitoring; g) implementation of robust design so that shipped product is less sensitive to external overstresses; h) rejection of all product that has undergone rework at any stage.

2) The class of failures that limited-duration elevated-temperature isothermal aging in a ground benign environment can address are laser-intrinsic, suddenly occurring, and due to mechanisms with modest thermal activation energies. Failures due to gradual degradation, of whatever origin, would be included in the scheme for estimating λ_{gradual}. To detect any laser-intrinsic low thermal-activation energy mechanism that might produce premature failure, electrical current, rather than temperature, is the appropriate screening accelerant [51], [52].

3) The constant failure rate (exponential) model is physically implausible as a description of intrinsic device failures. In the time domain, intrinsic failures are usually designated as infant mortalities (short-term failures) or wearout (long-term failures) [53]. Infant-mortality failures follow a time-dependant failure rate curve that decreases [5] for times at least up to $\approx 10^4$ h. Wearout failures for solid-state components may be well-modeled by either lognormal or Weibull statistics, in which the failure rate either increases or decreases with time, but is never constant in time [54]. The time evolution of intrinsic failures is not random. The constant failure rate or exponential model is typically invoked to describe failures due to temporally random *external* causes. While this would appear to be a reasonable application of the exponential model, examples may be cited to show that, at least conceptually, such a model provides an incorrect description. Consider a case in which the externally imposed overstress events are all of the same magnitude, but the failure thresholds are variable in a population of devices. In the first year after installation, the probability of failure might be large. After several years, only the more robust devices would remain functioning, so that the probability of failure in a subsequent year would be relatively lower. Thus the failure rate should decrease with time [55].

To provide a quantitative estimate of the failure rate for all modes other than gradual degradation, in an elevated-temperature aging regimen [41], in which the laser is otherwise operating under expected use conditions, the best available evidence favors the use of a decreasing failure rate Weibull model [5]. For the usual case in which shipped lasers do *not* undergo a predeployment burn-in, an expression for the time-averaged Weibull model failure rate, for a situation in which no failures are observed during aging, is given by [42]

$$\langle\lambda\rangle_w = \frac{10^9 \ln\left[\frac{1}{1-C}\right]}{\tau_s^\alpha \sum_i n_i (A_i t_i)^{1-\alpha}}. \tag{18}$$

The confidence level is $C = 0.5$ (50%), and the system life is $\tau_s = 10^5$ h. The parameter α in the Weibull model will be chosen as $\alpha = 0.75$, which appears to be an average among many components [56]. The thermal activation energy will be chosen as $E_a = 0.4$ eV [27], a value accepted as plausible for infant failures. For the 60°C aging study, $n = 30, A\,(60{,}25°\text{C}) = 5.14$ and $t = 3 \times 10^3$ h; for the 40°C study, $n = 20, A\,(40{,}25°\text{C}) = 2.11$ and $t = 3 \times 10^3$ h (Fig. 2). Substitution into (18) yields

$$\langle\lambda\rangle_w = 240 \text{ FIT's}. \tag{19}$$

This is roughly a factor of 6 less than the 1400-FIT estimate provided by the implausible exponential model.

One presentation to the customer then would consist of two quantitative assessments, one for gradual wearout degradation (500 FIT's), and another for all other intrinsic laser failures (240 FIT's). The sum, 740 FIT's, which is within 50% of the 500-FIT goal, might be acceptable to the customer, considering all of the uncertainties involved in the 240-FIT estimate.

An alternative presentation might consist of a quantitative and a qualitative assessment. The quantitative assessment (500 FIT's) is rigorous, but incomplete because it accounted for only gradual degradation. The qualitative assessment relies on the fact that a continual quality improvement program [see answer 1) above] has already been put into operation. As a consequence, the price exacted for making high-quality product is too few freak failures, and hence great inaccuracy in the associated failure rate estimate. Thus the qualitative part of the alternate presentation consists of the statement—"There is no reason to think that the 500-FIT goal cannot be achieved, even though it cannot be rigorously demonstrated that no freak failures exist."

2) Example Two: Good Data, Good Model, Not Enough Time, Not Enough Devices: A customer wants a particular device containing an IC to have a time-averaged failure rate $\langle\lambda\rangle = 1$ FIT, at a confidence level $C = 90\%$, for a transoceanic optical-fiber communication system which will be operating in an effectively ground benign environment. The anticipated ambient temperature is 40°C, and the system life, $\tau_s = 25$ year $= 2.19 \times 10^5$ h. It is essential, in this case, that the 1-FIT reliability goal be persuasively demonstrated prior to the deployment of the system, which is scheduled to be one year after the vendor has commenced laboratory aging.

The manufacturer places $n = 125$ IC's on high-temperature (150°C) powered aging for $t_a = 1$ year $= 8.76 \times 10^3$h. No failures are observed. Longer term previously conducted aging of similar IC's by the manufacturer has shown that well-characterized and understood wearout failures do not pose any reliability risk. The 125 IC's chosen for the aging study were the survivors of rigorous thermal cycling and thermal shock regimens designed to eliminate devices prone to low thermal activation energy mechanical-type failures such as chip debonding. The manufacturer has concluded that only intrinsic failure mechanisms of an infant mortality type are of any concern. A declining failure rate Weibull model is deemed appropriate to describe the experimental results. Making some reasonable assumptions, a relationship [5] connecting $n, t_a, \langle\lambda\rangle, C, \tau_s$ and an acceleration factor A is

$$\langle\lambda\rangle = \frac{10^9}{n\tau_s^\alpha (At_a)^{1-\alpha}} \ln\left[\frac{1}{1-C}\right]. \quad (20)$$

Conservative values are chosen for the Weibull model parameter (α) and the thermal activation energy (E_a) used to calculate A. With $\alpha = 0.6, \tau_s = 2.19 \times 10^5$ h, $t_a = 8.76 \times 10^3$ h, $C = 0.90$, $n = 125$, $E_a = 0.4$ eV, and $A(150, 40°\mathrm{C}) = 47.2$, it is calculated from (20) that

$$\langle\lambda\rangle = 65 \text{ FIT's} \quad (21)$$

which is far from the 1-FIT goal. Even if the number of aged devices had been ten times larger, the failure rate, according to (20), would have been 6.5 FIT's, which still exceeds the 1-FIT goal. The probability of failure (p) corresponding to (21) can be computed from (13) to be $p = 1.42 \times 10^{-2} = 1.42\%$.

In order to reach the 1-FIT goal, the manufacturer tells the customer that a redundant unit will be supplied, one that contains two IC's in parallel. In ocean bottom use, both IC's will be powered. The circuit will be configured so that if one IC fails, the other IC will keep the unit operating within specifications. In this instance of "hot" sparing, the failure of the unit will occur only if both IC's fail. Assuming statistical independence, the probability that both nominally identical IC's fail is

$$p' = p^2 = (1.42 \times 10^{-2})^2 = 2.03 \times 10^{-4}. \quad (22)$$

The corresponding failure rate from (13) is

$$\langle\lambda\rangle = \frac{p'}{\tau_s} 10^9 = 0.93 \text{ FIT's}. \quad (23)$$

Thus the introduction of redundancy into the final design has permitted a practical demonstration of a reliability goal that was not possible within the imposed time constraint for an unspared component [57].

The customer accepts this as reasonable, but in view of the increased cost of the unit which has two IC's instead of one, a question is raised about the length of time required to demonstrate a 1-FIT reliability if the 125 IC's at 150°C had been aged beyond one year. From (20), it can be calculated that for $\langle\lambda\rangle = 1$ FIT, the requisite aging time is $t_a = 3 \times 10^8$ h $\approx$ 34 000 years. All agree that this is too long.

IV. Reliability Predictions Versus Reliability Assessments

In 1969, E. O. Codier wrote an article entitled "Reliability Prediction—Help or Hoax?" [58] in which questions were raised as to the validity of reliability prediction and the concept of assigning a failure rate to a component as though it were an intrinsic characteristic, like color. There is no doubt that it is impossible to predict field reliability, where any kind of mishandling or "act-of-God" can cause the product to fail. [Give me a product, a reliability prediction, and a sledge hammer, and I will show you a poor prediction].

Variable stress environments, material variabilities, product quality, and product application and misapplication can 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. Depending on the diversity of the sources of data, failure rates can vary dramatically [6]. As another 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 on some devices. 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 [6].

The problem associated with incorporating manufacturing factors in a reliability model requires understanding the manufacturing process and the potential causes of failure. For example, Westinghouse had a digital integrated circuit package in which the "laser trimming" of the die produced a "rough" unpassivated edge. This edge, after trimming, "rose" approximately 50% of its original thickness above the die surface, thus reducing the clearance between the bonding wire that interconnects the bonding pad with the bonding port. The edge of the die was unpassivated and electrically grounded. The bonding wires after thermal cycling tended to bend, and with reduced clearance, ultimately shorted to the die edge ground strip. This type of failure mechanism is partly design-related, partly quality (workmanship)-related, and partly application-related. With respect to the latter point, this device did not exhibit problems in its commercially designed environment, but did exhibit problems in the military test environment, in which repeated temperature cycles from −54 to 70°C were required [6].

Another challenge with reliability prediction models arises when the model assumes that part failure rates govern equipment reliability. Electronic devices are typically developed over a 9–18-month time span and experience extensive accelerated reliability testing as part of the development cycle. The electronic subsystems of today, orders of magnitude more complex than the device, are given the same approximate time for development, but with far less extensive reliability testing than the device, due essentially to the cost of the subsystems. Thus 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, thermal mismanagement), than in a manufacturing or design defect in the device.

Another reason that reliability prediction is not consistent with field estimates, is that the reliability of devices is often represented by a constant hazard rate model [10]–[16]. The model was originally used to characterize device reliability because earlier data were "tainted by equipment accidents, repair blunders, inadequate failure reporting, reporting of mixed age equipment, defective records of equipment operating times, mixed operational environmental conditions..." [19] (see Section III-A). The totality of these effects conspired to produce what appeared to be an approximately constant hazard rate. Further, earlier devices were fragile and had several intrinsic failure mechanisms which manifested themselves as several subpopulations of infant mortality and wearout failures resulting in a constant failure rate [20], [21]. Most of the above assumptions of constant failure rate do not hold true for present-day devices.

Only laboratory failure analysis can determine true failure causes, although scientifically controlled testing may be incongruous with the "real world" where complex stress histories, mishandling, and misapplication can occur. Hence, the difference between reliability assessment and reliability prediction. Furthermore, because most electronic devices have successful average operating lives of many years, failure information must be either simulated or gathered under accelerated operating conditions which enable the results to be extrapolated to normal operating conditions. When conducting acceleration tests, data extrapolation errors due to the introduction or removal of failure mechanisms at the accelerated conditions must be assessed. Thus a criterion for judging models, their applicability, utility for the future, and design implications must also be established, and a consistent definition of failure, failure mechanisms, failure modes, and confidence levels must be applied.

Up-to-date collection of the pertinent reliability data is in itself a major undertaking, especially when manufacturers make rapid improvements in the manufacturing process. As an extreme example of this concern, it has been noted [59] that the connector models in MIL-HDBK-217 have not been updated for at least 20 years, and were formulated based on data at least that old. 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) than determine which part(s) of the card failed. Suppliers have often not been willing to take on the economic burden of conducting failure analysis—a cost composed of trouble-shooting, failure-site identification, failure-mechanism identification, and root-cause analysis. Suppliers have been, however, eagerly willing to supply spares. For global competition, this attitude has now been revised by the industry leaders.

Field reliability is typically measured in terms of actual equipment removals per operating time while predicted reliability per MIL-HDBK 217 is measured in terms of predicted part failures per operating time. In general, equipment removals and part failures are not equal. Often field removed parts are re-tested as operational (called RTOK for re-test OK) and the true cause of failure is never determined. Considering that the data from MIL-HDBK-217 type models come predominantly from field data, and that most of the parameters in the models are system-related, the accuracy is understandably poor. Typical factors affecting field reliability and their degree of occurrence [6] are:

28% RTOK (could not duplicate)
21% design
18% quality
17% maintenance shop
16% hardware reliability.

Thus failure reporting must be consistent with the development and use of the models. The fact that a part was mishandled, abused, or used or tested improperly must not be overlooked.

V. What are the Challenges and Research Opportunities in Reliability Assessment Modeling?

In an effort to develop highly reliable products in a global market where electronic products are rapidly changing, an auditable reliability assessment methodology must be established; one which accounts for the materials, manufacturing processes, and specific application of the product. Furthermore, because the timely delivery of products is critical to cost-effectiveness, the techniques of the methodology must be automated and executable in an efficient manner.

Many of the challenges in reliability assessment are providing unique opportunities for technical advancement. These include:

* Development of physics-of-failure models, an up-front approach to reliability which utilizes the knowledge of stresses, materials, and structure to identify potential failure mechanisms so as to prevent product failures. A stress refers to the impact of environmental and operating conditions, such as an applied force or an electric field. A failure mechanism refers to the physical process(es) that bring about failure, such as electromigration, corrosion or fatigue.
* Development of mixture models which consider both early and premature wear-out failures caused by the displacement of the mean and variability due to manufacturing, assembly, handling, and misapplication.
* Investigation of the sources of variability contributing to lifetime and failure data.
* Development of multiple-event and repeated failure models that address the problems in lifetime distributions and repairable systems.
* Development of a dual-use alternative to the U.S. Government and military, MIL-STD-785, "Reliability Program for Systems and Equipment, Development and Production," a document which specifies both general requirements and specific tasks for managing reliability programs.[3] The new document should replace the mention of reliability prediction, with reliability assessment.

Challenges still arise about how to physically examine small complex microelectronic structures, how to transform accelerated stress conditions to normal operating conditions, and how to assess the results of tests which are re-test ok or error-not-found (could not duplicate).

VI. Where can a Reader Find other Sources of Information?

There are various sources of current information in the field of reliability prediction, failure analysis, and modeling of electronic equipment. Sources include: *Proceedings of ISHM*; *IEEE Proceedings of the International Reliability Physics Symposium* (IRPS); *Proceedings on the Institute of Environmental Screening* (IES); IEEE Electronic Components Conference; IEEE Transactions on Aerospace Electronic Systems; Reliability and Maintainability Symposium; *SAMPE Technical Conference Proceedings*; IEEE Transactions on Computer Aided Design of Integrated Circuits and Systems; IEEE Transactions on Electronic Devices; IEEE Electron Device Letters; IEEE Transactions on Reliability; IEEE Transactions on Components, Hybrids, and Manufacturing Technology; *Metallurgical Transactions*; *ASME Journalon Electronic Packaging*; *IEDM Technical Digest*; *International Society of Hybrid Microelectronics Journal*; International Symposium on Heat Transfer in Electronic and Microelectronic Equipment; *Journal of Crystal Growth*; *Noncrystalline Solids*; *Journal of the Electrochemical Society*; *Microelectronic and Reliability*; *Quality and Reliability International Journal*; and *Thin Solids Films*.

The authors also have written various related books. In particular:

- F. R. Nash, *Estimating Device Reliability: Assessment of Credibility*. Boston, MA: Kluwer, 1993
- M. G.Pecht, Ed., *Handbook of Electronic Package Design*. New York: Marcel Dekker, 1991.
- M. G.Pecht, *Integrated Circuit, Hybrid and Multichip Module Package Design Guidelines*. New York: Wiley, 1994.
- M. G.Pecht *et al.*, *Quality Conformance and Qualification of Microelectronic Packages and Interconnects*. New York: Wiley, 1994.

[3] As a result of papers such as this one, MIL-STD-785 is currently being re-evaluated and a new standard is being developed in cooperation with the IEEE Reliability Society and the IEEE Standards Organization. The new document should replace the mention of reliability prediction, with reliability assessment.

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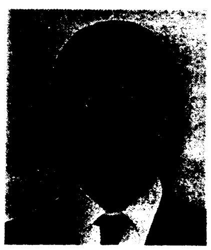

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